COLLEGE OF ENGINEERING, PUNE

DEPARTMENT OF ELECTRONICS & TELECOMMUNICATION
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B.TECH FINAL YEAR PROJECT PHASE I

TITLE:

DESIGN & STUDY OF HIGH POWER, HIGH FREQUENCY DC-DC POWER CONVERTER USING GALLIUM NITRIDE HeMTs

PRESENTED BY:

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ON 09/12/19

PROJECT GUIDE:

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1. Introduction

a. Motivation

Since the dawn of the electronics age over a hundred years ago, power design engineers have been on a quest for the ideal switch, one that will rapidly and efficiently convert raw electrical energy into a controlled, useful flow of electrons. Silicon quickly became the material of choice for the semiconductor transistor, not only because of its fundamentally superior electrical properties, but it was also cheap to produce.

Silicon power MOSFETs have now reached the end of the road in delivering better performance at a constantly declining cost. Fortunately, the quest for the ideal switch that has infinitely fast switching speed, no electrical resistance, and a lower cost, has not slowed and new base materials upon which to build high performance power conversion transistors and integrated circuits have emerged.

The leading candidate for taking electronic performance to the next level and a reactivation of positive momentum of Moore's Law is gallium nitride. GaN's ability to conduct electrons more than 1000x more efficiently than silicon, while being able to be manufactured at a lower cost than silicon has now been well established. Silicon is out of gas, and a new, higher performing semiconductor material is emerging – GaN is on the rise.

GaN HEMTs have been offered commercially since 2006, and have found immediate use in various wireless infrastructure applications due to their high efficiency and high voltage operation. A second generation of devices with shorter gate lengths will address higher frequency telecom and aerospace applications.

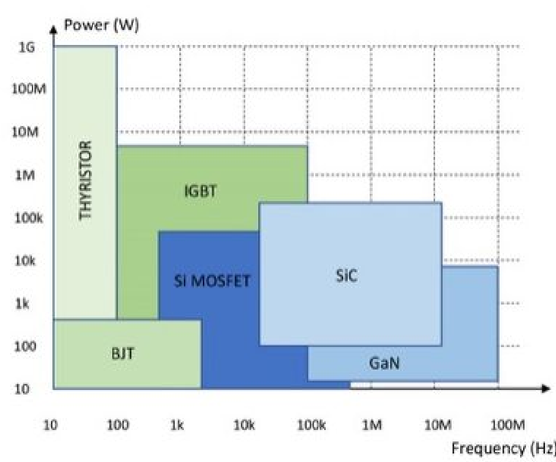


Fig: Ideal use range of semiconductors

Soon the price difference between Si and GaN will be appreciable in the favour of GaN and almost all circuits will use GaN in the power and frequency range where it beats the performance of Si.

Thus. the problem statement for this project has been defined as:
To build and test a 36V to 48V boost high frequency boost converter (power ~750W) to be cleanly integrated with a 48V DC bus. The high frequency will have to be designed from 200kHz to 1MHz, to test the limits of the converter.

b. Targets

- To study the application of Gallium Nitride HeMTs instead of Si FETs in a DC-DC converter
- To design a high power density boost converter prototype (~ 24W/in3) using DipTrace with 20% less power loss and 3X the power density.
- To implement soft switching for minimal losses at highest frequency operation
- To characterize the GaN converter with respect to that designed from a Si MOSFET using SIMetrix
- To fabricate and test the prototype with a DC bus

c. Applications

These unique features of GaN make it attractive for specific applications.
take advantage of GaN attributes:

- lower on resistance giving lower conductance losses
- faster devices yielding less switching losses
- less capacitance resulting in less losses when charging and discharging devices
- less power needed to drive the circuit
- smaller devices taking up less space on the printed circuit board
- lower cost

GaN-based electronics (not pure GaN) has the potential to drastically cut energy consumption, not only in consumer applications but even for power transmission utilities. It is also used in high-RF, power-hungry applications like those required to transmit signals over long distances or at high-end power levels (such as radar, base/ transceiver stations [BTS], satellite communications, electronic warfare [EW], etc.

In this project, the aim is a study of GaN HeMTs and the conversion efficiency of a DC-DC boost circuit. The design will be made agnostically, so it can be modified for various applications in the future.

2. Literature Review

a. IEEE Papers

From a thorough perusal of IEEE journals and conference proceedings since 2002, the following concepts and advancements relevant to this projects are collated. Wherever possible, references are provided in the footnotes.

i. Gallium Nitride High electron Mobility Transistors (HeMT)

From [1][1] we learn that Gallium Nitride (GaN) HEMT's are promising devices for both commercial and military electronic applications 1 up to 30 GHz and beyond. These GaN-based devices are capable of RF power performance at least one order of magnitude larger than current technologies. The three commercial communication bands of special interest are L/S-band for wireless infrastructure applications, Ku-band for VSAT systems, and Ka-band for Broadband VSAT systems.

Earliest 0.3um GaN HEMTs exhibited 22 dB of power gain (see Figure 5), corresponding to 8 dB of additional power gain (per stage) at 2 GHz over current silicon devices.

