What’s all this ‘thermal resistance’ stuff anyhow?

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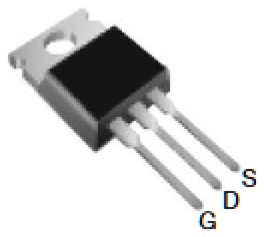
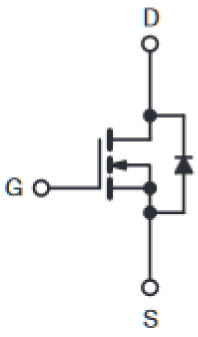
Recent discussions on the AeroElectric List have touched on demonstrably deficient designs for rectifier/regulators used on permanent magnet alternators. Designs for such devices are critically dependent on keeping solid state devices within the product below temperature limits. Rectifier/regulator components are in series with the alternator’s output. There are four (single phase) to six (three phase) devices within the R/R that must on average carry 50 or 33 percent of the system’s present load current.

A 10-Amp rated, PM alternator will require pairs of control devices to carry the output current on each half-cycle of the alternator’s AC output. Hence, they must be electronically sized to carry 5 amps of current in an environment that may well exceed 70°C. Given that the voltage drop across any device is never zero, then it’s a given that power will be dissipated within the device . . . power that will raise the device’s operating temperature. Maximum operating temperatures are bounded by the physics of virtually every electronic or mechanical design. As a rule, electronic devices fabricated from silicon will have maximum operating temperatures on the order of 175°C, mechanical devices will be temperature limited based on material strengths, wear rates or lubrication.

Energy always converts from a higher state to a lower state. Temperature is a manifestation of ENERGY. A design goal for our rectifier/regulator designs will be to maintain the silicon junctions of the control devices to some value below 175°C . . . preferably with some ‘head room’ for unanticipated variables in environment, operation or fabrication. To do this we need to channel the flow of energy from the ‘hot’ semiconductor to a ‘cooler’ medium.

TO-220AB

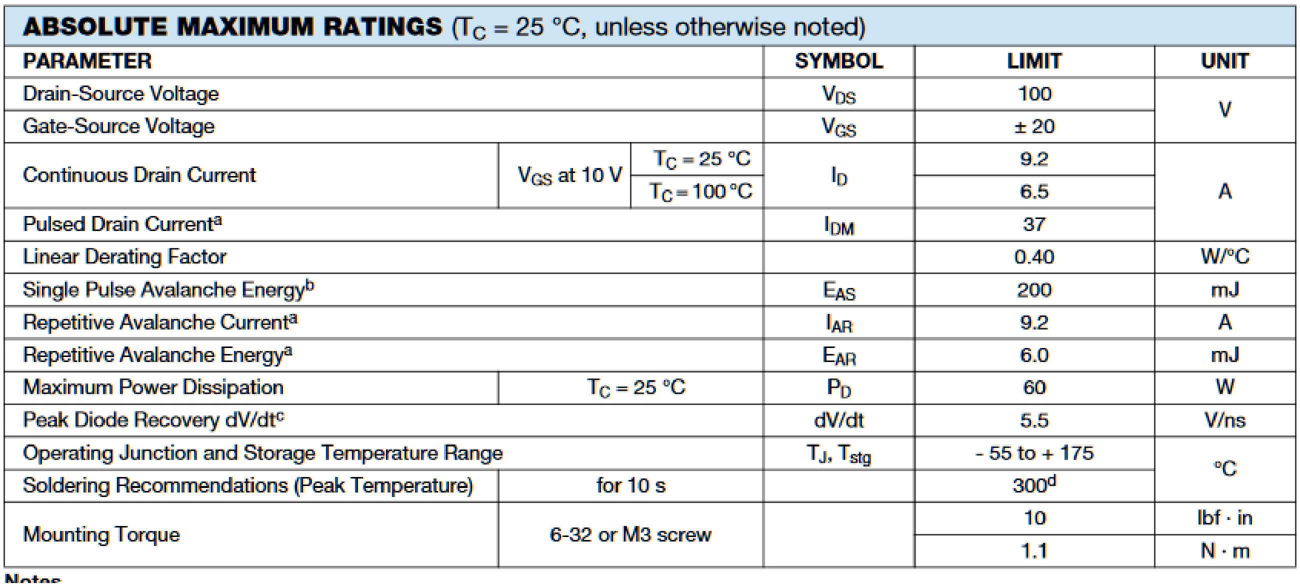




N-Channel MOSFET

This article will illustrate the design studies for implementing an IRF520 power mos-fet into a system wherein the device will dissipate 10 watts of power. The concepts described herein can be applied to every other instance for predicting temperatures for every other energy management situation.

