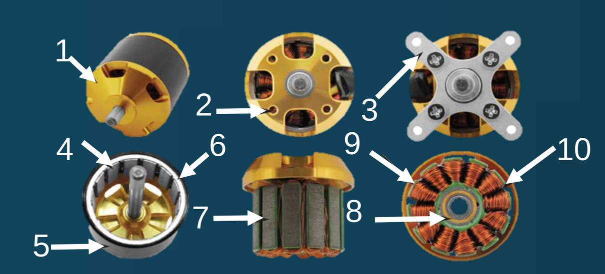
High Performance Brushless DC Motor Control

Patrick Fisher

Project Supervisor: Dr D.M.G. Preethichandra



1. Machined Aluminium Front Housing with Cooling Holes
2. Threaded Mounting Holes
3. Machined Aluminium Mounting Brace
4. NdFeB Permanent Magnets or 'Poles'
5. Flux Ring
6. Rotor Can
7. Stator Plates
8. Stator Windings
9. Bearings
10. High temperature adhesives used to secure stator windings

Figure 1. The BLDC Motor [2]

INTRODUCTION

Since their introduction in 1962 by T.G. Wilson and P.H. Trickey [1],Brushless DC (BLDC) motors have replaced their brushed counterparts in almost every application. BLDC motors are synchronous, electrically commutated motors which offer significant increases in efficiency, controllability and longevity compared to brushed DC motors. However, BLDC motors do have one drawback. They require complex and expensive control electronics in order to drive the motor. The current generation of commercial controllers for small (<300A) motors invariably utilise a scalar control technique known as six-step commutation. This technique is suitable for steady state, low performance applications such as RC planes and helicopters but is not adequate for high dynamic or generally higher performance applications. With the rise of high performance machines such as autonomous 'drones', which currently utilise commercial six-step BLDC controllers, a need for high performance BLDC motor controllers has been seen but as of yet, remains unmet by manufacturers.

This research investigated the possibility of applying an advanced vector control technique (currently employed in industrial AC machine drives) to small BLDC machine controllers. Specifically, the objective of this research was to develop a high performance BLDC motor controller by utilising *Field Oriented Control* techniques. The goals were for the controller to be capable of closed-loop precision control; 'sensorless' ('self-sensored'); and capable of low speed commutation (<100RPM).

Figure 2. DRV8301-69M-KIT [6]

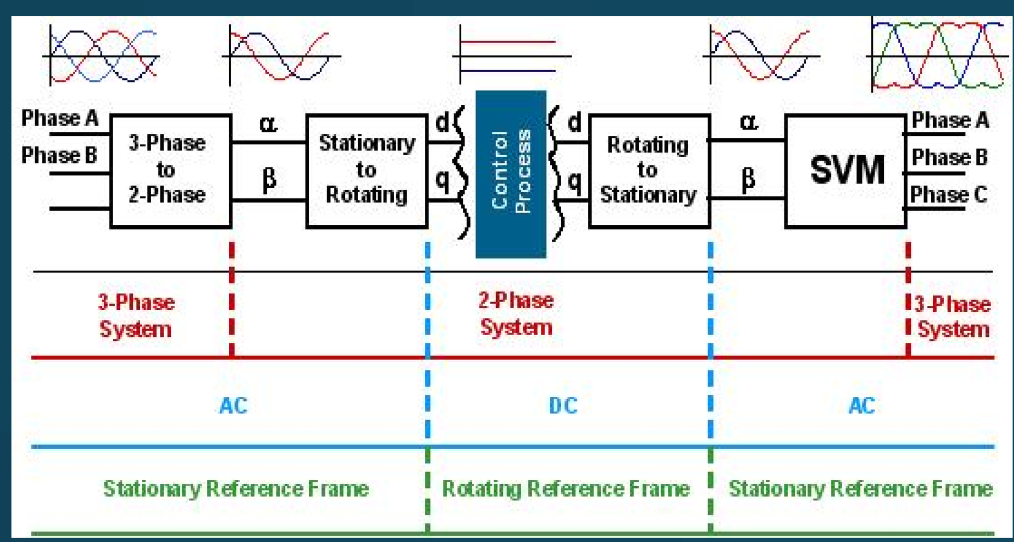


Figure 4. Functional block diagram of a generic FOC drive [4]

Methodology

Research was, by design, conducted in three distinct phases:

