Fabrication of a novel multi-layer electric vehicle half-bridge inverter module

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ABSTRACT

An electric vehicle's (EV) traction inverter is a critical component for vehicle operation and maximizing efficiency. Traditional EV inverter modules utilize two-dimensional ceramic substrates and numerous wire-bonded connections, introducing reliability challenges and structural constraints. Advancements in insulating layer materials for power electronics allows for the creation of novel inverter modules which address many of the shortcomings of the current standard. Here, we explore the fabrication of a new inverter module based on Temprion©, an electrically insulating film made by Dupont™. Modules are assembled using a custom-built hot press by binding layers of copper and Temprion© under 5000N of force at 300°C. Press is controlled using a comprehensive graphical python program with automatic operation and safety features. Early fabrication attempts indicate that the program works as desired and that further process optimization is necessary before modules can be reliably produced.

I. INTRODUCTION

The proliferation of electric vehicles (EVs) into the global automotive market in recent years has promoted significant investment into research focused on improving EV efficiency. Power electronics, the branch of electrical engineering centered around the control and conversion of electricity in high-voltage and high-current applications, encompasses much of this research. The Advanced Power Electronics and Electric Machines group at NREL is involved in significant research surrounding EV component efficiency and durability.

The power inverter, responsible for the conversion of DC electricity from the car batteries into AC electricity used by the high-power induction motors is a key area focus when it comes to improving vehicle efficiency and minimizing losses. Innovations such as the Silicon Carbide (SiC) MOSFET have greatly improved inverter performance due to their higher breakdown voltage and switching rate, on the order of hundreds of kHz.[1–3] While maximizing switching speed has the largest influence on inverter efficiency, the rapid changes in voltage and current (dV/dt and dI/dt, respectively) which occur as a result produce voltage overshoots and parasitic inductance and oscillation which deteriorate switching behavior.[4]

Many studies have been conducted looking into ways to minimize this detrimental parasitic inductance including adjusting gate driver parameters, bus-bar configuration, and varying module materials.[3,5–9] This paper expands on research surrounding alternative module configurations by considering the implementation of a novel substrate material called Temprion, made by Dupont, which shows many promising mechanical and thermal properties for application in an EV inverter.

The majority of modern high-current inverter modules rely on ceramic materials such as Al_2O_3 or AlN to electrically insulate and conduct heat between various module layers. These ceramics are useful because they are extremely durable, have high levels of thermal conductivity, and are effective electrical insulators. However, coefficient of thermal expansion (CTE) mismatch between the copper conducting elements within the module and the ceramic substrate often results in delamination between the layers after repeated thermal cycling thus rendering the module nonoperational. Additionally, the extreme hardness of this ceramic makes it costly to manufacture and incredibly challenging to alter post-production, thus significantly limiting the ability to create inverters with custom shapes.

Temprion addresses many of the shortcomings of a ceramic substrate, providing comparable levels of thermal conductivity while offering the potential to produce substantially less parasitic inductance. Temprion exists as an extremely thin, paper-like material only 25 microns thick. The thinness of Temprion results in many benefits, including the ability to easily cut the material into specific shapes allowing for the creation of customized power modules. Additionally, this material has an intrinsic flexibility due to its thinness such that it yields enhanced reliability as the Temprion is able to bend as the copper expands and contracts through variation in temperature.

The most important benefit of Temprion is that, unlike ceramic substrates, it allows for the creation of new, multi-layer inverter modules which have the potential to significantly reduce the parasitic inductance of the module thus improving overall switching speed and performance.[7] Stacking the positive and negative layers of the inverter allows for destructive interference between the charge-induced magnetic fields, substantially decreasing the parasitic electromagnetic interference. The thinness of this material reduces the high-frequency noise from the parasitic inductance thus further improving module performance compared to its current ceramic counterpart.[10]

Previous research has demonstrated the benefits of using layered busbars to interface with inverter components, but most commercially available modules rely on wire-bonded, 2-dimensional module packages with lower power density and greater potential for electrical losses.[10,11] This research explores bonding the switching SiC MOSFETS directly to the stacked busbars, thus creating a highly power-dense layered inverter module with no extraneous wire-bonded components.

