PSU Clamp Test Waveforms & Calculations

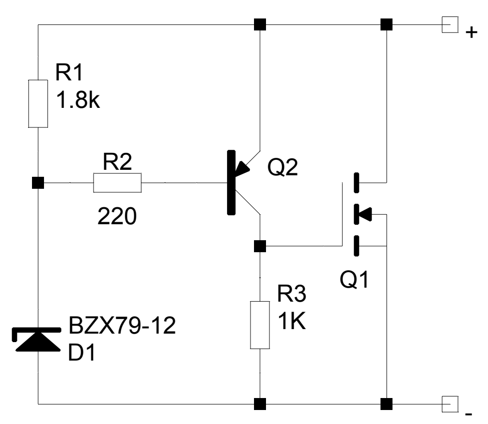
April & May 2025

Table of Contents

Setup

Motor: EMAX ECO 1106, K_v = 6000, 12 magnets, with flywheel
Connections: Separate connection from power supply to Remora & from power supply to the clamp circuit

Clamp Circuit Schematic



Q1: the prototype used SQJ140ELP mounted on a copper sheet 15mm × 8mm × 0.5mm

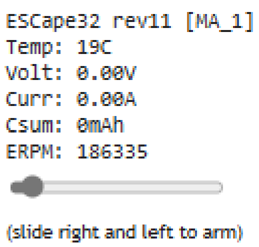
A few other possible mosfet candidates:

Part Number	Package
SQJ140ELP	PowerPAK (5x6)
SQJ160EP	PowerPAK (5x6)
IRFS7437	D^2PAK
SQM40016EM	D^2PAK 7 lead
RFP50N06	TO-220
SUP50020EL	TO-220
IRLB3034	TO-220

Q2: the prototype used KSA733, but almost any small PNP transistor would work.

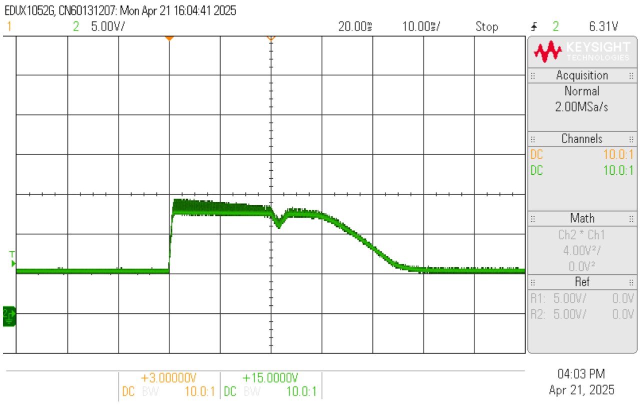
Method

In the ESC32 menu move slider right then left, this rapidly stops the motor sending energy back to the power supply (PSU), as power supplies only source current this raises the PSU voltage.
The clamp is designed to start operating at about 12.5V preventing damage to the WiFi and Remora.



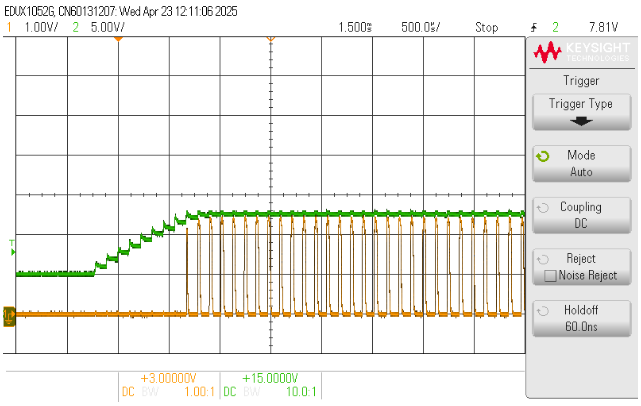
ERPM = rpm × pole pairs ∴ rpm = ERPM ÷ pole pairs ∴ rpm = 186335 ÷ 6 = 31056rpm
From Kv value: rpm ≈ 5V × 6000Kv = 30000rpm, so in reasonable agreement with ERPM reading from ESC32.
Commutation frequency, Fc = (rpm / 60) × pole pairs = ERPM / 60 = 186335/60 = 3106Hz
Measured Fc from oscilloscope is 3003Hz

