Protection and measurement systems for power electronics

Resistive current sensing

Low valued resistors are often used to provide voltage feedback proportional to current. They are connected to a load as shown in Figure 1.

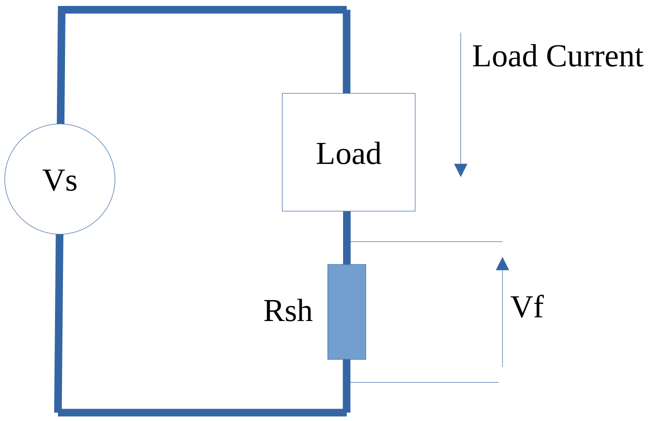
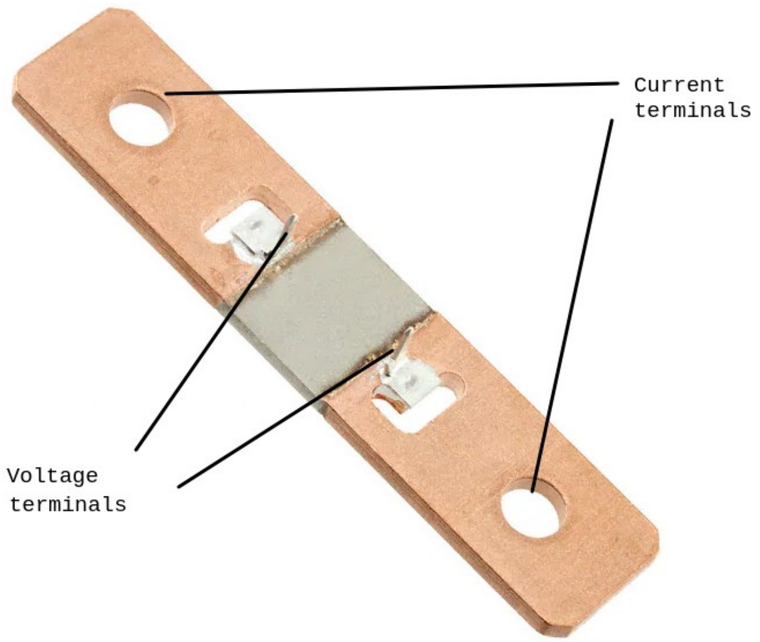


Figure 1: A shunt resistor providing current feedback

These low-valued resistors are often called ***Shunt*** resistors. They are chosen so that they can safely carry rated current (with headroom) and such that they do not cause significant voltage drops in the circuit. Often these resistors have values in the milli-ohm range and will have four terminals as shown in Figure 2.

Figure 2: A four terminal shut resistor. The resistor is bolted to the load and power supply using the current terminal holes. The voltage terminals are connected to the control circuit.



Why four terminals? The connections between the load and the shunt resistor can never be perfect and will have some small resistance. The copper strip of the resistor is also slightly resistive – especially if it heats up. These contact and copper resistances are not known and can vary. The resistive element in the centre is however known and should remain reasonably constant. It is the voltage across the resistive element that we need to measure to get an accurate representation of the load current.

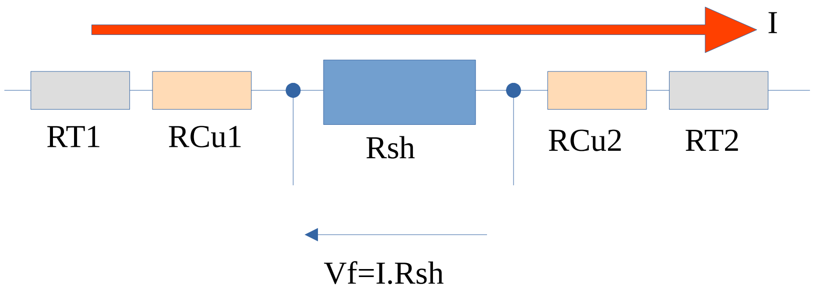


Figure 3: Equivalent circuit of a four terminal resistor showing contact (terminal) resistances RT1 and RT2; copper resistances RCu1 and RCu2 and known shunt resistance Rsh. Vf is measure across the voltage terminals

Shunt resistors such as this can be used with electrically isolated (Galvanic isolation) amplifiers such as the Si8920. This amplifier has a propagation delay of less than 2μs. Figure 4 shows a block diagram of the Si8920