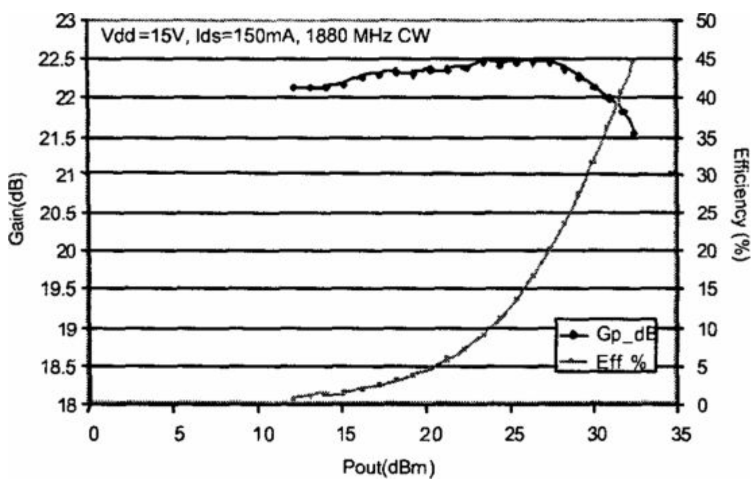


Fig: Power Gain Parameters of GaN

[1] J. Shealy et al., "Gallium nitride (GaN) HEMT's: progress and potential for commercial applications," 24th Annual Technical Digest Gallium Arsenide Integrated Circuit (GaAs IC) Symposium, Monterey, California, USA, 2002, pp. 243-246.

ii. Advantages over Si

From [3][2], 600 V class silicon power devices such as IGBTs and MOSFETs are widely used in power supplies, UPSs and motor drives, which are the most important applications of switching power devices. Characteristics of these devices have been improved to the level of the specific on-resistance RonA=10 mΩcm2 (IGBT) to 35 mΩcm2 (MOSFET) with switching frequency up to 200 kHz. Despite the recent improvement of silicon devices, further improvement of RonA and switching frequency will become very difficult due to the silicon material property limitations. As a candidate for future 600 V class power devices, high voltage AlGaN/GaN heterostructure devices have been demonstrated recently and showed attractive characteristics of low RonA of 1.7 mΩcm2 at 1300 V thanks to the material properties of both the high electron mobility in two-dimensional electron gas channel and the high critical electric field.

In the [3], we have the comparison of Si, SiC, and GaN based Isolation Converters for Onboard Charger Applications where the converters are tested at best performance characteristics. At best case, we can expect a 99% efficiency in converter.

TABLE I. COMPARISON OF SI, SIC AND GAN BASED ISOLATION CONVERTERS

	Si isolation converter	SiC isolation converter	GaN isolation converter
Power (kW)	5.2	6.8	6.6
Volume (L)	1.34	1.02	0.63
Mass (kg)	3.27	2.35	0.69
Power density (kW/L)	3.9	6.7	10.5
Specific power (kW/kg)	1.6	2.9	9.6
Peak efficiency (%)	98.4 (40 kHz)	99.0 (100 kHz)	99.0 (100 kHz)

[3]

The same GaN device characteristics as the chosen one, show the above outputs for a converter with a 100KHz switching frequency and following input characteristic.

[2] W. Saito, Y. Takada, M. Kuraguchi, K. Tsuda, I. Omura and T. Ogura, "600V AlGaN/GaN power-HEMT: design, fabrication and demonstration on high voltage DC-DC converter," *IEEE International Electron Devices Meeting 2003*, Washington, DC, USA, 2003, pp. 23.7.1-23.7.4

[3] Comparison of Si, SiC, and GaN based Isolation Converters for Onboard Charger Applications, Gui-Jia Su Power Electronics & Electric Machinery Group Oak Ridge National Lab Knoxville, TN, USA

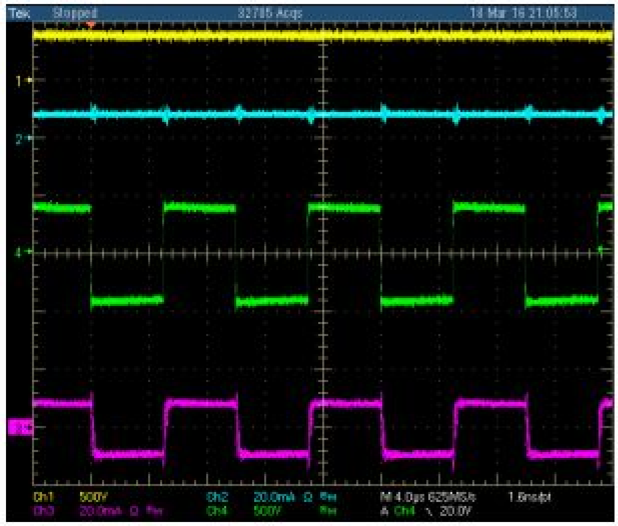


Fig: . Typical operating waveforms of the GaN converter at 100 kHz. From top: input dc bus voltage, 500 V/div; input dc current, 20 A/div; primary input Voltage 500 V/div; and transformer primary current, 20 A/div. Time: 4 μs/div

Characteristics of GaN wrt Si for converter:[4]

