Investigation of Brushless DC Motor Commutation Techniques

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January 2009

Abstract:

Brushless DC (BLDC) motors are cleaner and more reliable than their brushed counterparts. For this reason, a number of BLDC motors are used in the OMEGA laser system. Because of the extreme conditions these motors are exposed to during a laser shot, including a powerful electromagnetic pulse (EMP), the Hall effect sensors that govern the motors' commutation cycles sometimes sustain serious damage. This damage may render the motors inoperable using the installed motor drivers. This necessitates a difficult extraction process to recover the motors for repair. This project investigated sensorless motor commutation as a potential solution to this problem. With a sensorless commutation scheme, the motors could be extracted without the use of the damaged Hall sensors. Therefore, a test fixture has been developed that is capable of driving a BLDC motor sensorlessly. This will aid in extracting the target positioner and the off-axis parabola inserter/manipulators after Hall sensor damage has occurred.

Introduction:

In order to conduct inertial confinement fusion research at the Laboratory for Laser Energetics, a small target is exposed to high-intensity laser beams within the target chamber. This target is precisely positioned before an experiment by the target positioner, a mobile device which transports the target down a wide metal tube to the chamber. The target positioner is driven by a brushless DC (BLDC) motor.

Because BLDC motors lack contact brushes, commutation must be regulated electronically. The current hardware driving the target positioner's motor utilizes three Hall effect sensors. During a laser shot event, the target positioner is exposed to extreme conditions, namely a high-intensity electromagnetic field. This sometimes results in damage to the Hall effect sensors, effectively rendering the BLDC motor on the target positioner inoperable. This necessitates a difficult and time-consuming process to manually extract the device for repair.

It is possible, however, to effect commutation of the BLDC motor entirely without the use of its sensors. Rather than directly sensing the rotor's magnetic field, the back electromotive force (BEMF) generated in the stator windings can instead be sensed. Because this can be done without additional onboard hardware, such sensorless commutation would allow the target positioner to be extracted under its own power when its sensors fail.

This project investigated the possibility of sensorless commutation for the purpose of removing the target positioner and/or off-axis parabola inserter/manipulators (OAPI) in the event of sensor failure. Although no further onboard hardware (such as sensors) is required for this approach, a new controller is necessary to interpret the BEMF and, using this feedback, commutate the motor. This controller would be a separate unit that could be connected to the target positioner externally when needed.

Project Goals:

The main goal of this project was to investigate the feasibility of sensorless commutation as a secondary mode of operation for the target positioner and OAPI. To accomplish this, a proof-of-concept test fixture was created to evaluate this commutation technique. First and foremost, this fixture needed to be capable of driving a BLDC motor using sensorless feedback. It had to be capable of doing this at relatively high power outputs (24V at 5A or more), in order to drive the target motors. The test fixture also needed to be self-contained and portable, to allow for practical usage and avoid unnecessary complexity. Last, the fixture needed to incorporate commercial “off the shelf” hardware if possible, in order to minimize development time and simplify the end product.

Current Commutation Techniques:

The target positioner and OAPI are currently driven using Hall effect sensor feedback. This technique uses three digital Hall sensors evenly distributed around the stator (see Fig. 1). As the rotor spins, the magnetic field produced by its permanent magnet(s) shifts accordingly. This change in relative field strength as observed by the Hall sensors allows the motor controller to determine the approximate orientation of the rotor. With this information and a known cycle of corresponding "Hall states" and phase voltages, the motor can be commutated effectively.

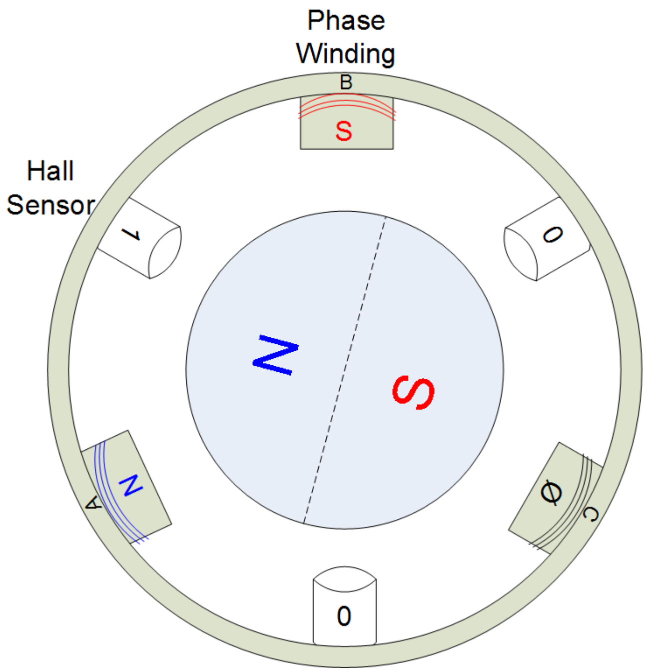

Figure 1: An example of a three-phase BLDC motor, in which Hall effect commutation directly senses the rotor's changing magnetic field.

