

DESIGN OF MOTOR DRIVE FOR HIGH TEMPERATURE ENVIRONMENT

Stephen Chiu*, Jie Chang*, Charles Neft*, Fred Morris*, Eugene Dines**, Jim Hughes**

*Rockwell Science Center
1049 Camino Dos Rios
Thousand Oaks, CA 91360
Phone: (805) 373-4408
FAX: (805) 373-4383
slchiu@rsc.rockwell.com

**Boeing Research & Technology Center
3370 Miraloma Ave.
Anaheim, CA 92803
Phone: (714) 762-8172
FAX: (714) 762-0844
eugene.l.dines@boeing.com

ABSTRACT

The trend towards more-electric aircraft and electric combat vehicles creates a need for electric motor drives that can operate in high temperature environments. The evolving industrial market for integrated motor and drive also presents similar thermal challenges for drive electronics as the drive must be joined with the motor in an increasingly compact package. This paper presents the design of a high temperature motor drive based on silicon-on-insulator (SOI) integrated circuits and commercially available power electronics.

Digital and analog integrated circuits based on SOI technology, which can operate at above 200°C temperature, are entering commercial production. The control logic section of a high temperature motor drive can be built straightforwardly by using SOI technology. The difficulty in building a high temperature drive resides in the lack of high temperature power components, such as power switches and high value capacitors. We discuss a combination of methods for overcoming this difficulty, including power component selection and derating, advanced power switching techniques to reduce DC-link capacitor, and high efficiency heat sinks for power electronics.

I. INTRODUCTION

In both defense and commercial sectors, there is a growing need for electronics that can be collocated with sensors and actuators in high temperature environments. High temperature electronics can significantly reduce the heavy, long wire harnesses needed to connect electronics from a benign central location to sensors and actuators in harsh environments. The reduction in wire harnesses and

cooling system requirement can produce significant weight savings. System reliability is also improved as a result of reduced wire harnesses and simplified interconnects.

The need for high temperature electronics has been partially addressed through the recent commercialization of silicon-on-insulator (SOI) integrated circuits by Honeywell.¹ While the reliability of conventional CMOS chips begins to degrade at temperatures above 100°C, SOI chips can operate reliably at above 200°C. The SOI wafer contains a thin silicon layer over a thick buried oxide layer on a bulk silicon substrate; at high temperatures, the leakage current of an SOI device can be two orders of magnitude less than that of a conventional CMOS device. However, similar to CMOS, SOI devices are limited to digital and low-power analog integrated circuits.

DoD applications such as the More Electric Aircraft and electric combat vehicles require the installation of electric power conversion and control systems within stringent size and weight constraints. Minimizing wire harnesses and cooling equipment is critical to the success of these onboard applications. However, developing high temperature electronic modules for these applications is extremely challenging because of the unavailability of high temperature power components, such as power switches and high value DC-link capacitors; furthermore, the problem of high ambient temperature is exacerbated by the significant heat generated internally by the power electronics. Commercial applications such as electric vehicle and integrated motor/drive pose similar thermal challenges to the control and power electronics.

This paper describes the design of a high temperature AC motor drive based on SOI control

logic chips and conventional power components. Methods for dealing with the lack of high temperature power components are discussed. These methods include power device selection and derating, power switching techniques to reduce DC-link capacitor, and high efficiency cooling mechanisms for power electronics. Our goal is to develop a high temperature drive that can be integrated with a 3HP motor in a highly compact package.

II. HIGH TEMPERATURE CONTROL LOGIC

The control logic section of the motor drive is responsible for generating the pulse-width-modulation (PWM) signals that turn on/off the power switches in the power converter section. The block diagram of the control logic section is shown in Figure 1; its key components are a 32-bit digital signal processor (DSP), static RAM, EEPROM, an analog-to-digital converter, a 16-to-1 multiplexer, and an Application Specific Integrated Circuit (ASIC) which performs special motor control functions and provides the glue logic between other components.

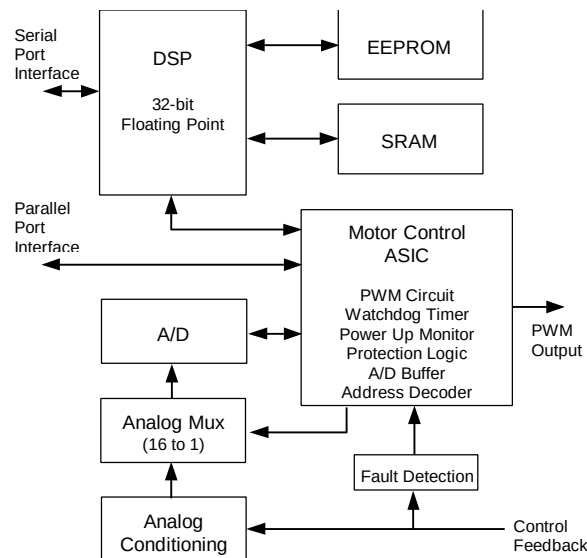


Fig. 1. Block diagram of control logic section.

