Next Generation of High Frequency Power Converters

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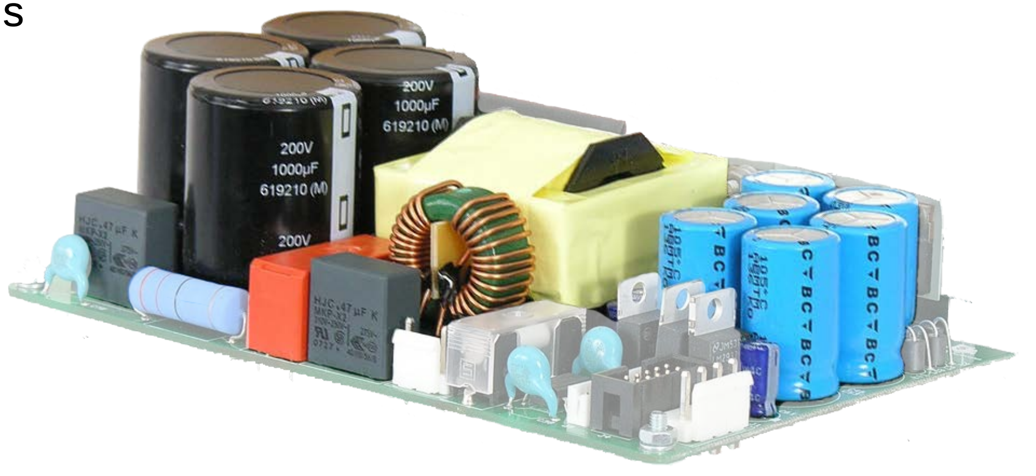
Agenda

1 Introduction
2 High frequency power conversion
3 Very High Frequency Switched-Mode Power Supplies (DC-DC)
4 Single-Phase Power Factor Correction (AC-DC)
5 PV inverters (DC-AC)
6 Challenges/opportunities
7 Summary

Power converters everywhere

Motivation

- Passive components dominate the size and price
- Lifespan limited by electrolytic capacitors
- Heavy magnetic components

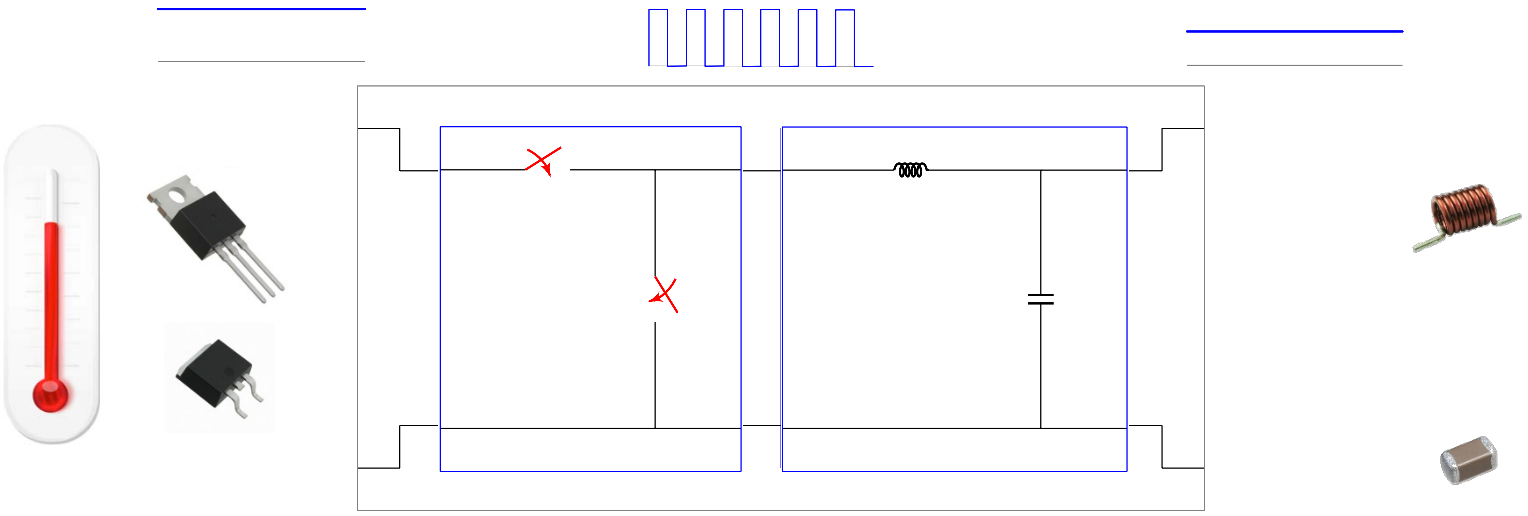


- All drawbacks are directly linked to the passive energy storing elements
  - They scale directly with switching frequency

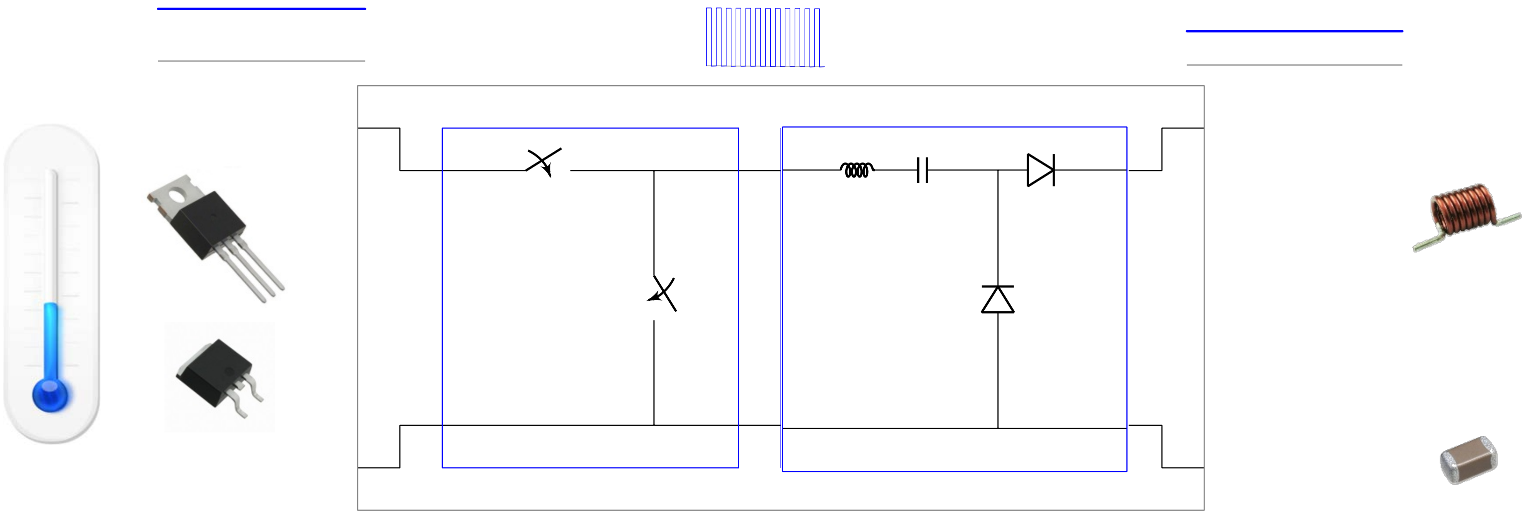
Additional benefits

- The highly elevated switching frequency will lead to:
  - Reduced size & weight
  - Decreased cost
  - Faster transient response
  - No electrolytic capacitors -> Increased reliability
  - No magnetic core -> Less dependent on rare earth materials