In addition to the Hall effect sensors, the BLDC motors used in the target positioner and OAPI are equipped with encoders. Although these encoders are not used in typical operation, they provide an auxiliary method of commutation in the case that the Hall sensors are damaged, but the encoder is still operational. However, the encoders experience failure rates greater than that of the Hall sensors, so this is sometimes not an option.

Sensorless Commutation:

Much like Hall sensor commutation, sensorless commutation relies on the sensing of magnetic fields. However, rather than directly detecting the rotor's field, the BEMF is sensed. BEMF is induced in the motor's phase windings as the rotor's spinning magnetic field interacts with them. Because only two of the phases have voltage applied across them at any given moment, the third, inactive phase can be used to sense the induced current (BEMF) across it (see Fig. 2). This provides an analog indication of the rotor's orientation, which takes the shape of a sinusoidal wave. The frequency of this wave, calculated by determining zero-crossing points, can then be used to estimate when to commutate the motor.

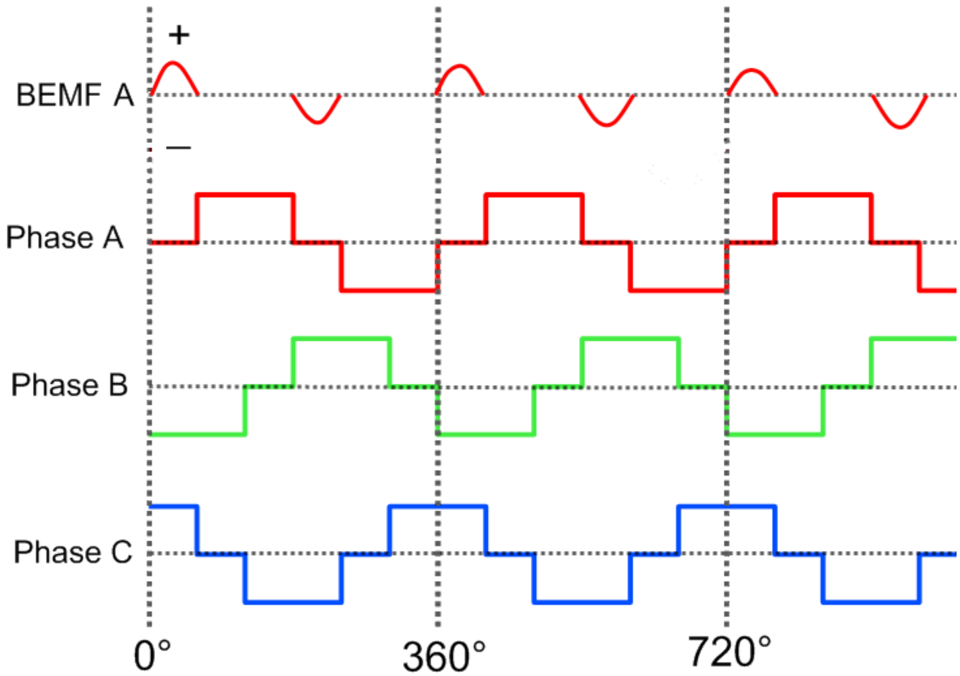

Figure 2: An example of the voltage waveforms as a three-phase BLDC motor operates. Note that the BEMF shown is only as read from phase A; it can only be sensed when the phase is inactive.

Because sensorless commutation relies on BEMF, the rotor must be spinning fast enough to induce a usable voltage for it to commutate reliably. This means that for low-speed applications, or for those where precise position control is necessary, sensorless commutation is not a viable option. Additionally, a smooth startup sequence is not possible, because the rotor's initial orientation cannot be determined. For this reason, many controllers begin in an arbitrary state and blindly cycle through the commutation sequence until the rotor is spinning fast enough to begin proper electronic commutation.

Although this works, it often results in an amount of “shuddering” during the startup sequence, and the rotor may momentarily spin in reverse.