- The gate charge values (Qgs, Qgd, and Qg) of GaN HEMT are five to ten times smaller than those of the Si MOSFET. As a result, with the same level of gate current, the gate
- capacitance of a GaN HEMT will be charged within ⅕ the time needed by Si MOSFET, which further translates into the fast turn-on and turn-off of the GaN conduction
- Channel.
- The GaN HEMT has a maximum on-state resistance RDSon of only 7 mΩ, which is less than half of the value for Si MOSFET (15 mΩ) and thus indicates halved conduction loss during operation.
- While the body diode of Si MOSFET has reverse recovery effect because of the p–n junction nature of the parasitic diode in a MOSFET, GaN HEMT has a “major carrier body diode” that features zero reverse recovery.
- Thermal resistance RθJC of GaN device is slightly higher than that of Si MOSFET, which is mainly because thermal contact resistance formed between GaN epilayer and Si substrate on which it is grown.

[4] Performance Evaluation of GaN-Based Synchronous Boost Converter under Various Output Voltage,Load Current, and Switching Frequency Operations Di Han* and Bulent Sarlioglu†, Journal of Power Electronics, Vol. 15, No. 6, pp. 1489-1498, November 2015

Expected Effect on Efficiency of Converter

The same paper demonstrates that for the following boost conversion topology and specifications, we can expect the following results.

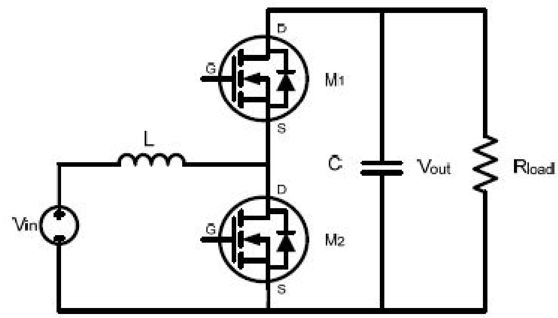


Fig. 1. Schematic of the boost converter under study.

TABLE II
SPECIFICATIONS OF THE BOOST CONVERTER UNDER STUDY

Specifications	Value
Low side voltage V_{in} (V)	24
High side voltage V_{out} (V)	48–80
Power rating P (W)	160
Switching frequency f (kHz)	100–300
Chock inductor L (μH)	20
DC bus capacitor C (μF)	60

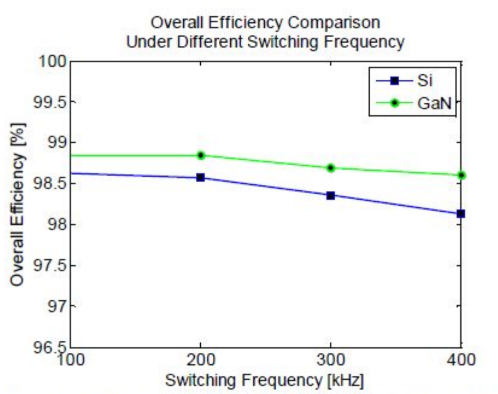


Fig. 7. Converter efficiency under different switching frequencies, 2-A load current, and 48-V output voltage.

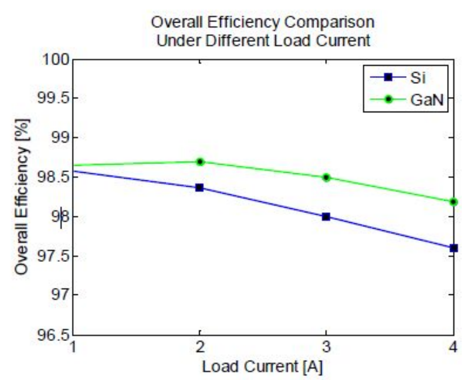


Fig. 5. Converter efficiency under different load current, 48-V output voltage, and 300-kHz switching frequency.

Lastly, discussions on GaN converter performances are given in the paper. The GaN converter shows 0.08%–0.77% higher efficiency than the Si converter over the whole operating range, featuring a maximum loss reduction of 1.23 W and a maximum temperature rise of approximately 51 °C.

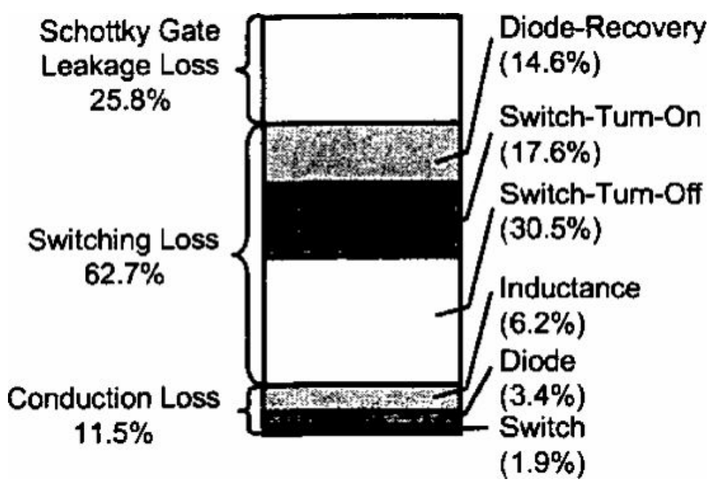
b. Application Notes & Choice of Switch

Infineon's CoolGaN 600V series has the following features that make the family especially suited to our application.

