# Advanced Low-Cost SiC and GaN Wide Bandgap Inverters for Under-the-Hood Electric Vehicle Traction Drives

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Cree Fayetteville, Inc.
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Project ID: EDT058

# OVERVIEW



## Timeline

**Project Start Date:** October 1, 2013
**Project End Date:** December 30, 2015
**Percent Complete:** 100%

## Budget

**Total Project Funding:** $3.8M
- **Non-Federal Share:** $2.0M
- **Federal/DOE Share:** $1.8M
  - **Funding in FY14:** $1,170,086
  - **Funding in FY15:** $ 630,046

## Barriers

- Unit cost ≤ $182 / 100,000
- Obtaining high-volume cost information
- High-current GaN HEMT device availability and maturity

## Partners

- Toyota - TRINA
- GaN Systems, Inc.
- National Renewable Energy Laboratory
- University of Arkansas National Center for Reliable Electric Power Transmission

# RELEVANCE: OBJECTIVES

- Develop two independent 55 kW peak traction inverter designs (one SiC based and one GaN based) to showcase the performance capabilities of WBG power devices – namely high efficiency, increased gravimetric and volumetric density through high operating junction temperature capability.
- Demonstrate a substantial cost reduction from the die level to the system level.
- Optimize proven productized high-temperature WBG power modules for increased manufacturability and reduced cost.
- Application of advanced system-level packaging techniques to completely eliminate a vehicle's secondary cooling loop system; utilize 85 °C rated capacitors, reduce interconnects, and enable increased system reliability.
- Demonstrate design robustness and reliability through extended testing of subsystems and systems under realistic application operating conditions.

# RELEVANCE: OBJECTIVES

- Application of advanced system-level packaging techniques to completely eliminate a vehicle's secondary cooling loop system, utilize 85°C rated capacitors, reduce interconnects, and enable increased system reliability.

- Demonstrate design robustness and reliability through extended testing of subsystems and systems under realistic application operating conditions.

- Complete cost and manufacturing analysis to aid commercialization effort.

The goal of this research is to **reduce traction inverter size** (≥ 13.4 kW/L), **weight** (≥ 14.1 kW/kg), and **cost** (≤ $182 / 100,000) while maintaining 15 year reliability metrics.

# RELEVANCE

The *USDRIVE* Electrical and Electronics Technical Team's mission is to enable cost-effective (A), smaller, lighter (C), and efficient (E) power electronics and electric motors for electric traction drive systems.

The DOE EE&RE Vehicle Technologies Program Multi-Year Program Plan (2011-2015) states power electronics technology targets of $3.30/kW (A), 14.1 kW/kg (C), and 13.4 kW/l by 2020 to reduce dependence on oil through electrification of vehicle drives with **15-year life (D)**.

| Requirement | Target |
|---|---|
| Continuous power output (kW) | 30 |
| Peak power output for 18 seconds (kW) | 55 |
| Weight (kg) | ≤ 3.9 |
| Volume (l) | ≤ 4.1 |
| Efficiency | > 93% |
| Unit cost for quantities of 100,000 ($) | ≤ 182 |
| Operating voltage (Vdc) | 200 to 450; nominal: 325 |
| Power factor of load | > 0.8 |
| Maximum current per phase (Arms) | 400 |
| Pre-charge time – 0 to 200 Vdc (sec) | 2 |
| Output current ripple – peak to peak (% of fundamental peak) | ≤ 3 |
| Maximum switching frequency (kHz) | 20 |
| Current loop bandwidth (kHz) | 2 |
| Maximum fundamental electrical frequency (Hz) | 1000 |
| Minimum isolation impedance-input and phase terminals to ground (MΩ) | 1 |
| Minimum motor input inductance (mH) | 0.5 |
| Ambient operating temperature ($^0$C) | -40 to +140 |

# TECHNICAL APPROACH / STRATEGY

- This program will develop two completely independent WBG traction inverters: one **SiC based and one GaN based.** This work will provide a unique, **direct comparison** between **inverter designs using SiC and GaN.** (Wolfspeed)

- This program will advance GaN HEMT power semiconductor device technology to **600 V, 100 A**. (GaN Systems)

- This program will utilize advanced **high performance power modules** to achieve high power density and efficiency. (Wolfspeed)

- This program will use **advanced packaging techniques** (Wolfspeed) and **active cooling technologies** (Toyota, NREL) to enable the use of low-cost, 85 °C-rated DC bus capacitors.

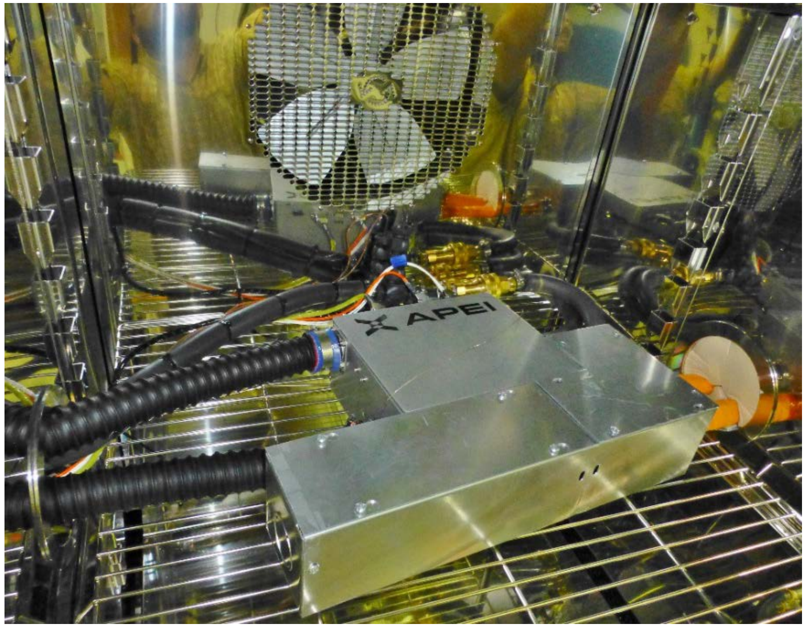
- **Custom, in-house HTSOI IC designs** will dramatically reduce the cost of high temperature capable support circuitry. (Wolfspeed, *abandoned*)

# Technical Accomplishments: Results vs. AOI 12 Targets

# HIGH-POWER DYNAMOMETER TEST BED AT THE UNIVERSITY OF ARKANSAS NATIONAL CENTER FOR RELIABLE ELECTRIC POWER TRANSMISSION




A view of the test bed beside the ABB/Baldor drive applying torque commands to the induction machine to load the interior PMSM




The Design Cycle 2 SiC inverter inside the environmental chamber ready for test

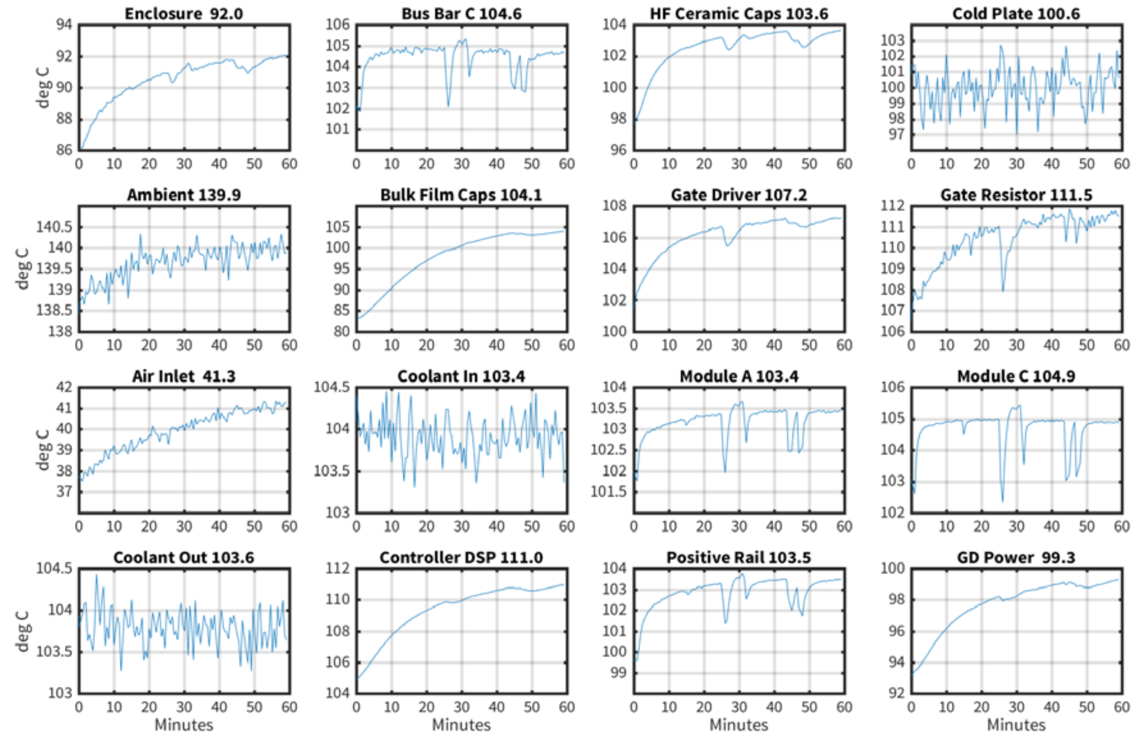
# ACCOMPLISHMENTS VERSUS PROGRAM TARGETS



| No. | Requirement | Target | SiC-Based Inverter | GaN-Based Inverter |
|---|---|---|---|---|
| 1 | Continuous power output (kW) | 30 | √+ | √ |
| 2 | Peak power output for 18 seconds (kW) | 55 | √+ | √ |
| 3 | Weight (kg) | ≤ 3.9 | √ | √ |
| 4 | Volume (l) | ≤ 4.1 | √ | √ |
| 5 | Efficiency | > 93% | √+ | Unknown |
| 6 | Unit Cost for quantities of 100,000 ($) | ≤ 182 | √+ | √ |
| 7 | Operating voltage (V dc) | 200 to 450; nominal: 325 | √+ | √ |
| 8 | Power factor of load | > 0.8 | √ | √ |
| 9 | Maximum current per phase (Arms) | 400 | √ | √ |
| 10 | Pre-charge time – 0 to 200 V dc (sec) | 2 | √ | √ |
| 11 | Output current ripple – peak to peak (% of fundamental peak) | ≤ 3 | √ | √ |
| 12 | Maximum switching frequency (kHz) | 20 | √+ | √+ |
| 13 | Current loop bandwidth (kHz) | 2 | √+ | √+ |
| 14 | Maximum fundamental electrical frequency (Hz) | 1000 | √+ | √+ |
| 15 | Minimum isolation impedance-input and phase terminals to ground (MΩ) | 1 | √ | √ |
| 16 | Minimum motor input inductance (mH) | 0.5 | √ | √ |
| 17 | Ambient operating temperature (°C) | -40 to +140 | √ | √ |

