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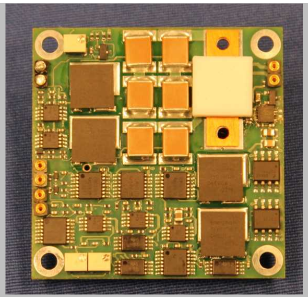

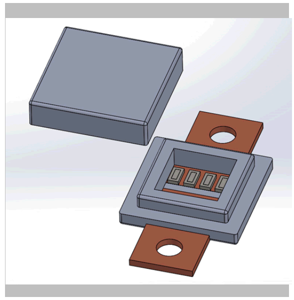

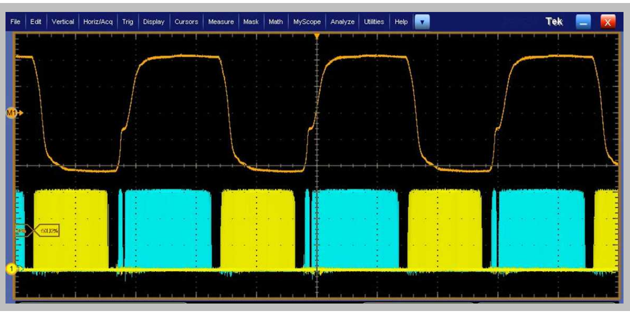

High Power-Density Photovoltaic Boost Converter and Inverter Using GaN and AlGaN Devices Housed in 3D Printed Packages

Robert W. Brocato
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA
National Nuclear Security Administration

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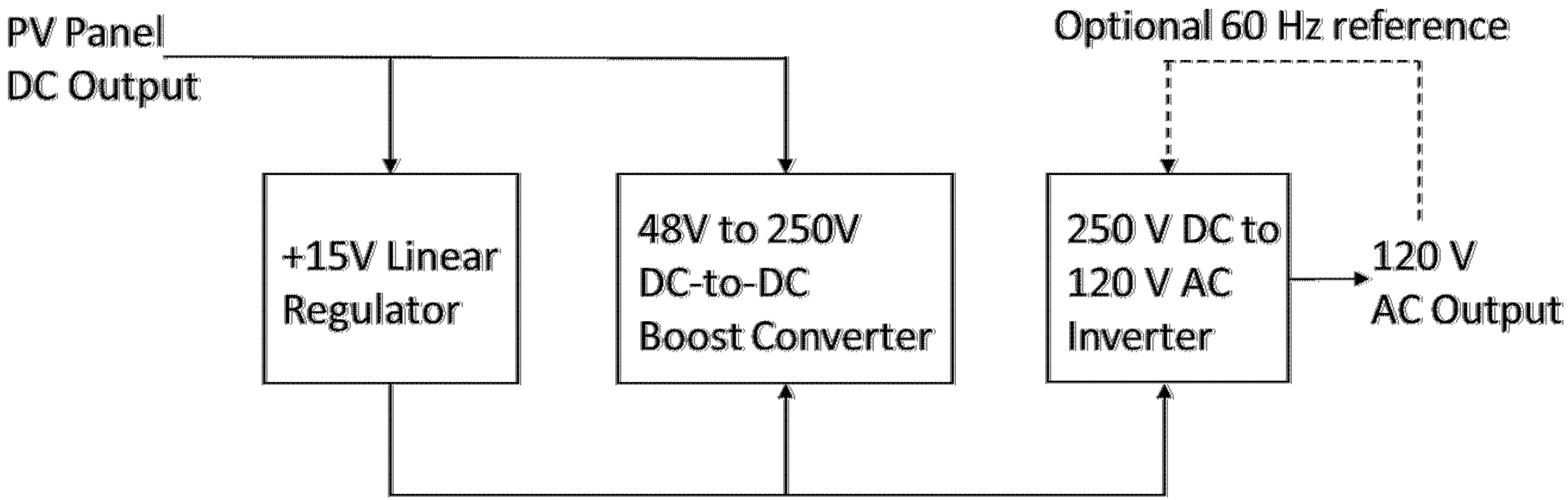
Project Objectives

1. Create a power converter module capable of converting the 48 VDC output of a photovoltaic panel into 120 VAC with up to 400 W of power.
2. The module should be as small as possible: ultimately 40 cc. (2.4 cu.in.).
3. GaN and AlGaN diodes and transistors should be used to help achieve the small size and high power density.
4. Both commercial and in-house produced devices should be used.
5. Custom 3D printed electronics packages should be used for the in-house produced diodes to achieve the smallest footprints possible.

Power Converter Overview

The converter consists of three different functional blocks, as follows:

1. A linear regulator to supply +15 V to the other converter circuitry while being powered from the 28-60 V input.
2. A switched boost converter to step the DC input up to 250 VDC.
3. An inverter to turn the 250 VDC into 120 VAC for stand-alone or grid connected operation.



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Power Converter Design

The power converter uses only basic logic and analog function IC's (i.e. op-amps, comparators, NAND gates, etc.) to produce the control signals. Voltage conversion functions are performed by discrete passive components (i.e. inductors, capacitors, and resistors) and GaN or AlGaN diodes and transistors.   The printed circuit board layout is dense but could be made more dense by using special function converter IC's.

1.8 in.

