ENEG14005 - ENGINEERING PROJECT IMPLEMENTATION
PROJECT TECHNICAL PAPER

High Performance Brushless DC Motor Control

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ABSTRACT

Field Oriented Control (FOC) is an advanced motor control technique currently employed in high end industrial AC machine drives. FOC has been applied to a custom brushless DC motor controller in an effort to prove its inherent superiority over control techniques currently employed in commercially available BLDC motor controllers. Of special concern is the controller's ability to sensorlessly and stably control brushless DC motors at low speeds and the controller's dynamic response. Results show that when applied to a small custom built brushless DC motor controller, *field oriented control* is far superior to commercial control techniques in regards to response times and low speed commutation capability.

1. Introduction

Commercially available brushless DC (BLDC) motor controllers are invariably based on a scalar control technique known as six-step control. While this technique is perfectly capable for most applications, certain high performance applications require control precision that commercially available controllers cannot provide. In addition, low speed sensorless commutation is simply not possible with commercially available (sensorless) six-step controllers. With the rise of high performance autonomous vehicles, namely, 'drones', a need for high performance controllers has been seen.

It is hoped that by applying advanced motor control techniques, currently reserved for high end industrial AC machine drives, to a custom BLDC motor controller, it will be possible to achieve a level of control performance far superior to any commercial options. This increase in performance is hoped to include better dynamic response, far superior low speed commutation capabilities and a moderate increase in efficiency. *Field Oriented Control* (FOC) was chosen to be the '*advanced motor control technique'* by literature review during the planning phase of this research. Finally, the custom controller developed should be comparable in both cost and physical size to current commercial offerings.

1.1 Literature Review

Research into advanced motor control techniques has been almost exclusively focussed on one of two competing methodologies, FOC or *Direct Torque Control* (DTC). Further, research has been largely focussed on large industrial machines with very little research focussed on small (<100A) BLDC motors. Hence, when conducting the literature review for this project, it was necessary to consider literature focussing on large machines and consider its application to small brushless DC machines.

While DTC was thoroughly investigated during the project planning phase, FOC was ultimately chosen. DTC has no bearing on this research and will not be discussed further.

1.2 Field Oriented Control

Field Oriented Control is a form of vector control that is fundamentally different from six-step (used for commercial controllers) control in that all processing is carried out in the direct (d) - quadrature (q) reference frame. This allows for precise motor control across a much wider speed range than any scalar commutation technique can offer because the stator windings are now 'managed' to keep the flux produced by the rotor's permanent magnets orthogonal (90^0) to the stator field. This provides exceptionally precise torque control and is the real advantage of operating in the d-q reference frame (1).

The direct and quadrature components are simply the decomposition of the flux linkage state vector into two discrete components, the flux (d) and torque (q) producing components. This is perhaps best shown graphically as in Figure 1 below. Note the intrinsically orthogonal nature of the direct and quadrature axes (2).

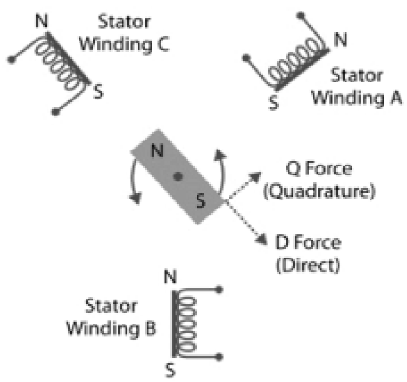

Figure 1. Direct (d)–Quadrature (q) force components (2)

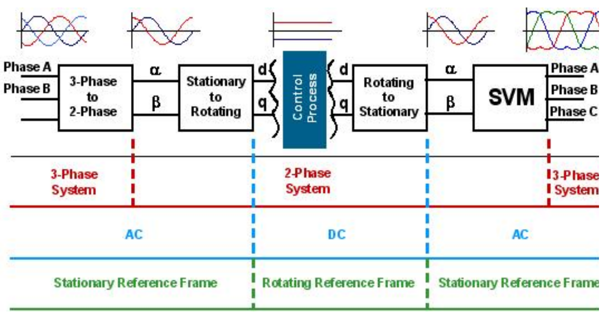

Figure 2. FOC Operation Overview (3)

Figure 2 above shows a general operational overview of FOC. It can be seen that FOC requires the measured phase currents to be transformed from the 3-phase static reference frame of the stator to a static 2-phase reference (α, β) and finally to a rotating two-phase reference system aligned with the rotor flux (d-q). To align the d-q reference frame with the rotor, detailed rotor position information is required. Significant research into rotor position estimation has been carried out over the past 50 years, and recently, particularly in the past decade, research into sensorless rotor position estimation has been undertaken. Rotor position estimation techniques range from the relatively simple, back-EMF zero crossing detection to complex sliding mode observers and extended Kalman filters.

