

Application Note



What do rated current values mean?

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1 Introduction

Despite the efforts of some passive magnetic component manufacturers, the concept of rated current continues to be a point of contention in the power electronics industry. There remains a difference of opinion in how manufacturers should report it and how design engineers can use it. Is it an absolute parameter? Are rated current values from different manufacturers directly comparable? The answer to these questions is no. Some manufacturers take advantage of these misconceptions and are deliberately vague about the measurement method used to obtain rated current values to achieve favorable results.

The operating temperature of a power inductor is an important parameter for any application. Electrical parameters, such as inductance and therefore the magnetic saturation, can vary considerably over temperature ranges. The operating temperature of the inductor in an application setting is defined by self-heating and the ambient temperature (Equation 1).

$$T = T_{\text{Amb}} + \Delta T \quad 1$$

where T is the operating temperature of the inductor, T_{Amb} is the ambient temperature and ΔT is the self-heating of the part.

The self-heating is a result of the heat generated by the electrical losses of the inductor. In an SMPS application setting, losses are caused both by DC and AC currents. However, this is highly dependent on the conditions of the SMPS, such as switching frequency and duty cycle. To simplify testing thermal dissipation, the self-heating of parts is measured when considering only DC copper losses (Equation 2).

$$P_{\text{DCLoss}} = I^2 \cdot R_{\text{DC}} \quad 2$$

where P_{DCLoss} (W) is the copper losses of the inductor, I (A) is the current of the inductor and R_{DC} is the resistance of the inductor (Ω). From this equation it is clear that parts with higher R_{DC} will generate more heat for the same current applied.

The heat generated from the copper losses, then conducts to the PCB trace through the solder pads, and to the core where it is dissipated through convection and radiation into the surrounding air. When current is applied to the part, the temperature of the part will continue to increase until an equilibrium is reached between heat generation and heat dissipation. The ability of the part to dissipate heat is defined by the thermal resistance of the component (Equation 3).

$$\theta_{\text{WA}} = \left(\frac{\Delta T}{P_{\text{DCLoss}}} \right) \quad 3$$

where θ_{WA} is the winding to ambient thermal resistance. Although this formula is simplified and only considers DC current, it still gives important information about how well the part can dissipate heat. More information based on the end application can be obtained using REDEXPERT, an online tool that accurately calculates losses and temperature rise for specific SMPS conditions.

At this stage, it is important to clarify terminology and principles regarding electrical and thermal parameters. The derivation of thermal parameters evolved in much the same way as electrical parameters with similarities in Ohm's law (Equation 4) and Newton's law of cooling (Equation 5). For this reason, analogies can be drawn between electrical and thermal parameters (Figure 1).

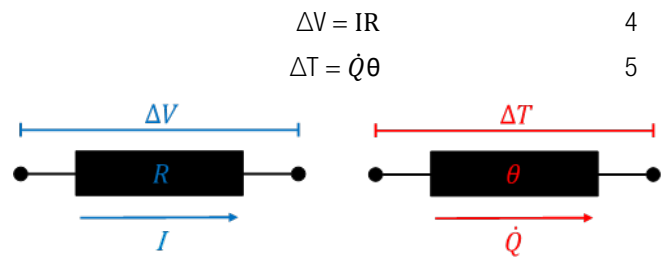


Figure 1: Visual representation of Ohm's law and Newton's law of cooling.

Heat flows through thermally conductive paths as electrical current flows through electrically conductive paths. Therefore heat generation is usually represented as a current source. Analogous to voltage drop across a conductor, the amount of current that can flow is limited by the conductive/resistive properties of the material, the cross section it flows through and the length of the path. This is equally true for temperature differentials between two thermally conductive paths. When considering a simple inductor model, there are two conduction paths of heat, through the winding to the solder pad and through the core to the outer surface of the core (Figure 2).

