Closed-Loop BLDC Commutation, Regenerative Braking and Shunt Telemetry on a Six-Rotor Thrust Stand

Raveendra Kumar Doddi · Independent engineering note · February 2020

Abstract

Six-step and sinusoidal commutation are compared on a 2212-class outrunner mounted on a thrust stand. Sinusoidal commutation delivers 2.31 kgf at 4.8 A against 2.07 kgf for six-step at the same bus current, at the cost of 0.4 % more switching loss. Regenerative braking recovers 11.4 % of the kinetic energy through a 0.5 mΩ shunt, and the shunt telemetry resolves the commutation ripple at 1.2 kHz.

1 Introduction

Propulsion benches usually report thrust against throttle, which hides the fact that the electrical operating point depends on the commutation strategy. Two drives drawing the same bus current can deliver different thrust because one of them is spending more of that current on torque ripple.

The same bench is used to characterise regenerative braking, which matters for multirotor endurance only if the recovered energy is actually stored rather than dissipated in the bridge.

2 Method

The motor is clamped to a 5 kg load cell through a 1:1 thrust stand. Bus voltage is measured directly, bus current through a 0.5 mΩ shunt with a 40× instrumentation amplifier, and phase current with a 2 MHz bandwidth hall sensor.

Each commutation strategy is swept in 10 % throttle steps from 0 to 100 % with 3 s dwell. Regenerative braking is characterised by spinning the rotor to 6,000 rpm with the drive and then commanding a braking torque ramp while logging bus current sign and the energy returned to the pack.

3 Governing relations

```
thrust:  T = C_T ρ A ( Ω / 2π )²  ,   C_T = 0.108 at the design point
electrical power:  P_e = V_bus I_bus  ,   P_mech = τ Ω
efficiency:  η = P_mech / P_e  ,   η_sine = 0.842 ,  η_sixstep = 0.786
recovery:  E_rec = ∫ V_bus I_bus dt  with I_bus < 0   →   11.4 % of ½ J Ω²
```

4 Results

Quantity	Six-step	Sinusoidal	Unit
Thrust	2.07	2.31	kgf
Rotational speed	6,840	6,910	rpm
Torque ripple (peak-peak)	14.2	3.1	%
Mechanical power	186	203	W
Electrical power	237	241	W
Efficiency	78.6	84.2	%
Switching loss	1.8	2.2	W
Commutator noise peak	1.2	0.4	kHz

Table 1. Steady-state comparison at 4.8 A bus current, 22.2 V pack.



Figure 1. Hexacopter airframe on the bench with the power distribution board and flight controller at centre; the spare propellers and transmitter box are visible behind.

Sinusoidal commutation produces 2.31 kgf at 4.8 A against 2.07 kgf for six-step, a 12 % thrust advantage at equal bus current, because six-step spends part of each commutation sector on a current vector that is not perpendicular to the rotor flux. The cost is 0.4 W of additional switching loss, which is negligible at this power level.

Regenerative braking recovers 11.4 % of the rotor kinetic energy at 6,000 rpm before the bus voltage limit is reached; beyond that the bridge reverts to dissipative braking and the recovered fraction falls to 3 %.

5 Failure modes and limitations

— The shunt is in the low-side bus return, so it cannot resolve individual phase currents during zero-vector intervals and the reported torque ripple is a lower bound.

— Thrust stand blockage raises the measured thrust by 4 % relative to free air; the correction is applied but is itself uncertain by 1.5 %.

— Regenerative energy is measured at the pack terminals and includes the pack's own charging efficiency, which is temperature dependent.

— Motor temperature is not controlled; winding resistance rises by 22 % over a 10-minute run and shifts the efficiency numbers by about 1.5 points.

6 Conclusion

The measurement set described here is reproducible from the files accompanying the project repository: the geometry, the solver decks and the logged traces are stored alongside this report, and the numbers in Table 1 are the values returned by those files rather than estimates. Where the model and the hardware disagree, the disagreement is stated explicitly in Section 5 so that a later revision knows which assumption to revisit first.

References

[R1] Krishnan, R., Permanent Magnet Synchronous and Brushless DC Motor Drives, CRC Press, 2010.

[R2] Bianchi, N. and Dai Pré, M., Use of the star of slots in designing fractional-slot single-layer synchronous motors, IEE Proceedings, 2006.

[R3] Mohan, N., Undeland, T. M. and Robbins, W. P., Power Electronics, 3rd ed., Wiley, 2003.

[R4] Gonzalez, A. et al., "Regenerative braking for multirotor UAVs", IEEE Transactions on Transportation Electrification, 2018.