Transformations from the static 3-phase reference frame into the two phase d-q reference frame result in two flux vector 'components', the direct and quadrature components. The direct (d) component offers no useful torque and only serves to increase ware on motor bearings. It follows that it is beneficial to minimise this component. The quadrature component is responsible for 'actual' motor torque and this component is set by the application. The direct and quadrature components are then fed with reference to zero and the application torque setting respectively into two PI (Proportional-Integral) controllers. This results in a vector output that is (optimally) exclusively in the quadrature axis with a resulting torque tracked to the application setting. The output of these PI blocks is two components (d and q) of a voltage vector in the rotating d-q reference frame (4). The output of the two PI controllers are the (new) direct and quadrature voltage components of the required stator voltage space vector. In order to actually drive the motor, these components are back-transformed to the stator reference frame and used for Space Vector Pulse Width Modulation (SVPWM).

1.3 Texas Instruments InstaSPIN FOC

InstaSPIN-FOC is a motor control solution by Texas Instruments which allows for the rapid development of advanced FOC based motor controllers. This solution includes a proprietary unified observer structure, FAST, and all required FOC 'blocks'. These 'blocks' include Clarke and Park transformations as well as the required PI controllers.

InstaSPIN™ FOC also provides torque and speed controllers as well as the ability to identify motors (with a minimal amount of name plate data) allowing the PI loop gains of the torque and (cascaded) speed controllers to be automatically tuned. This provides a quick way getting a motor to spin, but, to reach InstaSPIN's full performance capability, user fine tuning can still be done.

2. METHODOLOGY

Research was conducted, by design, in three distinct phases, initial InstaSPIN FOC evaluation, Custom Motor Controller development and finally Custom Motor Controller Evaluation.

2.1 Initial InstaSPIN FOC Evaluation

InstaSPIN™ FOC was initially evaluated using a DRV8301-69M-KIT development board by Texas Instruments. The development board supports up to 60V/40A motors and is driven by a C2000 TMS320F28069M MCU *controlCARD*.

Figure 3. DRV8301-69M-KIT (5)

A custom test board was developed to allow empirical analysis of the development board's performance. The 'test' board utilised a 48PPR rotary encoder, 40A Bus Current sense, 128*128 SPI OLED screen for real time feedback and an F28027 LaunchPad for control.

Automatic identification of BLDC motors with only minimal information was an integral part of the research as BLDC motors are rarely (if ever) provided with more nameplate information than the number of poles and voltage and current ratings. The ability to identify a motor's stator resistance, inductance and rated flux allows PI loop gains to be automatically tuned which in turns allows for stable speed and torque control. However, when using the development board with BLDC motors, identification would invariably fail to correctly identify any of the tested motors. The identification routine results were always invalid (impossibly small inductance estimate) and not at all consistent or repeatable. This, for obvious reasons, would result in extremely poor motor performance with only a very small stable control window (a few kRPM). In addition, low speed commutation was not possible, with the motors becoming very unstable at speed less than 1000RPM.

After discussion with Texas Instruments engineers, the most likely cause of motor identification failure was determined to be the hardware feedback scaling of the development board and the very low inductance of 'hobby-grade' BLDC motors. The only solution to this problem was to develop custom hardware with more suitable feedback scaling. A suggestion was made to simply guess the motors parameters such that the torque and speed controllers could be better evaluated. With guessed motor parameters, the torque controller's performance was excellent, with (subjectively) less vibration and a generally smoother 'ramp-up' than the commercial controllers tested. In addition, low speed commutation

(~200RPM) was now possible with the controller, although the speed controller was less stable when speeds above 5000RPM were commanded. The torque controller and commercial controllers were able to stably control the motors up to their Kv rating.

