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# How To Remove Heat From A MOSFET Bridge Quickly

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Nowadays electronic power devices shrink in size and consume or produce more power. This means power density rises. Although the efficiency of power supplies goes up continually with advances in technology, it cannot increase without limits. Even low power dissipation within a small volume creates substantial temperature rise.

In modern electric vehicles multi-phase motors and inverters are used. The power consumption of these motors and the associated power dissipation in the inverters driving these motors varies over a wide range. At startup when the motor is still stalled, the inverter transistors' current may reach 900 A to 1000 A, which causes instantaneous power release of up to 2.5 kW in the inverter transistors.

This power (heat) should be immediately removed from the transistors and diverted either to some power absorption component or some power conducting component for further dissipation to the atmosphere or cooling system. Typically, we are talking about time intervals of up to just 5 seconds long. Usually, under normal inverter operation when the motor is running, the inverter transistors do not see such high power levels.

Power can be removed in a few physical ways:

- Convection—not a good solution due to the low specific heat of air
- Radiation—also not good because there's no area to radiate to
- Conduction—much better if heat is transferred to a pre-cooled object, and
- Thermal absorption—the best alternative for fast heat removal when no further spikes in heating are expected.

If the two last methods utilize Peltier elements[1] to pre-cool the heat absorbing or dissipating device, the efficiency of the heat removal from the inverter improves and its reliability improves too.

The heat absorbing method is based on heating a massive thermally conductive pad, whose temperature rises within a safe range for a short time keeping the inverter transistors within their safe temperature range. The heat absorbing pad may be cooled by a system of pipes with flowing coolant inside and by use of convection or thermal conduction to remove the heat from the conductive pad.

Note that the removal of heat from the heat absorbing pad may be performed over a longer time period than the removal of heat from the inverter transistors. But the main job of cooling the transistors is performed by the massive heat absorbing pad (see the figure).

An alternative to the absorption method of cooling the transistors described above is the use of a conduction method whereby an interim thermally conducting pad diverts the heat flow from the inverter transistors directly to the water-cooled or air-cooled heat sink. However, that puts the burden of quick heat removal on the heatsink and may in fact require oversizing of the heatsink.

This article focuses on the absorption method. It derives equations for determining the size of the thermally conductive pad required based on the energy to be absorbed quickly and dissipated more slowly later. It also derives an equation for verifying that the rate of heating of the pad is greater than the rate of heating by design requirements. A design example is then presented that illustrates the use of these equations.