- Highest efficiency for SMPS
- Highest power density, small and light design
- Surface mount packaging ensures that switching capabilities of GaN are fully accessed
- Easy to use thanks to a compelling driver IC portfolio

c. Losses expected in Converter

This is a demonstration of the losses in early GaN converters from a journal paper in 2008.



In the future, a more detailed loss characteristic is studied in papers following it. It shows how GaN fabrication technology has helped maintain low semiconductor loss characteristics throughout converter operation range, and at various frequencies.

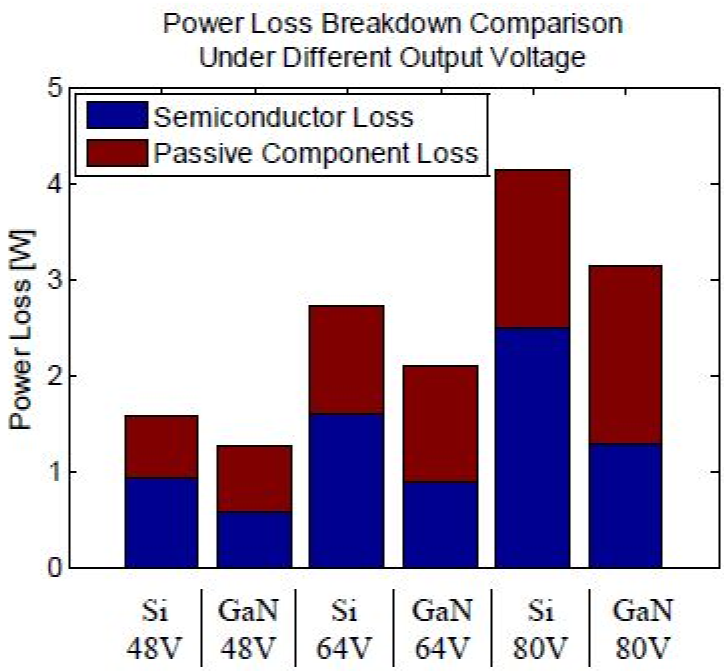


Fig. 8. Converter loss breakdown for different output voltage, 2-A load current, and 300-kHz switching frequency.

The passive component loss, which is mainly the loss on the inductor windings, presents itself as the major loss component in the GaN converter under most operating conditions, particularly under high current load. As a result, further reducing the semiconductor loss on devices will be less effective without minimizing the inductor loss, if the goal is to optimize the overall efficiency of the converter.

First, the major saving in a converter by using a GaN device comes from the reduction in conduction loss, particularly under large load conditions. Although the switching speed of GaN device is considerably faster than the Si device, the switching loss of the GaN converter is not significantly reduced because of the relatively large energy stored in the device output capacitor, as discussed earlier in Section II. This stored energy is lost in the conduction channel every time the device turns on and is irrelevant to the switching speed of the device.

d. Considerations for Driving Circuit

Negative Vni

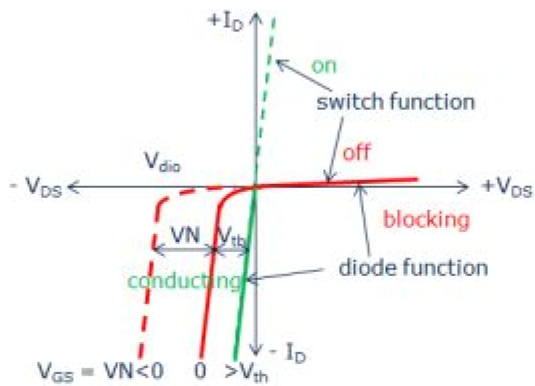


Fig: Reverse conduction of GaN HeMT

If a negative voltage VN is applied at the gate to switch a GaN transistor off, it is still able to conduct in the reverse direction, but the voltage drop will increase by VN. This is not a GaN-specific behavior, as any lateral symmetric transistor would behave similarly.

Hard-switching calls for fast transients. If in Figure 10b switch Swa is switched on, the switching node swings from 400 V to 0 at a very steep slope that might exceed 200 V/ns. Clearly the passive switch Swb then has to be kept off during this transient, otherwise cross-conduction and high losses would result. A falling switching node is equivalent to a fast rising drain node of Swb. From Figure 6, a rising drain leads to current into CGD, which has to be sunk by the gate driver. If the voltage drop between gate and source exceeds Vth, the transistor turns on, thereby increasing switching current and losses. This effect is often called “re-turn-on”. It can be minimized by a low driving impedance and, more efficiently, by a low driving voltage level in the offstate.

Obviously, e-mode GaN HEMTs are particularly sensitive to re-turn-on due to their low threshold voltage. And this is why the shift to a negative off voltage, resulting from the proposed gate drive, is highly valuable in hardswitching. It is the initial negative voltage VNi, as discussed in section 4.1, that appears at the gate of the passive transistor (diode) and helps to avoid re-turn-on during the switching transient.