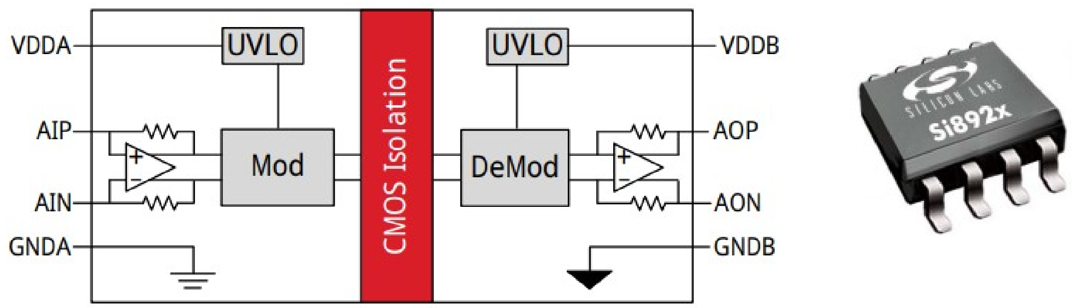


Figure 4: The Si8920 isolation amplifier

Some semiconductor bridge circuits make use of the on-state resistance of the lower MOSFET to sense excess currents. Power MOSFETs internally consist of many small MOSFETS wired in parallel. Sensing MOSFETS apportion a few of these smaller MOSFETS for current sensing purposes and “bleed off” a portion of the full load current to an external sense resistor.

The voltage obtained from the current feedback Vf can be used as a continuous variable in some control algorithm or simply logged. It could also be used as an input to a comparator where it is compared with some reference value. If the reference voltage is exceeded then a shutdown of the overall circuit may be triggered.

Hall effect sensors

An alternative to the sense resistor is a Hall-effect sensor.

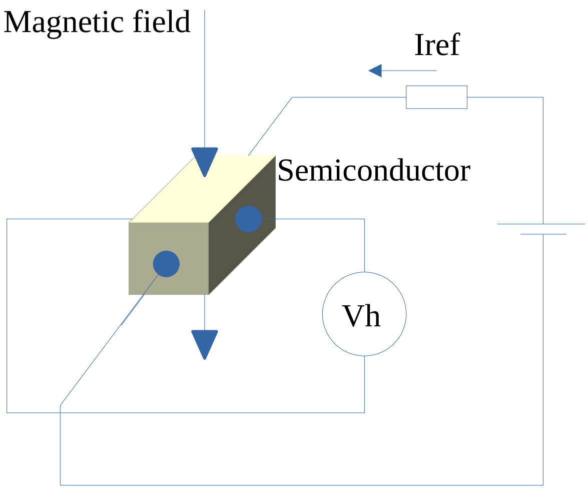


Figure 5: The Hall effect.

The Hall effect arises when you have a current carrying semiconductor in the presence of a magnetic field. The magnetic field deflect the flow of charge carriers through the the conductor causing them to flow along one side. This leads to a potential difference – the Hall Voltage (Vh) as shown in Figure 5 above. The voltage produced depends on the magnetic field and the reference current level. If the reference current is known then Vh only depends on the magnetic field strength. The magnetic field can be obtained by winding current carrying conductors around a ferrite core which concentrates the field on to the semiconductor. Figure 6 shows a two examples of commercial Hall effect current sensors.

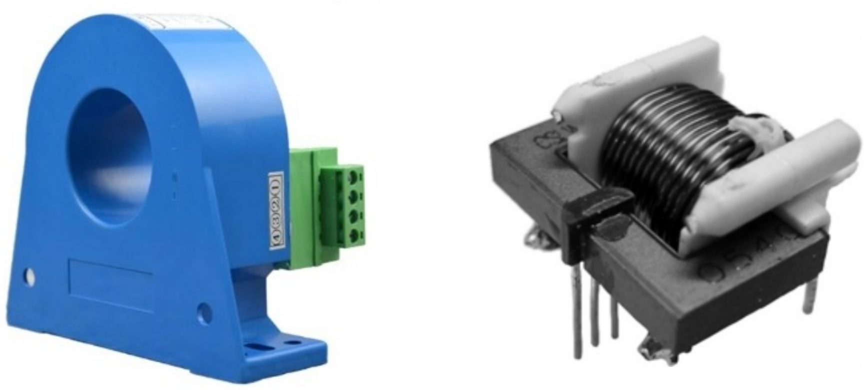


Figure 6: Commercial Hall effect current sensors

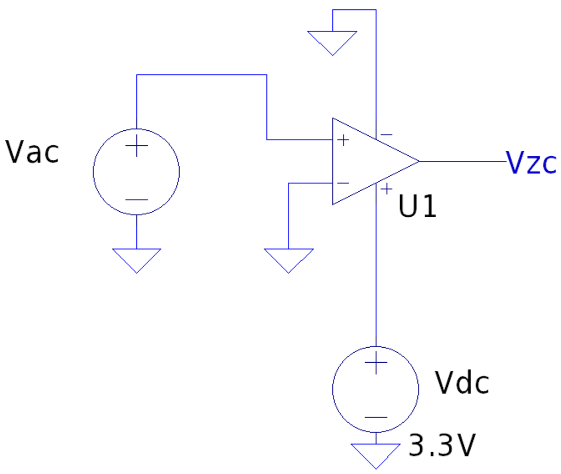
It is worth noting that Hall effect current sensors provide electrically isolated current measurement and, unlike traditional current transformers, they can operate down to DC and are much safer to use.

It is also possible to measure voltages using a Hall effect sensor

Zero cross detection

Zero cross detection is the process of converting a mains voltage waveform into a signal that is usable by control electronics. Typically this will involve converting the mains voltage signal to a square wave which is usable by a digital control device such as a DSP chip or a microcontroller. Zero cross detectors often are required to include electrical isolation between the mains and the control electronics.

