Gallium Nitride (GaN) based High Frequency Inverter for Energy Storage Applications

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Introduction

- Energy storage systems are the backbone of the future grid
  - Support the grid in meeting future energy needs
  - Reduce reliability and voltage stability concerns resulting from high penetration of renewable energy sources
- According to IHS Markit Ltd.,
  - Initial installation size was 0.34 GW in 2012
  - Estimated annual installation size of 6 GW in 2017
  - Expected to exceed 40 GW by 2022
- High power bidirectional inverters play a key role in the integration of energy storage devices into power grid

Existing High Power Bidirectional Inverters - Limitations

- Suffer from many drawbacks due to the utilization of Silicon (Si) devices
- Si-based devices suffer from higher conduction and switching losses
  - reduced efficiency
  - increased cooling needs
  - increased real estate requirements
- Low operating switching frequencies
  - large filtering inductors and capacitors
  - increased cost, weight, and volume
  - reduced efficiency due to increase of losses in inductors
- Wide band gap devices like Silicon Carbide (SiC) and Gallium Nitride (GaN) technologies offer superior performance compared to Si technology

Silicon (Si) vs. Silicon Carbide (SiC) vs. Gallium Nitride(GaN)

Material properties	Si	SiC	GaN
Band Gap (eV)	1.12	3.2	3.4
Critical Field (10^6 V/cm)	0.25	2.2	3
Electron mobility (cm^2/V-sec)	1,350	950	1,000-2,000
Electron saturation velocity (10^6 cm/sec)	10	20	25
Hole mobility (cm^2/V-sec)	480	80	30
Thermal conductivity (Watts/cm^2 K @ 300K)	1.5	3-4	1.3
Dielectric constant	11.9	10	9.5

Silicon (Si) vs. Silicon Carbide (SiC) vs. Gallium Nitride(GaN) Cont'd…

- Both SiC and GaN semiconductors have higher critical field allowing them to operate at higher voltages
- GaN has higher electron mobility and saturation velocity compared to Si and SiC, making it the most suitable device for high frequency operation
- SiC has better thermal conductivity compared to Si and GaN. Therefore, SiC devices can operate at high power densities compared to GaN and Si.
- The lower thermal conductivity of GaN devices makes heat management a challenge for designers

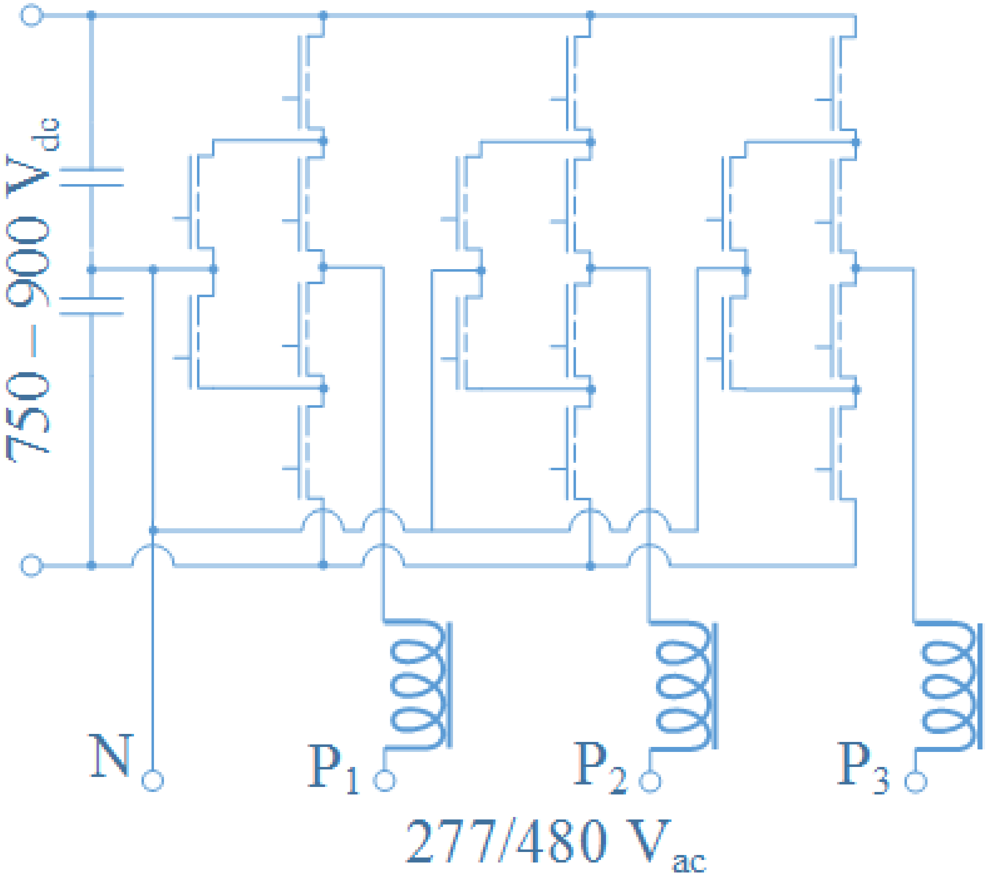
Neutral Point Active-Clamped Three-Level Inverter