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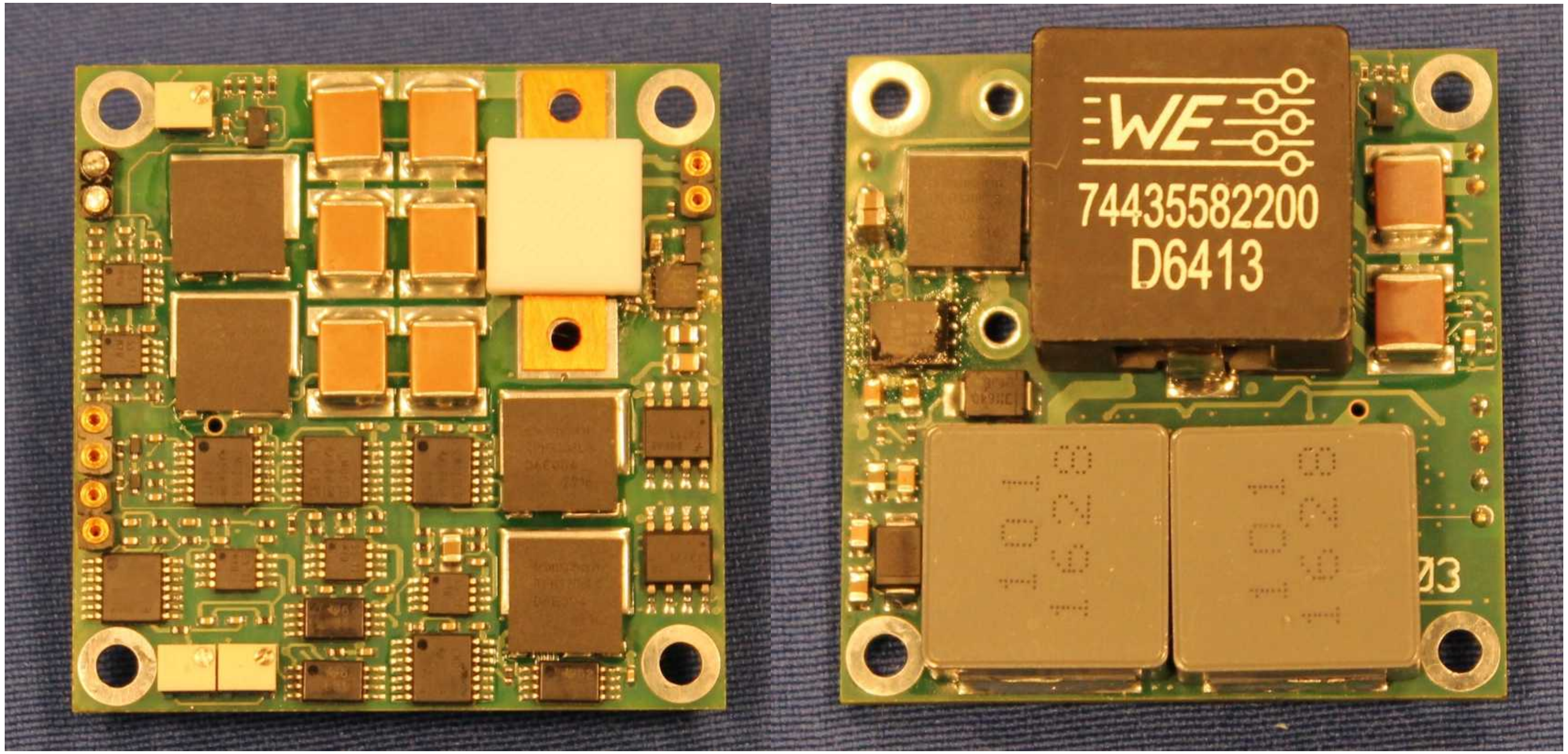
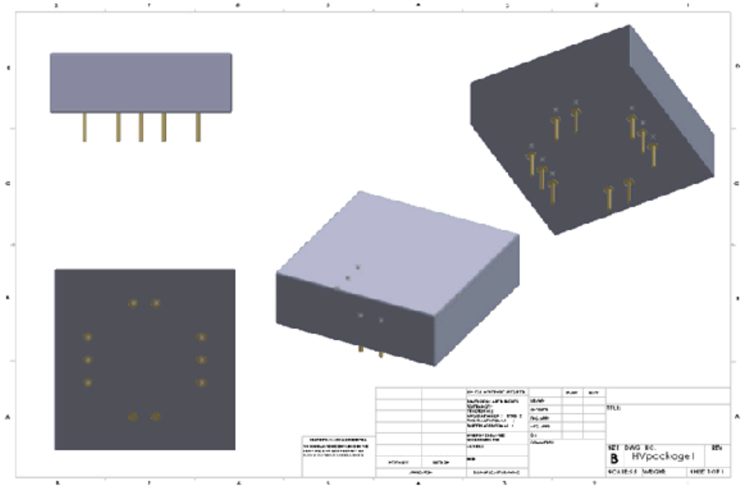
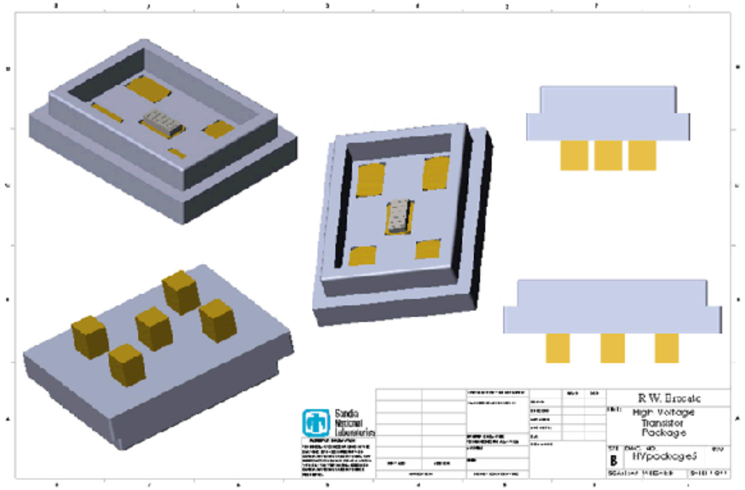
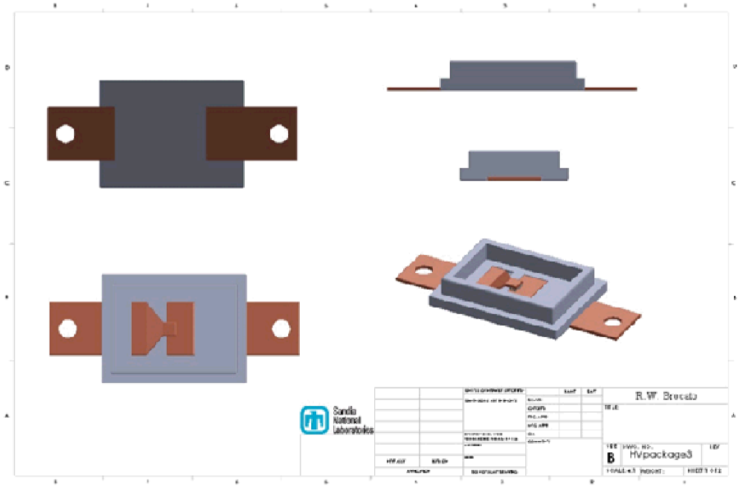
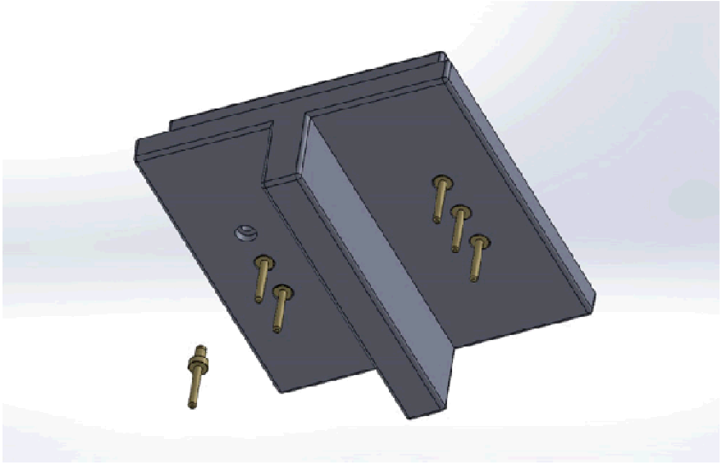


