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Automation Components

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White paper

Solid state relays

The benefits of utilising a heat sink at a higher temperature

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Why it may be a good idea to have a hotter heat sink

1.INTRODUCTION

In applications where a number of high current resistive loads are to be switched on and off, such as an industrial oven, a series of solid state relays (SSRs) need to be installed in a control panel. These can number from a few to some tens of SSRs, depending on the application.
Space for these SSRs therefore has to be allocated in the control panel, which very often is housed in the machine itself, like the example in Figure 1. Frequently the SSRs are lined up alongside each other.

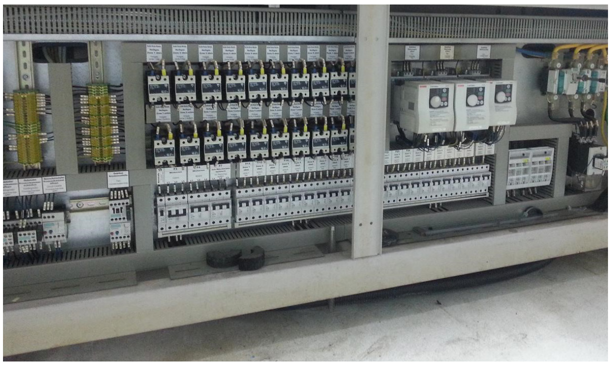

Figure 1 - Control panel in an SMT reflow oven [1]

SSRs, like many other power electronic devices, have one or more power semiconductor chips at their core which, by their very nature, operate with a power loss when a load current is conducted through them. This power loss is manifested in the form of heat dissipation that has to be managed to avoid overheating the sensitive components and materials making up the SSR. Not least of all the sensitive components are the power semiconductor chips themselves, which in most cases are a specific type of thyristor called a silicon-controlled rectifier or SCR. Two of these SCR's connected in anti-parallel would normally make up the core of a single-phase AC SSR.

SCR's should not exceed their maximum junction temperature T_{Jmax} for good and safe operation. T_{Jmax} depends on the type of SCR and the construction of the power module or power package in which the SCR is housed, but typically it is 125 °C, 257 °F. Operating slightly above T_{Jmax} would reduce the lifetime of the SSR, especially if done for a prolonged time. Operating much above T_{Jmax} would risk a thermal runaway and premature catastrophic failure.

In order to manage the heat generated by this power loss properly, the SSR most often needs to be mounted on a heat sink. The heat sink decreases the thermal resistance of the path from the case (usually considered to be the back side of the SSR) to the ambient surroundings, in such a way as to drastically reduce the junction temperature. The bigger the heat sink, the lower its thermal resistance normally is and the easier it is to hence lower the junction temperature.

Since the heat sink is in the direct thermal path of the heat dissipation, it will get hot. Exactly how hot depends on various factors such as the SSR type, the load current, the thermal interface material, the size and type of heat sink, the spacing between SSRs, the ventilation and the ambient temperature in the panel. The question is: should one strive for a hotter or a cooler heat sink? Is a hot heat sink a good thing or a bad thing? Should one worry when the heat sink is hot? How hot is too hot, and how hot is safe enough in terms of thermal management? This paper aims to clarify these questions.

2.THERMAL ANALYSIS

The thermal path between the power semiconductor chips (the junction) and the ambient surroundings can be represented by the simplified thermal circuit in Figure 2. Of main relevance in this discussion are the three thermal nodes J (junction), S (heat sink) and A (ambient surroundings, that is the air available to the heat sink inside the control panel). Only air-cooled heat sinks will be considered in this paper.