The ASIC was jointly designed by Boeing and Rockwell, and was fabricated by Honeywell in an SOI gate array. The motor control functions performed by the ASIC include PWM waveform generation and fault protection. The static RAM, analog-to-digital converter, and multiplexer are SOI devices designed and fabricated by Honeywell, all rated for operation at 225°C. The EEPROM is fabricated by Xicor and is rated for operation at 170°C. The DSP is a military temperature (125°C) version of the TMS320C32 DSP from Texas Instruments. The mil-temp DSP was used

because a high performance microprocessor based on SOI technology is currently not available. (An 8-bit SOI microprocessor is currently available from Honeywell.) Future versions of the ASIC will likely incorporate the required functions of the DSP and thus eliminate the need for a separate DSP.

The aforementioned SOI devices were produced through a DARPA-funded Technology Reinvestment Project to develop dual-use high temperature electronics technology.

III. SELECTION OF POWER DEVICES

The unavailability of high temperature semiconductor power devices is a major obstacle to the development of high temperature power converters. Power device characteristics affected by temperature include on-resistance or on-state forward voltage drop, break down voltage, leakage current, and switching speed.² A power electronics engineer must understand the change in the power device's characteristics with respect to temperature, and incorporate this characterization into the circuit design.

The key parameters that determine the suitability of a power device for high temperature environment are the device's maximum allowable junction temperature and its conduction loss. A power device must be cooled to an extent that its junction temperature does not exceed the maximum allowable value. A higher maximum junction temperature allows a higher base plate or heat sink temperature. A higher heat sink temperature, in turn, allows a higher ambient air temperature or coolant temperature. A device with low conduction loss generates less heat, which also leads to a higher allowed heat sink temperature (i.e., a small temperature difference between the device junction and the heat sink is sufficient to remove the generated heat).

Manufacturers of Insulated Gate Bipolar Transistors (IGBT) usually specify a maximum allowable junction temperature of 150°C. Although IGBTs have been reported to operate at higher junction temperatures, the device reliability and life expectancy at higher junction temperatures have not been adequately studied.

A new generation of MOS-Controlled Thyristors (MCT) developed by Harris Semiconductors under the Navy's Power Electronics Building Block (PEBB) program is expected to have a higher maximum junction temperature and lower conduction loss than IGBTs.³ However, these prototype MCT devices are in limited supply and not yet commercially available.

Although silicon carbide devices can handle high power at extremely high temperatures (near 600°C), these devices are in the early stages of development, and commercial production of these devices is not expected in the near future.

Based on commercial availability, we selected a 1200V, 25A IGBT power module with low conduction loss for building a 3HP high temperature motor drive. For a 3HP, 460V drive, approximately only 5A of the module's 25A current carrying capacity will be used. This margin was necessary for derating the device for operation at high temperatures.

IV. DC-LINK CAPACITOR REDUCTION

Traditional PWM controlled power switching assumes a constant DC input voltage is available on a power bus. This requires large (high voltage and high value) capacitors to filter out harmonics at six times the line frequency and reduce the peak-to-peak DC voltage ripple to 2-3% at loaded conditions. The electrolytic capacitor provides excellent energy storage capacity, but, unfortunately, it is also perhaps the most problematic power component in a high temperature environment. Capacitors made with an insulator with a high dielectric constant exhibit unstable capacitance and high leakage current at elevated temperatures. Hot spots induced by surge currents coupled with dielectric breakdown at high temperatures can cause catastrophic failures.

Commercially available aluminum electrolytic capacitors are rated for operation at up to 105°C only. While wet tantalum capacitors are capable of operating at 200°C and offer reasonable energy density, high voltage and high value tantalum capacitors are not available. Ceramic capacitors, which have temperature ratings ranging from 125°C to 200°C, are consigned to the picofarad to single-digit microfarad range. Due to the lack of suitable high voltage, high value DC-link capacitors, it is necessary to reduce the required DC-link capacitance to a minimum through advanced power conversion techniques.