- Why??
  - The inverter has to integrate a battery bank with a voltage ranging from 750-900V to a 3-phase 480V AC grid
  - The maximum voltage rating of existing GaN devices is 650V. Therefore, using a two level inverter is out of questions
  - A neutral point clamped three-level inverter would require GaN devices with a peak blocking voltage of 450V
  - Implementing neutral point clamping using Si diodes would increase losses
  - Neutral point active-clamping can be implemented with GaN devices
- Space vector pulse width modulation (SVPWM) is used for control as it offers low total harmonic distortion and better power factor

Neutral Point Active-Clamped Three-Level Inverter Cont'd…

- Target power rating = 80 kW
- 4 x 20 kW modules
- Input voltage = 750-900 V DC
- Output voltage = 277/480 V AC

- GSS66508T – 650 V GaN E-HEMT from GaN systems
- ADuM4121 – 2 A Isolated gate driver



Device Comparison:
Si (IGBT) vs. SiC (MOSFET) vs. GaN (E-HEMT)

Device type	**Si - IGBT**	**SiC - MOSFET**	**GaN – E HEMT**
Device name	IKW30N65EL5	SCT3060AL	GS66508T
Manufacturer	Infineon	ROHM Semiconductor	GaN Systems
Drain-Source voltage (V_{DS})	650 V	650 V	650 V
Continuous drain current (I_{DS})	85 A @ 25 °C 62 A @ 100 °C	39 A @ T_c = 25 °C 27 A @ T_c = 100 °C	30 A @ T_c = 25 °C 25 A @ T_c = 100 °C
Collector-emitter saturation voltage (V_{CEsat})	1.50V @ 25 °C	-	-
Drain-Source On resistance (R_{DSon})	-	60 mΩ @ T_j = 25 °C	50 mΩ @ T_j = 25 °C
Input capacitance (C_{iss})	4600 pF	852 pF	260 pF
Output capacitance (C_{oss})	64 pF	55 pF	65 pF
Reverse transfer capacitance (C_{rss})	18 pF	24 pF	2 pF
Gate charge (Q_G)	168 nC	58 nC	5.8 nC
Gate voltage (V_{GS}) – On/Off	15 V/ 0 V	18 V/ 0 V	6 V/ 0 V
Maximum junction temperature (T_j)	175 °C	175 °C	150 °C
Anti-parallel diode	Yes	Yes	No
Reverse recovery Losses (P_{Qrr})	Yes	Yes	No
Cost (for 250 pcs. on Mouser)	$3.39	$8.31	$13.92

GaN (E-HEMT)

- Pros
  - GaN E-HEMT has the lowest input capacitance (C_{GS}+C_{GD}), leading to lower total gate charge (Qg) which allows for faster turn-on and off.
  - Lower conduction losses and no reverse recovery losses (due to absence of diode)
- Cons
  - Lower gate voltage requirements and lower gate threshold make it more susceptible to noise
  - High cost of the device compared to Si and SiC counterparts

Loss analysis

GSS66508T GaN E-HEMT has

- Lower Drain-Source ON resistance of 50 mΩ - reducing conduction losses
- Total gate charge of 5.8 nC - 10 times lower than the SiC MOSFET and 28 times lower that the Si IGBT - fast switching ability with lower switching and gate losses

Specifications:

