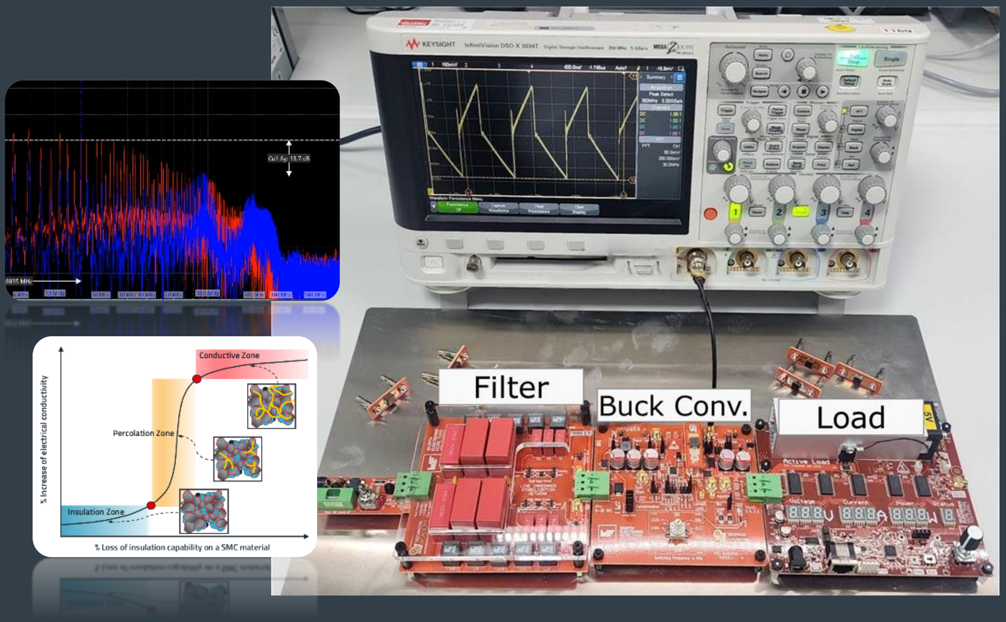


IMPACT OF ELEVATED VOLTAGE AND TEMPERATURE ON MOLDED POWER INDUCTORS: THE EFFECT OF PERCOLATION ON LIFETIME IN DC/DC CONVERTERS.

Dr.-Ing. Efrain Bernal
Power Magnetics Team
WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

AGENDA

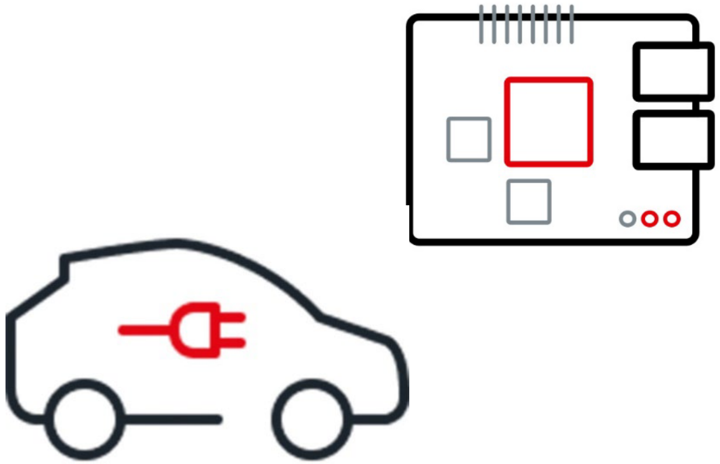
- **Introduction**
  - Market Trends
  - Impact of Percolation
  - Molded Inductor production process and materials
- **Percolation Phenomenon**
  - Definition
  - Molded Power Inductors degradation
- **Previous findings**
  - ANP126: Voltage specification
  - ANP128: Thermal aging
- **Performance repercution 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

Market Growth Overview

The molded inductors market is growing rapidly with a projected CAGR of 6.5%from 2024 to 2030.



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.