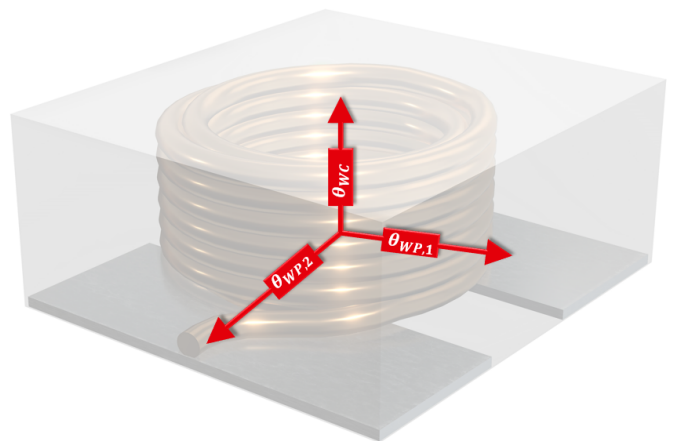


Figure 2: Visualization of thermal transfer paths in a simplified power inductor. Conduction through the solder pads is divided between the pads (θ_{WP1} and θ_{WP2}).

where θ_{WC} is the winding to core surface thermal resistance and θ_{WP} is the winding to solder pad thermal resistance.

However, what additionally comes into play is the effectiveness of the thermal earth. The lower the ambient temperature is, the greater the temperature differential and the larger the heat flow. For a PCB mounted inductor, the surface area of the core and the PCB trace size together with

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its surface area represent the thermal resistances that connect the thermal circuit to thermal ground. Therefore, a full yet simplified thermal model of a power inductor can be defined (Figure 3).

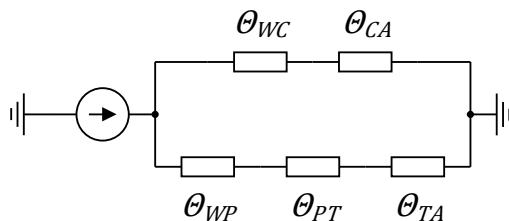


Figure 3: Equivalent thermal model of a power inductor.

where θ_{CA} is the core surface to ambient thermal resistance, θ_{PT} is the solder pad to trace thermal resistance and θ_{TA} is the trace to ambient thermal resistance. What this thermal equivalent circuit demonstrates is that we essentially have parallel resistors and a number of voltage dividers. If one resistance value changes, the flow of heat ("current") will change therefore resulting in temperatures ("voltage") changing at different parts in the circuit.

Consider increasing the size of the part while keeping all other parameters equal. This will significantly decrease θ_{CA} resulting in more heat flowing from the winding, through the core to the ambient air and less flowing through the solder pad to the trace and ambient air. Indeed this is what is typically observed with larger power inductors transferring more heat to the air whereas smaller inductors with smaller surface area transfer a greater proportion of heat to the PCB. Now consider increasing the thickness of the winding meaning lower thermal resistance from the winding to the trace. This will mean a lesser proportion of the heat will flow from the winding to the core surface with more flowing to the PCB trace. This behavior is typically observed in high current power inductors that use thicker winding to handle higher currents. Therefore, having a thicker wire both decreases self-heating and increases heat dissipation.

Both of the cases above facilitate the flow of heat from the winding to the ambient resulting in lower self-heating of the part. This means they can be operated at higher currents than smaller inductors that use smaller diameter wire.

2 How is rated current measured?

Simplified, the method comprises passing DC current through the part, measuring the hottest part of the inductor, waiting for the temperature to stabilize, and then recording the temperature difference from ambient temperature. The DC current begins low and steps up with each stabilized temperature raise recorded resulting in temperature vs. current graph. However, the specifics of the measurement technique can greatly affect the result of the measurement.

Consider including forced airflow (convection) over the part. This would reduce θ_{CA} , increasing the amount of heat that can be dissipated, in turn

increasing the rated current of the part. Indeed some manufacturers may not specifically note if any airflow is used, leaving room for doubt if the higher rated current values are comparable with values from other manufacturers.

