# Design Flexibility of Extended Temperature Inductors: Part II

## Abracon AMXLA-Q Molded Inductor Series

Gerald Capwelll
Engineering Manager- Magnetics
Abracon, LLC

**10/12/2022**

# Table of Contents

**Introduction**

**Power Loss and Sources of Heat**

**Closer Look at the Abracon AMXLA Family**

**Temperature effects on Inductor DC resistance (DCR)**

**Temperature effects on Inductance (L)**

**Temperature and Core Losses**

**Temperature and Copper Losses**

**Calcuating Total Loss**

**Conclusion**


5101 Hidden Creek Ln Spicewood TX 78669 | 512.371.6159 | www.abracon.com

## Introduction

This is the continuation of the original Part I of Design Flexibility of Extended Temperature Inductors application note released earlier this year. Part I explored the use of extended temperature inductors in extreme conditions and applications where increased current was required.

This application note (Part II) dives a bit deeper and explains the DC and AC components involved to adequately derate extended temperature inductors such that safe and consistent operation through the inductor's life is possible.

## Power Loss and Sources of Heat

A key aspect of derating an inductor is understanding the sources of loss or heat. Every application will have an ambient temperature which is the temperature of the surrounding environment. The ambient temperature will depend on several factors, like adjacent heat producing components, passive or active cooling of the system itself, etc. The ambient temperature of the inductor is used a baseline where other sources of heat will be additive to calculate the total inductor body/case temperature.

There are four main sources of heat generation from inductor losses when operating in an application. They can be categorized into two groups referred to as **copper losses** and **core losses.**

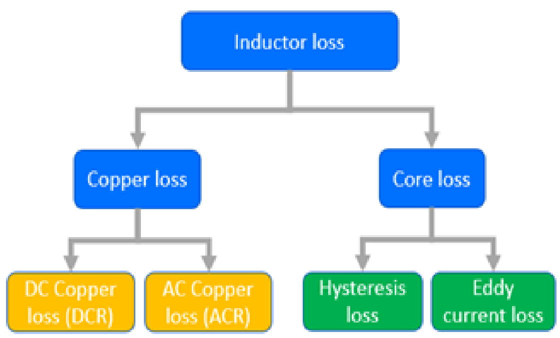


Figure 1: Components of Inductor Loss

1. **Copper losses** – these are losses primarily due to the inherent DC resistance (DCR) of the inductor's wire. The wire has a known DC resistance which is a function of the wire length and the cross-sectional area of the wire (aka gauge). The DCR parameter can be found in all the Abracon inductor's datasheets. The power dissipated from the effects of the DCR are:

$$P_{dc} = I_{dc}^2 \times DCR$$

There is, however, a frequency component to copper loss due to what is called the skin effect and proximity effect. The skin effect is where the electrons traveling through a conductor's magnetic field are forced towards the outside 'skin' of the wire. As frequency increases, the skin effect strengthens causing AC resistance to increase.

The proximity effect further reduces current (increases resistance) due to magnetic fields of adjacent wires within the coil. Inductor coils with more turns and tightly packed windings will be affected greater by the proximity effect. Power dissipation from these AC effects is calculated by taking the RMS value of only the change in current seen by the inductor (sometimes called ripple current), squaring the RMS value and multiplying by the equivalent AC resistance.

$$P_{ac} = \Delta I_{ac\,(rms)}^2 \text{ x ACR}$$

AC resistance (ACR) is a difficult parameter to document due to its dependency on so many factors. Abracon suggests that designers use an empirical method of measuring the copper loss from AC sources like the skin and proximity effects.

2. **Core losses** – are losses from the inductors core material. Core losses are caused by Hysteresis loss and Eddy current loss, both of which are converted to heat.

*Hysteresis* losses are caused by the friction of the molecular domains inside core material. These molecular domains become magnetized and polarized to the direction of the current flowing through the conductor. As the current alternates at a frequency, the magnetic domains must alternate polarity accordingly causing molecular friction and dispersed in the form of heat.

*Eddy currents* are circulating currents that manifest in the core due the changing magnetic field within the conductive core material. Eddy currents are a function of the frequency of the magnetization, volume of the magnetic core, peak flux density and other various parameters of the inductor.