This paper will begin by discussing the process of designing the hot press with which the power inverter modules were produced. We will then describe the control software used to operate the press with minimal user input, including the comprehensive system monitoring and safety mechanisms. Lastly, we will discuss the fabrication of complete inverter modules and evaluate their theoretical performance compared to the current standard.

II. METHODS

A. Hot press construction

Previous experimentation using Temprion as the insulating material between busbar layers revealed that sufficient adhesion was possible by applying heat and pressure to the materials. This research utilized a pre-existing press created for this purpose, using two high-torque stepper motors connected to an aluminum plate along a pair of linear stages to apply an even amount of force to the substrate. Figure 1 shows the full press assembly.

Press heating was provided by two ceramic heater cartridges embedded within the aluminum press baseplate. Substrate temperature was initially regulated by a Cole-Parmer Digi-Sense 89000-10 Temperature Controller, though this was later replaced by a custom-made PID temperature controller such that the heating could be integrated into an automated press program.

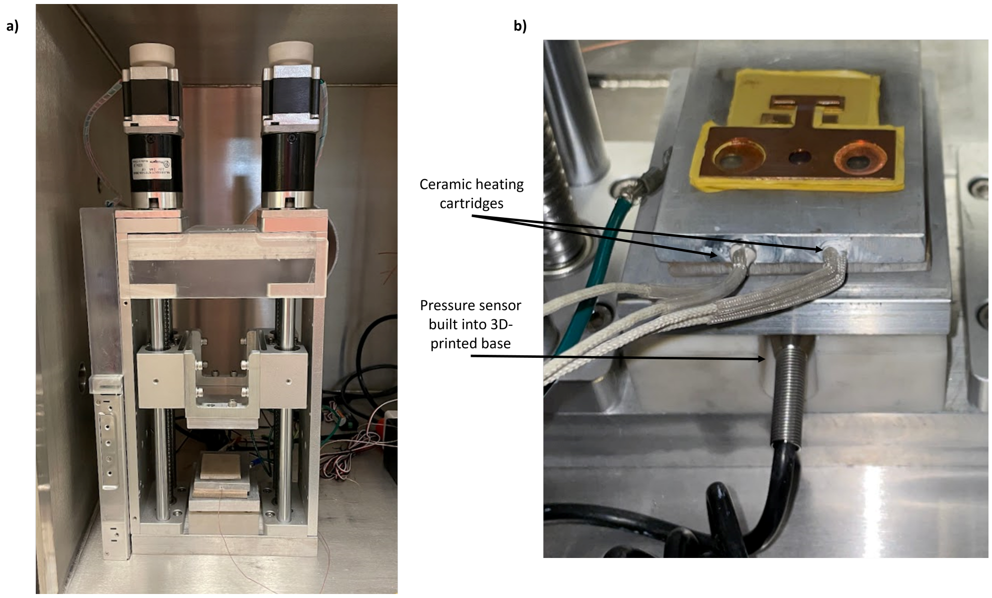


Figure 1: a) Full press assembly b) Close-up of press baseplate, showing embedded ceramic heating cartridges and load cell.

B. Control software

The primary focus of this research involved improving the control program for the hot press, introducing automation into many of the procedures such that minimal user input was required to utilize the full capabilities of the press. Additionally, a variety of safety and failsafe mechanisms were implemented to limit the need for user supervision and reduce likelihood of damage to the press in the event of a malfunction.

A graphical user interface (GUI) application was developed in python as the sole means of communicating with the press and heating elements to simplify equipment usage. The Tkinter python library was selected as the GUI platform for this project due to its simple, no-frills appearance and intuitive programming syntax. Integrating data monitoring and an activity log into the application allowed for easy troubleshooting during press operation, particularly in the event of a premature program termination due to a tripping of one of the failsafes. A data acquisition program was also implemented such that at the beginning of the automated press program the force, temperature, and elapsed time were stored to further help facilitate troubleshooting.