Custom 3D Printed Packages for High Voltage Applications



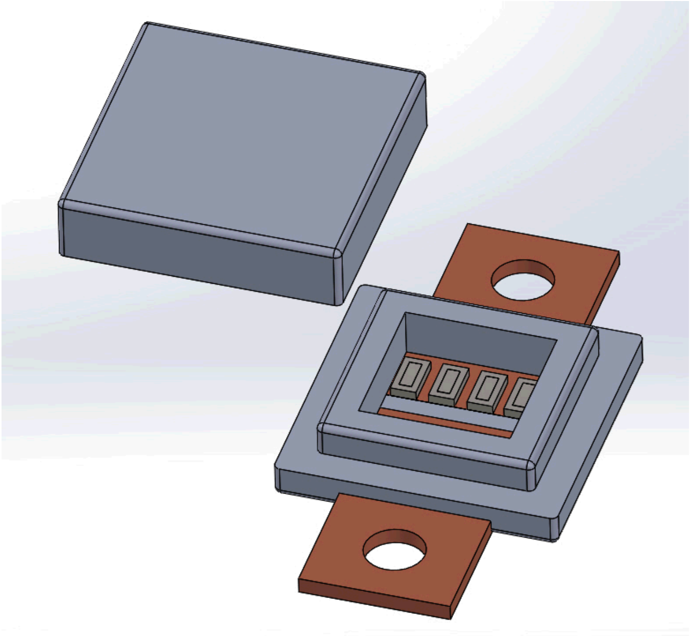






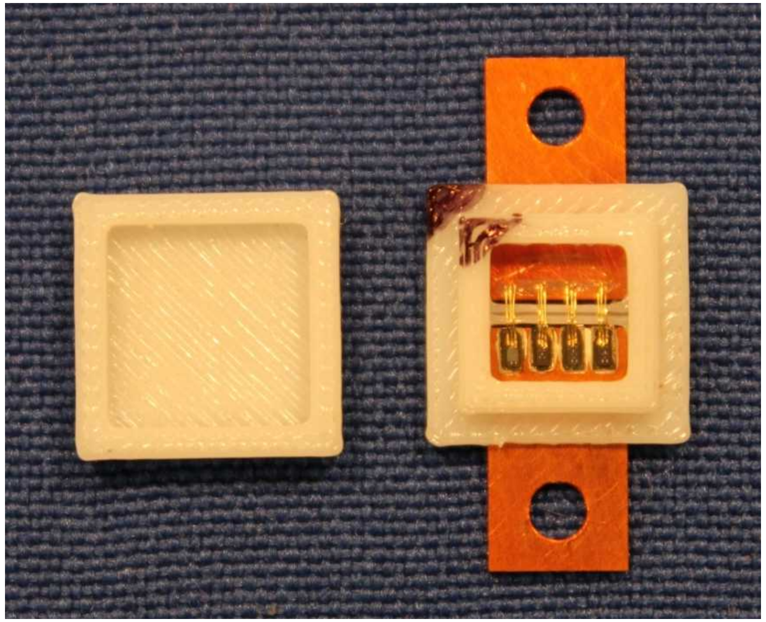
For the Ultra-Widebandgap LDRD Program at Sandia, we started out considering only commercially available high-voltage electronics packages to house our custom GaN devices. However, we found there to be a very limited selection of such packages. Consequently, we set about to develop a variety of different electronic packages. These were designed to be simple to fabricate and assemble while also being able to operate at high voltage.

Power Converter: 3D Printed Package for GaN Diode



The boost converter catch diode is a custom device that consists of four Avogy GaN diodes connected in parallel in a 3D printed package. First, 3D models of the package body and tabs were designed using Solidworks. The tabs were designed to press into the body using a zero spacing fit. Next, the package body and lid were 3D printed using polycarbonate.