Increasing the frequency



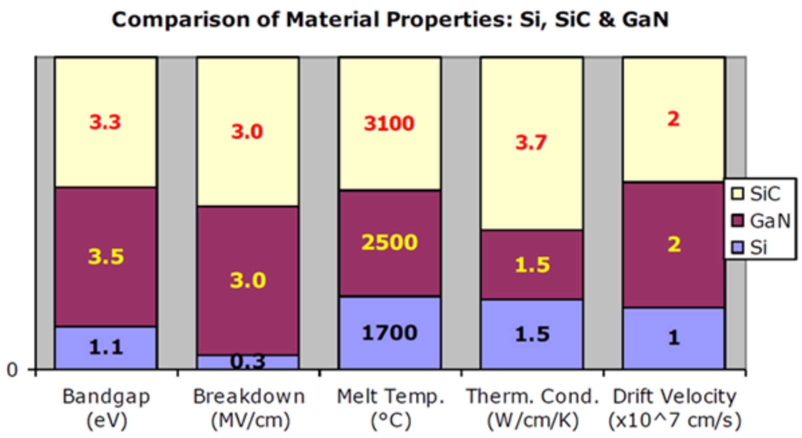
Resonant converters

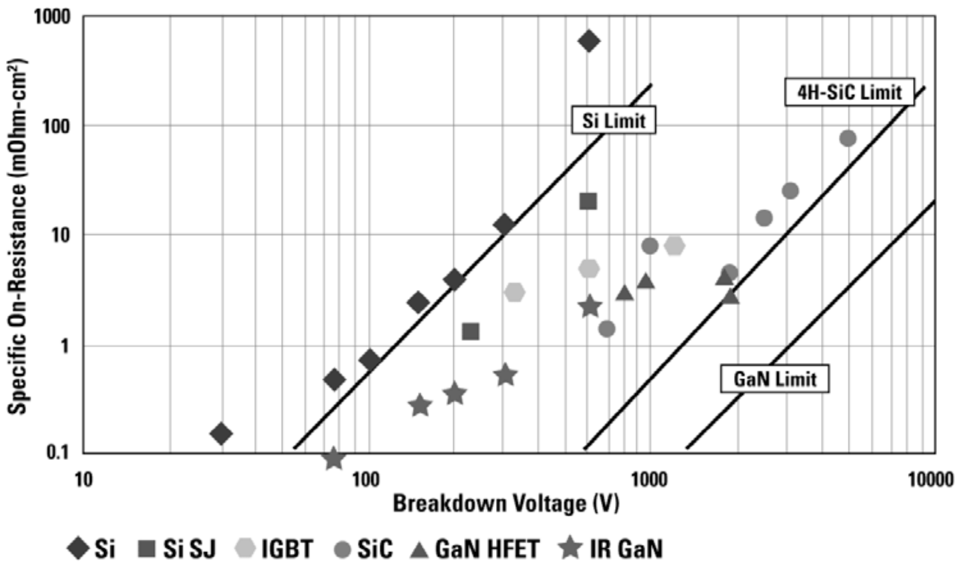


- Soft-switching topologies (fx. LLC converters), common operation:
  - Step down, several 100’s of volts to 10’s of volts
  - 400-4000 W output power
  - Switching frequencies up to ≈1 MHz
  - Efficiencies up to ≈96%
  - Power density up to 50 W/cm^3

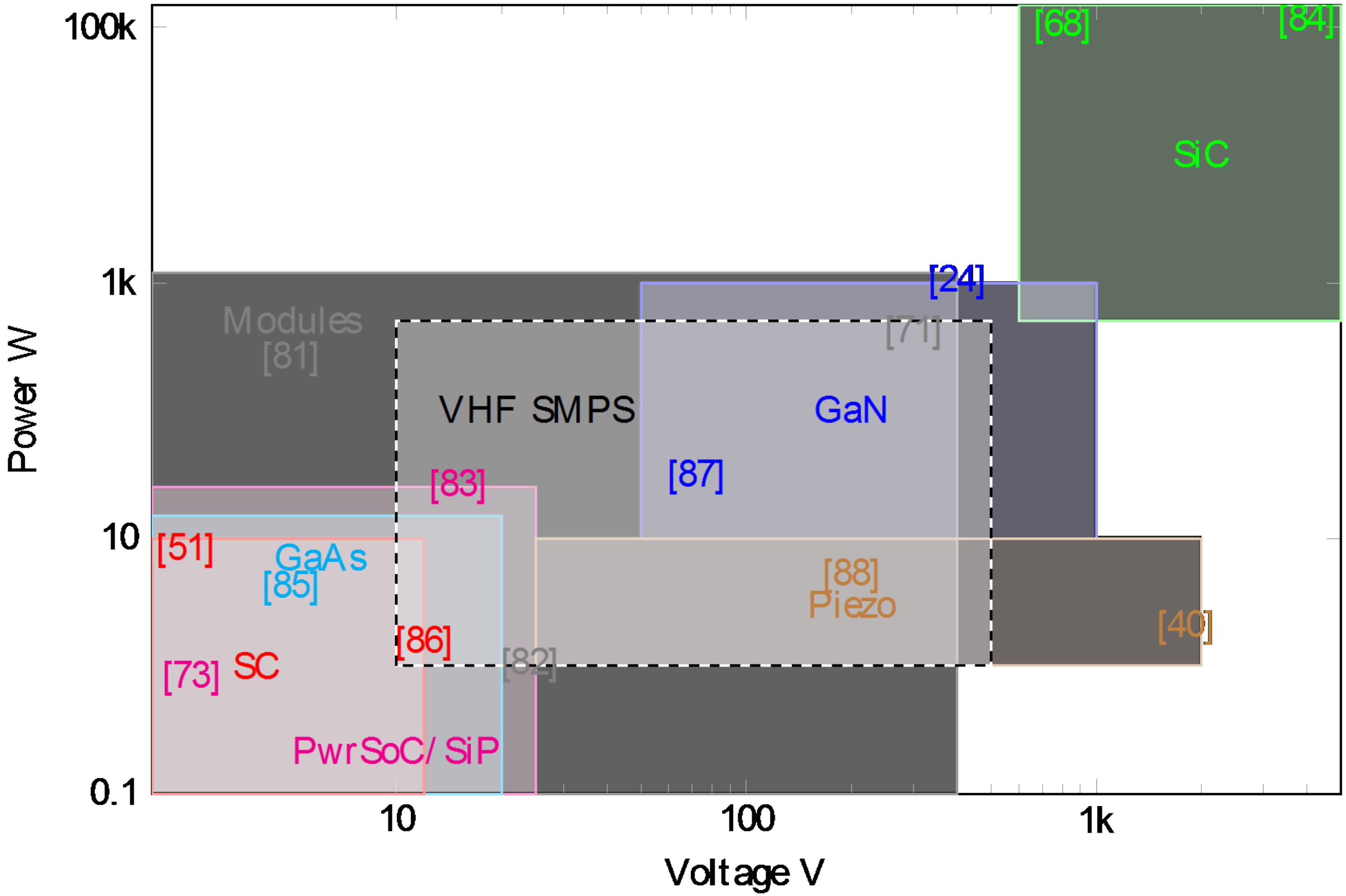
Wide Band Gap Semiconductors

- Higher operating temperatures
- Higher power densities
- Higher voltages
- Higher frequencies





