Emerging Technologies in Converter Design

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1. ABSTRACT

With the current push for electric vehicles and weapon systems, the need for high power, high density power converters is growing. Two technologies are examined that have the potential to increase power densities in converters.

The first technology is the hybrid Silicon (Si)/Silicon Carbide (SiC) IGBT module. The hybrid module consists of a standard Si IGBT with the Si diode replaced with a SiC diode. These devices are a direct replacement for the standard all Si IGBT modules. This paper compares the hybrid modules verses standard modules in a 100kW+, three-phase, PWM inverter, in both motoring and regeneration modes. Currently the inverter has been operated at 60kW with both types of modules. Further results are pending a rebuild on the interface circuit to prevent noise faults.

The second technology being examined is the use of embedded Rogowski coils as current sensors in an IGBT module. For a baseline of comparison, testing was done using an Allegro A1374 programmable linear Hall effect sensor. Currently the Rogowski coil is awaiting completion of the control circuitry, but test results for the Hall effect sensor are discussed, along with their primary limiting factor, frequency response.

2. INTRODUCTION

The work presented in this paper is still in progress. Unfortunately, due to some noise issues and supply issues, the research was not completed in the five week period given. However, results will come quickly once the issues are settled. The noise issues

were in reference to the hybrid inverter. At the power levels desired, the control circuitry would fault out due to an encoder fault on the motor. After much work tracing the fault, the issue was found to be noise coming through the interface circuitry. The interface circuitry is being rebuilt on a printed circuit board, which will be significantly more noise immune. The embedded current sensor results are awaiting the completion of the sensor. Due to the environment in which the coil is being used, it is being specially made to fit the application. Although it is not completed, the test setup is ready, and has been tested, and results will follow quickly with the completion of the device.

3. HYBRID Si/SiC INVERTER

Silicon Carbide (SiC) is finally starting to reach its promise of being a better, faster, and more thermally stable Silicon (Si) substitute. The advantages of SiC over Si are numerous. These advantages include a higher breakdown field, higher thermal conductivity, and a wider bandgap [1]. Power devices made from SiC also have the advantage of being extremely radiation hard, extremely stable over wide temperature variations, able to withstand significantly higher temperatures than Si parts, and have a much higher thermal conductivity [2].

Despite these advantages, numerous difficulties remain, mainly dealing with the manufacturing process for growing large wafers [1]. Since SiC has no liquid state, the wafers must be grown using a Chemical Vapor Deposition (CVD) technique, or sublimation [1]. With no liquid state, standard Si processing techniques such as crystal pulling, zone refinement, and Rapid Thermal Processing can not be used for SiC [1]. A final issue is the approximately 200 polytypes of SiC [1]. With so many polytypes, growing a large wafer of a single crystal is very difficult [1]. Depite these limitations, manufacturers are now creating 4 inch wafers of SiC (vs 12 inch wafers for Si).

With that aside, a growing number or researchers are looking at how best to use this new substance. Most promising to date has been the development of high power SiC Schottky diodes. These Schottky diodes have been demonstrated to be superior to their Si counterparts [1-4]. Despite having larger forward conduction losses than its Si counterpart, the SiC Schottky diode has significantly less switching loss [4]. As the switching frequency and temperature increases, so does the benefit of using SiC Schottky diodes [4].

Current research on the use of SiC Schottky diodes in inverters has been reported for a 55 kW three-phase inverter [5], and a 100 kW grid connect building block [1]. Both of these implementations show substantial decrease in over all device loss (a decrease of 20 – 30%) by replacing the Si diode. The research presented in this paper not only examines the efficiency of the inverter, but also presents data on the active die surface temperatures. Increasing efficiency results in a higher power density, which may be limited by the operating temperature of the Si IGBT. By examining the IGBT temperature of both inverters, a more accurate idea of power density gain can be realized.

Test Setup:

The experimental test setup consisted of two oil-cooled 600V/7500 rpm 3-phase induction machines, coupled with a three-phase inverter and controller for each machine. The machines are coupled together, allowing one machine to operate as a motor, and the other as a generator. Power to the inverter was supplied by an Aerovironment AV-900 DC power supply, capable of delivering up to 250 kW. Figure 1 shows the configuration of the induction machines.