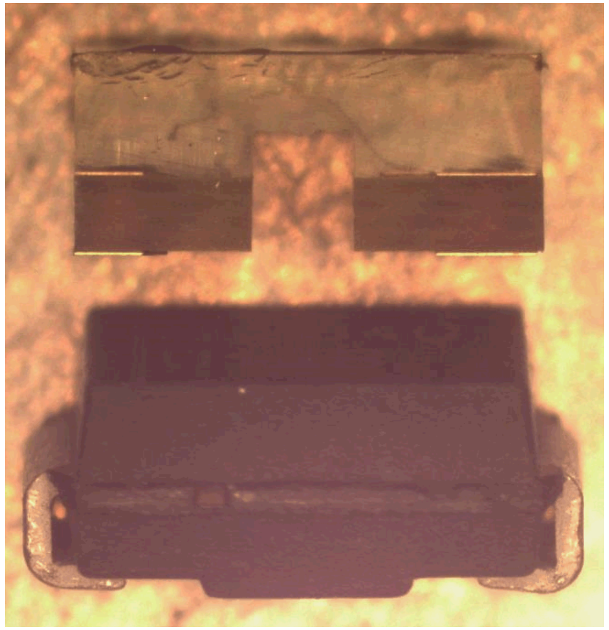
Since we lack a 3D copper printing capability, the tabs were machined separately from 110 copper stock. Then, the copper tabs were pressed into the body. Finally, the diodes were attached using conductive epoxy and were wire-bonded using 0.5x3 mil gold ribbon wire. We found that press-fitting of the tabs adequately secured them through subsequent processing, assembly, and testing.



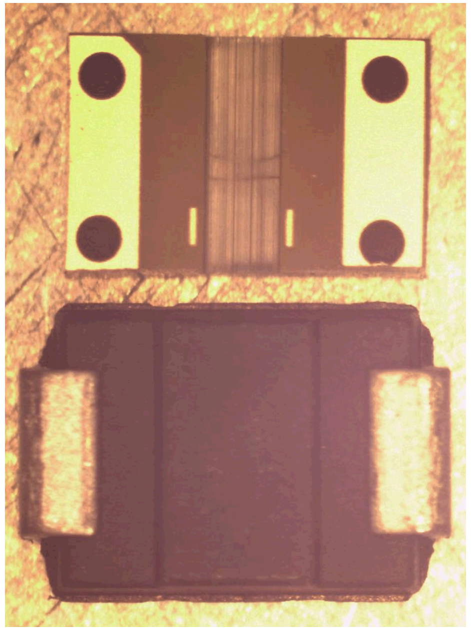
Power Converter: Custom Package for Sandia GaN Diode

We also used GaN diodes fabricated at Sandia in the inverter circuit. These diodes were packaged in the custom, miniature lead-frame package shown in these images. These GaN diodes (top in images) are physically small and are only capable of carrying 10's of mA of current. These devices were used in the charging circuits of the high side drivers of the inverter. The diode that the custom GaN diode replaced was a 600V, MURS160 diode (bottom in images) in a DO-214AA package.