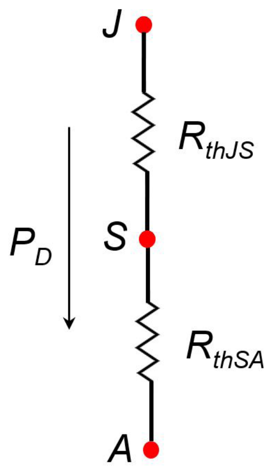

Figure 2 - Simplified thermal circuit of power semiconductor heat dissipation

The path between the junction and the heat sink has a thermal resistance R_{thJS} which consists of the thermal resistance within the power module of the SSR itself between the chips and the case, plus the thermal resistance of the thermal interface material, whether it is thermal grease (paste) or a thermal pad.

The thermal resistance between the heat sink and the ambient surroundings mostly occurs on the external surfaces of the heat sink and is a function of the convective and thermal radiation efficiency. Depending on the size and geometry of the heat sink, the temperature of the heat sink and that of the ambient surroundings, the type of surface and ventilation conditions, including whether the heat sink is equipped with a fan or not, usually the convective heat transfer is much larger than heat transfer by radiation. Figure 3 shows a simplified illustration of the thermal path as it corresponds to the thermal circuit.

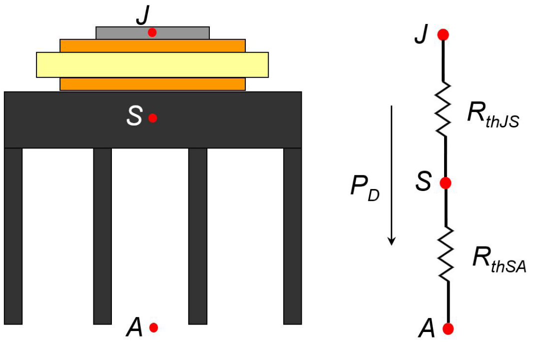

Figure 3 - Thermal representation of SSR

The convective heat transfer $\dot{Q}$ off the surfaces of the heat sink occurs by continuous air flow in direct contact with it. At the surface interface, the air, at a temperature below that of the heat sink, picks up the heat from the surface and carries it away from the SSR, thus keeping it cool. It is the temperature difference between the surface of the heat sink and the air in contact with it which drives the heat transfer. The higher the temperature difference the higher the heat transfer rate. In addition, the larger the surface available for convection, the larger the heat transfer also.
This can be represented by the equation:

$$\dot{Q} = h(T_S - T_A)A \ldots (1)$$

where $\dot{Q}$ is the rate of heat transfer by convection, h is the convective heat transfer coefficient and A is the surface area of the heat sink available for convection. The convective heat transfer coefficient depends on the geometry of the heat sink and its operating conditions.

A larger surface area (to increase the rate of heat transfer) is most easily achieved by making the heat sink larger. Since a higher load current generates more power loss and thus more heat dissipation, a larger heat sink is therefore needed for higher currents. A heat sink without any forced ventilation such as a fan is cooled by natural convection, which is the air flow created when hot air naturally rises and is replaced by cool air below. In this situation it is the external vertical surfaces of the heat sink that are available for convection as shown in Figure 4. Figure 5 shows a visualisation of the air flow and temperature distribution across the surface of the heat sink as simulated by computational fluid dynamics (CFD) software.

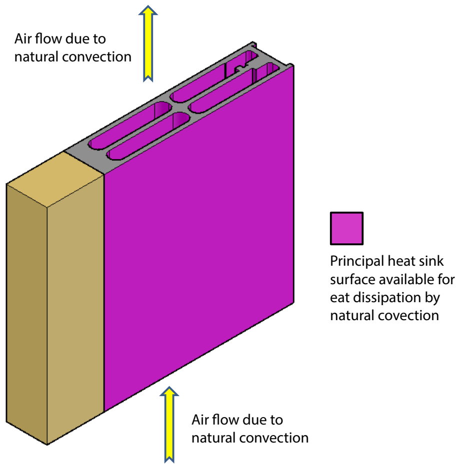

Figure 4 - Carlo Gavazzi heat sink (RHS51-03) showing faces available for convection

