NexGen Vertical GaN™ in a Boost Converter

Introduction

There is the ever pressing need to get higher efficiency, higher density, and lower cost for energy conversion. This is true for many power applications and has been for many years. Server manufacturers would like to have more volume and energy dedicated to processing. Data center manufactures would like to have more volume and energy dedicated to data movement and storage. Solar and wind energy harvesting manufacturers would like to move more harvested energy with less loss in conversion and less mass. Hybrid and electric vehicle manufacturers would like to move more energy in less volume and increase battery-based energy storage.

Silicon (Si) based technologies have enabled higher density and efficiency. With the introduction of the MOSFET in the 1970s, higher switching speeds and higher efficiency became feasible, although not really economical until the 1980s. Previously, switching power converter designs were limited by the silicon BJT-based technology that was economically available at the time. Such designs tended to run in the few kilohertz range, which were generally smaller than their analog counterparts, but are considerably larger in volume (see Figure 1) and mass than the modern switching power systems you typically see today. And these designs were previously and are now primarily driven by the silicon-based technology that has matured to this day.

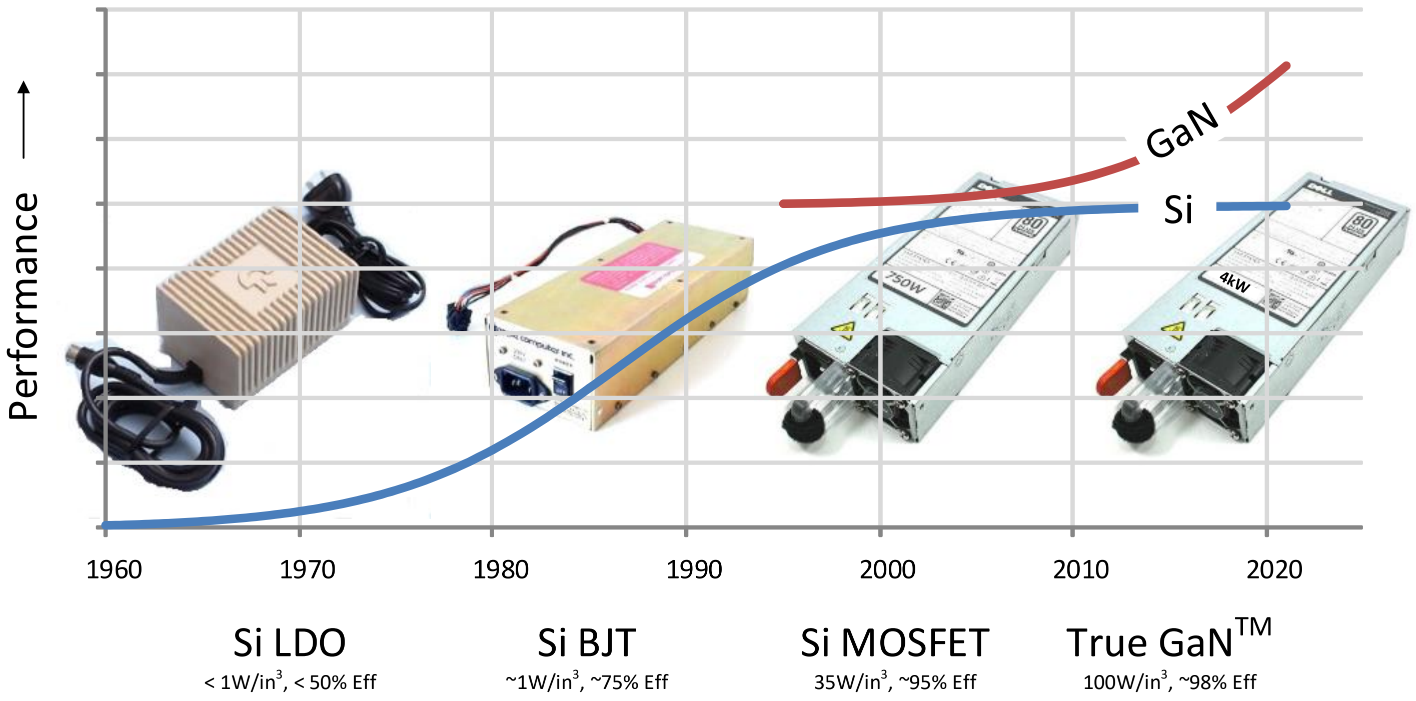

Figure 1: Silicon and GaN Based Trends.

Although silicon-based switching technology has matured and is still maturing, it appears to be near or at its intrinsic limit when it comes to being able to move energy with less loss in less space. This is where gallium nitride (GaN), a compound semiconductor, based technology is a leap beyond the norm. We call this a reset of Moore's Law for Power Electronics, leading to improved fundamental thinking in design practices for Power as well as improved materials, drives, and control systems for Power. This white paper is an example of this.

To demonstrate the unprecedented combination of speed and high voltage capability, NexGen has developed a 100W boost converter switching at 1MHz that steps up a 200V input to an 800V output.

About Vertical GaN™

Vertical GaN refers to the technology created when building GaN devices on GaN substrates. The idea revolves around building very compact device designs that are highly efficient compared to their voltage and R_{ds_on} equivalent silicon counterparts (including SiC). These devices are also more robust largely because of the material properties; additionally, Vertical GaN devices do not suffer from the inherent stresses of crystal mismatch designed into other GaN-based technologies built on non-GaN substrates (e.g. Si and SiC). Further, Vertical GaN enables extraordinarily compact devices, which is due to clever device structures designed to fully exploit material properties of GaN. These devices are therefore cost competitive devices when compared to their silicon counterparts.