Supply rail voltages & mosfet gate voltage



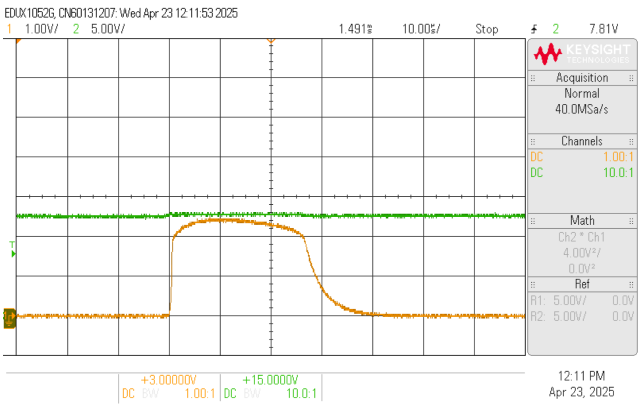
1
5V supply
green = supply at Remora, 5V/div, 10ms/div

Supply starts at 5V, then when the slider is moved left it rapidly rises to the clamp level of about 12.5V.
The clamp successfully holds the voltage at below 15V.



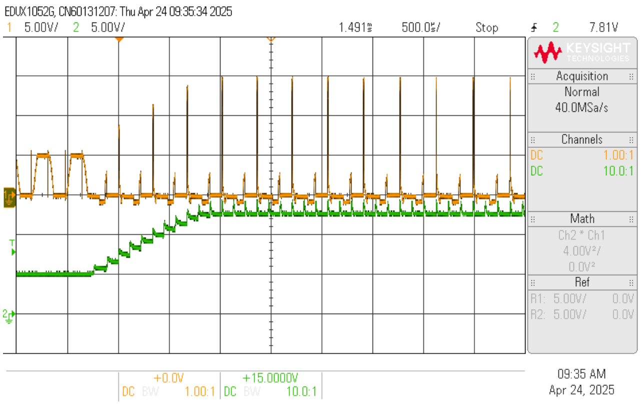
2
5V supply
yellow = mosfet gate, 1V/div, 500µs/div
green = supply at clamp, 5V/div, 500µs/div

The pulses occur at 3× the commutation frequency.
Initially at ≈115µs period ≈ 9kHz
Therefore one pulse for each of the ecom 3 phases.
See waveform 4 for an individual phase.



3, zoom of 2
5V supply
yellow = mosfet gate, 1V/div, 10µs/div
green = supply at clamp, 5V/div, 10µs/div

Gate voltage returning to zero indicates that the mosfet is being turned on & off during the clamping phase.
The voltage remaining high must then be due to the capacitance in the PSU & Remora.

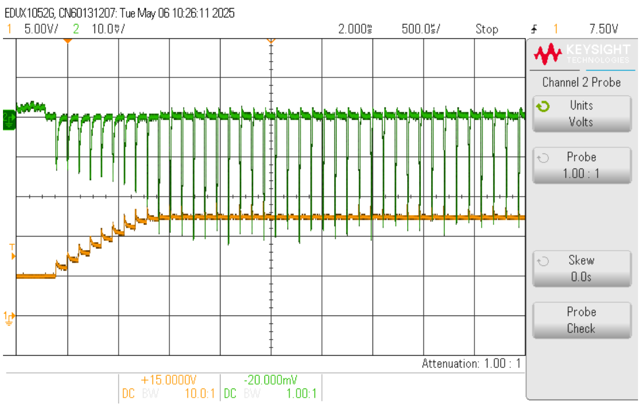


4
5V supply
yellow = ecom V phase output, 5V/div, 500µs/div
green = supply at Remora, 5V/div, 500µs/div

The high amplitude (>10V) spikes on V-phase occur at the commutation frequency.

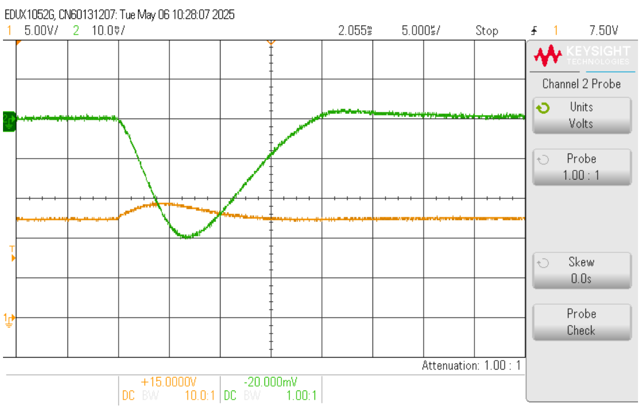
currents

(Remora settings slightly different to those for voltage measurements above, running at slightly higher rpm)



