# Inverter R&D


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# Overview

## Timeline

- Start – FY13
- Finish – FY15
- 50% complete

## Barriers

- Availability and the cost of the components for the inverter will be barriers for achieving the cost target.

## Budget

- Total project funding
  - DOE share – 100%
- Funding
  - FY13: $500K
  - FY14: $950K

## Targets Addressed

- DOE 2020 Power Electronics Targets
  - Power density: >13.4 kW/l
  - Specific power: >14.1 kW/kg
  - Efficiency: >94%

## Partners

- WBG manufacturers
- Inverter component suppliers
- ORNL – Steven Campbell, Curt Ayers, Cliff White, Randy Wiles, Burak Ozpineci
- NREL – Scot Waye

# Project Objective

- **Overall Objective**
  - Integrate wide bandgap (WBG) technology and novel circuit architectures with advanced packaging to reduce cost, improve efficiency, and increase power density.

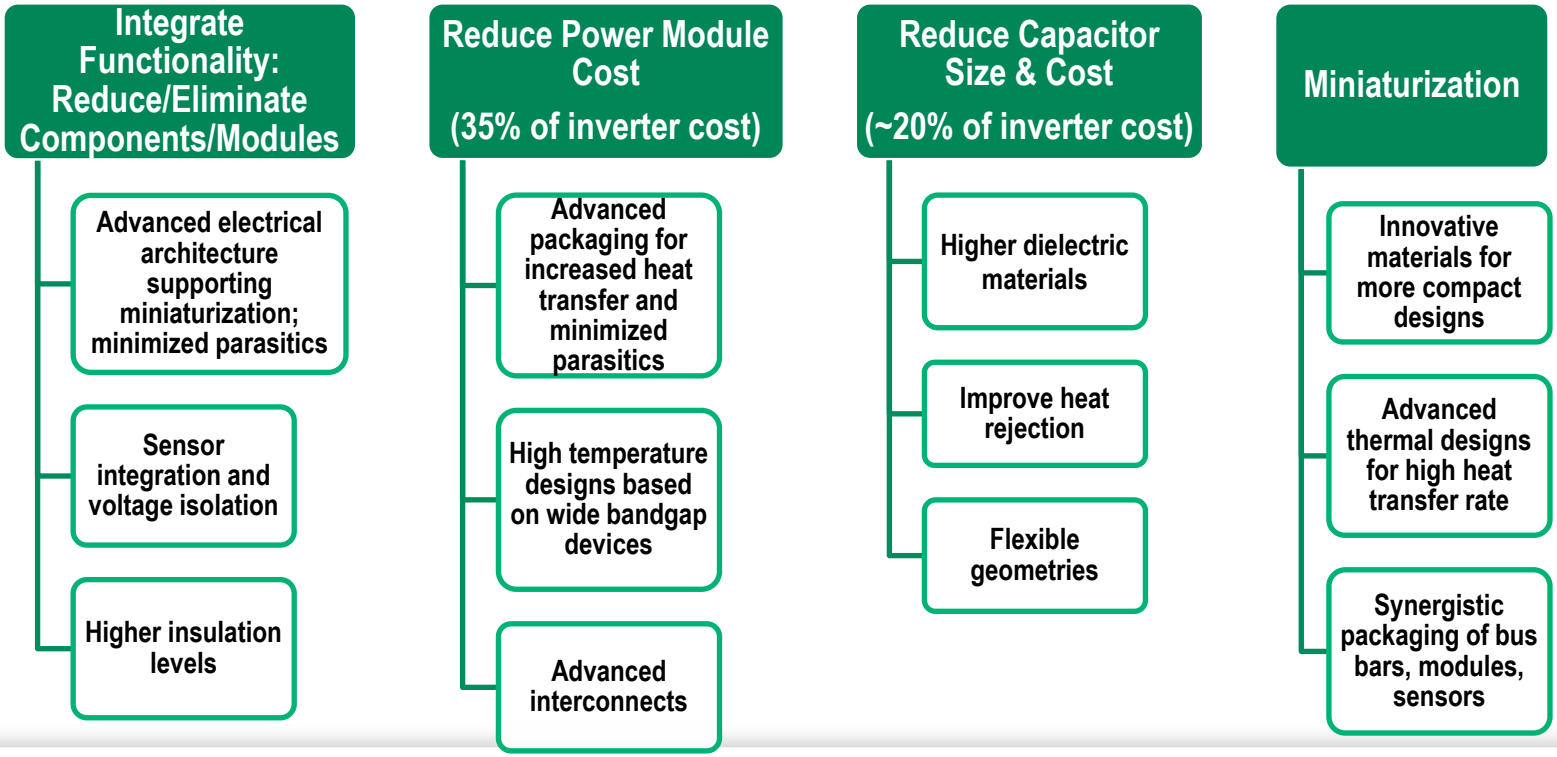
- **FY14 Objective**
  - Design, build, and test two 10 kW WBG-based prototypes using advanced packages:
    - ORNL module based, liquid cooled inverter and ORNL optimized air cooled inverter.