# CONTINUOUS POWER OUTPUT TARGET = 30 kW

- Thermal steady-state
- 59 minutes in duration
- 30 kW, 27 kVAr, 40 kVA @ 3480 RPM and 72 N-m load
- DPF ~ 0.75 lagging
- 105 °C coolant
- 140 °C ambient
- 40 °C air
- 450 VDC bus
- 16 thermocouples throughout the inverter system and averaged temperatures were recorded every 30 seconds



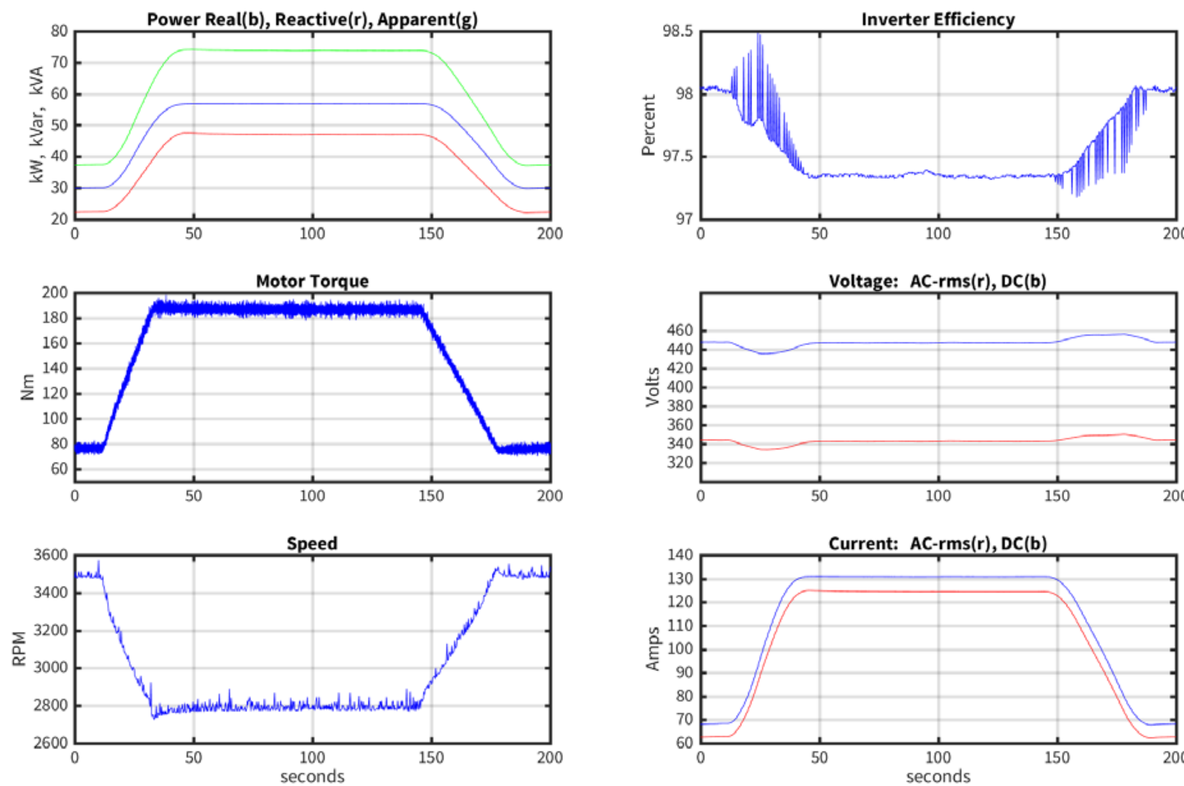

| | | | |
|---|---|---|---|
| K | -200°C to 1250°C (-328° F to 2282°F) | Greater of 2.2°C or 0.75% | Greater of 1.1°C or 0.4% |

*Source: www.omega.com*

# PEAK POWER OUTPUT FOR 18 SECONDS TARGET = 55 kW



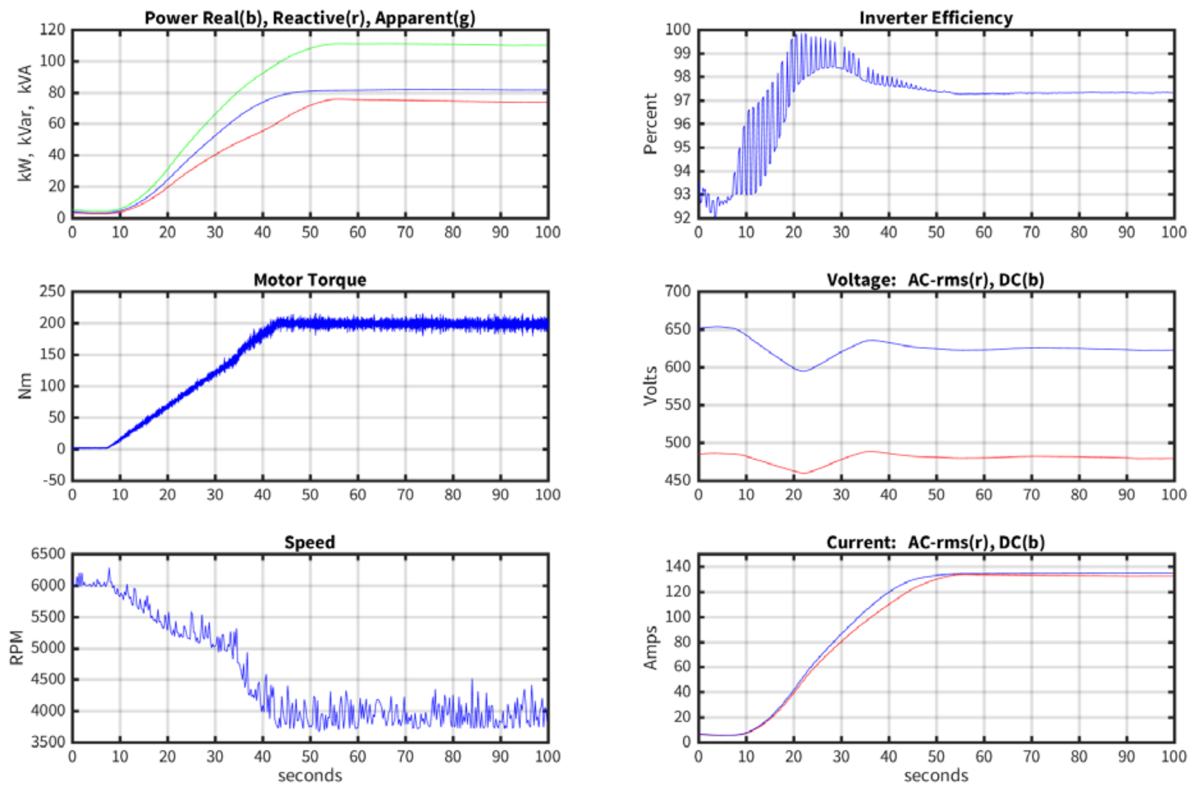
- Thermal steady-state @ 30 kW
- Load is raised to 55 kW for a finite duration, and then lowered back to 30 kW
- 105 °C coolant
- 140 °C ambient
- 40 °C air
- 450 VDC bus
- 56.9 kW, 47.3 kVAr, 74 kVA, 97.3%
- Test was repeated three times dwelling for 50, 60, and then 120 seconds



# MAXIMUM POWER (NO TARGET) = 81.8 kW

- Find the maximum continuous power for computing power density and specific weight
- Physical limitations existed: DC bus voltage, torque transducer, flexible shaft couplers
- 1st attempt: 650 VDC, 6000 RPM, and 180 N-m of load torque
- 81.8 kW, 74.7 kVArs, and 110 kVA
- DPF = 0.738 lagging
- $\eta$ = 97.4%
- ~60 seconds
- dV/dt = 650/50n = 13 kV/µs !
- EMI caused communication failures and locked up the GUI

**DYNAMOMETER LIMITED!**

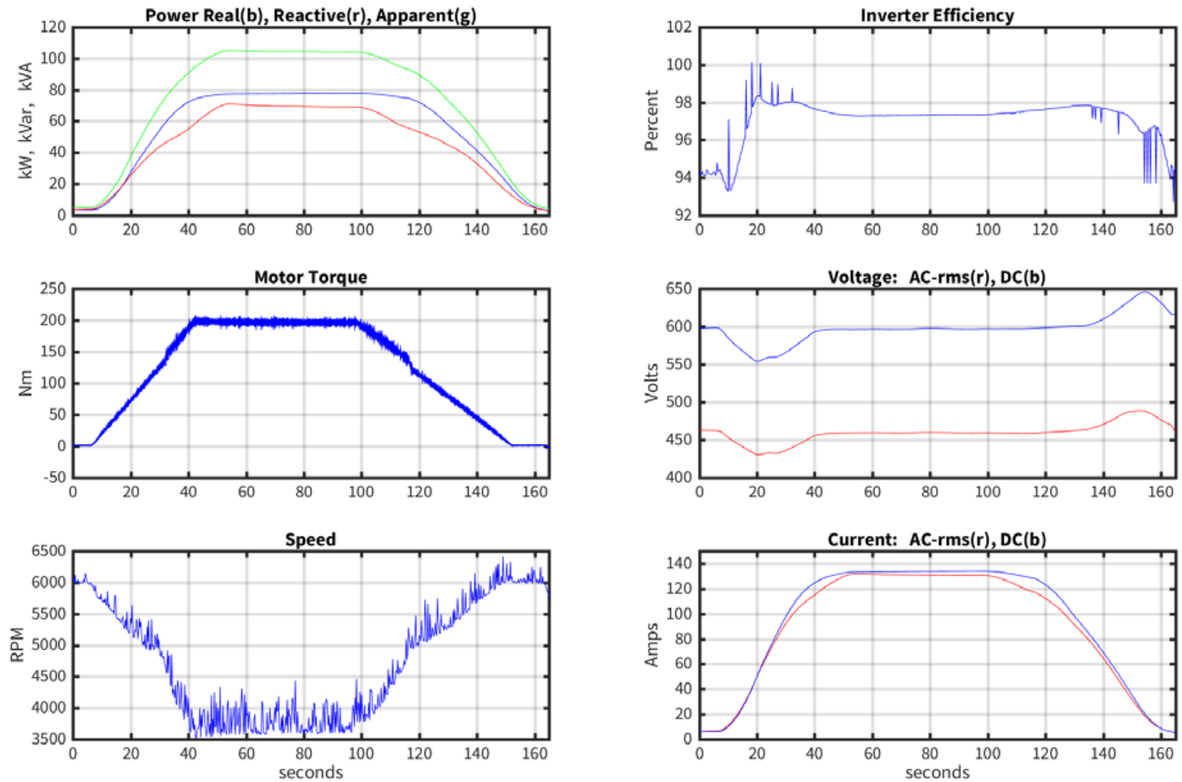


# MAXIMUM POWER TARGET = 77.9 kW

**DYNAMOMETER LIMITED!**

- 2nd attempt: 600 VDC, 6000 RPM, and 180 N-m of load torque
- 77.9 kW, 69.1 kVArs, and