Boost Converter

Figure 2 shows the boost converter powered by Vertical GaN. What is notably different than your typical high voltage boost is that this boost can convert energy efficiently at very high frequency. The device runs at a blistering 1MHz, which enables a relatively dense power demonstration for a high voltage 100W converter. As seen from the photo in Figure 2, the demo is relatively compact at 2.735in x 1.85in in its open frame construction.

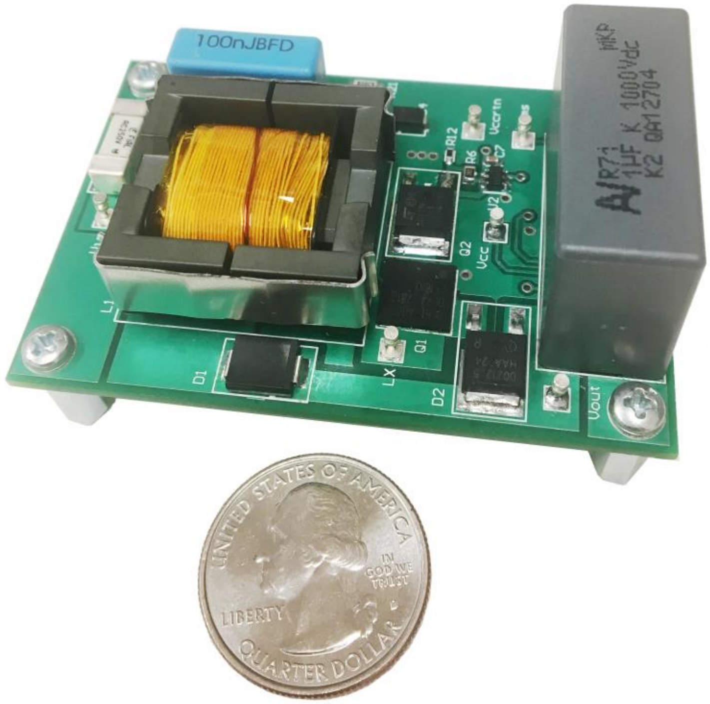

Figure 2: A 100W, 200V to 800V Boost Converter running at 1MHz.

The topology is a classic boost, and it is designed to take a 200V input and deliver 800V while sustaining 100W continuous power at the output of the supply; the complete design is shown in Figure 11. At the heart of the design is a 1-ohm JFET from NexGen's 1st generation of Vertical GaN devices, and it is the main boost switch cascoded with a silicon control switch. The Vertical GaN JFET has incredibly low $C_{oss} \approx 8pF$, $C_{iss} \approx 30pF$, and $C_{rss} \approx 8pF$. NexGen's 2nd generation JFET will further push these limits with improvements to the current process and device design in the form of an enhancement JFET. The high switching frequency makes it possible to have a low capacitance to maintain the output voltage. This low capacitance is implemented with a relatively small film capacitor. Not using an electrolytic capacitor at the output is a net improvement on overall system robustness, notwithstanding the inherent robustness benefits of Vertical GaN devices.

Theory of Operation

The 100W, 1MHz boost converter has been designed to operate at the CCM/DCM board to facilitate Zero Voltage Switching (ZVS) operation with a 240V input and 800V output. A simplified schematic of the power stage is shown in Figure 3.

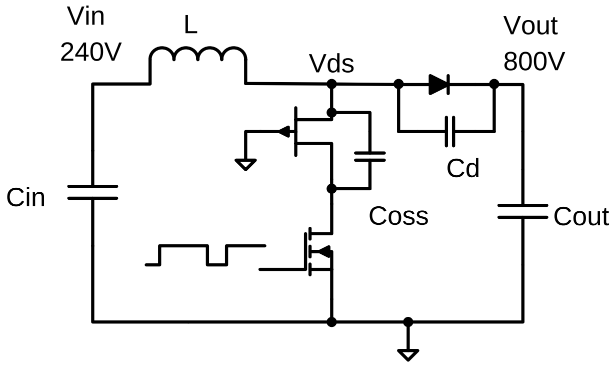

Figure 3: Boost Zero Voltage Switching (ZVS) Power Stage.

Switching Characteristics

Figure 4 displays the four segments of a complete switching cycle for the CCM/DCM boarder, ZVS boost converter.

The first segment duration, t1, is the time it takes for the inductor peak current to charge the total capacitance at the switch node to the output voltage (,). During segment t2, the inductor current decays from the peak value to zero (Equation 6). During segment t3 (Equation 7) the capacitance at the switch node discharges and transfers its energy to the inductor. During the final portion of the cycle, t4, the controller has sensed zero voltage at the drain of the transistor and at this time it is turned on. The inductor current charges from its negative peak value to the positive peak value to complete the cycle (Equation 8).

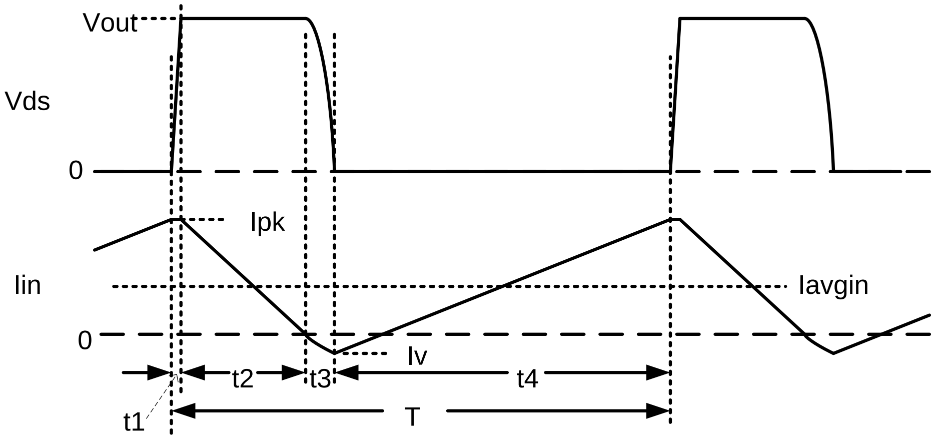

Figure 4: Boost ZVS Discontinuous Mode (DCM) Boarder Timing.