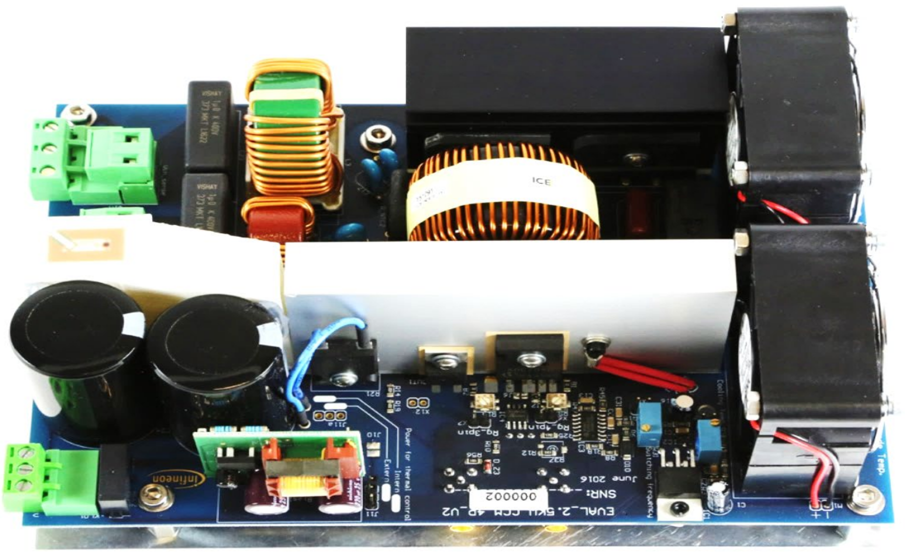
Key Drivers and Challenges

- 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^3

2.8x

Higher Density

GaN PFC @2kW

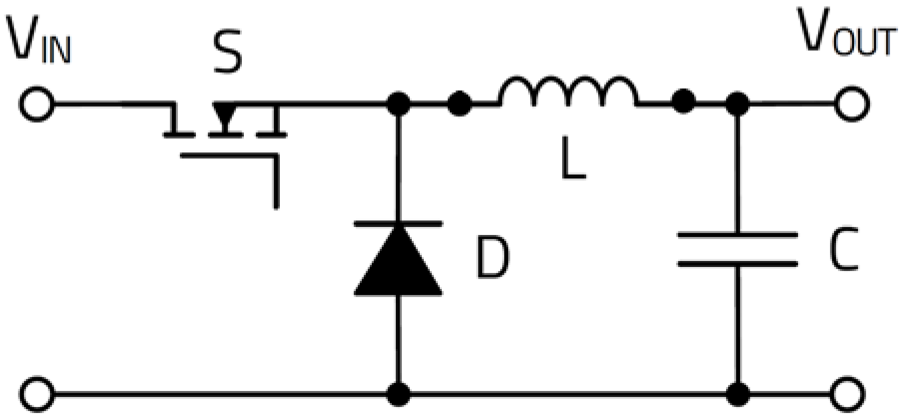
Power Density: 104 W/in^3

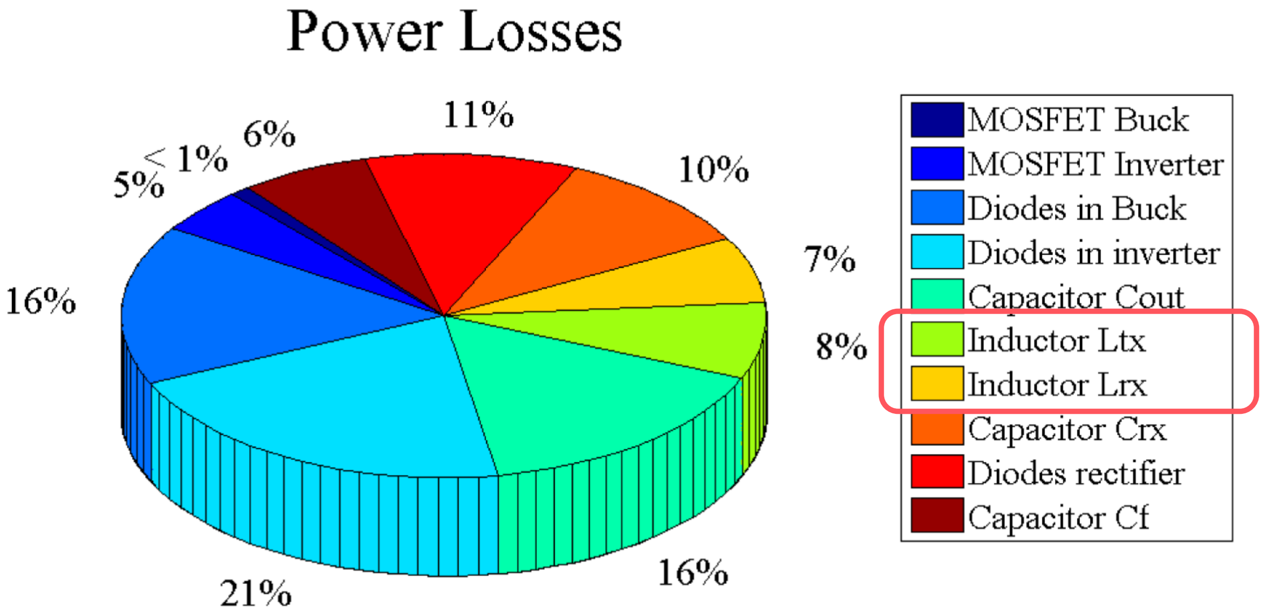
Fig.1. Example of the size reduction of a DC-DC converter using Texas Instruments' GaN technology.

INTRODUCTION

Why inductors matter for DC/DC converter efficiency and reliability?

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





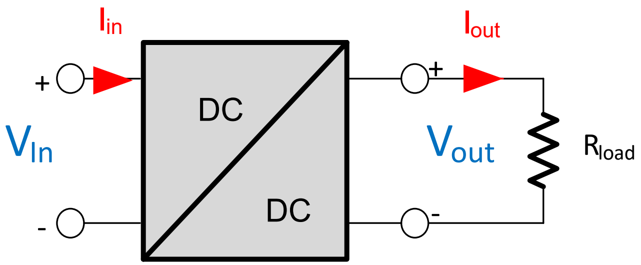
a. Reference schematic buck converter

b. Power losses in the components of a converter

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

INTRODUCTION

DC-DC converters



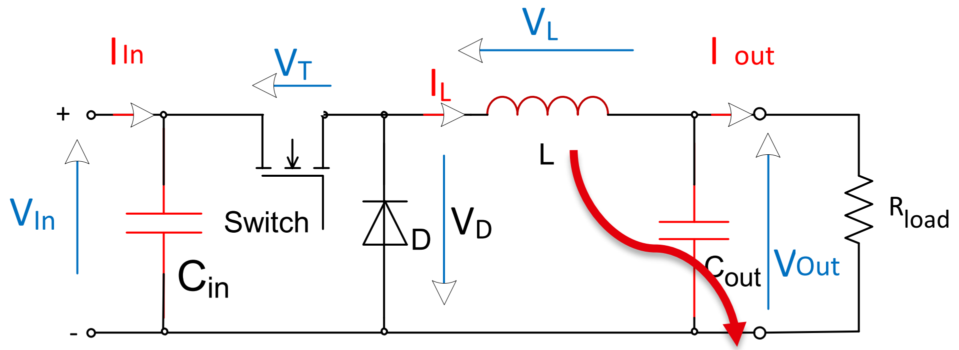
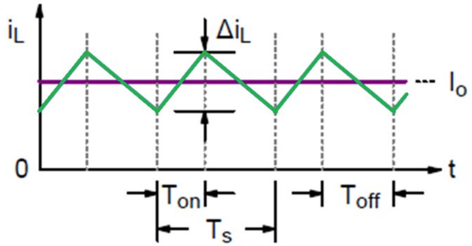


Fig.3. Buck converter.

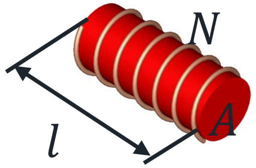


Inductance value definition:

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

Inductance in the equations of the Buck converter

The ripple current Δ_IL is linked to Voltage , Time, and inductance value

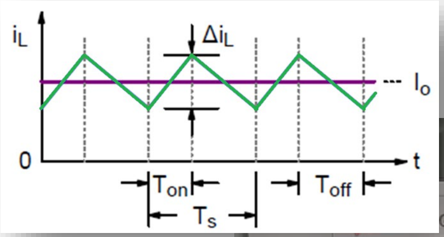


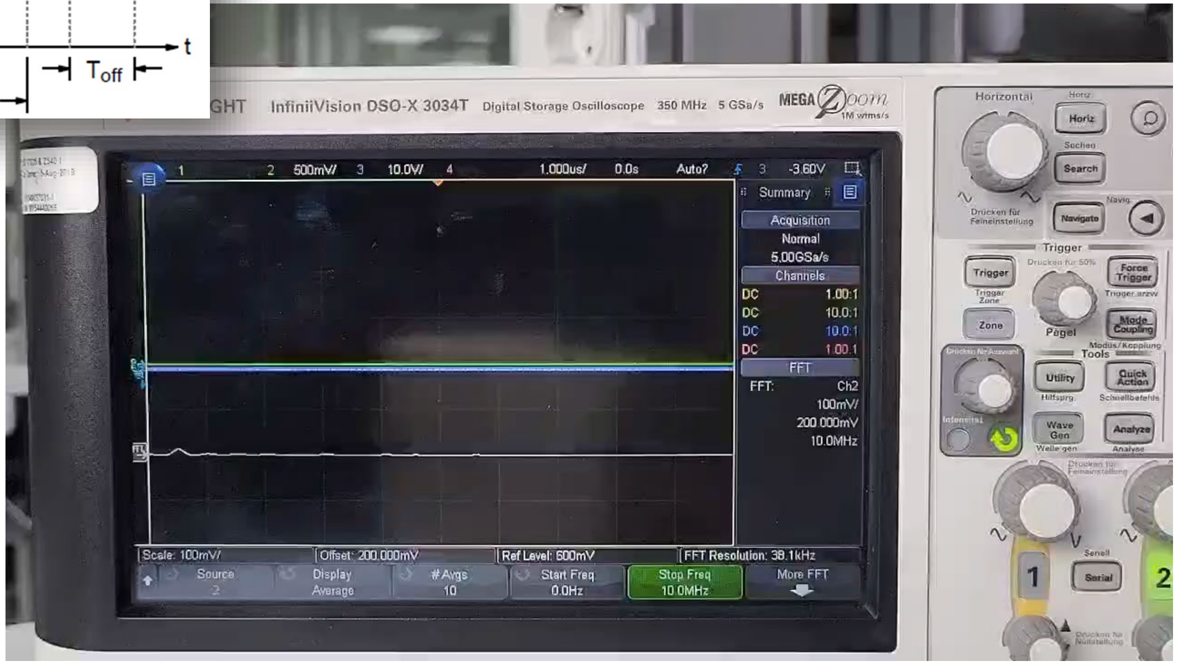
$$L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot N^2}{l}$$

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

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. Affectation of a percolated molded power inductor in a DC-DC converter.

INTRODUCTION

Is temperature to blame?

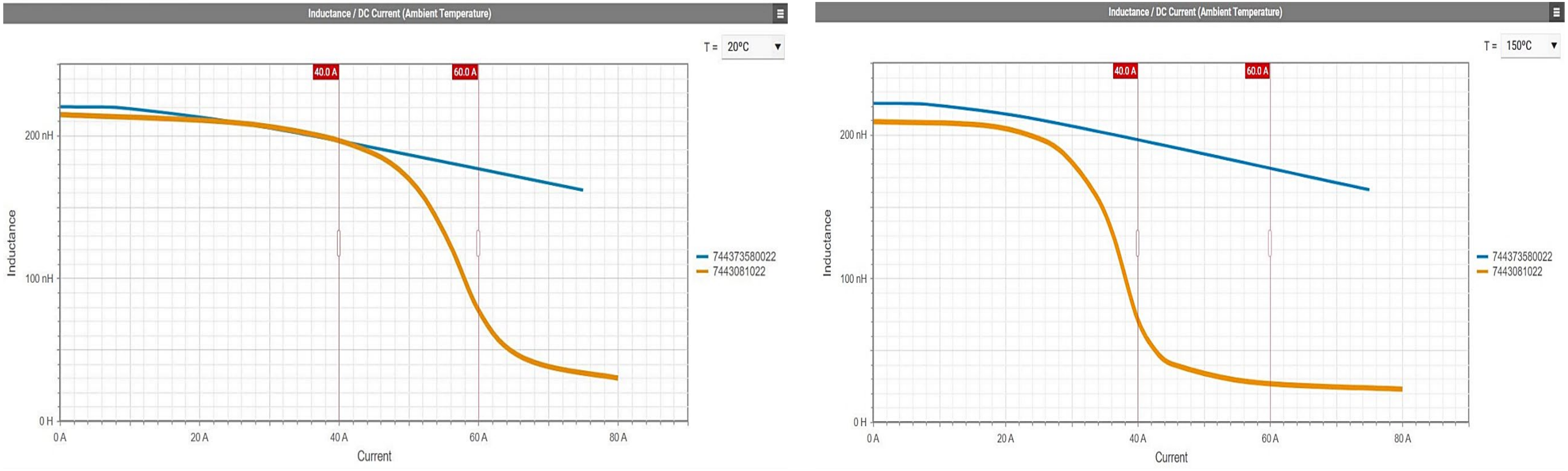
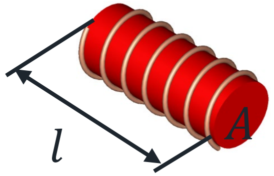


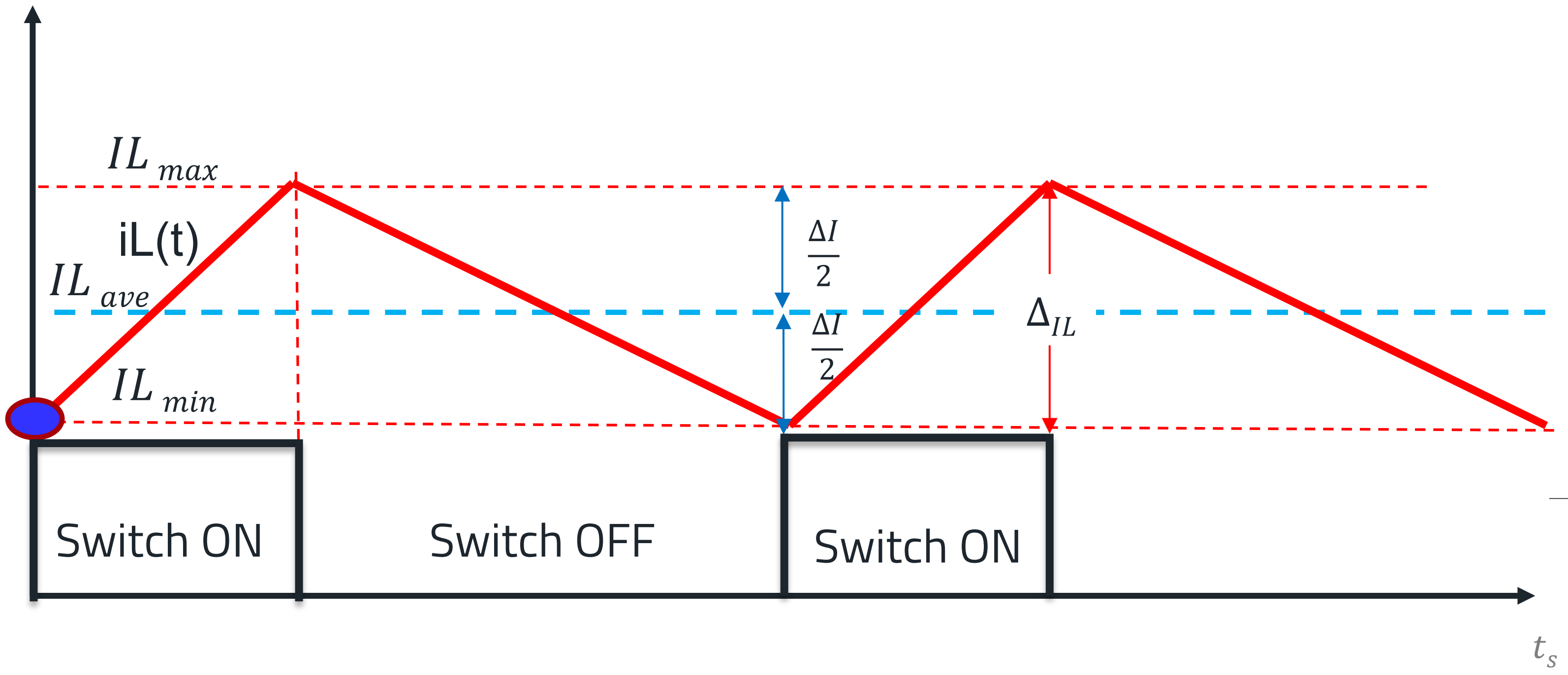
Fig 5: Comparison of the saturation current (Isat) between a ferrite power inductor with hard saturation (orange) and a molded power inductor with soft saturation (blue) at different ambient temperatures, as shown by RED EXPERT.