Top View



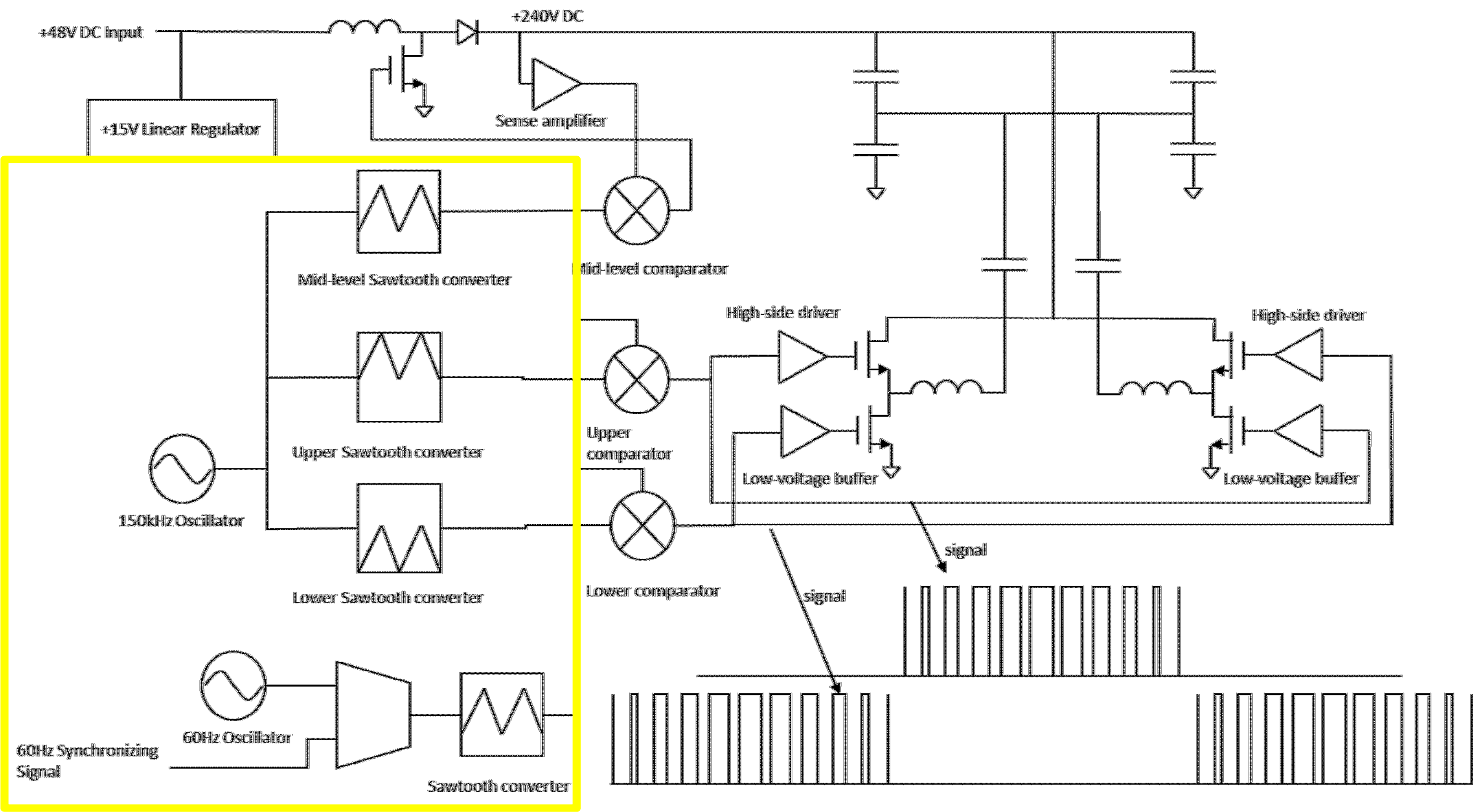
Side View



Bottom View

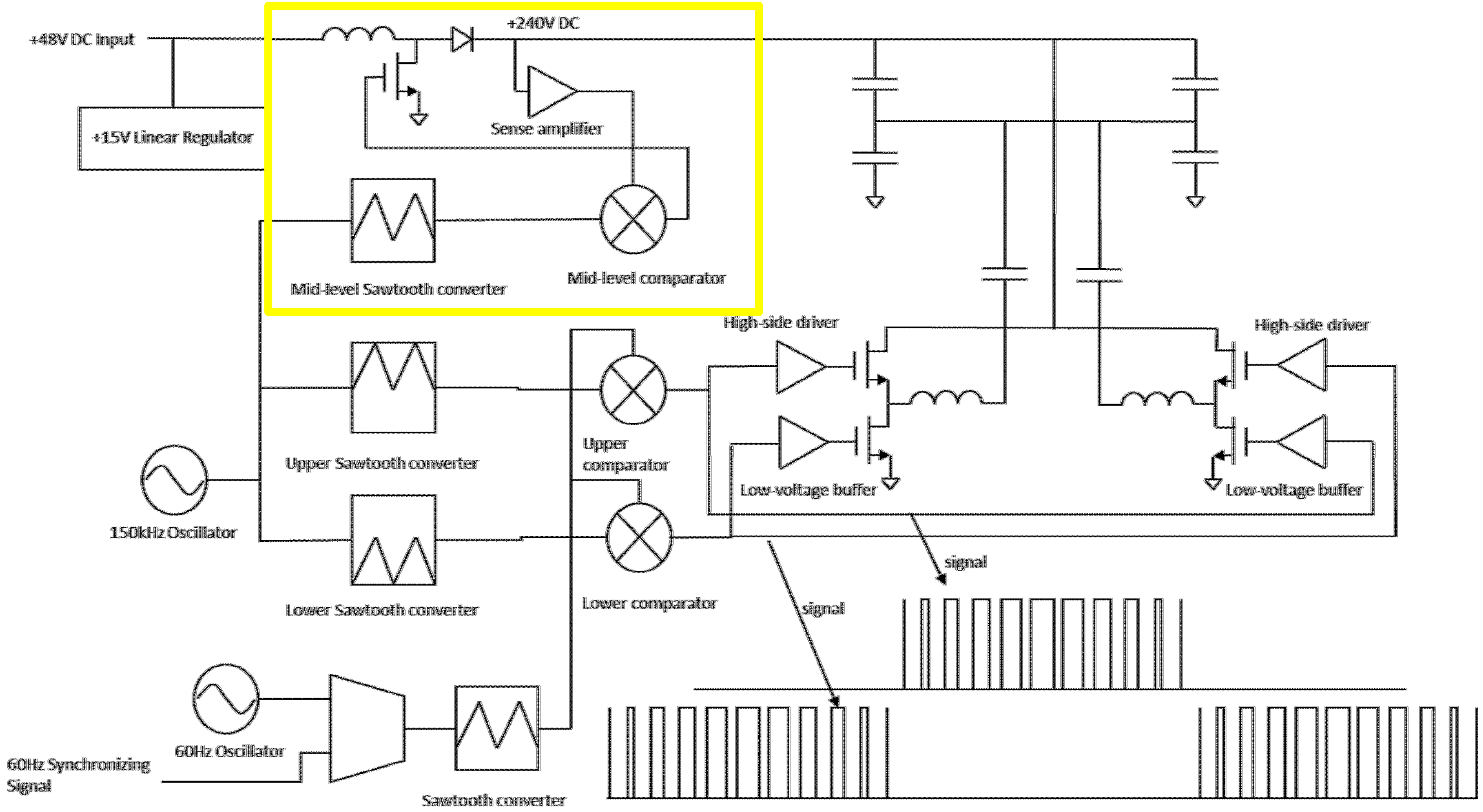
Power Converter Design

Both the boost converter and the AC inverter use a timing signal generated from a common 150 kHz clock. This clock is used to generate three different sawtooth signals. A separate 60 Hz clock is also generated internally, though it can be over-ridden by an external source. The 60 Hz clock is used to generate a single sawtooth waveform which is compared to two of the 150 kHz sawtooth signals.