The following equations detail the converter timing throughout a switching cycle. L is the boost inductor value and Cd is the total capacitance seen at the drain of the GaN transistor (Cd+Coss as seen in Figure 3).

- $L = 80\mu H$, Boost inductor
- $C_d = 25pF$, Total switch node capacitance (diode plus GaN)
- $P_o = 106W$, Measured output power
- $\eta = 0.963$, Measured converter efficiency
- $V_{in} = 240V$, input Voltage
- $V_{out} = 800V$, output Voltage
- $P_{in} = \frac{P_o}{\eta} = 110W$, Input power

$$F_{res} = \frac{1}{2\pi\sqrt{L * C_d}} = 3.56MHz\text{, resonant frequency of boost inductor with switch node capacitance (V}_{\text{ds}}\text{)} \quad (1)$$

$$I_v = V_{out} * \sqrt{\frac{C_d}{L}} = 440mA\text{, inductor valley current} \quad (2)$$

$$I_{avgin} = \frac{P_{in}}{V_{in}} = 459mA\text{, average input current} \quad (3)$$

$$I_{pk} = 2 \times I_{avg} + I_v = 2 * 459mA + 440mA = 1.36A\text{, inductor peak current} \quad (4)$$

$$t_1 = \frac{C_d \times V_{out}}{I_{pk}} = \frac{25pF \times 800V}{1.36A} = 14.7ns\text{, Vds charge} \quad (5)$$

$$t_2 = \frac{I_{pk} \times L}{V_{out} - V_{in}} = \frac{1.36A \times 80\mu H}{800V - 240V} = 194ns\text{, inductor current decay} \quad (6)$$

$$t_3 = \frac{1}{4 \times F_{res}} = \frac{1}{4 \times 3.56MHz} = 70ns\text{, ZVS resonant transition} \quad (7)$$

$$t_4 = \frac{(I_{pk} - I_v) \times L}{V_{in}} = \frac{1.8A \times 80\mu H}{240V} = 600ns\text{, inductor current ramp up} \quad (8)$$

$$T = t_1 + t_2 + t_3 + t_4 = 14.7ns + 194ns + 70ns + 600ns = 879ns\text{, switching period} \quad (9)$$

$$F_{sw} = \frac{1}{T_s} = \frac{1}{879ns} = 1.14MHz\text{, switching frequency} \quad (10)$$

Control

The NexGen high voltage boost demonstration board uses a simple, fixed on-time, burst mode regulation scheme. On a cycle by cycle basis, the energy delivered to the output via the inductor is made constant by the setting a fixed on-time. During the off-time an inductor sense winding signals to the controller when the inductor current has decayed to zero, at which time a new cycle is initiated. The output voltage is sensed by a fast “bang-bang” comparator with hysteresis which request the controller’s fixed on-time pulses necessary to meet the load demand at the regulated voltage. Figure 5 shows a simplified example simulation of this gating characteristic for two different loads.

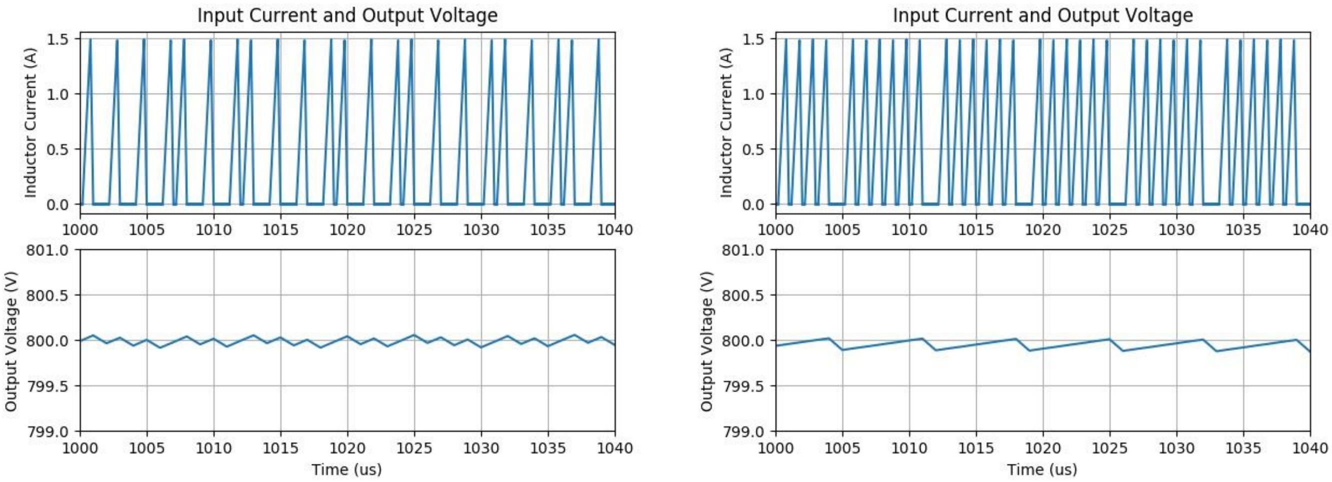

Figure 5: Boost Simulation at 75% Load (left) and 100% Load (right).

Efficiency and Loss Analysis

The dominant losses of the converter are due to the inductor, switching transistor and boost diode.
Other losses are due to the switching transistor gate drive, bias supply, feedback resistor string and current sense resistor. All loss calculations presume that the converter switching is gated 100% of the time at maximum power.

Inductor Losses

Inductor losses occur in two categories – the losses in the wiring of the inductor (Inductor Copper Losses) and the losses in the inductor core (Inductor Ferrite Losses).