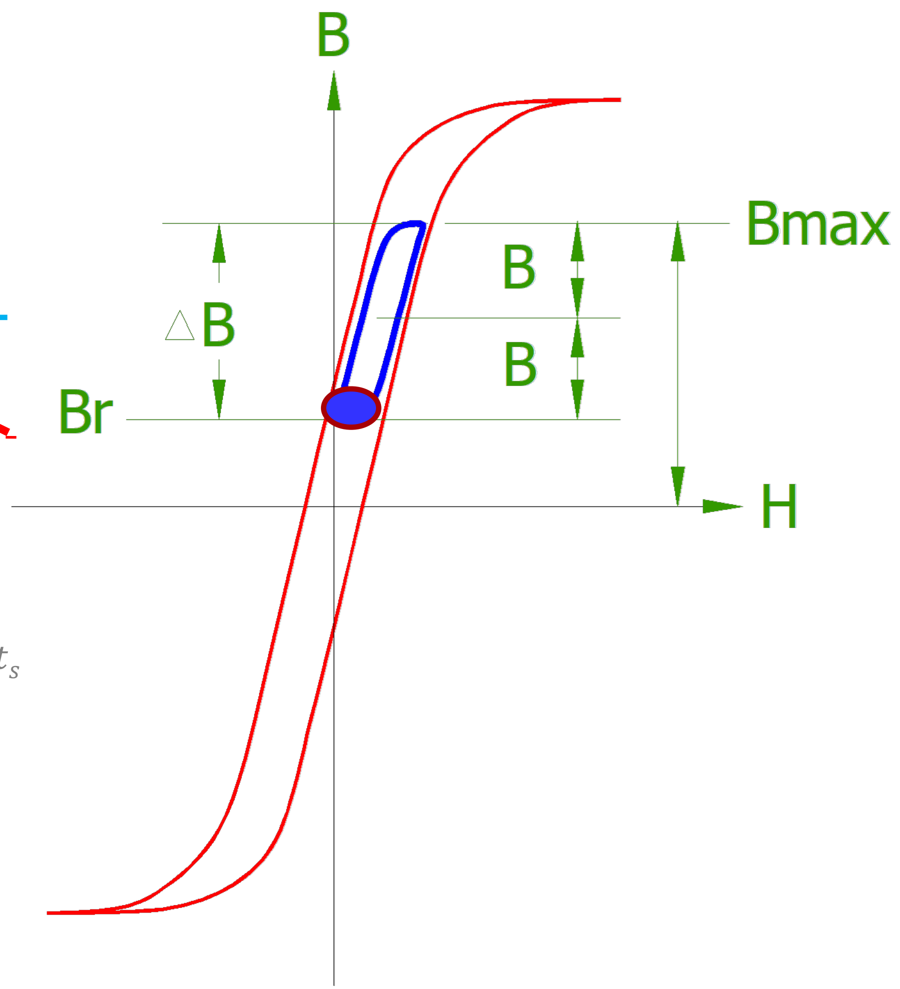
- **Theory:** Materials with soft saturation do not show an alteration n their behavior with increasing temperature.
  Reality: Their behavior could change drastically!