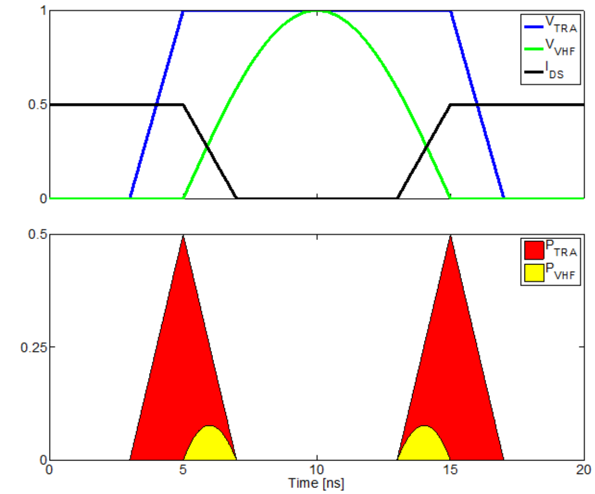
Summary

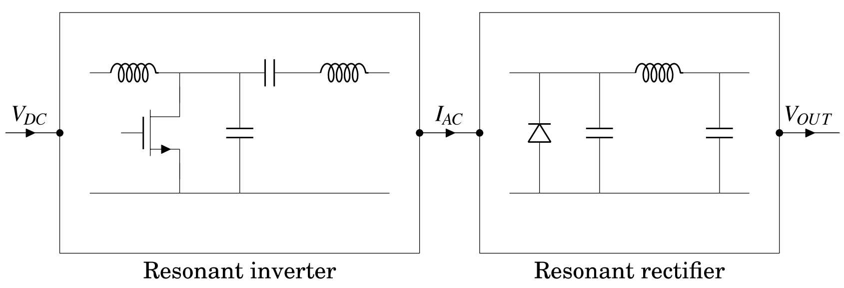


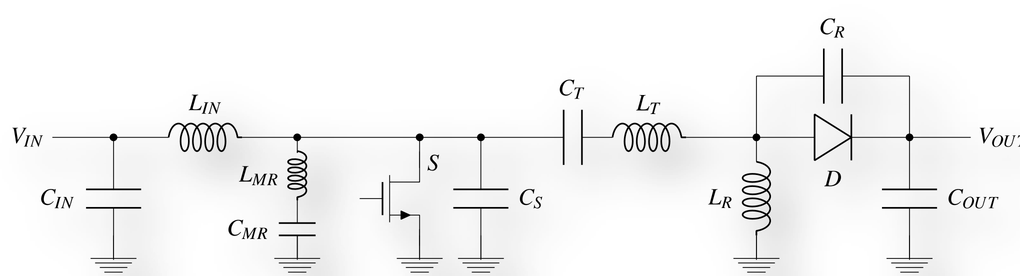
Source: Mickey P. Madsen, " Very high frequency switch-mode power supplies," PhD Thesis, 2015

Very High Frequency (30-300 MHz) Power Converters

- **Mickey Madsen**
- At VHF the switching losses becomes severe and results in unacceptable losses
- Resonant converters with ZVS capabilities are therefore used to eliminate these losses
- The converter is designed in two parts; a resonant inverter and a resonant rectifier



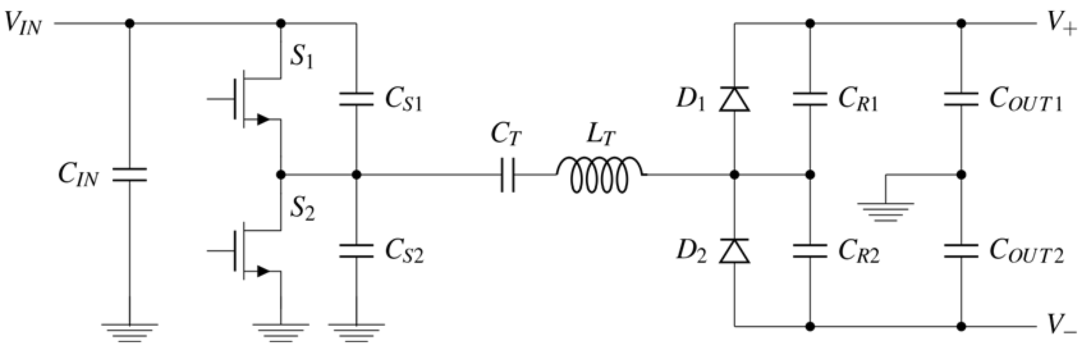




Class EF_2 (φ_2) inverter and class E rectifier

Increased voltage and power

- The voltage stress in the single switch topologies are very high
- Half bridge topologies are more suitable for increased voltage levels
- As the peak voltage is reduced so is the resonating currents, the k factor is hence lower for this topology
- This requires a high side gate drive, but the number of inductors is reduced an higher power densities are therefore expected



Class φ_2 vs DE inverter

Class φ_2	Component count	Class DE
1	MOSFETs	2
3	Inductors	1
3 (2)	Capacitors	3 (1)

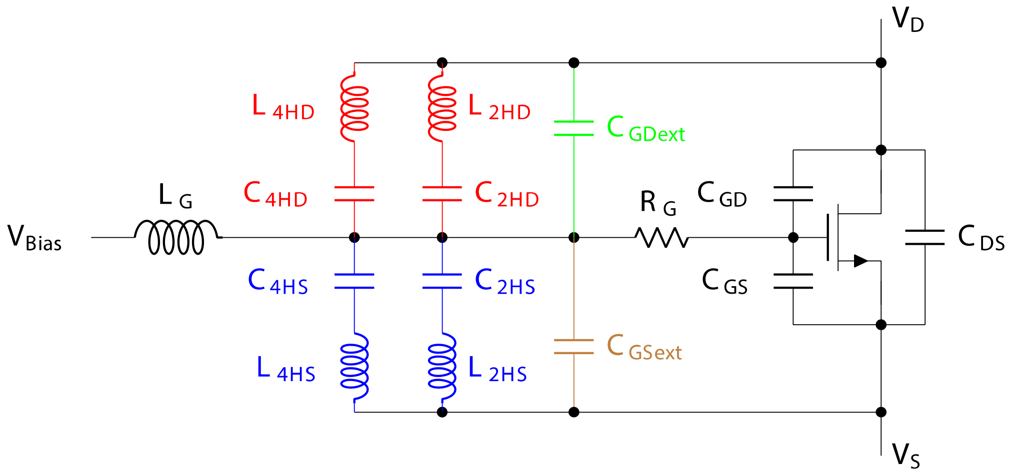
	MOSFET stress	
$\approx 2.5 \times V_{IN}$	Voltage stress	V_{IN}
$\frac{1}{2} C_{OSS} (2.5 \times V_{IN})^2$	Peak C_{OSS} energy	$\frac{1}{2} C_{OSS} V_{IN}^2$