Inductor Copper Losses

The inductor losses consist of copper losses at DC, the switching frequency fundamental (1MHz), and a small component at 3MHz. The dominant Fourier components of the inductor current triangle waveform are shown below.

$$I(t) = \frac{I_{pk}}{2} - \frac{4\times I_{pk}\times cos(\omega t)}{\pi^2} - \frac{4\times I_{pk}\times cos(3\omega t)}{3^2\times\pi^2} \tag{11}$$

$$I_{DC} = \frac{I_{pk}}{2} = 0.74A \tag{12}$$

$$I_{1MHzRMS} = \frac{4\times I_{pk}}{\pi^2\times\sqrt{2}} \cong \frac{I_{pk}}{\sqrt{12}} = 0.43A \tag{13}$$

$$I_{3MHzRMS} = \frac{4\times I_{pk}}{9\times\pi^2\times\sqrt{2}} = 68mA \tag{14}$$

Equation 1: Triangle Current Waveform Fourier Coefficients.

Two parallel 32 turn windings of Litz wire (30 strands of #46 wire) are used for the inductor winding. The resistance of the inductor winding vs. frequency is shown in figure 6. The DC resistance was measured at 0.36 Ohms, the 1MHz resistance is 5.8Ω and the 3MHz resistance was 15Ω. The values of resistance used here are measured resistance of a standalone inductor and do not include the additional increase in resistance due to fringing flux associated with the inductor gap while switching.

$$P_{cu} = {I_{DC}}^2 \times R_{DC} + {I_{1MHzRMS}}^2 \times R_{1MHz} + {I_{3MHzRMS}}^2 \times R_{3MHz} \tag{15}$$

$$P_{cu} = 0.74A^2 \times 0.36\Omega + 0.43A^2 \times 5.8\Omega + 68mA^2 \times 15\Omega = 1.34W \tag{16}$$

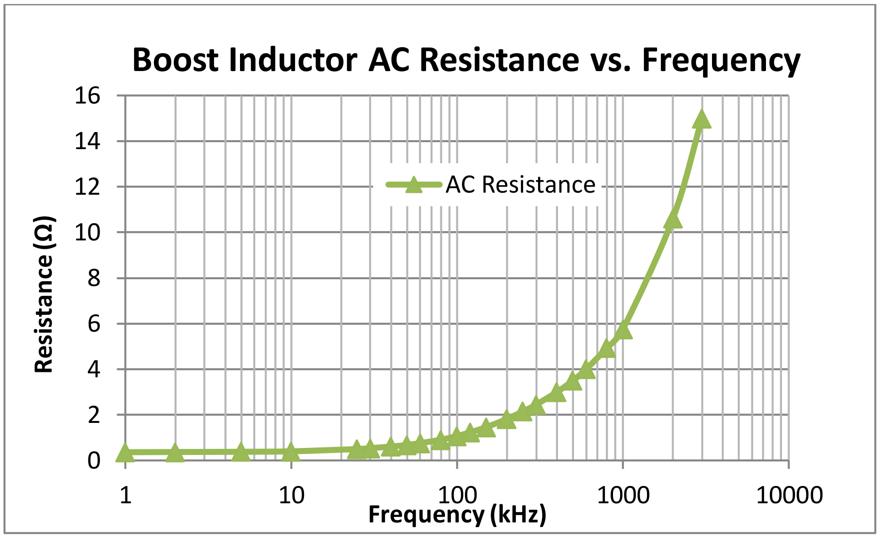

Figure 6: Inductor AC resistance vs. Frequency.

An additional 1 turn low current sense winding on the inductor is used to signal to the controller that the inductor current has decayed to zero at which time the controller initiates the subsequent GaN power device turn on.

Inductor Ferrite Losses

The inductor is designed with an EFD25 Ferroxcube core, using 3F46 material. The volume for the EFD25 core is 3.3cm^3 and the Steinmetz coefficients for the 3F46 material at 1MHz are: C_m=3.3*10^{-10}, x_1=2.5, and y_1=2.34. The derivation of the core loss per cm^3 using the Steinmetz coefficients in shown in equation 17. Where F_{sw} is the fundamental switching frequency and B_{pk} is the peak flux density of the inductor core. The total core loss is calculated in equation 21 where P_v is the loss per cm^3, and V_e is the core volume.

$$P_v = C_m \times (F_{sw})^{x_1} \times (B_{pk})^{y_1} \text{ mW/cm}^3 \tag{17}$$

The peak flux density is derived in Equation 18 where V_{in} is the input voltage ton is the switch on time, with N turns and a core cross-sectional area of A_e in m^2.

$$B_{pk} = V_{in} \times t_{on}/(2 \times N \times A_e) \quad \text{Tesla} \tag{18}$$

$$B_{pk} = 240V \times 578ns/(2 \times 32T \times 58mm^2 \times 10^{-6}) = 37mT \tag{19}$$

$$P_v = C_m \times (F_{sw})^{x_1} \times (B_{pk})^{y_1} = 3.3 \times 10^{-10} \times (1.04 \times 10^6)^{2.5} \times 0.037^{2.34} = 220mW/cm^3 \tag{20}$$

$$P_{fe} = P_v \times V_e = 220mW/cm^3 \times 3.3cm^3 = 726mW \tag{21}$$

Total Inductor Losses

$$P_L = P_{fe} + P_{cu} = 726mW + 1.3W = 2.026W \tag{22}$$

GaN Transistor Losses

The GaN transistor losses fall into two categories – conducted losses when the device is "on" and switching losses when the device transitions from the "on" to "off" state or vice-versa.

