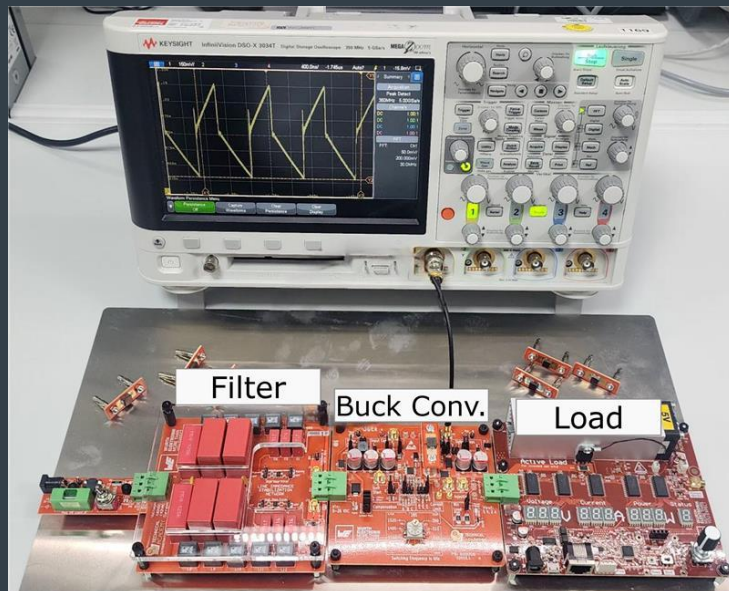




# IMPACT OF ELEVATED VOLTAGE AND TEMPERATURE ON MOLDED POWER INDUCTORS IN DC/DC CONVERTERS

Ing. Annika Frankemölle | Dr.-Ing. Efrain Bernal  
Power Magnetics Team

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT



# AGENDA

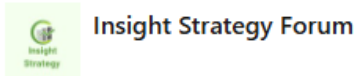
- **Introduction**
  - Market Trends
  - Impact of Percolation
  - Molded Inductor production process and materials
- **Percolation Phenomenon**
  - Definition
  - Molded Power Inductors degradation
- **Previous findings**
  - ANP126: Voltage specification
  - ANP128: Thermal aging
- **Performance repercution of Percolation**
  - Q factor change
  - Reliability
- **Impacts of the degradation in a DC/DC converter**
  - Different levels of percolation
  - Efficiency
  - EMC
- **Summary Findings**



# INTRODUCTION

## Market Trends

### Molded Inductors Market Trends: Dynamics and Growth Drivers in 2024



Insight Strategy Forum



December 23, 2024

Molded Inductors Market size was valued at USD 2.5 Billion in 2022 and is projected to reach USD 4.0 Billion by 2030, growing at a CAGR of 6.5% from 2024 to 2030.

#### Molded Inductors Market Overview

## Dynamics

- Technological advancements in manufacturing processes are driving the efficiency and performance of molded inductors.
- Increased focus on energy efficiency and sustainable solutions is propelling the demand for molded inductors in green technologies.

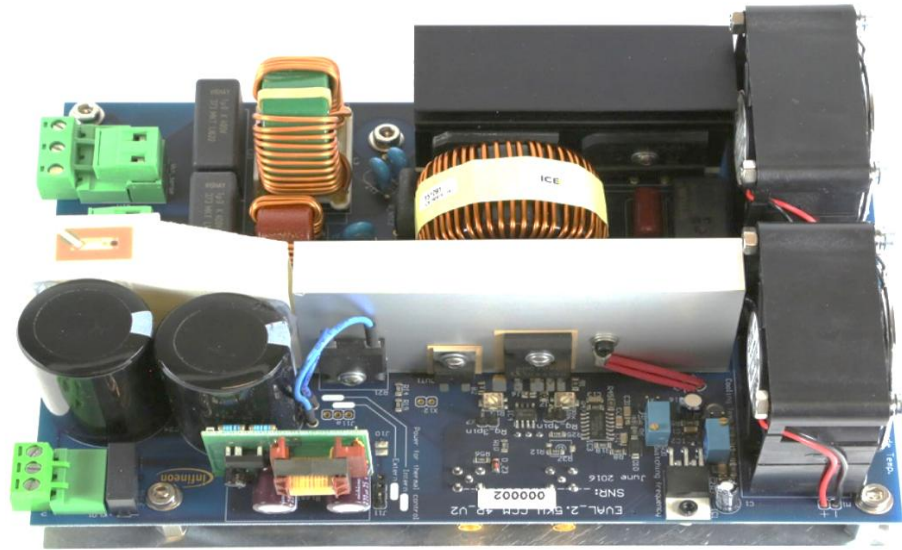
## Key Drivers and Challenges

- Key Driver: The rise of electric vehicles (EVs) is creating a burgeoning market for molded inductors, as they are crucial for electric power conversion.
- Key Driver: The proliferation of consumer electronics is leading to heightened demand for reliable and efficient molded inductors.

# INTRODUCTION

Market Trends

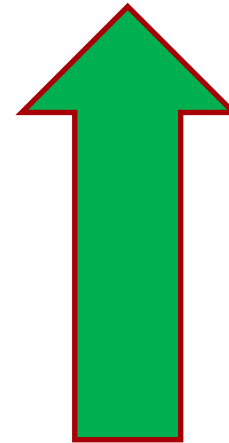
## Silicon PFC @ 2kW



**Power Density: 37 W/in<sup>3</sup>**

2.8x

Higher Density



## GaN PFC @2kW



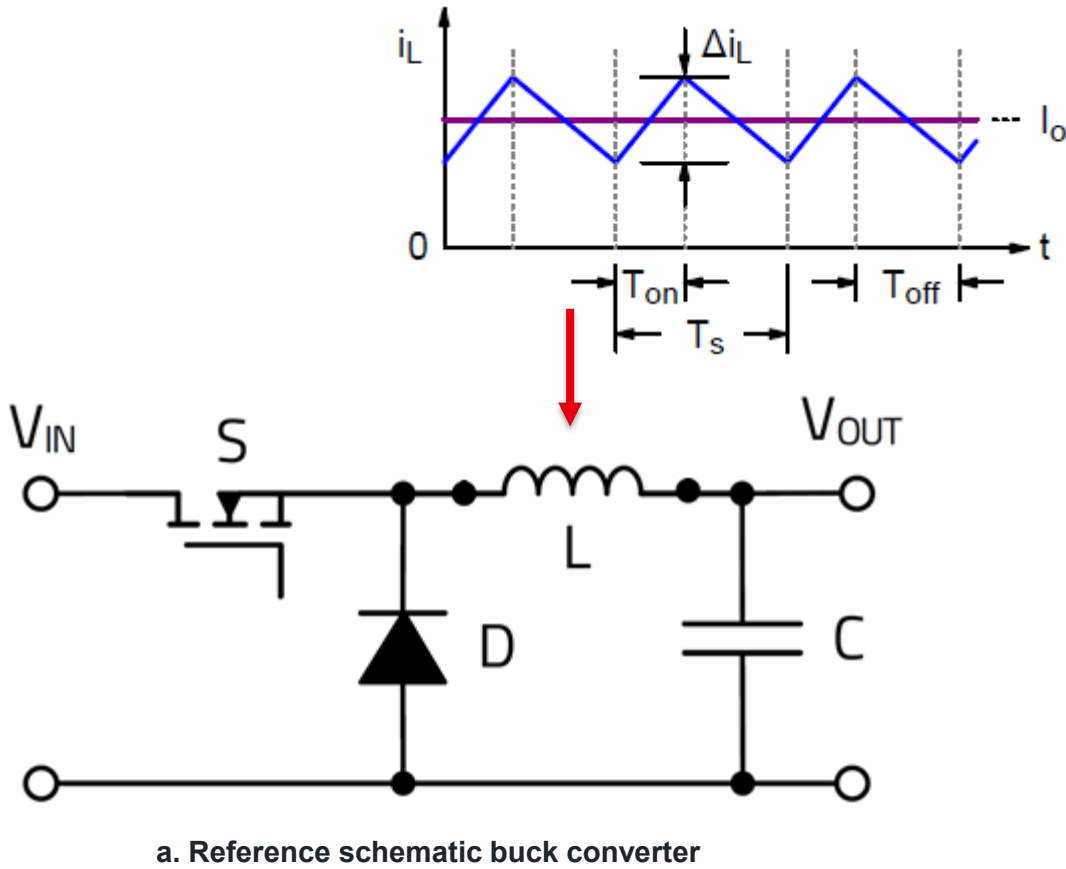
Learn more at [www.ti.com/GaN](http://www.ti.com/GaN)

**Power Density: 104 W/in<sup>3</sup>**

Fig.1. Example of the size reduction of a DC-DC converter using Texas Instruments' GaN technology.

# INTRODUCTION

Why inductors matter for DC/DC converter efficiency and reliability



Inductors design directly impacts efficiency through conduction losses and determines overall reliability:

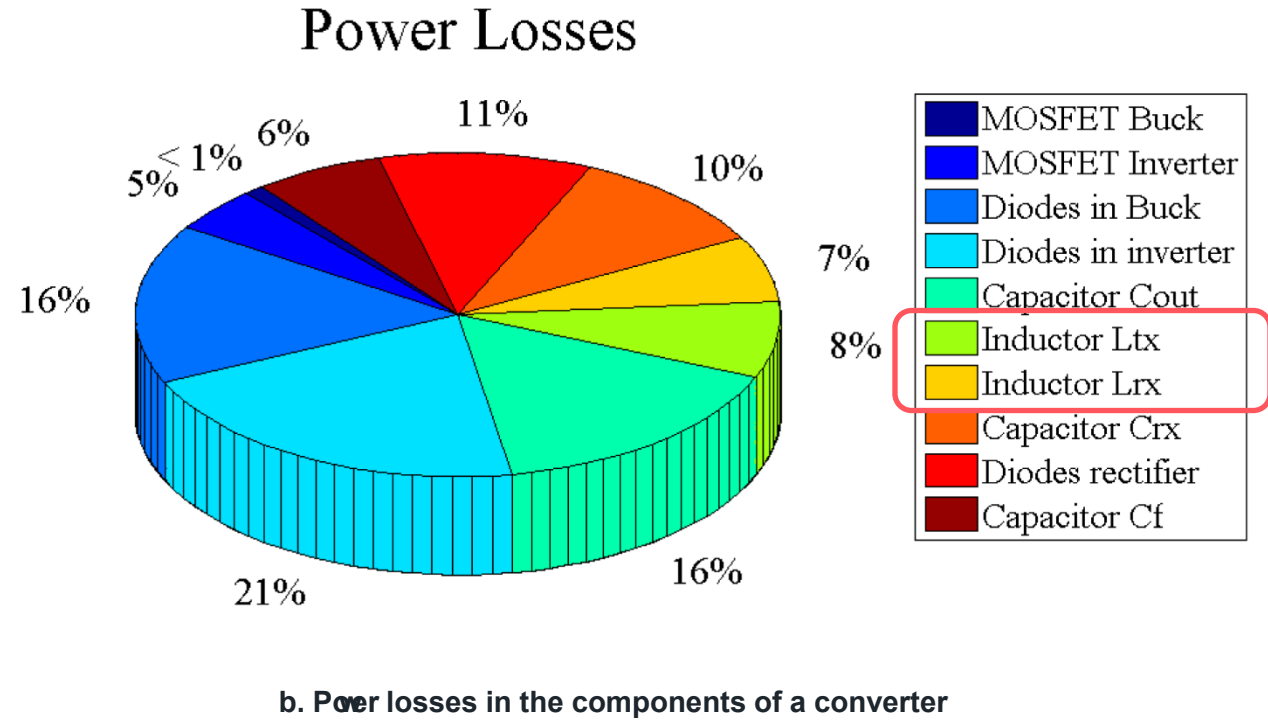


Fig.2. Buck converter topology and typical power losses in key components.

# INTRODUCTION

## DC-DC converters

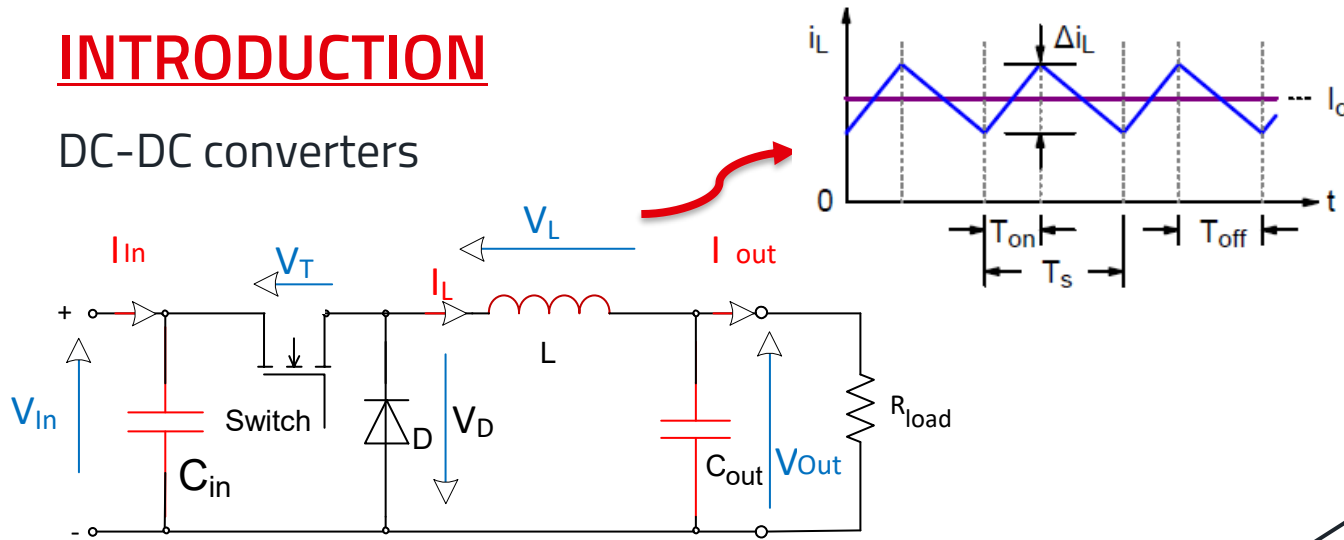


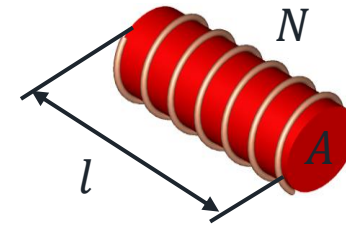
Fig.3. Buck converter.

