High-Temperature Brushless DC Motor Controller Design

Grzegorz Cieslewski, Scott Lindblom, Frank Maldonado, and Michael Echert

Sandia National Laboratory, Albuquerque, NM

ggciesl@sandia.gov

Keywords
Downhole, logging, high temperature, electronic tools, motor

ABSTRACT

High-temperature geothermal exploration requires a wide array of tools and sensors to instrument drilling and monitor downhole conditions. There is a steep decline in component availability as the operating temperature increases, limiting tool availability and capability for both drilling and monitoring. Several applications exist where a small motor can provide a significant benefit to the overall operation. Applications such as clamping systems for seismic monitoring, televiewers, valve actuators, and directional drilling systems would be able to utilize a robust motor controller capable of operating in these harsh environments. The development of a high-temperature motor controller capable of operation at 225°C significantly increases the operating envelope for next generation high temperature tools and provides a useful component for designers to integrate into future downhole systems.

High-temperature motor control has not been an area of development until recently as motors capable of operating in extreme temperature regimes are becoming commercially available. Currently the most common method of deploying a motor controller is to use a Dewared, or heat shielded tool with low-temperature electronics to control the motor. This approach limits the amount of time that controller tool can stay in the high-temperature environments and does not allow for long-term deployments. A Dewared approach is suitable for logging tools which spend limited time in the well however, a longer-term deployment like a seismic tool [Henfling 2010], which may be deployed for weeks or even months at a time, is not possible. Utilizing high-temperature electronics and a high-temperature motor that does not need to be shielded provides a reliable and robust method for long-term deployments and long-life operations.

System Design

The design objective for the prototype seismic tool clamping arm system is to provide a complete high-temperature motor controller capable of operation in environments with an ambient temperature of 225°C for 1000 hours. The system requirements are as follows.

- The motor and controller must operate over a two wire cable
- The motor must rotate in either direction
- The motor must occupy a cylindrical volume no more than 2.25” in diameter by 18” high
- The motor must generate at least 7.5 ft-lb of torque

Before the development of the design, it was critical to understand the limitations of the available components as there are very few options currently available. After determining the motor and the electronic components available, a control algorithm was selected capable of providing the desired performance while using these parts.

Motor Selection

There are very few compact electric motors that operate at 225°C, most of which lack significant performance data to appropriately evaluate. Options include a stepper motor, a brushed DC motor, and a brushless DC (BLDC) motor. All of the motors are designed for operation in an oil bath. After evaluating the options, the Maxon EC32HD BLDC motor was selected due to its compact size, flexibility and the test data provided by the company. Due to the temperature requirements, this motor does not contain Hall Effect sensors, which commonly provide rotation information in BLDC motors and therefore, requires a sensorless control algorithm. The motor is coupled with a planetary gearbox Maxon GP32HD which provides 132:1 reduction in output rotational speed, while increasing the output torque of the motor.

Electronics

The BLDC motor requires a complicated commutation scheme, which necessitates a significant amount of computation. The computational and temperature requirements limit the selection of the electrical components. Only two components are available which fulfill the needed requirements, a high-temperature HT83C51 microcontroller and a low temperature field programmable gate array (FPGA) that has been demonstrated to operate at 225°C.
for 1000 hours. The HT83C51 microcontroller needs additional hardware to operate and requires a communication link to load the programming, adding significantly to the overall footprint. The FPGA does not need any additional hardware to operate making it more desirable. In addition, it is not limited by the instruction set architecture (ISA) of the HT83C51 microcontroller and allows for parallel computation, however it constrains the complexity of the algorithm which it can store. The FPGA was chosen based on the analysis of available options.

Figure 1 shows the block schematic of the high-temperature motor controller. The FPGA controls the operation of the three half-bridge components that in turn provide the power to the BLDC motor and monitors output voltage of each half-bridge via independent analog-to-digital (ADC) converter chip. Each half-bridge consists of two primary transistors used as switching elements and supporting electronics (high-side and low-side drivers) which allow the FPGA to control the switching elements. The charge pump provides voltage higher than VCC necessary for the correct operation of the high-side driver circuit. The Cis-soid silicon-on-insulator (SOI) CHT-NMOS80 transistor was chosen as the switching element for the system. It is the highest rated SOI power MOSFET available and was extensively tested and characterized throughout the temperature range [Patterson 2009], however it has limitations that are not present in the low-temperature power transistors. Specifically, the CHT-NMOS80 has a significant on resistance causing it to dissipate excessive amounts of heat when high current is passed through it.

**Heat Sink**

To mitigate the limitation of the high-temperature power transistors, the SNL designed a heat sink which is capable of storing large amounts of heat to prevent the transistors from overheating. The heat sink consists of a 9”x2”x0.5”, 2.7 lb brass block. Brass was chosen as it has thermal properties similar to copper and it is easy to machine. The six power transistors (two from each half-bridge) are then attached directly to the heat-sink. Assuming equal spacing of the transistors, the average temperature of the heat sink will raise by 1°C for every 451J of resistive heat dissipated by the transistors. Assuming a worst case scenario where the power dissipated by the transistors is 20W and a maximum ΔT of 10°C, then the allowable continuous run time of the system is about four minutes. In the case of the clamping mechanism for seismic sensor the motor has to operate periodically and prolonged continuous operation is not required.