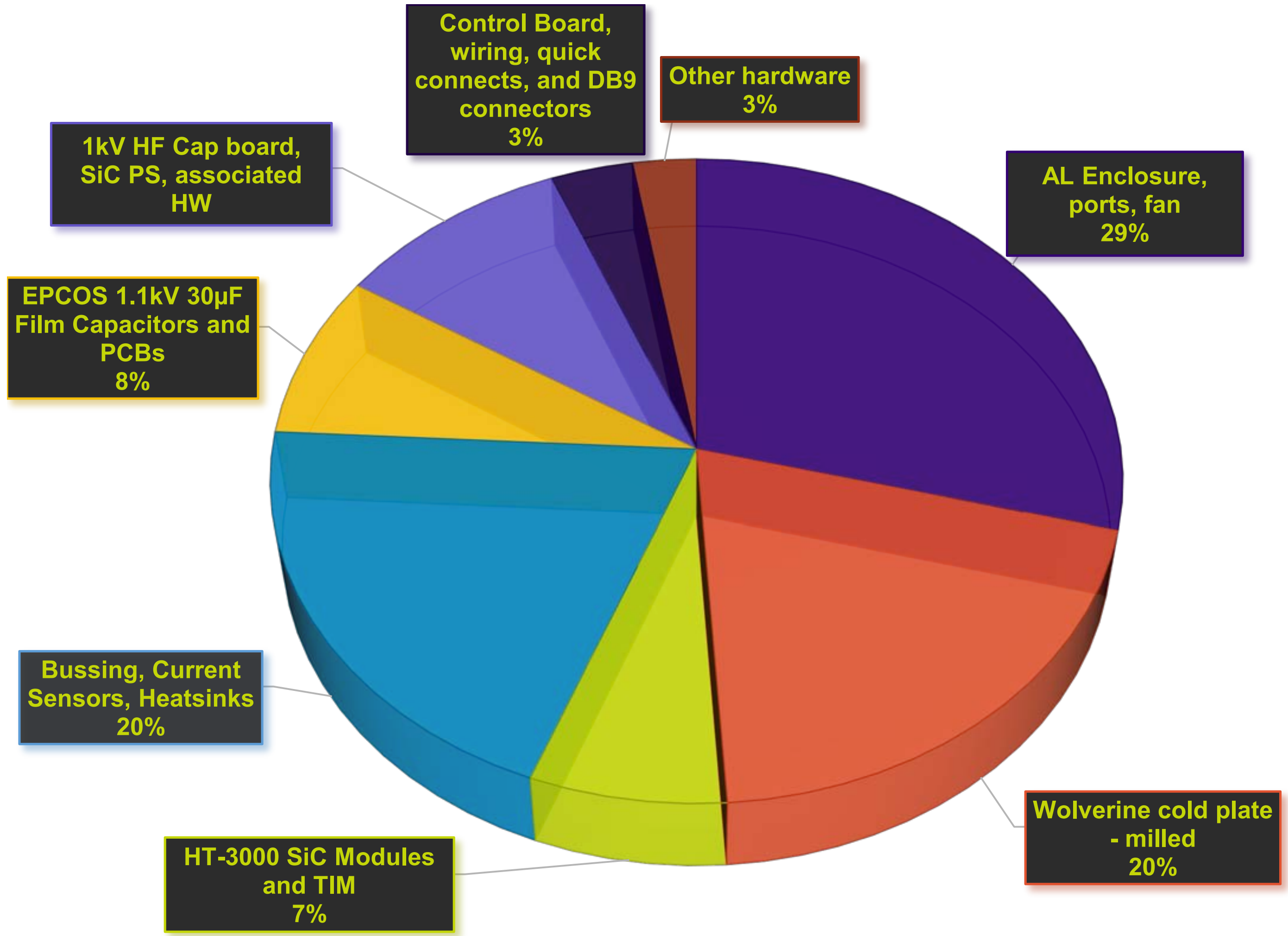
  104 kVA
- DPF = 0.748 lagging
- $\eta \geq 97.4\%$
- Ran 3 times: 1, 2, and 3 minutes
- dV/dt = 600/50n = still 12 kV/µs !
- DC bus caps reached their rating



# SiC INVERTER WEIGHT TARGET ≤ 3,900 G = 3.9 KG

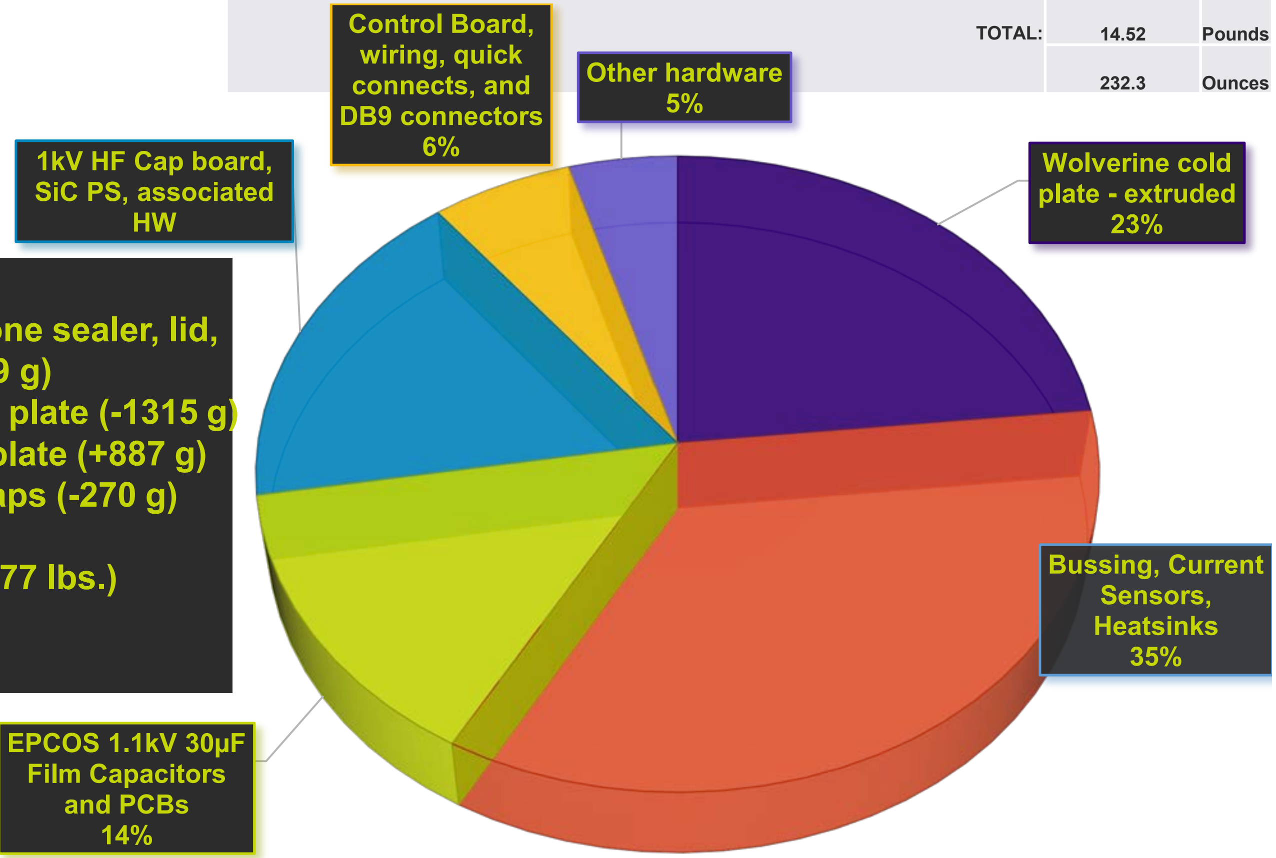


**Total weight = 6,586 g or 6.59 kg (14.52 lbs.)**



# SiC INVERTER WEIGHT TARGET ≤ 3,900 G = 3.9 KG, CONT.

| DOE VTP - Phase 1 Inverter Weights | | | | |
|---|---|---|---|---|
| Item Description | Grams | Qty | Component Total | Unit |
| AL Enclosure, ports, fan | 1909 | 1 | 1909 | Grams |
| Wolverine cold plate - milled | 1315 | 1 | 1315 | Grams |
| HT-3000 SiC Modules and TIM | 150 | 3 | 450 | Grams |
| Bussing, Current Sensors, Heatsinks | 1323 | 1 | 1323 | Grams |
| EPCOS 1.1kV 30µF Film Capacitors and PCBs | 90 | 6 | 540 | Grams |
| 1kV HF Cap board, SiC PS, associated HW | 216 | 3 | 648 | Grams |
| Control Board, wiring, quick connects, and DB9 connectors | 226 | 1 | 226 | Grams |
| Other hardware | 175 | 1 | 175 | Grams |
| | | | 6,586 | Grams |
| | | TOTAL: | 14.52 | Pounds |
| | | | 232.3 | Ounces |




NOTE:

- Remove enclosure base, silicone sealer, lid, ports, hardware, and fan (-1909 g)
- Remove milled Wolverine cold plate (-1315 g)
- Add Wolverine extruded cold plate (+887 g)
- Remove three of six DC bus caps (-270 g)

New TOTAL = 3,979 g = 3.98 kg (8.77 lbs.)