### Inductance value definition:

- Component behavior
  - Inductance value is defined by physics and geometry
  - Inductance value is sensitive to saturation ( $\mu_r$ ) reduction , magnetic field saturation.

### Inductance in the equations of the Buck converter

The ripple current  $\Delta_{IL}$  is linked to Voltage , Time, and inductance value



$$L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot N^2}{l}$$

$$\Delta_{IL} = \frac{(V_{in} - V_{out}) \cdot V_{out}}{f_{switch} \cdot L \cdot V_{in}}$$

$$V_L = V_{in} - V_{out}$$

$$V_L = L \cdot \frac{d(IL)}{dt}$$

$$L = \frac{(V_{in} - V_{out}) \cdot T_{ON}}{\Delta_{IL}}$$

$$T_{ON} = \frac{D}{f_{switch}} \quad D = \frac{V_{out}}{V_{in}}$$

$$L = \frac{(V_{in} - V_{out}) \cdot D}{f_{switch} \cdot \Delta_{IL}}$$

$$L = \frac{(V_{in} - V_{out}) \cdot T_{ON}}{\Delta_{IL}}$$

# INTRODUCTION

WE have „discovered“ that molded power inductors exhibit a percolation behavior as a result of being exposed to higher temperatures or voltages. This leads to a passive device degradation, which in turn affects the DC/DC converter's long-term performance.



a. Increment of core losses and harmonics



b. Increment of input power demand

Fig.4. Affection of a percolated molded power inductor in a DC-DC converter.

# INTRODUCTION

## Is temperature to blame?

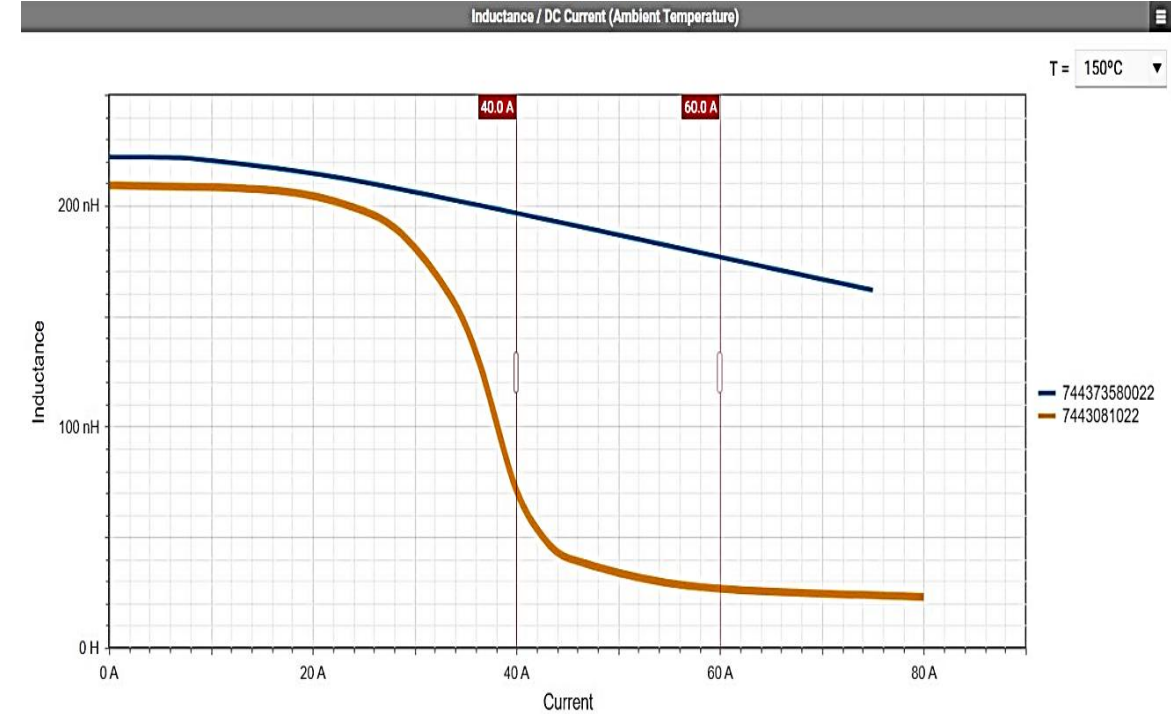
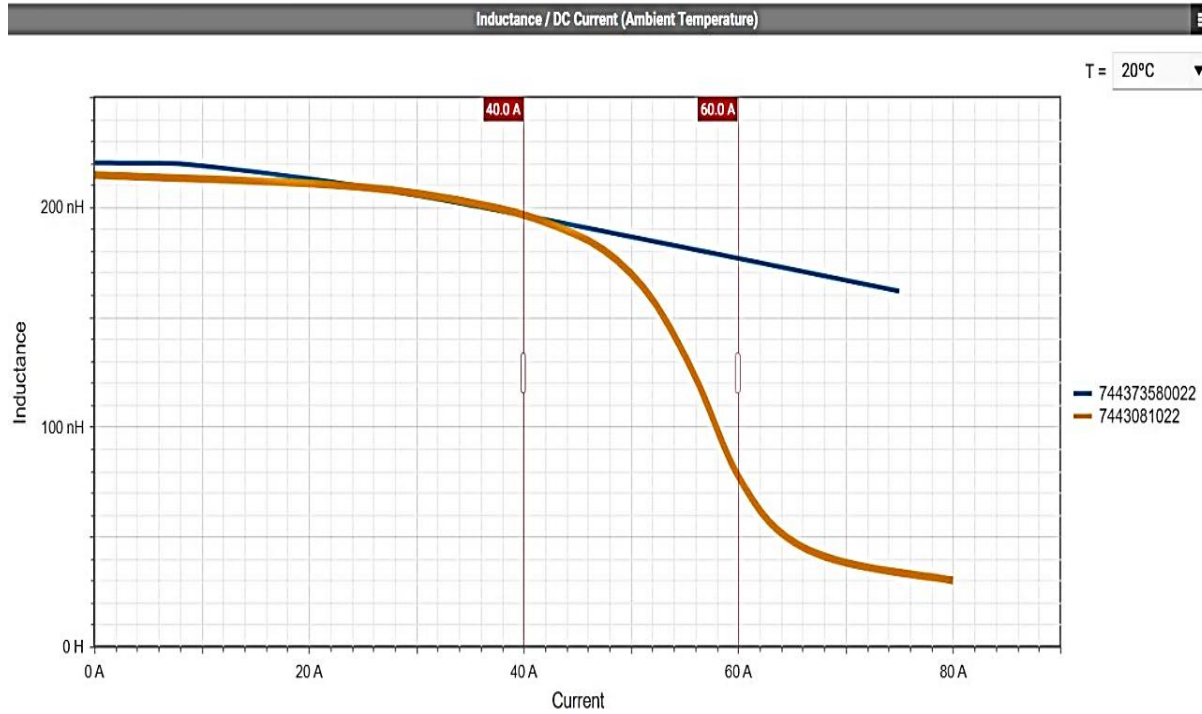
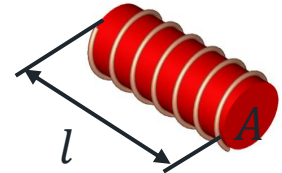


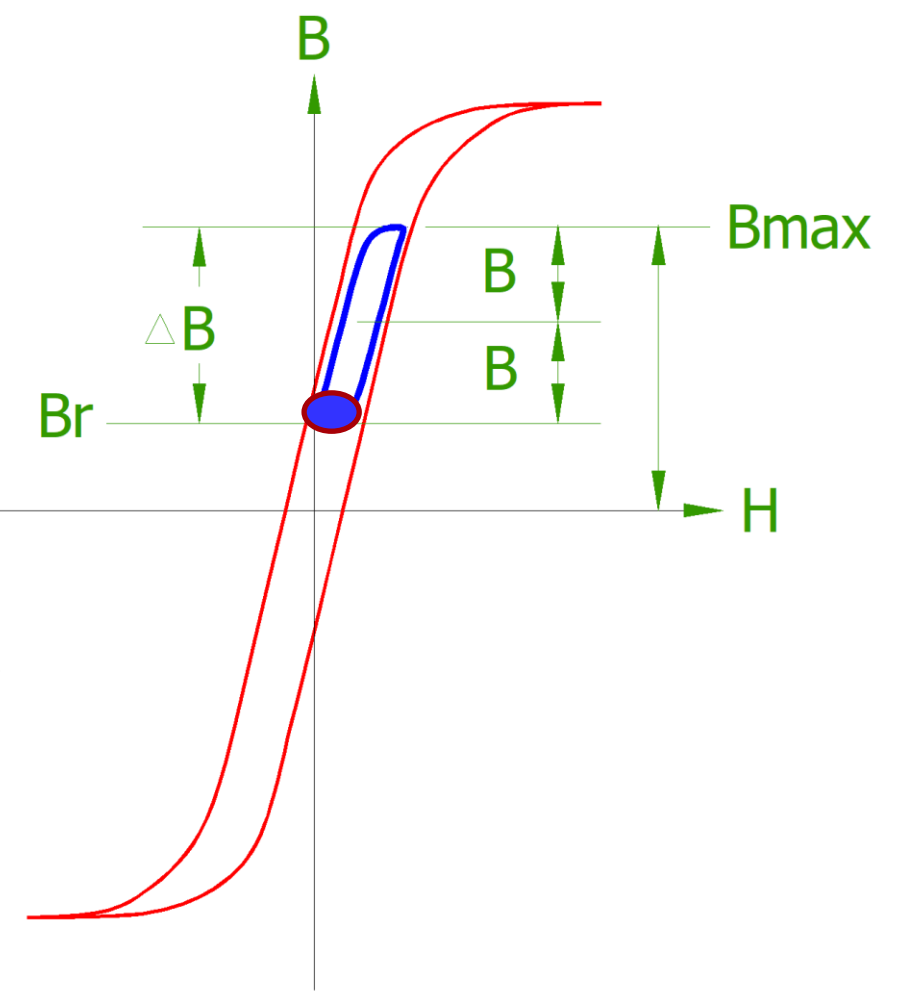
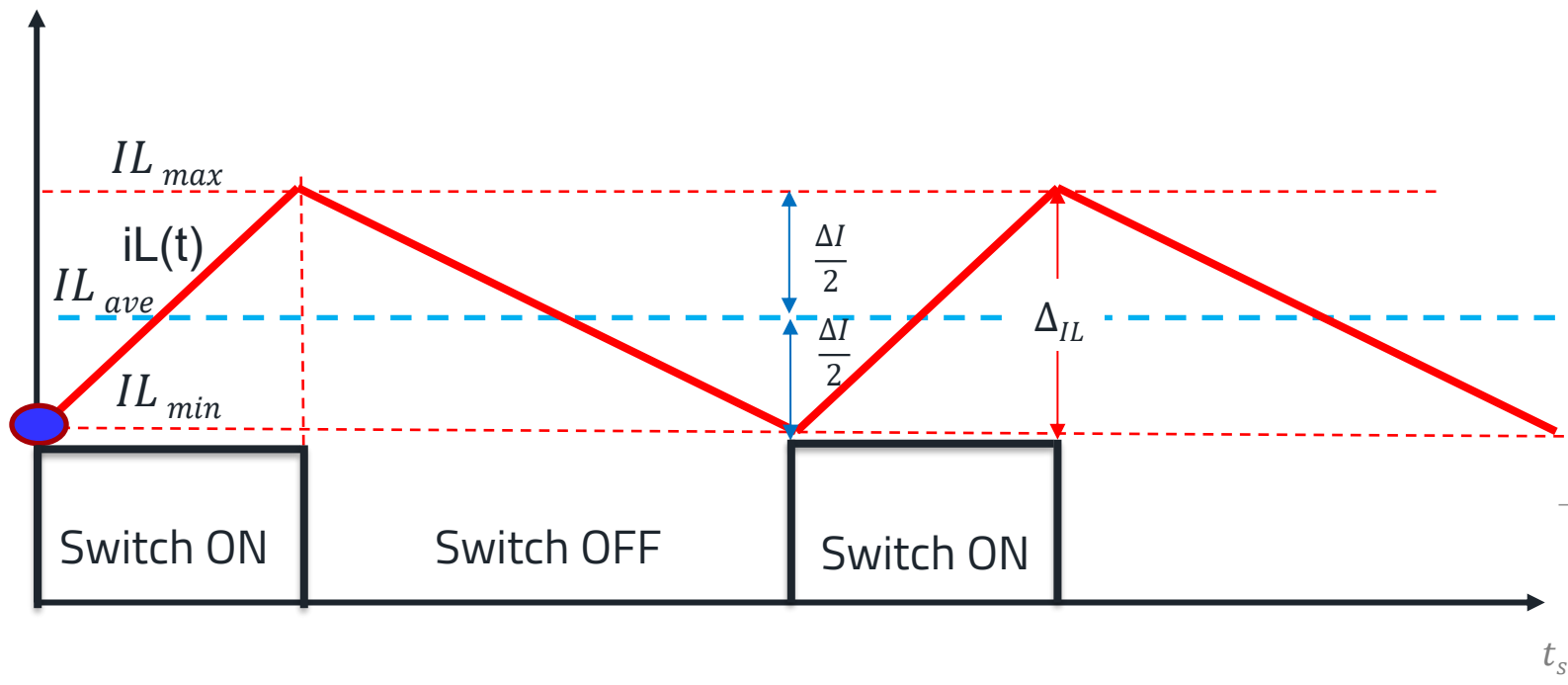
Fig 5: Comparison of the saturation current ( $I_{sat}$ ) between a ferrite core inductor with hard saturation (orange) and a molded core inductor with soft saturation (blue) at different ambient temperatures, as shown by RED EXPERT.

- **Theory:** Materials with soft saturation do not change their behavior with increasing temperature.  
**Reality:** Their behavior could change drastically.