5
5V supply
yellow = supply at Remora, 5V/div, 500µs/div
green = current in Remora +ve line, 2A/div, 500µs/div

The spikes occur at 3× the commutation frequency, i.e. one for each phase.
Initially at ~ 110µs period

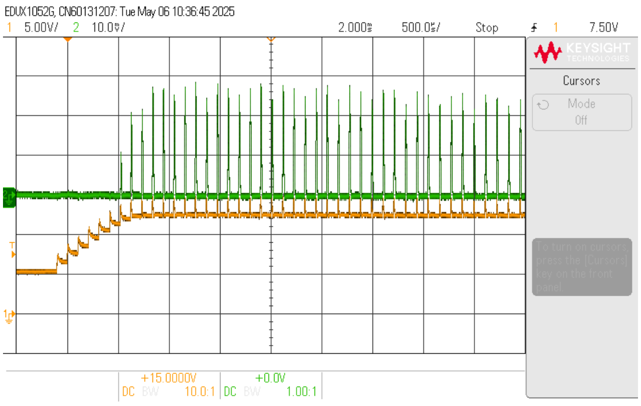


6 zoom of 5

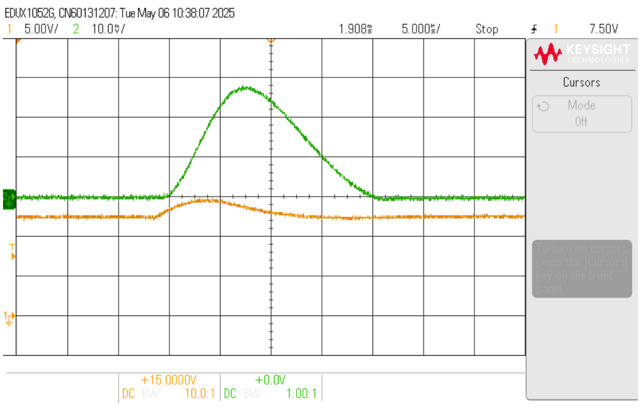
5V supply
yellow = supply at Remora, 5V/div, 5µs/div
green = current in Remora +ve line, 2A/div, 5µs/div

6A peak current fed from Remora to PSU & clamp circuit.
Approximately a triangular shape width 20µs
So average current ≈ 6A ÷2 × 40µs ÷ 110µs = 1.1A

The current & voltage both start to rise at the same time, but peak current is lags the peak PSU voltage by about 6.8µs



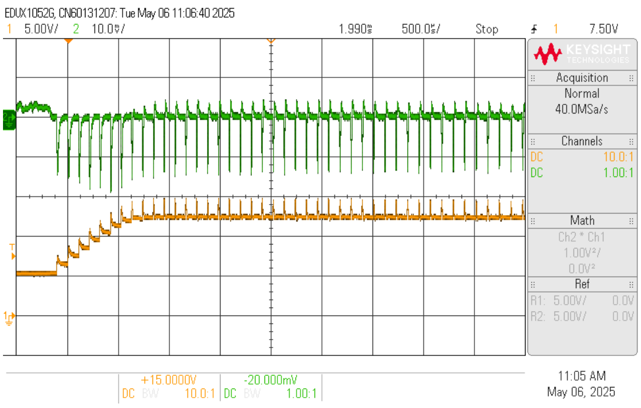
7
5V supply
yellow = supply at Remora, 5V/div, 500µs/div
green = current in clamp +ve line, 2A/div, 500µs/div



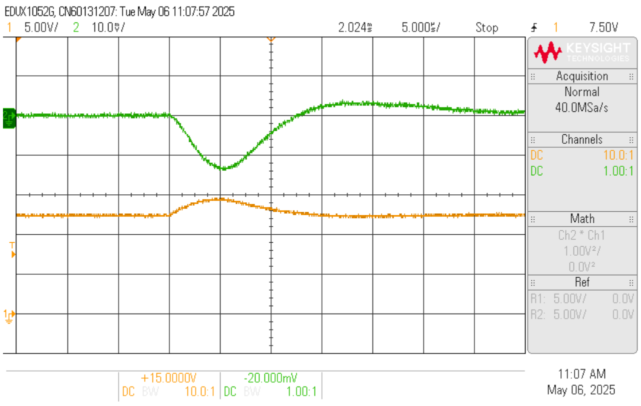
8 zoom of 7
5V supply
yellow = supply at Remora, 5V/div, 10µs/div
green = current in clamp +ve line, 2A/div, 10µs/div

peak current & width are very similar to the current from Remora, but some current must be flowing into the power supply output capacitor as indicated by the rise in the voltage.