INTRODUCTION



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

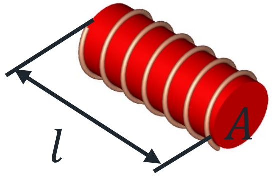


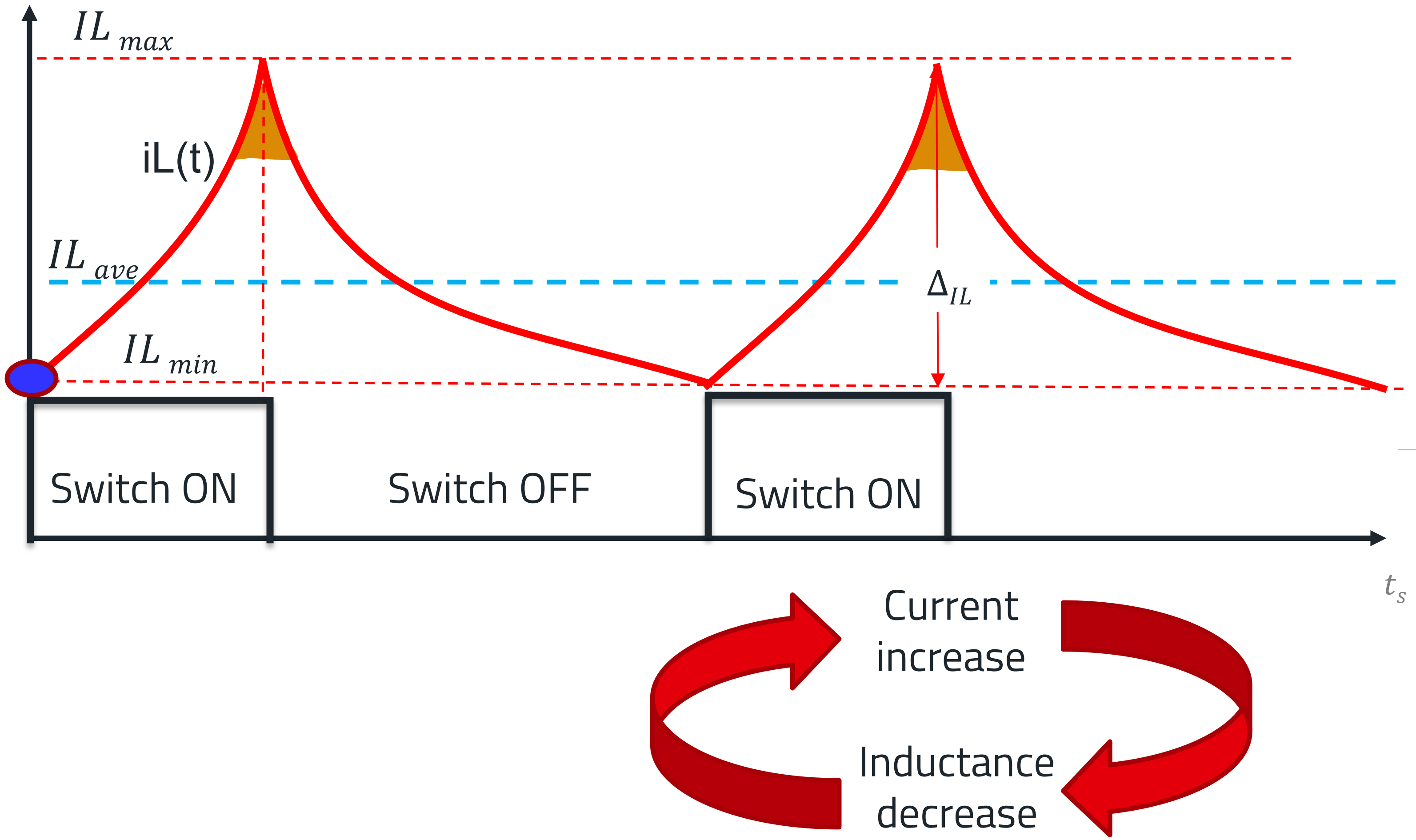


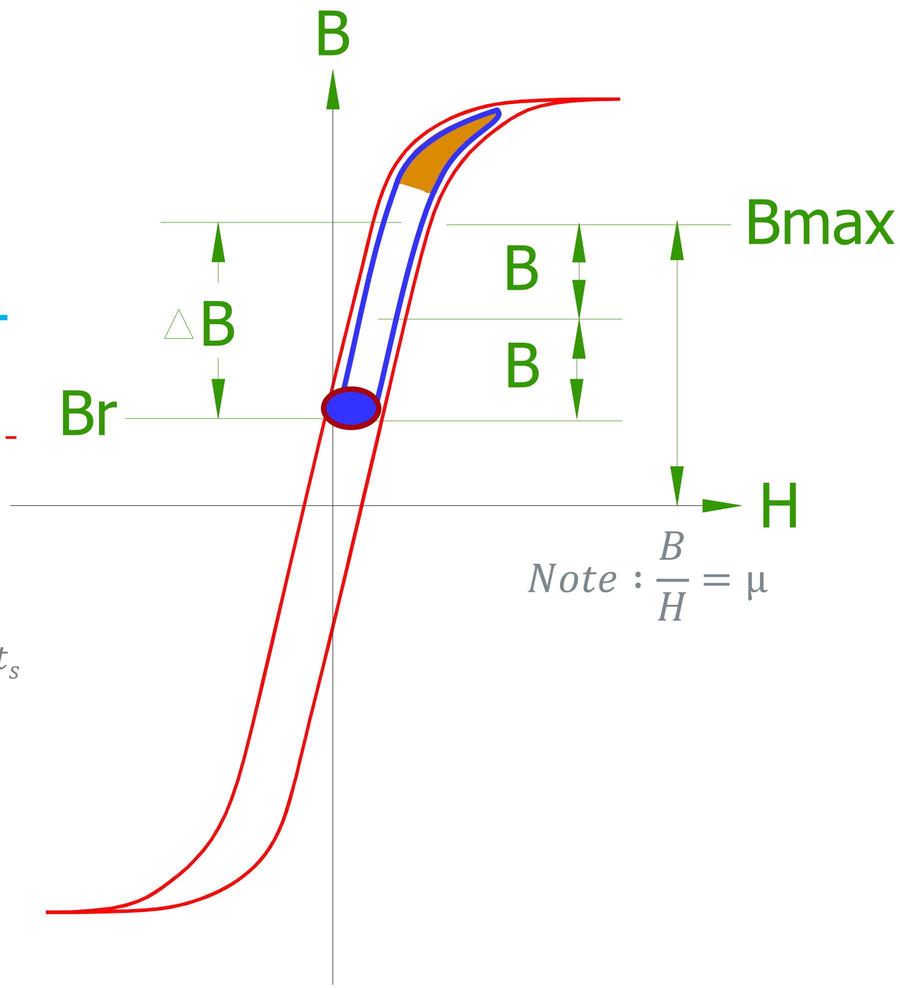
INTRODUCTION

Cycle explanation : saturation behavior for Hard Saturation material