The data sheet for the IRF520 offers keys to the kingdom for keeping the itty-bitty chunk of silicon inside from becoming toast.



ABSOLUTE MAXIMUM RATINGS (T_C = 25 °C, unless otherwise noted)

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-Source Voltage			V_{DS}	100	V
Gate-Source Voltage			V_{GS}	± 20	
Continuous Drain Current	V_{GS} at 10 V	T_C = 25 °C	I_D	9.2	A
		T_C = 100 °C		6.5	
Pulsed Drain Current[a]			I_{DM}	37	
Linear Derating Factor				0.40	W/°C
Single Pulse Avalanche Energy[b]			E_{AS}	200	mJ
Repetitive Avalanche Current[a]			I_{AR}	9.2	A
Repetitive Avalanche Energy[a]			E_{AR}	6.0	mJ
Maximum Power Dissipation	T_C = 25 °C		P_D	60	W
Peak Diode Recovery dV/dt[c]			dV/dt	5.5	V/ns
Operating Junction and Storage Temperature Range			T_J, T_{stg}	- 55 to + 175	°C
Soldering Recommendations (Peak Temperature)	for 10 s			300[d]	
Mounting Torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

Notes

We see this device is rated for 100V, fine . . . our voltage drops across the device will not exceed 28 Volts. We also see that maximum continuous current through the device is 9.2 . . . or 6.5 Amps. Here is the first time we’re presented with a temperature effects limit on the device. Note that 9.2 Amps can be tolerated only when the **case** of the device is kept at or below 25°C. Hmmmm . . . our operating evironment is going to max out at 50°C . . . how do we cool to 25°C? Simple, it cannot be done with ordinary heat-sinking/forced-air techniques.

Running the numbers

Our design calls for an operating drop of 10V at 1A for a dissipation value of 10W. The specs say our victim can handle 6.5A at up to 100°C. No problem . . . moving on . . .

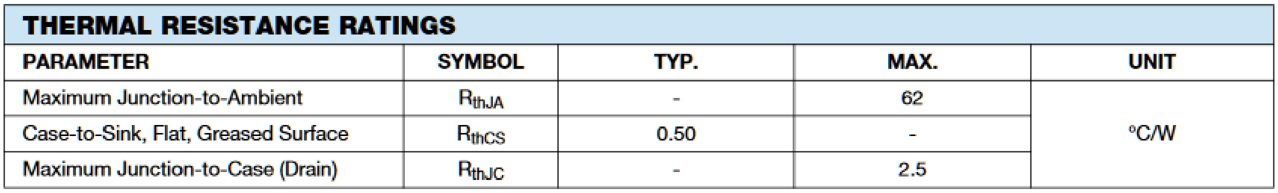
Let’s talk about ‘thermal resistance.’ There is an equation that states:

Theta = °C rise/Watts

where Theta is **thermal resistance** equal to **rise in temperature** stated in degrees C divided by **Watts of power** being pushed into the article under consideration.

Consider an air cooled object stabilized at 25°C over ambient with 3 Watts of power being pumped into it. it may be said to have a device-to-ambient thermal resistance of 8.3 °C/W. If the case of a transistor dissipating 10W mounted to a heat sink running 5°C hotter than the heatsink, the interface between transistor case and heatsink may be said to have a thermal resistance of 0.5°C/W.

Other charts in the IRF520 data cites thermal resistance from junction to ambient for the barefoot device is 62°C/W.