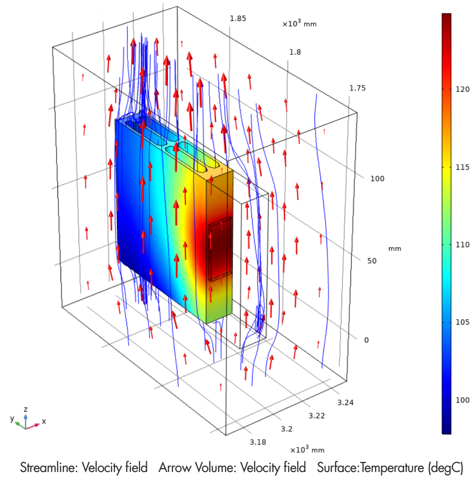

Figure 5 - Visualisation of air flow and temperature distribution by COMSOL simulation

The thermal resistance is defined by the ratio between the temperature difference between two points and the rate of heat transfer between those same points. Hence, the thermal resistance of the heat sink, that is between the heat sink and the ambient surroundings, from the preceding, can be derived as follows:

$$R_{thSA} = \frac{(T_S - T_A)}{\dot{Q}} = \frac{(T_S - T_A)}{h(T_S - T_A)A}$$

$$R_{thSA} = \frac{1}{hA} \ldots (2)$$

Thus, it can be easily seen that the thermal resistance of the heat sink is inversely proportional to the convective area, and hence the larger the heat sink the smaller its thermal resistance.

The thermal resistance of a heat sink is moreover not fixed for a given size and shape of heat sink but depends on the air flow rate passing across it. For a heat sink under natural convection, this is governed by the Five-Fourths Power Law [2], which states that the rate of heat transfer is directly proportional to five fourths the power of the difference in temperatures between the solid object and the surrounding fluid. This means that the thermal resistance of a heat sink under natural convection depends on its temperature as in the example in Figure 6.

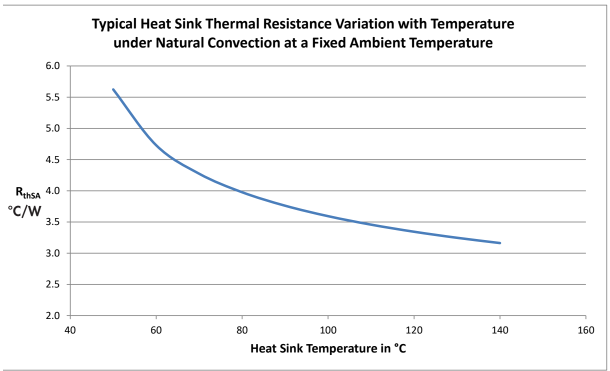

Figure 6 - Variation of heat sink thermal resistance with temperature under natural convection

In other words, a hot heat sink under natural convection is more efficient than a cold one.

This also means that the thermal resistance of a heat sink under natural convection decreases with increasing heat dissipation and increasing load current of the SSR.

Of course, all other operating conditions remaining constant, increasing the load current invariably still increases the junction temperature, but the preceding argument simply highlights that for a heat sink cooled by natural convection, the effect of the larger heat dissipation is somewhat offset by a heat sink operating more efficiently.

A heat sink cooled by forced convection such as an electric fan does not follow the same principle. The air flow rate in this case is determined by the fan itself and does not depend on the temperature. The thermal resistance of a fan cooled heat sink is therefore for all intents and purposes constant.

What does this all mean when it comes to the selection of a heat sink for an SSR with a given set of load conditions?