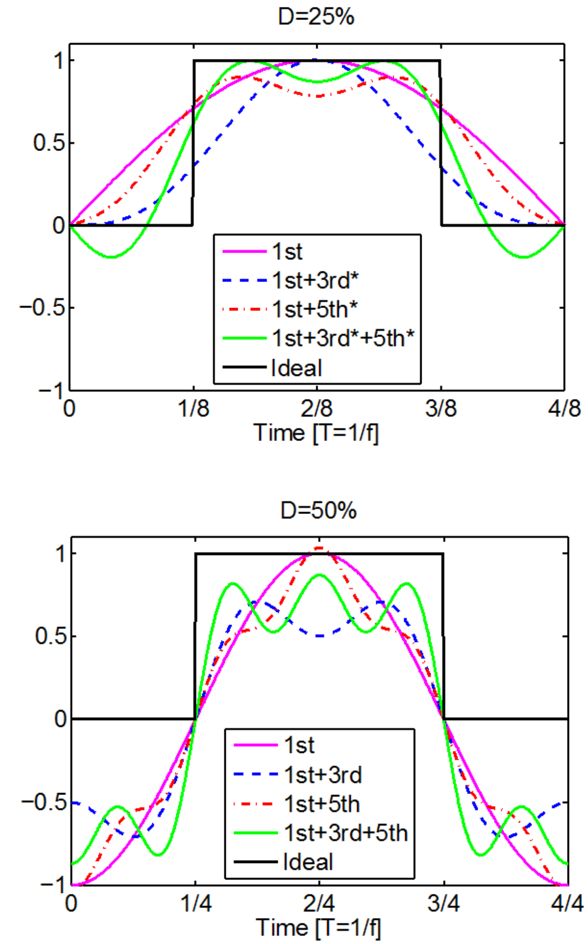
Fundamental drawbacks

- 6.25 times more energy in C_{OSS}
- Larger resonating currents due to 3rd harmonics
- Difficult to achieve high efficiency at low power
- 3 times as many inductors

- Requires a high side gate drive
- (Two MOSFETs, but with lower voltage rating)

Additional harmonics

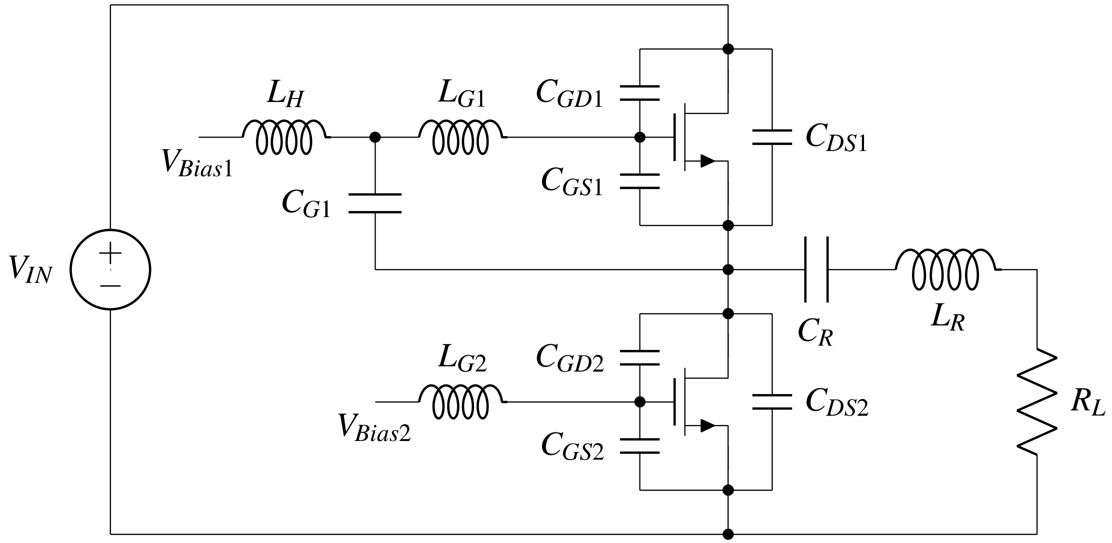




High side gate drive

- The same principle can be applied to a high side MOSFET

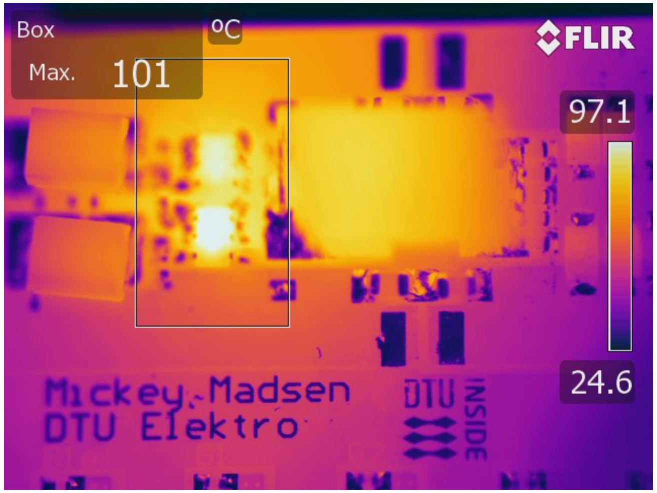
- Only two additional components
  - C_{G1} insure that the bias voltage has the source of the high side as reference
  - L_H make a pure dc path enabling control of the average bias voltage.

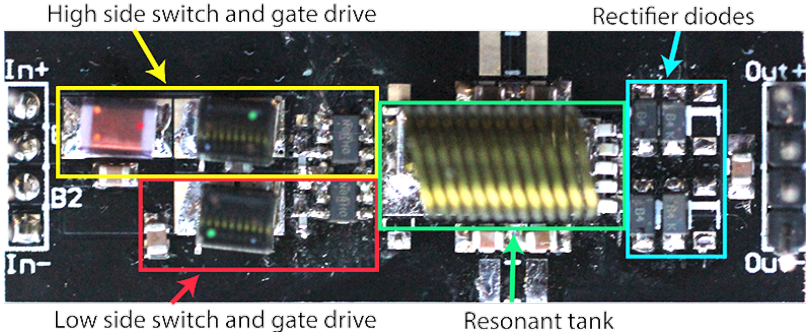


First half bridge implementation

- **The worlds first discrete VHF half bridge converter**

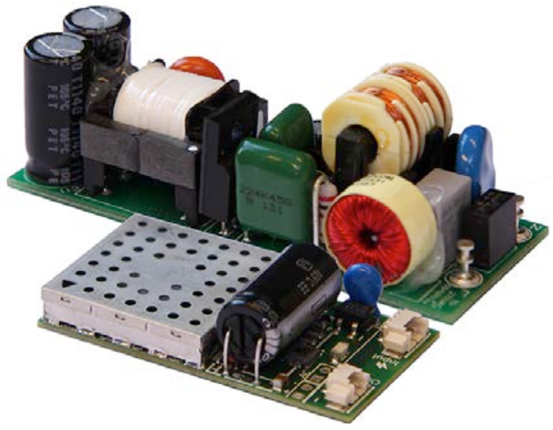
- Peak efficiency above 85%
- Input voltage up to 150 V
- Output power up to 16 W at 40 V
- Power density of 1.5 W/cm³
- Box volume of 50 x 17 x 12 mm