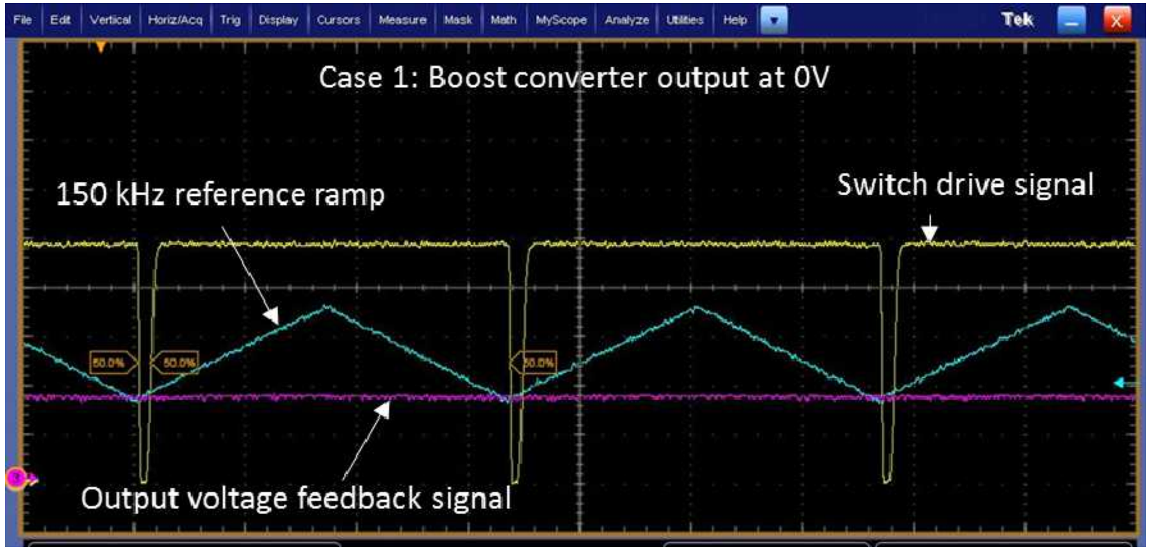


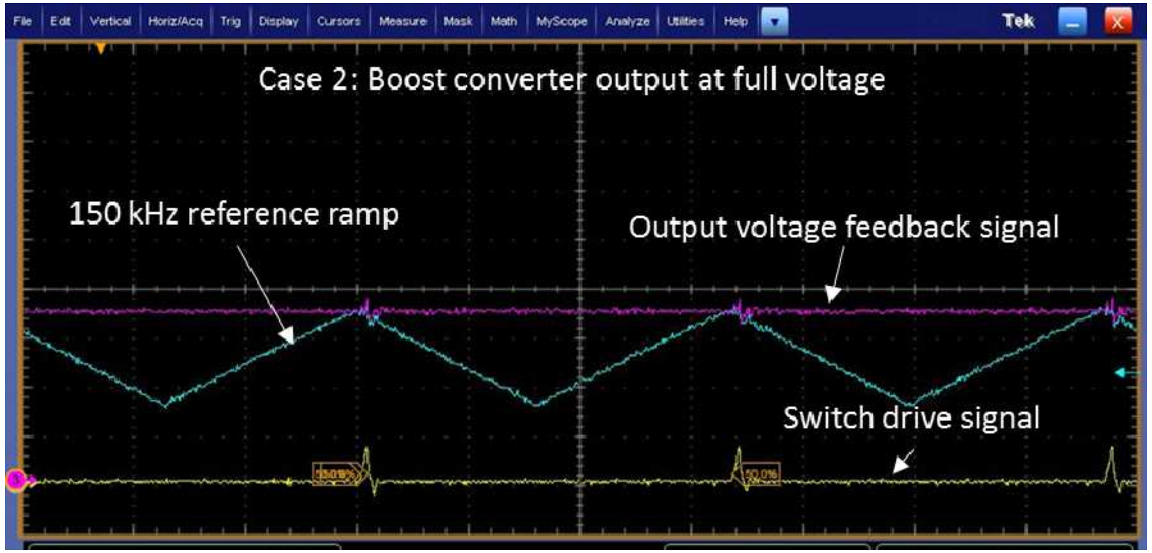
Power Converter Design

For the boost converter, the 150 kHz sawtooth waveform is compared against a feedback signal from the boost converter output. The comparator output forms a pulse-width modulated signal which is used to control the gate of the converter GaN FET switch. The resulting output is regulated at about 250 V and is capable of responding to varying loads.