Let us say that a given load current I_{RMS} needs to be handled by a chosen SSR model. The power dissipated by this SSR is determined by the equation

$$P_D = \left(\frac{2\sqrt{2}}{\pi}\right) I_{RMS} V_{TO} + {I_{RMS}}^2 r_T \ldots (3)$$

where V_{TO} and r_T are electrical parameters characteristic of the SCR's used in the SSR. So for a given load current a specific power dissipation is created. It is assumed in this discussion that all the power is dissipated through the heat sink. From the previous argument we therefore have

$$R_{thSA} = \frac{(T_S - T_A)}{P_D} \ldots (4)$$

$$T_S = T_A + R_{thSA} P_D \ldots (5)$$

Now it is normally desired to reduce the size of the heat sink as much as possible. But reducing the size of the heat sink, as was seen earlier, increases its thermal resistance R_{thSA}. And from the equation it can be seen that increasing R_{thSA} increases the heat sink temperature T_S. Therefore, if it is desired to reduce the size of the heat sink, it is evident that one has to look to operate the heat sink at a higher temperature.

Now, considering the other section of the thermal circuit, that is between the junction and the heat sink,

$$R_{thJS} = \frac{(T_J - T_S)}{P_D} \ldots (6)$$

$$T_S = T_J - R_{thJS} P_D \ldots (7)$$

the thermal resistance between the junction and the heat sink is for all intents and purposes a fixed value that depends on the design of the SSR and the type of thermal interface material used and does not vary with power dissipation. Hence, from the last equation, it can be seen that a higher heat sink temperature T_S will increase the junction temperature T_J. But it is always important to remember that the junction temperature of the SSR must not exceed the maximum allowable limit T_{Jmax}.
That is, $T_J \leq T_{Jmax}$

From the preceding analysis the following can be concluded. In order to keep the size of the product as small as possible, one must try to reduce the thermal resistance of the SSR (R_{thJS}) as much as possible, and choose the smallest allowable heat sink (higher R_{thSA}), thus having a heat sink which is as hot as possible.
Theoretically, from a thermal management point of view, the ideal situation would be to have $R_{thJS} = 0$ and have $T_S = T_J = T_{Jmax}$, but this is impossible in practice.

Nevertheless, the point is made that this is the target at which one needs to aim in order to optimise the efficiency of the SSR in the smallest space possible.

It is worth noting that with higher load currents the power dissipation P_D will be higher and therefore the temperature difference between the junction and the heat sink will be higher. So, **given that the junction temperature is maintained at the same level**, higher load currents will result in lower heat sink temperatures since a larger heat sink would have to be used.

3.BENEFITS OF HAVING A HOT HEAT SINK

When a system is designed that allows a higher heat sink temperature, this can be taken advantage of by improvements in load current and/or heat sink size. The following sections illustrate how.

3.1 INCREASING THE LOAD CURRENT

Equation (5) shows that, for a given ambient temperature and a given heat sink, allowing the heat sink temperature to increase must increase the power dissipation capability of that heat sink. This in turn allows an increase in the load current of the SSR mounted on the heat sink. Moreover, it was also shown in the graph in Figure 6 how a heat sink cooled by natural convection decreases its thermal resistance with higher temperatures, which leads to a further increase in power dissipation capability and thus a further increase in the maximum load current.

Figure 7 – 90 AAC SSR mounted on heat sink

Let us take as an example a 90 AAC SSR, mounted on a typical heat sink, as shown in Figure 7, at an ambient temperature of 60 °C. The power loss of the SSR is dissipated from the heat sink by natural convection of air.

By varying the heat sink temperature, different load currents can be applied through the SSR and the thermal resistance of the heat sink varies. As always, the junction temperature should not exceed T_{Jmax}. Table 1 shows how one can benefit from a higher load current with increasing heat sink temperature, without exceeding the maximum junction temperature.

Heat sink temperature T_S (°C)	Load current I_{RMS} (A)	Power dissipated P_D (W)	Junction temperature T_J (°C)	Heat sink thermal resistance R_{thSA} (°C/W)
80 °C	10.5 A	8.1 W	83.4 °C	2.98 °C/W
90 °C	16.9 A	13.5 W	95.6 °C	2.68 °C/W
100 °C	23.5 A	19.5 W	108.1 °C	2.48 °C/W
110 °C	30.3 A	25.9 W	120.7 °C	2.33 °C/W

Table 1 – Applicable load currents and heat sink thermal resistances for different heat sink temperatures at an ambient temperature of 60 °C

3.2 REDUCING THE SIZE OF THE HEAT SINK

Another significant advantage of having a hotter heat sink one could benefit from is that a smaller heat sink could be used for the same load current.