GaN Transistor "on" losses

GaN on losses are associated with the $R_{ds,on}$ of the GaN device and the current conducted through the device during the on-time. The Cascode MOSFET loss is assumed to be negligible and therefore not included.

$$I_{rms} = I_{pk} \times \sqrt{t_{on}/3T_s} \tag{23}$$

$$I_{rms} = 1.5A \times \sqrt{578ns/(3 \times 958ns)} = 673mA \tag{24}$$

$$P_{on} = {I_{rms}}^2 \times R_{dson} = 673mA^2 \times 1.5\Omega = 679mW \tag{25}$$

GaN transistor turn-off losses

The turn-off transition of the GaN transistor is lossless. The inductor current charges C_{oss} to V_{out} and discharges the boost diode capacitance. The zero-voltage switching behavior eliminates all turn-on loses associated with discharging C_{oss} and charging the boost diode capacitance.

Boost Diode Losses

The boost diode is a 1200V 2A Silicon Carbide Schottky part number IDM02G120C5. The diode losses consist of the forward current times the forward voltage where the average current is equal to the load current. Examination of the Boost waveforms shows that the diode conduction (effective t_{off}) time is 176ns with a peak current of 1.38A. The Switching period of the converter is 958ns and equals to a switching frequency of 1.044MHz. The average diode current is 127mA corresponding to an output power of 109W at 800V.

$$I_{out} = I_{pk} \times \frac{t_{off}}{T_s} = 1.38A \times \frac{176ns}{2 \times 958ns} = 127mA \tag{26}$$

$$P_{cr} = I_{out} \times V_{fwd} = 127mA \times 2V = 254mW \tag{27}$$

Other Losses

Other losses are associated with the V_{cc} bias (gate drive and control), feedback resistor divider, current sense resistor are included in the total losses section of the table below. The feedback resistor losses can be reduced by increasing the resistance of the string. The reference voltage is terminated with a 10kΩ (R20 of the schematic in Figure 11) resistor and the sting tied to the output voltage is 3.21MΩ. Increasing R20 to 100k and R3, R5, and R9 to 10.7MegΩ would decrease the feedback divider loss by 10x but would also increase the susceptibility to radiated noise.

Vcc Bias and Gate Drive Power

$$P_{cc} = I_{cc} \times V_{cc} = 16.3mA \times 10V = 163mW \tag{28}$$

Total Calculated Loss Summary

Type of Loss	Loss value
Inductor Ferrite and Copper Wire	2.026W
GaN Transistor (“on” losses only, no turn-off losses)	679mW
Boost SiC Diode	254mW
Feedback Divider	199mW
Vcc/Gate Drive	163mW
Current Sense Resistor	162mW
Cascode MOSFET C_{oss}	9mW
Total Calculated Losses	**3.49W**
Pout (Output Power)	109.5W
η (calculated efficiency)	**96.9%**

Measured Efficiency

The final efficiency measured with the center gapped only inductor are shown in Table 1.

Vin (V)	In (mA)	Vout (V)	Iout (mA)	Pin (W)	Pout(W)	η (%)
240	456	800	131.8	109.4	105.44	96.38
240.43	459.1	800.6	132.8	110.38	106.32	96.32
240.18	459	800.7	132.5	110.24	106.1	96.24

Table 1: Measure Efficiency at Regulated Input Voltages.

Table 1 results shows the measured efficiency of approximately 96.4%. This is in comparison to the 97% calculated losses which do not include the additional losses of the fringing flux due to the center gap. Since the largest contributor to calculated losses is still the Inductor winding, any additional improvements in efficiency will focus on the inductor.

Switching Waveforms

Various waveforms of the converter operating at 100W are shown in Figure 7 through Figure 10 below.

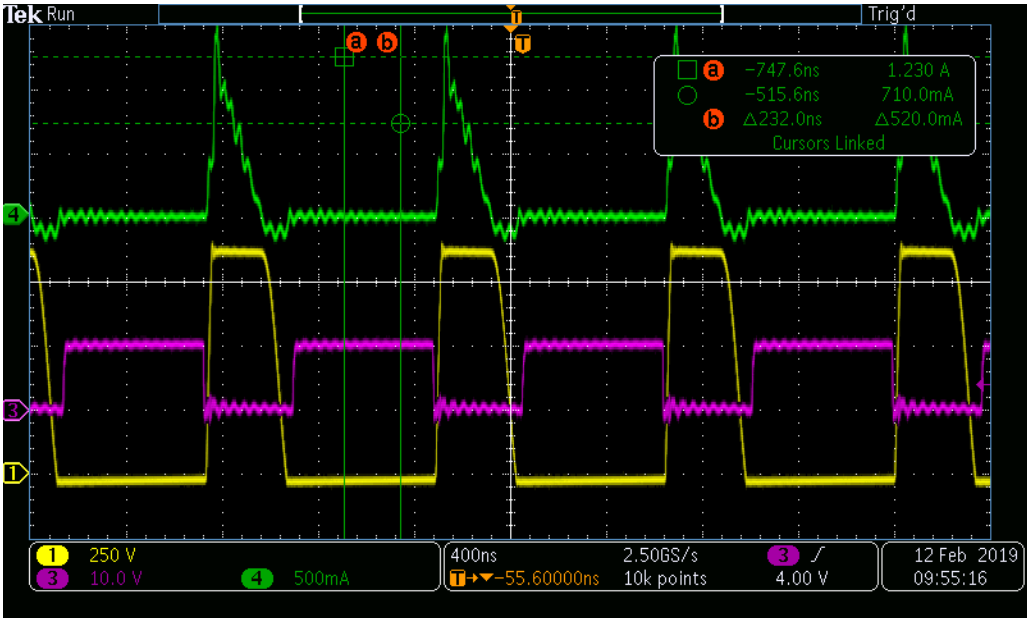

Figure 7: Switching Waveform, 400nsec/div, Yellow Vds 250V/div, Purple Cascode MOSFET gate drive 10V/div, Green Boost Diode Current 500mA/div.