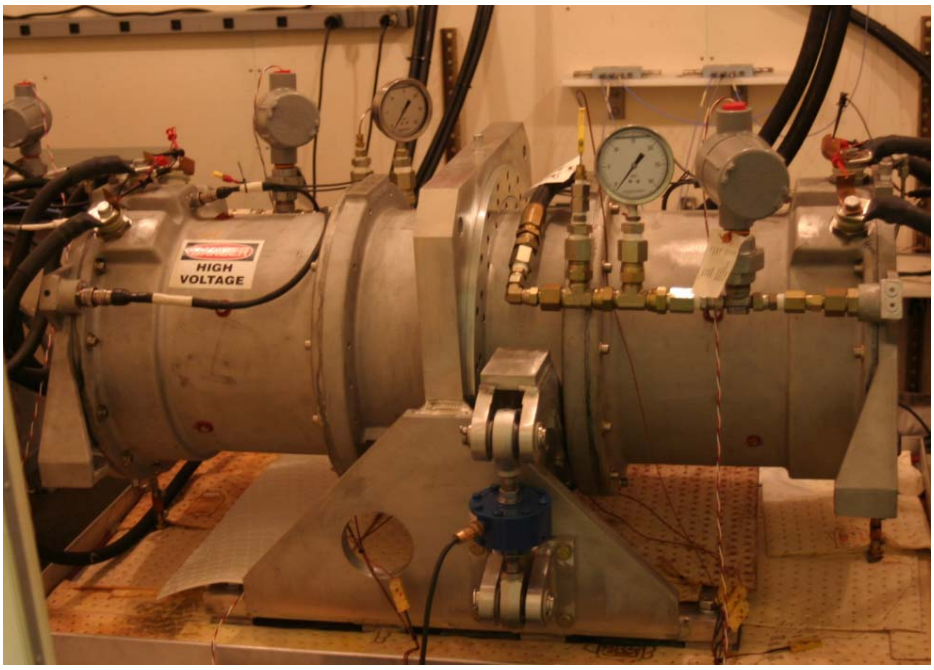

Figure 1. Twin 500 HP Induction Machines

The test motor inverter shown in Figure 2 was assembled using commercially available PowerEx CM300DY-24NF IGBT modules which could be readily replaced with custom Si/SiC hybrid modules. The hybrid modules were fabricated by Powerex using identical Si IGBT die as the commercial part. The only difference being the the three 100A freewheeling diodes were replaced with six 50A SiC Schottky diodes supplied by CREE. The modules were mounted on a liquid cold plate that had nominally 4.0 gpm of water coolant at an inlet temperature of 25 °C.

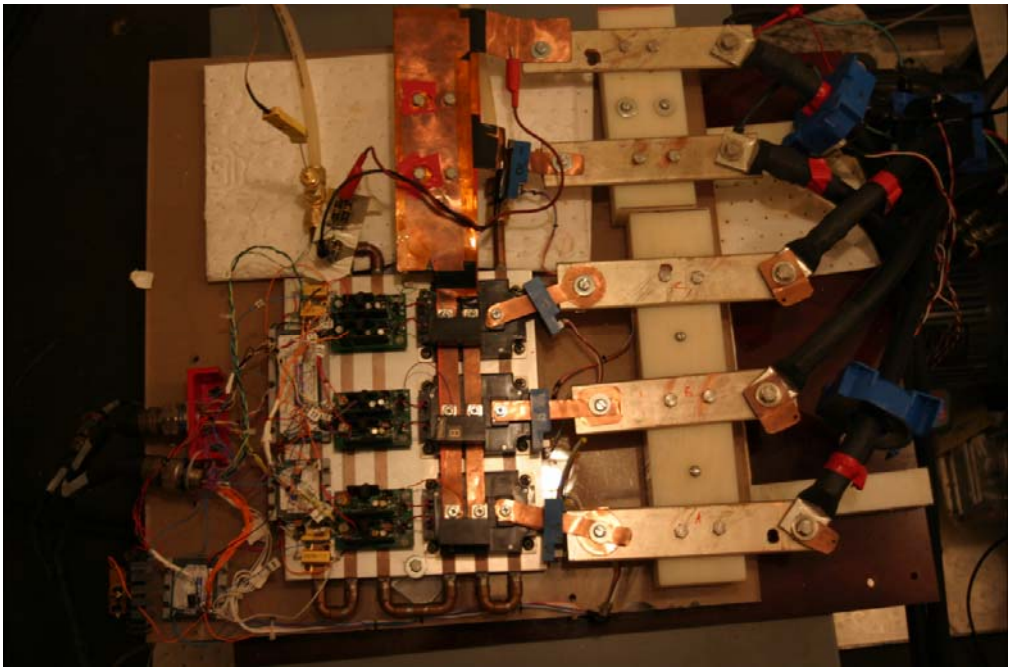

Figure 2. Three Phase Inverter

Test Results:

Initial testing of the inverters was done with a 400V DC bus at a motor speed of 5000 rpm. Both the all Si and the hybrid Si/SiC modules were operated up to an output power of 60 kW. Further testing was limited due to noise sensitivity of the circuitry, thus the test platform is being rebuilt with the interface circuitry being implemented on a printed circuit board. Once this rework is complete, testing will continue with a comprehensive examination of the module efficiencies and die surface temperatures.