A further effect of hard-switching is voltage overshoot. The worst situation happens at the passive transistor (“diode”) during the falling edge of the switched current. It must therefore be ensured that even in the worst case with VNf = 0 at the switch (fastest switching) the voltage ratings are not exceeded. Besides, situations with both transistors in the off-state for extended periods require careful consideration, as a switch-on event with VN= 0 at the diode leads to a significant re-turn-on. As such situations only happen at low rates, if at all, the resulting high switching loss is of minor importance; however, the increased current may lead to higher voltage overshoot, although strong re-turn-on also has a damping effect on over-voltage. Anyway, the situation can be avoided, if after long off-times for both switches the diode is always the first to be switched on.

Soft Switching

“Soft-switching” means to avoid simultaneous high current and high voltage in a power switch, i.e. to operate the switch at either zero voltage or zero current. This can be achieved by utilizing resonant transitions to charge the switching node capacitance, as is done in the well-known LLC topology of the DC-DC converter stage following the PFC stage in today’s most common SMPS architecture.

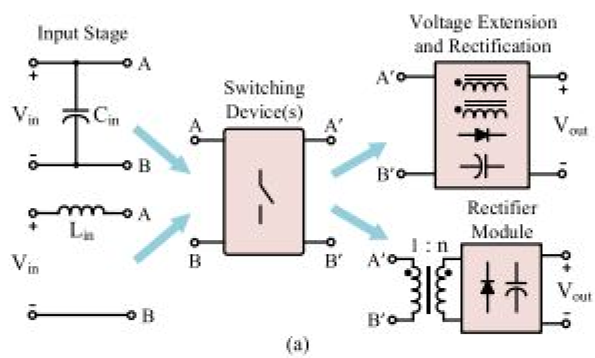
As soft-switching yields much slower voltage transients with typical slopes of only a few V/ns, the RC driving network should be slightly changed to optimize performance. In particular there is no need for significant negative off-voltages, and thus VNi should be chosen to be as low as possible. Thus we elect to use a soft switching driver IC at a frequency above 200kHz in our design.

3. Design Considerations

Our primary target is to improve efficiency and reduce footprint size.

a. Non Isolated Boost Converter Design

In the interest of conserving space, a single phase, non-isolated boost converter model is chosen. A MOSFET switch is available in the library, as the HeMTs are relatively new and designs are proprietary to individual manufacturers.



Specifications:
750W, 36V 20A input, 48V 16 A (technically 15.6A)
Freq: 200kHz

Assumptions:
Vin (minimum) = 36V
Efficiency = 0.9
Voltage variation = 1%
Current variation = 30%

