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)

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Si</th>
<th>SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap (eV)</td>
<td>1.12</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Critical Field ($10^6$ V/cm)</td>
<td>0.25</td>
<td>2.2</td>
<td>3</td>
</tr>
<tr>
<td>Electron mobility (cm$^2$/V-sec)</td>
<td>1,350</td>
<td>950</td>
<td>1,000-2,000</td>
</tr>
<tr>
<td>Electron saturation velocity ($10^6$ cm/sec)</td>
<td>10</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Hole mobility (cm$^2$/V-sec)</td>
<td>480</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>Thermal conductivity (Watts/cm$^2$ K @ 300K)</td>
<td>1.5</td>
<td>3-4</td>
<td>1.3</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>11.9</td>
<td>10</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Silicon (Si) vs. Silicon Carbide (SiC) vs. Gallium Nitride (GaN)

- 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)

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

• **Pros**
  - GaN E-HEMT has the lowest input capacitance \((C_{GS}+C_{GD})\), leading to lower total gate charge \((Q_g)\) 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 than 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
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!!