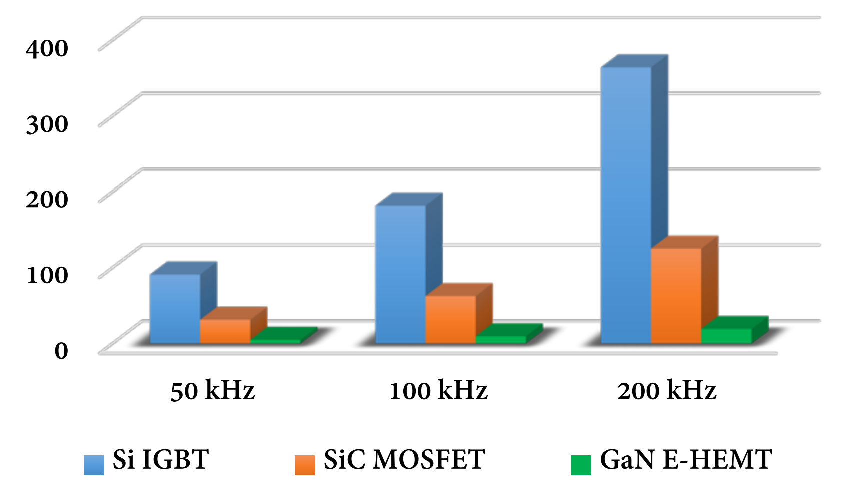
- 450 V blocking voltage
- 24 A RMS current

- Losses are analysis at switching frequencies of 50, 100, and 200 kHz

Loss analysis Cont'd…

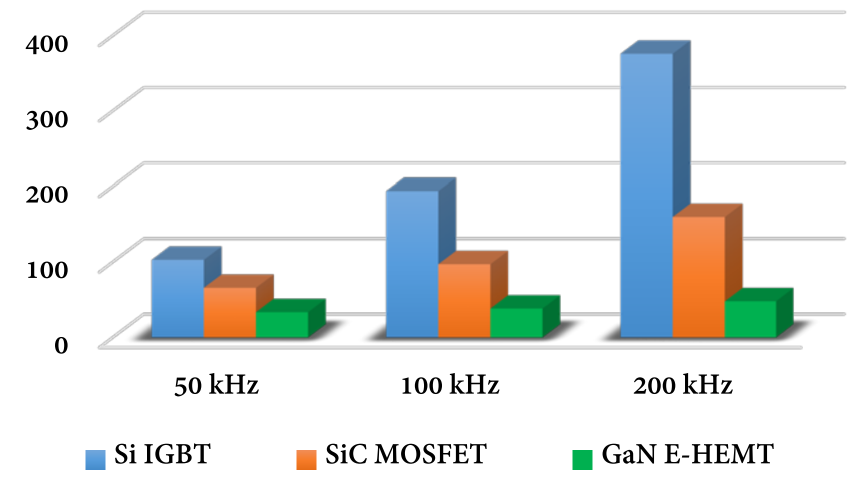
Switching losses (W) vs. f_{SW} (kHz)

- SiC MOSFET has 65.6% less losses compared to Si IGBT
- GaN E-HEMT has about 95% less losses compared to Si IGBT and about 85% less compared to SiC MOSFET



Total losses (W) vs. f_{SW} (kHz)

- At 200 kHz, GaN E-HEMT has only 30% of losses in SiC MOSFET and 13% of the losses in IGBT
- GaN E-HEMT at 200 kHz has lower losses than that of SiC MOSFET at 50 kHz



Practical Design Considerations

- Gate driver design is very critical
- Requires isolated gate drivers and isolated dc-dc power supplies for driving the gate
- When selecting the isolated gate driver and gate power supply, one should ensure that they can withstand the high dv/dt stress due to faster turn ON and OFF times
- With the fast switching of GaN E-HEMTs, any parasitic inductances in the gate switching loop will give rise to ringing which leads to losses and EMI problems - keep the PCB gate-source loop as small as possible
- Best switching performance can be achieved with proper selection of gate resistor