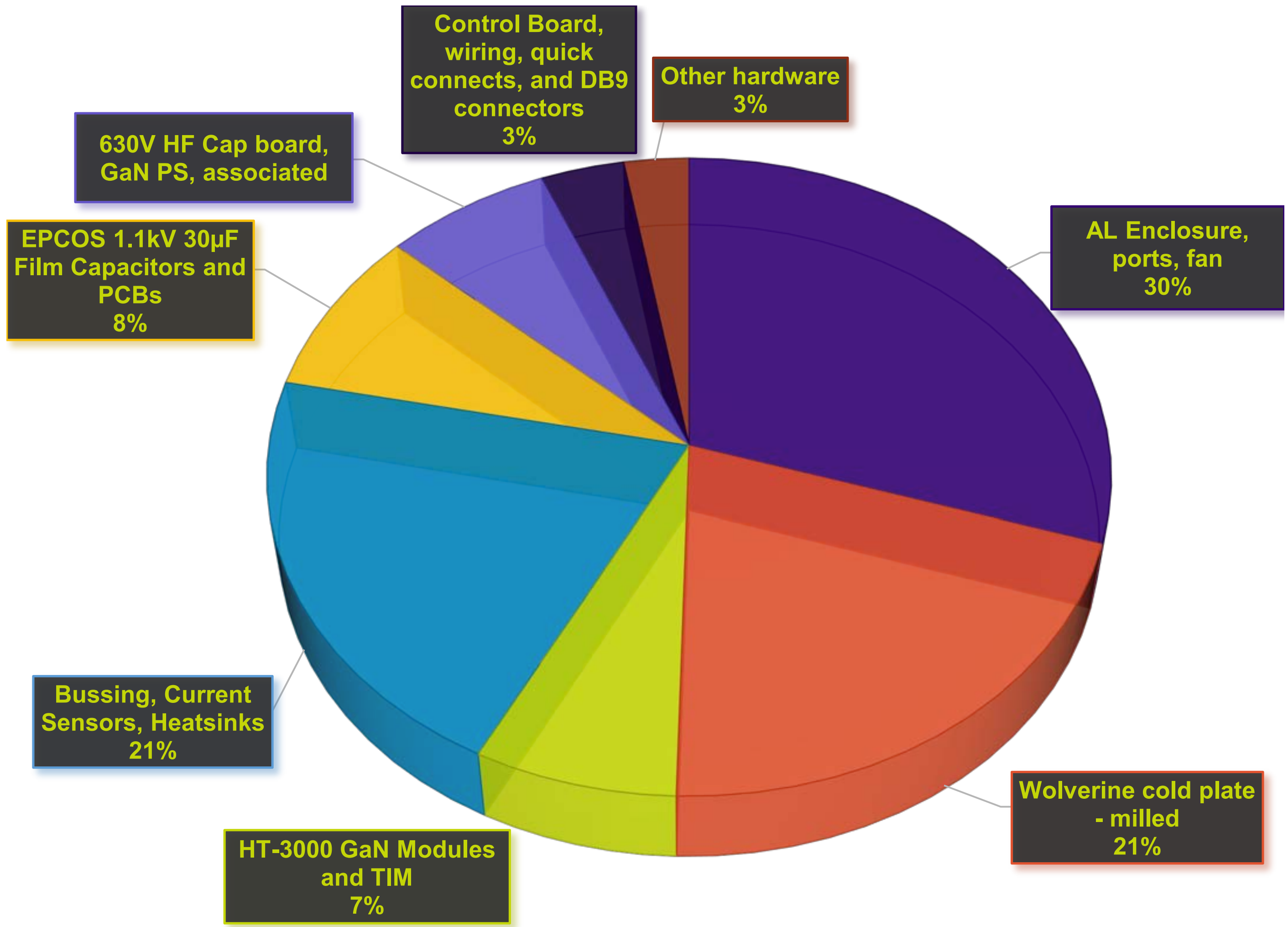
TARGET ≤ 3,900 g = 3.90 kg

# GaN INVERTER WEIGHT TARGET ≤ 3,900 G = 3.9 KG



**Total weight = 6,392 g or 6.39 kg (14.09 lbs.)**

**The SiC inverter weighs slightly more than the GaN inverter because the 1 kV HF MLCC X7R capacitors are physically larger than the ones rated at 630 V.**



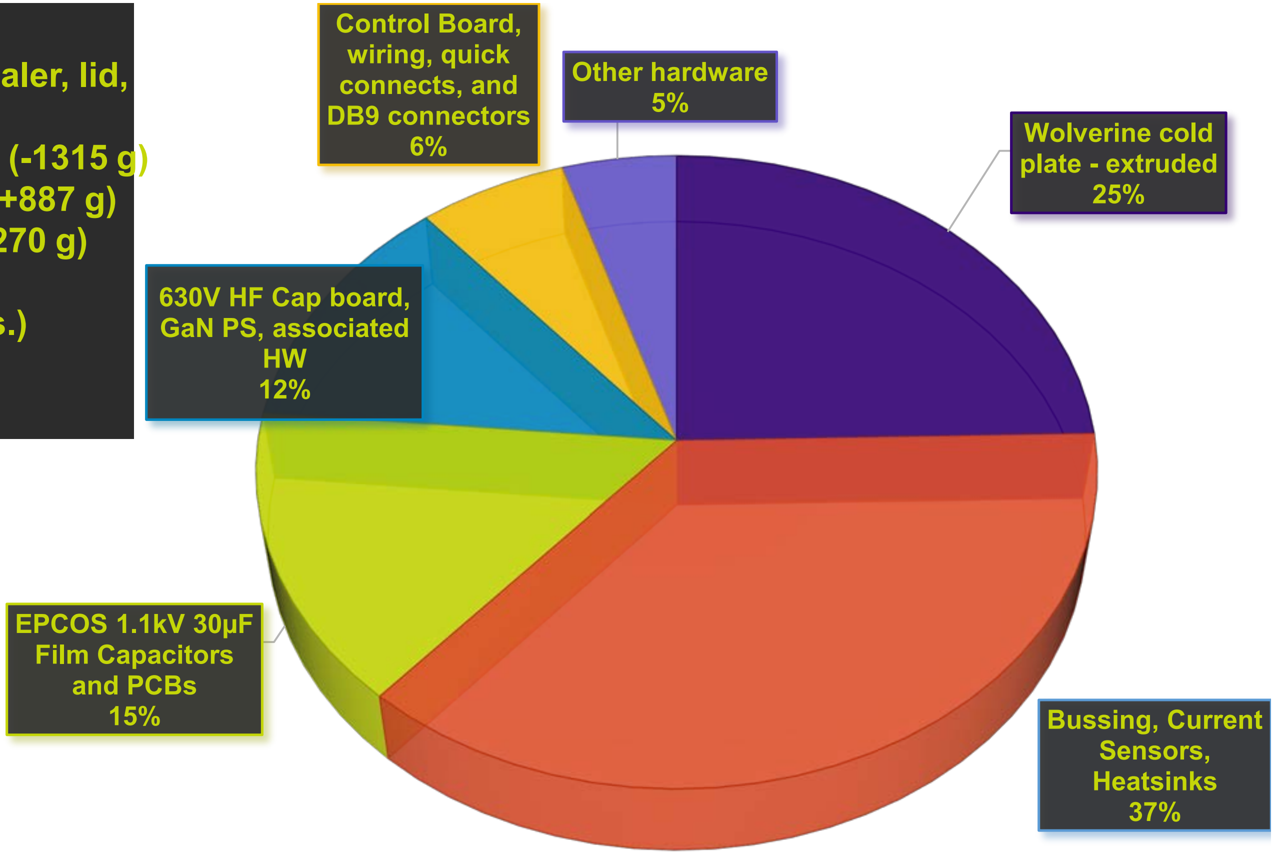
# GaN INVERTER WEIGHT TARGET ≤ 3,900 G = 3.9 KG CONT.

| DOE VTP - Phase 1 Inverter Weights | | | | |
|---|---|---|---|---|
| Item Description | Grams | Qty | Component Total | Unit |
| AL Enclosure, ports, fan | 1909 | 1 | 1909 | Grams |
| Wolverine cold plate - milled | 1315 | 1 | 1315 | Grams |
| HT-3000 GaN Modules and TIM | 152 | 3 | 456 | Grams |
| Bussing, Current Sensors, Heatsinks | 1323 | 1 | 1323 | Grams |
| EPCOS 1.1kV 30µF Film Capacitors and PCBs | 90 | 6 | 540 | Grams |
| 630 V HF Cap board, GaN PS, associated HW | 149 | 3 | 448 | Grams |
| Control Board, wiring, quick connects, and DB9 connectors | 226 | 1 | 226 | Grams |
| Other hardware | 175 | 1 | 175 | Grams |
| | | | 6,392 | Grams |
| | | TOTAL: | 14.09 | Pounds |
| | | | 225.5 | Ounces |

NOTE:
- Remove enclosure base, silicone sealer, lid, ports, hardware, and fan (-1909 g)
- Remove milled Wolverine cold plate (-1315 g)
- Add Wolverine extruded cold plate (+887 g)
- Remove three of six DC bus caps (-270 g)

New TOTAL = 3,785 g = 3.79 kg (8.35 lbs.)

TARGET ≤ 3,900 g = 3.90 kg




Wolfspeed

# SiC & GaN INVERTER VOLUME TARGET ≤ 4.1 LITERS

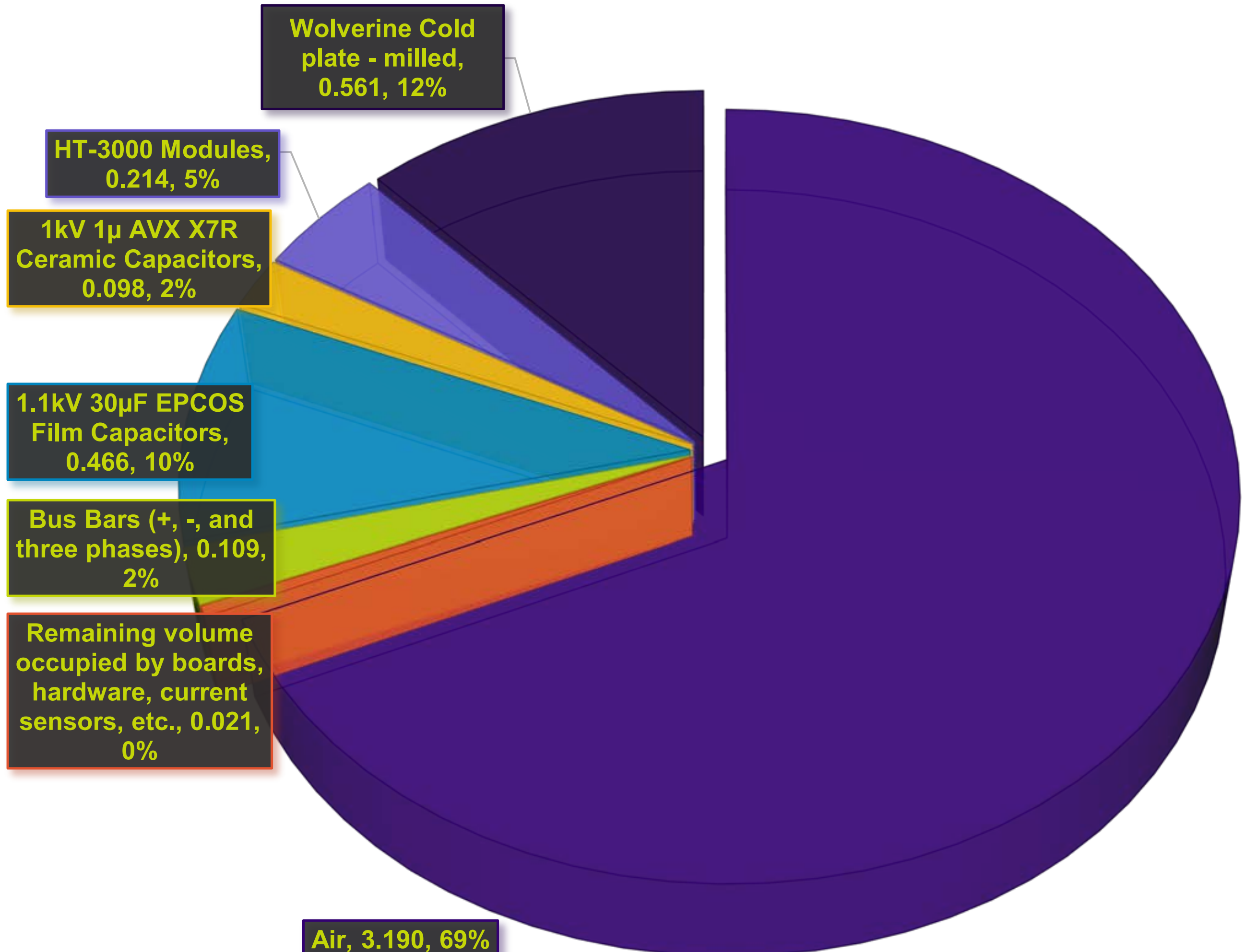


Note: This air volume excludes the displacement caused by internal wiring and associated quick connectors.

