

Pulse-Width Modulation (PWM) for Motorsport Fuel Delivery & Cooling

The Engineering Guide to Carrier Frequencies, Motor Physics & Hydraulic Boundaries

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Author: Aftermarket Industries Engineering
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1. EXECUTIVE OVERVIEW

Pulse-width modulation (PWM) has become an essential strategy in high-output motorsport fuel delivery and thermal management. By modulating the duty cycle of in-tank turbine fuel pumps (such as the Walbro 460, 525, 535, and Bosch BR540) or heavy-duty electric radiator cooling fans, calibrators can dramatically reduce electrical current draw, preserve fuel density, eliminate fuel aeration, and drop bulk fuel tank temperatures during idle and low-load cruising.

However, pulse-width modulating high-current inductive DC motors is governed by strict electromechanical and electromagnetic laws. Misunderstanding carrier frequencies, armature inductance, or switching semiconductors frequently leads to noisy fuel tanks, premature brush failure, stalled pumps, or catastrophically melted solid-state relays.

This guide provides the calibration boundaries, hardware topologies, and electrical physics required to configure pulse-width modulated systems safely and reliably, while introducing purpose-built hardware like the [Aftermarket Industries AI.SSR25 Solid-State Controller](#) designed specifically to eliminate these failures.

2. ELECTROMECHANICAL MOTOR PHYSICS: ARMATURE INDUCTANCE & CURRENT RIPPLE

A traditional automotive fuel pump or cooling fan is powered by a high-draw brushed DC permanent-magnet motor. From an electrical engineering standpoint, the motor armature winding is an inductive-resistive circuit: an inductor (L) in series with a resistor (R) and a rotating counter-electromotive force (back-EMF, V_{EMF}).

When a solid-state switch chops high-current DC power to the motor, the armature current cannot change instantaneously. The rate of current rise and fall across every switching cycle is governed by:

$$\text{Inductive Voltage Law: } V_L(t) = L \cdot [di(t) / dt]$$

The peak-to-peak inductive current ripple (ΔI) circulating through the armature windings during PWM operation is calculated as:

$$\text{Peak-to-Peak Current Ripple: } \Delta I \approx [V_{BAT} \cdot D \cdot (1 - D)] / [L \cdot f_{PWM}]$$

Where: V_{BAT} = Battery Voltage (V), D = Commanded Duty Cycle (0.0 to 1.0), L = Armature Inductance (Henries), f_{PWM} = Selected Carrier Frequency (Hz).

The Destructive Cost of Low-Frequency Ripple (< 200 Hz)

Modern high-flow turbine fuel pumps (such as the TI Automotive Walbro 525 / F90000285) feature low-mass, ultra-compact armatures designed to minimize rotational inertia and deliver rapid hydraulic spool-up. As a result, their internal winding inductance is exceptionally low—typically between **40 μ H and 80 μ H**.

When a calibrator runs a carrier frequency down at **100 Hz**, the switching period ($T = 1 / f$) is a massive **10.0 ms**. Because 10 ms is vastly longer than the motor's natural inductive time constant ($\tau = L / R$), the magnetic field inside the coils completely collapses and surges violently on every single stroke:

- **RMS Resistive Heating ($I_{RMS}^2 R$ Copper Losses):** While an average multimeter shows an expected average DC current, the root-mean-square current (I_{RMS}) spikes significantly higher due to the extreme sawtooth ripple profile. The thermal heat dissipated inside the copper armature windings scales strictly with I_{RMS}^2 . This concentrated copper heating cooks the motor internally without producing hydraulic pumping work.
- **Brush & Commutator Hammering:** The rapid collapsing and surging of current produces intense electromagnetic torque pulsing. The motor armature is continuously accelerating and decelerating thousands of times per minute. This produces micro-arcing across the carbon-metallic commutator brushes, fracturing the brush faces and rapidly shortening motor service life.
- **Audible Cabin Resonance:** At 100 Hz, the motor armature acts like an acoustic transducer, vibrating the pump body and using the sheet metal of the fuel tank or radiator core as an acoustic amplifier, generating harsh cabin drone.