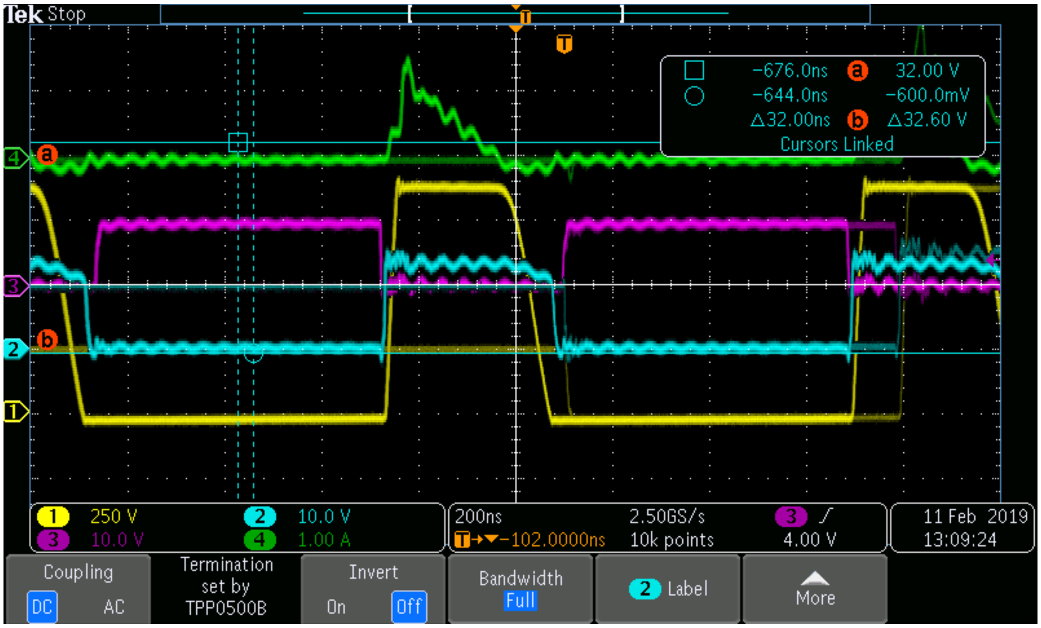

Figure 8: Switching Waveform 200nsec/div, Yellow Vds 250V/div, Purple Cascode MOSFET gate drive 10V/div, Green Boost Diode Current 1A/div, Blue Vds Cascode MOSFET 10V/div.

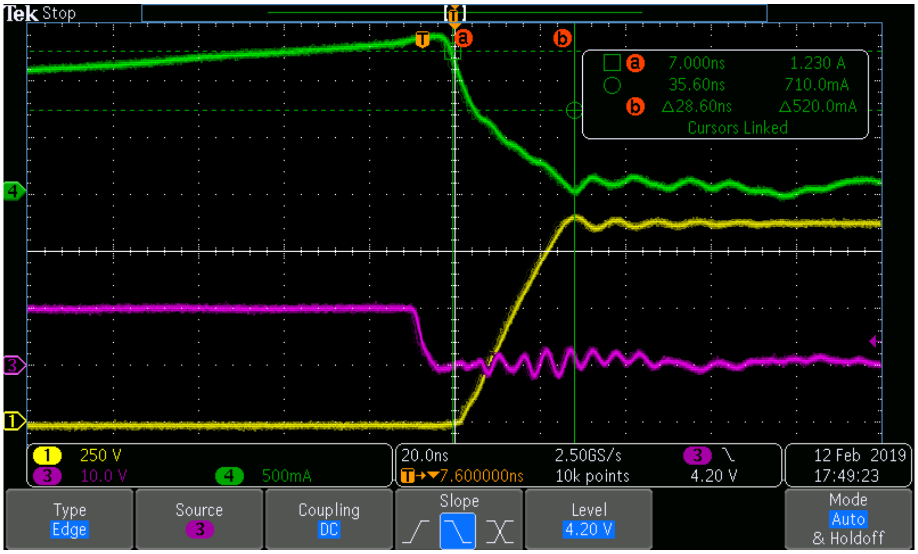

Figure 9: Turn off with drain current, 20 ns/div, Yellow Vds 250V/div, Purple Cascode MOSFET gate drive 10V/div, Green Drain Current 500mA/div.

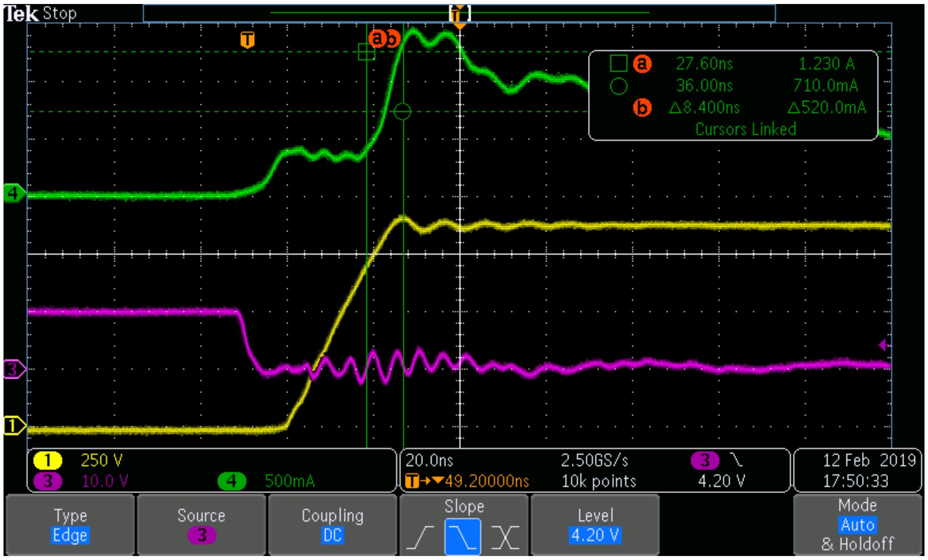

Figure 10: Transistor turn off with Diode Current 20nsec/div, Yellow Vds 250V/div, Purple Cascode MOSFET gate drive 10V/div, Green Boost Diode Current 500mA/div.