2.2 Custom Hardware Development

Several 'Custom FOC Controllers' were designed with two revisions being fabricated, populated and successfully tested. From the initial InstaSPIN FOC evaluation phase, it was known that hardware feedback scaling would be crucial to the success of the controller. It was discovered that hobby BLDC motors are usually driven from less than 21V (5cell LiPo) sources. This meant that ~24V would be ideal for full voltage scaling. A TI BoosterPack (analogous to the popular arduino 'shields') was found with 24V scaling and a continuous current rating of 10A. This hardware is open-source and its use a 'reference-guide' is permitted and even recommended by TI. This allowed the development time of the controller hardware to be substantially reduced and the chances of initial success to be dramatically increased. *Note, the BoosterPack is not a standalone controller and is designed for use with a TI LaunchPad*.

The Custom FOC Controller was designed with bidirectional phase current feedback on all three phases and was scaled for a peak current of 16.5A. Voltage feedback was also implemented and scaled for 26V on all three phases and the DC bus (allows the use of InstaSPIN's voltage compensation functionality). Key components of the Custom FOC Controller include:

- TMS320F28027F Microcontroller;
  - InstaSPIN Enabled C200 MCU.
- DRV8301 3-phase pre-driver;
  - 6V-60V supply range;
  - Three half bridge drivers each capable of driving two N-type MOSFETs.
  - Integrated buck converter to support 1.5A external load.
  - SPI interface.
- CSD18533Q5A 17A MOSFETs;
  - Power Inverter.
- Full 14pin JTAG breakout;
- I2C and (1)GPIO breakout used for communications;

Several PCB revisions were developed in Eagle CAD with substantial time dedicated to ensuring 'good' differential signal (feedback) routing, adequate power trace sizing and optimal component placement to allow board minimisation. The first revisions of the Custom FOC Controller were all fabricated using the CNC mill available at CQU. The first fully populated revision, 2A, may be seen in the figure immediately below.

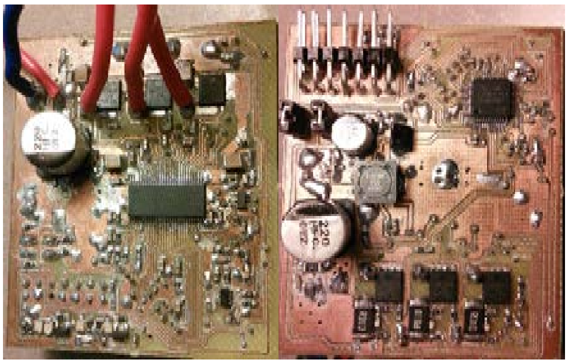

Figure 4. Custom FOC Controller Revision 2A, Top (Left) and Bottom (Right).

Revision 2A (while requiring a significant amount of time to be invested in troubleshooting) was successfully tested, and, using this board, a BLDC motor was, for the first time, successfully identified. This resulted in a dramatic performance increase relative to the TI development board initially tested. The speed controller was stable across the entire speed range (up to the motors Kv rating) and low speed commutation at rotor speeds as low as 100RPM (even with an unloaded motor) were possible. *Note, commercial (sensorless) controllers cannot commutate BLDC motors at speeds much below 1000RPM.*

Revision 2C was sent to a 'board-house' in the USA for fabrication. This allowed via through-plating, silk-screening and a solder mask to be applied to the board. Revision 2C may be seen in the figure below.

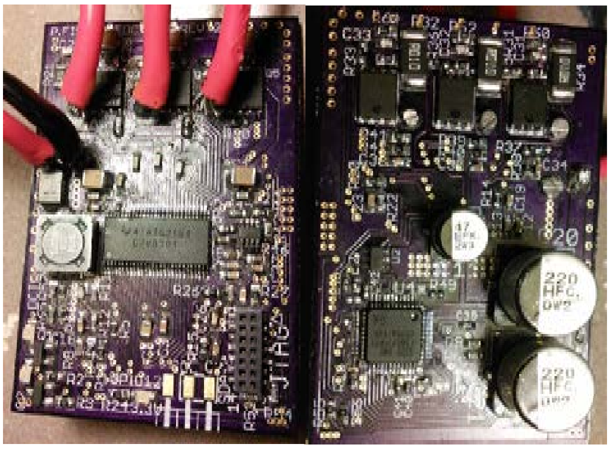

Figure 5. Custom FOC Controller Revision 2C, Top (Left) and Bottom (Right).