# Milestones

| Date | Milestones and Go/No-Go Decisions | Status |
|---|---|---|
| September 2013 | Milestone: Design, build, and test a 10 kW WBG based prototype using commercially available WBG modules. | **Completed** |
| September 2013 | Go/No Go Decision: Determine if inverter prototypes meets 2015 efficiency, power density targets at 10 kW of operation. | **10-kW inverter designs showed that 2015 targets can be achieved** |
| September 2014 | Design, build, and test 10 kW WBG based prototypes using advanced packages.<br>- Liquid cooling based inverter<br>- Air cooling based inverter | **On track** |
| September 2014 | Go/No-Go decision: Perform design review of the 10 kW inverter to determine if design can meet the DOE 2020 Power Electronics Targets. | |

# Proposed Technology
# Overall Strategy to Address Limitations of SOA

- Reduce size and weight of the power inverters to meet the 2015 inverter targets of 12 kW/l and 12 kW/kg.
- Reduce cost by:
  - lower component count by integrating functionality,
  - eliminating the existing liquid cooling loop,
  - manufacturing costs (part count and steps),
  - reduced high cost materials, like copper, through bus bar optimization and current reduction.



# Proposed Technology
# Specific Strategy to Address Limitations of SOA

| WBG Device Evaluation | Commercial module based liquid cooled Inverter *Version 1* | ORNL module based liquid cooled Inverter *Version 2* | Air cooled Inverter designs |
|---|---|---|---|
| Static and dynamic characterization: discrete devices | Build, test and evaluate a 10-kW commercial module based inverter | Build, test and evaluate a 10-kW ORNL module based inverter | Build and test a 10-kW air cooled inverter |
| Single phase test characterization: power modules | Use the test results as benchmark | Compare the results with the commercial module based inverter | Compare the results with the liquid cooled inverters |
| Device models | Scale the inverter as the modules become available | Scale the inverter as the devices become available | Scale the inverter as the devices become available |

# Accomplishments to Date – FY14

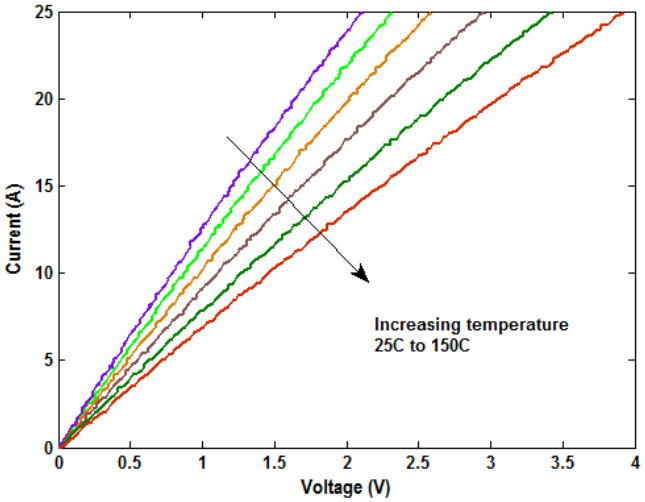
- **Acquired and evaluated device prototypes from WBG manufacturers**
  - ✓ 1200 V, 20 A, SiC MOSFETs
  - ✓ 600 V, 5 A gallium nitride (GaN) field effect transistor (FET)
  - ✓ 1200 V, 180 A, SiC MOSFET module.