Figure 3 shows the internal configuration for both IGBT modules.

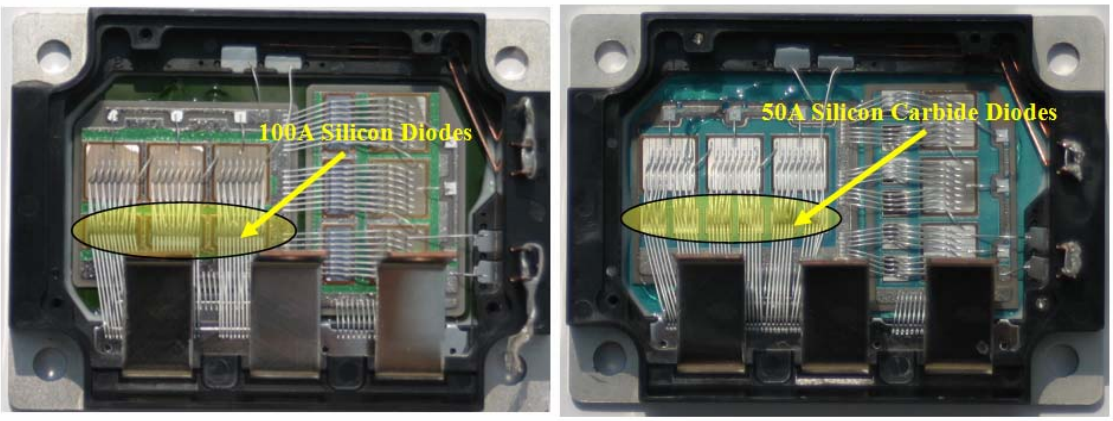

Figure 3. Image of open IGBT modules showing the die

Figure 4 below shows a thermal image of an open module during operation. The module is the unmodified PowerEx CM300DY-24NF operating at 25 kW. Using thermal imagery, a more extensive comparison will be completed of the two inverters.

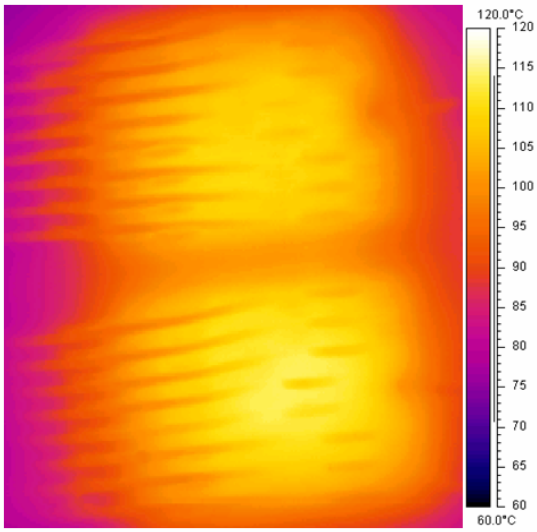

Figure 4. Thermal image of IGBT operating at 25 kW.

The test setup has been operational and is verified, both types of modules have been operated at 60 kW, and the thermal camera has been tested over the modules. Results will follow quickly with the completion of the printed circuit board.

4. EMBEDDED CURRENT SENSORS

Embedded current sensors in IGBT modules could help reduce size and cost of power converters. Unfortunately the high noise, high heat, and relatively confined environment of an IGBT module is not suited for many types of current sensors. This paper examines two possibilities and looks at there limitations. Of primary interest is the Rogowski coil, a small toroidal winding placed around a conductor [6]. Recently, the scientists at ARL were able to get a manufacturer to create a coil small enough to fit inside an IGBT module. The other transducer examined is the Hall effect sensor, and is used primarily as a basis of comparison for the Rogowski coil. Since the coil is not yet completed, the results section is limited to the Hall effect sensor.

Rogowski coils have several beneficial factors. The first, and probably most important for a general application such as an embedded current sensor, is the ability of a single coil to measure currents ranging from a few milliamperes up to several megamperes [6]. The application engineer only needs to change the conditioning circuitry (integrator components).