Another factor that has an influence on the inductor temperature rise are the PCB trace dimensions. As we have seen with the winding, a greater cross section area reduces thermal resistance. The same is true of PCB trace dimensions. Wider traces and increased copper thickness will reduce θ_{PT} increasing the flow of conducted heat from the inductor. This also reduces θ_{TA} as the greater surface area of the trace increase heat convection and radiation to the ambient. Again, this information may not be specified in datasheets, leaving room for interpretation by the design engineer.

3 What does this mean for rated current?

As can be seen, rated current values can be manipulated in such a way as to have potentially remarkable thermal characteristics and performance. But it also means the design engineer is selecting parts using incomparable data. This dilemma faced the semi-conductor industry some decades ago where design engineers found it increasingly difficult to directly compare ICs. For this reason associations like JEDEC (Joint Electron Device Engineering Council) began to standardize measurement procedures and the form of thermal performance reporting. What standardization brought was transparency and comparability. Thermal characteristics could not be artificially manipulated to be used as marketing data. However, because of the diverse forms of power inductors, it was some years until a requirement for the standardization of rated current became apparent.

4 How does WE measure rated current of power inductors?

Würth Elektronik endeavors to be transparent with the disclosure of the measurement procedures used and the reporting of rated current (I_r) data of the temperature rise of power inductors. The method used is based upon section 6 of the IEC 62024-2:2020 standard. The test PCB is contained within a box of roughly 20 cm on each side. The test PCB does not contact directly with the surrounding box. Only natural convection occurs, with no forced convection applied to the test PCB. Würth Elektronik measurement differs from the standard in that an infrared camera is used in place of thermo-couple. This is done to eliminate measurement error caused by placement of the thermocouple. In this way, the hottest external area of the magnetic core is measured. Current is passed through the sample with the temperature allowed to stabilize to less than 1 °C per minute.

Due to the range of sizes and construction types of the Würth Elektronik portfolio, a number of PCBs have been used, but primarily follow that of