After evaluating various power conversion techniques for reducing the DC-link capacitance, we selected an adaptive PWM controlled inverter scheme for the high temperature drive. The adaptive PWM scheme utilizes the standard rectifier-inverter topology (see Figure 2), but the scheme takes into account the DC-bus voltage fluctuations in each PWM cycle and adapts the width of the PWM waveform to produce the desired output. This PWM method can therefore accommodate a higher degree of DC-bus voltage fluctuation and allow the use of smaller DC-link

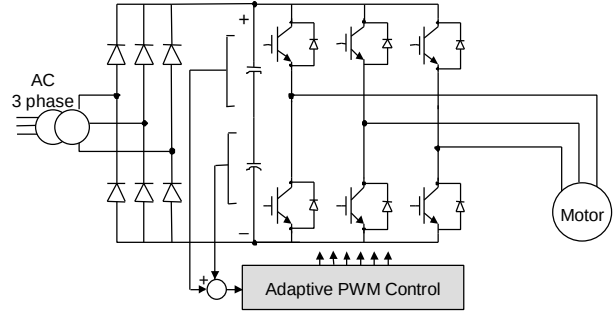


Fig. 2. Adaptive PWM control of inverter.

capacitors. This method provides good capacitance reduction at low cost. When the adaptive PWM controlled inverter is combined with a high efficiency AC motor with permanent magnet rotor (which has low reactive current), the required DC-link capacitance can be reduced by 60-70%.

Another excellent power conversion scheme for high temperature applications is direct AC-to-AC power conversion,⁴ which can completely eliminate the need for DC-link capacitors. The direct AC-to-AC power converter employs bi-directional power switches and performs power conversion in one stage without using passive energy storage. A simplified circuit schematic is shown in Figure 3. This power converter has higher cost because the circuit topology requires the equivalent of 3 times the number of power switches used in the adaptive PWM scheme. The direct AC-to-AC converter is suited for high temperature, high power motor drives. An important added benefit is that power regeneration capability is inherently built into this topology, which makes the drive also suitable for generator applications.

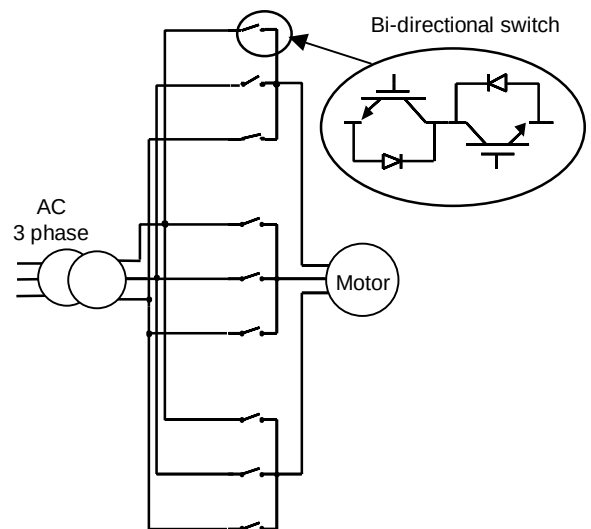


Fig. 3. Direct AC-to-AC power converter.

V. COOLING OF POWER ELECTRONICS

The IGBT power module is the primary source of heat generation within the drive. A significant part of our drive design effort is devoted to designing compact, self-contained cooling mechanisms for the power module. We developed two prototype compact mechanisms for cooling the power module: two-sided air cooling of the power module and immersion cooling of IGBT die.

The two-sided cooling mechanism consists of micro-channel fin structures for cooling both the front face and the back face of the power module. The schematic of the cooling mechanism is illustrated in Figure 4, where the larger fin structure is attached to the back plate of the IGBT module similar to a conventional heat sink, and a smaller fin structure is attached above the IGBT die by using a high thermal conductivity, high electrical insulation epoxy. The small fans attached to the fin structures provide forced air convection through the fin channels. Prototype fin structures fabricated from copper are shown in Figure 5. These compact, air-cooled fin structures are suited for low horsepower (less than 5HP) applications with moderate ambient temperature in the 60°C range.

Figure 6 shows the back-face cooling fin on a prototype high temperature power converter for the

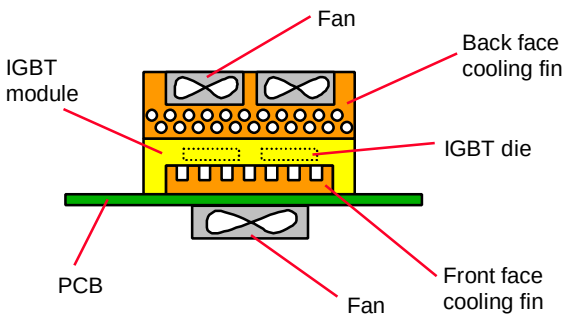


Fig. 4. Schematic of two-sided cooling mechanism.