600 V, 5 A
GaN FET

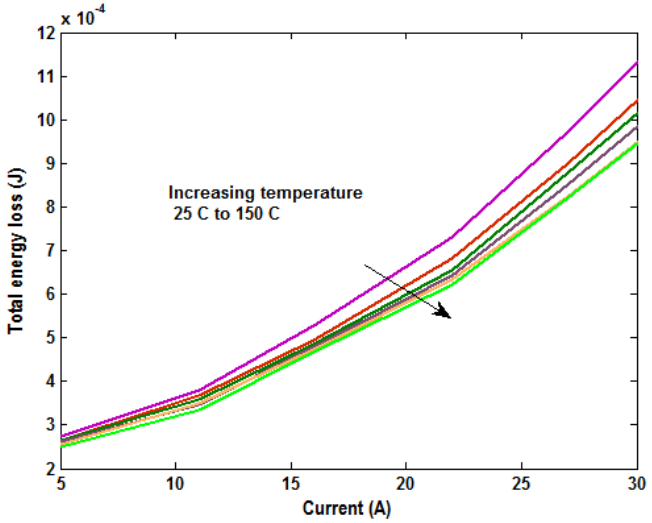
1200 V, 30 A SiC
MOSFET

1200 V, 180 A, SiC
MOSFET module

Device database:
http://peemrc.ornl.gov/Testing.shtml




Forward characteristics of a 1200 V, 20 A, SiC MOSFET



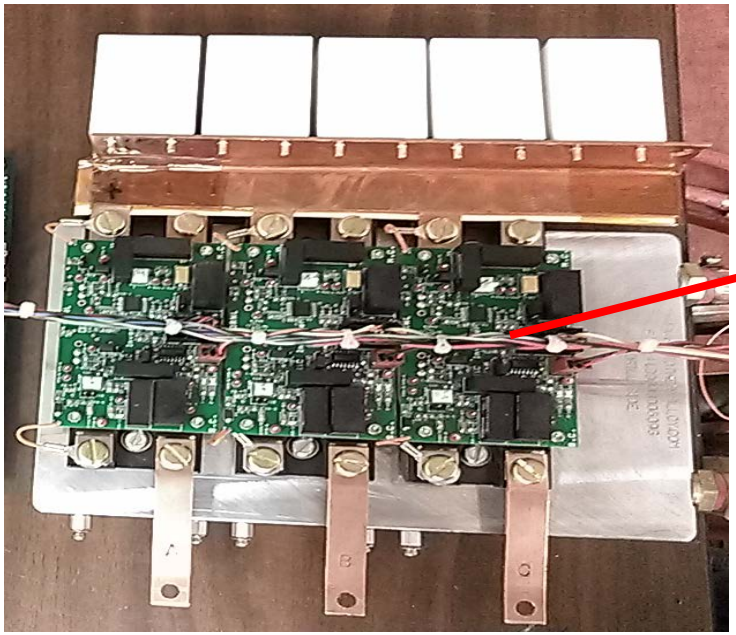

Total energy losses of a 1200 V, 20 A, SiC MOSFET at 600 V

# Accomplishments to Date – FY13
# 10 kW Inverter - Version 1

- Tested up to 10 kW in FY13.
- The inverter will be scaled to 55 kW with the new modules.
- Implemented advanced protection features with the commercial gate driver chip.