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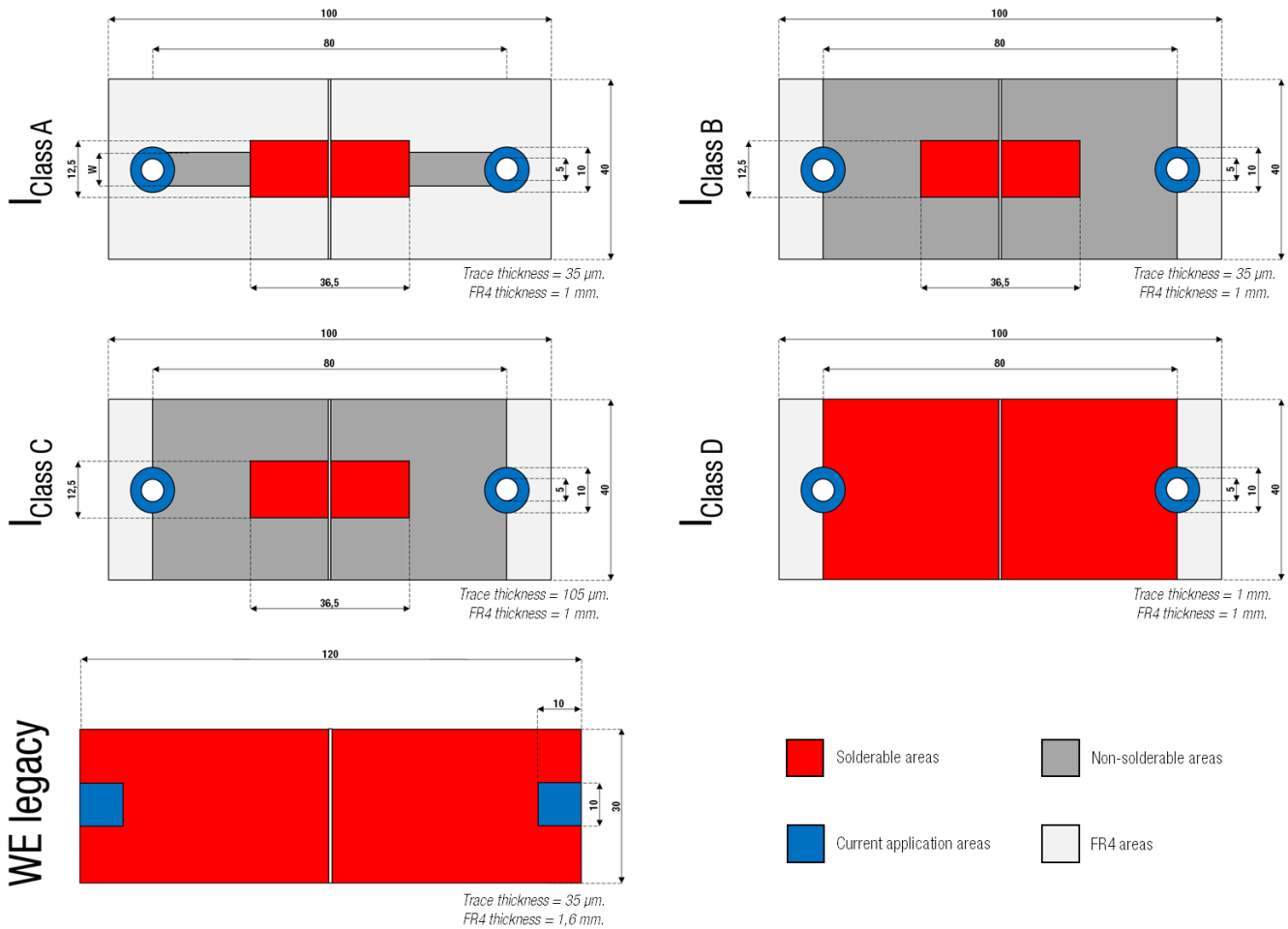


Figure 4: Diagram of PCBs used for rated current measurements

section 6.3 of the standard (Figure 4). For IEC $I_{Class A}$ PCBs, the trace width is different dependent on the rated current (Table 1).

Irrespective of the PCB used, it should be remembered what rated current values on datasheets actually represent. These values are not absolute that can be applied to any application. They are there to give a rough guide as to the current range they can be used in and to serve as a parameter for comparison with other power inductors. The thermal characteristics of a power inductor are influenced by so many factors, it is impossible to characterize the behavior in the final application. This is where precise knowledge of the measurement technique becomes extremely useful to the design engineer. When all parameters are known, rated current values cannot be manipulated facilitating manufacturers to be transparent and consistent avoiding the sham of rated current.

5 Comparison of inductors

In the following section, a Würth Elektronik eiSos power inductor from the WE-LHMI (744 373 460 68) product family is compared with a power inductor of similar construction from a competitor. Additionally, an inductor from the WE-XHMI (744 393 46 100) series is compared with a comparable competitor's power inductor.

Rated Current Class	Rated current of inductor I_r (A)	Trace width W (mm)
$I_{Class A}$	$I_r \leq 1$	$1 \pm 0,2$
	$1 < I_r \leq 2$	$2 \pm 0,2$
	$2 < I_r \leq 3$	$3 \pm 0,3$
	$3 < I_r \leq 5$	$5 \pm 0,3$
	$5 < I_r \leq 7$	$7 \pm 0,5$
	$7 < I_r \leq 11$	$11 \pm 0,5$
	$11 < I_r \leq 16$	$16 \pm 0,5$
	$16 < I_r < 22$	$22 \pm 0,5$