However, although these properties limit sensorless commutation's application range, there are also advantages over Hall effect commutation. Most importantly, sensorless commutation does not require any onboard sensors. This means that it can be used in situations where extreme conditions may make Hall effect sensors or encoders unreliable, such as the OMEGA target chamber. While sensorless commutation is not an attractive option for normal operation of the target positioner and OAPI, it is excellent for short-term extraction in the event of sensor failure. Therefore, a test fixture was created to evaluate its effectiveness for this task.

Test Fixture Creation:

Because an “off-the-shelf” implementation was preferable for this project, it was necessary to select and purchase a commercial controller. Many packages were considered, and Luminary Micro's BLDC development kit was ultimately chosen, for several reasons. First, it shipped pre-loaded with Luminary's BLDC demonstration program, which could interface with a PC running a GUI client. Luminary's solution also offered several development environments to choose from, including Code Red's red_suite, CodeSourcery, IAR Embedded Workbench, and the ARM/Keil Microcontroller Development Toolkit for ARM. The development kit also featured the Stellaris LM3S8971 microcontroller (based on 32-bit ARM Cortex-M3 architecture), which was a very capable processor for the task. All of these points, combined with a very affordable price, made the Luminary Micro development kit the best option for this project.

The RDK-BLDC kit's included BLDC motor control software allowed the user to control drive parameters in real time from a connected PC over an ethernet interface. This functionality was very useful in zeroing in on the optimal parameters for driving the specific motors used in the target positioner and OAPI. These parameters were later inserted into the final source code as constants.

To program the microcontroller, a separate Luminary product, the LM3S8962 Evaluation Kit, was used. This kit was capable of programming the motor control board over USB/JTAG, an interface commonly used to test and program microcontrollers. It also included a daughter board, which could be connected via CAN (controller area network), a protocol used for communication between electronic control units. This board included several pushbuttons, which made it a useful addition to the motor control board.

To begin, Luminary's stripped-down version of the motor control source code was loaded in IAR Embedded Workbench. This version had the ethernet, serial, and CAN interfaces removed, and simply started and stopped the attached motor. Using preprocessor commands and jumper settings on the board, it could be toggled between Hall effect and sensorless commutation. After much experimentation and editing of the source code (in the C language), the code was modified to accept input over the CAN interface. This allowed for easy push-button control when testing; however, it also resulted in communication that was sometimes unreliable.

Because motor control requires completely dependable controls, the CAN interface was removed. In its place, several external pushbutton switches were connected to the board's inputs that were normally reserved for the motor's Hall sensors – in this application, they are not necessary, freeing up three input screw terminals.

The code was then further modified to handle limit switches. The target positioner and OAPI both utilize these switches in order to ensure a safe operating range, and so the test fixture had to incorporate these inputs in its design. Care was taken to thoroughly test the logic governing motor operation, to prevent the motor from running in unsafe ways when the user presses an unforeseen combination of buttons.

Next, the source code was further modified to accept an analog input, provided by an external potentiometer. Because the original code was designed to run at a fixed speed, major changes were necessary to allow the speed to change. In the final implementation (Fig. 3), the user can adjust the speed in real-time using scaled input from the potentiometer.