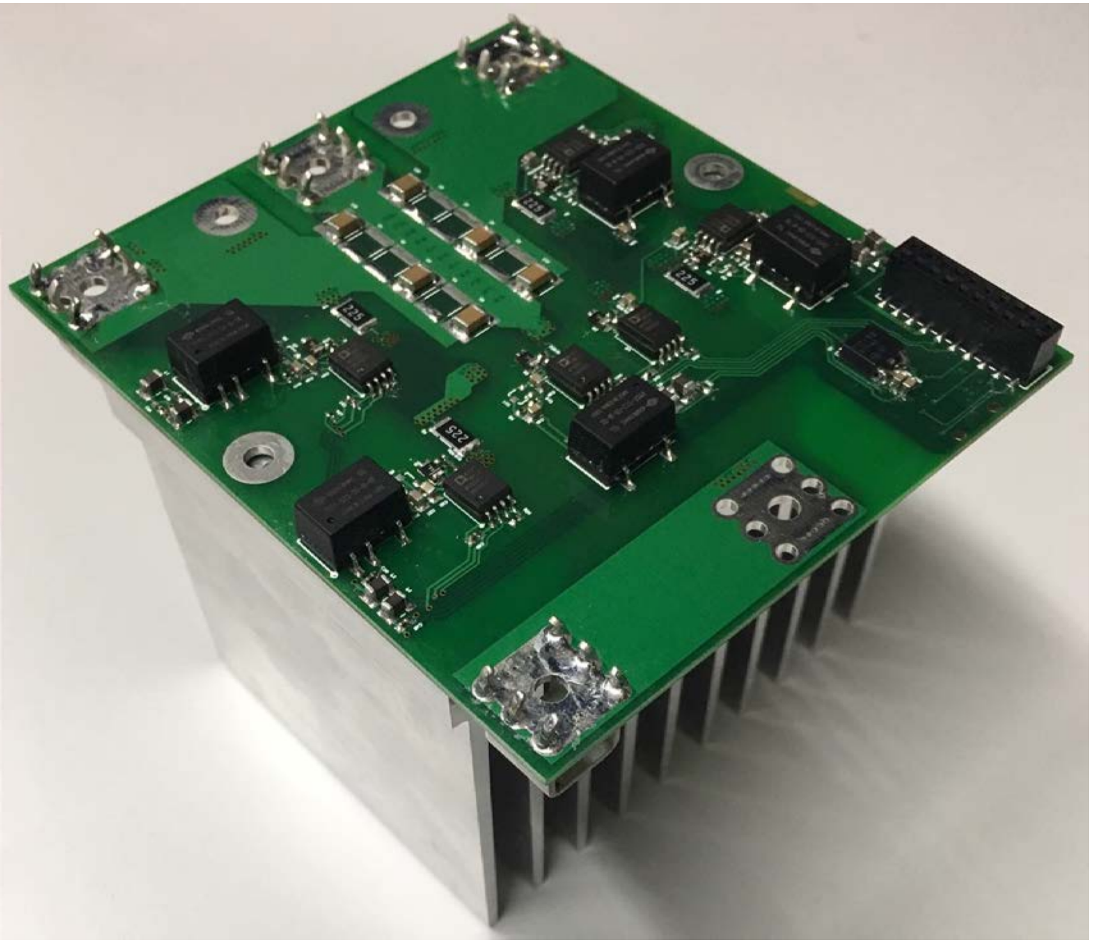
Practical Design Considerations Cont'd…

- Poor thermal conductivity of GaN semiconductor calls for special attention to thermal design
- GaN E-HEMTs have tiny packaging compared to SiC. Therefore, the heat generated within the device has to be dissipated fast and effectively to keep the junction temperature within allowable limits
- Also, the maximum junction temperature of the GaN E-HEMT selected is low compared to the SiC device
- If using a single heat sink for multiple GaN devices, they have to be aligned flat with the surface of heat sink
- Using thermal grease along with thermal tape will provide the best thermal conductivity