Total external volume = 4.83 liters (excluding glands and connectors)

Total internal volume = 4.66 liters

With ½ the DC bus capacitors, 4.43 liters



# POWER DENSITY TARGETS ≥ 13.4 KW/L & 14.1 KW/KG



| Design Cycle 2 SiC Inverter, 4.8 L, 6.6 kg, HT-3201-R modules @ *max.* ambient and coolant temperatures | | | | | | |
|---|---|---|---|---|---|---|
| **kW** | kVAr | kVA | kW/L | kW/kg | kVA/L | kVA/kg |
| **30** | 27 | 40.4 | 6.2 | 4.5 | 8.4 | 6.1 |
| **56.9** | 47.3 | 74.0 | 11.8 | 8.6 | 15.4 | 11.2 |
| **77.9** | 69.1 | 104.2 | 16.2 | 11.8 | 21.7 | 15.8 |
| **81.8** | 74.7 | 110.8 | 17.0 ★ 2020 | 12.4 ★ 2015 | 23.1 | 16.8 |

| Design Cycle 2 SiC Inverter, 4.4 L, 4.0 kg, HT-3201-R modules @ *max.* ambient and coolant temperatures | | | | | | |
|---|---|---|---|---|---|---|
| **kW** | kVAr | kVA | kW/L | kW/kg | kVA/L | kVA/kg |
| **30** | 27 | 40.4 | 6.8 | 7.5 | 9.2 | 10.1 |
| **56.9** | 47.3 | 74.0 | 12.9 | 14.2 | 16.8 | 18.5 |
| **77.9** | 69.1 | 104.2 | 17.7 | 19.5 | 23.7 | 26.0 |
| **81.8** | 74.7 | 110.8 | 18.6 ★ 2025 | 20.4 ★ 2025 | 25.2 | 27.7 |

# THEORETICAL/ACHIEVABLE POWER DENSITY TARGETS ≥ 13.4 KW/L & 14.1 KW/KG



| Design Cycle 2 SiC Inverter, 4.8 L, 6.6 kg , HT-3201-R modules @ < *max.* ambient & coolant temperatures | | | | | | |
|---|---|---|---|---|---|---|
| **kW** | kVAr | kVA | kW/L | kW/kg | kVA/L | kVA/kg |
| **166.3** | 124.7 | 207.9 | 34.6 | 25.2 | 43.3 | 31.5 |
| **199.5** | 149.6 | 249.4 | 41.6 ★ 2025 | 30.2 ★ 2025 | 51.9 | 37.8 |

- With a DC bus of 650 VDC, the achievable AC output voltage is 400 V rms line to line.
- With a DC bus of 800 VDC, the achievable AC output voltage is 480 V rms line to line.

- Assume an achievable AC output current of 300 A rms and a worst-case DPF = 0.8.
- $P_{3\phi} = \sqrt{3}$ (400 [480]) (300) (0.8) = 166.3 kW [199.5 kW]
- $Q_{3\phi} = \sqrt{3}$ (400 [480]) (300) (0.6) = 124.7 kVAr [149.6 kVAr]
- The apparent power, $|S_{3\phi}|$ = 207.9 [249.4 kVA]

| Design Cycle 2 SiC Inverter, 4.4 L, 4.0 kg , HT-3201-R modules @ < *max.* ambient & coolant temperatures | | | | | | |
|---|---|---|---|---|---|---|
| **kW** | kVAr | kVA | kW/L | kW/kg | kVA/L | kVA/kg |
| **166.3** | 124.7 | 207.9 | 37.8 | 41.6 | 47.2 | 52.0 |
| **199.5** | 149.6 | 249.4 | 45.3 ★ 2025 | 49.9 ★ 2025 | 56.7 | 62.3 |

# SiC INVERTER EFFICIENCY TARGET > 93%, CONT.



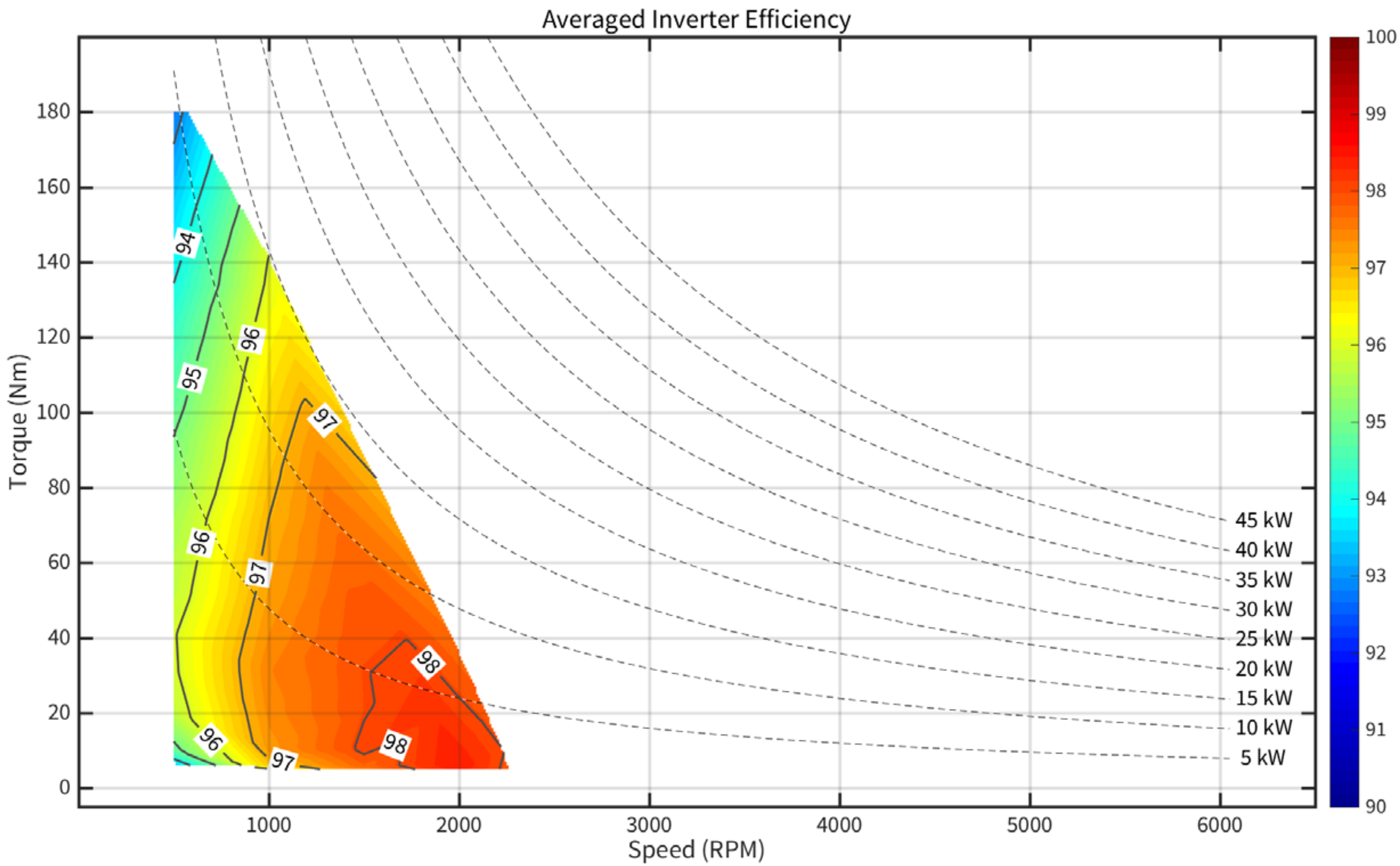
- 650 V DC bus has a slightly lower efficiency
- “Sweet spot” may be outside the range of torques and speeds that were tested
- The nominal 325 V DC bus yielded the best overall efficiency
- Efficiencies measured at loads < 5 kW are not as reliable due to current signal scaling and its impact on the Yokogawa’s resolution being no greater than 10 W

- 200 VDC, 66 operating points
- 325 VDC, 135 operating points
- 450 VDC, 151 operating points
- 650 VDC, 155 operating points
- 4 bus voltages, 507 operating points
- 6 thermal cases: 3,042 operating points

| Bus Voltage | Average Efficiency (%) | Peak Efficiency (%) |
|---|---|---|
| 200 | 96.7 | 98.7 |
| 325 | 97.0 | 99.0 |
| 450 | 96.3 | 98.2 |
| 650 | 95.2 | 97.9 |
| All 4 | 96.3 | 98.9 |