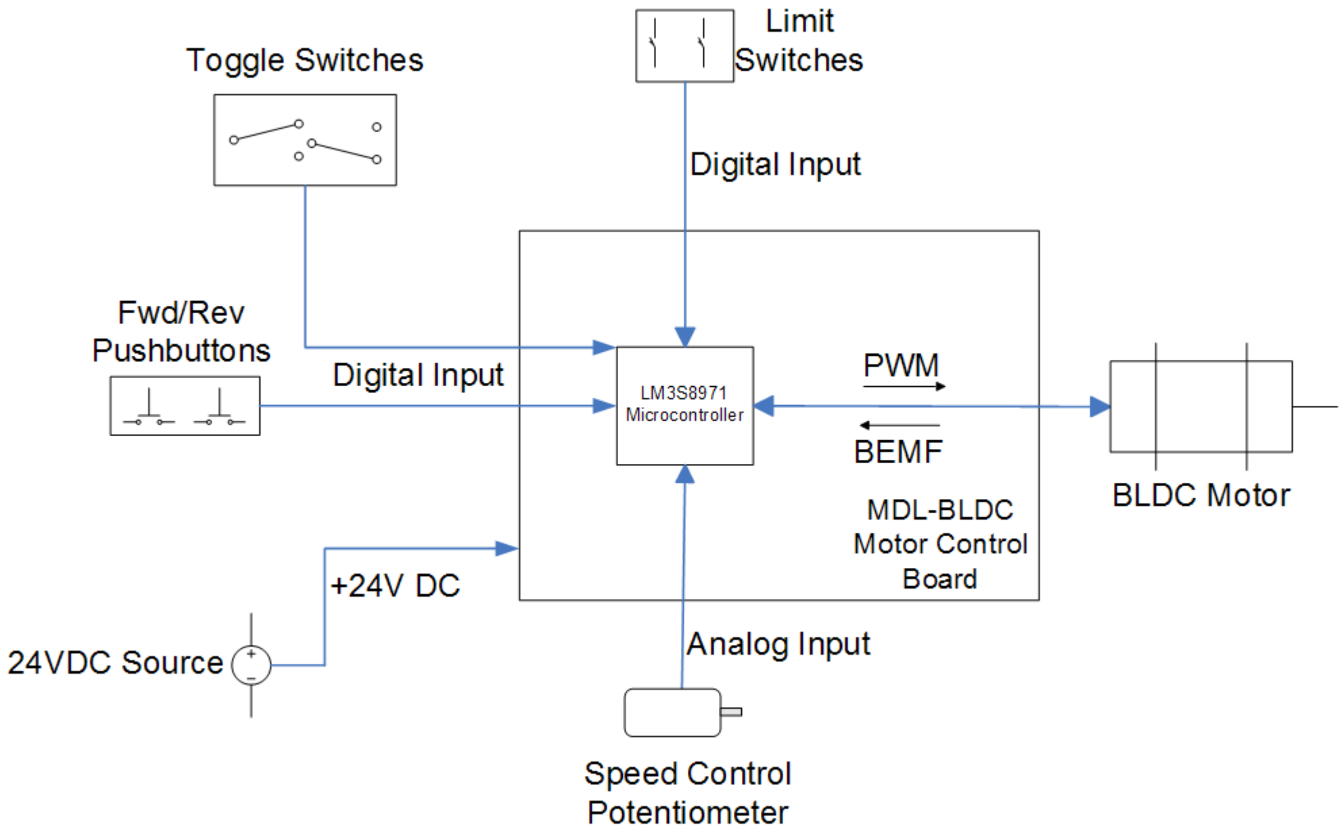

Figure 3: A block diagram of the final implementation of the test fixture. The microcontroller receives input from the user and from the motor's BEMF, and drives the motor using pulse-width modulated (PWM) signals.

Finally, toggle switches were added to allow the user to select between the target positioner and OAPI motor parameters at startup, as they required different voltage ranges (see Fig. 4). Additionally, a "hold" switch was added to allow the motor to be operated for longer time periods without forcing the user to hold down a pushbutton. This switch effectively preserves the state of the forward/reverse buttons while it is on, acting as a sort of "cruise control". Of course, the limit switches can still stop the motor in this state, to maintain safety while adding convenience.

To accomplish the design goal of creating a self-contained, portable device, an appropriate enclosure was purchased to contain the electronics. Holes for the various user interface elements were drilled, as well as those for the electrical connections to external elements. For simplicity and ease of use, two circular plastic connectors were used – one for the power connection, and the other for the motor's phases and the limit switches. Different sizes were chosen to make it impossible to confuse the power and motor/limit switch connectors, which might result in damage to the device.

Figure 4: Photograph of the finalized test fixture. The CPC connectors on the right side provide connections to a power source and the motor, as well as the limit switches.

Conclusions:

The final implementation of the test fixture demonstrates that sensorless commutation is a viable technique for extracting stranded devices such as the target positioner and OAPI. While it is an experimental unit, it has been used successfully in the OMEGA EP laser bay. This project has met all of its original goals and has produced a device useful to LLE in the process.

However, there is still room for improvement. Due to time constraints, several minor issues remain. Because the motor control board was mounted in the center of the enclosure, it is currently difficult to reprogram, as the JTAG cable will not fit. This means the board must be removed before it can be programmed, which is inconvenient when testing. If the mounting holes could be relocated, more space could be allocated to allow for this.

Additionally, the “hold” switch is currently nonfunctional. This is because during development, one of the board's digital inputs (Quadrature Encoder B) was accidentally damaged and is no longer usable. Therefore, although the code for this feature is fully functional, the switch is currently useless. If this switch could be wired to an alternative input somewhere on the board, this problem could be eliminated as well.

Acknowledgements:

I would like to thank Scott Ingraham and David Lonobile for their continual guidance and support during my project. Their mentorship was invaluable to my project and taught me a great deal about the design process.

I would also like thank Dr. R. S. Craxton for accepting me into this incredible program, and the entire Laboratory for Laser Energetics for continuing to provide such an outstanding opportunity to high school students.