Another way to categorize the losses previously described are as AC and DC sensitive components. The DCR is purely a DC component and easiest loss to calculate. AC losses include the AC copper loss, hysteresis loss and eddy current loss. The total power loss (Watts) of the inductor is calculated using the following equation:

$$P_{total\_loss} = P_{loss(DC)} + [P_{loss(AC)}]$$
$$P_{total\_loss} = I^2(DCR) + [I^2_{ripple}(ACR) + P_{Core\_Hyst} + P_{Core\_Eddy}]$$

## Closer look at the Abracon AMXLA Family

The AMXLA family consists of two series that are of different dimensions and different performance. As with any inductor, the AMXLA family is influenced by all the previous mentioned effects. However, the AMXLA extended temperature inductor family allows designers to operate these inductors at elevated temperature making it necessary to clearly understand how heat affects the inductor performance.

This section includes performance graphs of the AMXLA-Q1040 series. In order to minimize the size of this app note, graphs will not include all inductors in the series. The 1.0µH inductor is used as an example where the whole series cannot be illustrated.

## Temperature effects on Inductor DC resistance (DCR)

The inductor's DC resistance is affected by the ambient temperature and inherent self-heating of the inductor body. Fig.2 below illustrates the change in DCR of the AMXLA-Q1040 series as body/case temperature increases as ambient temperature increases. The graph shows that the DCR of larger inductance values are influenced more by temperature than smaller inductance values. However, as a percentage change in DCR, the temperature change from 25°C to the maximum 180°C will cause approximately a 60% linear increase in DCR regardless of the inductance value.

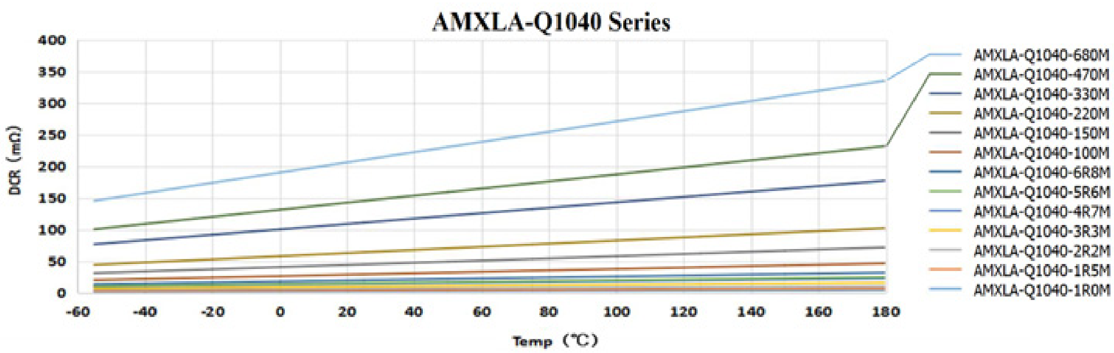


Figure 2: Changes in DCR as a function of Temperature

For example, the 68uH inductor has a DCR ≈ 210mΩ at 25°C. Adding 60% more DC resistance calculates to approximately 336mΩ at 180°C. For comparison, the 47uH inductor has a DCR ≈ 145mΩ at 25°C and a high temp DCR ≈ 232mΩ.

The increase in DCR negatively affects the inductor's performance by increasing DC loss. With the additional loss, more self-heating is generated and is the primary reason for derating inductors in extended temperature applications.

## Temperature effects on Inductance (L)

Inductance of the AMXLA series increases slightly as temperature increases. Fig.3 shows how the inductance changes with temperature. The AMXLA-Q1040 series has an extremely stable inductance across the operating temperature range. In fact, the change in inductance from 25°C to the maximum temperature of 180°C will cause less than a 2% increase in inductance.

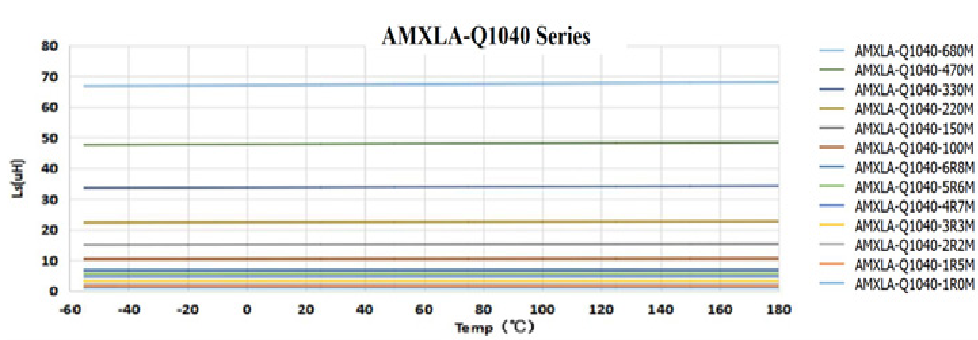


Figure 3: Changes in Inductance as a function of Temperature

Due to the stability of inductance over temperature, we can ignore this aspect when derating the inductors for extended temperature applications.