Other benefits include an extremely large bandwidth, ranging from less than 1Hz up to several hundred kHz [6] depending on the type of coil. The coils are linear, which makes them useful for harmonic analysis since they do not create any harmonics of their own [6]. The coils have no core saturation effects making them suitable for for

protection applications [6]. Finally, they can be manufactured to have an accuracy of better than .1% [6].

Despite these numerous benefits, there are still some limitations with Rogowski coils. The first and foremost up to this point was finding a manufacturer to create a device small enough to fit inside an IGBT module. Currently the scientists at ARL have located a vendor capable of manufacturing such a device. Another limitation that needs exploration is the thermal characteristics of the coil. The temperature in an IGBT module can swing from room temperature to 140°C.

The thermal properties of the coil are largely dependent on the transducer design [7, 8], and are caused by the thermal expansion of the coil and former [7]. For a swing from 30 to -30, a coil showed a 1.33% change in output for the same current [7]. Careful selection of material for both coil and former will be necessary to minimize the errors introduced by the thermal expansion.

Hall effect sensors have their own advantages and disadvantages. The primary advantage being the size, cost, and ease of implementation. Currently Hall effect sensors are available for a few dollars with the linearization circuitry on the chip, giving a voltage output signal linear to the current. Also, these chips are programmable, allowing adjustment of gain, temperature coefficient, polarity, and offset bias. All of this makes for an extremely easy to implement current sensor.

The primary limitation to these commercially available parts is there frequency response. The part chosen had a frequency bandwidth of 20 kHz. At first glance this might appear suited for some high frequency applications, but due to the non-sinusoidal nature of DC-DC converter current waveforms, the device is not suited for such applications. Even with a 10 kHz switching converter, the part was unable to capture enough harmonics to accurately represent the current waveform. Switching frequencies below 10 kHz are impractical for most DC-DC converters applications.

Current Sensor Test Setup:

A simple buck converter was designed to test the embedded current sensors. The circuit used the same power supply used for the inverter. One side of the power supply was used as the source, while the other side was used as the load, simplifying test setup and operation. The test circuit is shown in Figure 5. Figure 6 shows the actual IGBT module with the Hall effect sensor and core inside it.

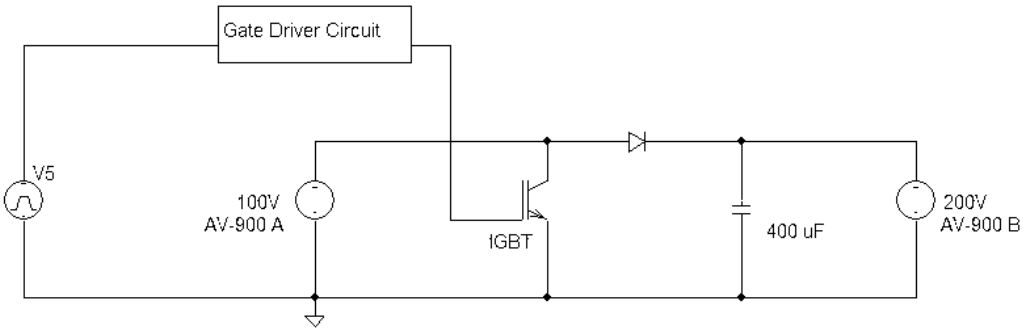

Figure 5. Test Circuit, DC-DC Buck Converter

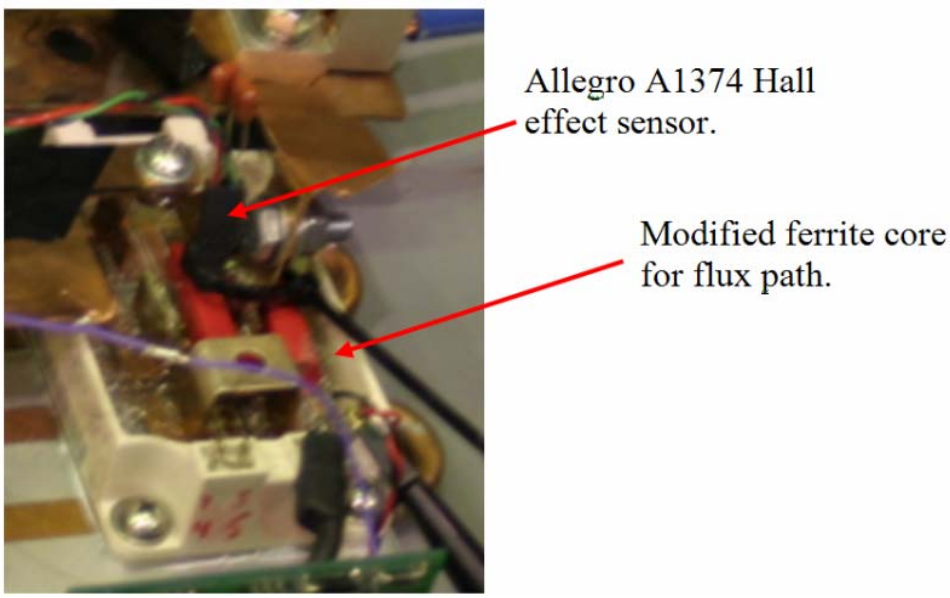

Figure 6. Photo of IGBT with Hall effect sensor installed.