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







INTRODUCTION

Limit of saturarion

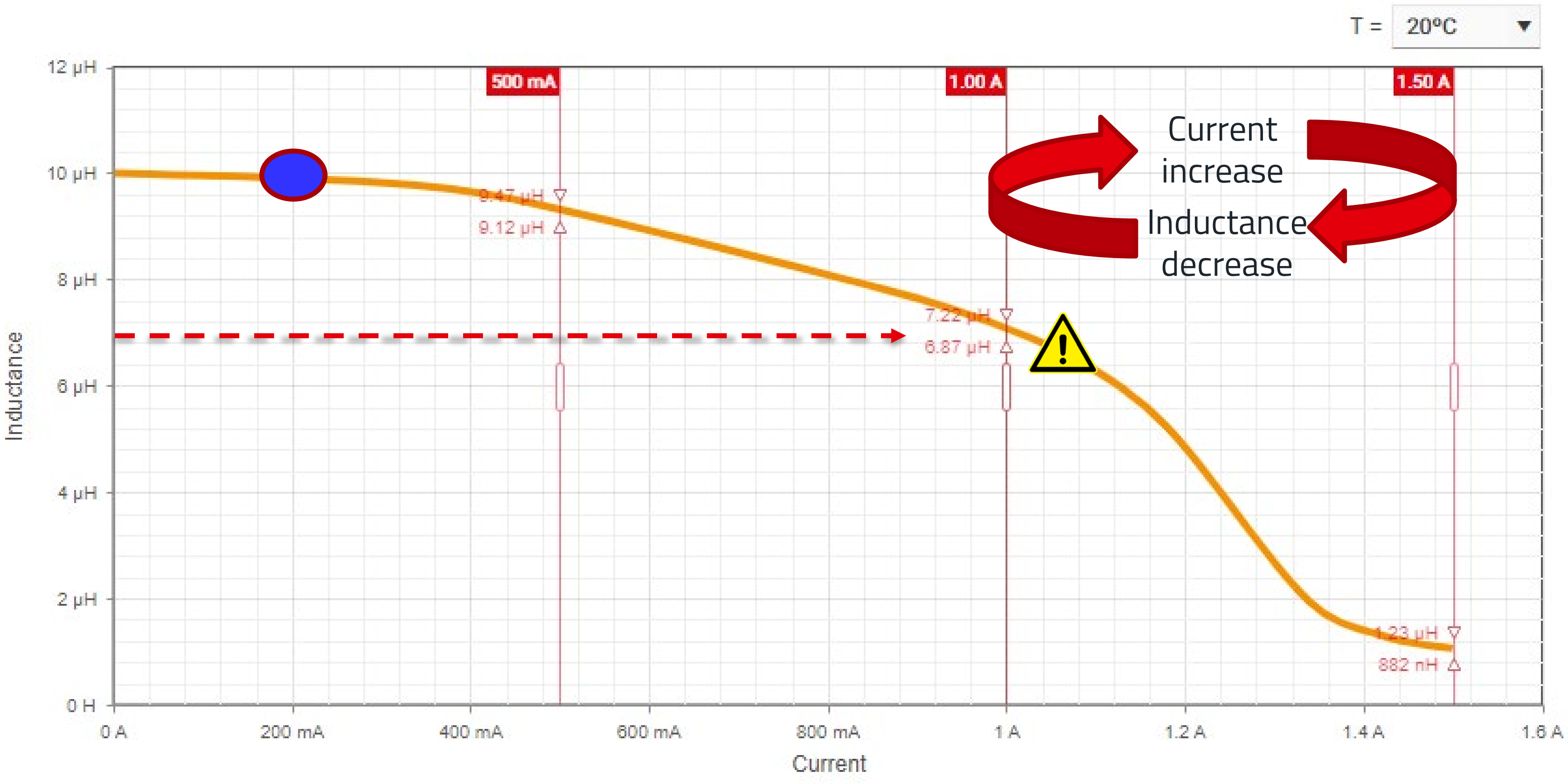
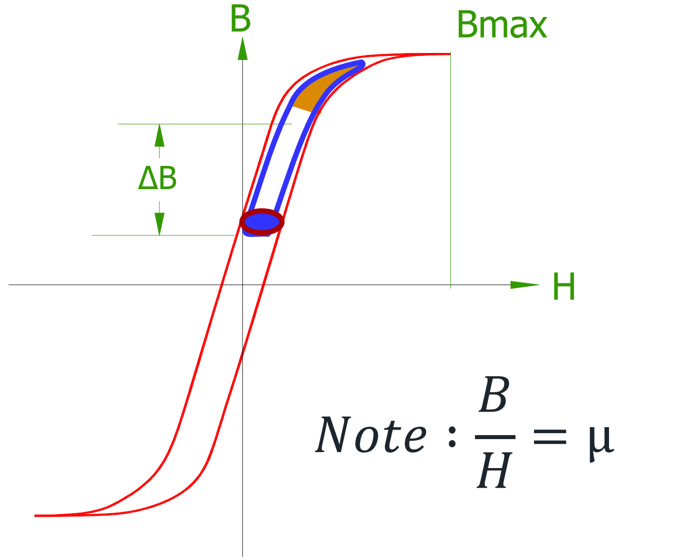
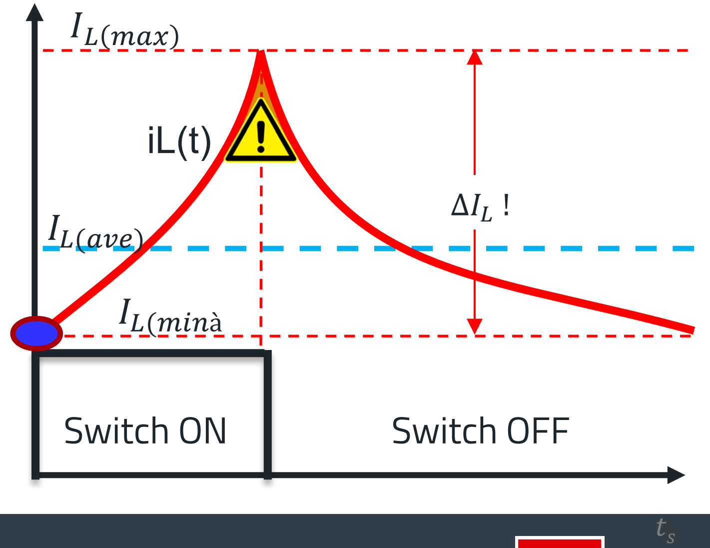


