

THE CAPACITORS CARRY THE HARDEST CURRENT

Sizing the bus bank for a two second pass — and the resonance nobody warns you about

01 · NOT THE BATTERY

HALF THE PHASE AMPS

At part throttle the bank carries more RMS current than the pack does. The battery supplies the average; the caps supply everything that changes faster than the leads allow.

02 · ESR BEATS μF

2.6 V vs 2.0 V

In an 8S example at 4,000 μF the ESR term is bigger than the capacitance term. Choose parts by milliohms and ripple rating, not by microfarads.

03 · A BURST, NOT A DUTY

13 $\times$ THE RATING

In the worked example the launch asks 13 times the bank's continuous ripple rating. The rating assumes forever. A pass is two seconds, so the limit is joules, not amps.

04 · THE TRAP

MORE μF CAN BE WORSE

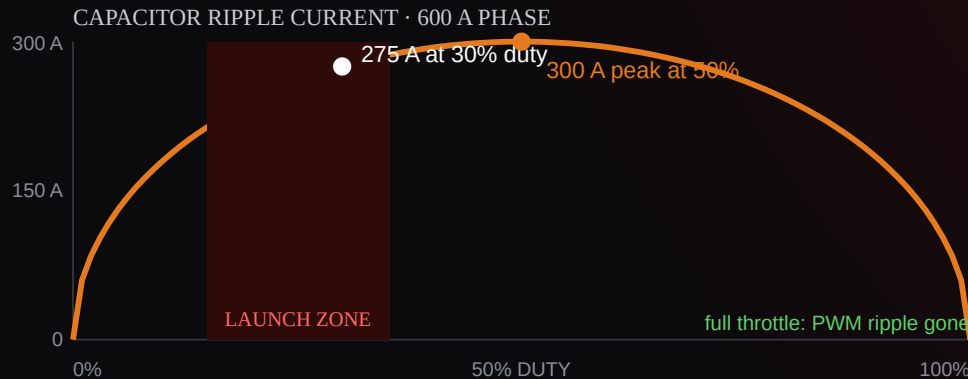
Adding capacitance drags the bank's resonance down into the motor's rpm range. There is a window, not a "more is better".

Every number in this guide is a clearly labelled example assumption, not measured EVUL data — pack voltage, phase current, duty, PWM frequency, lead inductance. Put your own in, and confirm on a scope. The companion **EVUL Ripple Pak Calculator** does all of this live and picks a real orderable part.

Who this is for: anyone adding capacitors to an RC ESC for drag, speed runs or pulling — and especially anyone going above 8S, where the resonance section stops being academic.

THE ESC CHOPS, THE CAPS CATCH

Below full throttle the bus current is a square wave. The battery only supplies its average.



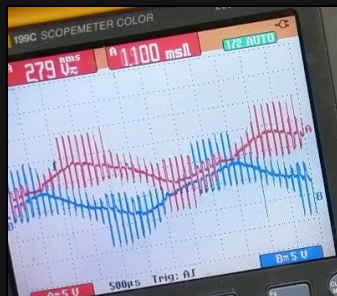
Example: 600 A phase current. The curve is $I \times \sqrt{D(1-D)}$ — it peaks at 50% duty, where the bank carries half the phase current.

$$I_{\text{cap}}(\text{rms}) = I_{\text{phase}} \times \sqrt{D \times (1-D)}$$

Phase	Duty	Battery	Caps
600 A	20%	120 A	240 A
600 A	30%	180 A	275 A
600 A	50%	300 A	300 A
600 A	80%	480 A	240 A
600 A	100%	600 A	0

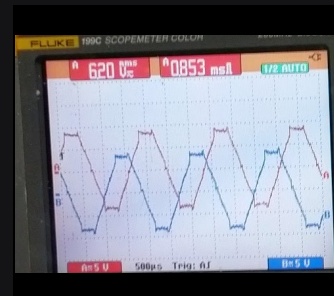
READ THE RIGHT CURRENT

Castle logs battery current. The bank runs on phase current. At 30% duty a logged 180 A means 600 A in the winding and 275 A in the caps. XC's X.BUS reports phase current directly.