- InstaSPIN-FOC was evaluated using hobby BLDC motors and a development board (*Figure 2 above)* from Texas Instruments;
  - A test board was developed with Bus Current Sense and a Rotary Encoder to test InstaSPIN empirically;
  - Motor Identification Routines Failed despite numerous attempts;
    - After Discussion with Texas Instruments Engineers, the reason for this was found to be poorly suited (oversized) hardware, particularly feedback scaling, and the very low inductance of hobby motors. The only solution to this was to design custom hardware with more suitable feedback scaling.
  - InstaSPIN's Torque and Speed Controllers were evaluated with guessed motor parameters.
    - Excellent results were found with the Torque Controller;
    - The speed controller was plagued by instability when speeds were commanded outside of a very narrow range – **1500RPM to 8000RPM.**
      - This was a result of the guessed motor parameters as they directly effect the PI loop gains, K_i and K_p. It was hoped that more suitable hardware scaling would allow the controller to commutate the motor over a much wider speed range.
- Custom Hardware Development
  - A custom FOC controller based on a Texas Instruments BoosterPack was designed.
    - Texas Instruments establishes several hardware prerequisites for InstaSPIN hardware, including phase current and voltage feedback requirements.
    - Two versions were fabricated, populated and successfully tested.
- Custom FOC Controller Evaluation
  - The Custom FOC Controller developed was evaluated against commercial options.
  - Relative efficiency, minimum and maximum commutation speeds as well as motor response times were tested.
  - General Observations were made of the operation of the motors as driven by different controllers.

Custom Controller Development

Several versions of Custom FOC Controller were developed with two revisions (2A and 2C) being fully populated and successfully tested. Power and feedback stages of the controller used TI's BOOSTXL-DRV8301 'BoosterPack' (analogous to Arduino 'shields' – not a standalone controller) documentation as a reference design. *Note, Texas Instruments releases all design documentation for the BOOSTXL-DRV8301 for public use and encourages the use of their designs as references for custom designs.*

Revision 2A of the Custom FOC Controller was fabricated using the CNC mill at CQU. This version was successfully tested and showed considerable improvements on the TI development board initially tested. The controller was capable of commutating a BLDC motor at speeds as low as **100RPM**. In addition, InstaSPIN identification routines were successful on all motors tried.

Revision 2C of the Custom FOC Controller was professionally fabricated, although, still manually populated. Performance was increased still further and commutation speeds as low as **65RPM** were possible with a completely 'sensorless' controller.

Key components of the Custom FOC Controller (Revision 2C) include:

- TMS320F28027F Microcontroller;
- DRV8301 3-phase pre-driver;
- CSD18533Q5A 17A MOSFETs;
- Bidirectional current sense – scaled for 10A continuous current;
- 3-phase and bus voltage sense- scaled for 24V;
- Full 14pin JTAG breakout;
- I2C and GPIO breakout;
- 10A RMS Current Rating;
- Up to 24V Bus Voltage;

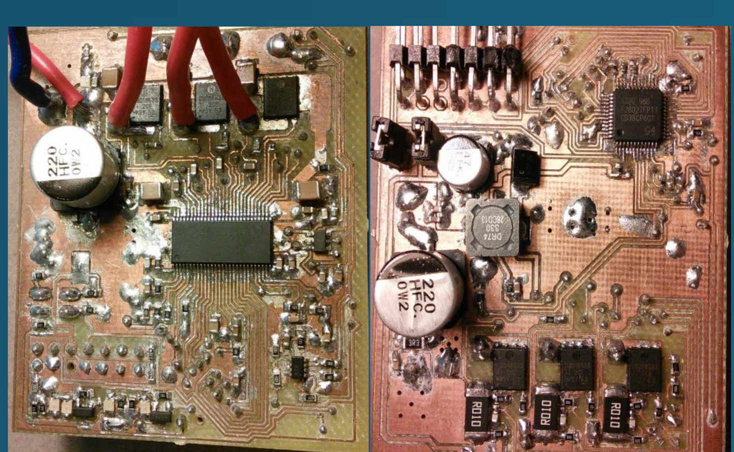


Figure 7. Custom FOC Controller (Revision 2A)