Power density with commercial module:
10 kW/3.6 L = 2.77 kW/L

Overall inverter efficiency:
~98% for different operating conditions



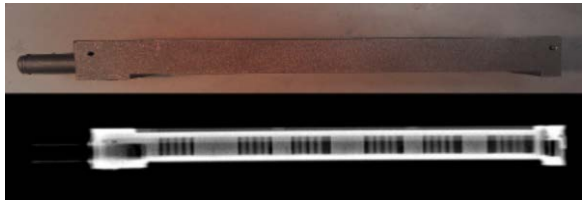
Final assembled 10 kW inverter prototype

1200 V, 100 A, SiC MOSFET commercial single phase module gate driver chip

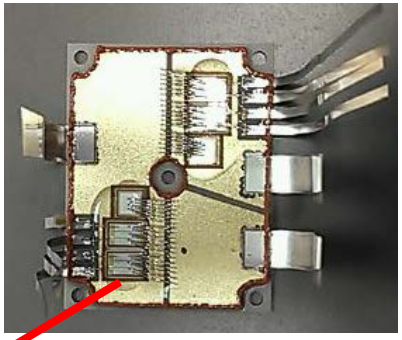
# Accomplishments to Date – FY14
# 10 kW Inverter - Version 2

**Completed the initial design of 10 kW WBG inverter with *ORNL high temperature SiC 1200 V, 100 A module layout***

**Single phase module gate driver**



**X-ray of the heatsink**



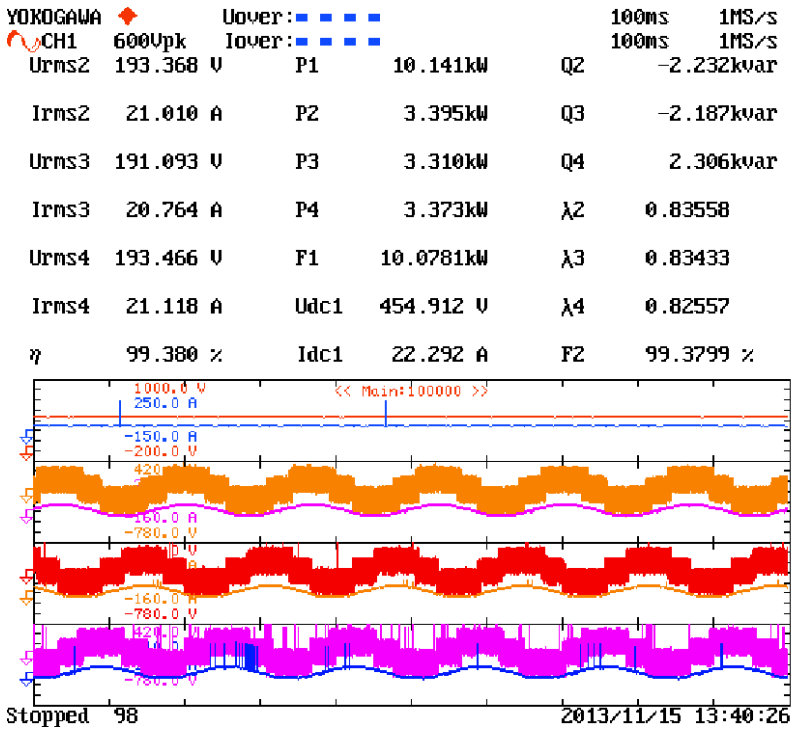
**1200 V, 100 A, SiC MOSFET single phase module layout designed at ORNL**