PART THROTTLE · THE BUS IS BEING CHOPPED

Dense PWM hash across the whole waveform, with a spike at every switching edge. Every one of those edges is a current step the bank has to swallow. The spikes overshooting the envelope are the ESL term.



HIGHER THROTTLE · THE HASH IS GONE

Same bench, higher duty. What is left is the commutation trapezoid itself. The PWM ripple the bank was carrying has largely gone — which is why the curve above falls back toward zero at 100%.

EVUL bench captures, 2015 · Fluke 199C ScopeMeter, 200 MHz / 2.5 GS/s · 5 V/div, 500 μs/div

THREE TERMS, AND ESR USUALLY WINS

Capacitance, resistance and inductance each put their own voltage on the bus.

$$\Delta V \approx \underbrace{I \cdot D(1-D) / (C \cdot f_{sw})}_{\text{capacitance}} + \underbrace{I \cdot \text{ESR}}_{\text{resistance}} + \underbrace{L \cdot di/dt}_{\text{inductance}}$$

CAPACITANCE TERM

2.0 V

The charge the bank gives up while the FET is on. More microfarads or a higher PWM frequency shrink it. $600 \text{ A} \times 0.21 \div (4,000 \mu\text{F} \times 16 \text{ kHz})$.

ESR TERM

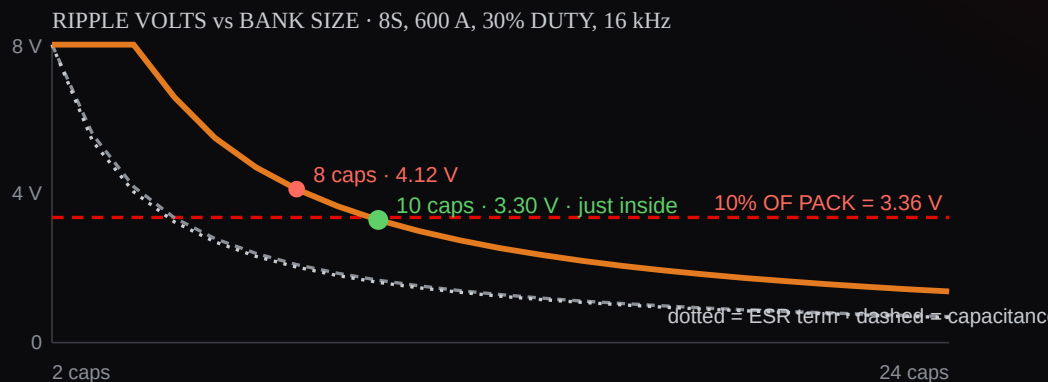
2.6 V

The cap current steps by the full phase current at every switching edge; that step times ESR lands straight on the bus. Only lower ESR shrinks it. $600 \text{ A} \times 4.3 \text{ m}\Omega$.

ESL TERM

~30 V

A 100 ns edge through even 5 nH of loop. No bulk capacitance fixes this — it needs ceramics at the FETs and the shortest possible bus loop.



Both terms fall as $1/n$. Ten 470 μF / 27 $\text{m}\Omega$ parts in parallel bring the total just inside the 10% guideline.

WHY PARALLEL

Caps in parallel divide ESR and share the heat. Two 470 μF parts beat one 1,000 μF part of the same family, because ESR halves while capacitance only doubles — and ESR is usually the bigger term.

THE SPIKE IS SEPARATE

The ESL term is not in the chart and no amount of bulk capacitance removes it. A 35 V cap on a full 8S pack has 1.4 V of headroom; the spike is what kills it. Mount the bank at the ESC bus, keep the loop short and wide, and leave a voltage class in hand.

CHOOSE BY MILLIOHMS

Distributors publish ripple current and case size. ESR is the number that matters, and it is often the one missing.