Fig.6. **REDEXPERT** WE-TPC# 744043100 deviation for10µH I_{sat} = 1,0A



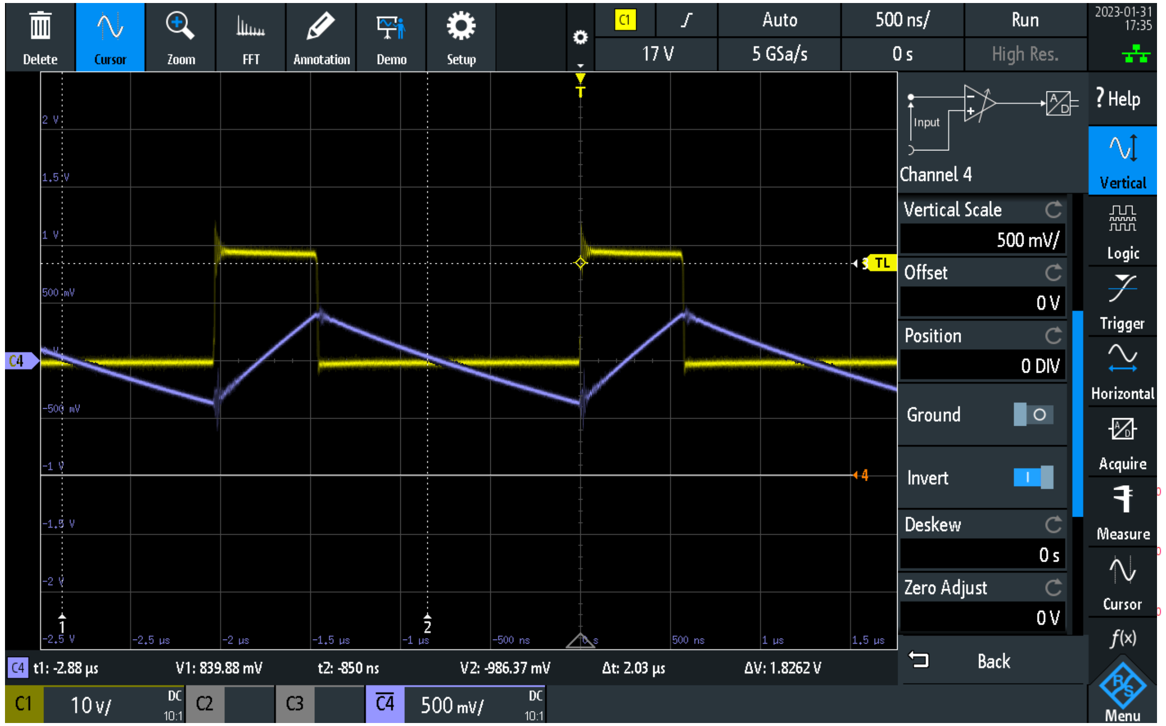
$$Note : \frac{B}{H} = \mu$$



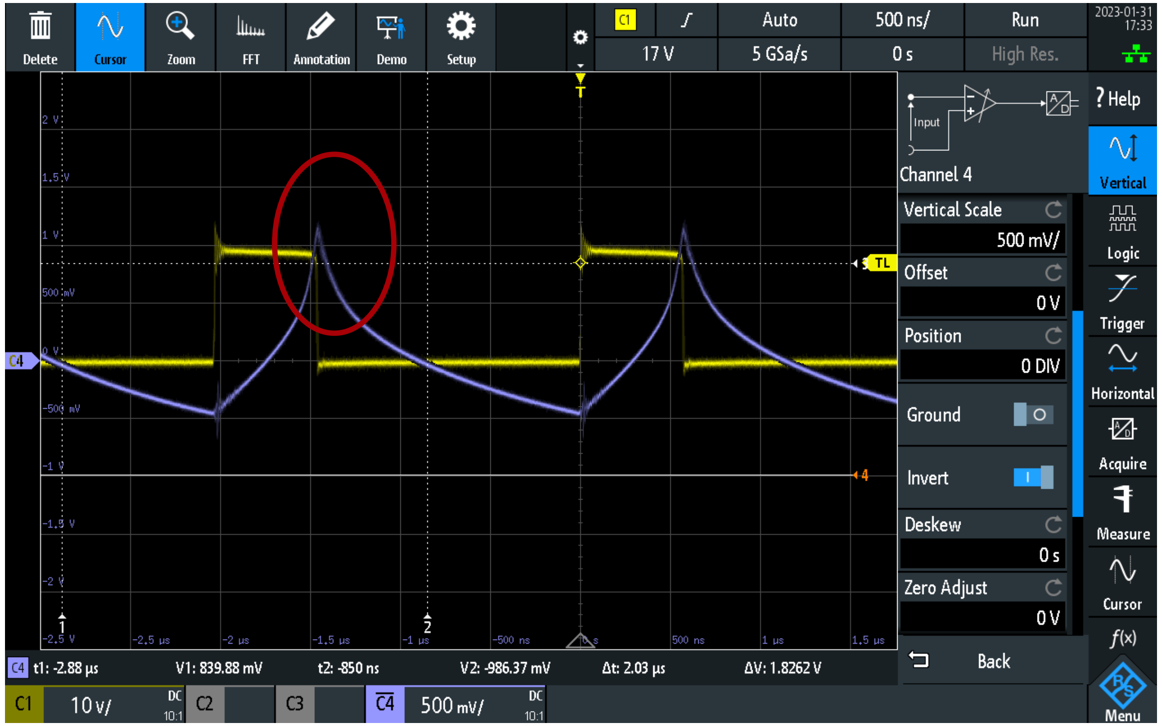
INTRODUCTION

No saturation effect is an advantage of molded power inductors

Without saturation | **With saturation**



10µH WE-LHMI# 74437346100 original Isat=7,3A



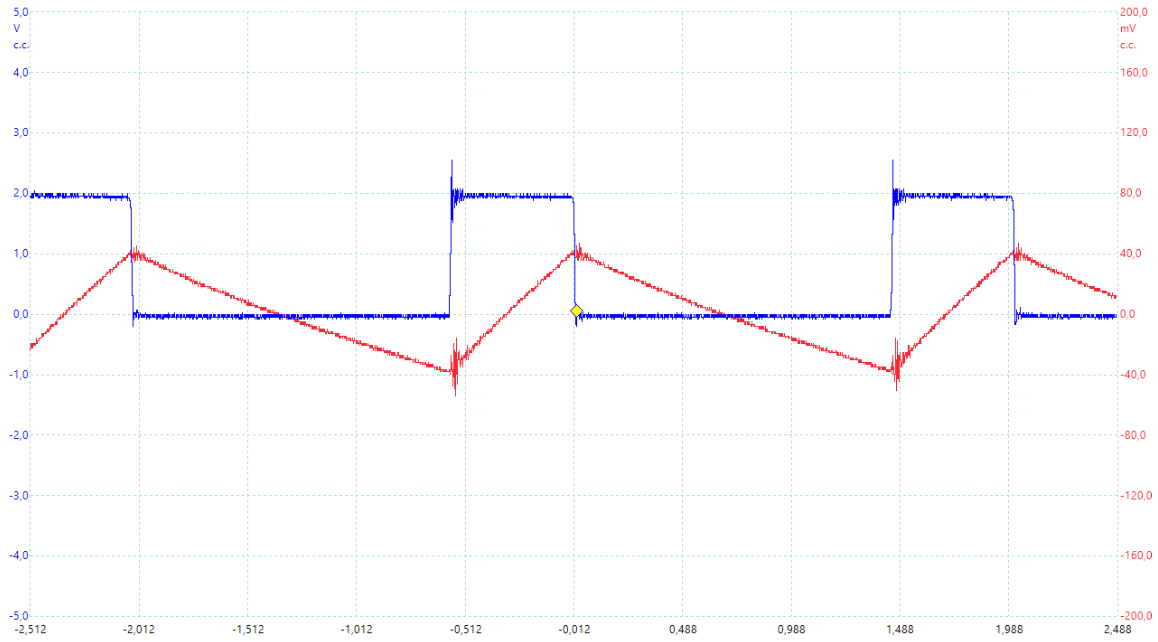
10µH WE-TPC# 744043100 Isat=1,0A

Fig.7 Measured with R&S oscilloscope

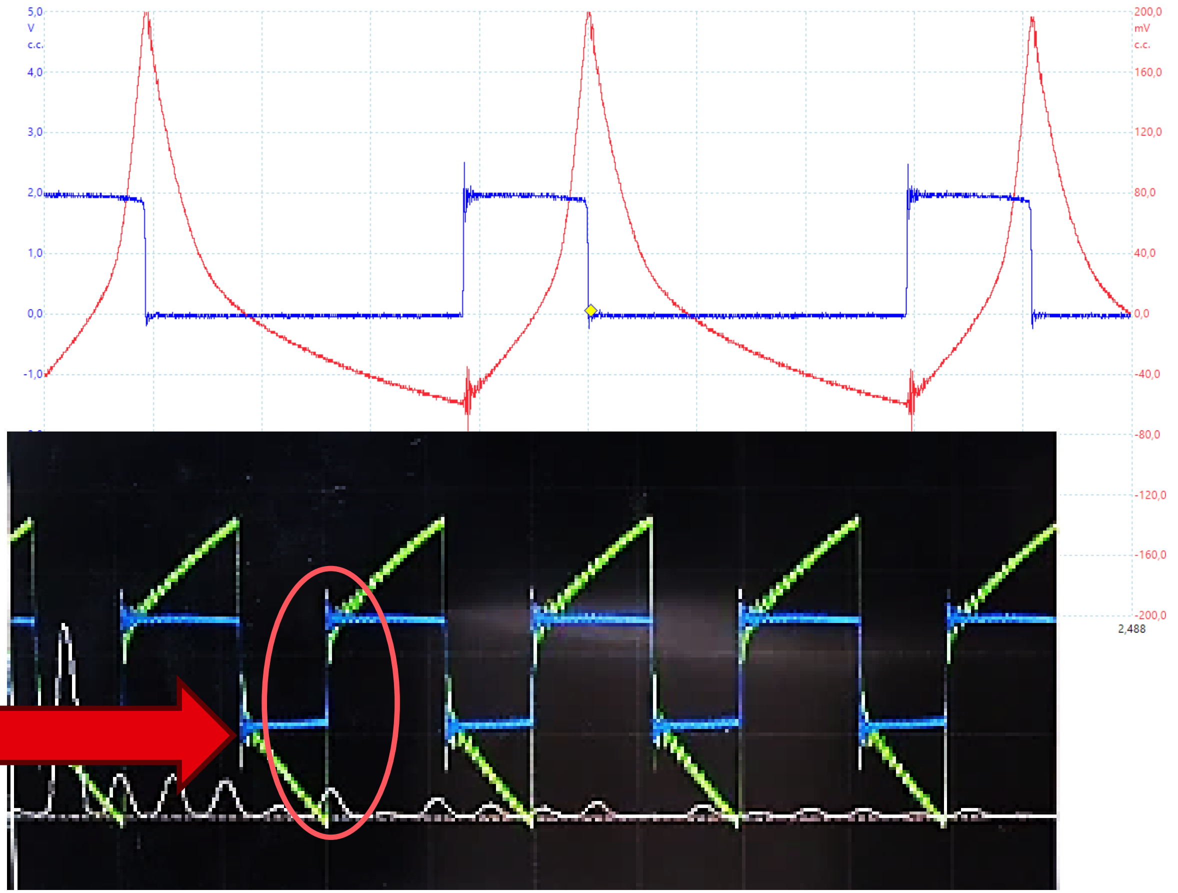
INTRODUCTION

However...

Without saturation



With saturation



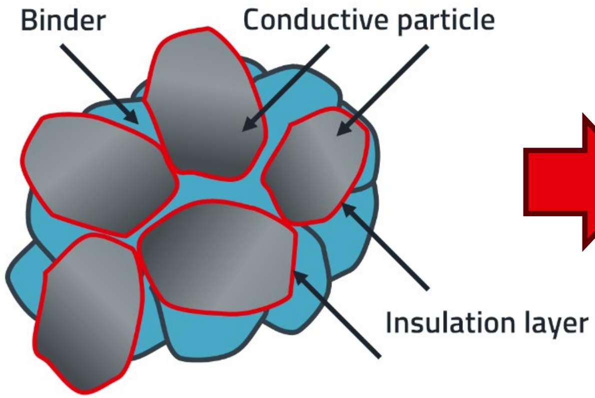