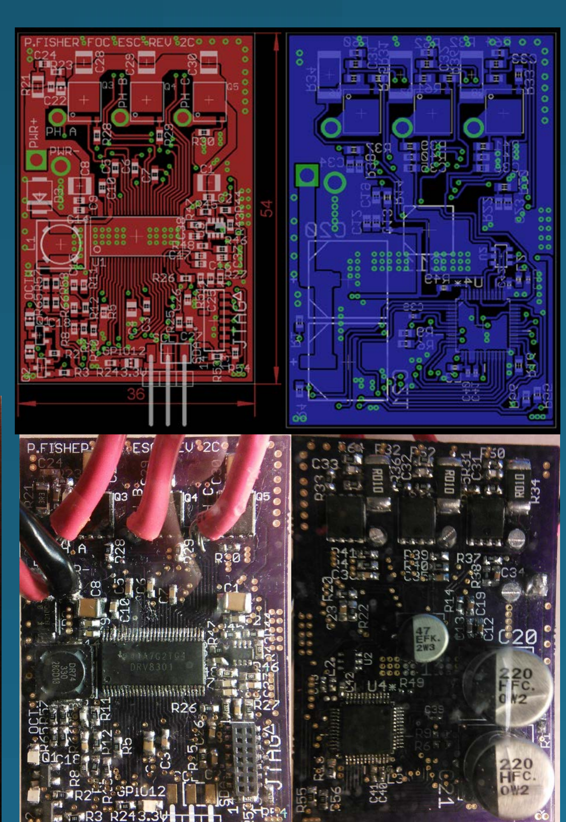


Figure 6. Custom FOC Controller (Revision 2C)

Field Oriented Control

Field Oriented Control (FOC) is a vector control scheme currently employed in some high end industrial machine drives. *At the time of writing, no commercially available motor controller designed for small BLDC motor control could be found that utilised field oriented control.* Field Oriented Control or Vector Control manipulates space vectors in the direct (d) and quadrature (q) axes in order to accomplish very precise and efficient motor control. The operating principle of FOC is to 'manage' the stator windings to keep the flux produced by the rotor's permanent magnets orthogonal (90^0) to the stator field. This provides exceptionally precise torque control [3].

FOC processing is carried out entirely in the direct-quadrature (d-q) reference frame. 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 best shown graphically as in *figure 3* to the right. It is clear that the direct component offers no useful torque and only serves to increase ware on the motor bearings. It follows that it is beneficial to minimise this component while maximising the quadrature component to the application set point.

Proportional-integral (PI) controllers are used to control the direct current component to zero and the quadrature component to the application set-point. At this point, the controller requested direct and quadrature components are back transformed to a static three-phase reference frame and used to generate Pulse Width Modulation signals to drive a three-phase inverter. The FOC process is best summed up as in *figure 4* to the left.

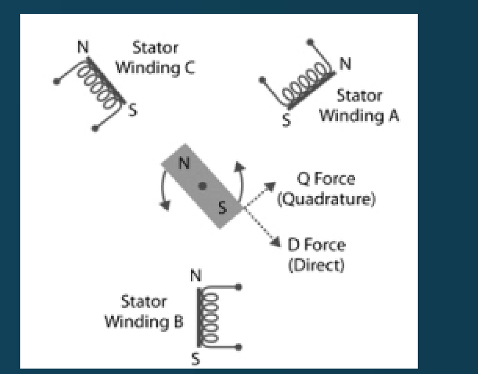


Figure 3. Direct (d) and orthogonal (q) force components [5]

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 is best summarised by Figure 5 to the right.

An InstaSPIN-FOC feature critical to the success of this project is automatic motor identification. This is critical because small BLDC motors are rarely (if ever) provided with information required for the tuning of the PI controllers. This information includes the stator resistance, inductance and total flux linkage. Using InstaSPIN, these parameters can be found by running a one-time identification routine.

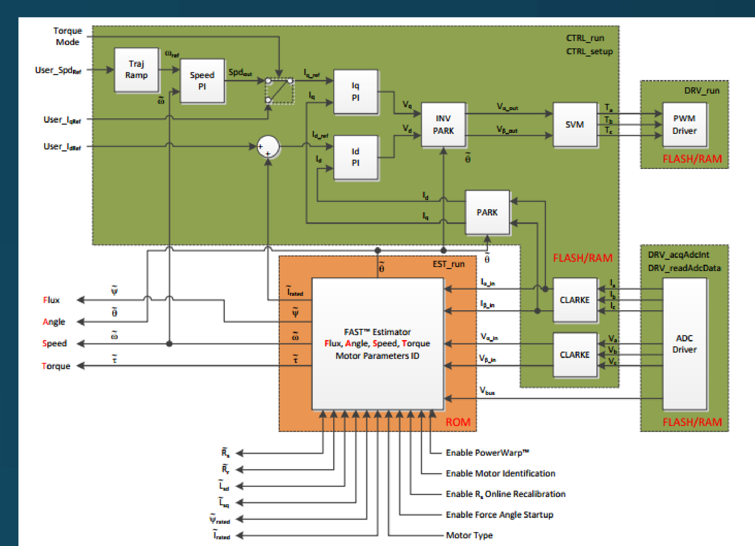


Figure 5. InstaSPIN™-FOC Block Diagram [6]

Results

All testing was conducted using revision 2C of the Custom FOC Controller and the same power supply and load was used for all motors and controllers tested. The six-step controllers chosen reflected mid-high range (Plush 40) to low range (Hobyking SS) commercially available controllers.