Calculations:
Duty cycle D= 1- (Vin * E)/Vout
= **28.2%**

del I= Iripple* Iout* Vout/Vin
= **6.4A**

L= Vin * (Vout-Vin)/ (del I * fs* Vout)
= **7.03125e-6**

Del V= **0.48V**

C= I/fs * D/dv
= **2.167e-5**

Rload= **3ohm**

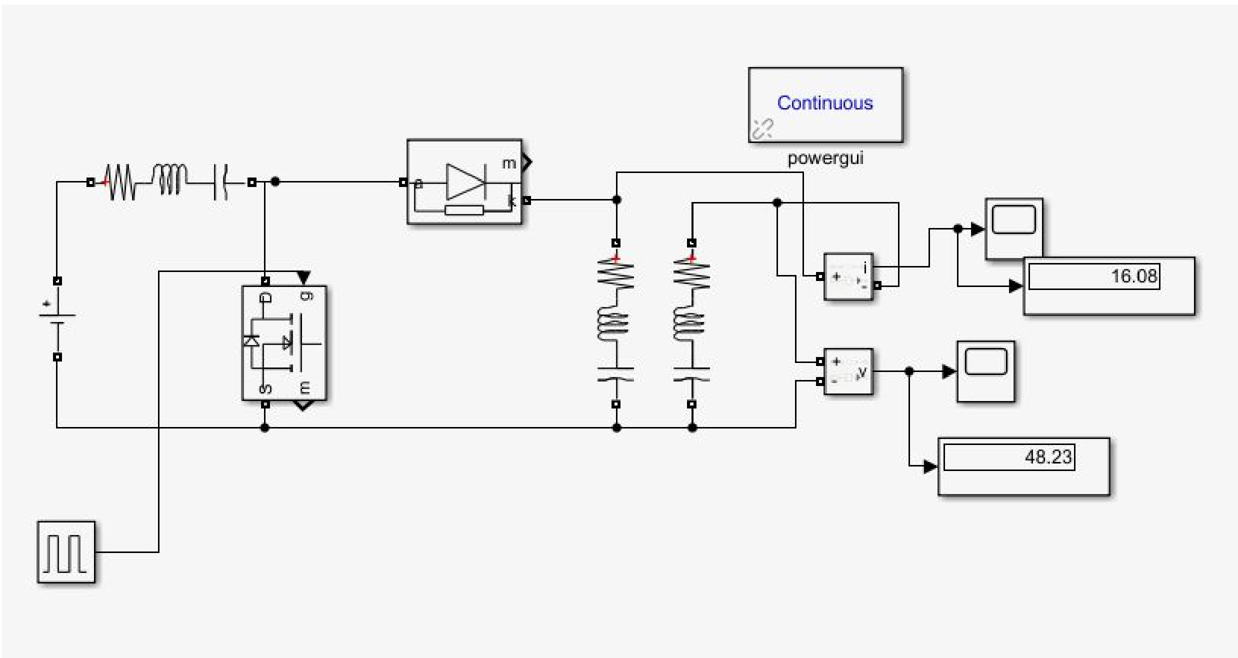


Fig: SIMULINK Model of Proposed Design

Choice of External Components

		COIL		CL *	SD *	EXTERNAL TR.	EXTERNAL TR. (BIPOLAR)	
		L	DCR			(POWER MOSFET)	R_B	C_B
For heigher current		Small	Small	Large	Small V_F	(Low ON resistance)	Small	Large
For higher efficiency	Light load	Large	Small	-	Small I_R	-	Large	Small
	Heavy load	Large	Small	-	Small V_F	(Low ON resistance)	Small	Large
For low ripple output voltage		Large	-	Large	-	-	-	-
For better transient resonse		Small	-	Large	-	-	-	-

Note : No RB or CB is needed when power MOSFET is used as external transistor.

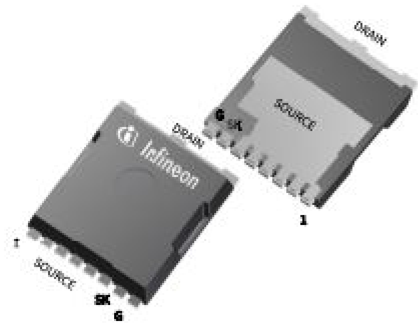
*CL : Load Capacitor, SD : Schottky Diode

b. Choice of GaN Switch

Choice of switch for a high frequency DC-DC converter depends on:

- Ciss and Coss less than 1000pF.
- A switch with fast switching speed should be selected. fast switching speed is to have a short turn-on delay time (td (on)), rise time (tr), turn-off delay time (td (off)).
- A gate to source cut-off voltage (Vgs (off)) much lower than the input voltage should be selected. When starting up the step-up DC/DC converter ICs, a voltage more than the gate to source cut-off voltage (Vgs (off)) needs to be applied to the power supply pin.
- ON resistance (Rds (on)) between drain and source of the switch should be low. However, switches with extremely low ON resistance commonly have large input capacitance (Ciss) and output capacitance (Coss). There is a tradeoff among ON resistance, input capacitance and output capacitance.
- For the step-up DC/DC converters, please choose a MOSFET with a rated current two or three times more than the peak current.
- The rated voltage for step-up DC/DC converter ICs should be one and a half times larger than the output voltage.
- Heat dissipation of switch, and capacity to withstand all loss at switch IC should be assumed before choice.

Among the family, we identify the **IGT60R070D1** as the switch of choice due to leadless packaging (low loss SMD packaging) and 70 mΩ RDSon. It has key performance characteristics that make it suitable to our requirement:



Enhancement mode transistor – Normally OFF switch
• Ultra fast switching
• No reverse-recovery charge
• Capable of reverse conduction
• Low gate charge, low output charge
• Superior commutation ruggedness

Table 1 Key Performance Parameters at $T_J = 25\ °C$

Parameter	Value	Unit
$V_{DS,max}$	600	V
$R_{DS(on),max}$	70	mΩ
$Q_{G,typ}$	5.8	nC
$I_{D,pulse}$	60	A
Q_{oss} @ 400 V	41	nC
Q_{rr}	0	nC

c. Drive Design Parameters

To achieve optimum switching performance with Infineon's e-mode GaN HEMTs driven by Infineon's isolated gate-drive IC 1EDI20N12AF (pictured below), we must implement the following in the design:

