Advancing Novel Electronic Control Methods for Hydrofoil Propulsion

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Hydrofoil Surfing

A relatively new water-sport where participants fit a hydrofoil system (like aerofoils on airplanes) to a type of surfboard:

Forward momentum pushes water around the wings, which the wings use to **generate lift** and push the surfboard above the water. An *eFoil* surfboard uses an **electric motor** to provide constant forward thrust, allowing the user to glide above the water. Flite is building an in-house **Electronic Speed Controller** (ESC) to drive Brushless DC (BLDC) and Permanent Magnet Synchronous Motor (PMSM) motors.

Electronic Speed Control

Typically with a 3-phase inverter, ESCs **energise coils (phases)** with current designed to create a magnetic field that is misaligned with the current rotor position[1]. Naturally, they **need to know where the rotor is** - this is a big challenge for ESCs.

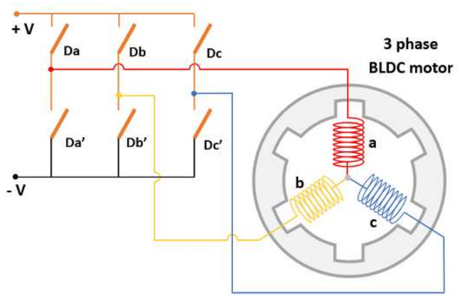

Figure 1. Inverter MOSFETs are driven with PWM from the MCU[1]

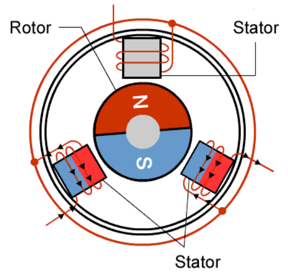

Figure 2. Rotor Spinning in a Brushless Motor[4]

Above a rotor can be seen **yanked** by two phases. This **opposites attract** phenomenon drives motion.

Data-Logging Platform

The **backbone** of any research & development platform is a **solid logging system**. It allows developers to 'see' what the firmware sees, run simulations and apply filters after test runs.

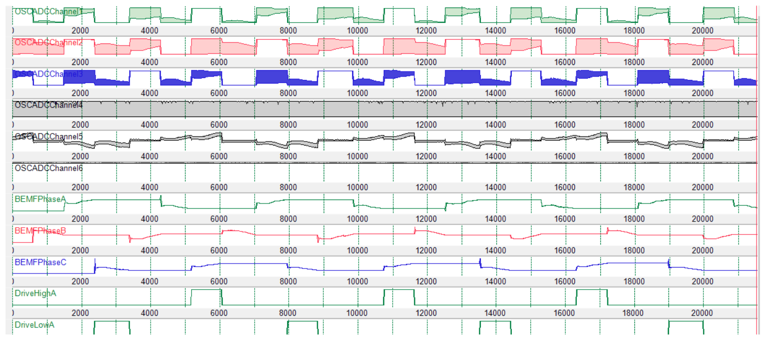

Figure 3. Logs produced by the ESC

Logs are captured at a rate of 111kHz and stored in RAM, until RAM is filled, when they are dumped to the PC. This provides high resolution windows for analysis.

Preliminary Back-EMF Readings

Back-EMF is used to determine the rotor position. As the rotor moves, it induces a voltage on the inactive phase according to Faraday's Law of Induction[2]:

$$\epsilon = -N\frac{\Delta\phi}{\Delta t}$$

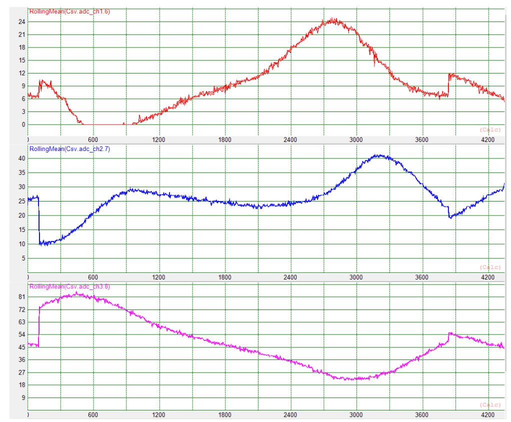

Figure 4. Free-Spin Back-EMF from the motor

The motor was spun with a drill to observe back-EMF readings when the **phases are inactive**. When someone is riding a wave on an eFoil, force from the water can cause the rotor to move. These results show it may be possible to **track the on-wave movement to provide smoother takeoff.**

References

[1] BLDC Average-Value Inverter. https://www.mathworks.com/help/mcb/ref/bldcaveragevalueinverter.html.