## Temperature Core and Losses

As mentioned earlier, core losses are AC-dependent losses due to the inherent properties of the core material. These losses include Hysteresis and Eddy current losses and are calculated using the Steinmetz equation.

$$P = K \times f^{\alpha} \times B^{\beta}$$

The K, α, β coefficients pertain to the core material and are constants. The f is switching frequency in KHz, while B is the peak magnetic flux density. The peak magnetic flux density is calculated by the using RMS value of the ripple current. Therefore, the power loss of the core material can be directly correlated to the switching frequency and the ripple current.

Fig. 4 below illustrates the effect of the switching frequency. The 1.0µH inductor is shown in the plots, while sweeping frequency and maintaining a reasonable constant ripple current of 4A. Core loss is primarily affected by the switching frequency. By analyzing the core loss at the 1MHz switching frequency, the difference between 25°C and 180°C is approximately a 100mW increase. For a 500KHz switching frequency the increase in core loss is only approximately 25mW.

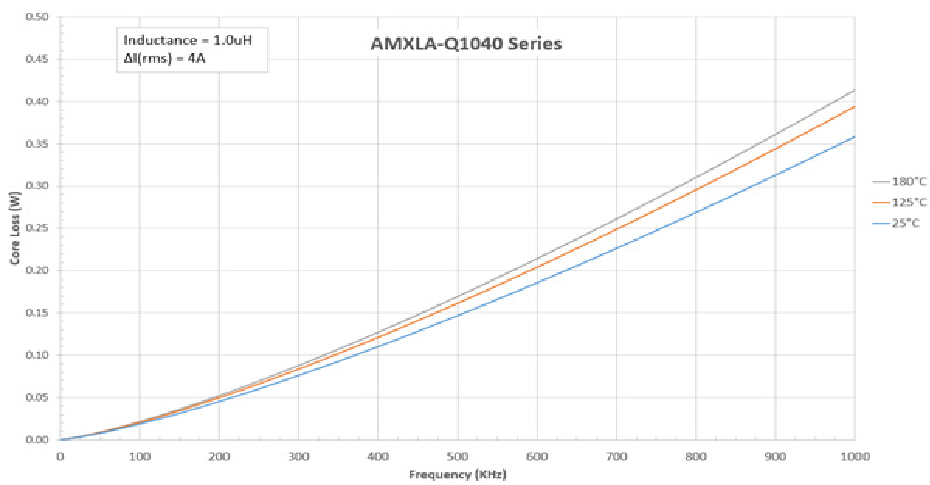


Figure 4: Core loss vs switching frequency

As illustrated in Fig. 5 below the core loss is also affected by the ripple current. The frequency is kept at 500KHz to align with our previous graph and example. In this case the ripple current is swept, and the core loss is plotted for 25°C, 125°C and 180°C temperatures. As ripple current increases to 10A, the change in core loss from 25°C to 180°C is approximately 160mW.

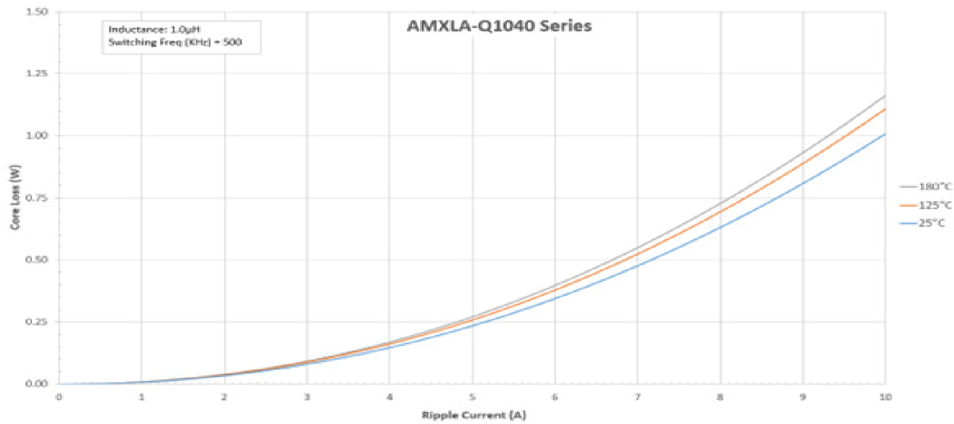


Figure 5: Core Loss vs Ripple Current

Ripple current is sometimes specified as a percentage of the full load current. Ripple currents of 15-20% are not uncommon. For example, if using the AMXLA-Q1040-1R0 with max Irms of 24A with approximately 17% ripple would equate to 4.0A p-p ripple. From the graph in Fig. 5 show that core loss from the ripple would be ≈170mW.