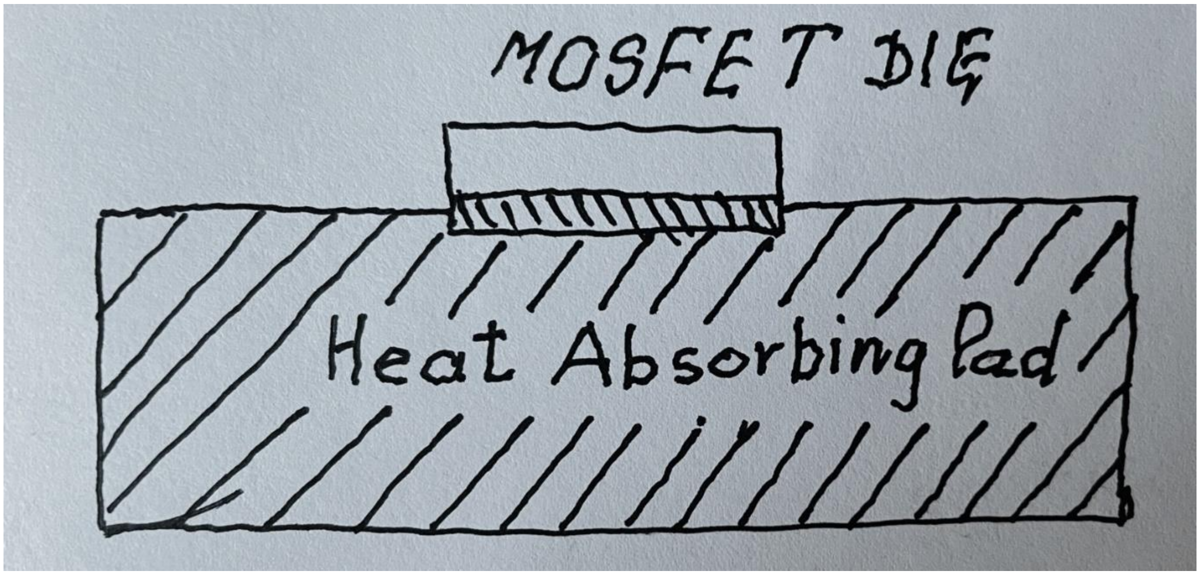

*Figure. A single MOSFET die mounted to a heat absorbing pad. The bare die is passivated and electrically isolated from the pad with a few layers of high-resistivity material.*

**Ability Of Metal Pad To Absorb And Conduct Heat**

While absorbing energy in the form of heat, the temperature of the absorbing pad goes up due to the increase in the oscillation speed of its molecules and, in the case of metals, the increase in the speed of the electrons' movement. This is why the bigger the pad's mass, the higher power it can absorb for a given temperature change.

To determine the relationship between a pad's mass and its ability to dissipate power, we'll start by defining the following parameters.

$Q_{abs}$ = energy to be absorbed by the absorbing pad

$m_{pad}$ = mass of the absorbing pad

$\Delta T$ = temperature change that the absorbing pad should experience due to energy absorption

$\delta_{abs}$ = specific absorption constant for the absorption pad material

$I_{pk}$ = peak current through the bridge diagonal

$R_{DS(ON)}$ = The effective channel on-resistance of the MOSFET(s). There might be a few connected in parallel, including bare dies

$\tau_h$ = duration of the peak current occurrence in the MOSFETs defined by the project requirement.

The energy absorbed by a thermally conducting pad is defined by the following equation. (Note that the best results are obtained with copper pads.)

$$Q_{abs} = m_{pad} \cdot \Delta T \cdot \delta_{abs} \qquad (1)$$

Thus

$$m_{pad} = \frac{Q_{abs}}{\Delta T \cdot \delta_{abs}} \qquad (2)$$

Since there are two MOSFETs in series in the bridge that are active at any time with a 50% duty cycle and assuming switching loss is equal to static loss per design, we must quadruple the value of energy dissipated by one MOSFET $Q_{diss}$ to get the energy dissipated by the whole bridge.

$$Q_{diss} = 4 \cdot \left(I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \tau_h\right)$$

This energy should be equal to the energy absorbed by the heat absorbing pad, thus

$$Q_{abs} = Q_{diss} = 4 \cdot \left(I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \tau_h\right) \qquad (3)$$

Plugging in equation (3) into (2), we get an expression for the required mass of a heat absorbing pad for two MOSFETs:

$$m_{pad} = \frac{4 \cdot I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \tau_h}{\Delta T \cdot \delta_{abs}} \qquad (4)$$

Now, we can calculate the volume and thickness of the heat absorbing pad. Defining the material (copper) density as $\delta_{CU}$, we find the volume of the heat absorbing pad as

$$\text{Volume} = \frac{m_{pad}}{\delta_{CU}} \qquad (5)$$

and the pad thickness as

$$\text{Thickness} = \frac{\text{Volume}}{A_{pad}} \qquad (6)$$

where $A_{pad}$ is the heat absorbing pad area.

Now, using reference [2] we can define how fast the heat absorbing pad changes its temperature by ΔT

Starting with equation (3), the heat to absorb $Q_{abs}$ is

$$Q_{abs} = 4 \cdot \left(I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \tau_h\right) \qquad (7)$$

and from reference [2] the expression defining heat travel along a thermal conductor is

$$Q_{abs} = \frac{t_{abs} \cdot k_{\Theta cond} \cdot A_{pad} \cdot \Delta T}{\text{thickness}} \qquad (8)$$

where $k_{\Theta cond}$ is the coefficient of specific thermal conductivity of metal that the heat absorbing pad is made from.

