Understanding MOSFET Current Ratings

By: *Chuck McManis* August 9th,, 2002

Introduction

The new power MOSFETs from International Rectifier and others are wonders to behold, very low resistance, fast switching times, and reasonably priced. That makes them attractive to use in things like speed controllers. However, before you use them you have to understand what the numbers mean or you may be in for a bad surprise. Many people I know are more than happy to just solder things together and then work on it until their circuit works the way they want. I did that with the first speed controller I built. While the speed controller worked for what I wanted it to do, it also failed for others in mysterious ways that I could not explain. So when I embarked on this process again to build a speed controller for my BattleBot I really wanted to *understand* what was going on. I like to think of it as the difference between *designing* a circuit and *building* a circuit.

Description

The core thing I needed to understand was this, "How much current can the FETs I'm using safely carry?" or conversely, "How many FETs do I need to safely carry my design target of 200 amps?"

The first mistake I made when I set out to design a speed controller was to take the "I_d max" number that people like International Rectifier specify, de-rate it by 20 - 30% and then divide my desired current by that number to figure out how many FETs I need to share the load. Turns out, that was completely, and utterly bogus. Once I understood where this number came from I found I could predict with certitude how any controller I might design would perform.

The first surprise was that the TO-220AB package the FETs were installed in had a lower current limit than the FETs! Discussions with the International Rectifier FE and later with a rep from Motorola confirmed that the limits on the TO-220AB were approximately 75 amps. This limit was due to the heating of the lead frame to the point where the legs would melt. Not something you want to have happen on your board. So even though a FET like the IR1405 has a current spec of 169 amps, the package it is in will melt before it reaches that point. But more importantly, that 169 amp number was crap too, at least it wasn't usable.

So let's walk through this using the IRF1405 as an example since it is a popular low voltage FET. The FET manufacturers report a number of parameters that *when combined* describe how this FET will perform with a given current load. Using the IR1405 as an example we can build up a model.

Building the Model

The first parameter (and the one everyone goes for first) is maximum current through the drain Id(max). For the IR1405 that is:

Id @ 25 °C 169A max.

As it turns out, this is a *derived* number (from the model). That means its basis in reality is limited in terms of design. However it is always true that a "169A FET" is "better" at carrying current than a "75A FET" but how? Let's continue.

Since the next line in the data sheet specifies the current limit at 100 °C, its clear that current and temperature are linked so the next parameter we need for the model is the Max Junction Temperature. That is the limit of how hot the silicon can get before it decrystalizes (a fancy way of saying it melts :-). For the IRF1405 we've got

175 °C Max Junction Temperature

This number establishes and upper limit on our junction, and to complete this part of the puzzle we need to know what is the relationship between current and temperature.

That relationship is defined further on in the data sheet where there thermal resistance of the TO-220 package is specified by the term, Rtheta(jc). The data sheet lists it as:

Rtheta(jc)   0.45 °C/W

What this means in real terms is this, as you start to dissipate power in the FET the difference between the case temperature and the junction temperature is a linear function based on the constant Rtheta(jc). That's the thermal constant between the case and the junction.. Or put another way, the junction temperature on an IR1405 is 0.45 degrees warmer than the case temperature for every watt that the FET is dissipating. When the FET is 'off' and dissipating no power then the case and junction have exactly the same temperature. If the FET is dissipating 100 watts then the junction temperature will be 100 * 0.45 or 45 °C greater than the temperature measured at the case (that's the metal tab on the TO-220).

The power that the FET is dissipating is governed by Ohm's law. The power form is simply:

$$P = I^2R$$

But what's R? That would be the FET's resistance between the drain and source or Rds(on), the datasheet lists it as 5.3 milliOhms. But before we go there, let's take what we know and compute backwards.

Given the junction melts at 175, the case is at 25 degrees (its part of the Id(max) spec), and Rtheta(jc) is .45 dC/Watt. How many watts would we be dissipating if the case was at 25 degrees and the junction was at 175? Answer :

$$(175 - 25) = 0.45 * \text{Watts}$$
$$333 = \text{Watts}$$

This matches another value in the datasheet which is the P_D @ T_C 25 °C. (Or in english, Power Dissipated at a case temperature of 25 degrees) which is 330 watts. Now, what is the maximum current we can carry in this FET ? Again by the data sheet 169A. So now we can use the formula $P = I^2R$ to compute what the internal resistance is, if we're dissipating 333 watts.

$$333 = (169)^2 * R$$
$$.0117 = R$$

But wait, isn't Rds(on) on this fet 5.3 milliOhms not 11.7 milliOhms? Why yes it is, **at 25 °C**, but looking into the data sheet reveals a table that shows Rds(on) increases with temperature. How much? Well at 175 degrees (again based on the data sheet) Rds(on) is at about 2.25 x its nominal value. 5.3 mOhms * 2.25 is, wait for it, 11.9 milliOhms.