## Temperature and Copper Losses

Copper losses have both AC and DC components. As previously mentioned, the AC component is extremely difficult to calculate and it is suggested that AC copper loss be measured empirically. The DC component is simple to calculate using the datasheet Irms value and squaring it, then multiply by the temperature effected DCR. The DCR in Fig. 2 is very small so the graph below is provided to help illustrate power loss from the DCR as a function of temperature using the previous example of a 1.0µH inductor.

$$P_{dc\_loss} = I^2(DCR)$$

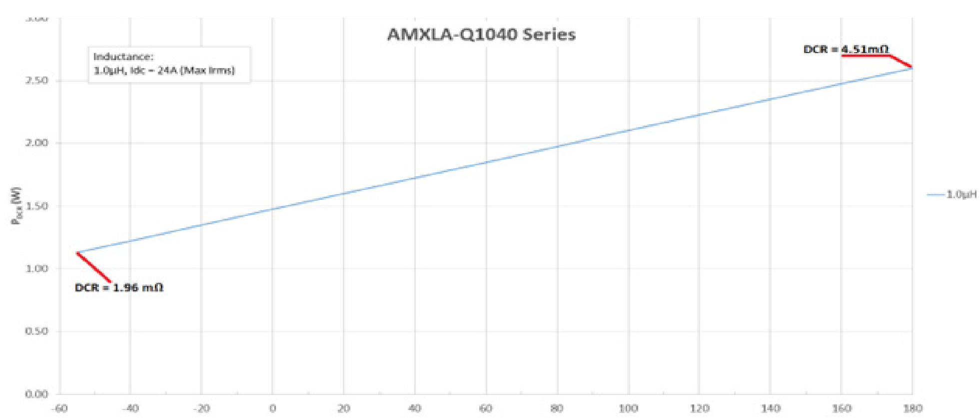


Figure 6: DCR related power loss vs temperature


5101 Hidden Creek Ln Spicewood TX 78669 | 512.371.6159 | www.abracon.com

AC copper losses can be estimated by measuring the inductors equivalent series resistance (ESR) as a function of frequency.

$$P_{ac} = \Delta I_{ac\,(rms)}^2 \times ESR$$

When measuring ESR it is important to use test methods with very little DC bias such that core losses will not influence the results. The ESR example shown in Fig. 7 includes both AC and DC resistance, where point [A] is the inductor DCR is at 0Hz. The AC resistance will remain flat until the frequency starts to influence the skin and proximity effects, at which point a 'knee' in the curve will appear as shown at point [B].

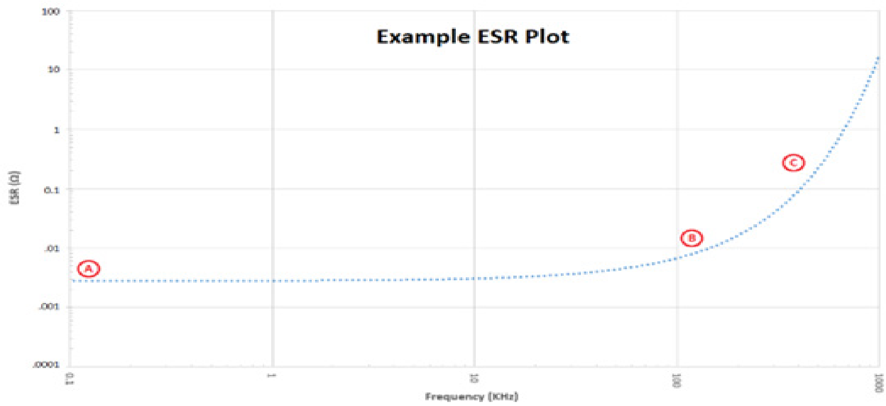


Figure 7. Example Equivalent Series (ESR) Measurement

Using the previous example of a 500KHz switching frequency, the ACR would be approximately 0.2Ω shown at point [C]. The total AC loss in our example would be:

$$P_{ac} = \Delta I_{ac\,(rms)}^2 \times ESR$$
$$P_{ac} = (4.0 \times 0.707)^2 \times 0.2$$
$$P_{ac} = 1.6W$$