Comparator based zero-cross detector



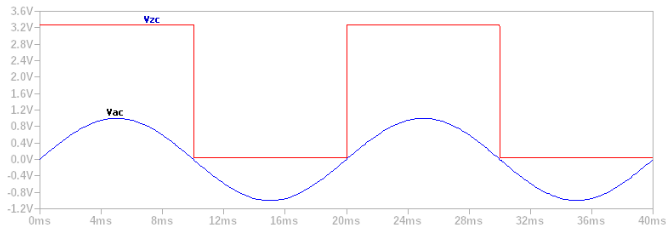


Figure 7: A comparator based zero cross detector.

An idealized comparator based zero cross detector is shown in Figure 7. When Vac goes above 0V, the output of the comparator Vzc goes high. When Vac goes negative, Vzc goes low. The AC input in this idealized case is a pure sine-wave it's negative excursions don't cause problems for the comparator (this is not always the case). What happens when noise is introduced?

Figure 8 shows the effect of this on the output of the comparator. As you can see there are oscillations around each zero crossing because the noise pushes the comparator's non-inverting input above and below zero repeatedly in a random fashion.

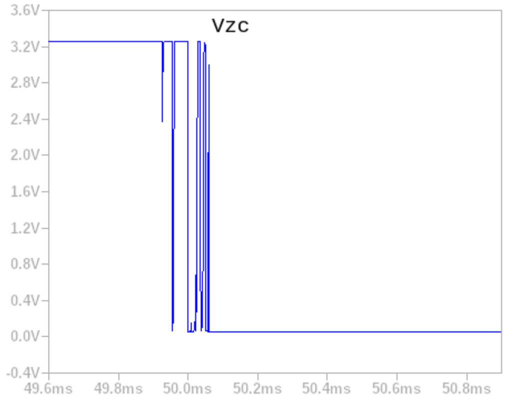


Figure 8: Oscillations due to noise in zero cross detector

Adding an input filter (or output) can reduce or eliminate these oscillations. Adding hysteresis to the comparator can also help. Both of these solutions can lead to an undesirable side effect: a phase shift between the zero cross detector and the ZCD output signal. Figure 9 shows the comparator with a hysteresis feedback loop and protection against large negative input voltages.

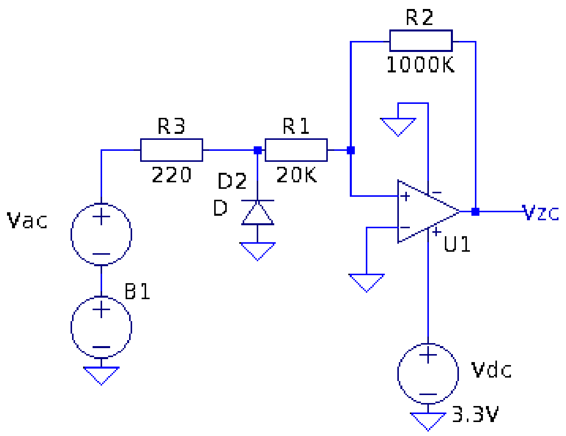


Figure 9: ZCD with hysteresis and input protection

The AC input to this form of zero cross detector can be obtained from a low VA transformer which will provide electrical isolation from the mains. Transient over-voltage suppression (see below) may need to be fitted also.

Optically coupled zero cross detector

An optically coupled zero cross detection can also be constructed using an opto-isolator as shown in Figure 10.

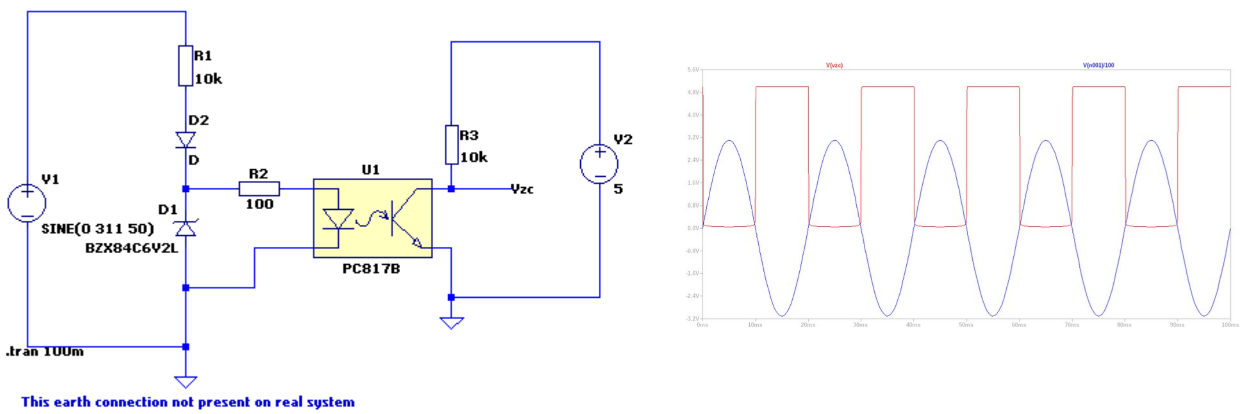


Figure 10: Optically coupled Zero Cross Detector.

Off-the-shelf IC solutions are also available such as this:

https://fscdn.rohm.com/en/products/databook/datasheet/ic/power/isolated_converter/bm1z002fj-e.pdf

Over-voltage protection.