**Control Algorithm**

The control algorithm provides the necessary input signals to the half-bridge drivers in order to effectively operate the BLDC motor. Due to the constraints of the high-temperature components used, SNL designed a control algorithm, implemented in an FPGA to effectively operate the motor.

Commutation is achieved by applying drive pulses to each of the half-bridge drivers in such a way as to create a rotating magnetic field in the motor which applies torque to the motor shaft. There are six discrete steps, known as phase indexes, in one revolution of the BLDC motor. Each phase index corresponds to driving each of the three motor windings either to positive voltage, ground, or left unconnected. The order in which these voltages are applied to the motor windings determines the direction of the magnetic field created inside. By using a look-up table programmed with the correct steps required to create a rotating magnetic field, the FPGA is able to drive the motor windings in this order via the half-bridge driver circuits. The timing that each new phase is applied to the windings determines the speed at which the motor shaft turns.

In a traditional BLDC control scheme, rotor position is directly sensed via Hall effects sensors, and the next phase step can be applied at the optimal timing for the greatest efficiency. However, the lack of Hall effects sensors necessitates a complex control algorithm in order to electronically control both the speed and torque of the motor. In order to implement such an algorithm and still meet the size constraints of our FPGA, a constant speed approach was implemented, which significantly reduces the size of the controller design. The constant speed algorithm commutes the motor at a known rate without adjusting to match varying loads. From a stand-still, the motor is provided enough current to ensure sufficient torque output, and slowly brought up to the constant operating speed. By using voltage feedback from the ADC, the power provided to the motor can be adjusted to match the requirements of the load.

The controller uses a switched power supply pulse width modulation (PWM) scheme to control the amount of voltage available to the motor windings. By dynamically adjusting the PWM duty cycle, the motor controller can increase or decrease the amount of torque the motor generates at any one time. In addition, the voltage feedback is used to detect a stall condition, at which point the control algorithm will stop motor commutation, and decide what to do next, which may vary by application. Such behavior is pre-programmed into the FPGA, and can be customized to fit different applications.
**Clamping Arm Operation**

On startup, the direction of rotation will be determined based on the voltage being applied to the system. If the voltage is lower than a certain level the motor will turn clockwise otherwise it will turn counter-clockwise. To deploy or stow a clamping arm (Figure 2), the controller will step through a discrete number of steps during which the controller will operate the motor in a constant torque and constant speed mode. The torque is increased and speed is decreased between each step to achieve desired clamping force. Each step consists of startup sequence, normal operation and stall condition. During the startup sequence the motor is internally aligned and then accelerated to desired speed over a period of 500ms. While in normal operation mode the motor maintains the constant output torque and speed until the stall condition is detected and then the controller moves to the next step until desired force is achieved or stops the operation pending power down or reset.

![Figure 2. Prototype Clamping Arm for a Seismic Tool.](image)

**Testing**

To test the initial performance of the system we have performed two forms of testing: torque testing and heat sink testing.

**Torque Testing**

To measure the output torque of the motor and the controller we used dynamometer shown in Figure 3. The high-temperature motor was placed in a housing filled with oil and then coupled to the dynamometer. To decrease the heat dissipated, we chose a 15V supply for this test. The motor and the controller were tested by setting the desired PWM duty cycle and speed while adjusting the load that the dynamometer is generating. The highest continuous output torque was recorded. The motor was not characterized at lower PWM duty cycles as not enough power is provided to the motor to overcome the approximatley 3.3 ft·lb of drag torque exerted by the dynamometer. To obtain the no load speed, the motor was uncoupled from the dynamometer, the desired PWM duty cycle was set while the speed increased until the motor stalled.

Figure 4 shows the results of the test. The maximum achieved torque was 18.8 ft·lb at 300 rpm, while the highest no load speed was 2051 rpm. The motor speed was measured at the motor output while the torque was measured at the output of the gearbox. For the BLDC motors the relationship between the rotation speed and torque (at constant voltage) is linear and our results demonstrate that trend showing a correct operation of the high-temperature controller.

![Figure 4. Motor Output Torque.](image)

**Heat Sink Testing**

To verify the design of the heatsink, eight themocouples were placed along the center line of the copper block to observe the temperature change. During the test, electronics and the heatsink were enclosed in a plastic housing with no air circulation in order

![Figure 5. Constant Torque and Speed Heat Sink Temperature.](image)
to minimize heat dissipation. The motor was run at 100% PWM duty cycle using 12V power supply (roughly equivalent to 80% PWM duty cycle with 15V supply) while the load was 12.8 ft·lb and measured approximately 2.9A at the power supply. The motor was run for 20 min and followed by rest period. During that time the data from each thermocouple was collected every 10s. The graph in Figure 5 shows the temperature of each thermocouple during the experiment. The difference in temperature over the period of 20min. was 27.6 °C. The temperature of the block did not raise evenly as the transistors are not attached symmetrically along the block due to space constraints. The temperature along the whole heat sink equalized in about 10 min. The experiment shows better performance than the worse case scenario. Based on the average final temperature we estimated the power dissipated by the transistors is about 9.03W.

Conclusion and Future Work

The motor controller has been designed to operate the BLDC motor using sensor-less control algorithm. The preliminary results show that chosen motor and motor controller can generate 18.8 ft·lb of torque well in excess of required torque and is suitable for periodic operation. The further testing will characterize the performance of the motor and the motor controller at 225°C as well as test the force which the clamping arm will exert on the borehole.

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2013-3919 C.

References