## Calculating Total Loss

Finally, continuing to use the example with the following parameters, we can calculate to total estimated power dissipation:

Inductor Irms: 24A
Inductor Ripple Current (17% of total): 4.0A
Switching Frequency: 500KHz
Temperature: 180°C

The DCR at 180°C can be read from Fig. 6
The ESR estimate can be read from Fig. 7
The Core loss, which is the lump sum of losses from Hysteresis and Eddy currents, can be read from either Fig. 4 or Fig. 5.

$$P_{total\_loss} = I^2(DCR) + I^2_{ripple}(ESR) + [P_{Core\_Hyst} + P_{Core\_Eddy}]$$
$$P_{total\_loss} = 2.6W + 1.6W + 0.17W$$
$$P_{total\_loss} \approx 4.37 \text{ Watts}$$

The AMXLA family's DCR is very low, even at 180°C. The DCR is the most important parameter to consider when the design must keep power efficiency high. Maintaining high power efficiency will keep the inductor running cooler such that the allowable ambient temperature can be increased.

One final question that needs to be asked is how much heat is generated by 4.37W? Any easy way to approximate how the inductor handles heat dissipation, sometimes referred to as a thermal coefficient, is to analyze the inductor's Irms response. The Irms graph can be used to estimate how many degrees Celsius increase per watt (°C/W).

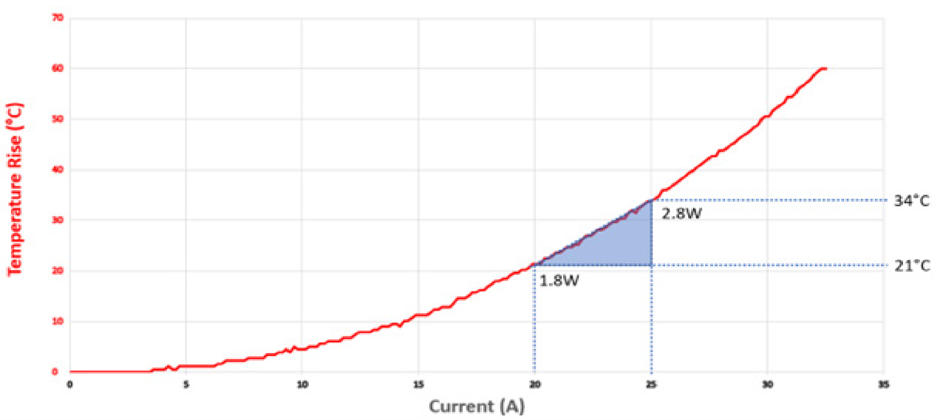


Fig 8. AMXLA-Q1040 1.0µH IRMS graph

The Irms graph in Fig. 8 show the thermal response of the inductor as a function of DC current. The Irms graphs found in datasheets are measured at an ambient of 25°C. Changes in ambient temperature will change the DCR linearly as mentioned earlier. Therefore, finding the slope of this line around the expected operating current, will yield a good estimate for the thermal coefficient. Continuing with the previous example, calculating the power around 24A and using the DCR at 180°C of 4.51mΩ, will give a thermal coefficient of 13°C/W.

$$DCR_{180} = 4.51m\Omega$$
$$\Delta P_{180} = (25^2 DCR - 20^2 DCR)$$
$$\Delta P_{180} = 2.8W - 1.8W = 1W$$
$$\Delta T_{180} = 13°C$$
$$T_{Coeff} = 13°C/W$$

For 4.37 watts of power dissipation, the estimated case temperature will be ~56.8°C.

## Conclusion

In summary, heat is generated from the two categories of loss -Copper and Core. Hopefully, it is now more obvious the effects of copper losses far outweigh the core losses. In fact, changes in ambient temperature from 25°C to 180°C influenced the DCR by ~60%, while core losses only changed by ~15%.

Abracon's extended temperature inductors promote design flexibility by allowing design for higher case temperatures. Higher case temperature allows for applications requiring higher ambient temperatures or applications that require the inductor to be driven harder causing the case temperature to increase. In fact, the AMXLA family permits the operation of the inductor beyond the AEC-Q200 Grade 0 (150°C) specification. Therefore, it is very important to understand how copper and core losses influence the total self-heating of the inductor.


5101 Hidden Creek Ln Spicewood TX 78669 | 512.371.6159 | www.abracon.com