3. THE CARRIER FREQUENCY SPECTRUM: OPERATING BANDS & RULES

Carrier frequency selection must balance motor current ripple against semiconductor switching losses:

CARRIER FREQUENCY	OPERATING STATUS	PHYSICAL IMPACT ON FUEL PUMP / COOLING FAN	CONTROLLER DEMANDS
0 Hz (Continuous DC)	FULLY APPROVED	100% full flow. Zero ripple, pure DC flow. Standard relay behavior.	Requires continuous DC charge-pump bias.
< 200 Hz (e.g. 100 Hz)	STRICTLY PROHIBITED	Severe current ripple, destructive I²R heating, brush chatter, tank buzzing.	Harsh inductive hammering on solid-state switch.
250 Hz – 500 Hz	STANDALONE BASELINE	Armature inductance maintains continuous conduction. Cuts ripple by 60%.	Optimal baseline for MoTeC, Haltech, Emtron, Syvecs.
1 kHz – 5 kHz	AUDIBLE MID-BAND	Smooth motor flow, but produces distinct high-pitch audible coil whine.	Melts industrial hockey-puck relays due to switching lag.
10 kHz – 20 kHz	OPTIMAL ULTRASONIC	Pure ripple-free DC flow, zero brush fatigue, completely silent in cabin.	Requires sub-50 ns gate driver (AI.SSR25).

4. RADIATOR COOLING FANS: BRUSHED DC VS. SMART BRUSHLESS DRIVES

The distinction between motor types is critical when calibrating cooling fans:

- **High-Power Brushed DC Cooling Fans:** Large radiator cooling fans (such as extreme-duty 16" high-output brushed fans) feature large iron motor armatures with inductances exceeding 300 µH to 600+ µH—roughly ten times greater than a miniature fuel pump. Their high natural inductance provides stronger passive ripple smoothing at 250 Hz. However, because fans are mounted in open air against radiator shrouds, modulating a brushed fan between 500 Hz and 2.5 kHz generates noticeable acoustic coil hum. Running high-speed power stages at **10 kHz to 15 kHz** provides silent fan operation and smooth speed transitions as coolant temperatures rise.
- **Smart Brushless (BLDC) Cooling Fans:** Modern brushless fans (such as SPAL brushless 300W, 500W, and 850W units) integrate internal 3-phase inverter drives and brushless motors directly into the hub. They require continuous, unswitched battery power on their main studs, with speed controlled via a low-current PWM logic control wire. Factory SPAL brushless input circuits are designed to accept low-speed command frequencies between **50 Hz and 500 Hz** (standard benchmark: 100 Hz or 128 Hz). Feeding a high-frequency 7 kHz to 20 kHz signal into a SPAL brushless control wire will cause its internal input filter to reject the signal, preventing the fan from running.

5. SEMICONDUCTOR ARCHITECTURE: WHY INDUSTRIAL SSRS BURN OUT

Calibrators frequently make the costly mistake of using industrial DC "hockey puck" solid-state relays (such as the Crydom D06D100 or i-Autoc KSJ30D100) to modulate fuel pumps and fans. While advertised with a "100A DC" catalog rating, these industrial units suffer catastrophic thermal failure in automotive PWM environments.

Total Power Dissipation:
$$P_{TOTAL} = [I_{LOAD}^2 \cdot R_{DS(on)} \cdot Duty] + [0.5 \cdot V_{BAT} \cdot I_{LOAD} \cdot (t_R + t_F) \cdot f_{PWM}]$$

- **Slow Optocoupler Transitions (150 µs Drag):** Industrial pucks use slow optocouplers with total transition times ($t_R + t_F$) of 150 µs to 180 µs. Every time the relay turns on or off, the internal MOSFET spends a significant window dragging through its linear ohmic region.
- **Frequency-Induced Thermal Runaway:** At 250 Hz driving a Walbro 525 (21.3A draw at 60 PSI), an industrial puck wastes over **7.8W to 9.1W of pure heat**, requiring a large heatsink to survive. Stepping up to 1 kHz, linear transition drag consumes over 30% of the entire cycle: internal dissipation jumps to **24.5W to 29.2W**, melting the plastic potting and welding the FET die closed into a permanent short. At 15 kHz ultrasonic frequencies, they cannot switch at all.
- **Discrete 4A Gate Driving:** Fast switching reduces, not eliminates, losses. At 14.5 V and 21.3 A, with 35 ns rise / 40 ns fall times, the stated model gives approximately 0.012 W at 1 kHz and 0.174 W at 15 kHz (**switching only**). The reported 1.18 W total at 15 kHz is not verified here and needs test conditions, including conduction, diode and driver losses.
- **Inductive Flyback Hazards:** A high-flow fuel pump stores significant magnetic energy in its windings. Every time the switch turns OFF, back-EMF spikes easily exceed 80V to 120V. Industrial pucks contain *no internal flyback suppression diodes*. Without an external fast-recovery diode, the internal MOSFET breaks down in avalanche mode. Motorsport controllers integrate high-capacity (30A) Schottky freewheel diodes directly on the PCB copper plane.