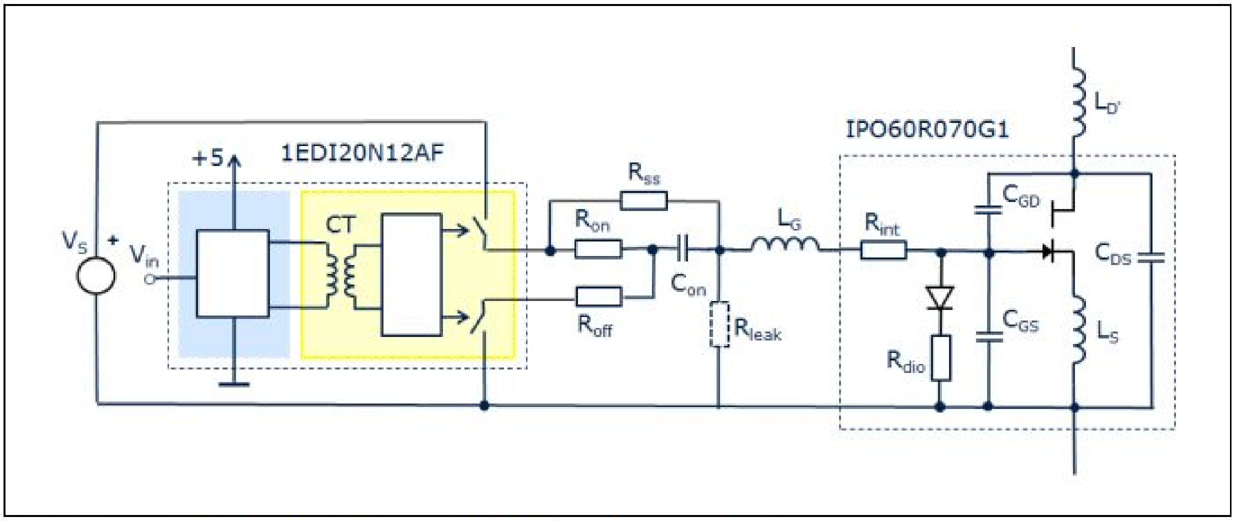


Figure 6 **Switch, driver and interface with parasitic elements**

- Choose the minimum possible gate resistors Ron and Roff. The actual values depend on the power-loop design. As a criterion, voltage stress must not exceed specified limits even with a completely discharged Con.
- Choose a combination of supply voltage VS and coupling capacitance Con that fulfills the requirements for the initial negative switch-off voltage VNi. As a rule of thumb, VNi = -3 to -4 V for hard-switching and VNi = -1 to - 2 V for soft-switching are good choices.
- At a given VNi, high VS and low Con is preferable with hard-switching, whereas low VS and high Con are recommended for soft-switching.
- Driver and switch dynamic properties are well balanced, resulting in robust operation, and relatively insensitive with respect to the driving-circuit parameters. Choice of Rss is therefore not critical; a time-constant = Rss * (Con + Ciss) in the range of a few s is recommended.
- In soft-switching applications clamping of the negative VGS can be a worthwhile option. If the system allows long off-times for both switches (both Con discharged), it is recommended to start switching with the “diode” to avoid an excessive current peak due to re-turn-on.

4. Simulations and Results

a. Tools Used

The design was modelled and simulated on **MATLAB-SIMULINK** in Phase I, with a standard Si switch and pulsed by a 200kHz PWM generator.

In the future, we will Simulate designs and create schematic on SIMPLIS/ SIMetrix software. On the purchase of the HeMT, we will obtain the component library files of CoolGaN 600V which is only compatible with that particular software. Upon completing the purchase, we will be to test the circuits with Si IRFZxxn series and CoolGaN series.

SIMPLIS

SIMPLIS (SIMulation of Piecewise LInear Systems) is a circuit simulator specifically designed to handle the simulation challenges of switching power systems. Like SPICE, SIMPLIS works at the component level but typically can perform a transient analysis of a switching circuit 10 to 50 times faster. For switching power systems, piecewise linear (PWL) modeling and simulation techniques employed by SIMPLIS result in qualitatively superior convergence behavior compared to SPICE.

The further testing and schematic will be built with SIMPLIS and a broader analysis of circuit performance can be made. Driver IC components are also discreetly available in the SIMPLIS library, making the design test as accurate to real circuit as possible.

- Quickly find the steady-state Periodic Operating Point.
- Perform AC analyses on the full nonlinear time-domain switching circuit.
- Perform time-domain transient analyses 10 - 50 times faster than SPICE.
- Exhibit superior convergence behavior.

These tests can accurately model the frequency responses between Si and GaN based converters and help characterize the performance of the design with the selected components.

b. Results of Simulation

The boost converter design was tested for the proposed design with an n type Si MOSFET. With the applied parameters as reported above and in the simulation conditions without losses, the performance is slightly better than expected. However considering non ideal behaviour of components and losses in circuit, we can assume that we will build a 98% efficiency converter similar to that of industry standards.