**5x40 uF capacitors, 900 V**

**Power density: 10 kW/1.7 L = 5.88 kW/L ~ 2 times higher than the commercial module based design**

# Accomplishments to Date – FY14
# 10 kW Inverter - Version 2

Experimental setup for evaluating inverter's performance

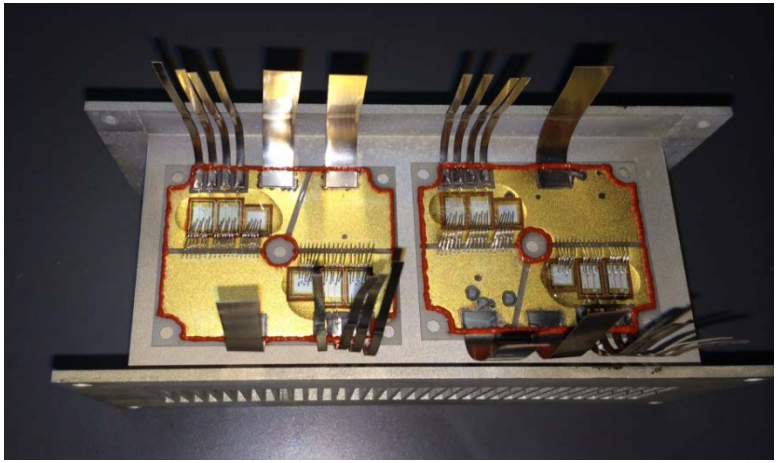



Experimental waveforms of 10 kW SiC inverter screen shot at 450 V dc-link operation

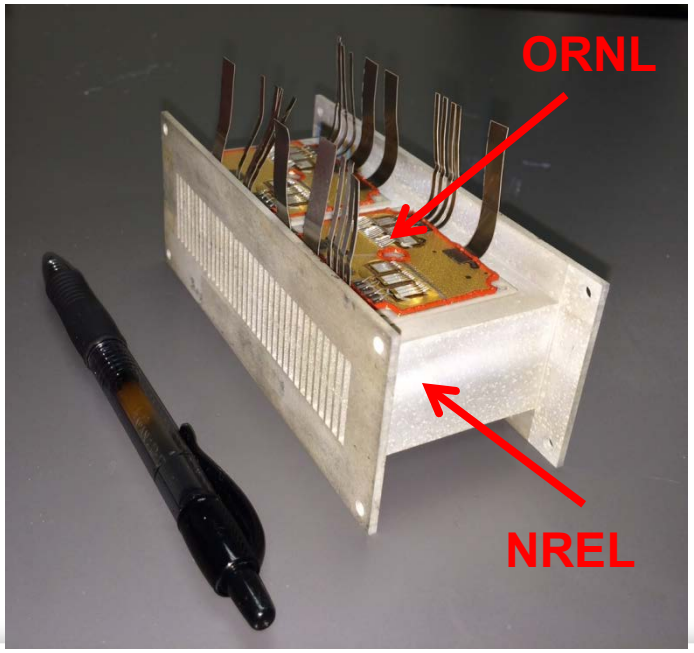
**Overall inverter efficiency of up to 99.3% was achieved**

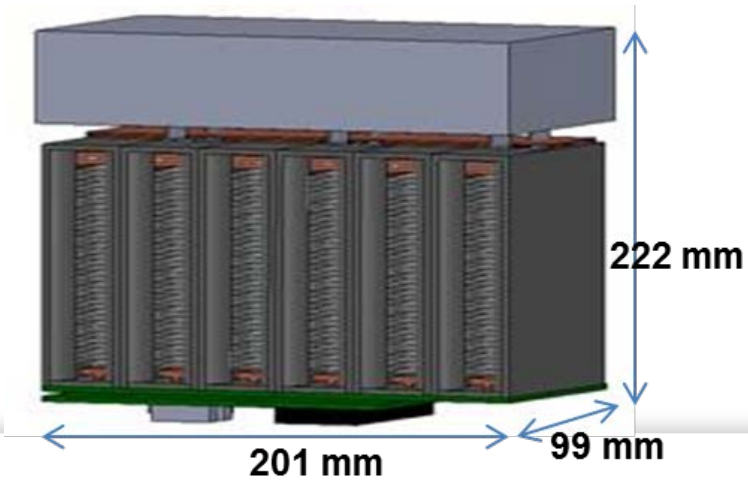
# Accomplishments to Date – FY14
# 10 kW Inverter – Version 3 – Air cooled