The Custom FOC Controller was able to reliably identify all tested BLDC motors (including several that are not included in the tables below). Importantly, identification was run several times on each motor without issue and results were very consistent. A completely unknown motor was also identified to prove the robustness of the identification routine.

Tables 1 and 2 below show that the custom FOC controller's response time and capability for low speed commutation was considerably superior to any of the tried commercial controllers.

The Custom FOC Controllers relative efficiency was also tested against the selected commercial controllers. This test showed the FOC Controller, on average, using **35%** less power than the commercial controllers for any given commutation speed. It is doubtful that a comprehensive test suite would show such a profound efficiency improvement. However, the results were repeatable and no serious flaw in test methodology is known.

Table 1. Loaded Motor Results.

Controller:	InstaSPIN FOC			Plush 40			Plush 10		
Motor:	NTM PropDrive 28-36	Unknown Motor	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown Motor	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown Motor	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

Table 2. Unloaded Motor Results.

Controller:	InstaSPIN FOC			Plush 40			Plush 10			HobyKing SS		
Motor:	NTM PropDrive 28-36	Unknown Motor	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown Motor	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown Motor	2728 Brushless Outrunner	NTM PropDrive 28-36	Unknown Motor	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

Conclusion

All of the stated objectives of this research were met. The viability of Field Oriented Control for use on small hobby BLDC motors has been proven with results showing considerable improvements against the six-step controllers tried. The developed controller was able to identify a wide range of hobby BLDC motors and control them over their entire speed range. The low speed commutation capability of the custom FOC controller is a distinct improvement over commercially available controllers. The minimum commutation speeds were substantially lower for the Custom FOC Controller than for any of the commercial options tested. It is important to note that at low speeds, the motors were capable of generating a substantial amount of torque when driven by the Custom FOC Controller. This is in contrast with the commercial controllers tested which would stall at a few thousand RPM when the rotor was touched.

The primary shortcoming in this research is the lack of controller testing. All efficiency testing was conducted relative to commercially available controllers and the developed controller's 'actual' efficiency remains unknown. In addition, many planned tests were omitted from the research due to a lack of lab equipment. These tests include torque output, vibration testing and thermal response. It is recommended that a more complete test suite be developed to further test the controller developed. This would include efficiency, vibration and torque output tests.

It is also recommended that the I2C abstractions, already started, be completed. This would allow the Custom FOC Controller to send motor data, including rotor speed, bus voltage and even motor temperature, to a 'master' controller. In addition, I2C can also be used to send commands to the controller to re-identify motors, change between torque and speed controller modes and send more accurate set-points.

SPRT702

References

[1] NMB Technologies, 2010. Brushless DC Motors. [Online] Available at: http://www.nmbtc.com/brushless-dc-motors/brushless-dc-motors.html [Accessed 12 August 2013].
[2] Scorpion Power System, 2007. Brushless Outrunner Motors. [Online] Available at: http://www.scorpionsystem.com/info/brushless_outrunner_motors/ [Accessed 15 May 2014]
[3] Copley Controls Corp, n.d. What is 'Field Orientated Control' and what good is it?, s.l.: Copley Controls Corp.
[4] Lepka, J., 2009. Sensorless PMSM Drive for Dishwasher Pump Using Freescale MC56F8006 Device. [Online] Available at: http://dev.emcelettronica.com/sensorless-pmsm-drive-dishwasher-pump-using-freescale-mc56f8006-device-12 [Accessed 11 September 2013].
[5] John, J. P., Kumar, S. S. & Jaya, B., 2011. Space Vector Modulation based Field Orientated Control Scheme for Brushless DC Motors. IEEE, pp. 346-351.
[6] Texas Instruments, 2013. Breakthrough InstaSPIN™-FOC motor control technology is here!, Dallas: Texas Instruments

Acknowledgements

The author wished to acknowledge the continuous help and support of Dr. Preethi Preethichandra (CQU), Mr Chris Clearman (Texas Instruments) and Mr Nicholas Oborny (Texas Instruments) without whom this work would not have been possible.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265