The following components are commonly used for over-voltage protection

Zener diodes

Zener diode clamps are useful for protecting inputs to sensitive electronics.

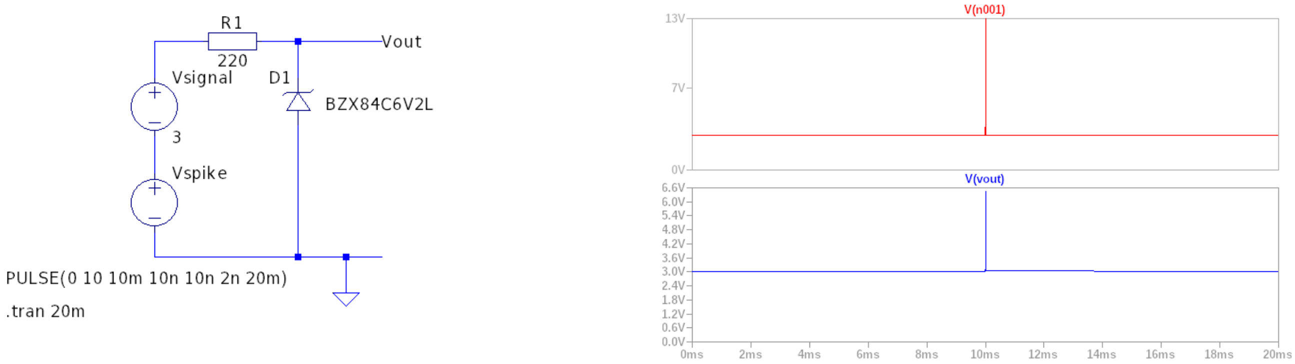


Figure 11: A zener voltage clamp

Figure 11 shows a zener diode and resistor protecting a circuit. The input voltage V(n001) is a steady DC level with a transient spike of 13V. The output voltage from the clamp circuit (V(vout)) is clamped at approximately the zener voltge. R1 is necessary to limit current in to the zener diode. See here for TVS diodes:
https://www.mouser.ie/datasheet/2/240/Littelfuse_TVS_Diode_SMCJ_Datasheet_pdf-1317380.pdf

Metal-Oxide-Varistor

Higher voltage (and energy) protection can be achieved using a Metal-Oxide Varistor. MOV's behave a little like a zener diode in that they conduct when the voltage across them goes beyond a specific level. The symbol used for them is shown in Figure 12. MOV's clamp in both directions. Figure 13 shows the VI characteristic for an MOV

An example data sheet for an MOV is
https://www.bourns.com/docs/Product-Datasheets/MOV07D.pdf

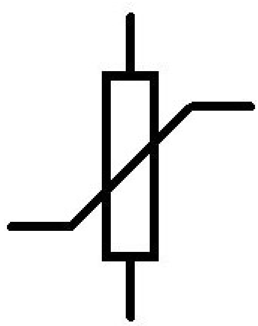


Figure 11 : Symbol for an MOV

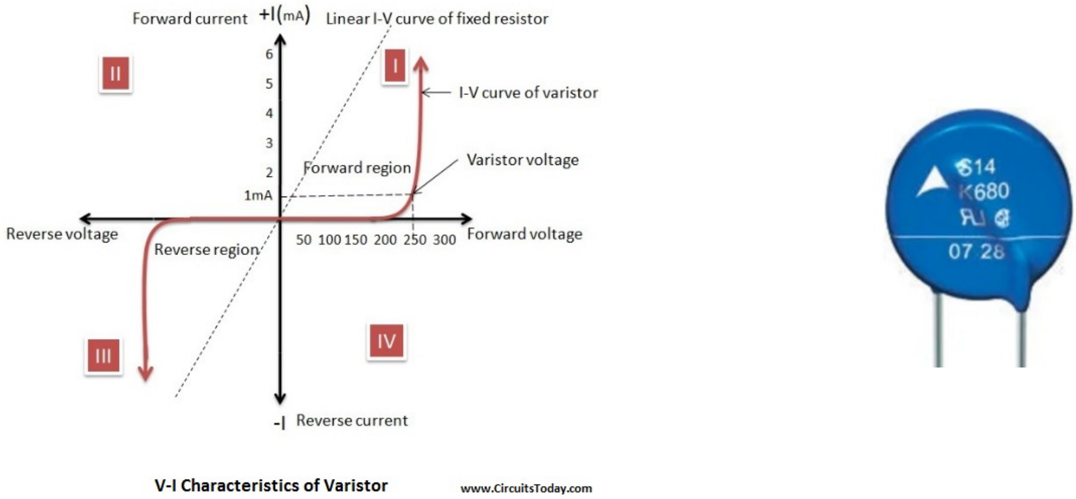


Figure 13: VI curve and image of an MOV

MOV’s are available in a range of power and voltage ratings (up to quite high powers and voltages).

Crowbar circuit

A crowbar circuit creates a short circuit across a circuit to protect a connected load. It usually works in conjunction with a fuse which isolates the power supply (eventually).