Table 1: Trace width (W) used for $I_{Class A}$ PCBs

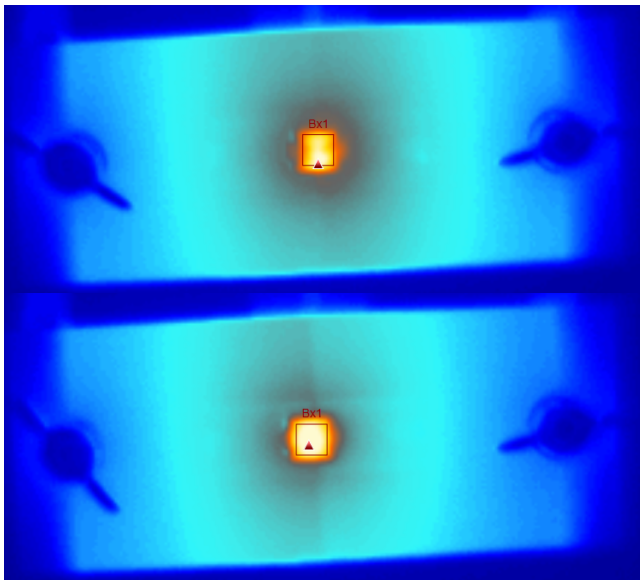
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Ref. no.	Size	Inductance (μH)	Rated Current (A)	Performance Rated Current (A)	Saturation Current (A)	DC Resistance ($\text{m}\Omega$)
744 373 460 68	7030	6.8	3.4	4.45	8 @ 20% L drop	54
Competitor 7030	7030	6.8	4.5	-	8 @ 20% L drop	54
744 393 46 100	6060	10	5.0	6.4	9.7 @ 30% L drop	26.5
Competitor 6060	6060	10	7.0	-	7.6 @ 30% L drop	27

Table 2: Comparison of datasheet parameters



25°C 65°C

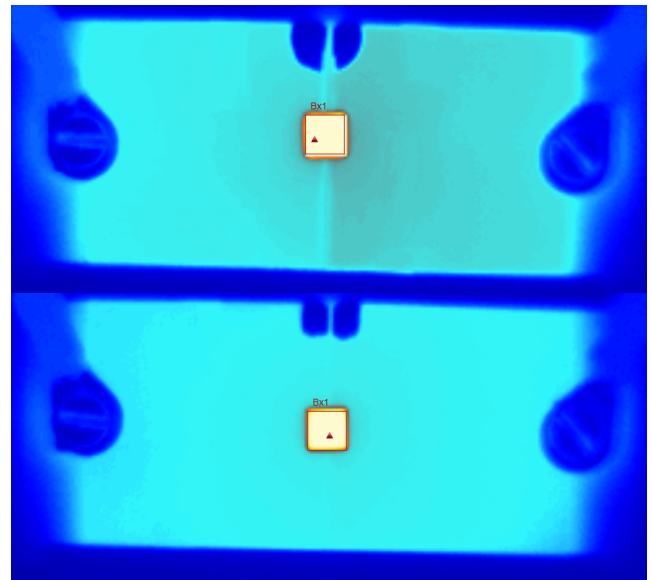


Figure 5: Thermal images of WE-LHMI 744 373 460 68 (upper) and competitor 7030 (lower)

Figure 6: Thermal images of WE-XHMI 744 393 46 100 (upper) and competitor 6060 (lower)

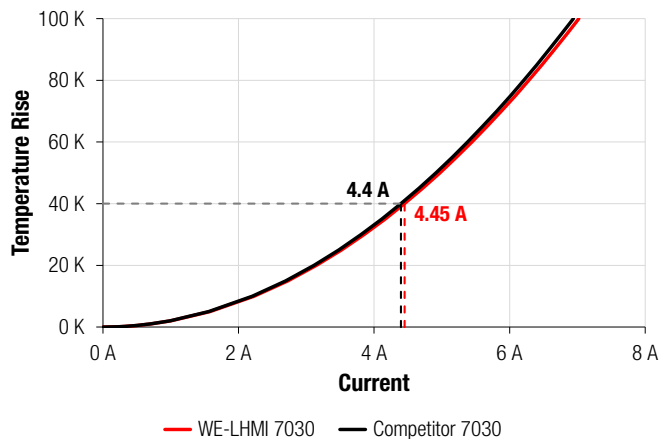


Figure 7: Self heating comparison of WE-LHMI 744 373 460 68 (red) with competitor 7030 (black)