# INTRODUCTION



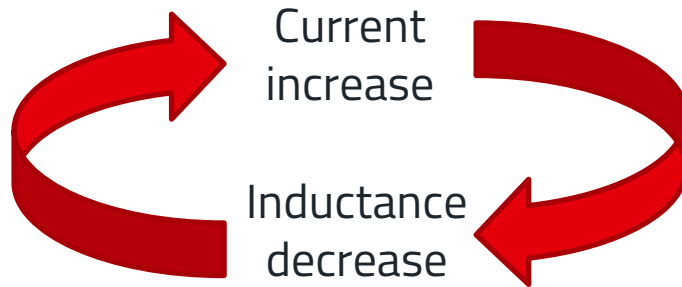
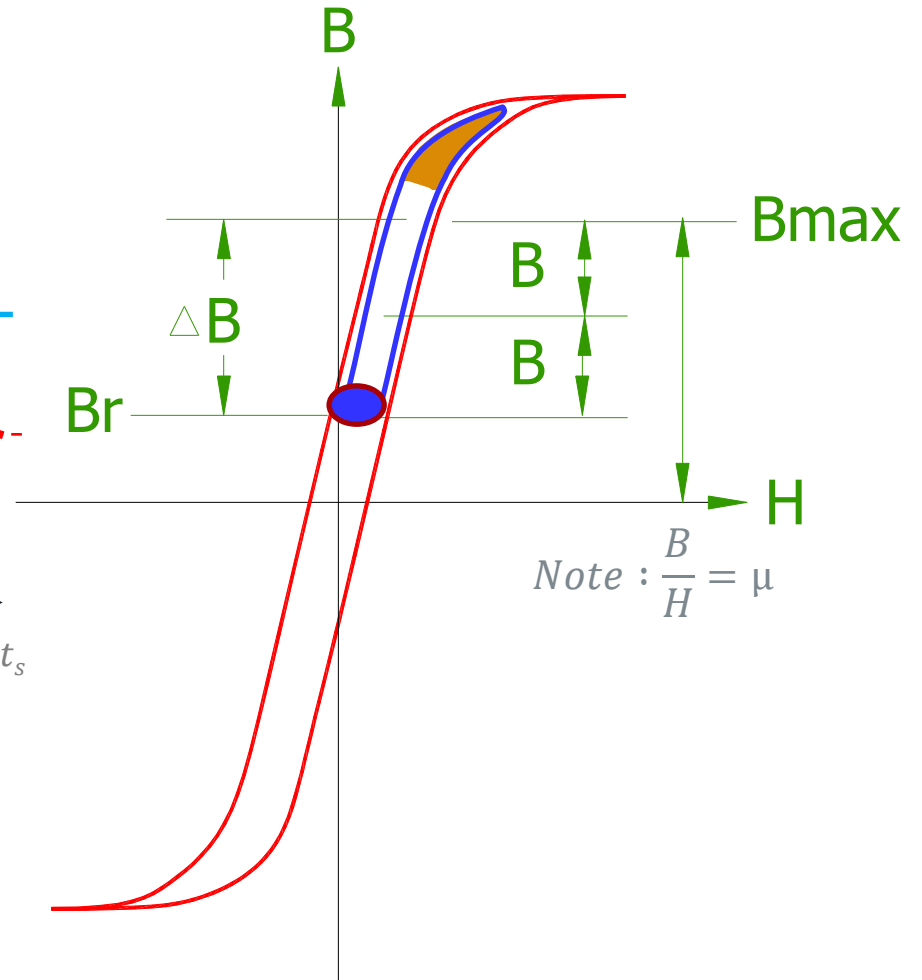
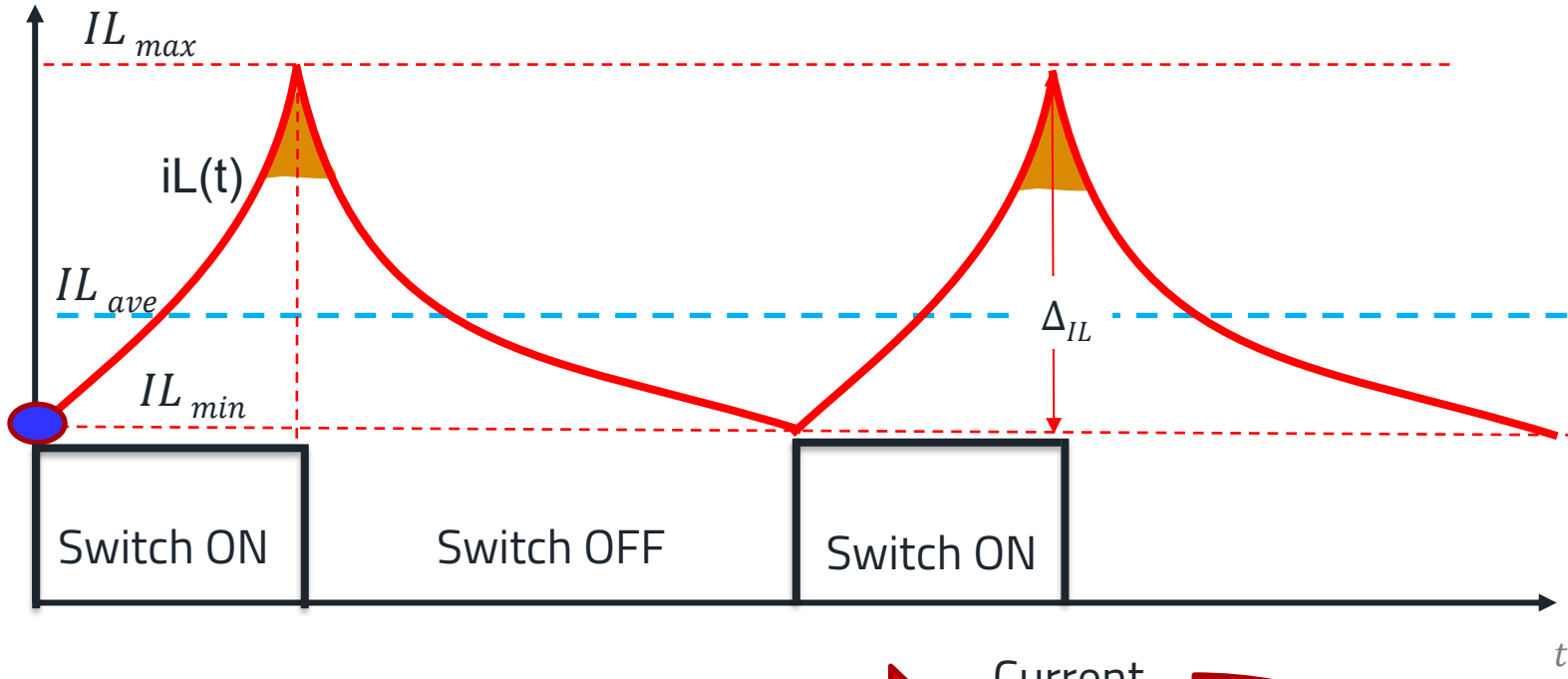
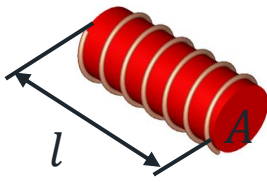
Cycle explanation : linear behavior (Buck in Steady State equivalent to soft saturation)



# INTRODUCTION

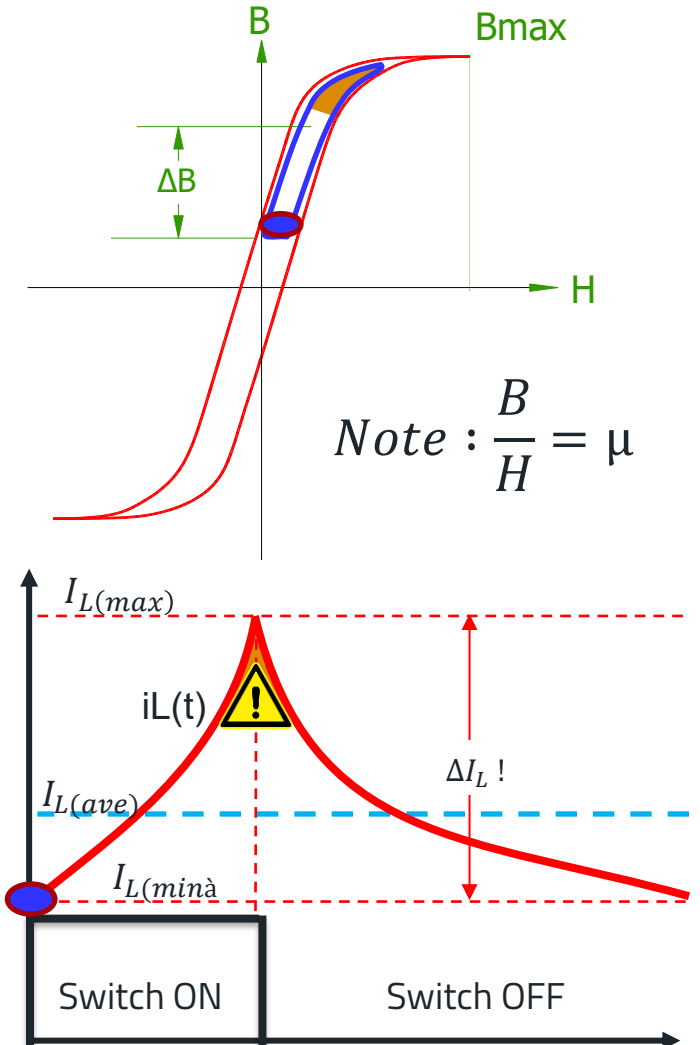
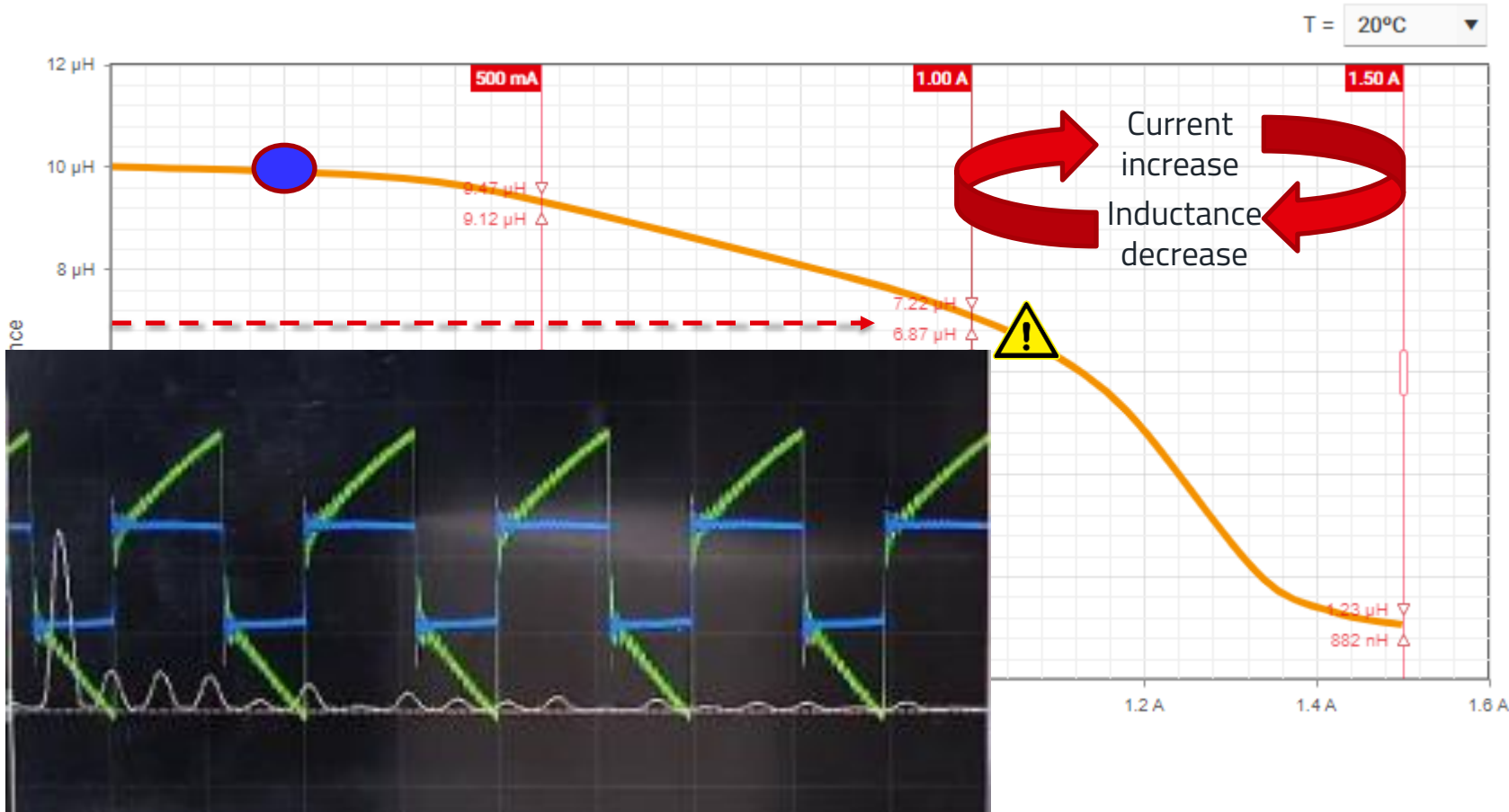
Cycle explanation : saturation behavior for Hard Saturation material

$$L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot N^2}{l}$$



# INTRODUCTION

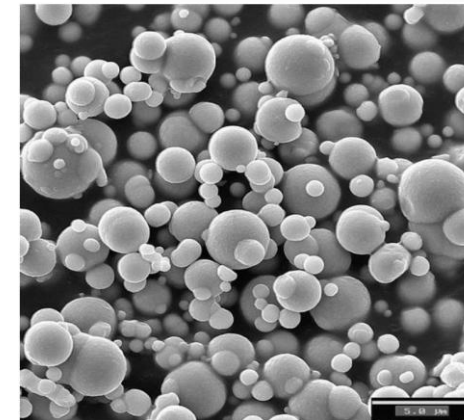
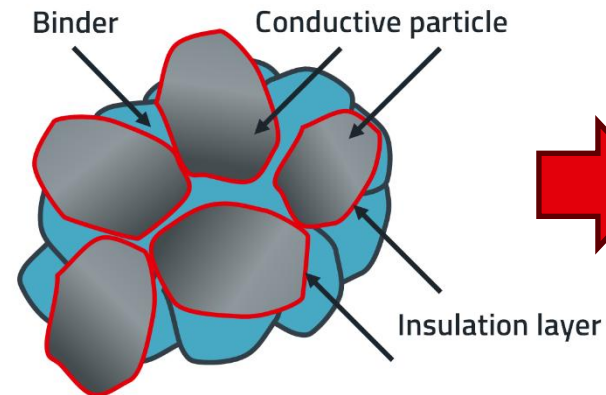
REDEXPERT [WE-TPC# 744043100](#) deviation for  $10\mu\text{H}$   $I_{sat} = 1,0\text{A}$