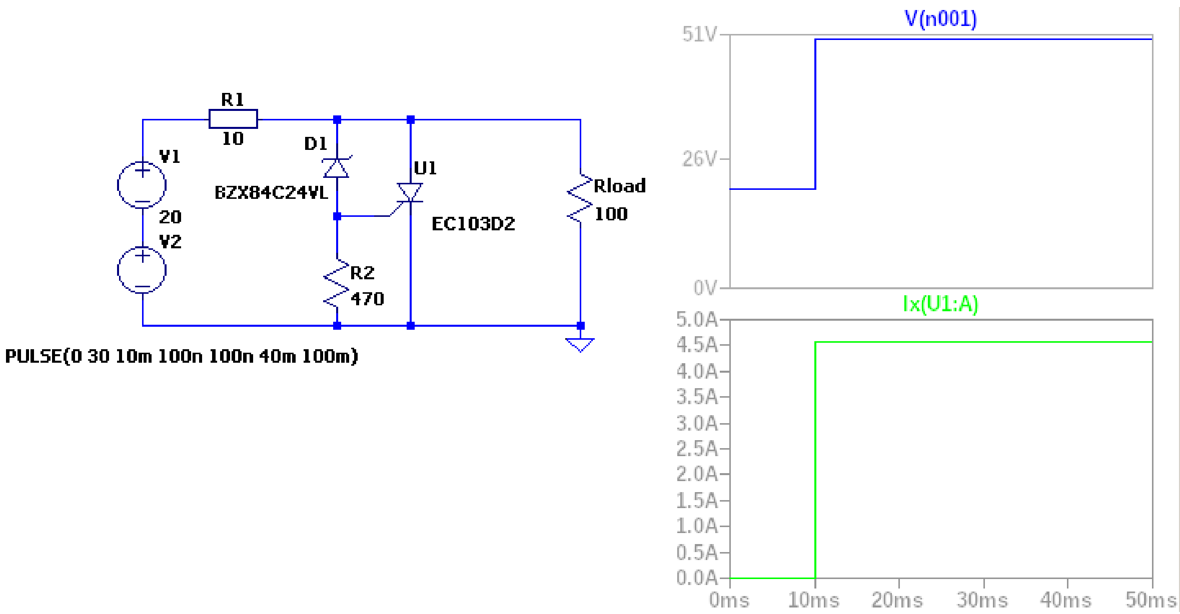


Figure 14: A thyristor based crowbar circuit

When the input voltage (V(n001) above) exceeds the Zener Diode’s breakdown voltage Thyristor U1 turns on. R1 is necessary for the purposes of simulation – in reality it would be a fuse that would blow after a few milliseconds. The crowbar circuit offers protection for the load for the period before the fuse blows.

Over-temperature protection

Semiconductors incur energy losses when in use. These energy losses are manifested as heat and may require that the device be cooled either by passive or active methods. Passive cooling typically involves adding more surface area through which heat can be shed. This can be done by bolting on a heat-sink or by attaching the semiconductor to the device case. Calculation of heat-sink size is often done by modelling the thermal "circuit" as an electrical one. In this case, electrical resistance is replaced with thermal resistance, electrical current flow is replaced with heat (power) flow and electrical voltage is replaced with temperature.

Example: An IRFZ44N dissipates 5W. Determine the thermal resistance of a heat sink necessary to keep the internal device temperature below 80C. Maximum expected ambient temperature is 30C.

Solution:
From the datasheet:

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	——	1.5	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.50	——	
$R_{\theta JA}$	Junction-to-Ambient	——	62	

The thermal equivalent circuit is shown in Figure 15. Note, the thermal resistance direct from junction to ambient is not shown as this is a high impedance path so little heat will flow by this route. (See reference section for a TI application report on loss).