- ORNL redesigned the inverter developed in FY11 using the thermal simulation results from NREL.
- Reduced the size of the initial inverter design by 33% using fin design optimization.
- Balance of plant analysis is currently being conducted to establish the feasibility of air-cooling at system level.
- The module has been fabricated in collaboration with NREL. The module is currently being tested.
- For results on thermal analysis refer to NREL's presentation APE019 (Scot Waye)



Single phase power module for an air cooled inverter



# Responses to Previous Year Reviewers' Comments

**One reviewer commented:**

**"The reviewer expressed that it would be a very good thing if the project team can show a path to the 2020 targets in August using WBG materials, but WBG may be one of many challenges needed to overcome to meet the targets. For example, if an air cooled WBG inverter is chosen to meet the 2020 targets the costing should also include a fan and ducting. The reviewer asked what might happen if the fan and the inverter location required a twisted route to duct the air."**

**Response/Action:**

**Generally the liquid cooled inverters do not include the cooling pipes and the radiator volume involved. Thus, we think that air cooled should inverter numbers should not include the ducts and fans. However, ORNL is working with NREL on the balance of plant analysis to evaluate the system specifications and also optimize the location.**

# Responses to Previous Year Reviewers' Comments

**One reviewer commented:**

**The reviewer noted that there was nothing mentioned about the project team's plans for capacitors, but there were three capacitor manufacturers listed as collaborators. The reviewer wanted to know if there was a custom capacitor that was part of the design or if it was just a repackaged PP capacitor.**

**Response/Action:**

**The capacitors used in this project so far have been commercially bought off the shelf and in future we anticipate to custom design as needed. The PP capacitor will be repackaged based on the design requirements. One of listed vendors will be contacted as per the design need.**

# Collaboration and Coordination

| Organization | Type of Collaboration/Coordination |
|---|---|
| WBG manufacturers:<br>International Rectifier, GeneSiC, CREE, USiC, General Electric, Infineon, HRL. | Device prototype supply |
| Capacitor manufacturers:<br>SBE, KEMET, AVX | Custom capacitor supply |
| NREL | Thermal analysis |

# Proposed Future Work

| |
|---|
| **FY14 Focus: Develop, design, and test a 10-kW prototype WBG inverter with advanced packages.** |
| Deliverable: 10 kW, WBG inverter prototype. |
| Go/No Go Decision Point: Determine if inverter prototype(s) meets 2015 efficiency, power density targets at 10 kW of operation, then build full scale version(s) |
| **FY15 Focus: Develop, design, and test a 55 kW prototype WBG inverter with high temperature module and high temperature smart gate driver and integrate the novel protection and sense controls.** |
| Deliverable: 55 kW, high temperature, WBG inverter prototype with advance controls. |
| Go/No Go Decision Point: Project complete. |
| Final Deliverable: **55 kW prototype WBG inverter.** |

# Summary

- **Relevance:** Project is targeted toward reducing volume, weight and cost of the traction drive inverter.
- **WBG inverter development approach:**
  - 1st yr: 10 kW WBG inverter prototypes: Commercial based module, liquid cooled Inverter and ORNL air cooled inverter.
  - Go/No Go Decision Point: Determine if inverter prototype(s) meets 2015 efficiency, power density targets at 10 kW of operation, then build full scale version(s).
  - 2nd yr: 10 kW WBG inverter prototypes: ORNL module based, liquid cooled inverter and ORNL optimized air cooled inverter.
  - 3rd yr: 55 kW WBG inverter prototype(s): ORNL module based, liquid cooled Inverter and/or air cooled inverter.
- **Collaborations:** Collaborations with WBG device manufacturers, inverter component suppliers, and NREL are being used to maximize the impact of this work.
- **Technical Accomplishments:**
  - Completed evaluation of 1,200V, 30 A, SiC MOSFET.
  - Completed design, build, and test a 10 kW WBG-based liquid cooled inverter prototype using commercially available WBG modules.
  - Completed design, build, and test a 10 kW WBG-based liquid cooled inverter prototype using advanced package built at ORNL.
  - Completed the design and build of power module for the 10 kW air cooled inverter.