Summary

With Vertical GaN, high frequency and high voltage is viable and the future of power electronics. Vertical GaN devices enable efficient, high frequency designs. With high frequency comes higher power density. With higher power density comes less materials in components, less board area, less copper, and less mass. With less materials the power system cost is reduced.

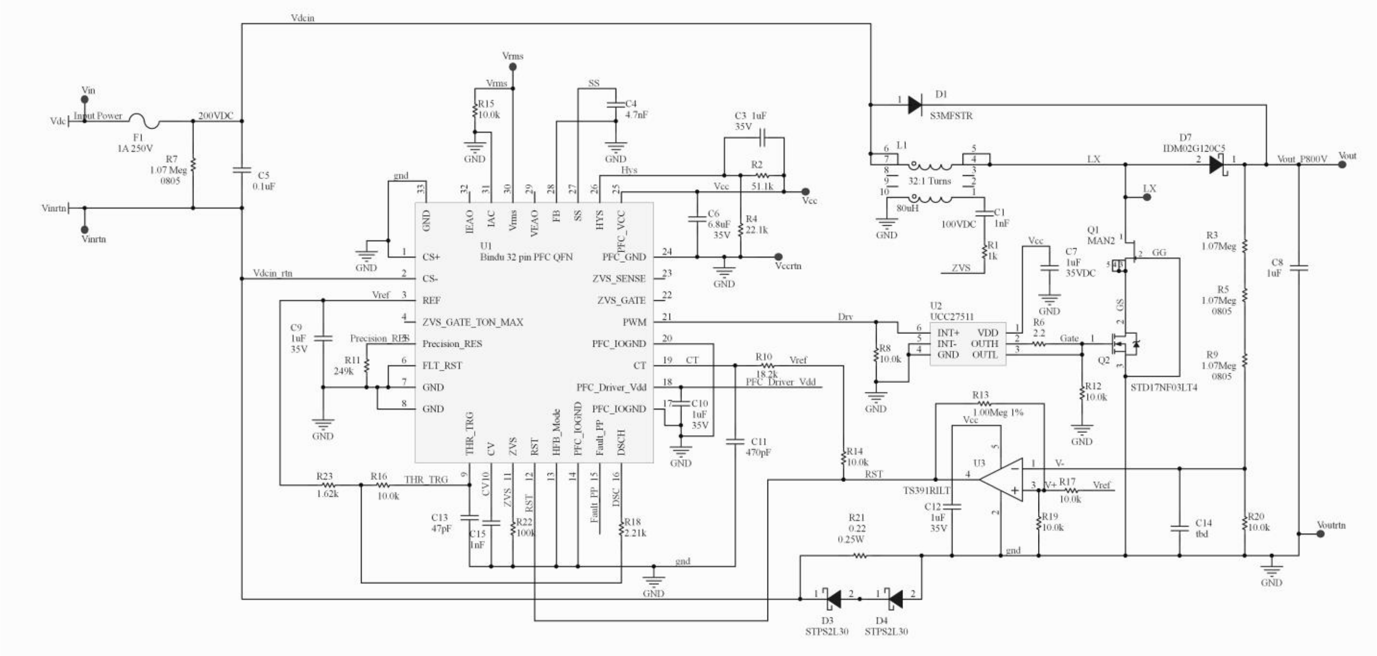

Figure 11: Boost Board Schematic.

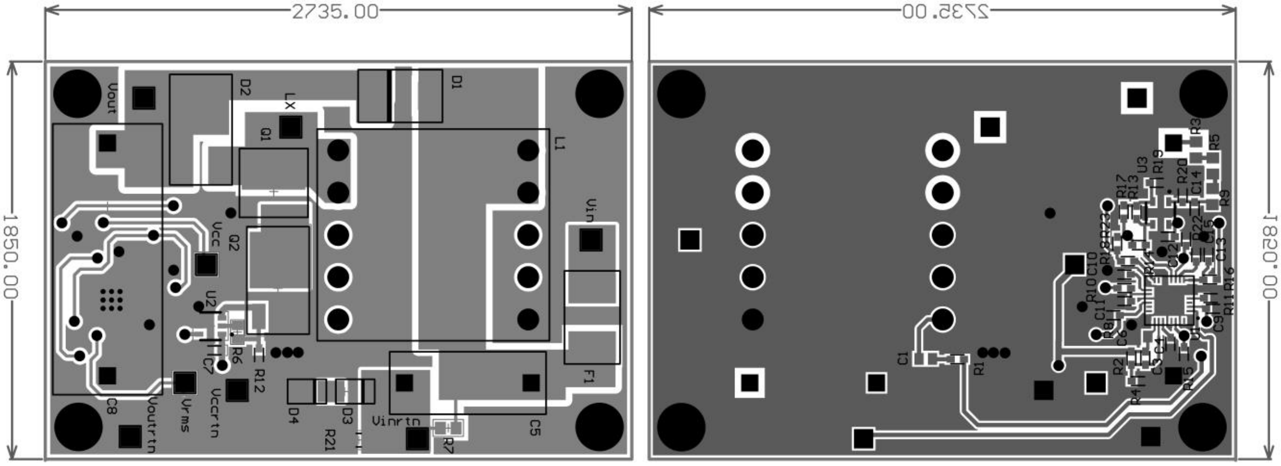

Figure 12: Board Layout Top (left) and Bottom (right).