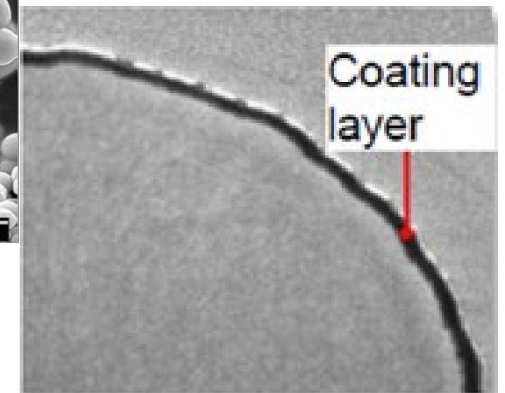
# INTRODUCTION

## Molded Inductor production process and materials

- **Production Process** (simplified)
  - Wound insulated copper wire
  - Material mixed containing Iron Powder and Binder
  - Pressed in mold
  - Cured in Oven
- **Core Material**
  - Mostly contain Iron Particles
  - Iron is conductive
  - Particles are coated
  - Binder used as „glue“



*Iron Powder Particles  
- BASF Website*



*Iron Powder Particles Coating  
- BASF Website*



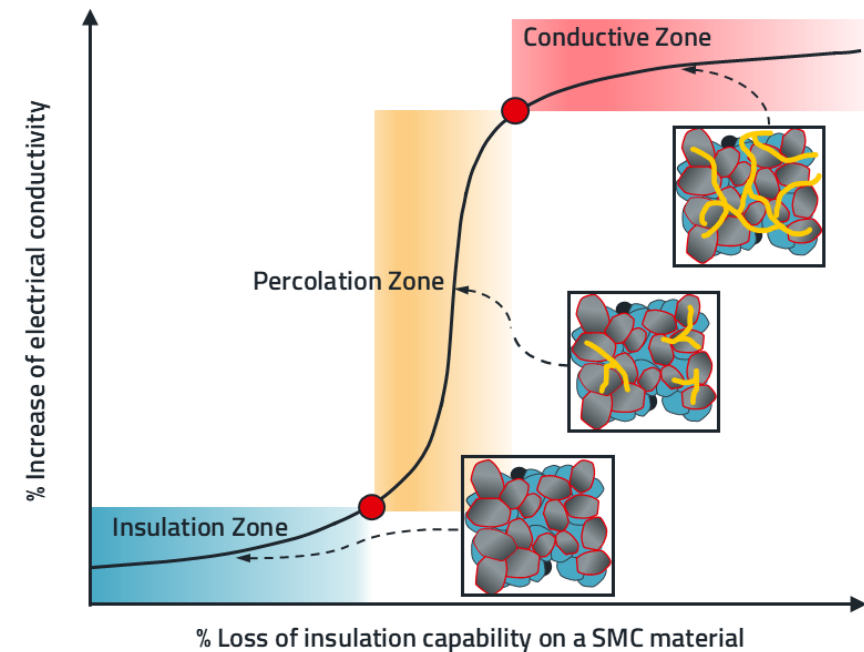
Fig.7. The assumption from inductor designers.

# PERCOLATION PHENOMENON

## Definition

“The **percolation phenomenon** in a molded power inductor is defined as the **material degradation that transitions from an insulating to a conductive state.**”

The percolation threshold is defined as the critical filler fraction of a material when it transitions from an insulating to a conductive state.



b. Threshold curve.

Fig.8. Percolation phenomenon in materials.

# PERCOLATION PHENOMENON

## Molded Power Inductors degradation

- High Voltage
- High Temperature

The higher **electrical and thermal stress** on molded power inductors can lead to an **increase in magnetic core loss** over time due to a material degradation related to the percolation phenomenon.

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**APPLICATION NOTE**

ANP142 | Effects of molded power inductor degradation due to higher voltage or temperature in a DC/DC converter

Dr.-Ing. Efraim Bernal Alzate

**1. INTRODUCTION**

For DC-DC converter applications molded power inductors enable both smaller footprints and lower profile due to the properties of the magnetic material. The reduced dimensions of current designs demand the employment of smaller inductors capable of operating at elevated voltages and currents in more extreme thermal conditions. The higher electrical and thermal stresses can lead to an increase in magnetic core loss over time due to material degradation related to the percolation phenomenon. Würth Elektronik eiSos has pioneered the introduction of these phenomena as the common failure mechanism between the material degradation found under high voltage operations [ANP126 – Voltage specification for molded inductors](#)<sup>[1]</sup> and the degradation obtained when a molded power inductor is exposed to high temperatures [ANP128 – Introduction to thermal aging in molded power inductors](#)<sup>[2]</sup>.

But what are these percolation phenomena? What are the repercussions of percolation in a molded power inductor? And more importantly, how does it affect the long-time performance of a DC-DC converter? Let us answer these questions in the following sections.

**2. BACKGROUND**

Historically thermal aging tests performed over extended periods of time at elevated temperatures have been used to

percolation threshold is the critical point where the material turns from insulating to conductive.

**2.1 Percolation phenomenon on molded power inductors**

Percolation has generated great interest in the scientific community for decades and has promoted the development of theoretical models and experimental research work in understanding connectivity phenomenon<sup>[4]</sup>. It has been used from traffic analysis, artificial intelligence programming, to materials design. In the materials field, percolation theory is a type of analytical-mathematical model, commonly referenced in the literature for the development and modeling of electrical conductivity in different materials<sup>[5]</sup>.

In general, percolation theory refers to the slow movement of liquid through a material with tiny spaces or holes, as well as describes the behavior of a network when nodes or links are created.

For composite material, percolation phenomenon occurs when the increasing amount of added conductive metallic particles reaches a point where the electrical conductivity increases abruptly. This is called the percolation threshold<sup>[6]</sup>. Particularly, many experiments have demonstrated that the conductivity of composites has a nonlinear relationship with the doping of conductive particles<sup>[7]</sup>. Composites are materials made by combining two

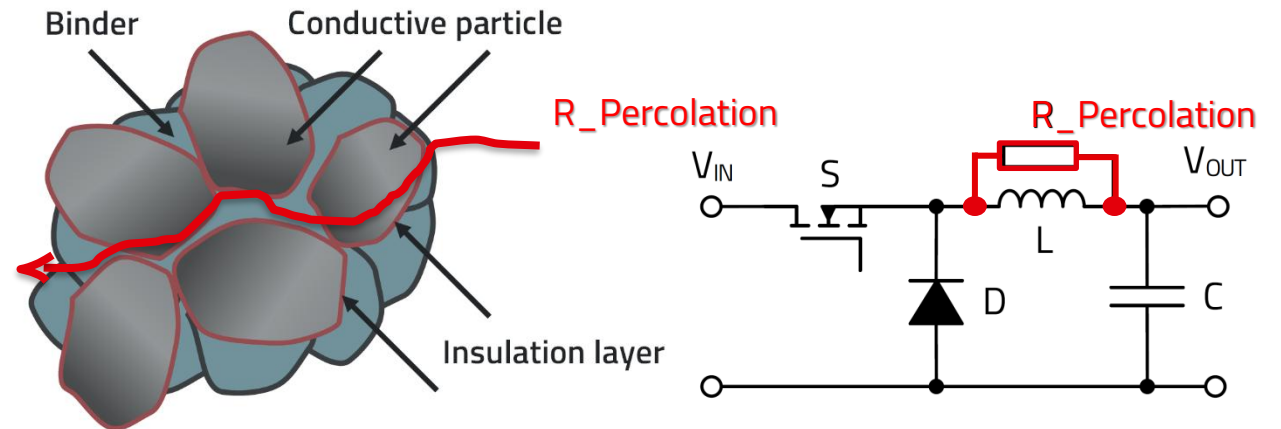
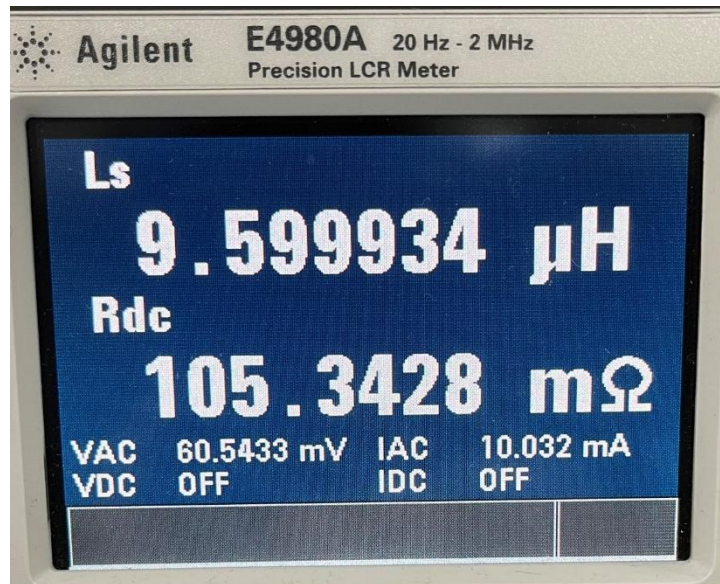


Fig.9 Percolation on Molded Power Inductors.

## PREVIOUS FINDINGS

ANP126: Voltage specification

Material degradation not detectable during standard AECQ200 qualification testing:



a. Good part

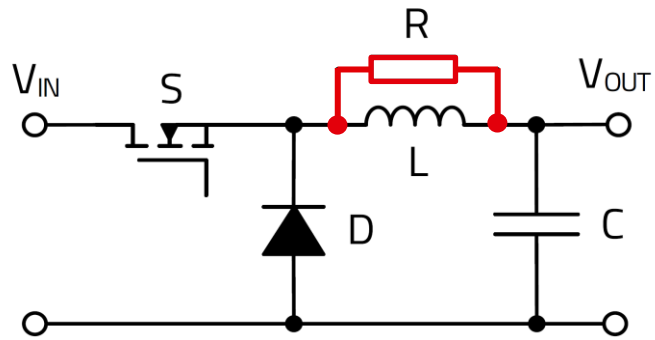


b. Compromised part

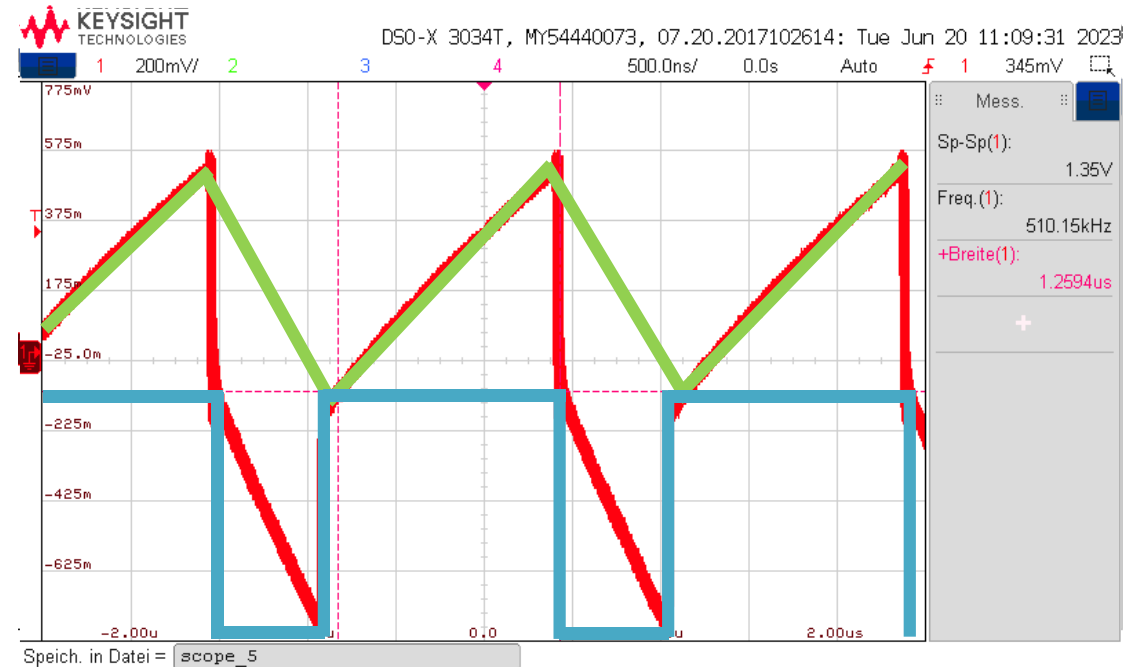
Fig. 10. LCR measurements at 100 kHz 10 mA.

# PREVIOUS FINDINGS

## ANP126: Voltage specification



a. Simplified Buck Converter with parallel Resistor R



— Inductive component of the Current Waveform

— Resistive component of the Current Waveform

b. Buck Converter Current Waveform with Resistor R

Fig. 11. Interpretation model for percolation losses.