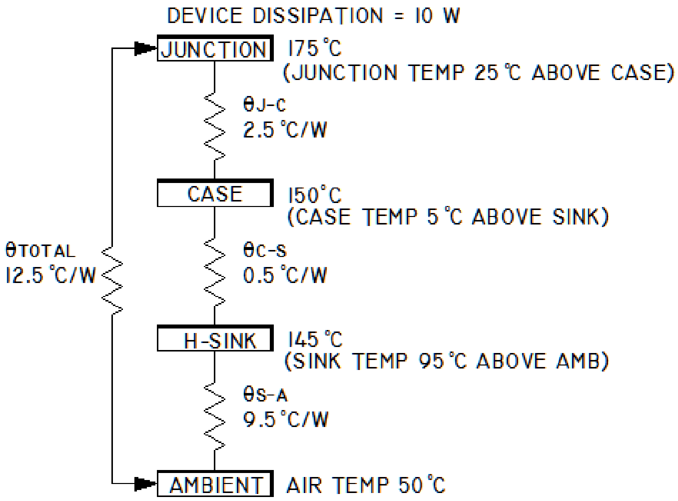
THERMAL RESISTANCE RATINGS

PARAMETER	SYMBOL	TYP.	MAX.	UNIT
Maximum Junction-to-Ambient	R_{thJA}	-	62	°C/W
Case-to-Sink, Flat, Greased Surface	R_{thCS}	0.50	-	
Maximum Junction-to-Case (Drain)	R_{thJC}	-	2.5	

Hmmm . . . if our design calls for dissipation of 10 Watts, a Theta of 62°C/W would yield a 620°C rise. I think our transistor would be trashed. Obviously cannot operate the device at that power level just waving around in free air . . . we MUST provide a lower Theta path over which 10 Watts of power can be dissipated more effectively into the environment.

How low? Assume a 50°C ambient and 175°C maximum junction temperature. That’s a 125°C rise over ambient. Hmmmm . . . 125°C divided by 10 Watts says that total Theta from junction to ambient cannot exceed 12.5°C/W.

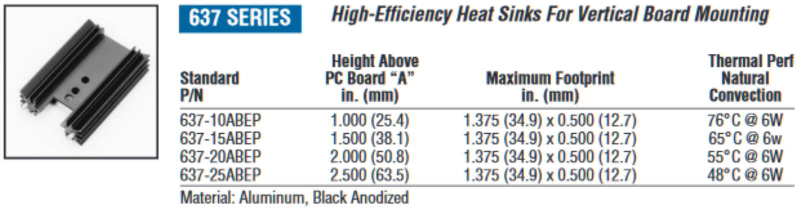
Referring to the IRF520 data we see that junction-to-case Theta is 2.5°C/W. This means Theta for everything outside the transistor cannot total more than 10°C/W. The interface Theta for mounting such devices on heat-sinks is on the order of 0.5°C/W. Here’s how we draw the thermal model for this problem:



At the top we have a silicon junction that cannot be allowed to exceed 175°C. Junction-to-case Theta is 2.5°C/W. Heat-sink insulator and grease under the transistor adds another 0.5°C/W. This means that whatever heat-sinking we provide must present a value for Theta no greater than 9.5°C/W.

Selecting a heat-sink

How much heat sink is that? Referring to a venerable supplier of semiconductor cooling products at http://tinyurl.com/glvb4ox we find this collection of devices:



637 SERIES *High-Efficiency Heat Sinks For Vertical Board Mounting*

Standard P/N	Height Above PC Board “A” in. (mm)	Maximum Footprint in. (mm)	Thermal Perf Natural Convection
637-10ABEP	1.000 (25.4)	1.375 (34.9) x 0.500 (12.7)	76°C @ 6W
637-15ABEP	1.500 (38.1)	1.375 (34.9) x 0.500 (12.7)	65°C @ 6w
637-20ABEP	2.000 (50.8)	1.375 (34.9) x 0.500 (12.7)	55°C @ 6W
637-25ABEP	2.500 (63.5)	1.375 (34.9) x 0.500 (12.7)	48°C @ 6W

Material: Aluminum, Black Anodized

Here we find that the 637-20ABEP has a Theta value of 55°C/6 or ~9°C/W. Note that with dimensions of 2.0 x 1.4 x 0.5 inches, this is NOT an insignificant chunk of metal.

Okay, how do we check any other proposed heat-sink against this limit? Easy. Mount a power resistor and thermocouple to the proposed heat sink. Cause the resistor to dissipate some known wattage. Measure the temperature rise and calculate Theta for the proposed heat sink.