Let us consider the same SSR in the previous example. To show the advantage of increasing the heat sink temperature, we will consider two similar heat sinks shown in Figure 8, referred to as RHS51-03 and RHS52A.
Both heat sinks are 90 mm long and 83.2 mm deep. The only difference is that the RHS51-03 is 17.7 mm wide and the RHS52A is 22.7 mm wide. The wider heat sink has a smaller thermal resistance, mainly because of wider spacings between fins.

Figure 8 – RHS51-03 and RHS52A dimensions

Let us assume the SSR is mounted on both heat sinks and the load current set to 25 A in each case. Table 2 shows the heat sink temperatures and the thermal resistances of both heat sinks at an ambient temperature of 60 °C.

Heat sink	Load current I_{RMS} (A)	Power dissipated P_D (W)	Heat sink temp. T_S (°C)	Junction temp. T_J (°C)	Heat sink thermal resistance R_{thSA} (°C/W)
RHS51-03	25 A	21 W	105.7 °C	114.1 °C	2.71 °C/W
RHS52A			102.2 °C	110.7 °C	2.45 °C/W

Table 2 - Heat sink temperatures and heat sink thermal resistances for both heat sinks at a load current of 25 A

The table shows that for the same load current, a smaller heat sink can be used if the heat sink temperature is increased. Again it must be emphasised that the maximum junction temperature T_{Jmax} should not be exceeded.

A reduction of 5 mm in the heat sink width can thus be obtained by increasing the heat sink temperature by slightly more than 3 °C for a load current of 25 A. Reducing the heat sink width from 22.7 mm to 17.7 mm could provide a huge benefit when mounting multiple SSR's in a panel.

Further improvement can be achieved when comparing these heat sinks to a smaller heat sink such as the RHS37A shown in Figure 9. This has the same width and length as the RHS51-03. The depth of the RHS37A is almost half that of the RHS51-03 at 45.6 mm. A same ambient temperature of 60 °C was considered.

Heat sink	Load current I_{RMS} (A)	Power dissipated P_D (W)	Heat sink temp. T_S (°C)	Junction temp. T_J (°C)	Heat sink thermal resistance R_{thSA} (°C/W)
RHS37A	20 A	16 W	112.3 °C	118.2 °C	4.48 °C/W
RHS51-03			96.6 °C	103.2 °C	2.75 °C/W
RHS52A			94.7 °C	101.4 °C	2.58 °C/W

Table 3 – Heat sink temperatures and heat sink thermal resistances at a load current of 20 A and ambient temperature of 60 °C

Table 3 shows clearly that by increasing the heat sink temperature, the size of the heat sink can be reduced significantly for the same load current. When comparing RHS37A to RHS52A (Figures 8 and 9), one can notice that the size of the heat sink is reduced by almost half. This is achieved by allowing the heat sink temperature to increase by 17.6 °C.

Although the heat sink temperature increases as the size of the heat sink decreases for the same power dissipation, this will not affect the ambient temperature inside the cabinet. The ambient temperature of the cabinet T_A depends on the power dissipated from the SSR's through the heat sinks inside the cabinet, and this is only dependent on the load current. In this case, the power is constant (16 W), although the heat sink temperatures and junction temperatures are different for different heat sinks.

The improvement in heat sink dimensions is shown in Figure 10. By allowing the heat sink temperature to increase, the same current can be conducted through all the heat sinks shown below.