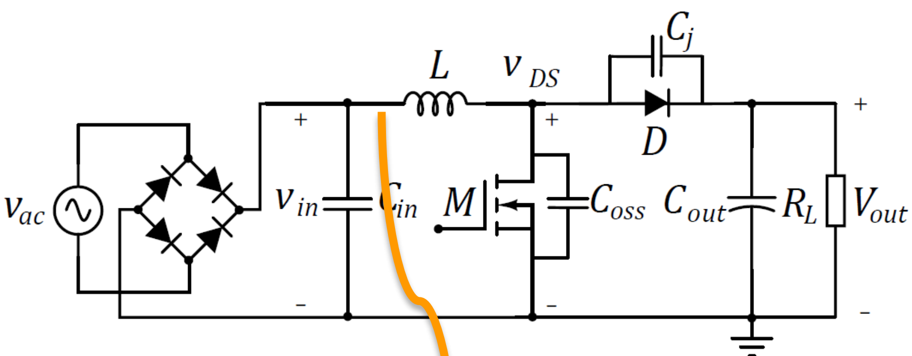
Conclusion

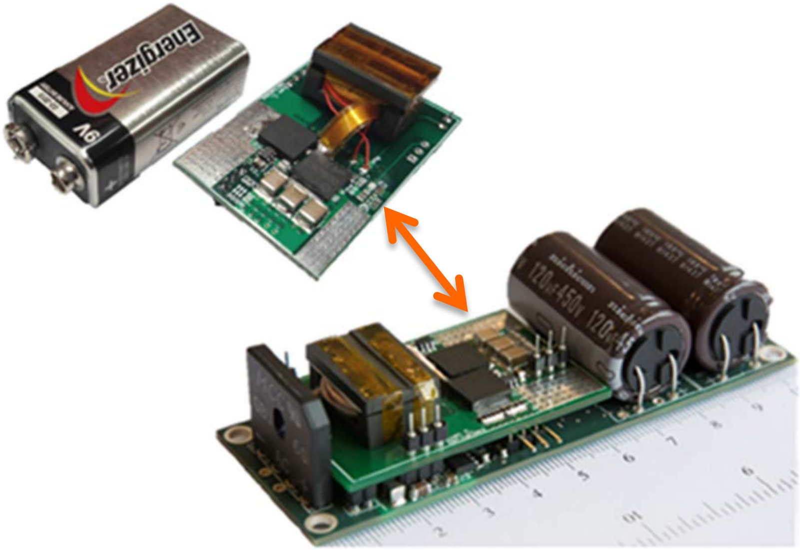
Parameter	Commercial	Thesis result	Improvement
Power	20 W	20 W	0%
Efficiency	85%	89.5%	4.5%
Size	33 cm^3	9.9 cm^3	70%
Weight	53 g	10 g	81%
Cost	≈$3.2	≈$1.4	56%