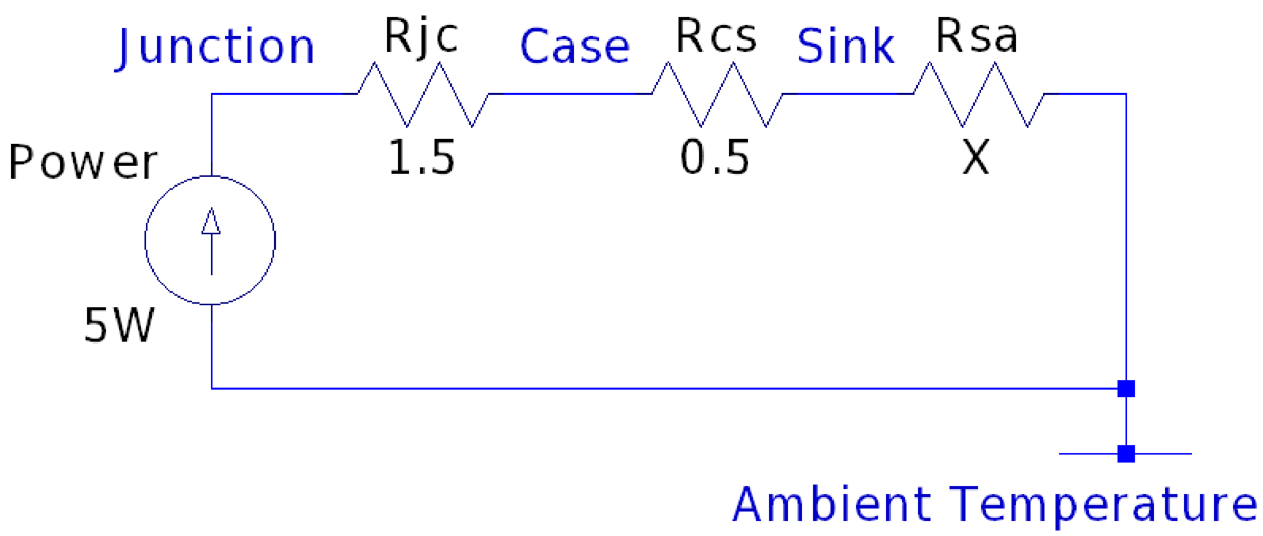


Figure 15: Simplified equivalent thermal resistance circuit for IRFZ44N

The junction (semiconductor) temperature is given by

$$T = 5(R_{\Theta JC} + R_{\Theta CS} + R_{\Theta SA}) + Ambient\ temperature$$

Setting Ambient temperature to 30 we find

$$R_{\Theta SA} = ((80-30)/5) - R_{\Theta JC} - R_{\Theta CS}$$
$$R_{\Theta SA} = 10 - 1.5 - 0.5$$
$$R_{\Theta SA} = 8\,C/W$$

Such a heatsink is shown in Figure 16. It costs around €2.

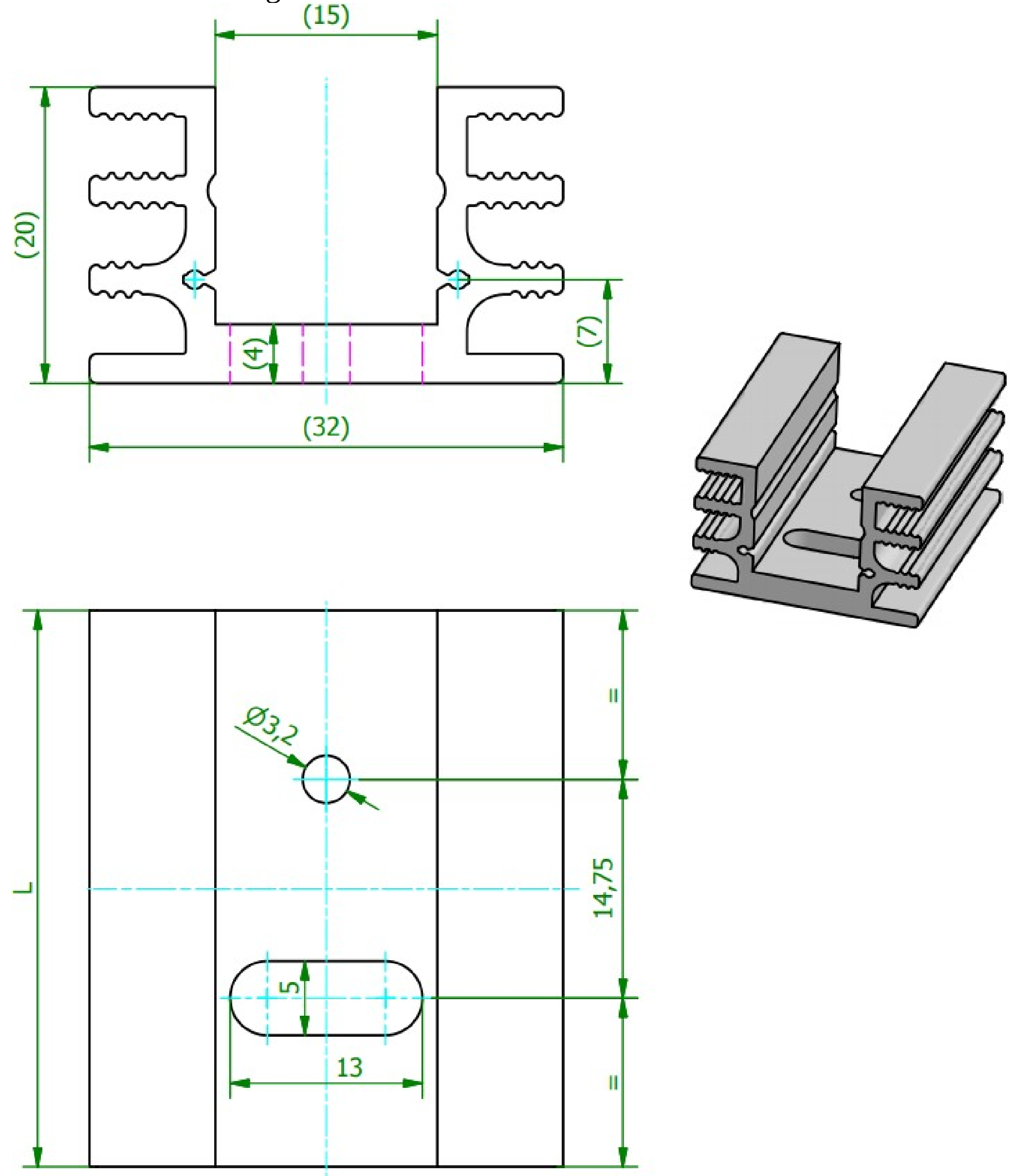


Figure 16: An 8 C/W (8K/W) heatsink

This is a passively cooled heatsink. The heatsink should be mounted such that air can flow upward along its fins. Care must be taken when attaching the MOSFET to the heatink. The metal tab of a TO-220 case is often connected to an internal part of the semiconductor within. In this case, it is connected to the drain of the IRFZ44N. You may need to electrically isolate this metal tab from the heatsink while at the same time maintaining a good thermal contact. Heat sink washers and inserts such as those shown in Figure 17 can help you do this.