RHS37A

Figure 9 – RHS37A heat sink dimensions

RHS52A RHS51-03 RHS37A

Figure 10 – 90 AAC SSR mounted on each of the three heat sinks

4.CASE STUDY ON CARLO GAVAZZI 90 AAC SSR - RGS1..90

The examples described in Section 3 can only be exploited by a 17.5 mm wide SSR. Carlo Gavazzi's RGS series is a range of SSR's with a width of 17.5 mm. The power module of this series is designed with a technology that optimises the thermal performance in this slim width that distinguishes it from conventional SSR's. Its excellent heat dissipation capability means that it has a low junction to heat sink thermal resistance R_{thJS} and therefore a low ΔT_{JS}, which in turn means that the heat sink temperature will naturally be closer to the junction temperature.

The calculations in the previous section were actually made on the RGS1..90 version which is rated at 90 AAC. The values in the tables were calculated considering a stand-alone unit. Of course, when the SSR's are installed close to or touching each other in a row in a panel, one has to account for space derating, however the benefits of having a higher heat sink temperature still apply in this scenario.

Consider for example a typical case where 50 of these SSR's are installed with zero spacing on a DIN rail, as shown in Figure 11. When each of the SSR's is mounted on the RHS52A heat sink, which is 22.7 mm wide, the total width occupied by the mounted assemblies will be 1.135 metres. Contrast this with mounting the same SSR's on the RHS51-03 heat sink, which is 17.7 mm wide. The occupied width of the DIN rail will now be 0.885 metres. This is 25 centimetres less.

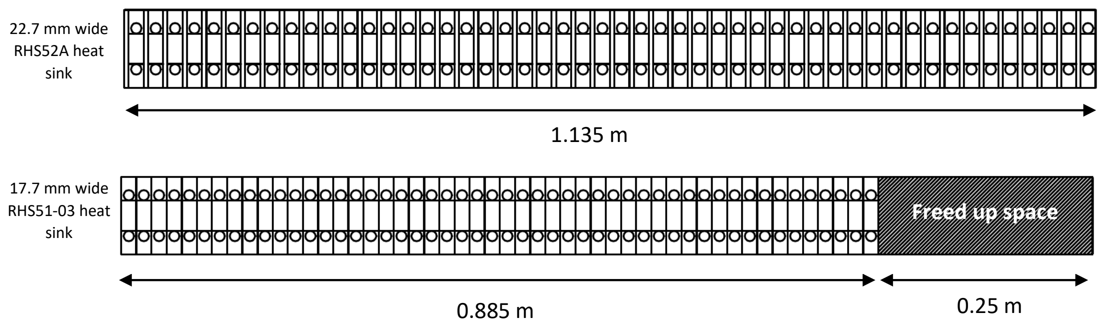

Figure 11 – 50 SSRs mounted in a row for 22.7 mm and 17.7 mm heatsinks

5.CONCLUSIONS

The thermal analysis and product examples presented in this paper show how the space available in a control panel occupied by SSR's can be optimised. By allowing the heat sink temperature to increase, one can apply a higher load current or use a smaller heat sink. The SSR is designed to operate reliably at a junction temperature up to T_{Jmax}.

Heat sinks without an integrated fan, cooled mainly by natural convection, actually operate more efficiently at higher temperatures. This is because the difference in temperatures between the heat sink and its ambient surroundings drives the air flow which dissipates the heat from the heat sink.

For a given SSR with a given load current, the power dissipated is the same, irrespective of which heat sink is used. The temperature of the cabinet in which the control panel is housed is then only determined by the power dissipated from the SSRs and the thermal conditions of the cabinet (other heat sources within the cabinet, size, cabinet wall material, ventilation, temperature outside the cabinet and so on). For given load conditions, the temperature of the cabinet is independent of the heat sink temperature.

Summarising, a higher heat sink temperature means a higher power density and this can be exploited by:

- Fitting more SSRs in a panel
- Handling higher load currents
- Reducing the size of the panel
- Reducing the overall system cost

6.REFERENCES

[1] Viewed 26 August 2020,
Image of a Control panel in an SMT reflow oven - from cdn.caeonline.com

[2] R. Muncaster, "A-Level Physics", Nelson Thornes Ltd., 1993

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