# PREVIOUS FINDINGS

ANP128: Thermal aging

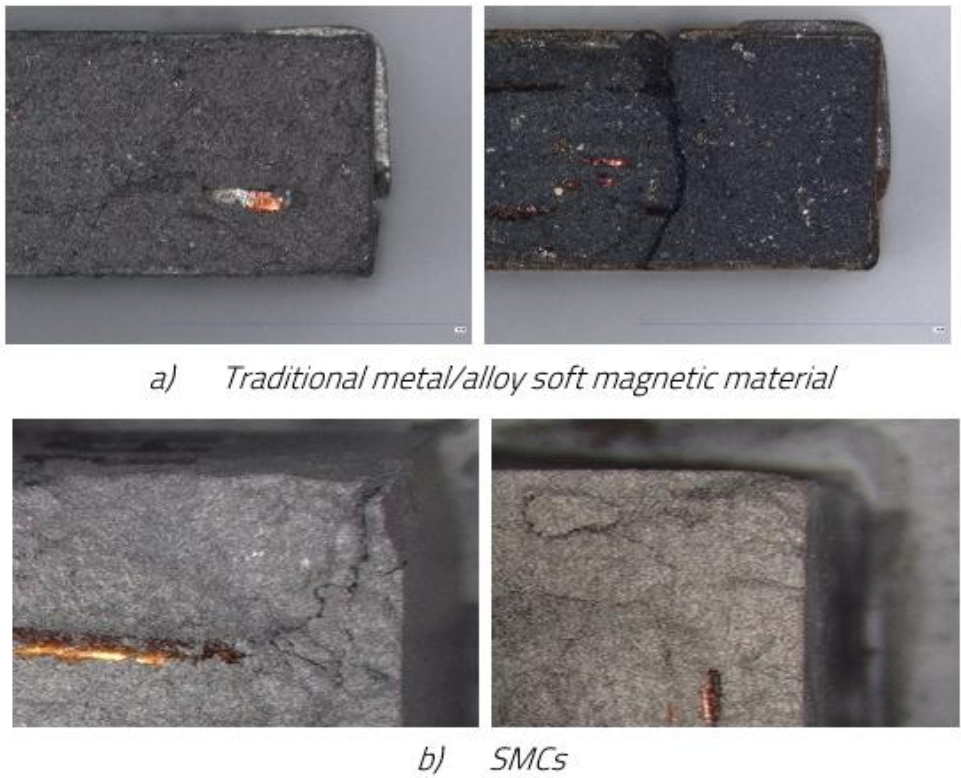
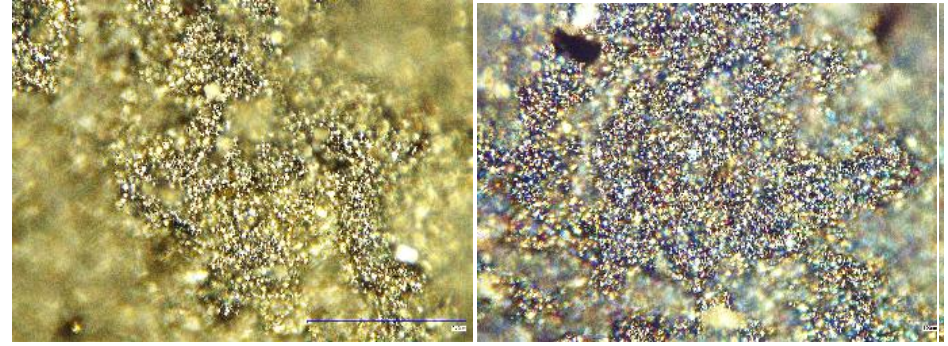
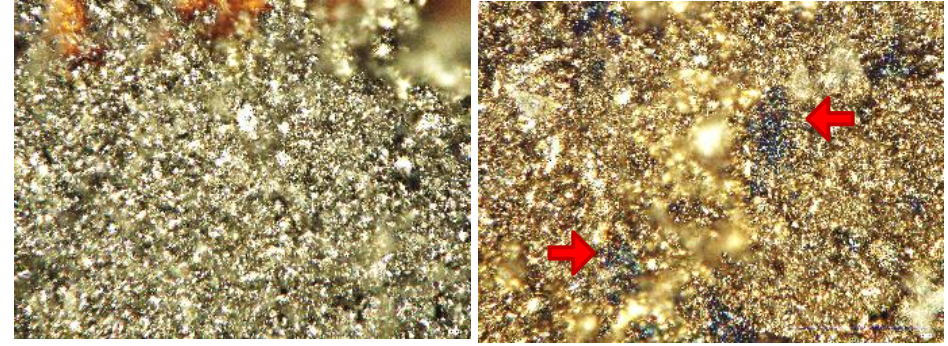


Fig. 12. Mided Power Inductors before test (left column) and after test (right column) zoom at 10X.

AEC-Q200 Grade 1  
Competitor samples  
with a 165 °C max part  
temperature



AEC-Q200 Grade 0  
Competitor samples  
-55 °C bis +150 °C



AEC-Q200 Grade 0  
-55 °C bis +150 °C  
WE-LHMI HT

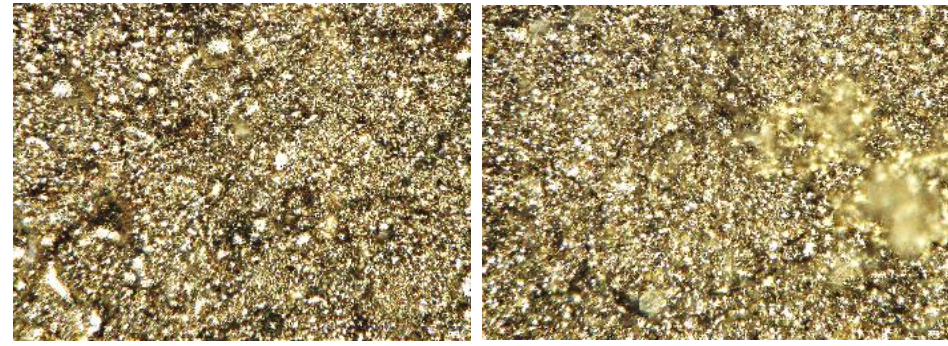
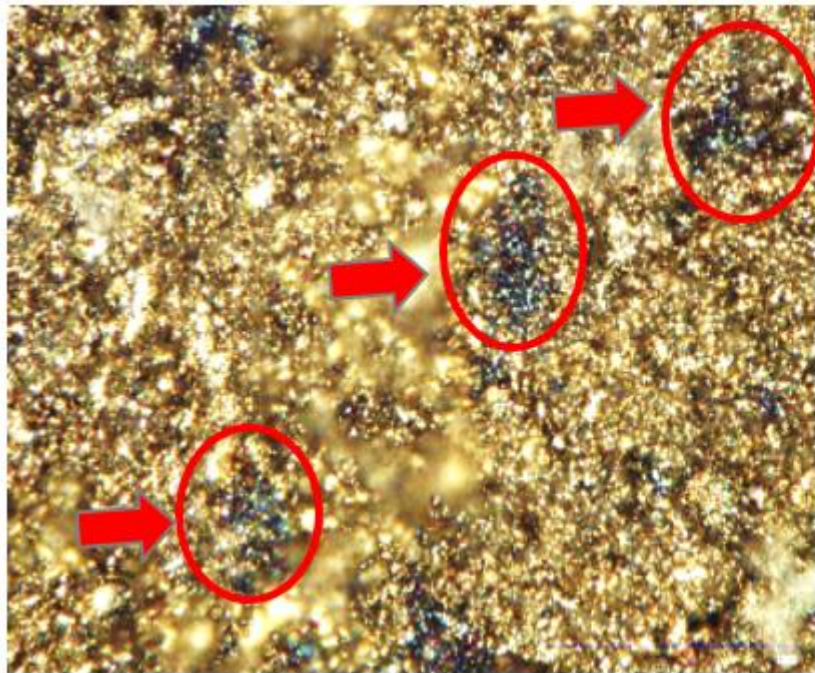


Fig. 13. Mided Power Inductors before test (left column) and after test (right column) zoom at 1000X, Test setup: 1000 h @ 200 °C.

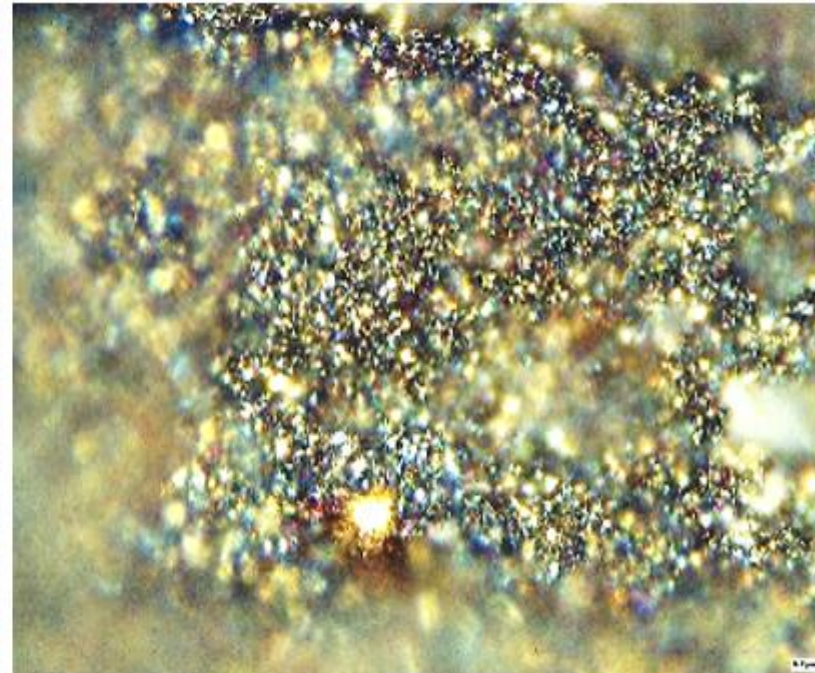
## PREVIOUS FINDINGS

ANP128: Thermal aging

Percolation induces new conductive connections between the iron particles, and with it, the creation of clusters that can deteriorate the molded power inductor:



a. First percolated cluster formations.

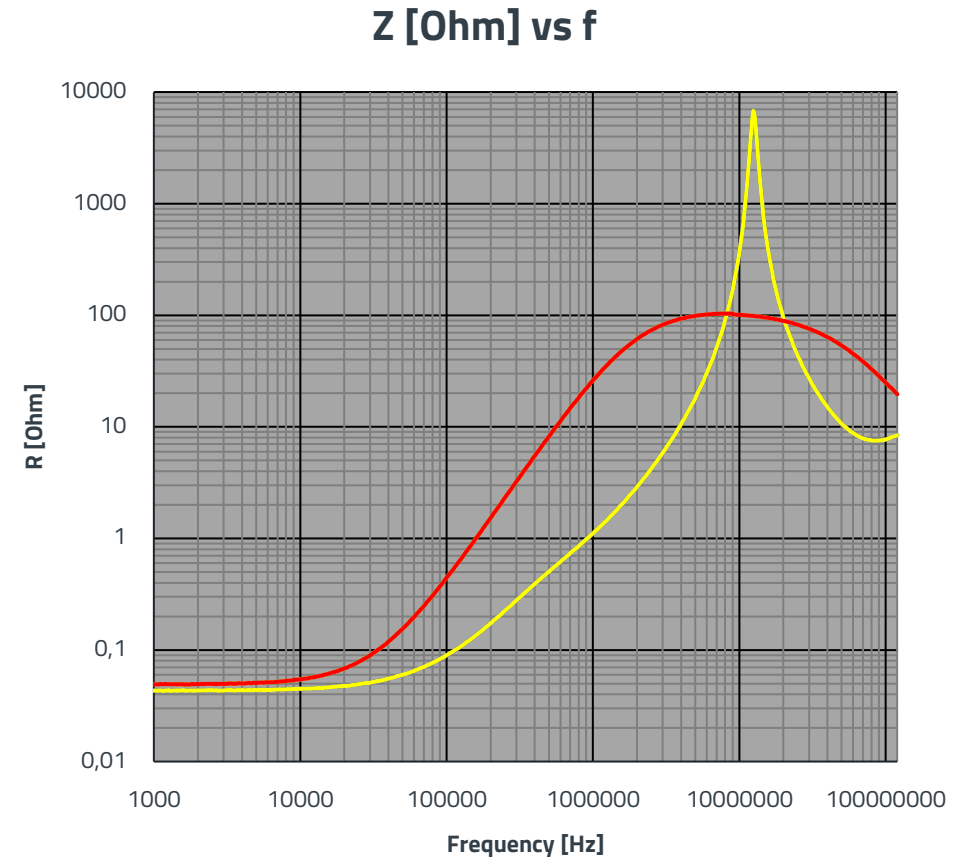
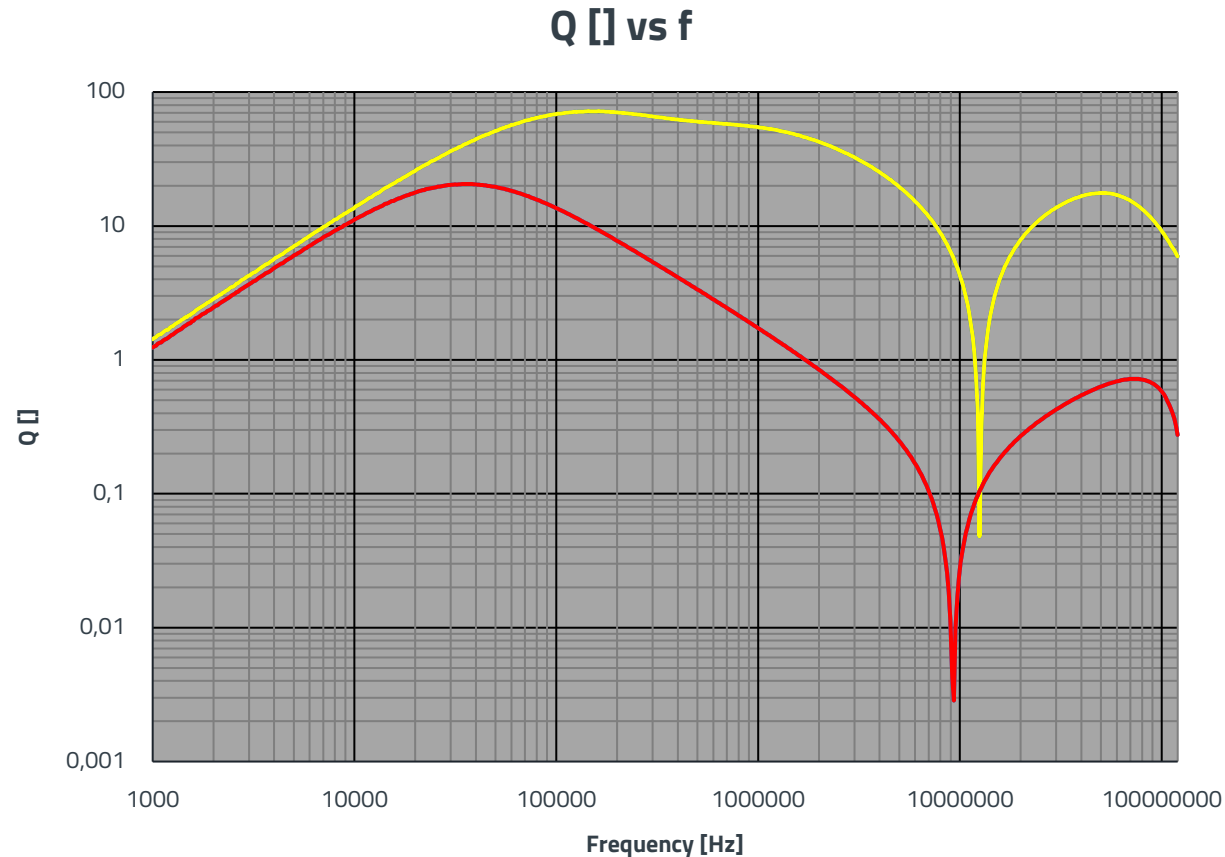


b. Material with strong percolation.

Fig. 14. Some burned areas obtained with a microscope reference zoom at 1000X after a stressful test on a molded power inductor.