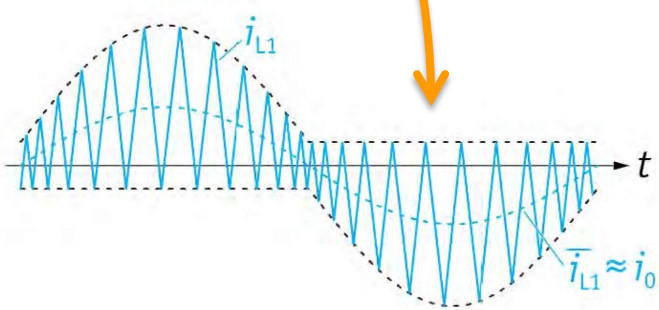


GaN-Based Single-Phase PFC

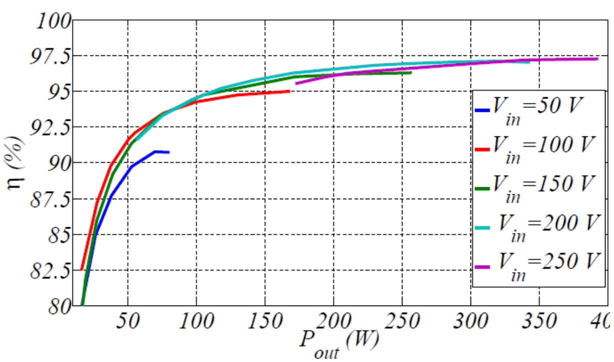
- **Juan Carlos Hernandez Botella**

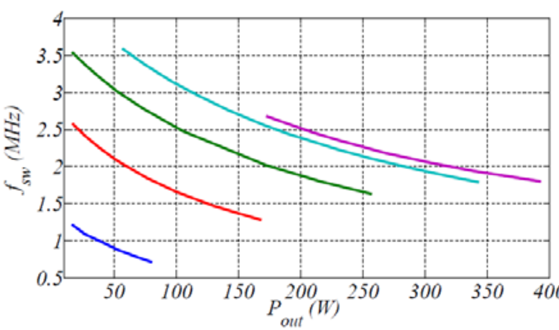






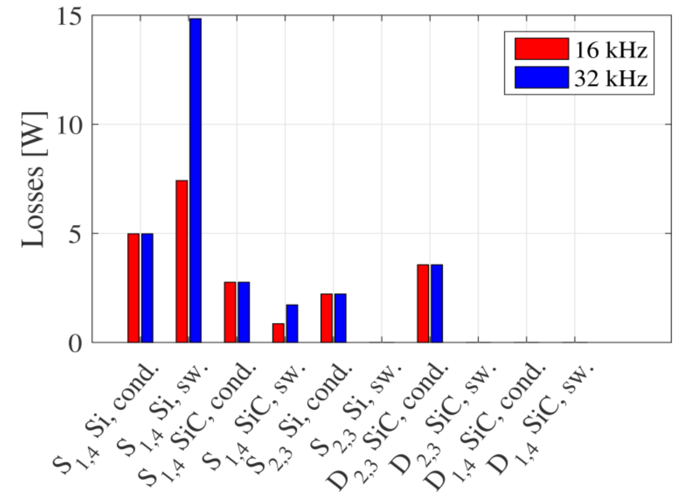
Boundary mode control



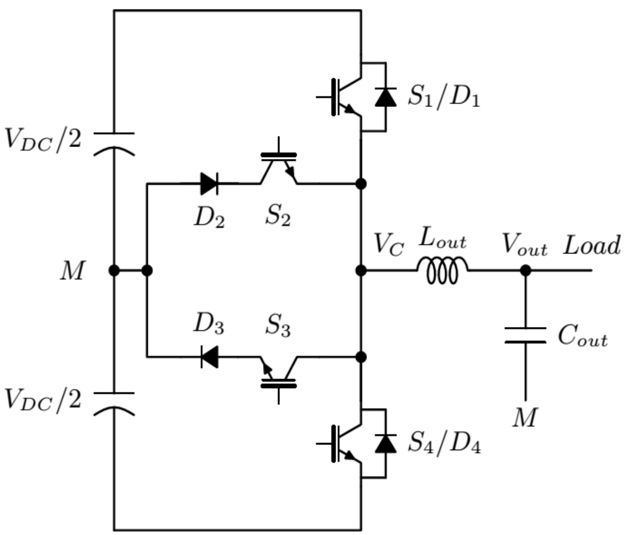


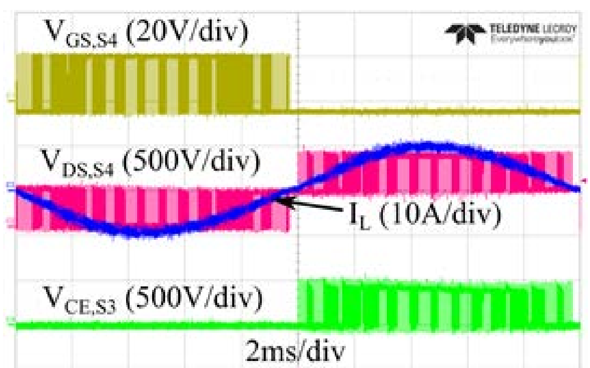
T-Type Inverter w. SiC

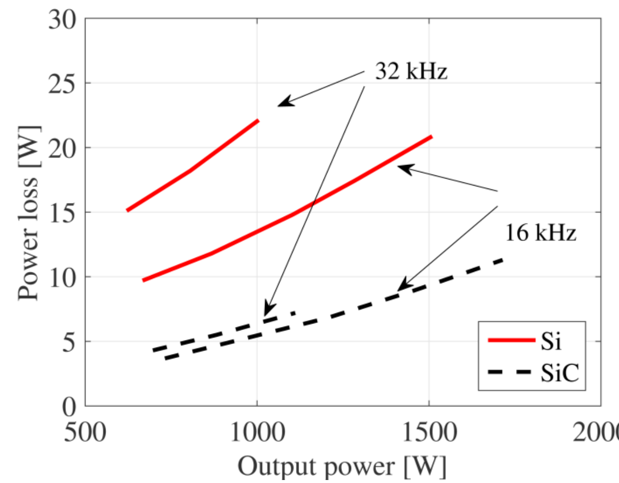
- **Alexander Anthon**



- Three-level topology
- Efficiency suffers from switching losses at high frequency;
- SiC devices replace Si devices (depending on operation)

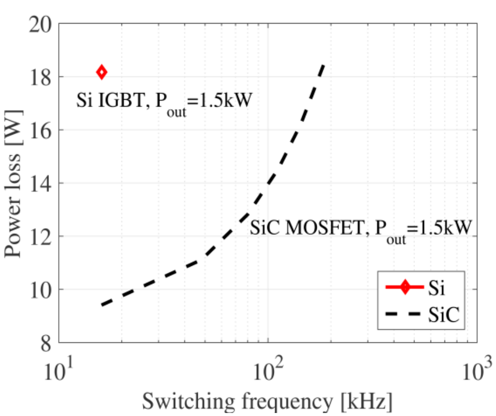


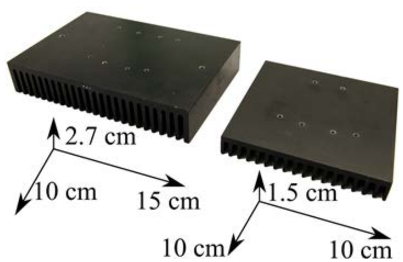


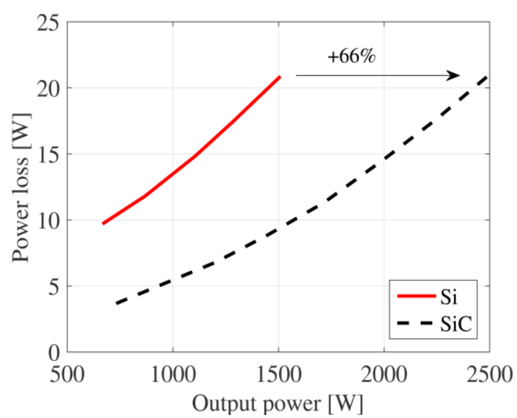


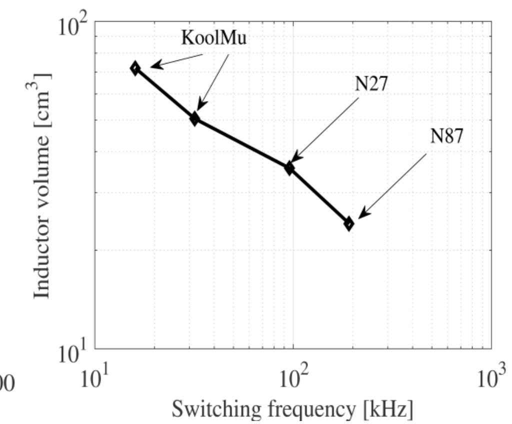
T-Type Inverter w. SiC- cont’d

- For a given inverter, retain its electrical design and use the increased overall **efficiency**;
- Reduce the heat sink requirement to reduce the converter **volume**;
- Increase the power rating of the inverter for the same heatsink design in order to increase its **power density**;
- Increase the inverter switching frequency, with a consequential reduction in filter component sizes.