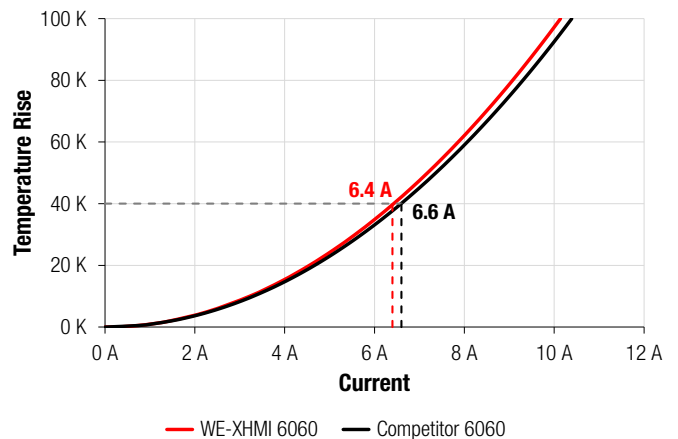


Figure 8: Self heating comparison of WE-XHMI 744 393 46 100 (red) with competitor 6060 (black)

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Interestingly, in both comparisons the competitor parts have a higher rated currents stated in their datasheets despite having a higher R_{DC} than the WE parts (Table 2). The rated current of both inductors were measured and compared using the IEC 62024-2:2020 measurement set-up. For each comparison measurement, the same measurement set-up, the same contacting method and the same type of measurement board were used. The WE-LHMI and its competitor on the $I_{Class C}$ and the WE-XHMI and its competitor on the $I_{Class D}$.

The temperature of both coils were measured with a thermal imaging camera. DC current was applied to the test boards until at least 65 °C was reached, 40 K above ambient 25 °C (Figure 5 and 6). Despite having a higher rated current value on the datasheet, the competitor 7030 part had a lower heating current of 4.4 A when compared to the 4.45 A of the WE-LHMI, measured on the same $I_{Class C}$ PCB (Figure 7). Similarly, the WE-XHMI had similar heating current values to the competitor 6060 part, 6.4 A compared to 6.6 A (Figure 8) when measured on an $I_{Class D}$ PCB. It must be noted that small deviations in the self-heating curve can be caused by component tolerances, especially in R_{DC} , and can occur even when comparing coils of the same construction originating from the same series from the same manufacturer.

This raises questions about how manufacturers achieved this level of heat dissipation. The use of bus bars, heat sinks, and forced convection can all be used to achieve higher heat dissipation. This should be remembered when comparing rated current values and selecting parts for prototyping.

6 Performance Rated Current

For some power inductors, an additional rated current, specified as Performance Rated Current (I_{RP}), may be included on the datasheet. This is the rated current of the part measured on an $I_{Class C}$ or $I_{Class D}$ PCB. Some may argue, why use $I_{Class C}$ and $I_{Class D}$ PCBs for testing the rated current? As discussed, increasing the PCB area and thickness increases heat dissipation, leading to higher rated current values. Essentially, the larger trace area and thicker trace layer is to replicate the effects of using multilayer boards, heat-sinks and forced convection that are increasingly being utilized by electrical engineers. This is especially noticeable in automotive and e-mobility applications.