So what does this tell us? Well we can validate numbers on the data sheet and that's pretty cool. But it also tells us that at 169 amps the FET would be dissipating 333 Watts and we would have to remove all 333 watts from the case instantly to keep it cool (zero thermal resistance) and frankly that's not possible without some interesting cryonics or a really big heat sink. Further we know that at 75 amps the legs on the FET would melt so it would be a futile effort. Bottom line, we can't really use this number for anything except to help us build the model.

Real World Applications

However, now that we've got a good model for the FET let's explore the datasheet a bit more and find out another interesting tidbit. Which is, how much current can this FET safely carry standing in free air without any sort of heat sink? (something of interest to Victor 883 owners no doubt :-)

Let's do the math:

Looking further into the data sheet we see that the Rtheta(ja) which is junction to ambient air. Is 62 °C/Watt. This tells us that in still air, the junction is 62 degrees warmer than the temperature of the ambient air for each watt of power we're dissipating.

Again we know the max junction temperature is 175 degrees. Assuming the FET is sitting in air that is at room temperature or 25 degrees there is 150 degrees difference between the ambient air and the junction. Using that number and plugging in our 62 degree constant we get:

$$P = 150\ °C\ /\ Rtheta(ja)\ (°C/W)$$
$$P = 150\ °C/\ 62\ \ (°C/W)$$
$$P = 2.42\ Watts$$

This means that the FET can be dissipating 2.42 Watts and continue working.

As we know that the Rds(on) value at 175 degrees will be 11.3 milliOhms from our previous exercise so we use that to calculate our current using Ohm's law again as follows:

$$P = I^2R$$
$$2.42\ W = I^2 * 11.3\ mOhms$$
$$214.16 = I^2$$
$$sqrt(214.16) = 14.6\ Amps$$

Since we don't know really what the ambient air temperature will be, but we do know that it probably won't be more than 40 °C, if we re-do this calculation substituting that as the ambient temperature we get about 13.8 amps. So **this** is the number you might want to use when calculating current capacity for an "unaugmented" system. (i.e. one without additional heat dissipation capacity.) Remember however that while the ambient air is only 40 degrees, the difference between the case and the junction is still ruled by that .45 °C/W constant so the case will be 175 - (2.4 W * .45 °C/W) or 174 °C! That's still way hotter than boiling water so its hot!

Now one really cool thing is that I used an HP power supply (current limited) and a clamp on temperature probe to validate my FETs based on this understanding and they correlated very nicely with the data sheet. Remember it never hurts to cross check your results.

Thermal Management

To build a 200 amp controller I knew I couldn't use 200/14.6 or 14 FETs per "leg" in the H-bridge. Not only is that a boatload of FETs (56 for a full bridge) but its really difficult to get them all to turn on at the same time and quickly. So I had to ask a different question, but one the model is prepared to answer.

"If I use 8 FETs, what does that Rtheta(ja) need to be to keep them at 175 °C junction temperature given a 40 °C ambient air temperature?"

To solve this question we need to add another parameter from the data sheet. This one is Rtheta(cs). This is the thermal constant between the case (c) and the heatsink (s). In the IR datasheet this is specified as 0.5 °C/W. This value **adds** to the Rtheta(jc) number since they are thermally "in series" if you will, and so we have a Rtheta(js) junction to sink of 0.95 °C/W.

With 8 FETs equally carrying the 200 amp load, we have each FET carrying 25 amps. Since we're doing a worst case calculation with the junction temperature at 175 degrees and thus Rds(on) at 11.3 milliohms, we know that power dissipation will be 25 amps squared times 11.3 milliOhms, or 7 watts.

As we know the temperature differential between the junction (175 degrees) and the ambient air (40 degrees) is going to be 135 degrees. And we know we're dissipating 7 watts. Then the Rtheta(ja) of our heat sink system must be at least 135/7 or 19.3 °C/W.

Given that we know the Rtheta(js) is .95 °C/W, that means our heatsink needs an Rtheta(sa) (sink to ambient) of 19.3 - .95 or 18.3 °C/W.

If we reach that point or do better (and even lower Rtheta(sa)) we can say authoritatively that the speed controller will carry a 200 amp load continuously without the MOSFETs failing.

The bottom line is that is how I know *exactly* how much current my speed controller can deal with steady state, and in short bursts. (the bursts get a bit more complicated because you have to know the thermal "mass" or capacity of your sink system.)

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