The fundamental circuit remained unchanged from revision 2A to 2C. However, the placement of several components was changed, critical signal routing was further optimised and the JTAG header was changed from a standard 2.54mm throughhole header to a 1mm surface mount micro header.

2.3 Custom Motor Controller Evaluation

Revision 2C of the Custom FOC Controller was used for all comparison testing (see Results below). However, the board was first subjected to stress-testing (10A continous-current for 10minutes) and general performance testing. Motor indentification was tested on a wide selection of motors with all motors successfully identified (with consistant, repeatable results), the controller was able to commutate the motors (stably) at speeds around 80RPM loaded and slightly higher when unloaded. Finally, all motors were loaded with a model aeroplane propeller and run up to either their maximum speeds or until the 10A continuous current limit was reached.

3. Results

The developed Custom FOC Controller was tested against several commercial controllers using several typical BLDC motors. The Figures opposite show the motors and controllers tested, with the rotary encoder used also visible mounted on the motors.

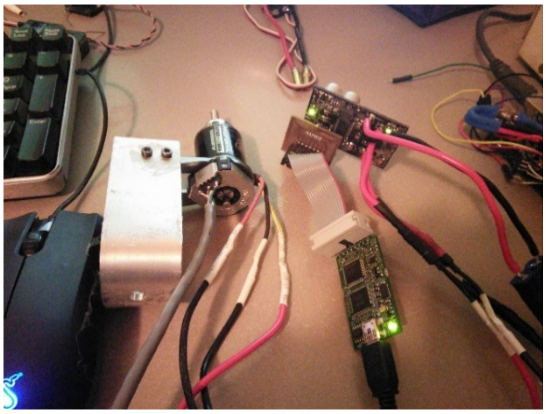

Figure 6. PropDrive 1200Kv motor with Custom FOC Controller.

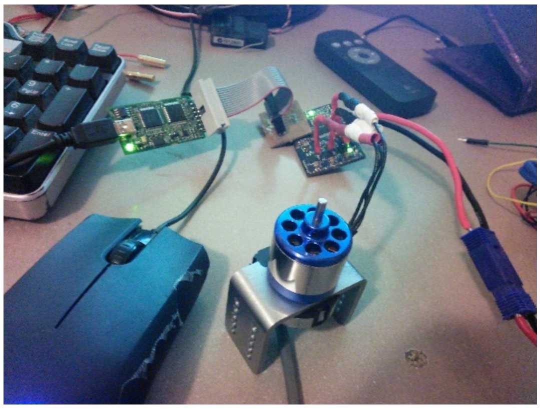

Figure 7. 2278 1000Kv motor with Custom FOC Controller.

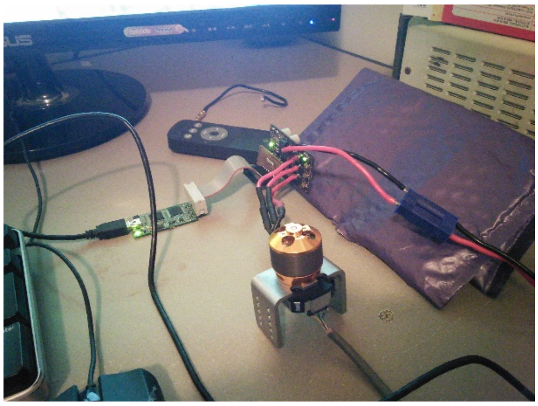

Figure 8. Unknown motor with Custom FOC Controller.

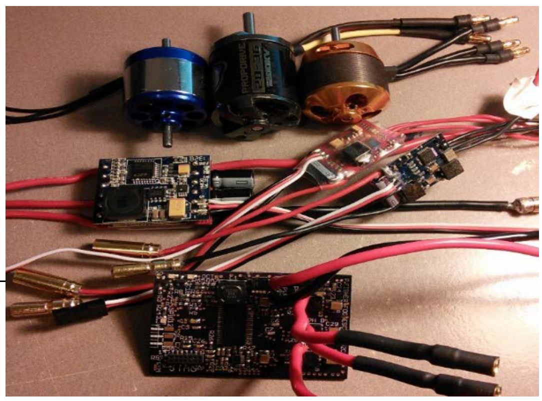

Figure 8. All motors and controllers tested

Tables 1 and 2 below show the results of both unloaded and loaded (with the same model aeroplane propeller) motors as tested with the Custom FOC Controller and three commercially available options. To maintain the validity of the comparisons, all motors were run from the same bench supply, at the same voltage and all test equipment was mounted in an identical manner.