The rise in current is delayed from the start of the voltage rise & the peak current lags the peak PSU voltage by about 9µs



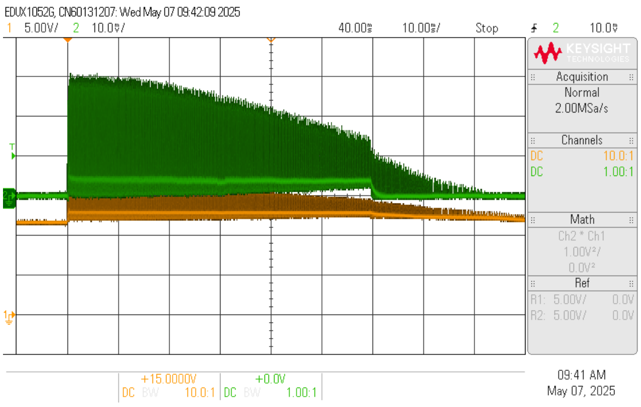
9
5V supply
yellow = supply at Remora, 5V/div, 500µs/div
green = current in PSU +ve line, 2A/div, 500µs/div



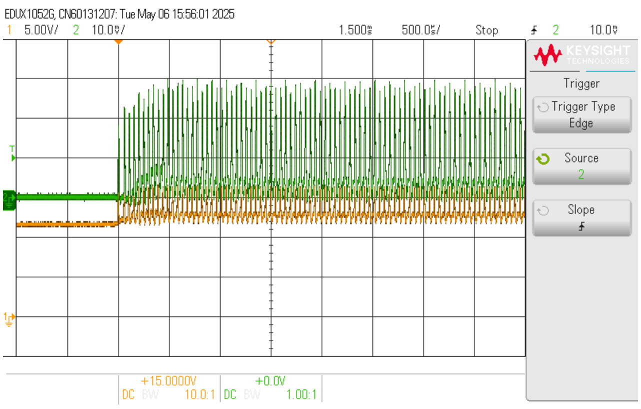
10 zoom of 9

5V supply
yellow = supply at Remora, 5V/div, 5µs/div
green = current in PSU +ve line, 2A/div, 5µs/div

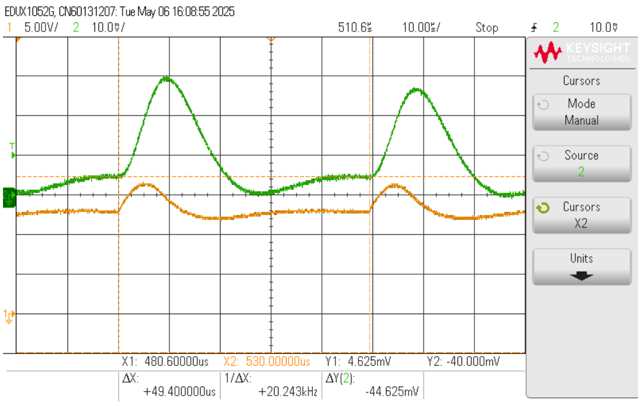
The current & voltage both start to rise at the same time, and peak current is coincident with the peak PSU voltage



11
<u>11.5V</u> supply
yellow = supply at Remora, 5V/div, 10ms/div
green = current in clamp +ve line, 5A/div, 10ms/div



12, as 11 but faster time-base
<u>11.5V</u> supply
yellow = supply at Remora, 5V/div, 500µs/div
green = current in clamp +ve line, 5A/div, 500µs/div



13 zoom of 12

11.5V supply
yellow = supply at Remora, 5V/div, 10µs/div
green = current in clamp +ve line, 5A/div, 10µs/div

ipk = 14.5A
iav from scope measurement =4.22A
irms from scope measurement = 6.1A
current prior to steep rise = 2.3A
period = 49.4µs
Approximately a triangular shape width = 23µs
2.3A step width = 9.4µs
0A to 2.3A ramp width = 10µs

check on iav:
Iav ≈ [(14.5÷2×23µs)+ (2.3÷2×10µs) + (2.3×9.4µs)]÷ 49.4µs = 4A, in reasonable agreement with scope measurement.