[2] Faraday's Law of Electromagnetic Induction. https://byjus.com/physics/faradays-law/.

[3] Fliteboard ULTRA L. https://au.fliteboard.com/pages/ultra-l.

[4] What are Brushless DC Motors.

Open-Loop Waveforms

Open-loop trapezoidal control is done by stepping through a predetermined wave table at a set rate. Paired with the right duty cycle, this can force the **rotor into alignment and begin commutation.**

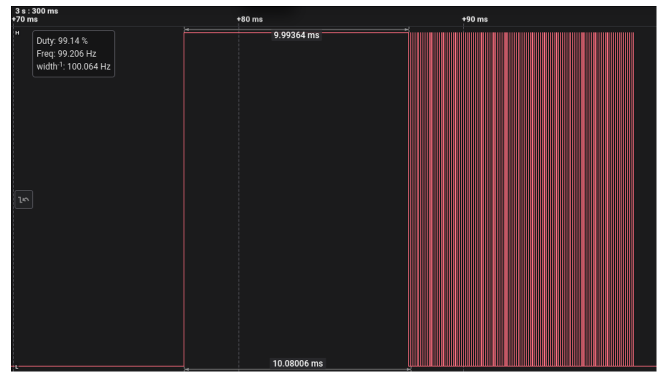

Figure 5. A PWM sector generated by the ESC

Feedback Control

Superior motor control relies on the ESC **making decisions** based on back-EMF readings as the rotor spins. It uses zero-crossings to pick **commutation points** where it changes the waveform applied to the phases.

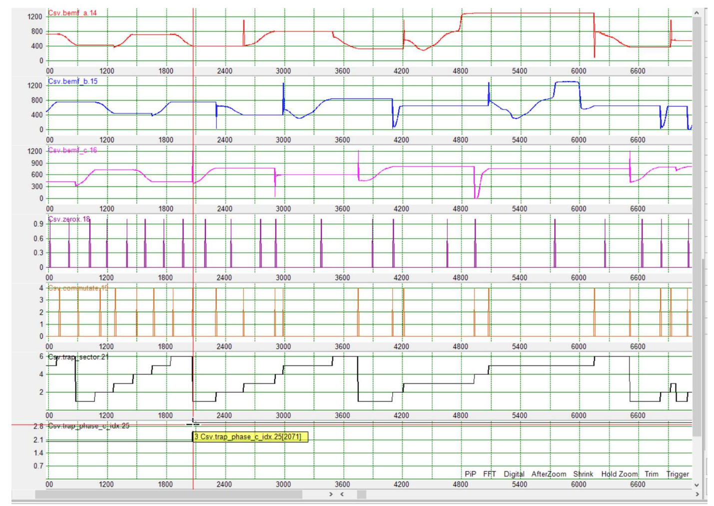

Figure 6. The ESC Running Feedback Trapezoidal Control

Visualising these decisions in the PC software is essential for **tuning the control parameters** and **perfecting the algorithm**. Above is an example of algorithm behaviour on both perfect and imperfect input waveforms - it is useful to test this and observe behaviour in error states.

Electrical Efficiencies Gained and Noise/Vibration/Harshness (NVH) reduction using novel control methods in Electric Motor Applications.

Sebastian Bilios supervised by Rahul Sharma in partnership with Fliteboard.

Introduction: Motor control in Electric Hydrofoils

Electric hydrofoils utilise a brushless dc motor to create thrust and propel the system through the water. Maximising thrust output and conserving energy maximises the opportunity for anyone to enjoy hydro foiling for hours.

A large impact to the experience comes from the inefficient commutation of the motor.

Nonideal performance of the motor controller creates sources of:

- **Torque ripple**
- **Audible motor whine**
- **Excess current draw**

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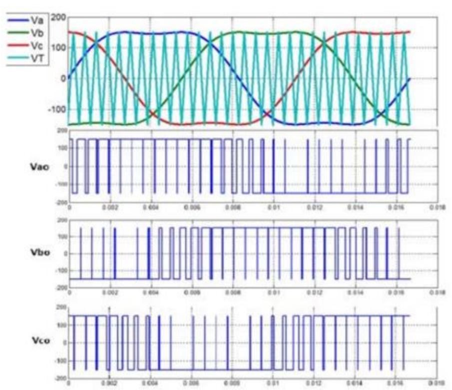
- Power loss
- Increased mechanical wear.
- Reduced torque output

Solution: Maximise efficiency by combining the strengths of multiple control methods.