The interface between the motors and sensors used in the press and the program controlling it used Phidgets, a series of programmable sensors and microcontrollers[12]. The Phidgets application programming interface (API) allowed for seamless integration into the python-based GUI, greatly facilitating program automation.

1. Press Control

Automated control of the press motors relied on receiving a force reading from a one-ton load cell located in the base of the press platform. This load cell, connected to the control program using a Phidget module, provided updated force readings to the program every

100 ms. This force reading was constantly being checked against a user-determined force reading, set at 5000 N for this process, and motor control was dictated by proximity to this set force value. Using a hemispherical contact point on the load cell

2. Heater Control

We were unable to communicate with the Cole-Parmer Digi-Sense 89000-10 Temperature Controller via serial communication, thus necessitating an alternative path to control the ceramic heating cartridges. A new temperature controller was created using a Phidget programmable 15A relay, allowing us to toggle power to the heater on and off. Temperature monitoring was conducted using a thermocouple embedded within the aluminum bottom plate of the press. A simple proportional-integral-derivative (PID) controller was developed using the 'simple-pid' python library to control power to the heating cartridge, elevating the temperature to a setpoint established by user input similar to the force value mentioned previously.

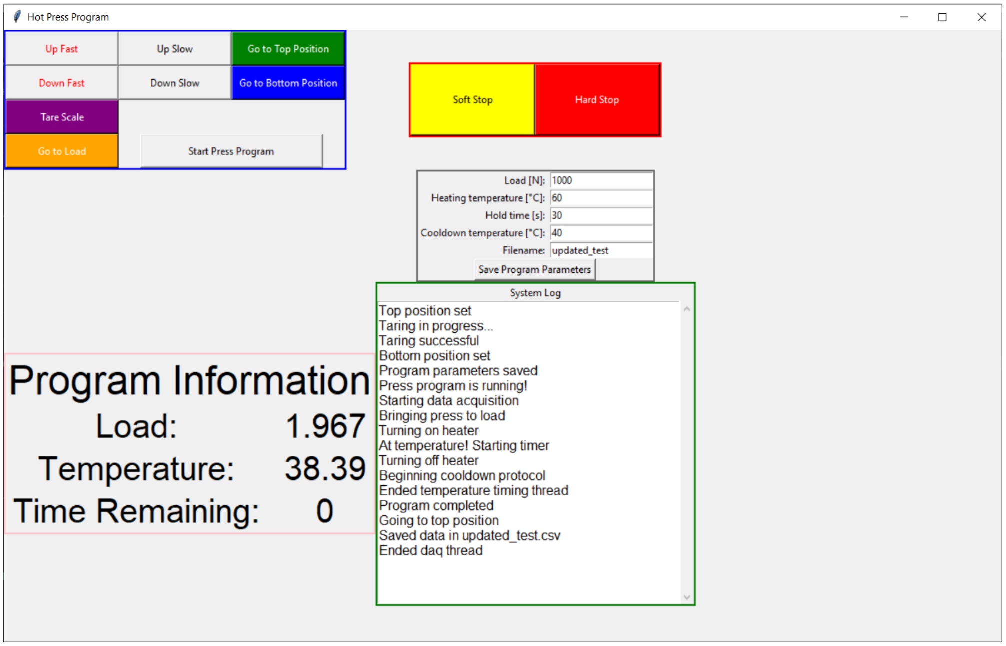
Several temperature safety measures were implemented including an external over-temperature watchdog and a temperature check integrated into the press program. The over-temperature watchdog was configured to cut power to the heating cartridges should the temperature exceed the setpoint by more than 10 °C. The temperature check built into the program monitored whether the temperature increased by at least 5 °C within 10 seconds of the heater cartridges turning on, and if that condition was not met then the program would be aborted and the user notified.