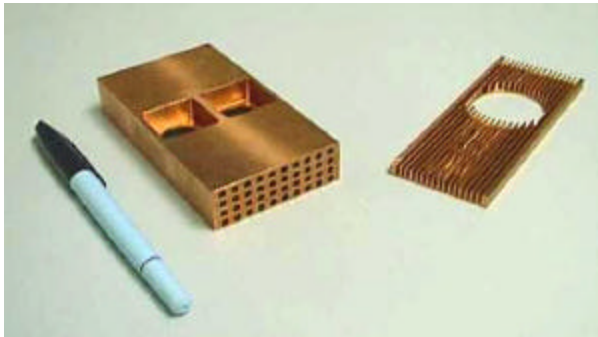


Fig. 5. Fin structures fabricated for two sided cooling.

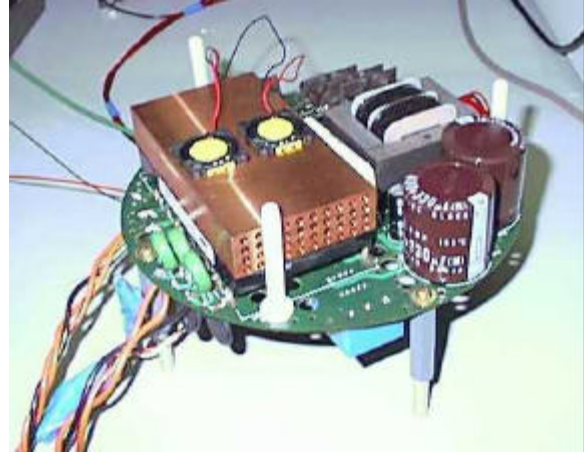


Fig. 6. Prototype high temperature power converter for compact integrated motor/drive.

compact integrated motor/drive. The circular power converter board, which is less than 7 inches in diameter, will be enclosed in a cylindrical casing attached to the end of the motor.

The immersion cooler shown in Figure 7 uses vapor phase transformation to increase the cooling efficiency. The structure contains alternating open air channels and closed, interconnected vapor channels. IGBT dies are to be immersed directly in liquid coolant; the heated liquid evaporates upward and condenses back down through the vapor channels. Heat is conducted from the vapor channels to the walls of the adjacent air channels and carried away by forced air convection. The vapor phase cooling structure has been successfully tested by using resistors to emulate IGBT heat loss. This cooling mechanism is best suited for high ambient temperature, high power applications.

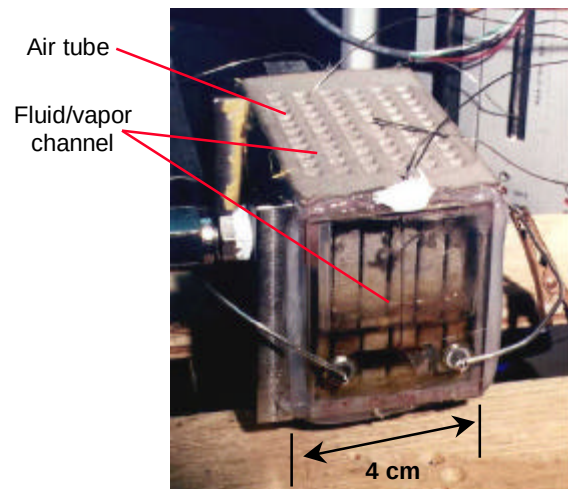


Fig. 7. Prototype vapor phase cooler.

VI. CONCLUSION

We presented the design of a high temperature motor drive that uses high temperature silicon-on-insulator integrated circuits and commercially available power components. We addressed the problem of the lack of high temperature power components through power device selection and derating, DC-link capacitor reduction, and efficient heat sink design. The design choices are largely dictated by the power level of the application. These techniques are being incorporated into a highly compact 3HP integrated motor/drive currently under development.

ACKNOWLEDGMENTS

The authors thank Mr. Scott Stetson, Mr. Gary Heimbigner, and Dr. David Seib at Boeing Research and Technology Center, as well as Dr. Chung-Lung Chen and Dr. Changming Liao at Rockwell Science Center, for their invaluable technical support. Funding support from Boeing and the HiTeC Technology Reinvestment Project is gratefully acknowledged.

REFERENCES

1. G. Swenson and B. Ohme, "HTMOS: Affordable high temperature product line," *Proc. 3rd International High Temperature Electronics Conference*, June 9-14, 1996, p. P-89, Albuquerque, New Mexico (1996).
2. J. Bromstead, et al., "Silicon device performance measurements to support temperature range enhancement," Auburn University report (1994).
3. V. Temple, D. Watrous, S. Arthur and P. Kendle, "MOS-controlled thyristor power switches," *Power Conversion and Intelligent Motion (PCIM) magazine*, November 1992 issue (1992).
4. L. Gjugyi and B. Pelly, *Static Frequency Changes*, John Wiley & Sons, New York, New York (1976).