Consider the WE-LHMI (744 373 460 68) which has a rated current of 3.4 A (Figure 9a) and a performance rated current of 4.45 A (Figure 9d) measured on a WE Legacy and $I_{Class C}$ respectively (Figure 10a and 10d). Using the part on a 5 mm wide trace at the rated current results in a temperature rise of 49 K (Figure 9b and 10b), well within the operating temperature of the part. If the application includes forced convection (FC) for reasons of thermal management the same part on the same PCB at the same current results in a 19.5 K temperature rise (Figure 9c and 10c). Although this may be desirable in some applications, there is a lot of thermal "head room". When the performance rated current of 4.45 A was

applied to the part on a 5 mm wide trace with FC, the temperature rise was 34 K.

This comparison demonstrates how the performance rated current (I_{RP}) parameter mimics application conditions that implement thermal management methods. Indeed, in this scenario the inductor could be operated at even higher currents as long as it is below that of the inductance drop (I_{SAT}) permitted by the specific application. It also demonstrates that I_r and I_{RP} are numbers to compare and guide in the selection of inductors before prototyping. It should be remembered that these are basic parameters, considering only DC currents with no additional heat generating parts on the PCB. In real conditions, AC losses and the thermal effects of surrounding components would also have to be considered. The actual temperature rises seen in the end applications will vary considerably dependent on the conditions.

7 Conclusion

Rated current values found on datasheets serve as a guide for the selection of power inductors. However, the temperature rise in power inductors can be influenced by many factors that are not always reported in datasheets by all manufacturers giving a false sense of what the rated current values actually represent.

Measuring and comparing similar parts from competitors, demonstrates despite large differences in datasheet rated currents their performance can be very similar when using the IEC 62024-2:2020 standard to define rated current. Comparing the behavior of a single inductor in different conditions demonstrates how I_r and performance I_{RP} parameters may be used to gauge the performance of an inductor under application conditions.

As an early implementer of the IEC 62024-2:2020 standard, Würth Elektronik eiSos brings new levels of trust and transparency to the rated current values of power inductors, demonstrating no form of manipulation or misinterpretation during measurement or reporting.

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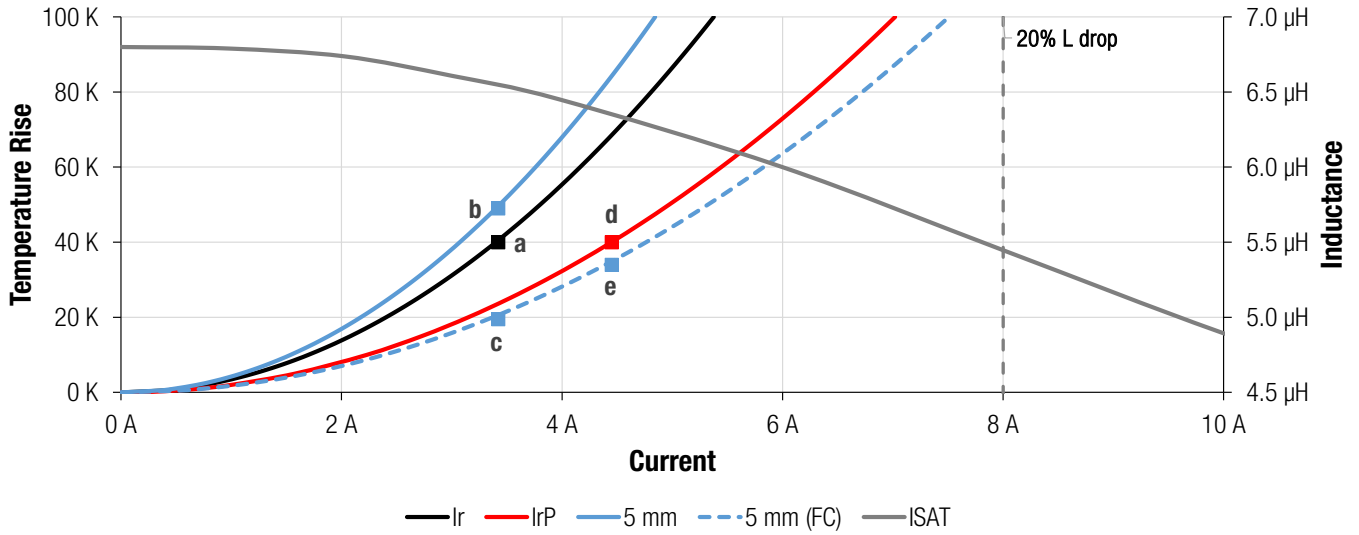