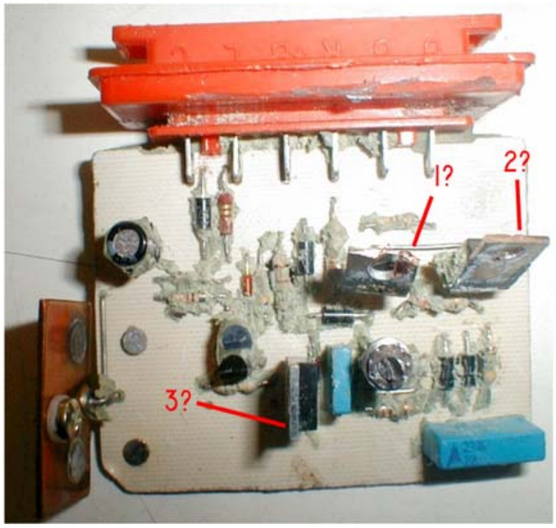
No prudent designer intentially PUSHES semiconductors to maximum operating temperatures. As a general rule, I like to maintain 20-25°C headroom on power devices. My target junction operating temperature drops to 150°C. Okay, now we have total rise of 100°C for 10W for a total Theta of 10°C/W. Substracting fixed Theta values for the transistor and mounting interface we have a new heat-sink target of 7°C/W . . . the heat sink gets bigger.

Where rubber hits the road

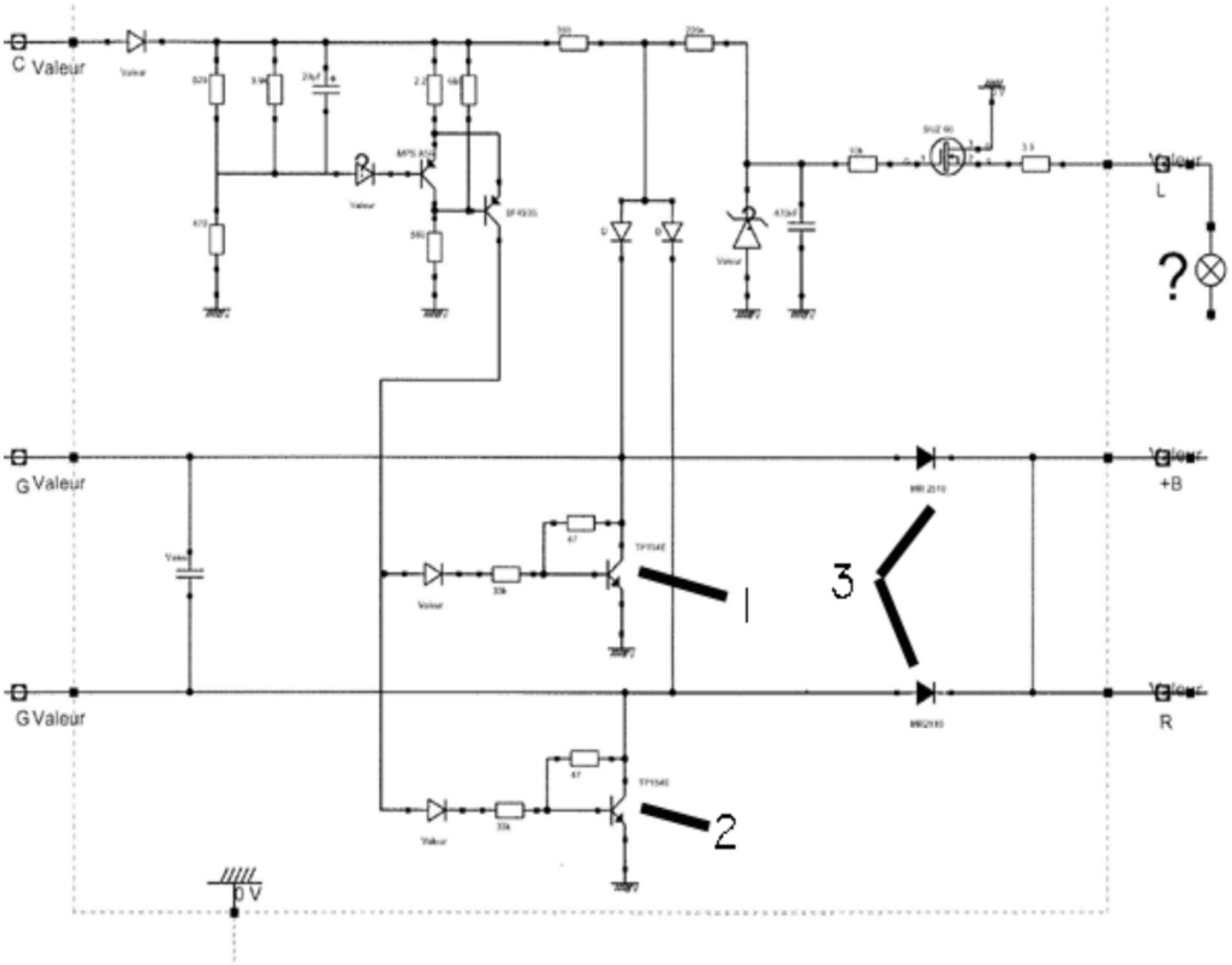
This little ‘practice study’ illustrates thermal management deficiencies in the disassembled Ducatti regulators we’ve seen. The Ducatti R/R supplied with Rotax engines has an outwardly robust appearance with respect to shedding heat.