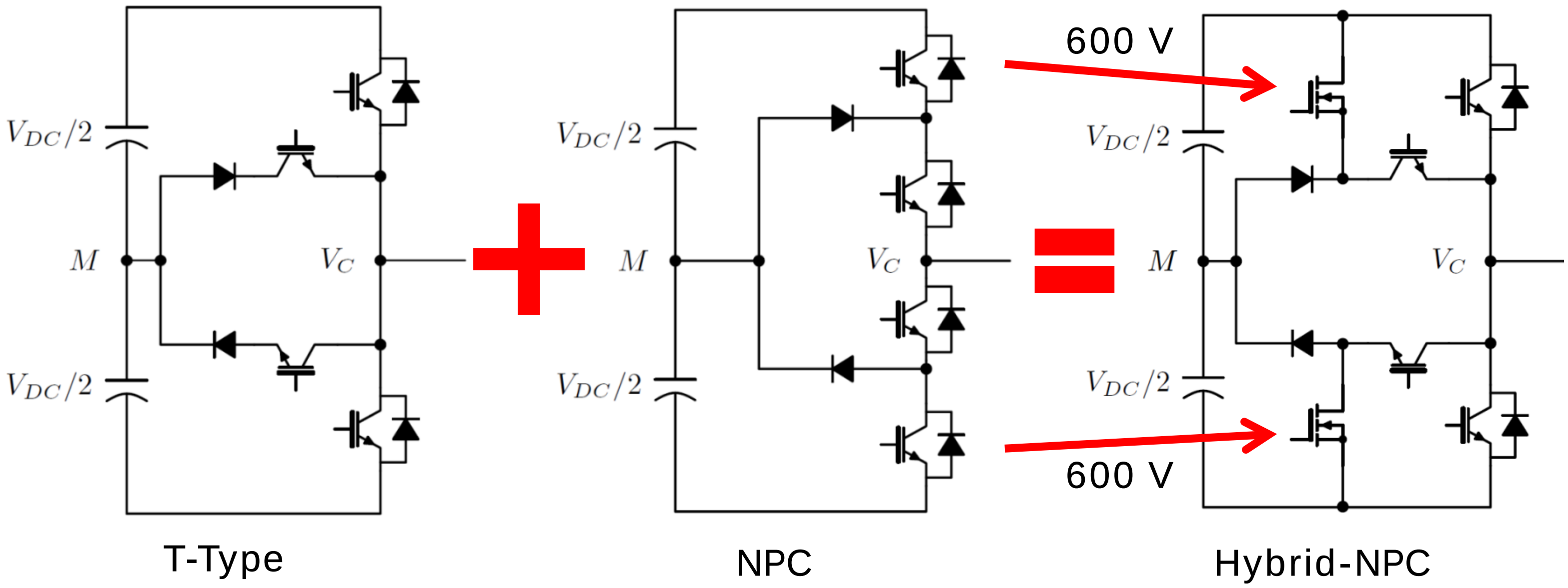






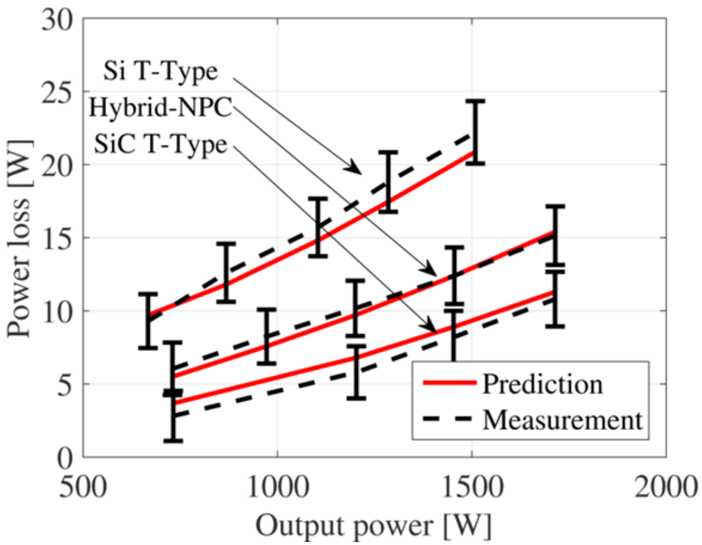
The Hybrid-NPC alternative (w/o SiC)

- or add 600V CoolMos devices in addition to the conventional T-Type topology
- 600V CoolMos devices aim to support the commutation events

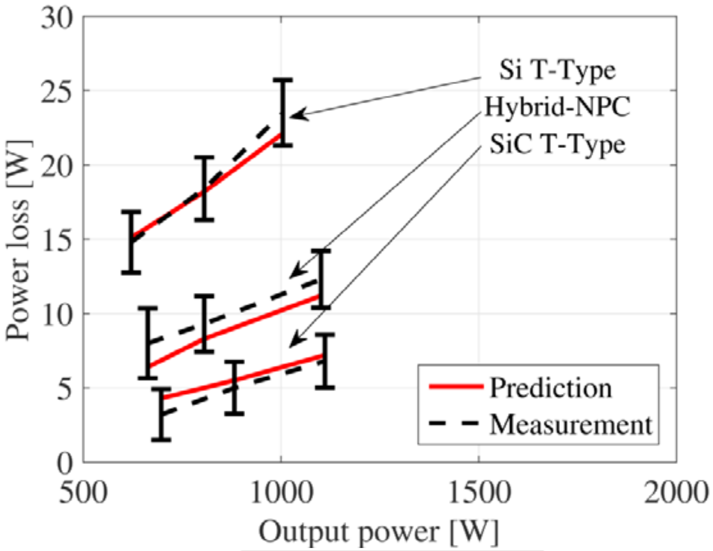


The Hybrid-NPC alternative (w/o SiC)- cont'd

- As expected, Si based T-Type converter has highest losses
  - Also highest loss increase with increased switching frequency
- Both SiC based T-Type and Hybrid-NPC can significantly reduce the semiconductor losses
- Using the semiconductor devices in this work, the SiC based T-Type can achieve lowest losses of all investigated alternatives



f_S=16 kHz



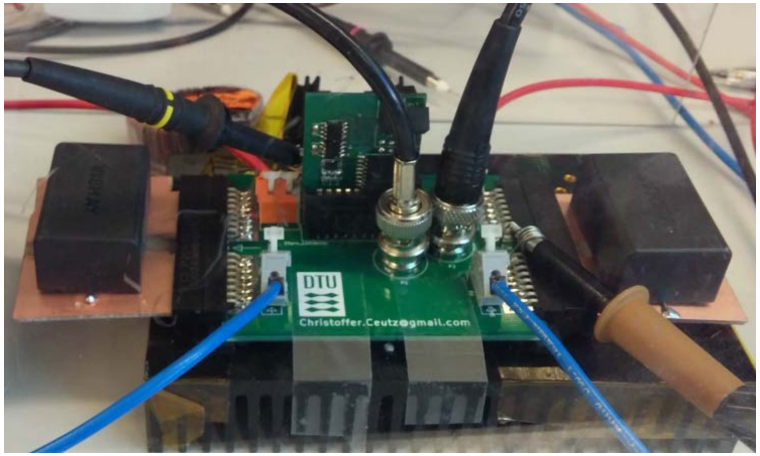
f_S=32 kHz

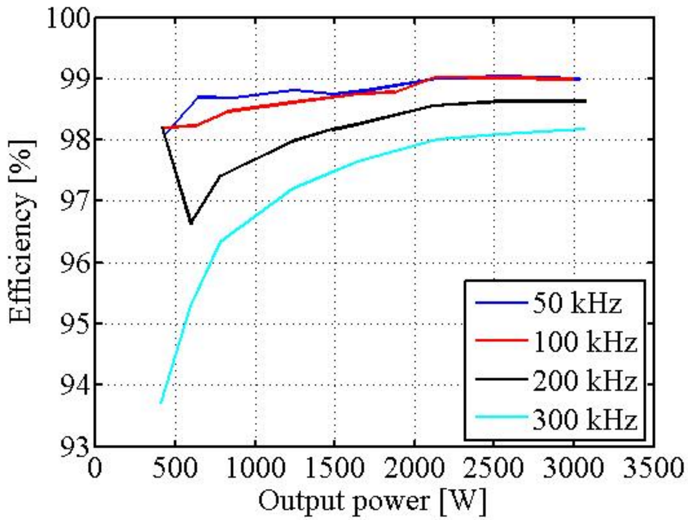
SiC-Based DC-DC Converter

- **Student project #1**

- Boost converter
- SiC switch and diode
- Maximum 3.2 kW
- 400V input→600V output

Educating the Next Generation of Engineers!