Vpk = 16.5V Vav = 13.25V
so power = 13.25V × 4.22A = 56W scope maths = 55W
From waveform 11 duration ≈ 60ms so energy = 3.36J

Mosfet Safe Operating Area (SOA) & Thermal considerations

Mosfet SOA
Using IRLB3034 as an example of an SOA chart, because used it in the thermal calculation example below

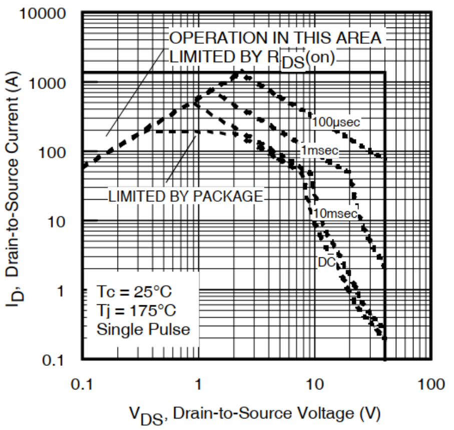


Fig 8. Maximum Safe Operating Area

At 11.5V supply the current pulses are about 15A with a triangular shape of width 23µs, but to allow a generous safety margin use 30A & 50µs. SOA data usually has plots of curves at 100µs so use this instead of 50µs giving an even greater safety margin. The voltage for the SOA will be 15V.

Taking the IRLB3034 SOA as an example its DC SOA at 15V is only about 3A, but its 100µs SOA is about 200A, however this is for a temperature rise of 150°C from 25°C to 175°C. For a good lifetime better to restrict the temperature rise to 75°C so therefore the 100µs SOA current would be reduced to 100A.
This is still in excess of our requirement of 30A so is OK.
The actual temperature rise for the 15A 23µs triangular pulse will be very considerably lower than 75°C.

Thermal calculations

just to get an estimate of whether a heatsink is required or not.

thermal energy formula: Q = m × c × Δt
Q = energy J
m = mass kg
c = specific heat capacity J / kg · K
Δt = temperature rise K (or °C)

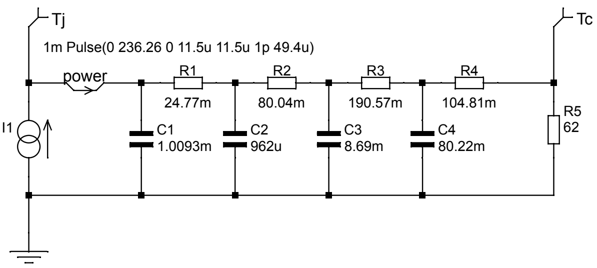
If the energy was dumped in an aluminium heatsink
specific heat capacity = 900 J / kg · K
allow 20K temperature rise for the aluminium
∴ mass = 0.19g

If the energy was dumped in a copper sheet
specific heat capacity = 385 J / kg · K
allow 20K temperature rise for the copper sheet
∴ mass = 0.44g

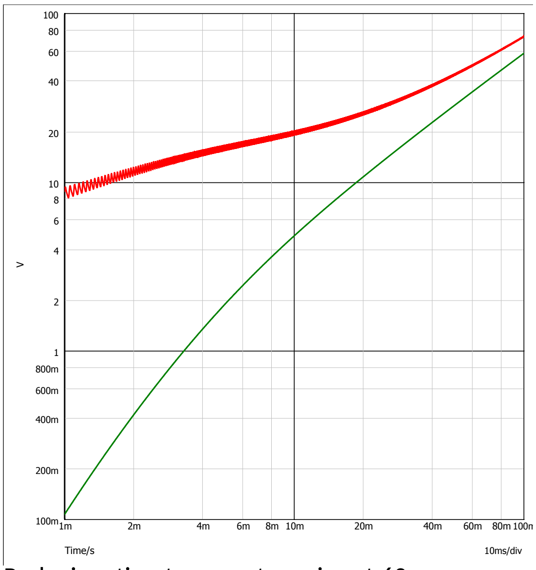
For reference the total mass of a TO-220 is about 1.9g, so it may be able to absorb the energy without an additional heatsink.

Thermal simulation model

Using IRLB3034 in a TO-220 package as an example.
Because it has a thermal model on the data-sheet.
(Although it only has a moderate DC SOA its pulse SOA is acceptable).
Triangular power pulses applied with 55W average, see waveform 13.
R5 with a thermal resistance of 62K/W represents a TO-220 without a heatsink.
In the model:
current represents thermal power
voltage represents temperature



IRLB3034 thermal model results



Red = junction temperature rise at 60ms, average = 50°C & temperature ripple due to the individual triangular power pulse is small at about 2°C.
green = TO-220 case temperature rise, at 60ms = 35°C

So a TO-220 package without a heatsink has an acceptable temperature rise for a single 60ms burst of pulses, even with an 11.5V supply.