6. HYDRAULIC CALIBRATION BOUNDARIES: THE 11.0V MINIMUM STALL LIMIT

A common tuning error is treating a high-pressure turbine fuel pump like an electric cooling fan or LED dimmer, mapping PWM duty down to 20%–40% at engine idle. **This practice often damages the pump.**

HYDRAULIC STALL LIMIT WARNING (40 TO 60 PSI HEAD PRESSURE)

Unlike a fan spinning in ambient air, a motorsport fuel pump operates against the static spring pressure of the mechanical fuel pressure regulator (typically 40 to 60 PSI / 2.75 to 4.1 Bar base pressure). To generate sufficient armature torque to displace fuel against that spring pressure, a brushed turbine pump requires a minimum effective terminal voltage of **11.0 Volts**.

If terminal voltage drops below 11.0V, hydraulic counter-torque overcomes the pump's rotational force. The impeller stalls, fuel cavitation begins inside the turbine channel, and fuel rail pressure drops or oscillates erratically. Because in-tank pumps rely on fuel flow for cooling and lubrication, prolonged operation below the stall floor leads to rapid brush failure.

Minimum Duty Cycle Formula: $\text{Minimum Duty Cycle (\%)} = (11.0 \text{ V} / V_{\text{BAT_ACTUAL}}) \times 100\%$

- **At 13.8V Nominal (Battery/Crank Rail):** Clamp table floor to **80.0% Minimum Duty**.
- **At 14.5V Nominal (Alternator Rail):** Clamp table floor to **76.0% Minimum Duty**.

RECOMMENDED MOTORSPORT FUEL PUMP CALIBRATION STRATEGY

ENGINE STATE	EFFECTIVE TERMINAL VOLTAGE	TARGET PWM DUTY	OPERATIONAL BENEFIT
Ignition Key-On Prime	Full Rail (13.8V – 14.5V)	100.0% CONTINUOUS	Instantly overcome line head pressure & purge rail air.
Warm Idle & Light Cruise	11.0V Minimum Effective	76.0% – 80.0% DUTY	Drops fuel recirculation by >100 LPH, eliminates vapor lock.
Moderate Load / Part Boost	12.5V Effective	85.0% – 90.0% DUTY	Smoothly steps fuel volume ahead of injector demand.
Full Boost / WOT	Full Rail (13.8V – 14.5V)	100.0% CONTINUOUS	Delivers maximum pump volume up to 100 PSI rail head.

7. IGNITION PRIME STRATEGY & MOTORSPORT WIRING ARCHITECTURE

- **2.5s Full-Voltage Pre-Crank Prime:** When the ignition key is first switched ON, standalone ECUs trigger a pre-crank prime cycle for 2.0 to 3.0 seconds to pressurize the fuel rail. *Never pulse-width modulate the prime cycle.* The prime must run at a hard 100.0% duty cycle to instantly seat the mechanical fuel regulator diaphragm.
- **High-Side Switching Topology:** Always switch the positive (+12V) power rail to the pump, leaving the pump negative lead permanently bonded to the chassis. This eliminates galvanic terminal corrosion in the fuel tank and prevents accidental pump runaway during a harness pinch.
- **Logic Ground Isolation:** Connect Pin 4 (GND REF) directly to the ECU sensor ground. This isolates sensitive ECU input comparator thresholds from high-current chassis return surges.
- **Vibration-Proof Motorsport Interfaces:** Avoid open screw terminals (IP00). Use sealed, vibration-proof motorsport connectors (such as the TE Connectivity Deutsch DTP 4-Pin series with Size 12 solid contacts).
- **Autonomous Analog Hardware eFuse:** Traditional automotive fuses take hundreds of milliseconds to blow. Modern motorsport controllers incorporate an autonomous analog hardware eFuse that monitors internal shunt resistance, isolating dead shorts in **< 4.0 µs**.