## PREVIOUS FINDINGS.

Effect of percolation of competitor B.



**A DECREASE IN THE Q FACTOR CORRESPONDS TO AN INCREASE IN CORE LOSSES.**

# PERFORMANCE REPERCUTION OF PERCOLATION

Q Factor change

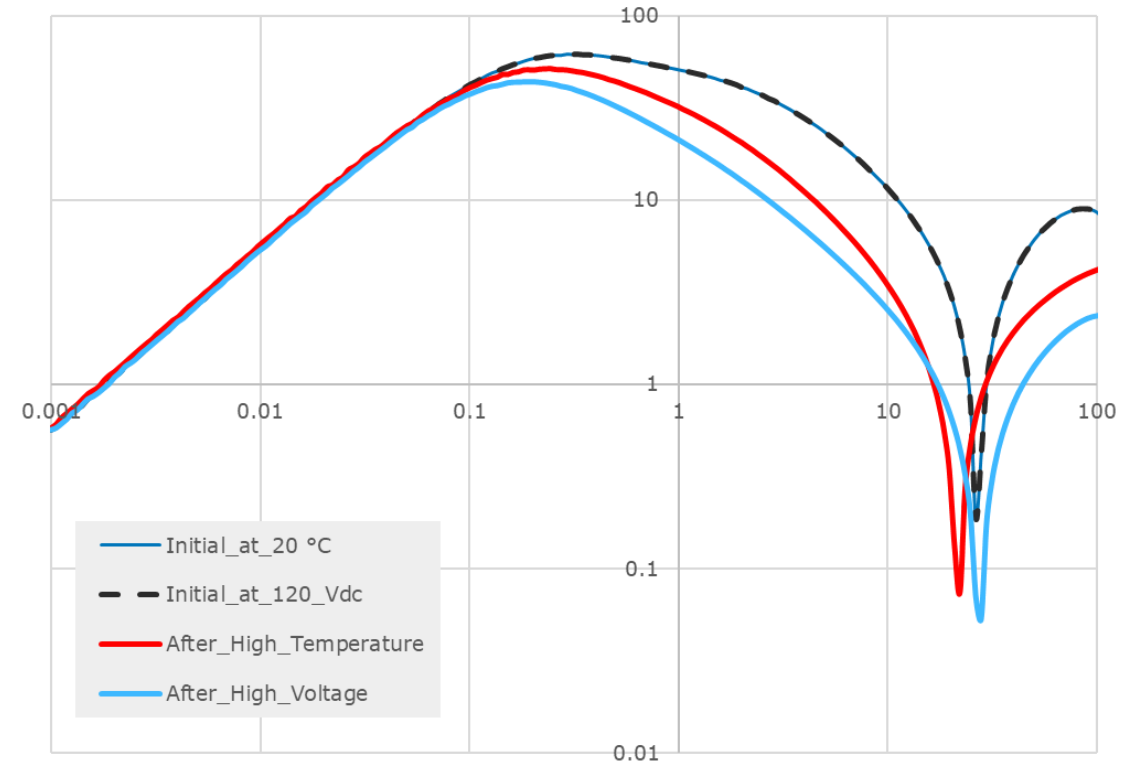
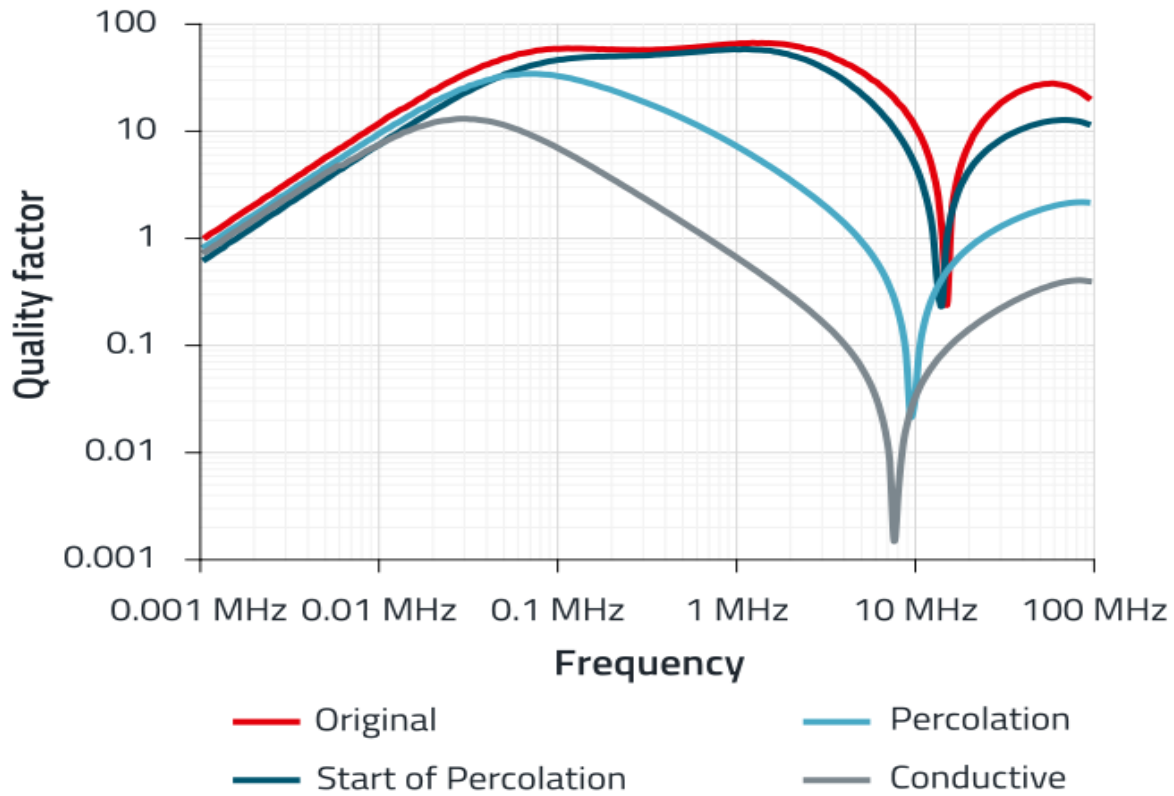


Fig. 15. Change of the Q factor due to high temperature or high voltage exposure.

# PERFORMANCE REPERCUTION OF PERCOLATION

## Reliability

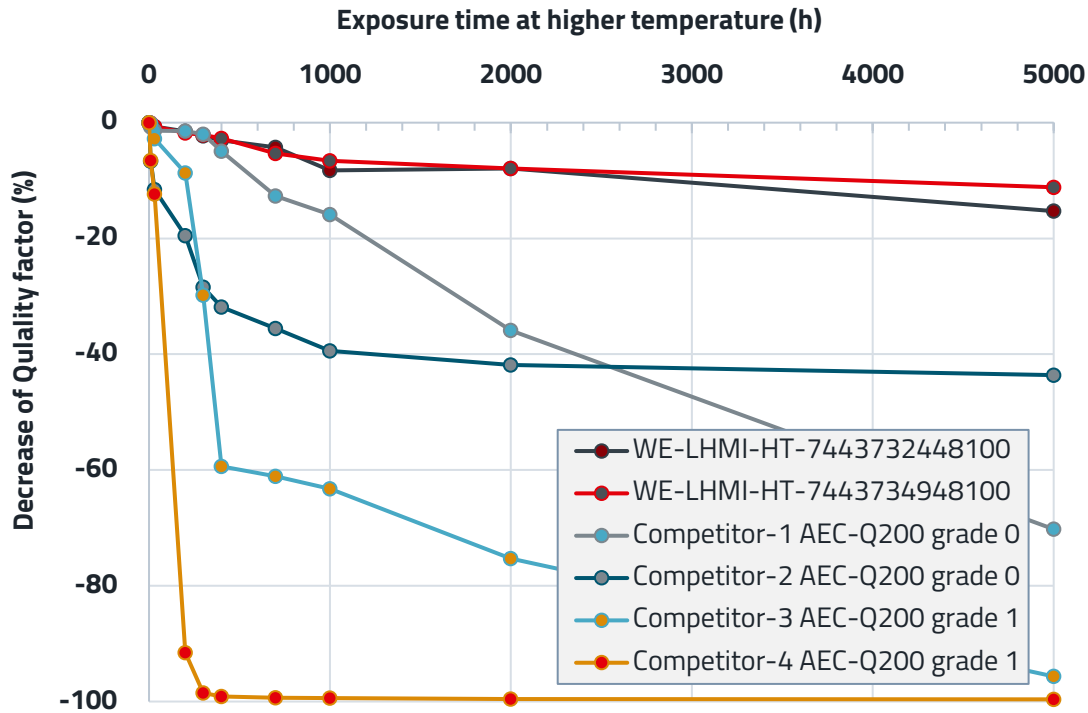


Fig. 16. Decrease of Q value at 2MHz during 5000 h at 200 °C.

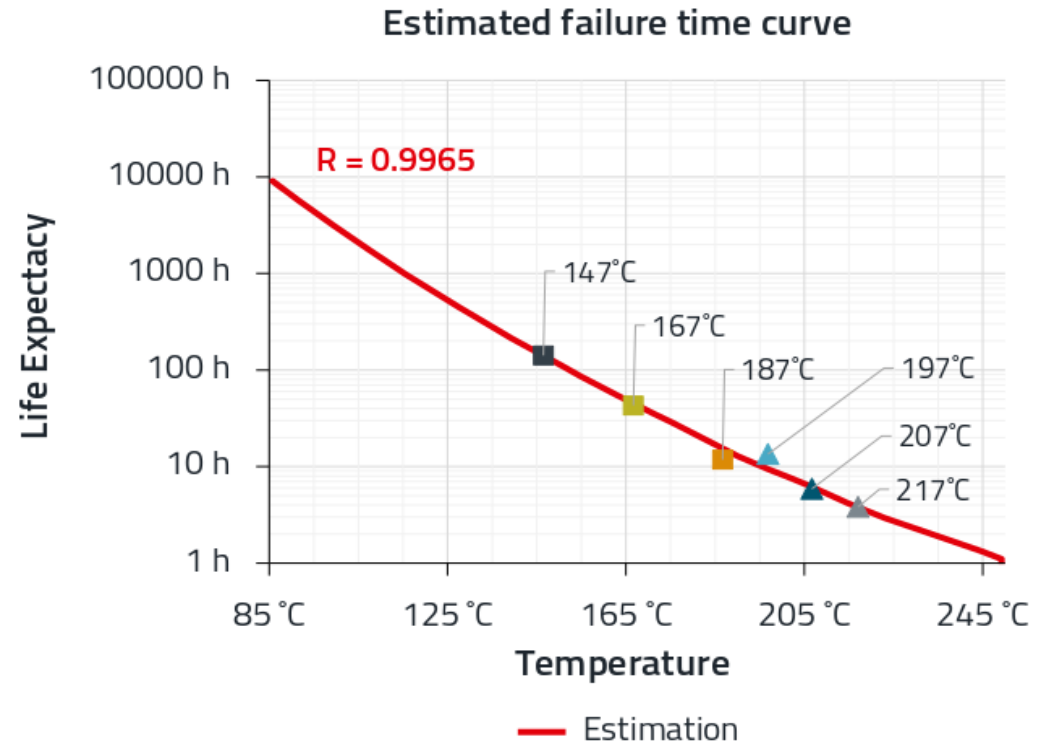


Fig. 17. Arrhenius plot to analyze the percolation at different temperatures on the tested molded power inductor.

# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER

Example setup

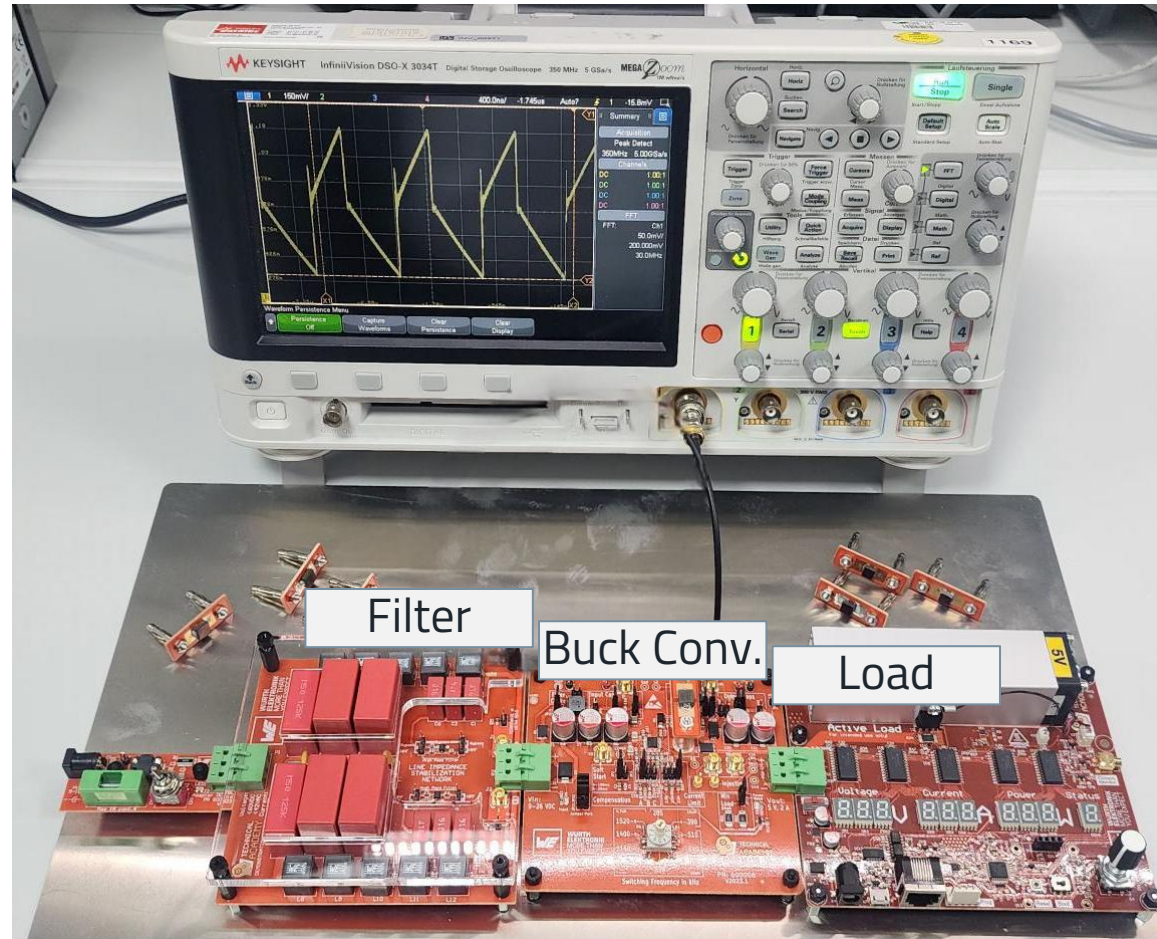


Fig. 18. WE DC-DC converter for test setup.