Power Converter Design



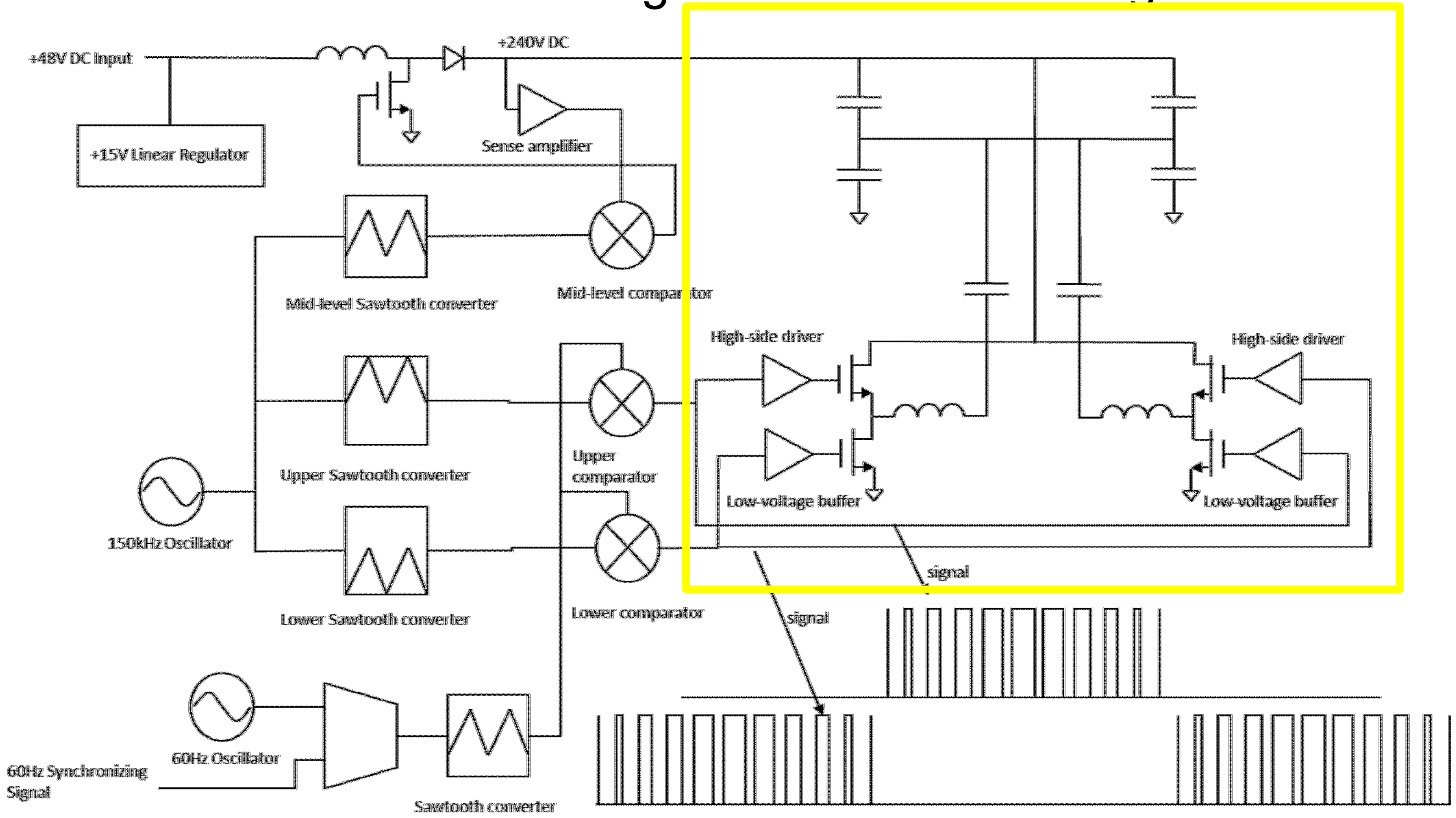


The control signals for the boost converter are shown here. The green and red traces are the input to the boost converter comparator, and the yellow trace is the comparator output and boost converter switch control signal. The top view shows the converter at start up or under a heavy load condition. The switch control signal is at its maximum duty cycle to produce maximum current out of the boost converter stage.

The bottom view shows the converter at full voltage while under a light load condition. The switch drive signal is at its minimum duty cycle to produce the minimum current out of the boost converter stage.

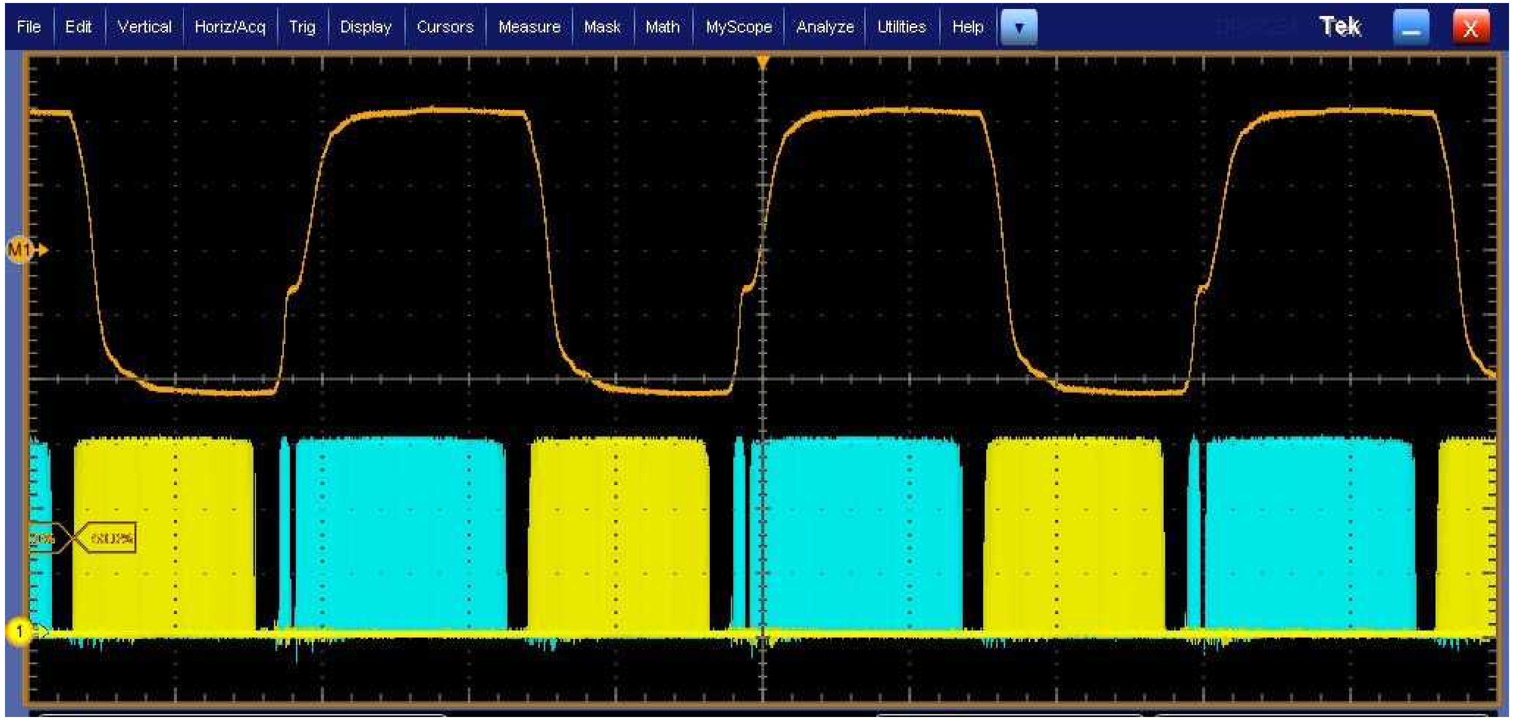
Power Converter Design

The DC output of the boost converter is used to power a bridge circuit. The bridge is driven by the mixed 60 Hz and 150 kHz sawtooth waveforms. The resulting signals are complementary pulse-width modulated waveforms. The pulse-width modulation signal samples at the 150 kHz rate while encoding a 60 Hz sawtooth signal.