Figure 9: Self heating comparison of WE-LHMI 744 373 460 68 on different PCBs and conditions. I_r = WE-LHMI measured on the WE legacy PCB, I_{rP} = WE-LHMI measured on $I_{class C}$ PCB, 5 mm = WE-LHMI measured on 5 mm trace width, 5 mm (FC) = WE-LHMI measured on 5 mm trace width with forced convection and I_{SAT} = the magnetic DC saturation of the WE-LHMI.

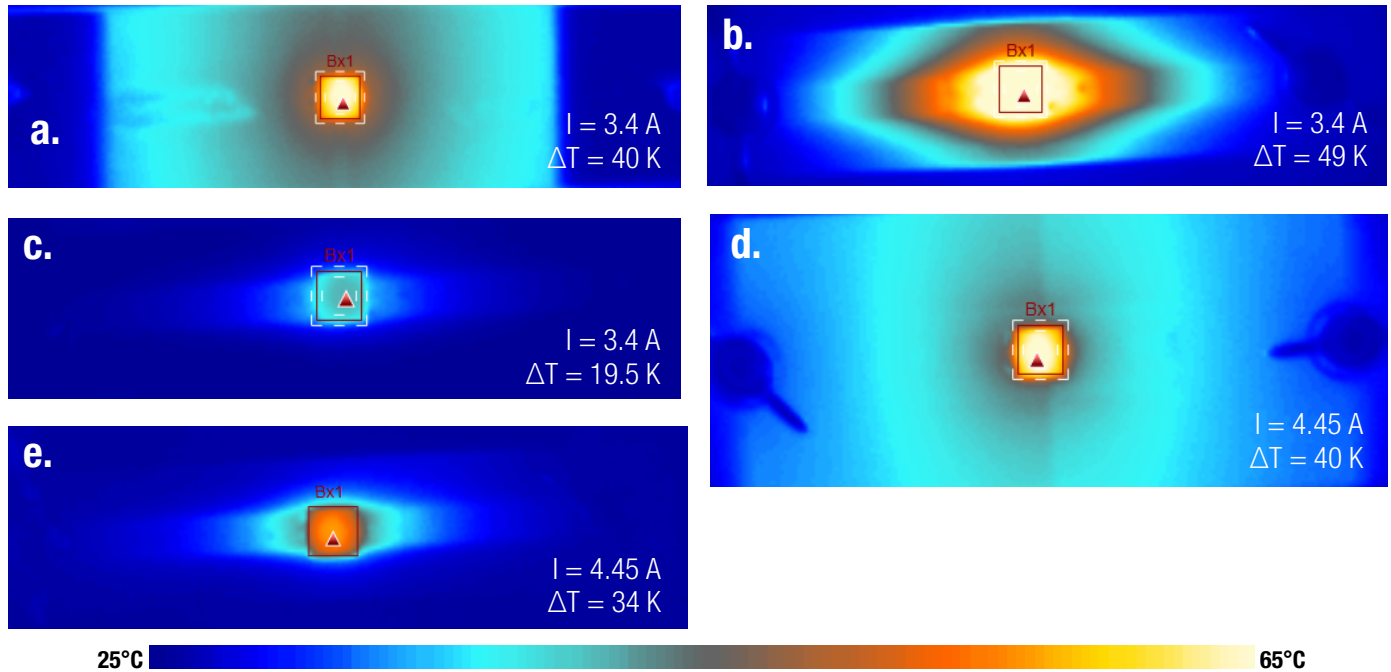


Figure 10: Thermal images of WE-LHMI 744 373 460 68 on different PCBs and conditions

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