8. THE PURPOSE-BUILT HARDWARE SOLUTION: AFTERMARKET INDUSTRIES

AI.SSR25

Most solid-state relays sold into the performance aftermarket are repackaged industrial automation "hockey pucks" designed decades ago for low-speed factory heaters. When repurposed to control high-draw motorsport fuel pumps (Walbro 460/525/535) or cooling fans, their slow optocouplers (150 µs switching lag) generate extreme dynamic switching heat, causing thermal runaway above 250 Hz. Furthermore, their lack of inductive flyback protection and exposed screw terminals introduce critical track-day failure points.

The [Aftermarket Industries AI.SSR25 \(25A Continuous / 33A Latched Cutoff\)](#) was engineered from the ground up specifically to solve these motorsport failure modes:

- **High-Speed Gate Drive & Thermal Performance:** The AI.SSR25 has a maximum potential PWM frequency of **100 kHz**, not a recommendation for every load. Its 4 A driver reduces switching loss; total heat depends on current, duty, frequency, diode losses and cooling. The claimed **<1.2 W** total requires defined test conditions.
- **Onboard 30A Schottky Flyback Clamping:** No external diodes required in your wiring harness. High-voltage inductive back-EMF spikes from inductive turbine motors are clamped internally on the heavy 2oz copper plane.
- **Autonomous <4 µs Hardware eFuse:** An onboard analog comparator continuously audits the precision alloy shunt. If a pump stalls, locks up, or suffers a harness short-circuit, power is isolated in under 4 microseconds—safeguarding vehicle wiring and latching a solid Red diagnostic LED.

- **Dual-Mode Static DC & PWM Operation:** Featuring an internal charge pump trickle path, the AI.SSR25 can be deployed as an indestructible direct drop-in replacement for traditional mechanical cube relays (100% static DC), or modulated via your ECU for closed-loop variable fuel speed control.
- **Motorsport-Grade Packaging:** Housed in a CNC 6061-T6 billet aluminum base that acts as its own heatsink, sealed with a custom Viton (FKM) perimeter gasket against ethanol/fuel washdowns, and terminated with genuine TE Connectivity Deutsch DTP 4-pin connectors.

9. CALIBRATOR COMMISSIONING CHECKLIST

- ☐ **Identify Motor Architecture:** Confirm whether the load is a 2-wire brushed DC turbine/fan motor or a smart brushless drive with internal commutation logic.
- ☐ **Prohibit Frequencies Below 200 Hz:** Never operate high-draw brushed motors below 200 Hz; set the standalone ECU baseline to **250 Hz to 500 Hz**, or **10 kHz to 20 kHz** if the ECU supports high-speed ultrasonic timers.
- ☐ **Avoid Industrial Pucks:** Do not use optocoupler-based industrial relays (Crydom/i-Autoc) for automotive PWM; their 150 μ s switching lag generates rapid thermal runaway past 250 Hz.
- ☐ **Verify Inductive Clamping:** Ensure the controller features an integrated high-capacity freewheeling diode (or install a 30A fast-recovery diode across the load leads if using legacy hardware).
- ☐ **Enforce the 11.0V Floor:** Clamp minimum duty cycle tables to **76% (at 14.5V)** or **80% (at 13.8V)** to prevent motor brush stalling against fuel rail head pressure.
- ☐ **Command 100% Pre-Crank Prime:** Force a 2.0 to 3.0 second prime at 100% duty cycle on key-on to fully seat regulator line pressure prior to cranking.
- ☐ **High-Side Switching:** Ensure the power stage switches +12V to the load, with the pump or fan ground bolted securely to the vehicle chassis.
- ☐ **Verify Thermal Performance:** Check AI.SSR25 switching and conduction losses, flyback-diode dissipation, mounting and cooling for the intended load, duty and frequency. Do not assume low heat at every frequency; verify protection and connector specifications separately.