# SIC INVERTER EFFICIENCY TARGET > 93%

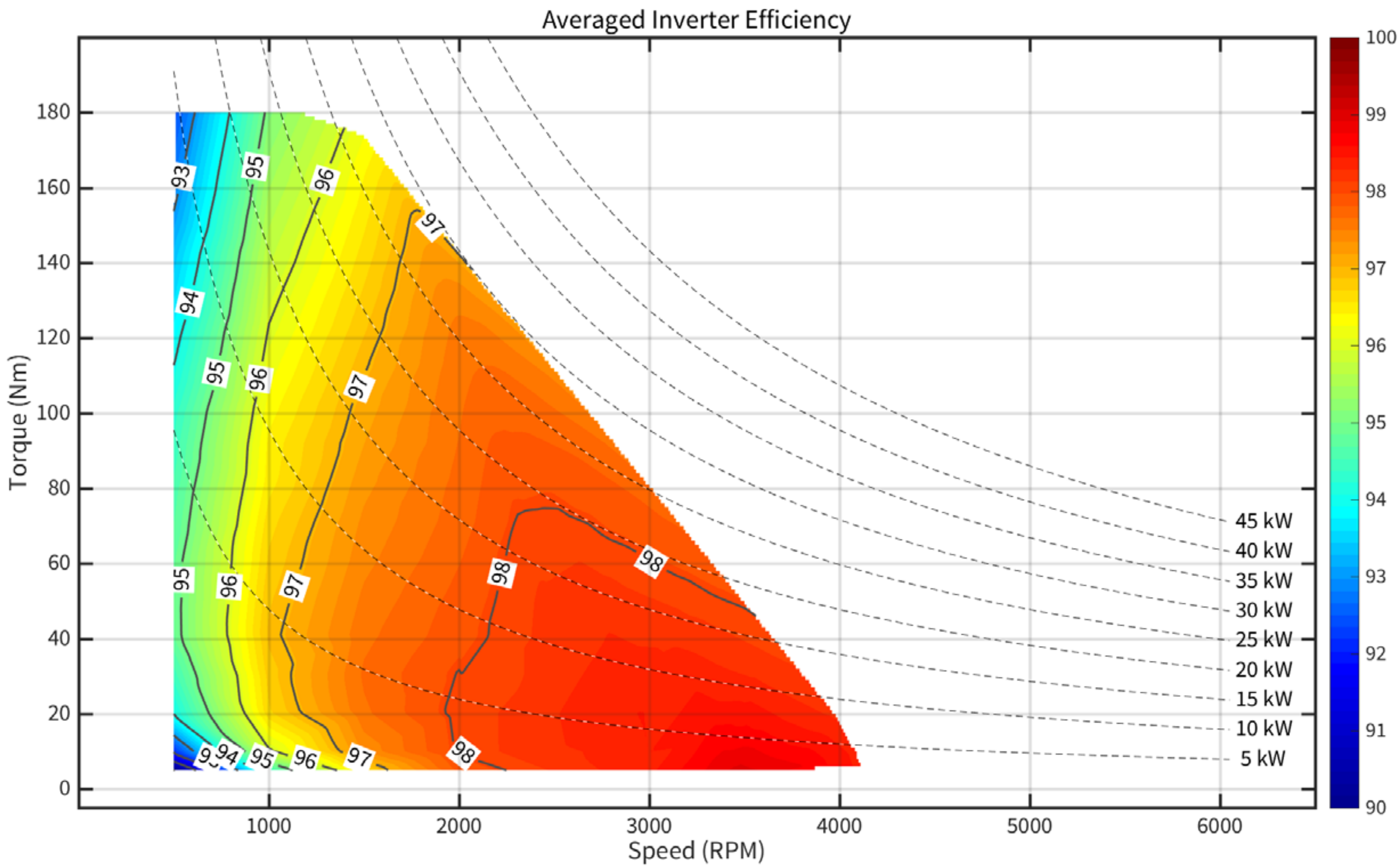





Average of 6 thermal cases, 200 VDC, Mean = 96.7%, Peak = 98.4%

# SIC INVERTER EFFICIENCY TARGET > 93%, CONT.

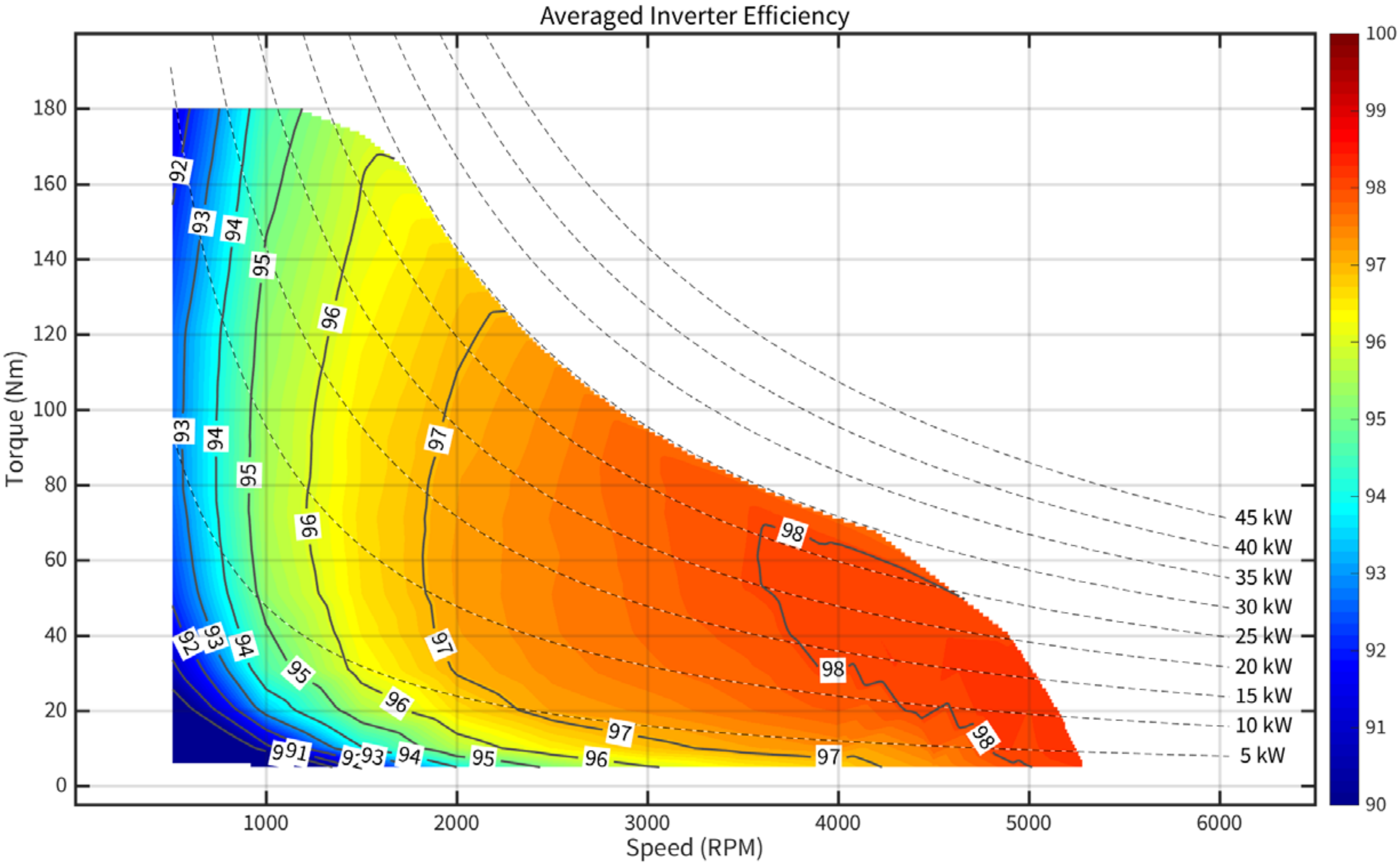





Average of 6 thermal cases, 325 VDC, Mean = 97.0%, Peak = 99.0%

# SIC INVERTER EFFICIENCY TARGET > 93%, CONT.

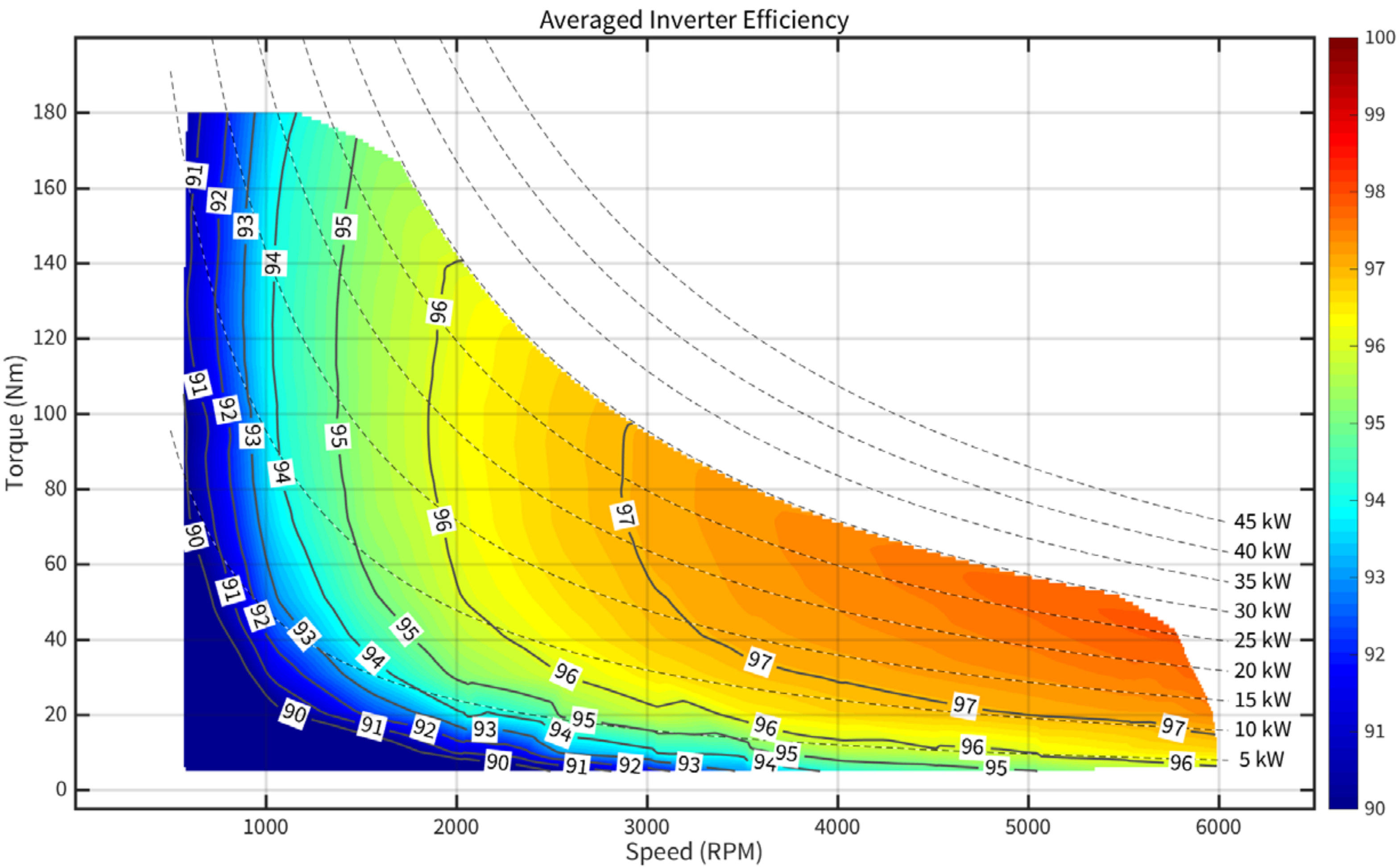





Average of 6 thermal cases, 450 VDC, Mean = 96.2%, Peak = 98.2%

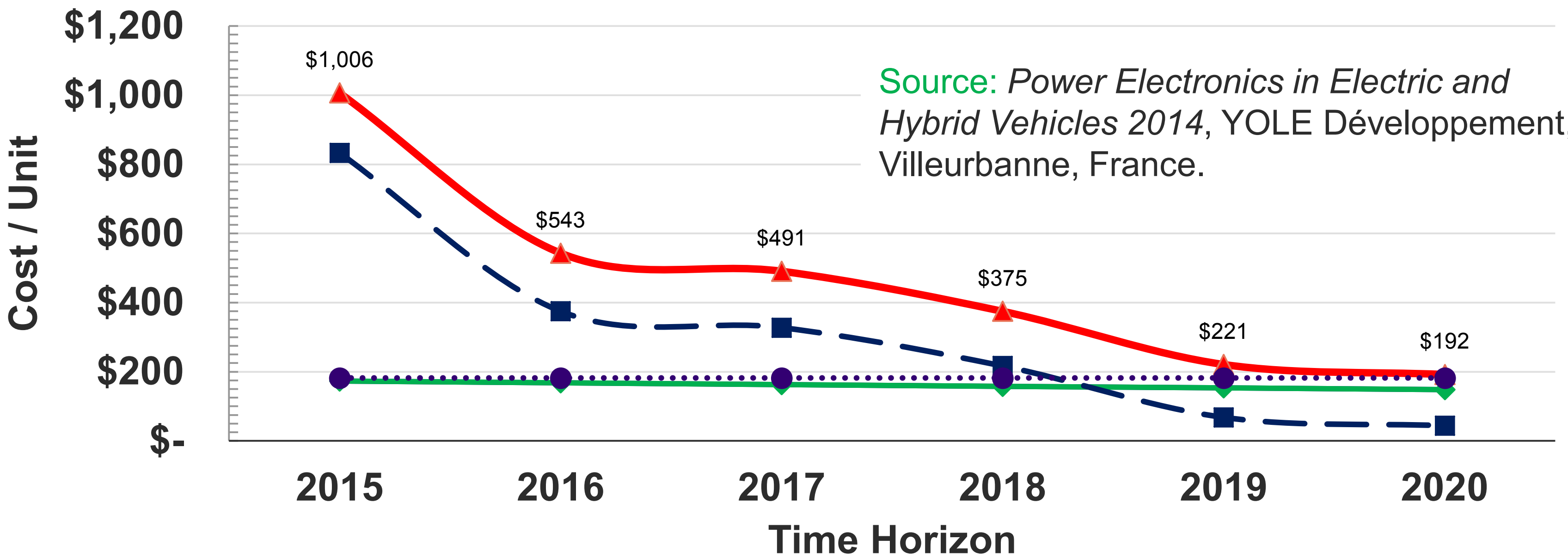
# SIC INVERTER EFFICIENCY TARGET > 93%, CONT.