Output Waveform

The oscilloscope traces shown below include the complementary bridge drive signals on the bottom in yellow and cyan and the converter output on the top in yellow. The output of the bridge is filtered by a differential LC-filter pair. This filter eliminates the 150 kHz component in the signal while preserving the 60 Hz fundamental component. The output of the converter was only lightly loaded when this trace was captured. Loading the output more heavily results in the output voltage becoming more sinusoidal than the waveform in this diagram.



Test Results

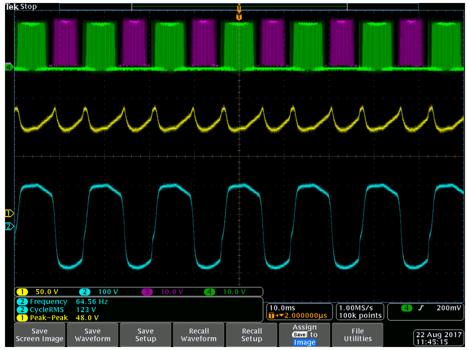
We were able to test the converter both in sections and fully configured with a variety of different loads connected to the inverter output.

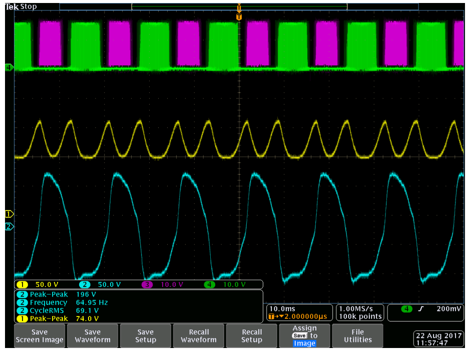
An overview of our test results is as follows:

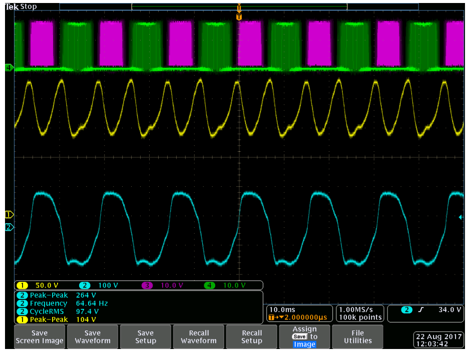
We built a total of five of the converter boards. Each board first went through functionality checks to confirm that all of the major functional blocks were working correctly.

1. The linear regulator was tested with other converter circuitry operating but with the boost converter's inductor disconnected. The linear regulator experienced its full expected load for this test.
2. The boost converter was tested with the inverter disconnected. Because the boost converter's output voltage, feedback gain, and feedback response time constant are all adjustable, the boost converter was tested with a variety of different parameter settings.
3. Finally, the entire board was tested with the linear regulator, boost converter, and inverter connected and with the inverter output connected to varying loads.

Preliminary Loaded Output Test Results







The accompanying images show the inverter AC output (blue), the boost converter DC output ripple (yellow), the bridge drive signals (green and magenta). The loads shown are 10 kOhms (1.5 Watts) in the top image and 1000 Ohms (11 Watts) in the center and bottom images. Input voltage was 25 Volts in the top and center images and 48 Volts in the bottom image.

Initial Loaded Output Test Conclusions:

1. The board produced expected 120 VAC output for light loads.
2. Inverter output higher order harmonics (which contribute to the output's square wave appearance) are significantly suppressed as the load resistance is decreased.
3. Output ripple from the boost converter stages was excessive, and more capacitance should be added to the output of the boost converter. Room on the board exists to do this by stacking capacitors.
4. Component heating on the board did not appear to be a problem at these input voltage and output load levels.

GaN Transistor Failures

We were prevented from testing the board at full power by failures of the commercial GaN FETs used in the design. We used these GaN FETs in five locations on the board, four in the inverter bridge and one in the boost converter. We did not experience any failures in GaN diodes used on the boards. All five boards experienced catastrophic failures of these GaN FETs, and the last board failed before we could complete load testing.

Some characteristics of GaN FET failures were as follows:

1. Failures occurred steadily throughout all of the tests, not just at the final test.
2. GaN FETs failed in all five locations where they were used on the board. However, since some failures were caused by a cascade effect from failure of a GaN FET in another location, failures cannot be reliably tied to a location on the board.
3. Failures occurred when parts were not hot and were idling, lightly-loaded, and in-between tests.
4. GaN FETs were kept well within manufacturer recommended operating limits.
5. No significant ringing was observed during device switching.

Conclusions

1. The converter functioned as expected, serving as a test and demonstration platform for new wide-bandgap devices.
2. 3D printing of electronic packages for power applications was very successful; we were to conceptualize, design, fabricate, and test electronics packages.
3. GaN FET failures posed a severe problem that caught us completely off-guard.
4. The high component density on the board limited our ability to monitor conditions that might have contributed to GaN FET failure.
5. Since failures occurred under different operating conditions and while performing different functions on the board, it is unlikely that these failures were due to improper use of the GaN FETs.
6. Reliability studies of GaN FETs for power applications need to be pursued.
7. GaN developers should not be discouraged; GaN FETs for RF applications also had reliability problems that have since been overcome.