Equating (7) and (8), we obtain

$$4 \cdot \left(I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \tau_h\right) = \frac{t_{abs} \cdot k_{\Theta cond} \cdot A_{pad} \cdot \Delta T}{\text{thickness}} \qquad (9)$$

Solving (9) for $t_{abs}$ we get

$$t_{abs} = \frac{4 \cdot I_{pk}{}^{2} \cdot R_{DS(ON)} \cdot \text{thickness} \cdot \tau_h}{A_{pad} \cdot \Delta T \cdot k_{\Theta cond}} \qquad (10)$$

If $t_{abs} < \tau_h$ the absorption process is faster than the heat creation process, and the heat absorption pad works properly. Otherwise, some pad geometry tweaking might be required.

## Design Example For A Heat Absorbing Pad

Suppose we need to remove heat quickly and efficiently from an automotive inverter at startup. The relevant inverter parameters are as follows:

Peak current at startup is

$I_{pk} = 920$ A

The combined channel resistance for a few SiC MOSFET dies in parallel:

$R_{DS(ON)} = 0.0019\ \Omega$

$\tau_h = 5$ s

Maximum operating temperature is

$T_{max} = 170$ K

Minimum temperature at startup defined by the cooling system is

$T_{min} = 70$ K

The die's allowed temperature change is

$$\Delta T = T_{max} - T_{min} = 100\ K$$

For a copper pad

$$\delta_{abs} = 385\ \frac{J}{kg \cdot K}$$

Using equation (4) we obtain:

$$m_{pad} = \frac{4 \cdot I_{pk}{}^2 \cdot R_{DS(ON)} \cdot \tau_h}{\Delta T \cdot \delta_{abs}} = 0.835\ kg$$

This means that a thermally absorbing copper pad having a total mass of $m_{pad}$ can absorb the following amount of energy

$$Q_{abs} = 4 \cdot I_{pk}{}^2 \cdot R_{DS(ON)} \cdot \tau_h = 3.216 \text{ x } 10^4\ J$$

produced by an inverter's bridge at startup.

It is interesting to know how big the heat absorbing pad would be.

Copper density is:

$$\delta_{CU} = 8940\ \frac{kg}{m^3}$$

Thus

$$\text{Volume} = \frac{m_{pad}}{\delta_{CU}} = 0.093\ L$$

Assuming an absorbing pad area of

$$A_{pad} = 6.5\ \text{cm} \cdot 6.5\ \text{cm} = 4.225\ \text{x}\ 10^{-3} \text{m}^2$$

the pad thickness should be

$$\text{Thickness} = \frac{\text{Volume}}{A_{pad}} = 0.022\ \text{m}$$

We can verify that the pad performs adequately by checking that $t_{abs} < \tau_h$.

First, we can calculate $t_{abs}$.

Given the values determined above and noting that $k_{\Theta cond} = 392 \frac{W}{m \cdot K}$, we find

$$t_{abs} = \frac{4 \cdot {I_{pk}}^2 \cdot R_{DS(ON)} \cdot \text{thickness} \cdot \tau_h}{A_{pad} \cdot \Delta T \cdot k_{\Theta cond}} = 4.295\ \text{s}$$

Recalling that $\tau_h$ = 5 s, we see that

$t_{abs} < \tau_h$

Therefore, this heat absorbing pad will work properly for a four-transistor MOSFET bridge at a 920-A startup current.

## References

1. Thermoelectric Handbook, Laird Thermal Systems website.
2. "Steady Heat Conduction," by M. Bahrami, Simon Fraser University website.

## About The Author

*Gregory Mirsky is a design engineer working in Deer Park, Ill. He currently performs design verification on various projects, designs and implements new methods of electronic circuit analysis, and runs workshops on MathCAD 15 usage for circuit design and verification. He obtained a Ph.D. degree in physics and mathematics from the Moscow State Pedagogical University, Russia. During his graduate work, Gregory designed hardware for the high-resolution spectrometer for research of highly compensated semiconductors and high-temperature superconductors. He also holds an MS degree from the Baltic State Technical University, St. Petersburg, Russia where he majored in missile and aircraft electronic systems.*

*Gregory holds numerous patents and publications in technical and scientific magazines in Great Britain, Russia and the United States. Outside of work, Gregory's hobby is traveling, which is associated with his wife's business as a tour operator, and he publishes movies and pictures about his travels online.*

For more on thermal management in power electronics design, see How2Power's Design Guide, locate the "Design area" category and select "Thermal Management".