Motor control methods:



Field oriented control:

Transform **phase current** into **rotor field position** using Clarke and Park transforms. Control torque level directly.

Requirements:
Precise and high frequency current measurement.

Sinusoidal control:

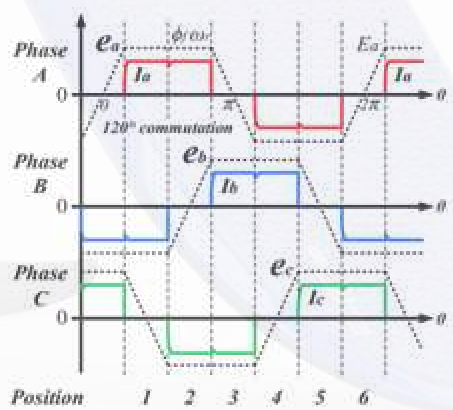
Modulate gate drive **duty cycle** to drive a **high-resolution sine wave** on the motor phases. Maintain optimal torque level.

Advantage at lower RPM for maximum torque with high efficiency and lower NVH (Noise Vibration and Harshness).

Back-emf control:

Rotate the stator magnetic field in **discrete steps**, only driving 2 phases at a time. **Sample back emf** on the inactive phase to determine the **position** of the rotor **based on the zero crossing** or polarity change in measured back-emf.

Requirements:
Voltage measurement on all three phases. Compare with floating neutral point calculated with the average of the measured phase voltages.



Trapezoidal control:

Modulate gate drive duty cycle in discrete steps to drive a trapezoidal voltage wave on the motor phases.

Advantage at higher RPM and High loads due to lower switching losses and fast response to load demands.

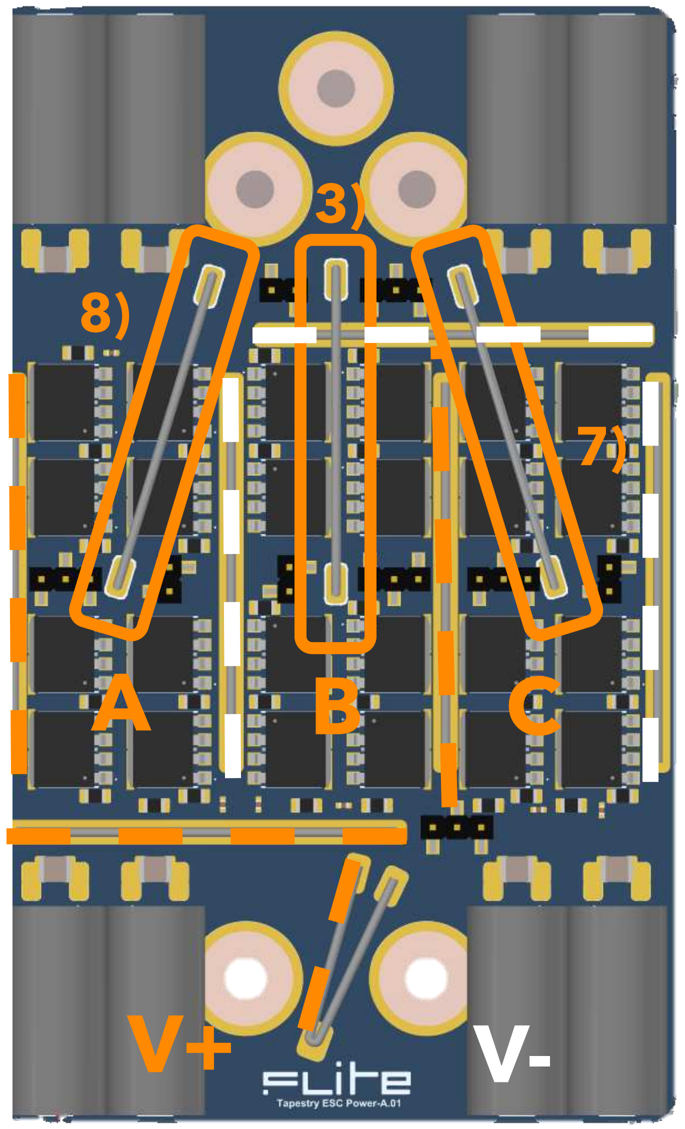


Figure 3. High voltage Inverter PCBA.