PART	MAKER	μF	V	ESR 100 kHz	RIPPLE	SIZE mm	WHERE IT FITS
35ZLH1000MEFC12.5X20	Rubycon ZLH	1000	35	17 mΩ	2.48 A	12.5×20	3–6S bulk, best μF per milliohm
ESY477M035AH4AA	KEMET ESY	470	35	26 mΩ	1.82 A	10×20	3–6S, small cans, easy to parallel
ESY477M050AL3AA	KEMET ESY	470	50	27 mΩ	2.05 A	13×20	8S with headroom — the worked example
ESL108M063AM9AA	KEMET ESL	1000	63	26 mΩ	2.62 A	16×30	12S, 1/5 scale
ESL188M063AM4AA	KEMET ESL	1800	63	21 mΩ	3.25 A	16×40	12S where space allows
ESL687M100ANAAA	KEMET ESL	680	100	30 mΩ	2.87 A	18×35	16S and up

WORKED EXAMPLE · 8S

33.6 V pack, 600 A phase at 30% duty, 16 kHz, 10% ripple target = 3.36 V. Ten × ESY477M050AL3AA in parallel: 4,700 μF, bank ESR 2.70 mΩ, ripple 1.68 V + 1.62 V = **3.30 V — inside**. 42 g, 26.5 cm³. Voltage headroom 50 V on 33.6 V.

ESR you need = $(\Delta V_{\text{target}} - \Delta V_{\text{capacitance}}) \div I_{\text{phase}}$
 number of caps = $\text{ESR}_{\text{one part}} \div \text{ESR}_{\text{you need}}$ (round up)

WHEN ESR IS NOT PUBLISHED

Derive it from the part's own rated ripple and can area. At rated ripple the heat flux off a can is remarkably consistent — **92 to 119 W/m²** across nine datasheet parts from three makers. So:

$$\text{ESR} \approx 108 \times A_{\text{can}} \div I_{\text{rated}}^2$$

$$A_{\text{can}} = \pi \cdot D \cdot L + 2\pi(D/2)^2 \quad \text{in m}^2$$

Check: Rubycon ZLH 1,000 μF — 2.48 A rated, 10.31 cm² can → 17.0 mΩ, which is the datasheet figure. Label any ESR you derive this way as an estimate, not a rating.

THE RATING ASSUMES FOREVER

A pass is two seconds. The limit is the energy the cans can soak, not the amps on the label.

$$P = I_{\text{cap}}(\text{rms})^2 \times \text{ESR}$$

$$(\text{mass} \times 1.3 \text{ J/g} \cdot ^\circ\text{C})$$

$$E = \sum P \cdot \Delta t$$

$$\Delta T \approx E \div$$

PART OF THE PASS	CAP RIPPLE	HEAT	TIME	ENERGY
Launch, 30% duty, 600 A	275 A	204 W	0.5 s	102 J
Rest of pass	~96 A	25 W	1.5 s	38 J
PASS TOTAL			2.0 s	140 J

Ten ESY477M050AL3AA weigh about 42 g. $140 \text{ J} \div (42 \text{ g} \times 1.3) \approx 2.5 \text{ }^\circ\text{C}$ per pass, more in the core of each can. Three back-to-back passes stack to about 8 °C.

HEAT COSTS LIFE

Every 10 °C hotter roughly halves an electrolytic's service life. A bank that comes off the track hot every pass will not see a season — and as its ESR climbs with age, it heats more each time.

THE NUMBER THAT LOOKS IMPOSSIBLE

13×

The bank's continuous rating is 20.5 A. The launch asks 275 A. That is thirteen times the rating and it is **normal** — the rating is for steady heat with no time limit, and a pass has a time limit.