Designator	Value	Description	Manufacturer	Manufacturer Part Number	Footprint	Qty
C1	1nF	CAP CER 1000PF 50V C0G/NP0 0805	Kemet	C0805C102J5GACTU	CC2013-0805HD	1
C3, C7, C9, C10, C12	1uF	CAP CER 1UF 35V X5R 0603	TDK	C1608X5R1V105M080AB	CC1608-0603HD	5
C4	4.7nF	CAP CER 4700PF 50V C0G/NP0 0603	Murata Electronics North America	GRM1885C1H472JA01D	CC1608-0603HD	1
C5	0.1uF	CAP FILM 0.1UF 5% 400VDC RADIAL	KEMET	PHE450KB6100JR17	CF_TH_L18.5_T7.4_S15	1
C6	6.8uF	C2012X5R1V685M125AC	TDK Corporation	C2012X5R1V685M125AC	CC2013-0805HD	1
C8	1uF	CAP FILM 1UF 10% 1KVDC RADIAL	KEMET	R71QR41004010k	CF_TH_L27.5_T12_S22	1
C11	470pF	CAP CER 470PF 100V C0G/NP0 0603	Murata Electronics North America	GCM1885C2A471JA16D	CC1608-0603HD	1
C13	47pF	CAP CER 47PF 100V C0G/NP0 0603	Murata Electronics North America	GCM1885C2A470JA16D	CC1608-0603HD	1
C14	n/a	Capacitor, MLCC 0805	n/a	n/a	CC1608-0603HD	1
C15	1nF	CAP CER 1000PF 50V X5R 0603	TDK Corporation	CGA3E2X5R1H102K080AA	CC1608-0603HD	1
D1	S3MFSTR	DIODE GEN PURP 1KV 3A SMC	ON Semiconductor	S3M	SMCJ	1
D3, D4	STPS2L30	DIODE SCHOTTKY 30V 2A SMA	STMicroelectronics	STPS2L30A	SMA	2
D7	IDM02G120C5	DIODE SCHOTTKY 1200V 2A TO252-2	Infineon Technologies	IDM02G120C5XTMA1	T_TO-252-2	1
F1	1A 250V	FUSE BOARD MOUNT 1A 250VAC 2SMD	Littelfuse Inc.	0464001.DR	Fuse 464 Series 1A 250V	1
L1	SMD inductor	EFD25 Transformer Bobbin	Ferroxcube	3F46 EFD25 Core	EFD25	1
LX, Vcc, Vccrtn, Vin, Vinrtn, Vout, Voutrtn, Vrms	Mill Max	TERM TURRET SINGLE L=3.96MM	Mill-Max Manufacturing Corp.	2308-2-00-44-00-00-07-0	Test Point	8
Q1	MAN2	GaN JFET N-Channel, 1200V 1 Ohm	Nexgen Power Systems	MAN2	T_PQGN	1
Q2	STD17NF03LT4	MOSFET N-CH 30V 17A DPAK	STMicroelectronics	STD17NF03LT4	T_DPAK_MOSFET	1
R1	1k	RES SMD 1K OHM 0.5% 1/10W 0603	Yageo	RT0603DRD071KL	CR1608-0603HD	1
R2	51.1k	RES SMD 51.1K OHM 1% 1/10W 0603	Panasonic Electronic Components	ERJ-3EKF5112V	CR1608-0603HD	1
R3, R5, R9, R7	1.07Meg	RES SMD 1.07M OHM 1% 1/8W	Vishay Dale	CRCW08051M07FKEA	CRES2012-0805	4
R4	22.1k	RES SMD 22.1K OHM 1% 1/10W 0603	Panasonic Electronic Components	ERJ-3EKF2212V	CR1608-0603HD	1
R6	2.2	RES SMD 2.2 OHM 5% 0.4W 0805	Rohm Semiconductor	ESR10EZPJ2R2	CC2013-0805HD	1
R8, R12, R14, R15, R16, R17, R19, R20	10.0k	RES SMD 10K OHM 1% 1/10W	Vishay Beyschlag	MCT06030C1002FP500	CR1608-0603HD	8
R10	18.2k	RES SMD 18.2KOHM 0.1% 1/10W 0603	Yageo	RT0603BRD0718K2L	CC1608-0603HD	1
R11	249k	RES SMD 249K OHM 1% 1/10W 0603	Yageo	RC0603FR-07249KL	CC1608-0603HD	1
R13	1 Meg 1%	RES 1 MOHM 1% 1/10W 0603	Rohm Semiconductor	SFR03EZPF1004	CC1608-0603HD	1
R18	2.21k	RES 2.21K OHM 1% 1/10W 0603	Vishay Dale	CRCW06032K21FKEAC	CR1608-0603HD	1
R21	0.22	RES 0.22 OHM 1% 1/4W 1206	Stackpole Electronics Inc	RMCF1206FTR220	CRES3216-1206	1
R22	100k	RES SMD 100K OHM 1% 1/4W 0603	Rohm Semiconductor	ESR03EZPF1003	CC1608-0603HD	1
R23	1.62k	RES SMD 1.62K OHM 1% 1/10W 0603	Vishay Dale	CRCW06031K62FKEA	CR1608-0603HD	1
U1	Nexgen PCF Controller	PFC ZVS PWM Controller	Nexgen Power Systems	PFC1	QFN 32 5x5	1
U2	UCC27511	IC GATE DVR LOW SIDE 1CH SOT23-6	Texas Instruments	UCC27511DBVR	SOT23-6	1
U3	TS391RILT	IC COMPARATOR SGL LP SOT-23-5	STMicroelectronics	TS391RILT	SOT23_5	1

Table 2: Bill of Materials (BOM) for Boost Board.

Revision History

Revision	Date	Description of Change
V00	10/30/2018	Initial draft.
V01.1	5/30/2019	Detailed User guides Additions
V01.2	6/6/2019	Syntax edits
V02.1	6/6/2019	Formatting edits and rewriting some paragraphs
V02.2	6/6/2019	Re-Formatting equations