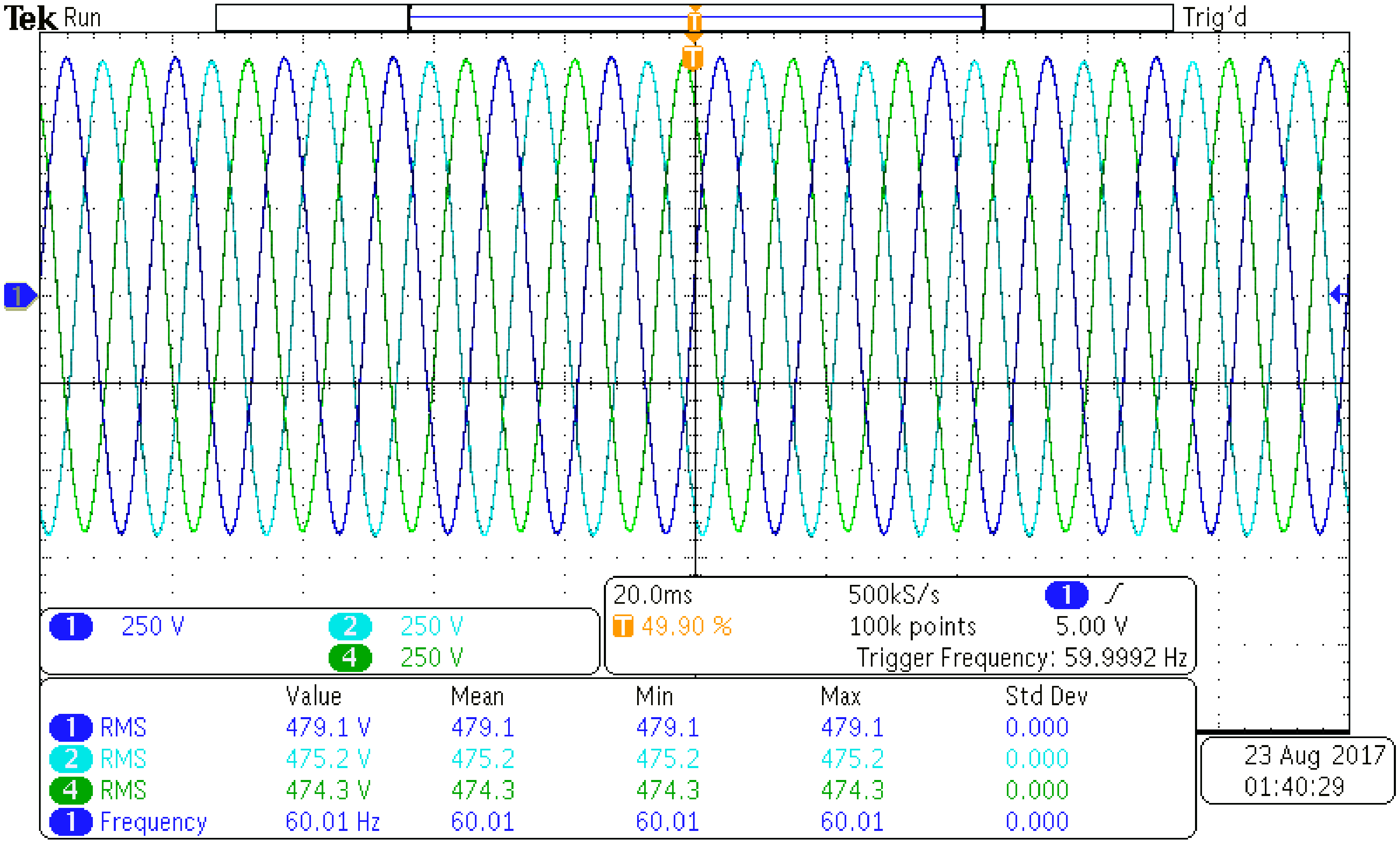
Single Phase Leg of Three-level Active-clamped Inverter

Using SiC MOSFETs

Using GaN E-HEMTs



Output Waveforms



1 250 V
2 250 V
4 250 V

20.0ms 500kS/s 1 ⟋
T 49.90 % 100k points 5.00 V
Trigger Frequency: 59.9992 Hz

	Value	Mean	Min	Max	Std Dev
1 RMS	479.1 V	479.1	479.1	479.1	0.000
2 RMS	475.2 V	475.2	475.2	475.2	0.000
4 RMS	474.3 V	474.3	474.3	474.3	0.000
1 Frequency	60.01 Hz	60.01	60.01	60.01	0.000

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Conclusion

- GaN enables overcoming the limitations seen with the use of Si devices
- A three level neutral-point active-clamped inverter enables the use of commercially available 650 V GaN devices when operating with energy storage devices around 1000 V
- GaN allows the use of faster switching frequencies – greatly reducing the cost and size of the converter while maintaining high efficiency
- The designers would have to pay great attention to the following details:
  - Gate driver design
  - Thermal design
- GaN devices enable the development of faster and smaller energy conversion devices

Thank You!!