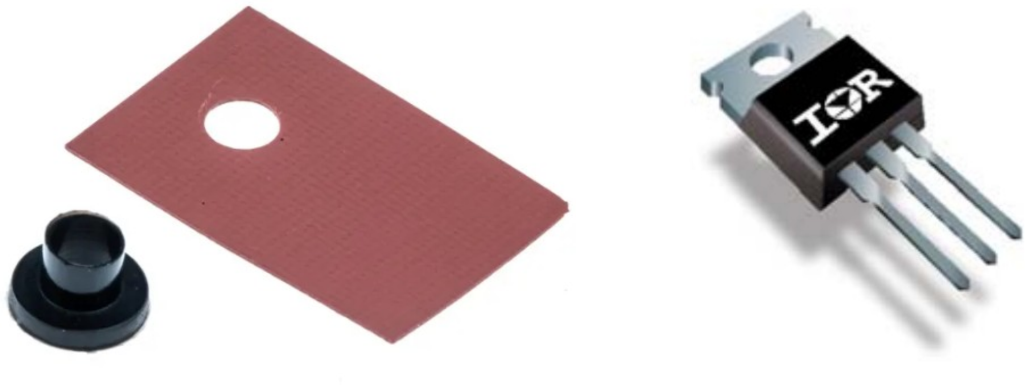


Figure 17: Heatsink pad and insert.

The insert goes in to the screw hole of the TO-220 case which allows a mounting screw pass through without contacting any metal. The pad goes between the transistor and the heatsink. The tab is impregnated with a thermal paste which improves thermal conductivity. You should re-chedk your calculations to ensure that the additional thermal resistance of the pad does not push the device temperature beyond design requirements. All surfaces should be clean and mounting screw and nut tightened. You should test for NO conductivity between the heatsink and the MOSFET tab (drain). Heat-sink paste is sometimes used to improve thermal conductivity.

Some circuits monitor device temperatures during operation and will throttle or shut down completely if things get too hot.

Time delay fuse and quick blow fuses

Used in situations where there may an in-rush current at power-on e.g. Transformer, SMPS. Figure 18 shows an excerpt from Muticomp 5x20mm Glass fuse datasheet (http://www.farnell.com/datasheets/2869805.pdf) The Y-Axis shows time before fuse blows. The fuse. Taking the 100mA fuse as an example it can be seen at a current of 200mA (twice rated value) it will take the fuse about 20 seconds to blow while at 1A , it will blow in about 0.03 seconds.

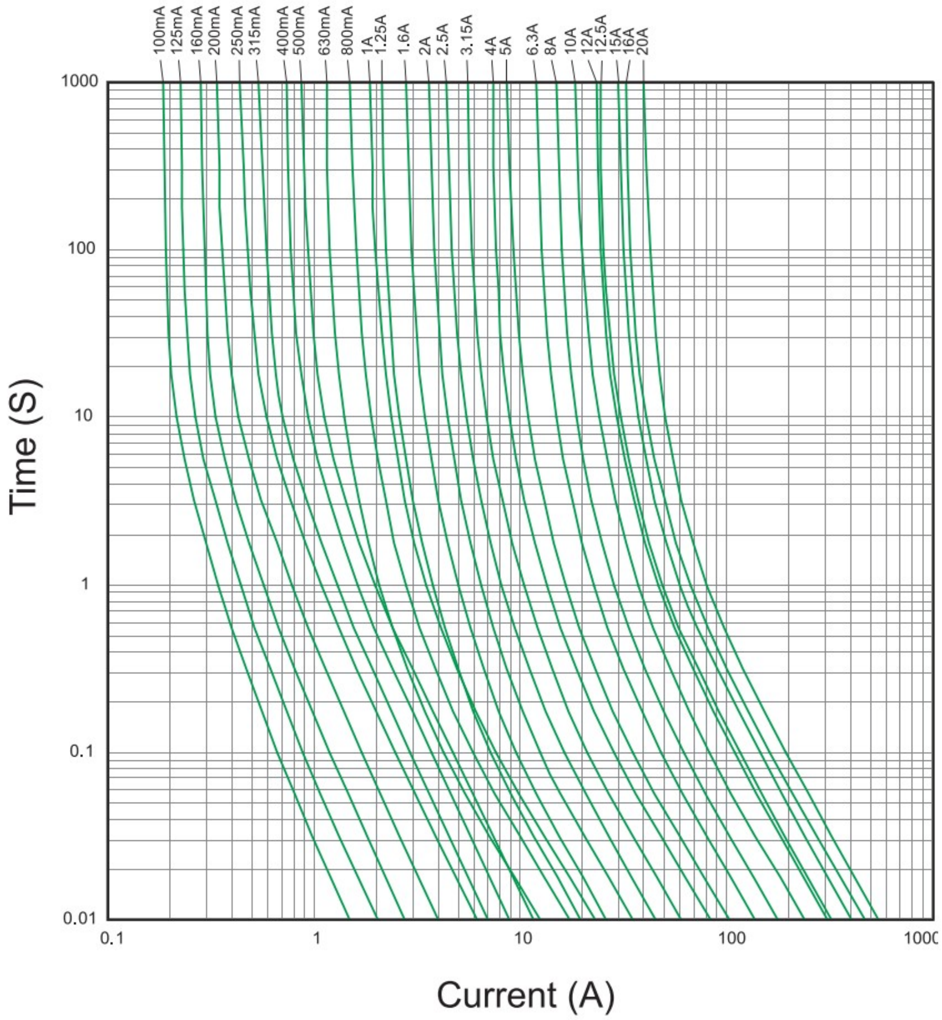


Figure 18: Interrupt time for time-delay fuses

The equivalent set of curves for fast blow fuses are shown in Figure 19.

