ESC Failure Analysis

Why the Shear Force weapon ESC caught fire, and what I'd change

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At 2 am on the day of SCAR Carnage at the Cube (April 2026), during a final test, the weapon ESC on Shear Force caught fire. This is my analysis of that fire and the fixes I'm considering. The two other ESC failures, which happened without a stall, are covered on the Shear Force project page.

1. Reasonable Assumptions

1. The ESC's current limit was 100 A, set low out of caution for testing (it would have needed to go up for the robot to be competitive). I'm treating it as a steady-state limit, not a transient one.
2. **The weapon stalled first.** The video of the fire is consistent with that, and so are the bearings. They had gone in without grease and came out flattened, with marks on the shaft.

> So the weapon stalled on its flat, ungreased bearings, and the stall burned out the ESC. That makes this a transient (stall) failure, not a steady-state current problem. The 100 A limit was doing its job. It just can't react fast enough to a sudden stall.

2. Basic Electrical Analysis

The current through the motor follows the usual equation:

$$\mathbf{I = (V - E_{back}) / R}$$

- E_{back} is the back-EMF. As the rotor spins, it induces a voltage that opposes the supply (Lenz's law), so $E_{back} = k \cdot \omega_{motor}$.
- In a stall, $\omega = 0$, so $E_{back} = 0$ and the equation reduces to Ohm's law, **I = V / R**.
- The weapon motor is a TP-5660 at 950 KV with R = 0.0049 Ω (its winding resistance). On 12S, V ≈ 50.4 V fully charged, so I = 50.4 V / 0.0049 Ω ≈ **10,286 A**.

> *Nothing actually reaches 10 kA. That is where the current would go if nothing failed, and in practice something breaks first, usually the MOSFETs. The same equation also explains why current drops as the weapon spins up: E_{back} climbs toward V, so I falls toward zero.*

3. Why Startup Isn't a Problem

Startup has the same $\omega = 0$ condition, so why doesn't it burn out the ESC every time? Because the ESC controls the duty cycle carefully during startup.

- It ramps the duty cycle (PWM) up slowly, so voltage goes on gently and back-EMF builds before the current can run away.
- The effective voltage is V_{eff} = duty cycle × 50.4 V. Each MOSFET is either fully on or fully off, but switching them at about 48 kHz gives an effective voltage below the full 50.4 V.

How Software Current Limiting Works

The ESC's software current limit is a loop:

1. Measure the current through the internal shunt resistors.
2. Compare it with the software limit.
3. If it's too high, lower the duty cycle to reduce V_{eff}.
4. Repeat, continuously.

> This read-decide-act loop can't respond fast enough to a real stall. The stall current rises in microseconds, and the firmware reacts in milliseconds.

Other Protections Are Also Too Slow

- Stall protection relies on detecting a de-sync, which takes milliseconds. That's about three orders of magnitude too slow.
- Stuck Rotor Protection only helps at startup. It does nothing when the weapon stalls mid-spin.

4. Why Normal Stopping Isn't a Problem

When I stop the weapon normally, the ESC is at **0% throttle**, so it isn't commanding any current. In a sudden stall, the ESC is still commanding current at the moment the rotor locks. That's the difference.

5. Fixes

5.1 Avoid the Stall (Primary)

- Bearings that actually work (greased this time) and proper belt tensioning.
- This is necessary but probably not enough on its own. The weapon can still stall in a match, for example if it gets stuck on another robot.

5.2 Mechanical Decoupling

In theory, the motor and belt could be decoupled from the weapon, so the motor can keep spinning even if the weapon stalls. Two options I'm considering:

- A shear pin, a sacrificial part that breaks first.
- A slip clutch, which lets the motor keep turning while the weapon is held.

Conceptually this is the real fix, but I haven't worked out whether either one is feasible here.

5.3 Hardware Over-Current Protection (Electrical Redundancy)

An ESC with hardware over-current protection cuts off at the gate driver in **microseconds**, so it's the only electrical fix fast enough to matter. The fire showed that firmware current limiting isn't enough.

5.4 Fuses

A fuse won't stop a stall; it's too slow for a transient spike this big. I'd still fit one as a second layer of protection, so if the ESC fails, thermal runaway doesn't spread to the batteries and other components.