C. Program operation

Program workflow is simple and well-documented in the onboard system log. At program start, the user load the sample onto the press plate and manually sets a top and bottom positions to provide information to the program about where to start and end the automated execution. After setting the top and bottom positions, a menu appears where the user can input values such as desired force, substrate temperature and the duration to keep substrate at temperature. The user is also given the option to input a cooldown temperature at which the press will release the load and return to its resting state, as well as a filename used to store the recorded data and system log.

There also exists a button to tare the press scale to account for any associated mass of the substrate. After the program parameters have been saved and the scale has been tared a button appears enabling them to begin the press program, after which time no further user input is required. An image of the program interface is shown in Figure 2.

The press program begins by bringing the sample to the desired load value, decreasing compression rate as the value approaches the setpoint. Once the press reaches the desired value, the heating cartridges are turned on and the substrate temperature is increased to the setpoint. Once the desired temperature is reached a timer runs for the duration specified by the user, after which the heating element is turned off and the system begins a cooldown procedure. A visual program workflow is shown in Figure 3.



Load [N]: 1000
Heating temperature [°C]: 60
Hold time [s]: 30
Cooldown temperature [°C]: 40
Filename: updated_test

Program Information
Load: 1.967
Temperature: 38.39
Time Remaining: 0

```
Top position set
Taring in progress...
Taring successful
Bottom position set
Program parameters saved
Press program is running!
Starting data acquisition
Bringing press to load
Turning on heater
At temperature! Starting timer
Turning off heater
Beginning cooldown protocol
Ended temperature timing thread
Program completed
Going to top position
Saved data in updated_test.csv
Ended daq thread
```

Figure 2: Press program graphical user interface after successful program execution.

D. Module preparation

The power module consisted of several layers of copper and Temprion cut into specific patterns and then pressed into a stack. Busbar pieces were machined out of 0.65 mm thick sheets of copper using a desktop CNC router, while Temprion sheets were prepared using a stencil to cut pieces to the proper size. After individual pieces were cut, the copper was sanded to remove any surface impurities and oxidation which might interfere with adhesion to the Temprion.

E. Module fabrication

Power modules were assembled one layer at a time, binding sheets of copper and Temprion in the press under 5000 N of force and 300 °C for two minutes. A thin sheet of PTFE was placed beneath the bottom copper plate and above the top layer to promote even pressure distribution across the substrate. Two pieces of thermally insulating ceramic were placed beneath the hot plate and on the top of the substrate to prevent excess heat from being transferred into the press body.

III. PRELIMINARY RESULTS AND CONCLUSION

Early attempts at fabricating modules with the updated press program were successful, as shown in Figure 4. The automatic PID temperature controller was able to heat the substrate sufficiently to allow for proper bonding between the copper and Temprion, and all temperature safeties worked as expected.

This module fabrication highlighted several areas of future improvement, most notably implementing a way to consistently align the layers of copper and Temprion during the