The enclosure is massive. It appears to be a casting. Heat radiating fins are a substantial proportion of total height. A photograph of a disassembled device reveals three, TO220 style semiconductors labeled 1, 2 and 3 in the image.

The schematic shown here was found on the internet. I do not know its source. I cannot confirm or discount its accuracy. I do know that searches on Google and Digikey produced no hits for TIP154E semiconductor. But the architecture is in the right church, if not the right pew.



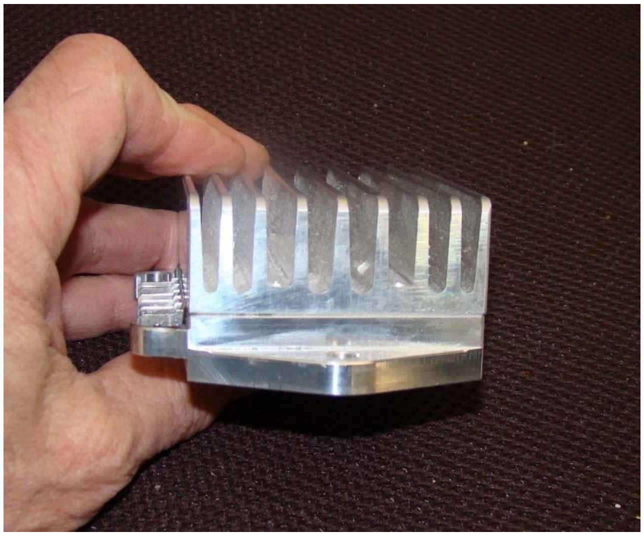
Comparing the schematic with the photo, I am guessing that the two diodes (3) are combined into a single TO220 package. The two control devices shown as transistors at (1, 2) are probably silicon controlled rectifiers. This regulator is supplied with an engine that mounts an 18A, PM alternator. At full load the control devices (1,3) will carry an average current of 9A. The dual diode device is not so lucky. While EACH side of the dual device carries only 9A maximum, they SHARE a heat rejection system. Hence BOTH junctions will be operating at a temperature as if each device was carrying an 18 Amp load.



This design might well work with the components selected if these devices were bolted firmly to an enclosure with substantial heat sinking ability. However, the photo suggests that these devices must depend on the thermal conductivity of the surrounding potting compound. I can tell you from experience that NO electrically insulating potting compound offers more than a small FRACTION of the thermal management properties of the artfully designed power product.

New Kid on the Block

In recent years, a new R/R for PM alternators has been gaining attention in OBAM aviation circles. This product from Silent-Hektik has a nameplate rating of over 30 amps. The heat sink fins are proportionately taller than the Ducatti device while the space for electronics is thinner. It’s a certainty that control devices for this design lay down and are bolted directly to the heat sink.



Feedback Solicited and Welcome

I’ve been intending to do a piece like this for years but kept expecting the marketing folks at Rotax and/or Ducatti to bring the R/R to the next level. As far as I know, the design has remained unchanged for 20 plus years.

I produced this piece in a bit of a hurry . . . seems things around here are breaking about as fast as I fix ‘em. If anyone finds an error of math, perception or deduction, let’s work together to fix the potholes.