Our conventional buck converter (step-down converter) with a  $V_{in}$  from 9 V to 26 V, a  $V_{out}$  of 5 V with a maximal output current of 2 A.

Test setup:

- A molded power inductors of 10  $\mu$ H
- Input voltage of the external power supply fixed to 14 V.
- A switching frequency of 1020 kHz
- A programmable load fixed at 6.5 W.

# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER

Example setup



Four different levels of percolation detected:

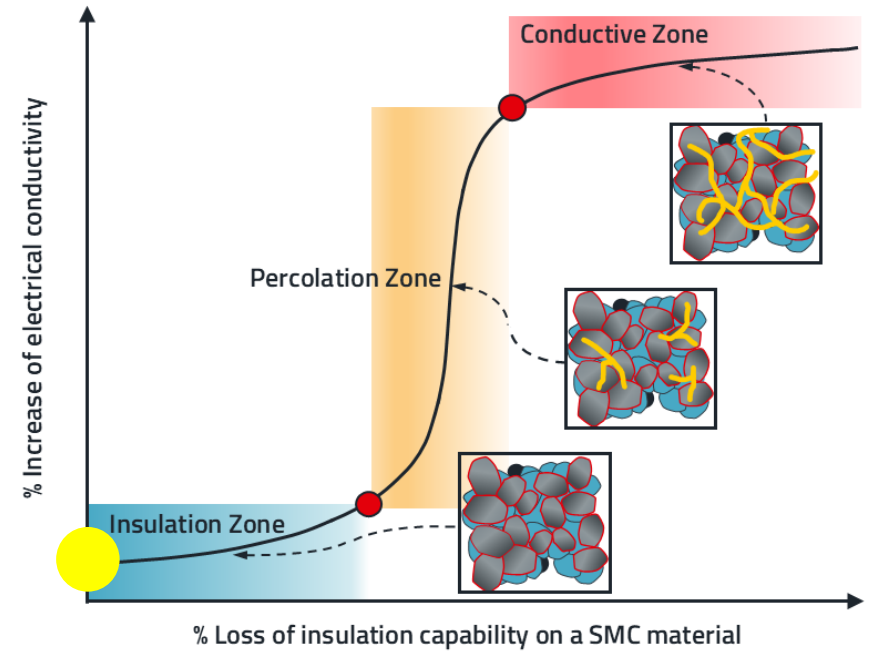
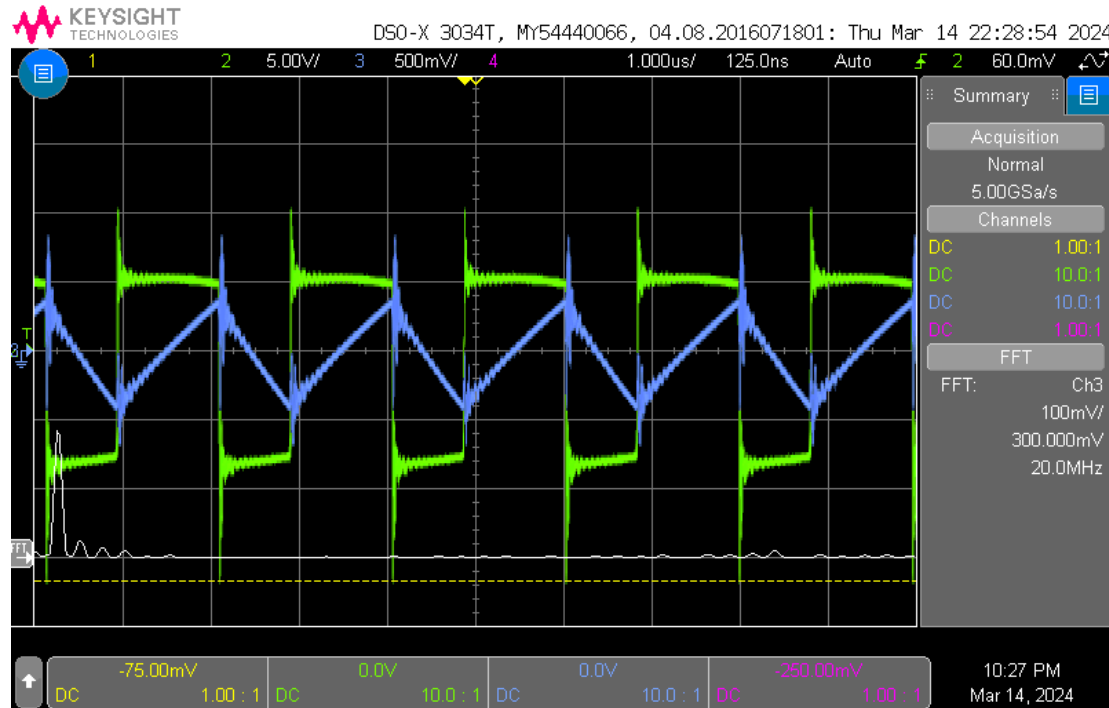


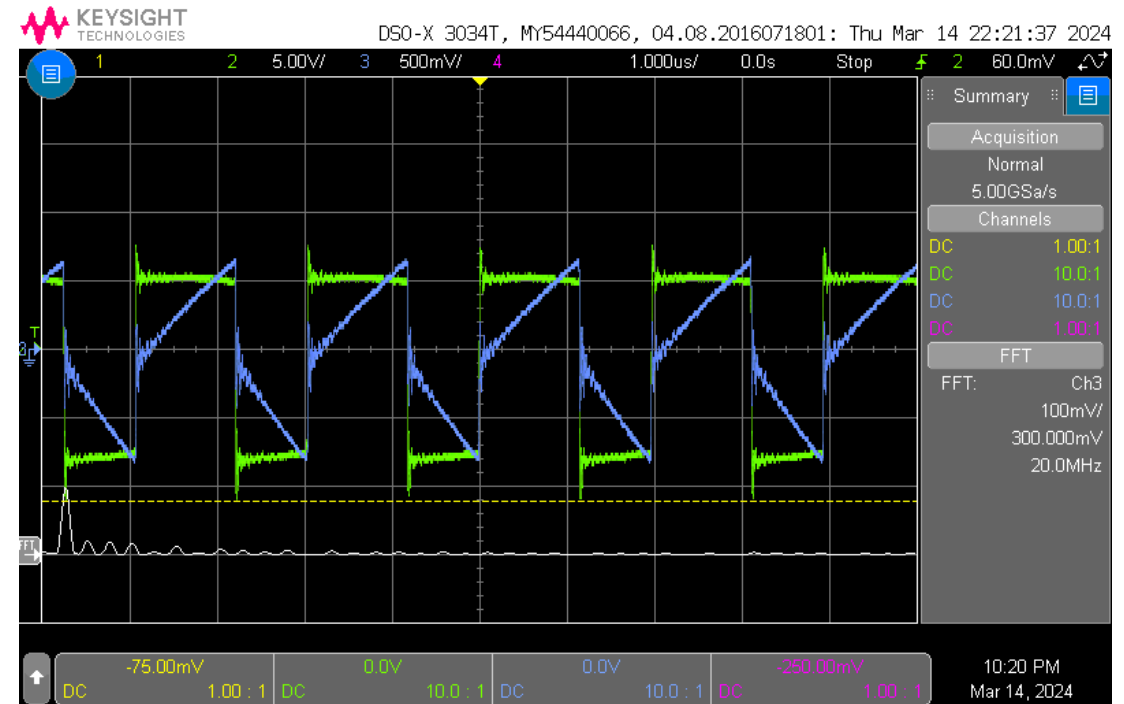
Fig. 19 Affection of a percolated molded power inductor in a DC-DC converter.

# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER.

Different levels of percolation



a. Current/voltage inductor waveforms with a non-percolation.

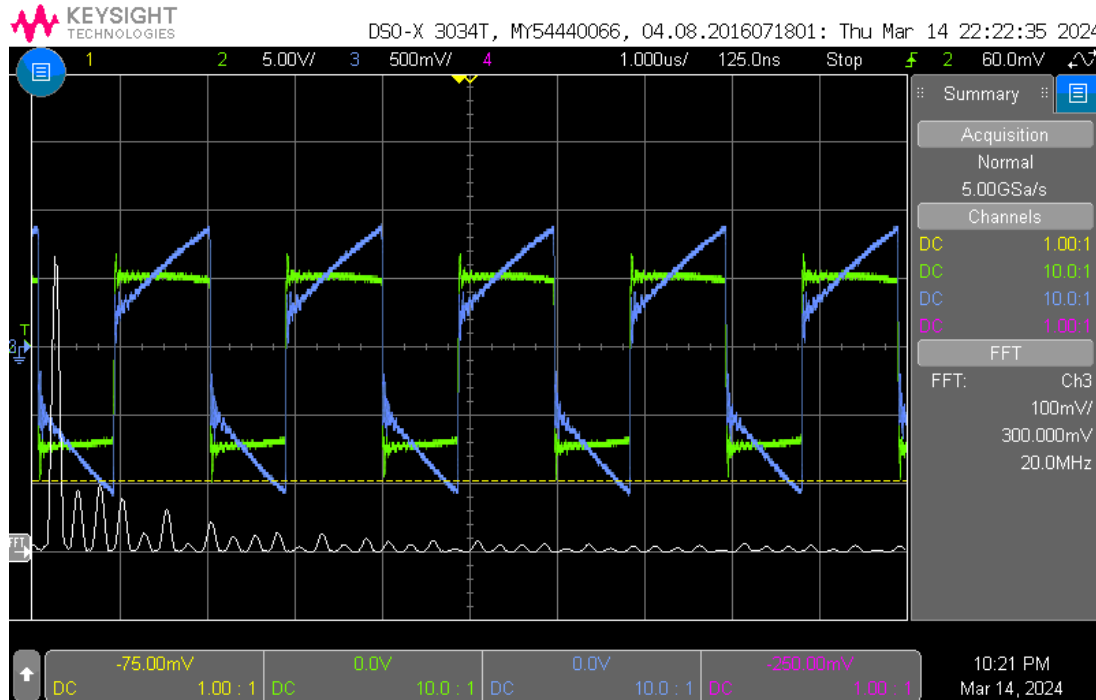


b. Evidence of percolation phenomenon.

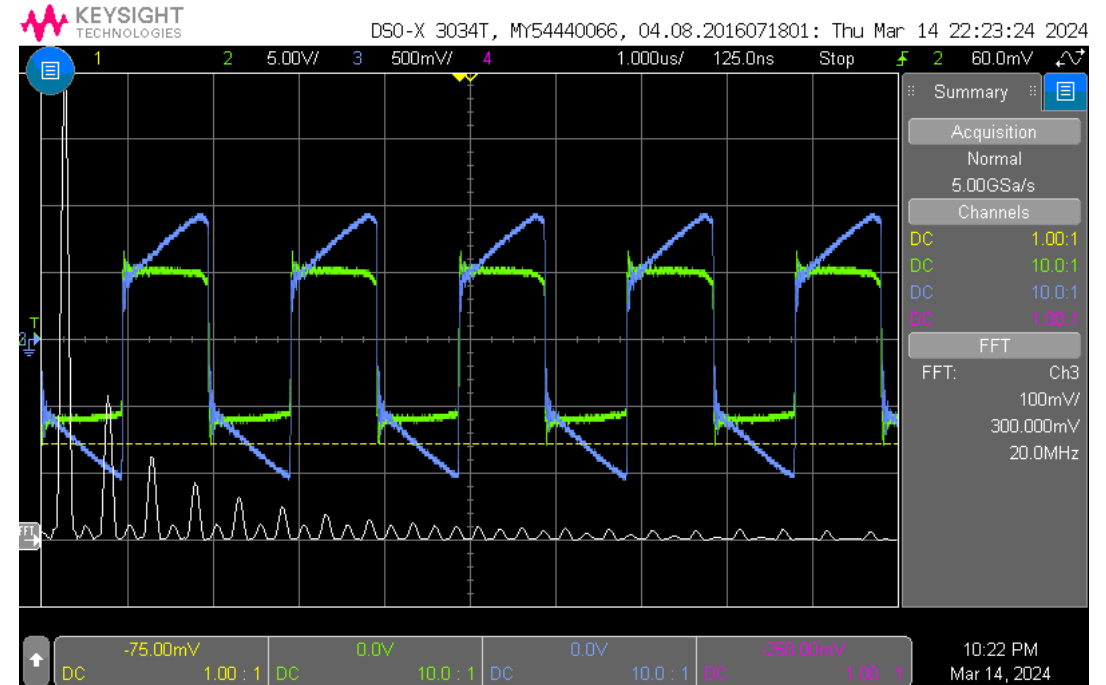
Fig. 20. Oscilloscope captures at beginning percolation test.

# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER.

Different levels of percolation



c. High level of percolation phenomenon.



d. Waveforms for the inductor closer to conductive zone.

Fig. 21. Oscilloscope captures at the end of percolation test.

# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER.