109 A/mm² COPPER

13× CAP RIPPLE

SAME IDEA

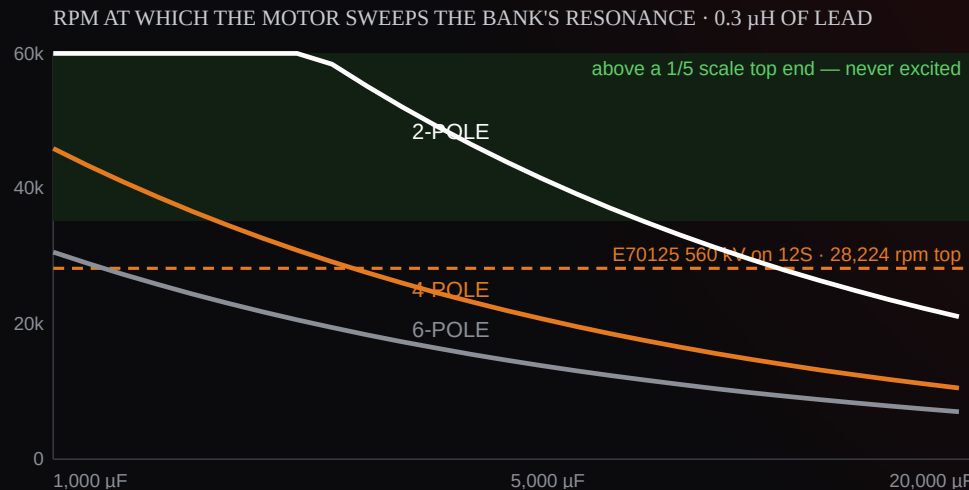
This is the same burst-energy argument as the copper in the Burst Physics book. Ratings describe steady state. Racing does not run steady state.

WHAT TO MEASURE

An infrared thermometer on the cans right after a pass tells you more than any calculation. Warm is fine. Hot to the touch, or climbing pass after pass, means the bank is too small or its ESR has aged.

MORE MICROFARADS CAN MAKE IT WORSE

The battery leads and the bank form a tuned circuit. The motor sweeps through it as rpm climbs.



Bigger bank → lower resonance → the crossing moves down into the working rpm range. A 2-pole crosses highest, nearest trap speed, which is the worst place for it.

$$f_{\text{res}} = 1 / (2\pi \sqrt{L_{\text{lead}} \cdot C_{\text{bank}}})$$

$$\text{rpm}_{\text{cross}} = f_{\text{res}} \times 60 \div (6 \times \text{pole pairs})$$

IT IS VOLTS, NOT WATTS

On resonance each commutation step arrives in phase with the ringing already there, so amplitude builds toward Q times the single kick. A 300 A step on a 4,700 μF bank rings **7.1 V** — 14% of a 12S pack, past the 10% guideline, and it lands on top of pack voltage. Heat rises about 9× too, but a bank survives that for two seconds. The overshoot is what kills parts.

THE RULE

Put the resonance either **above** $6 \times \text{pole pairs} \times \text{rpm}_{\text{max}} \div 60$, or **below** the same at launch rpm. Never let it land in the top third of the rpm range. If it does: change bank size, shorten the leads, or add a damping leg — one deliberately higher-ESR cap in parallel, which lowers Q without raising the bank's ESR where it matters.

SHORT LEADS ARE WHAT MAKE IT POSSIBLE

XC E3MAX at 500 A, E70125 560 kV (4-pole) on 12S. Top commutation 5,645 Hz. Ripple target 5.04 V.

BANK	RIPPLE VOLTS	MEETS TARGET?	f_res · SHORT LEADS	VERDICT	f_res · +20 cm	VERDICT
3,000 µF	6.52 V	No	7,503 Hz	above top	5,305 Hz	94% of top
4,000 µF	4.89 V	Yes	6,497 Hz	above top ✓	4,594 Hz	81% of top
5,000 µF	3.91 V	Yes	5,812 Hz	above top ✓	4,109 Hz	73% of top
6,000 µF	3.26 V	Yes	5,305 Hz	94% of top	3,751 Hz	66% of top
8,000 µF	2.45 V	Yes	4,594 Hz	81% of top	3,249 Hz	58% of top

THE FLOOR

4,000 µF

Below this the launch ripple exceeds the 10% target. Set by phase current, duty and PWM frequency.