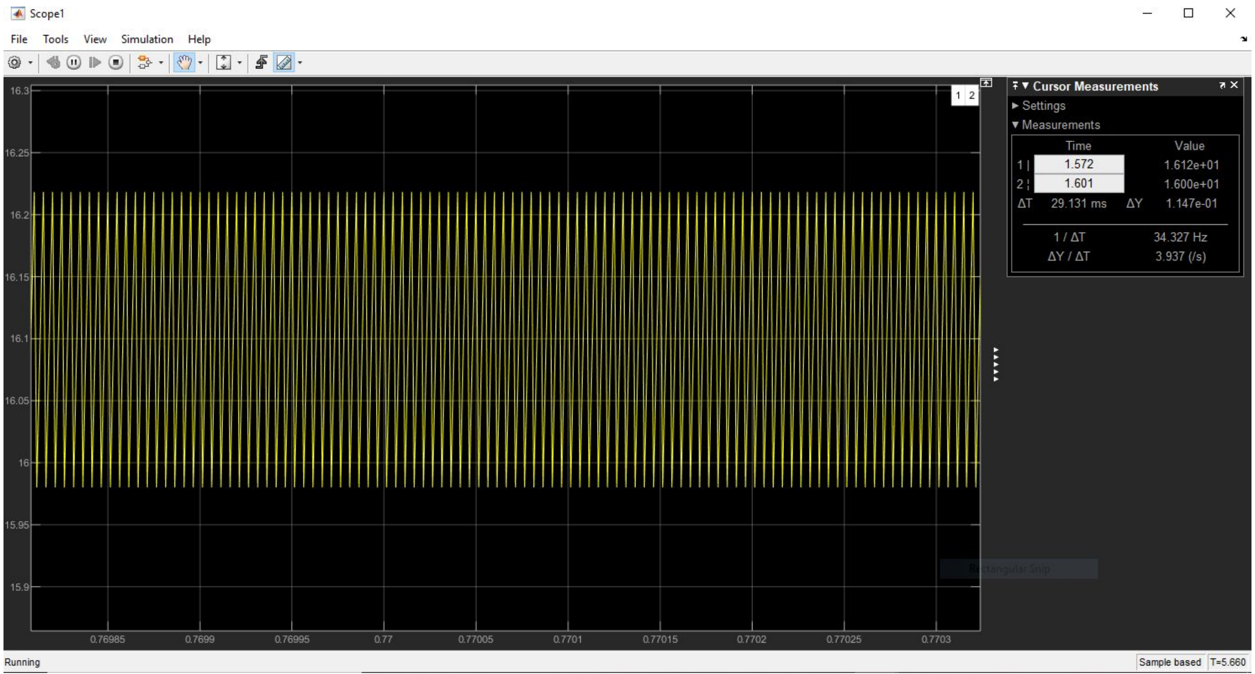


Fig: Simulated current output of boost converter with desired ripple of .3A

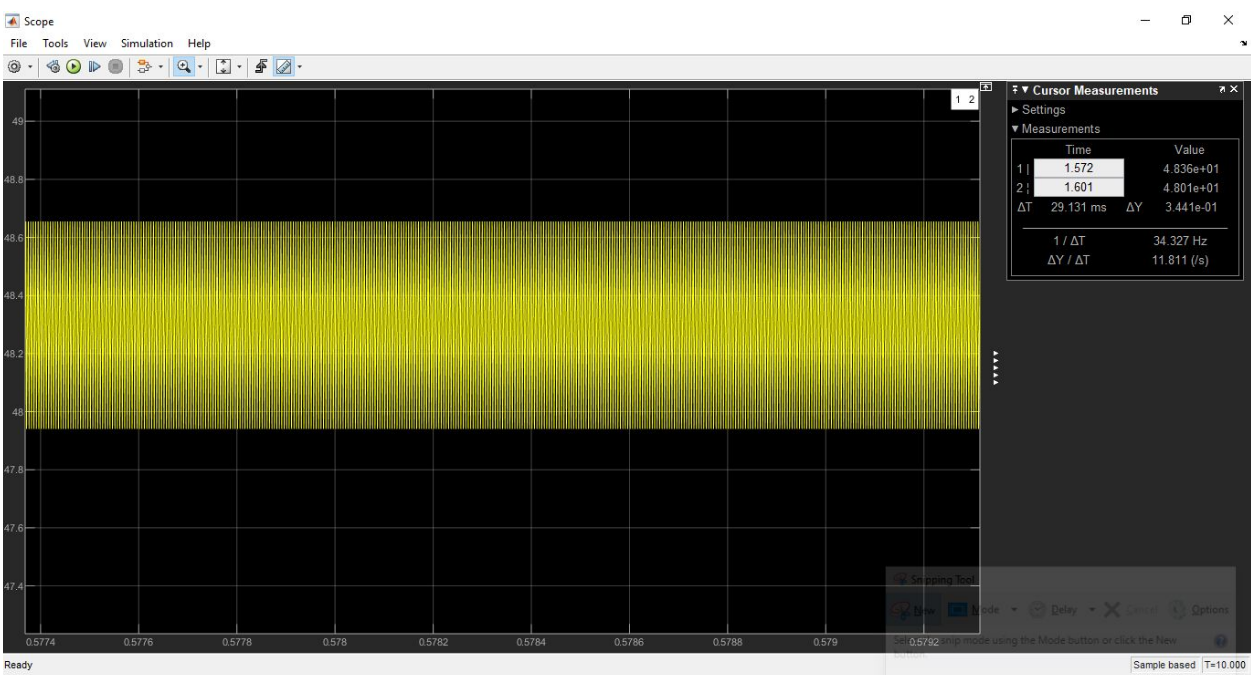


Fig: Simulated voltage output of boost converter with 1V ripple

5. Targets Achieved in Phase I

So far, significant study of GaN HeMT and boost converter design has been completed. A significant understanding of soft switching, agonistic behavior of boost converter achieved, with an idea of the behaviour with changes in parameters like load current and impedance.

- Literature Survey since 2003
- Optimal GaN device choice characterization
- Efficient non-isolated boost converter design
- Choice of components and softwares

6. Goals for Phase II

The next phase will be conducted from December 2019- April 2020 in the Power Electronics Laboratory in Indian Institute of Technology, Bombay. The goals for this phase:

- Simulation and schematic with chosen components
- Ordering & Purchase
- Compact design fabrication with necessary heat dissipation and frequency response
- Testing prototype for real time conversion at various system variables to find peak efficiency efficiency
- Achieving improved or state-of-the-art power density results

7. Acknowledgements

I would like to thank my mentor at COEP, Dr. S. P. Mahajan for his support and guidance on Phase I of the project and the members of the Power Electronics Lab I at IIT Bombay, under the guidance of Prof. B. G. Fernandes, for their hardware support.