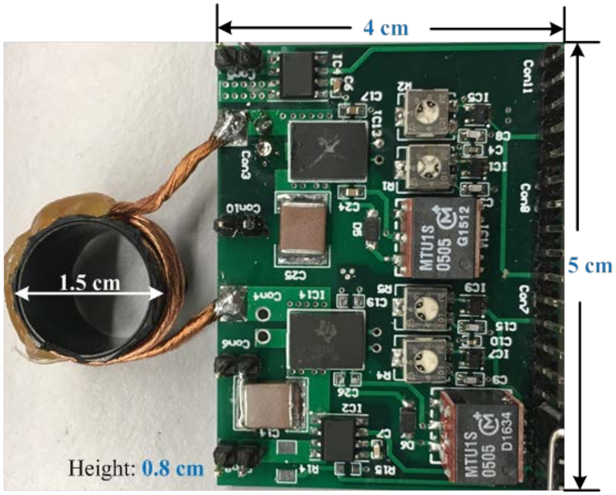


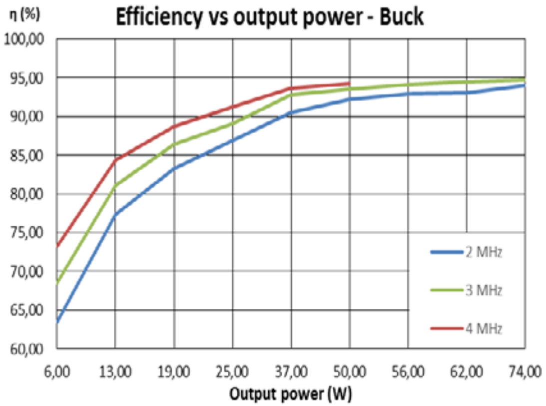


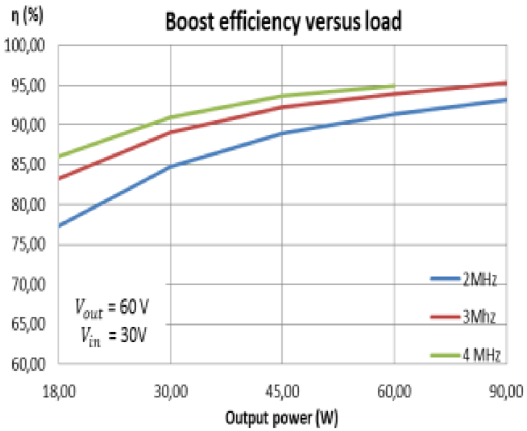
10-MHz non-isolated Bidirectional DC-DC

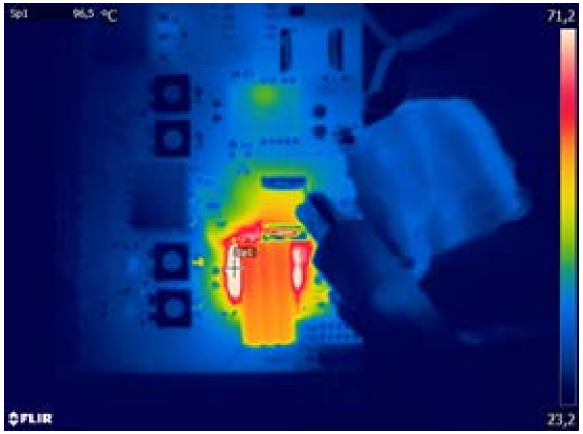
- **Student project #2**
  - GaN based converter
  - 24V to 60V input/output, and 100 W output
  - Switching frequency up to 10-MHz
  - 6.2W/cm3

  - A conference paper in the coming APEC 2017









Challenges / Opportunities

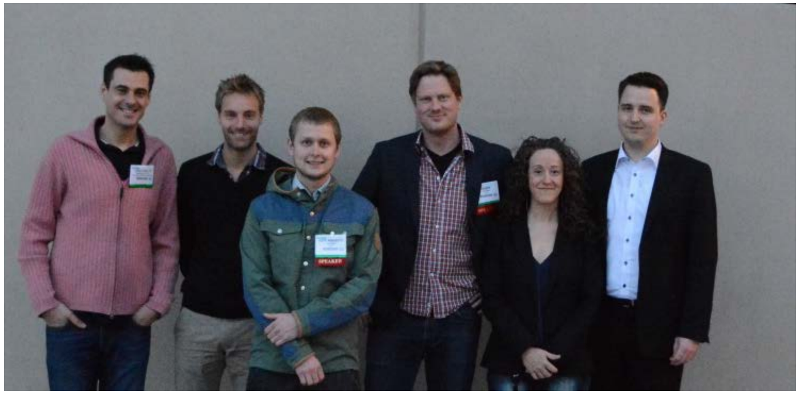
- New converter topologies (soft-switching)
- Efficient gate drives (embedded)
- Accurate zero-voltage-switching control—Timing challenges@fs>1MHz
- Advanced digital control circuits
- HF Magnetics, in particular for high-power application (>10 kW)
- High Bandwidth Sensors
- Packaging/Integration (3D)
- Thermal management (3D)

During this IEPE, at DTU

- 4 PhD projects
- Over 10 MSc and BSc thesis projects
- Over 30 scientific publications
- 5 Patents
- 1 Spinoff company—Nordic Power Converter
- Several awards/prizes
- Industrial Cooperation: Danfoss, Grundfos

Nordic Power Converters

Powering a brighter future™



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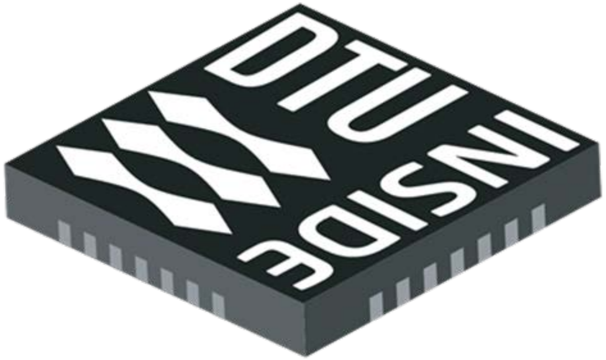

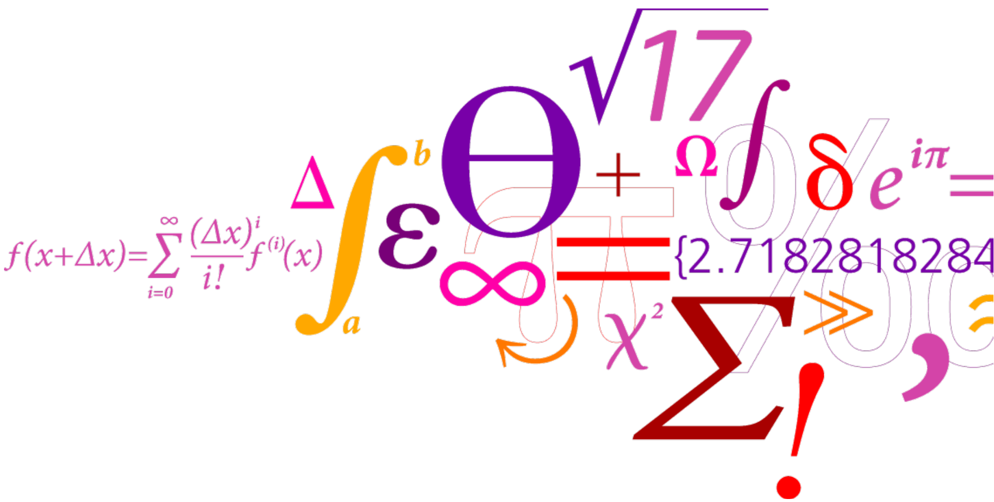

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