THE CEILING, LONG LEADS

2,650 µF

Above this the resonance drops below the motor's top commutation frequency. With 0.3 µH there is **no overlap** — no bank satisfies both.

THE CEILING, SHORT LEADS

5,300 µF

Halve the lead inductance and the ceiling rises above the floor. A window opens at 4,000–5,000 µF.

WHAT THIS MEANS IN THE PITS

On this build, "keep the battery leads short and paired" is not tidiness — it is the difference between a bank that works and one that cannot exist. Move the ESC toward the pack and run longer **motor** wires instead; motor leads do not carry the switching ripple.

TIMING DOESN'T MOVE IT, IT HITS IT HARDER

Advance changes when each step fires, not how often — so the crossing rpm is unchanged. What grows is the size of every step.

SET TIMING	DESIGN ANGLE	PHASE CURRENT	RING	% OF 12S
0°	30°	1.15×	8.19 V	16%
10°	40°	1.31×	9.26 V	18%
15°	45°	1.41×	10.03 V	20%
26°	56°	1.79×	12.68 V	25%

Design angle is the set timing plus the $\pm 30^\circ$ six-step swing. Only the $\cos \gamma$ part of phase current makes torque, so current scales as $1 \div \cos \gamma$.

THREE THINGS CONVERGE

Turbo ramps advance in with rpm. A low pole count crosses resonance at high rpm. Full throttle removes the PWM ripple that was damping the bank. All three peak in the last third of the track. **Plain six-step at zero advance is already at 16%** — you cannot time your way out of it. FOC has no discrete steps and largely removes the mechanism.

HOW TO CHECK IT

CHECK	TOOL	GOOD
Can temperature	IR thermometer, right after the pass	A few degrees over ambient
ESR	ESR meter (they test near 100 kHz)	Close to the datasheet figure
Bus ripple	Scope across the caps, short ground lead	Peaks under 10% of pack
Ringling	Same scope, at top rpm	No sustained oscillation after each edge
Physical	Eyes	Flat clean tops, no discolouring

THE ONE MEASUREMENT THAT SETTLES IT

Scope the bus at top rpm, at full throttle, with your race leads and pack. Everything on page 6 and 7 is derived from an estimated lead inductance. One scope trace replaces the estimate with a fact.

- **Write the new ESR on each can** with a marker when you build the bank
- **Check temperature** after the first three passes of a session
- **Re-check ESR** every few race days; replace any cap well above its siblings
- **Log phase current and duty together** — X.BUS gives both; $\text{duty} \approx \text{battery} \div \text{phase}$

APPENDIX · THE MATH, STEP BY STEP

01 CAPACITOR RIPPLE CURRENT

$$I_{\text{cap(rms)}} = I_{\text{phase}} \times \sqrt{D(1-D)}$$

600 A at 30% duty = 275 A rms

02 RIPPLE VOLTAGE

$$\Delta V = I \cdot D(1-D) / (C \cdot f_{\text{sw}}) + I \cdot \text{ESR} + L \cdot di/dt$$

$$600 \times 0.21 / (0.0047 \times 16000) = 1.68 \text{ V}$$

$$600 \times 0.0027 = 1.62 \text{ V}$$

03 HEAT AND TEMPERATURE RISE

$$P = I_{\text{cap}}^2 \times \text{ESR}$$

$$E = \sum P \cdot \Delta t$$

$$\Delta T \approx E \div (\text{mass} \times 1.3 \text{ J/g} \cdot ^\circ\text{C})$$