The part used for our test was an Eupec 300A IGBT module with the Allegro A1374 high presicion linear Hall effect sensor. The Allegro Hall effect sensor was chosen due to its programmability an its bandwidth. The programmability would allow it to suit a wide range of applications which would be necessary for a general application such as an embedded current sensor in an IGBT module. The Allegro part had the highest bandwidth (20 kHz) of the Hall effect sensors found in the limited time period.

The buck converter was operated at a variety of switching frequencies to validate the performance of the current sensor. An external Rogowski coil current sensor was used as the baseline of comparison for the embedded current sensor.

Test Results:

At the time of this writing, the embedded Rogowski coil was still not completed for testing. The test results are going to be limited to the Hall effect sensor. As expected, the Hall effect sensor does not perform well in a buck converter due to the high switching frequencies used. Figure 7 shows the output of the Hall effect sensor along with the external current sensor with a 10 kHz switching frequency.

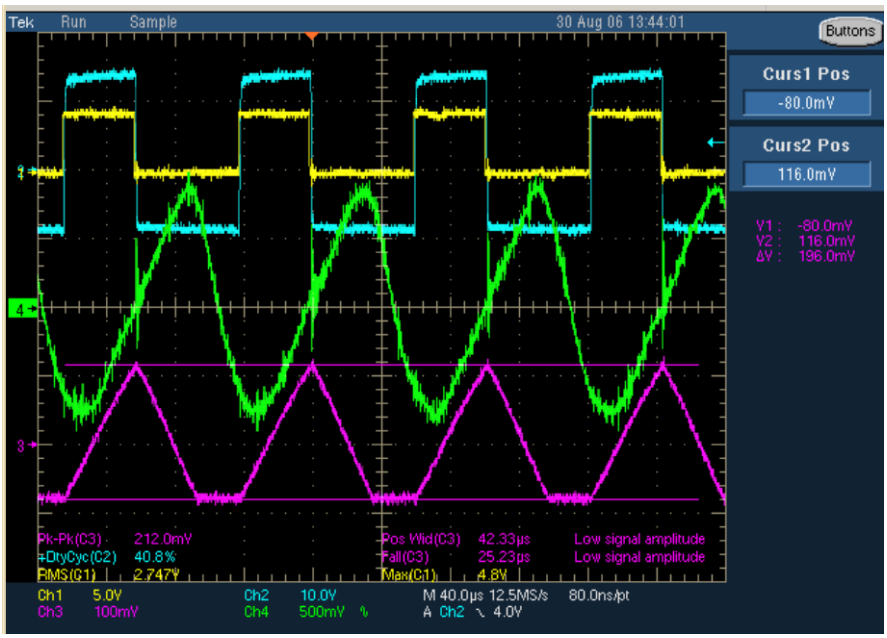

Figure 7. Waveform Capture of embedded current sensor (upper triangular waveform) and the external current sensor (lower triangular waveform).

As can be seen from the Figure 7 (fourier analysis has not been done), the sensor is only catching the fundamental and perhaps one or two harmonics. This is expected based on the manufacturer's spec of a 20kHz bandwidth. Although testing below 10 kHz did show better results, for DC-DC converters, even with switching at 1 kHz, the Hall effect sensor still showed some distortion of the actual current waveform.

Discussion:

Despite the inability to test the Rogowski coil during the time allotted, some interesting information was gained. The simplicity in integrating the Hall effect sensor in to the module was unexpected. Also, despite the frequency limitations, the Hall effect sensor was effective in operating in the high heat, high noise environment of the IGBT module. From Figure 7, there can be seen some minor noise on the Hall effect sensor during switching events, but it is relatively limited, and could filtered out. Although not suited for all applications, an integrated Hall effect sensor in IGBT modules specifically for DC-AC inverters which have low frequency currents should work extremely well. Based on the cost of the components used and the ease of implementation, the additional cost of an IGBT module equipped as such should be minimal.

5. REFERENCES

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