Percolation effects will severely degrade efficiency of a DC-DC Converter

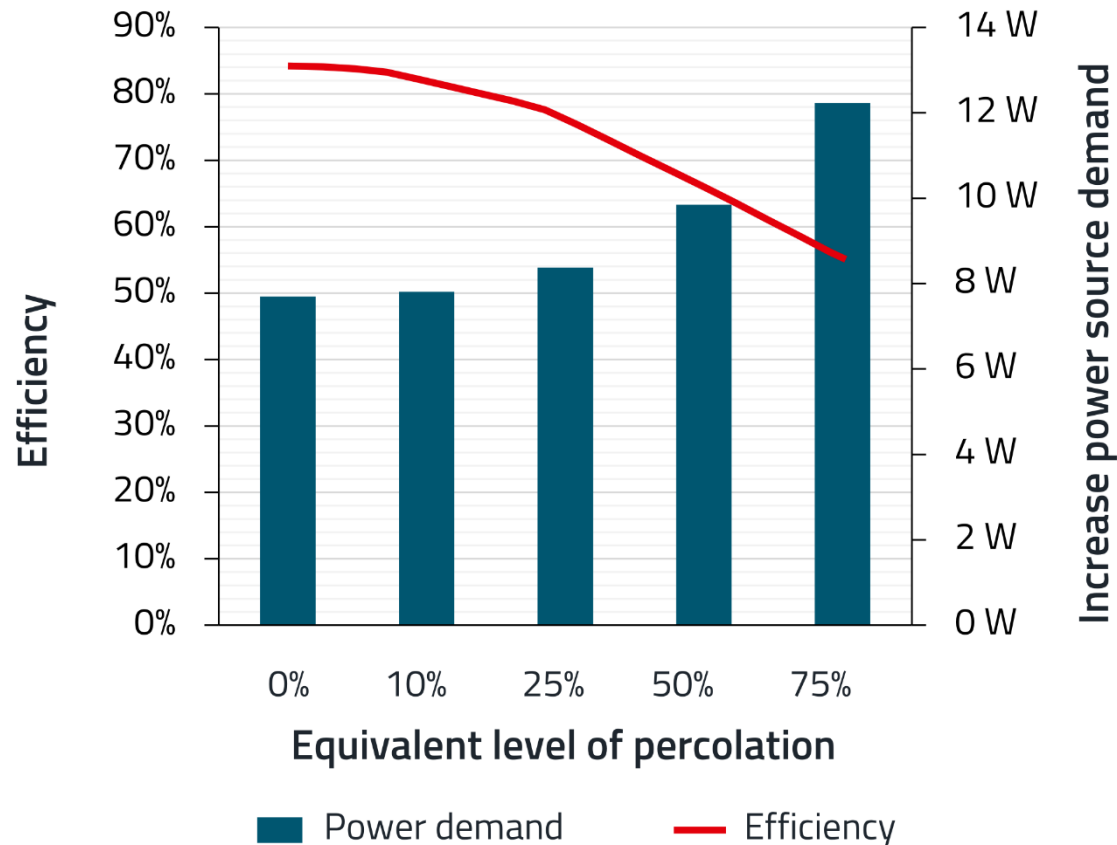
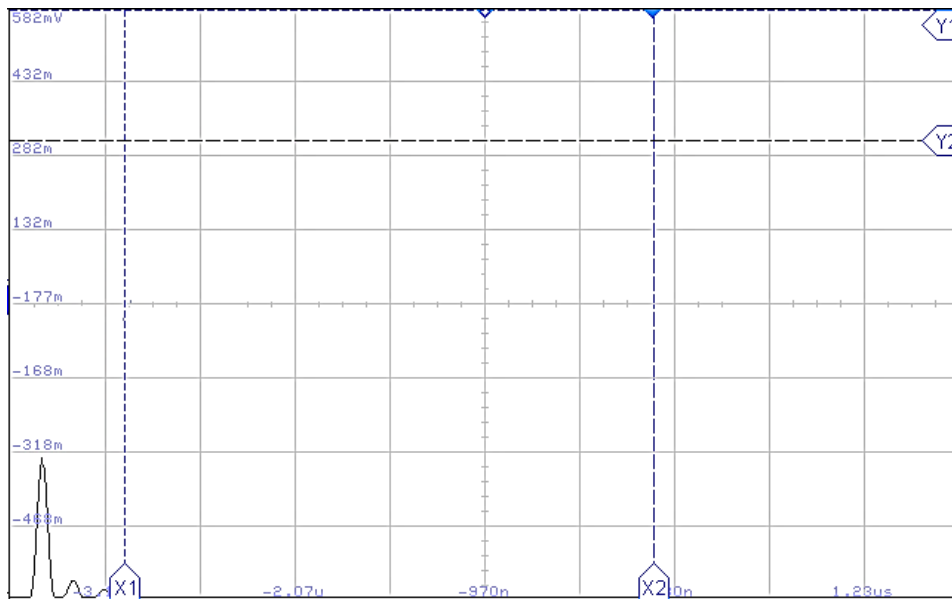


Fig. 22. Efficiency decrease due to percolation of the molded power inductor.

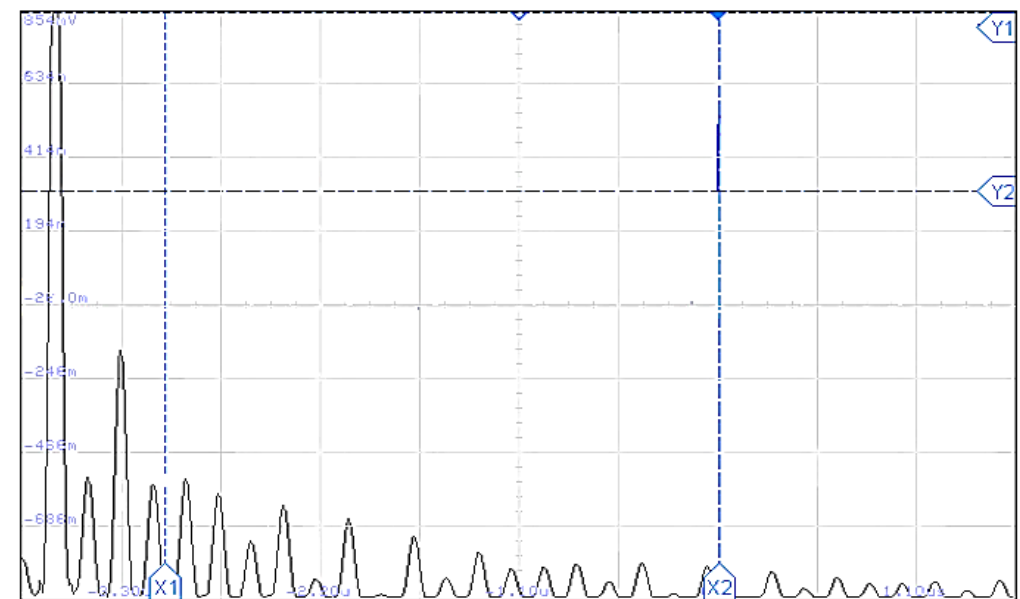
# IMPACTS OF THE DEGRADATION OF A MOLDED POWER INDUCTORS IN A CONVENTIONAL DC/DC CONVERTER.

Percolation phenomenon from EMC point of view

Significative presence of harmonics = Several EMC issues, both conducted and radiated?



a. Recorded FFT for initial set up without percolation.



b. Recorded FFT for a percolated molded power inductor.

Fig. 23. FFT increase due to the percolation phenomena on the molded power inductor with a scale of 100 mV/div until 30MHz.

# SUMMARY FINDINGS



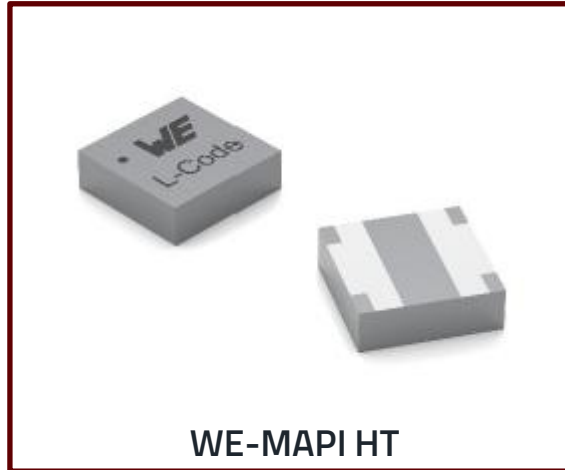
- Percolation phenomenon starts after the exposition to high temperature or a high voltage
- The percolation phenomenon in a Molded Inductor which refers to a material degradation when transitions from an insulating to a conductive state, increasing the core losses due to wider eddy currents, which directly affect the longevity and reliability of the device itself
- The distinct critical decrease of Q at higher frequencies is evident with the observation of the change of the ripple current waveform and increase of harmonic and the eventual decrease of power converter efficiency over time



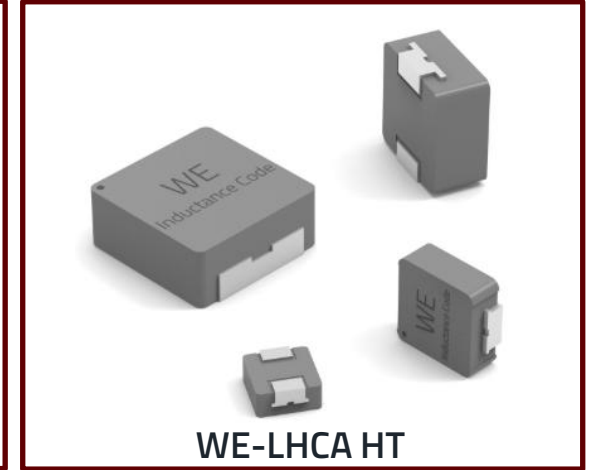
# WÜRTH ELEKTRONIK: HIGH-TEMPERATURE MOLDED INDUCTORS

Molded Power Inductors for demanding HT applications

## Standard



## Automotive



- Especially designed to handle high temperature and high voltages with **no percolation** concerns
- Tested for more than 5000 h @ 200 °C **without decrease of electrical performance**

# THANK YOU!

## Do you have any questions?

Please contact us or your sales contact directly – our experienced team will be happy to support you.

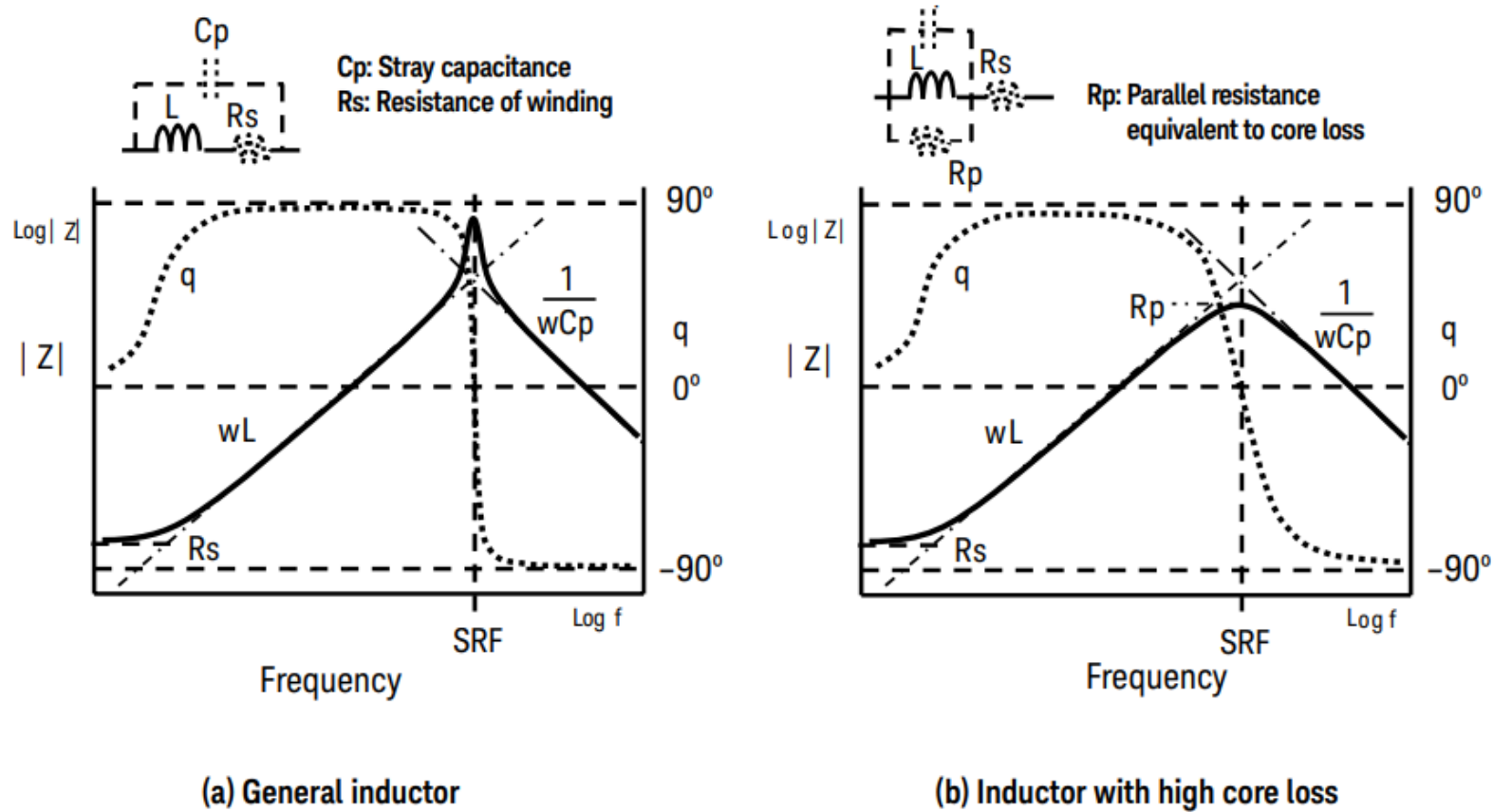


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[Annika.Frankemoelle@we-online.de](mailto:Annika.Frankemoelle@we-online.de)

# FREQUENCY DEPENDENCY IS COMMON TO ALL REAL-WORLD COMPONENTS BECAUSE OF THE EXISTENCE OF PARASITICS



# MATERIALS FOR POWER INDUCTORS COMPARISON

Material	Soft Saturation	Core Losses	Frequency Range	Temperature Stability	Advantages	Disadvantages
<b>Iron Powder</b>	Yes (Moderate)	Medium	20 kHz – 500 kHz	Low	High flux density, good mechanical strength, low cost	Higher losses at high frequency, poor thermal stability
<b>Alloy Powder (FeSi, FeNi)</b>	Yes (Good)	High	10 kHz – 300 kHz	Medium	High saturation, good for high current	Higher cost, higher hysteresis and eddy losses
<b>Sendust (Fe–Si–Al)</b>	Yes (Good)	Low–Medium	50 kHz – 1 MHz	Good	Low hysteresis loss, good thermal stability	Moderate saturation, medium cost
<b>MPP (Molypermalloy)</b>	Yes (Excellent)	Very Low	100 kHz – 2 MHz	Excellent	Very low losses, excellent thermal stability	Very expensive, low magnetic flux density
<b>Nanocrystalline</b>	Yes (Excellent)	Low	100 kHz – 2 MHz	Excellent	High permeability and saturation, good high-frequency behavior	High cost, complex processing
<b>Ferrite (NiZn, MnZn)</b>	No (Hard Saturation)	Very Low	100 kHz – 1 MHz	Good	High resistivity, low cost, good thermal stability	Sharp saturation, brittle, low saturation flux density