Average of 6 thermal cases, 650 VDC, Mean = 94.9%, Peak = 97. 9%

# SiC INVERTER COST BREAKDOWN




Source: *Power Electronics in Electric and Hybrid Vehicles 2014*, YOLE Développement, Villeurbanne, France.

Total Price of 60 kW SiC MOSFET HEV Inverter - Agarwal Price Projections

Price of 60 kW SiC MOSFET HEV Inverter Cost Less SiC MOSFETs and SBDs

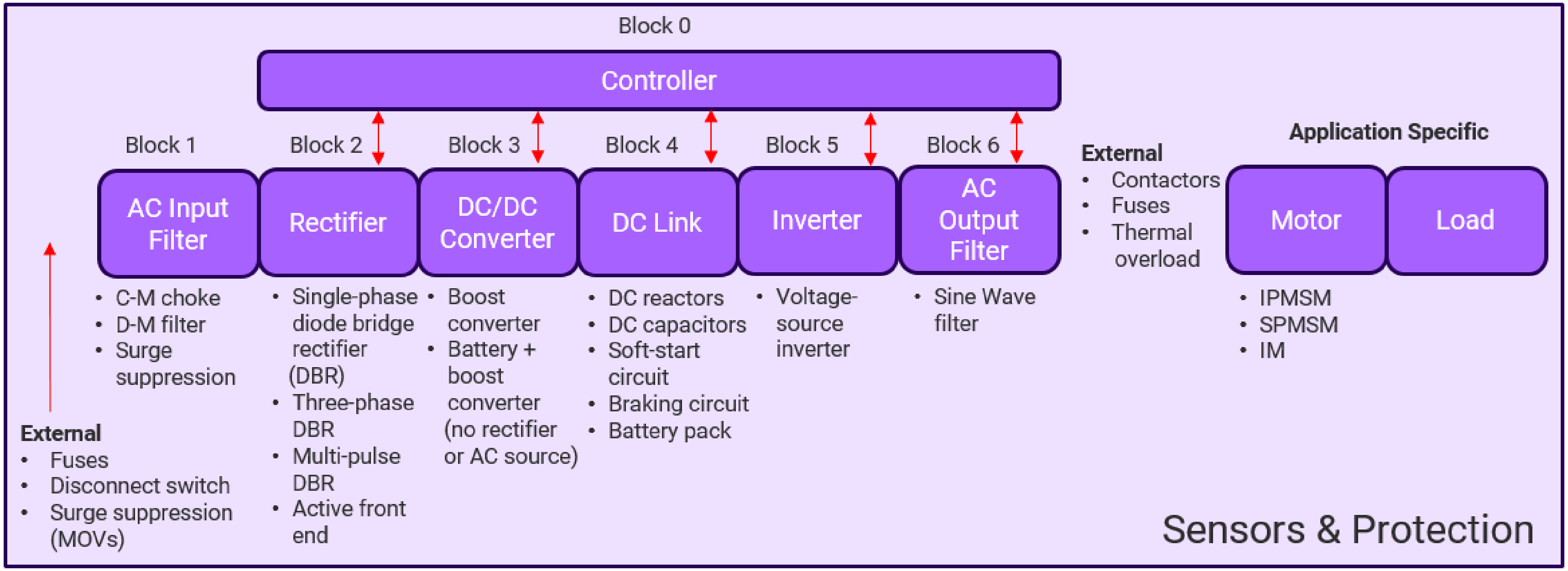
Agarwal's Projection for SiC Costs

DOE Inverter Target, $182

*Source:* A. K. Agarwal (DOE), “Manufacturing Perspective on Wide Bandgap Devices,” MRS 2014, Session T6: SiC Power Devices, December 3, 2014.

# Commercialization Activity

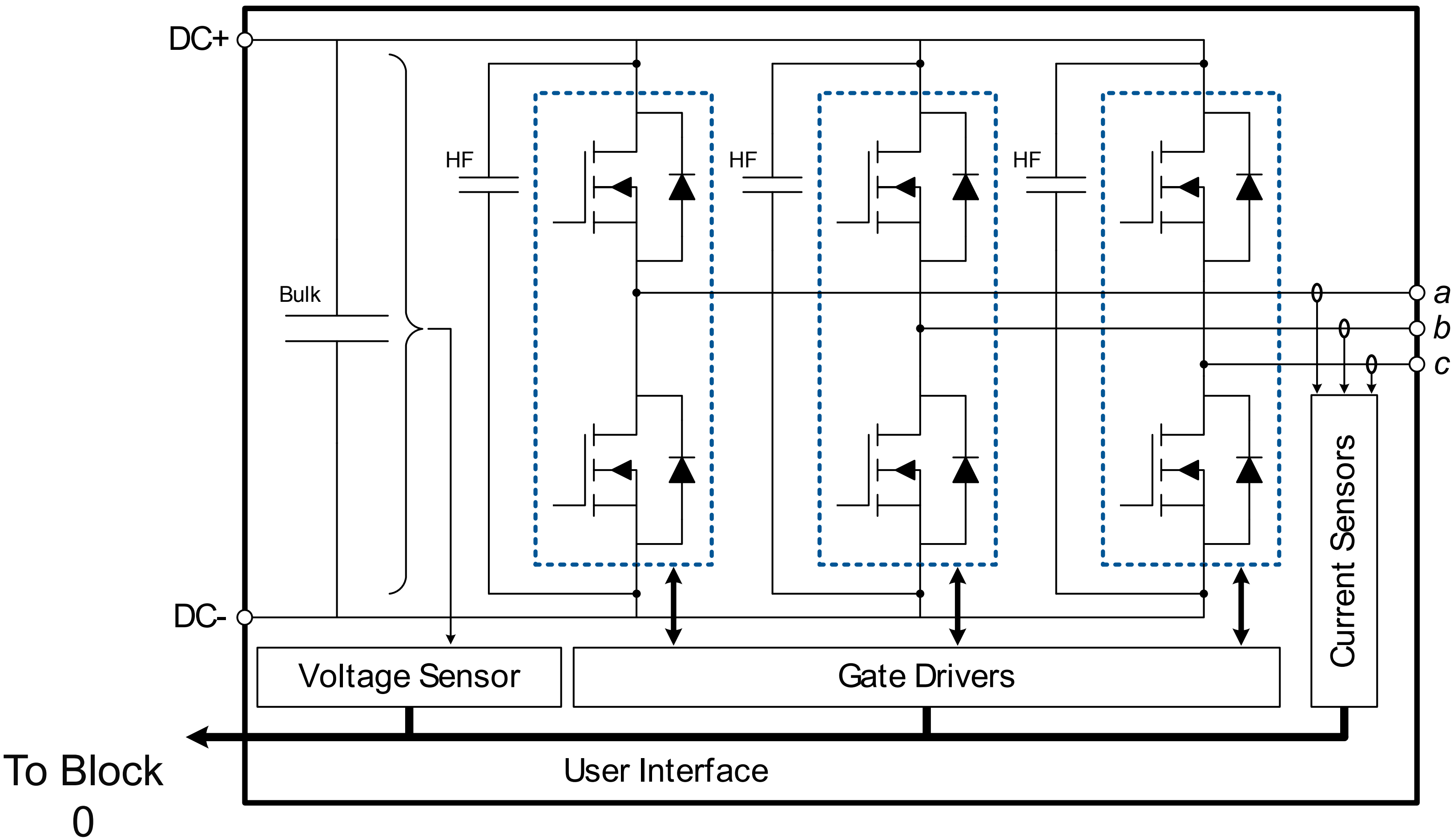
# PATH TO PRODUCT MANUFACTURING AND COMMERCIALIZATION




- Wolfspeed-led education initiative for WBG semiconductor adoption
- Building block philosophy (e.g., ONR’s PEBB initiative from many years ago)
- A highly WBG-optimized stack up that allows the user to “plug and play” in order to show ROI / PP on either legacy product designs or new product development
- We leveraged what we learned herein to focus on Blocks 0, 4, and 5
- Block 2 and Block 5 differ only by sensor suite
- Example: Block 0 + Block 2 + Block 4 + Block 5 give use an industrial motor drive

# PATH TO PRODUCT MANUFACTURING AND COMMERCIALIZATION, CONT.

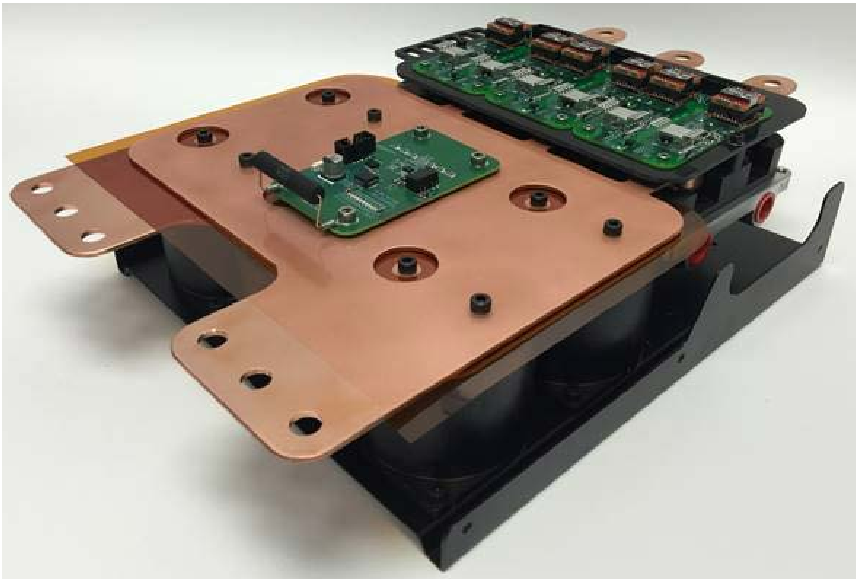


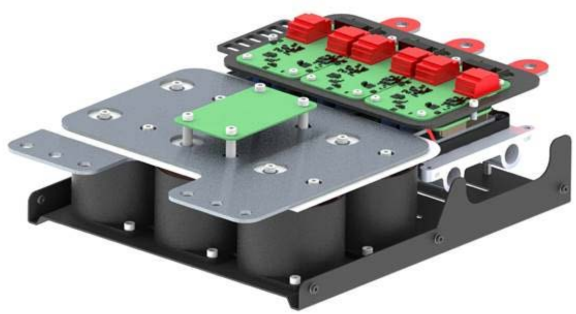



A Circuit Schematic of Blocks 4 and 5

# PATH TO PRODUCT MANUFACTURING AND COMMERCIALIZATION, CONT.








Prototype build of Blocks 4 and 5 – Block 0 is not shown.

# RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS



Questions and/or comments can be classified into one of two areas: (i.) **Production costing**; and (ii.) **EMI issues**.

**<u>Wolfspeed's Response</u>**: (i.) Three data points have been provided in this AMR presentation: the BOM costs for the Design Cycle 1 SiC inverter; the BOM costs for the Design Cycle 2 SiC inverter; and the Design Cycle 2 SiC inverter builds for N = 20, 50, 100, and 300. Further refinement will best be done after another design cycle is complete in concert with either an OEM or a Tier 1 supplier with a known insertion platform identified. Significant cost savings may be achieved if the maximum ambient temperature is relaxed from 140 °C to 125 °C.

**<u>Wolfspeed's Response</u>**: (ii.) The reviewer's are correct in pointing out EMI challenges associated with WBG semiconductors. But, any power device technology exhibiting "ideal power switch" characteristics and attributes will have similar challenges. As such, the system designer must be diligent in all aspects of grounding and shielding between, among, and within assemblies and subassemblies. Wolfspeed had to overcame numerous obstacles to achieve the electro-thermal targets of the program. For example, no 140 °C shielded inverter-grade cables were found. This necessitated designing and building our own.

# COLLABORATIONS AND COORDINATION WITH OTHER INSTITUTIONS

- OEM – Toyota. Toyota collaborated on system-level **specifications** and on the design of the **thermal management system**.
- Device Manufacturer – GaN Systems, Inc. GaN Systems were to fabricate and test ≥ 600 V, ≥ 50 A **GaN HEMTs**.
- Supporting Research Organizations
  1. National Renewable Energy Laboratory – NREL performed **thermal and reliability analysis** at the module- and system-levels, respectively.
  2. University of Arkansas NCREPT – UA NCREPT assisted in the extensive **characterization and testing** of the traction inverter system using a custom-designed dynamometer test bed.

# PROPOSED FUTURE WORK

- This project is complete as of December 31, 2015. Reporting continues.
- Candidate future work will be continued either through other DOE funding, or future IR&D funding
  - Package Si IGBTs within the HT-3000 package to overlay T vs. $\omega$-plane efficiencies with those presented herein
  - Optimize the DC bussing for maximum current throughput with minimum temperature rise
  - Optimize the AC bussing for maximum current output with minimum temperature rise
  - Design using 1700 V creepage and clearance rules
  - Migrate design from Gen2 to Gen3 SiC MOSFETs
  - Design, build, and test efficacy of EMI enclosure for local controller
  - Design, build, and test efficacy of EMI enclosure for the power stage
  - Design, build, and test efficacy of output filter between inverter and traction motor
  - Others…

# PROJECT SUMMARY

Source photo courtesy of Toyota.


TOYOTA GaN Systems NREL NATIONAL RENEWABLE ENERGY LABORATORY UNIVERSITY OF ARKANSAS

# ACKNOWLEDGMENTS




- **DOE**
  - Susan Rogers, DOE VTO, Technology Manager, Electric Drives R&D
  - Steven Boyd, DOE VTO, Technology Manager, Electric Drives R&D
  - John Tabacchi, DOE NETL, Project Manager
  - Amanda Lopez, DOE NETL, Contract Specialist

- **Toyota/TRINA**
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  - Ercan (Eric) Dede, Ph.D., Manager, Lab E-2
  - Feng Zhou, Ph.D., Senior Scientist
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- **GaN Systems Inc.**
  - Girvan Patterson, President
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  - Greg Klowak, Director of R&D
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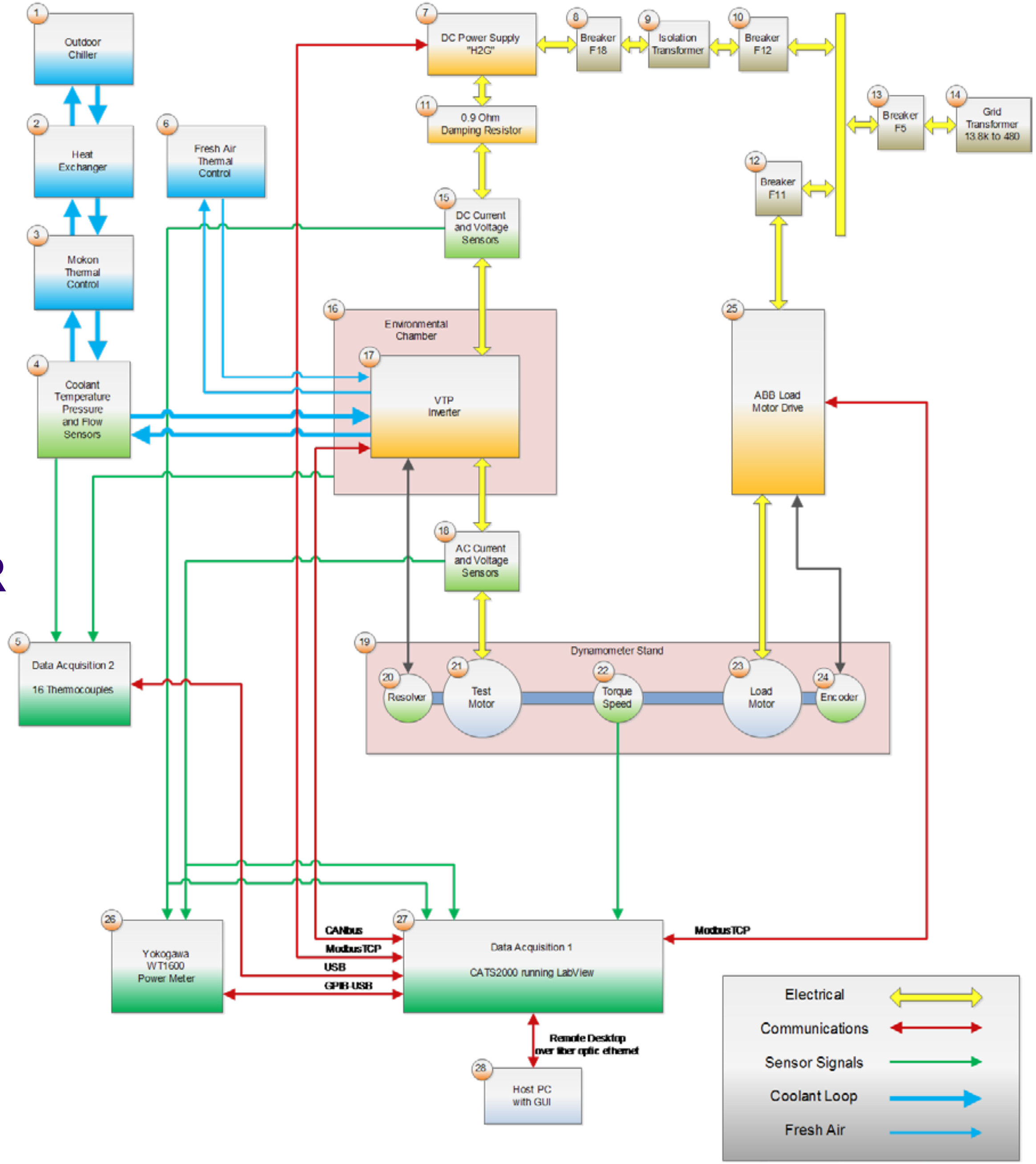
  - Paul Paret, Power Electronics Thermal Modeling and Test Engineer
  - Doug DeVoto, Power Electronics Reliability Engineer

- **UA National Center for Reliable Electric Power Transmission**
  - Chris Farnell, Test Engineer
  - Dr. H. Alan Mantooth, Executive Director

Questions?

# Technical Back-Up Slides

# UA NCREPT HIGH POWER DYNAMOMETER



## OPERATING VOLTAGE, TARGET = 200 TO 450 VDC; NOMINAL: 325 VDC

- Target met for SiC; target not met for GaN
- SiC: 200, 325, 450, and 650 VDC
- GaN: 200, 325, and 450 VDC

## POWER FACTOR OF LOAD, TARGET > 0.8

- Target met for SiC; target not met for GaN
- SiC: 0.75 lagging to 1.0
- GaN: No load

## MAXIMUM CURRENT PER PHASE, TARGET = 400 Arms

- Target met for SiC; target not met for GaN
- SiC: > 200 Arms was all that was required to achieve 30 kW continuous & 55 kW peak; module met this target
- GaN: < 25 Arms

## PRE-CHARGE TIME – 0 TO 200 VDC, TARGET = 2 SECONDS

- Target met for SiC; target met for GaN
- SiC: < 1 second
- GaN: < 1 second

## OUTPUT CURRENT RIPPLE – PEAK TO PEAK, TARGET ≤ 3% OF FUNDAMENTAL PEAK

- Target met for SiC; target not met for GaN
- SiC: 2.5% of the fundamental peak
- GaN: NA

## MAXIMUM SWITCHING FREQUENCY, TARGET = 20 kHz

- Target met for SiC; target met for GaN
- SiC: 20 kHz
- GaN: 20 kHz

## CURRENT LOOP BANDWIDTH, TARGET = 2 kHz

- Target met for SiC; target met for GaN
- SiC: 4 kHz
- GaN: 4 kHz

## MAXIMUM FUNDAMENTAL ELECTRICAL FREQUENCY, TARGET = 1000 Hz

- Target met for SiC; target not met for GaN
- SiC: 3000 Hz
- GaN: NA

## MINIMUM ISOLATION IMPEDANCE – INPUT AND PHASE TERMINALS TO GROUND, TARGET ≥ 1 MΩ

- Target met for SiC; target met for GaN
- SiC: > 1 MΩ
- GaN: > 1 MΩ

## MINIMUM MOTOR INPUT INDUCTANCE, TARGET = 0.5 MH

- Target met for SiC; target met for GaN
- SiC: 0.55 mH tested
- GaN: 0.55 mH tested

## AMBIENT OPERATING TEMPERATURE, TARGET = -40 TO +140 °C

- Target met for SiC; target not met for GaN
- SiC: +140 °C
- GaN: RT