Half bridge Inverter:

6) Integrated half bridge gate drivers:
- 15V supply with internal bootstrap for high-side gate control.
- 100ns hardware deadtime to prevent shorting phase to ground via high and low side conduction.
- High voltage isolation from logic level components.

7) 2 stage half bridge.
- Two half bridges per phase increase the current capacity by spreading conduction over more MOSFETS at higher loads.

8) Zobel network:
- Reduces high frequency switching noise by diverting transient/ high frequency spikes.

Phase current feedback:

1) Current measurement: ADC
- 1Mhz sample rate.
- 12bit resolution 2.5V reference.
- 20Mhz SPI interface.

2) Bidirectional current amplifier:
- 20x gain.
- Inline phase current amplification for high and low side sampling.
- Bidirectional measurement

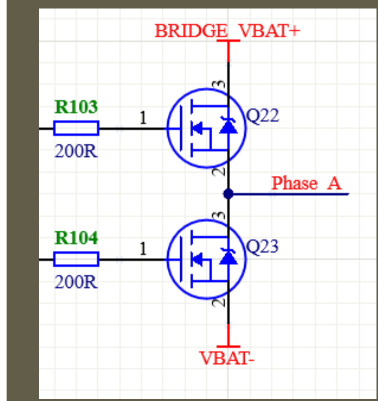
3) Current shunt:
- Length tuned formed copper wire.
- Low temperature coefficient of resistance.
- Low BOM cost.

Low noise power supply:

4) 3v3 Switching buck regulator:
- Stable 3.3V supply for noise sensitive measurement ADC and current amplifiers..

5)15V switching buck regulator:
- Steps down 60V battery supply voltage to supply gate drives and provide stable input for lower voltage regulator.
- Type 3 compensator for load and line regulation to support high frequency gate drive switching current demands.

Dual NPN Half-bridge Inverter



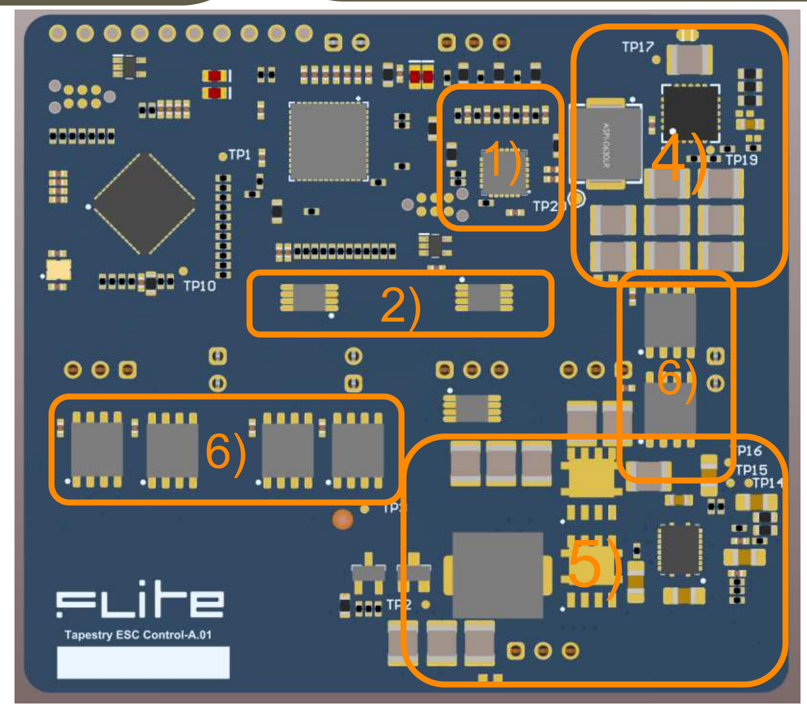


Figure 4.Control PCBA containing MC, external ADC, switching power supplies and Gate drives.

Future Steps and improvements:

Current measurement: ADC
- Suppress noise by separating gate driver phase connection from the high current path.
- Improve source impedance matching to increase settling bit resolution.

Utilise FPGA:
- Continue motor control development using FPGA for greater flexibility with gate drive signal frequency and resolution.

Switch Faster and more efficiently: GANfets
- Leveraging the lower input and output capacitance, GANfets allow faster switching and higher efficiencies leading to reduced losses due to heat and higher resolution switching for more accurate FOC at higher RPM.

Acknowledgements
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