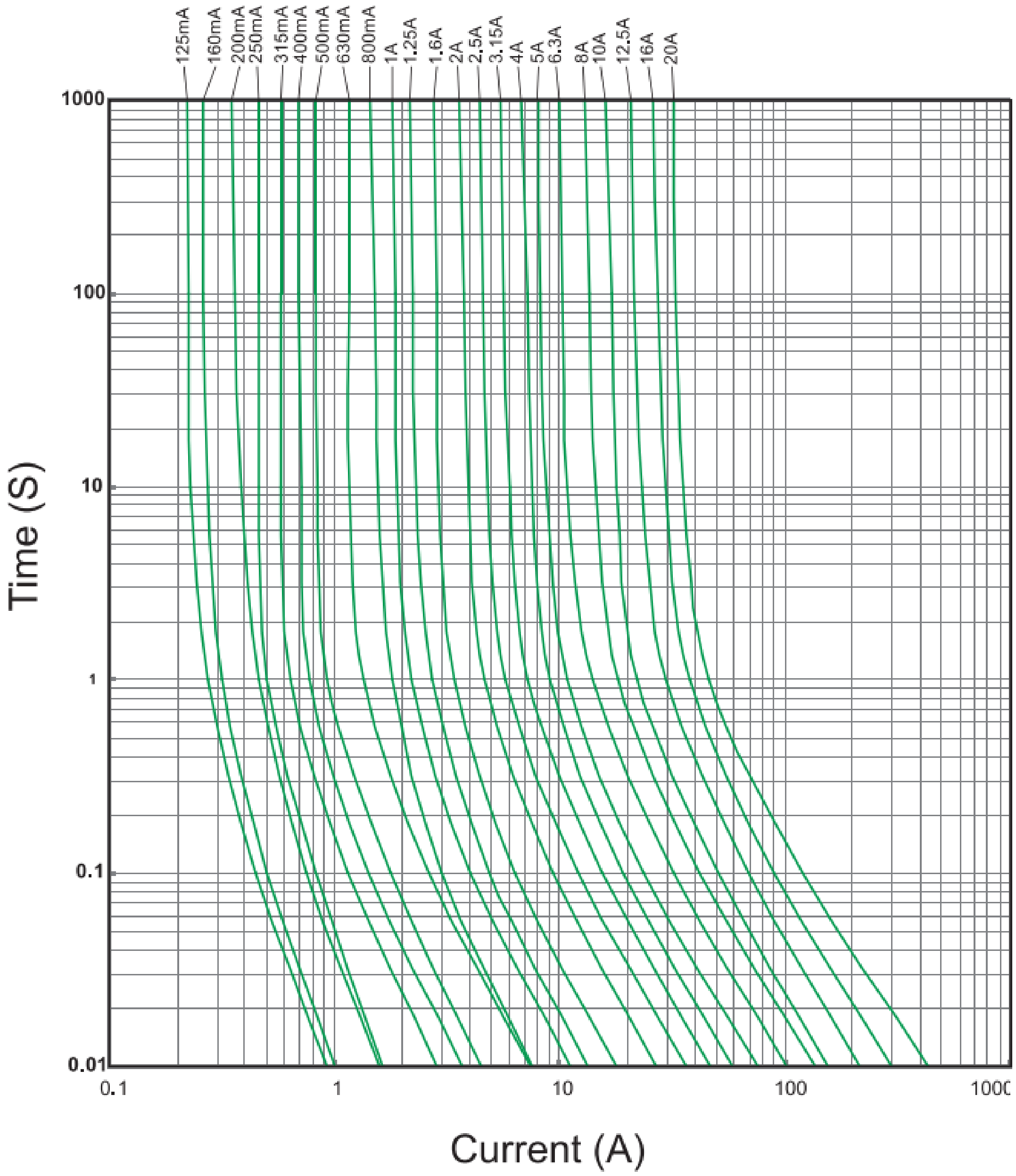


Figure 18: Interrupt time for time-delay fuses

Exercise:

Compare the interrupt time for time-delay and quick blow fuses rated 1A when the current is 2A.

Semiconductors can easily be destroyed within the interruption time of even quick-blow fuses. A datasheet for such a fuse can be found here

https://www.littelfuse.com/~/media/electrical/datasheets/fuses/semiconductor-fuses/littelfuse-industrial-l75qs-fuse-datasheet.pdf

While these fuses are indeed faster than the quick-blow ones it should be noted that they still take some time to blow and that they are quite expensive. Active current monitoring and circuit shutdown using control logic can be a quicker and cheaper. Having said that, regulatory requirements may demand expensive fuses be used in certain situations.

When choosing a fuse you should also be aware of maximum breaking capacity of a fuse. If current levels exceed maximum breaking capacity the fuse may explode and/or experience an electrical arc between its ends leading to a fire and a failure to protect the circuit.