04 ESR WHEN IT IS NOT PUBLISHED

$$\text{ESR} \approx 108 \times A_{\text{can}} \div I_{\text{rated}}^2$$

$$A_{\text{can}} = \pi \cdot D \cdot L + 2\pi(D/2)^2 \quad [\text{m}^2]$$

05 BUS RESONANCE

$$f_{\text{res}} = 1 / (2\pi\sqrt{L_{\text{lead}} \cdot C_{\text{bank}}})$$

$$Z_0 = \sqrt{L_{\text{lead}} / C_{\text{bank}}}$$

$$Q = Z_0 \div \text{ESR}_{\text{bank}}$$

06 WHERE THE MOTOR CROSSES IT

$$f_{\text{comm}} = 6 \times \text{pole pairs} \times \text{rpm} \div 60$$

$$\text{rpm}_{\text{cross}} = f_{\text{res}} \times 60 \div (6 \times \text{pole pairs})$$

07 RING AMPLITUDE AT RESONANCE

$$\text{single kick} = \Delta I \times Z_0$$

$$\text{built up} \approx Q \times \Delta I \times Z_0$$

08 TIMING SCALING

$$I(\gamma) = I(0) \div \cos \gamma$$

design γ = set timing + 30° (six-step swing)

09 LEAD-LENGTH ALLOWANCE

220 μF per 10 cm of added battery lead
(Retzbach rule, as circulated by racers)

CONSTANTS USED

Heat flux at rated ripple **108 W/m²** (92–119 across nine parts)

Can heat capacity **1.3 J/g·°C**

Can packing density **1.6 g/cm³**

Lead inductance **10 nH/cm** paired, plus **0.2 μH** layout

Ripple guideline **10% of pack**, as circulated from Castle

ESR model **15 m Ω + 0.12/(2 π fC)** for a 1,000 μF low-ESR can

WHAT IS ESTIMATED

Lead inductance, can mass, the heat-flux constant, and any ESR not taken from a datasheet. Every one of these is labelled where it appears. The capacitor ratings themselves — capacitance, voltage, ESR, ripple current, case size — come from manufacturer datasheets and distributor listings.

COMPANION TOOLS

EVUL Ripple Pak Calculator — runs all of this live and picks a real orderable part

Ripple, ESR and the DC Bus — the long-form notes behind this guide

Burst Physics — the book; capacitors sit alongside copper heat, saturation, demagnetisation and timing

This guide gives physics-based estimates, not guarantees. Real results depend on wiring, layout, traction and parts. Confirm every setup with a scope and a logged pass.

THE SAME PROBLEM, AT 25,000 VOLTS

Before the RC cars, twenty years of capacitor banks on the transmission grid.

Mike Behanna spent his career commissioning and testing **static VAR compensators** for Mitsubishi Electric Power Systems — reactive-power plants that hang off a transmission system to hold voltage steady. Jobs up to **\$40 million**, on systems from 69 kV to 765 kV, and not one of them late or over budget.

Every one of those jobs is a capacitor-bank problem. An SVC is banks of capacitors and reactors switched by thyristor valves, and the valves are gated over **fiber optic** — because the stack floats at line potential and nothing made of copper is allowed to bridge that gap. The compensator bus ran at **25 kV**, then stepped up through the transformer to the primary and out onto the line.

And the thing that gets designed around first, every single time, is **resonance**. The filter banks are deliberately detuned so the capacitance cannot ring against the system's inductance at a harmonic of the line. Page 6 of this guide is that same argument six orders of magnitude down in energy — with your battery leads playing the part of the system impedance, and your commutation frequency playing the part of the harmonic.

The scope captures on page 2 came off a Fluke 199C in 2015, when the EVUL bench work started. Same instinct either way: **measure it, don't assume it.**



SVC commissioning: site build, valve and filter rows, night commissioning, and transformers inbound by rail.

WHY THAT MATTERS TO YOUR CAR

None of this makes the numbers in this guide measured data — they are still labelled estimates, and a scope on your own bus beats every one of them. What it means is that the resonance chapter is not a curiosity out of a textbook. It is the failure mode utilities spend millions designing out, turning up in a 1/5 scale drag car because the physics does not care about the voltage.

SYSTEMS

69 – 765 kV

COMPENSATOR BUS

25 kV

JOBS RUN

UP TO \$40M

VALVE GATING

FIBER OPTIC