Table 1. Unloaded Motor Results

Controller:	InstaSpin FOC			Plush 40			Plush 10			HobyKing SS		
Motor:	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner
Minimum **Stable** Rotor Speed (RPM)	*150*	*100*	*100*	*3275*	*2750*	*2700*	*2150*	*1650*	*1700*	*1575*	*NA*	*NA*
Maximum **Stable** Rotor Speed (kPRM)	*17.2*	*18.5*	*15.0*	*16.5*	*18.1*	*14.5*	*16.5*	*18.3*	*14.7*	*16.4*	*NA*	*NA*
Transition time zero to full speed (s)	*0.49*	*0.51*	*0.39*	*0.76*	*0.61*	*0.54*	*0.69*	*0.68*	*0.54*	*0.61*	*NA*	*NA*
Maximum Bus Current (A)	*1.14*	*1.7*	*1.14*	*2.15*	*2.62*	*1.21*	*4.4*	*3.3*	*1.34*	*2.42*	*NA*	*NA*

Table 2. Loaded Motor Results

Controller:	InstaSpin FOC			Plush 40			Plush 10		
Motor:	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown	2728 Brushless Outrunner
Minimum **Stable** Rotor Speed (RPM)	*80*	*70*	*75*	*1150*	*850*	*820*	*1050*	*750*	*920*
Maximum **Stable** Rotor Speed (kPRM)	*5.95*	*4.65*	*4.8*	*5.90*	*4.60*	*4.57*	*5.4*	*4.3*	*4.6*

Transition time zero to full speed (s)	*0.51*	*1.12*	*1.12*	*1.12*	*1.27*	*1.23*	*1.1*	*1.53*	*1.12*
Maximum Bus Current (A)	*10.87*	*9.93*	*10.07*	*13.56*	*18.46*	*12.21*	*10.87*	*12.62*	*13.56*

The tables above show the Custom FOC Controller as the superior controller in every metric tested. The stated goal of superior low speed commutation ability has clearly been met, with the FOC Controller able to control the motors at several hundred RPM slower than the commercial controllers trailed. Further, the 'ramp-up' time from zero to full speed was smallest for the Custom FOC Controller (except in one case where it was the same), and, the ramp-up curve (not shown here) was considerably smoother for the FOC Controller.

A relative-efficiency test was also conducted by changing the torque set point until a pre-determined rotor speed was reached, at which point, a bus current reading was taken with the motor steady-state. This test was conducted using loaded motors and is an effective way of proving the superior efficiency of the FOC Controller. The results of this test may be seen in Figure 9 below.