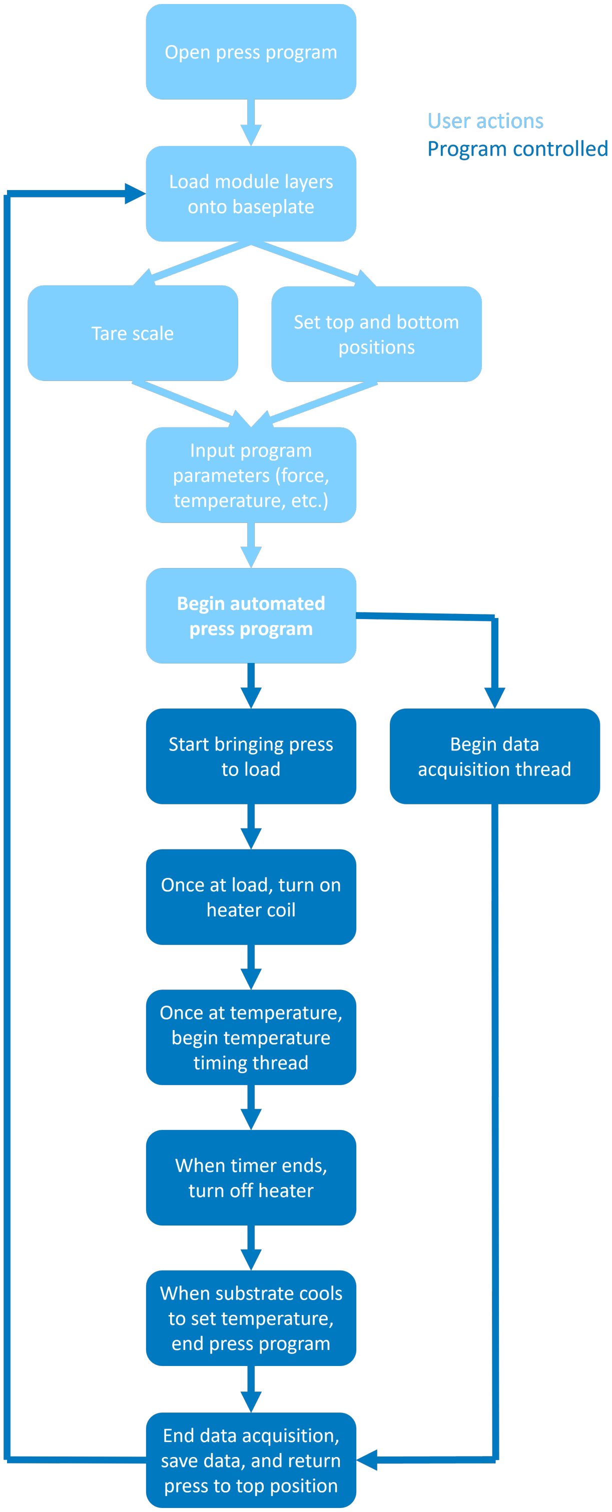


Figure 3: Automatic press program workflow, where user actions are colored light blue and actions performed automatically by the program are darker blue.

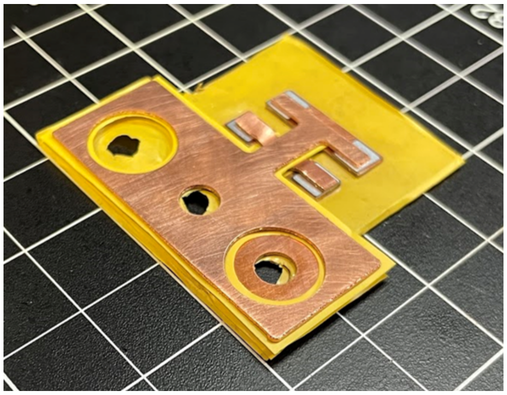


Figure 4: Finished sample inverter module created with the updated press program, representative of improved module layout. Note the four Si diodes representative of the SiC MOSFETs.

press process. The thinness of the Temprion and general lack of mass of each individual layer introduced unpredictable movement of the layers as they were being positioned in the press, resulting in undesired misalignment of layers within the module which jeopardized the usability of the module. Minimizing the impact of human error and improving repeatability of module fabrication is critical for future implementations of this press.

In spite of these challenges, the comparatively low cost of the equipment used to create both the press and power module suggest the possibility of widespread adoption of this material and process into a variety of research areas. Additionally, the speed of construction of new inverter modules allows for rapid validation of simulation data which will be advantageous for future research.

Future research will explore the implementation of a double-sided heating system for the substrate, such that the entire module could be pressed in a single operation instead of assembling the module one layer at a time. Enclosing the press apparatus within a vacuum chamber will give further control over the press conditions and may yield stronger bonding between layers of copper and Temprion.

IV. ACKNOWLEDGEMENTS

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