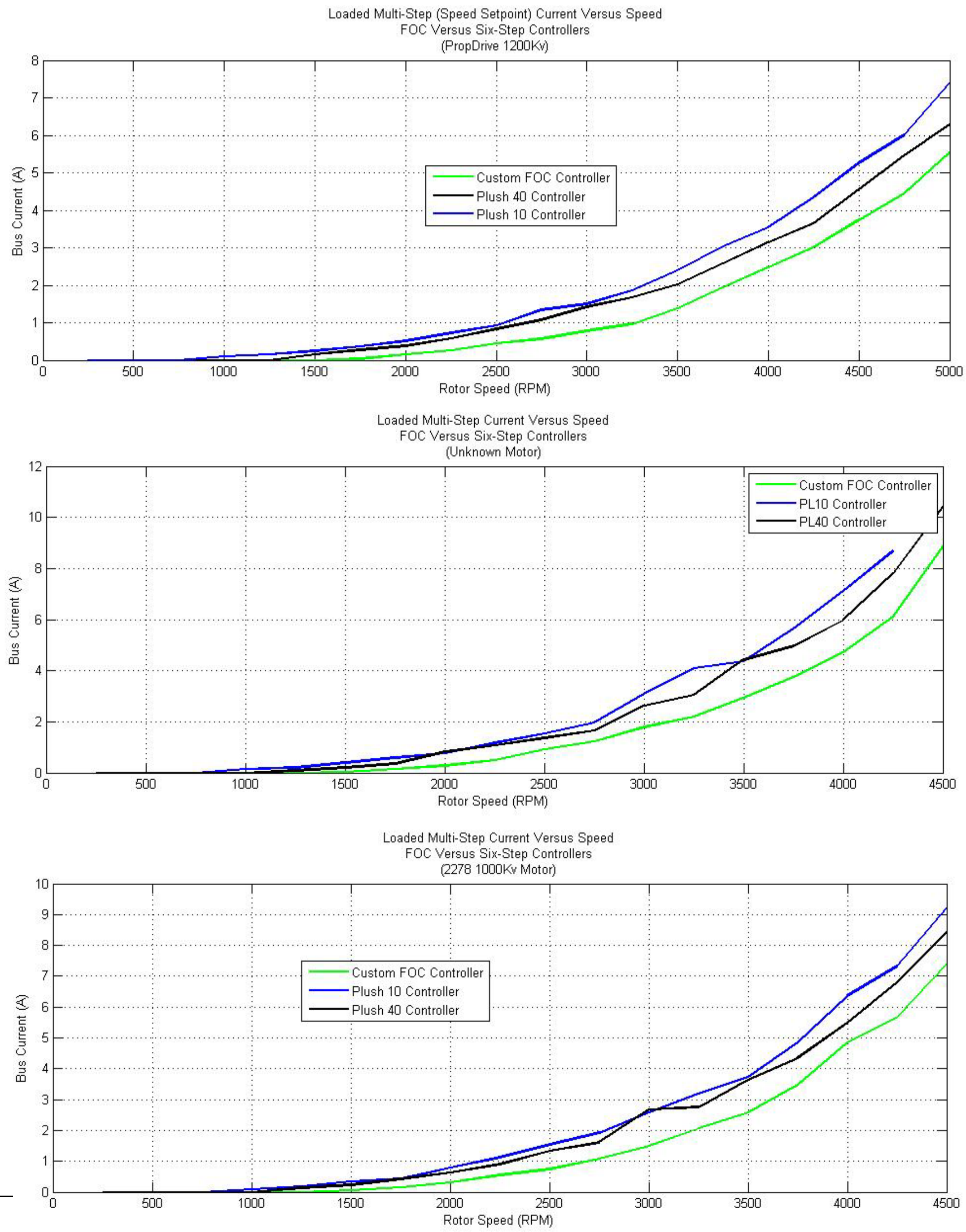

Figure 9. Multi-Step Response of controller/motor combinations

Figure 9 above shows the clearly efficiency superiority of the Custom FOC Controller under steady-state conditions. A noticeable decrease in vibration was also observer (under steady-state conditions) when using the custom FOC Controller. This was never investigated empirically due to a lack of test equipment.

4. Conclusion

The stated goals for this research have all been met. Field Oriented Control has been shown to be a superior control methodology to six-step control. This has been proven by designing a custom FOC based controller and comparing it with several commercially available six-step controllers. The tests showed the custom FOC controller consistently outperforming the selected six-step controllers in all areas tested. The most dramatic advantage of the FOC Controller is its ability for low speed commutation and closed loop speed control.

Further, the Custom FOC Controller is comparable in size to commercial options (though slightly larger), and, while the FOC controller would be more expensive if commercially produced, it is still cheap in comparison to sensored controllers, which are currently the only commercial (very rare) options which could match its performance.

4.1 Recommendation for Future Studies

Arguably the biggest shortcoming of this research is the lack of direct controller efficiency testing. This was not done as no suitable dynamometers could be found to accurately measure the motor output torque. This also meant the low speed torque production of a motor when coupled with the Custom FOC Controller could not be empirically tested. It is recommended that if a suitable dynamometer cannot be found, a programmable load be placed on a BLDC motor and that motor be directly coupled with the test motor.

Several improvements could also be made to the custom hardware developed. These improvements include, moving to a four layer PCB to allow for a much smaller board, larger MOSFETs could be used to allow a high continuous current rating, though, this would require phase current feedback scaling to be changed accordingly.

Finally, I2C abstractions should be completed (they have been started) to allow the controller to unitised this communication topology instead of the 50Hz RC PWM currently used. This would allow the controller to provide motor feedback to a master controller, including, output torque, rotor speed and even motor temperature (functionality already included with InstaSPIN™-FOC).

5. References

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