PERCOLATION PHENOMENON EFFECT

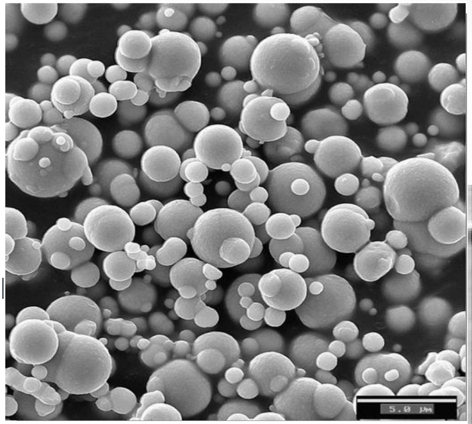
PERCOLATION PHENOMENON

Molded Inductor production process and materials

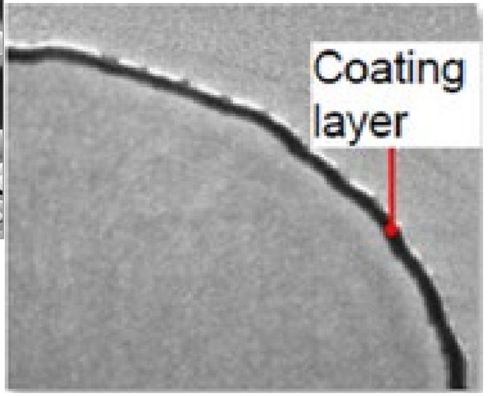
- **Production Process** (simplified)
  - Wound insulated copper wire
  - Material mixed containing Iron Powder and Binder
  - Pressed in mold
  - Cured in Oven

- **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

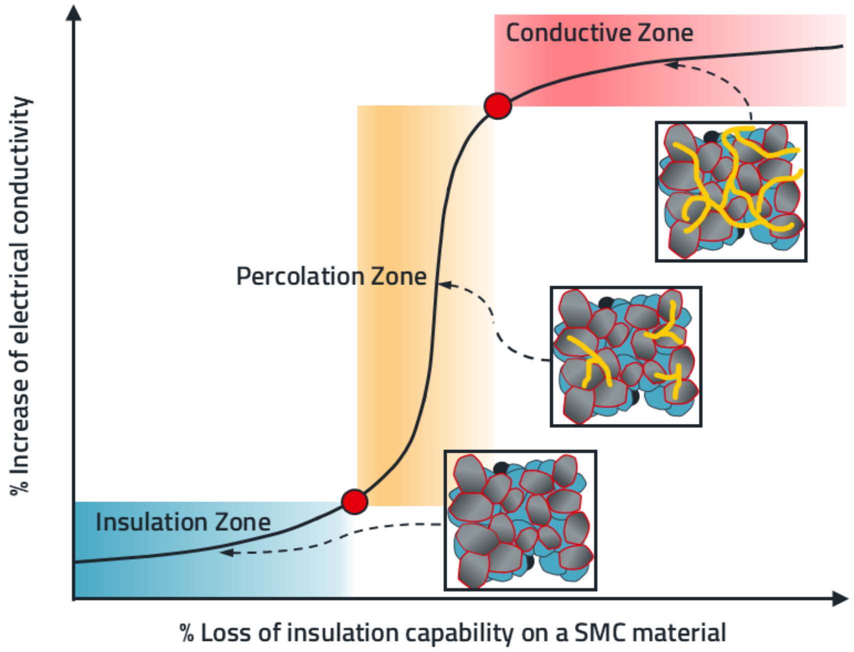
Fig.8. The assumption from inductor designers.

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 performance change of a molded power inductor that can affect a real application.



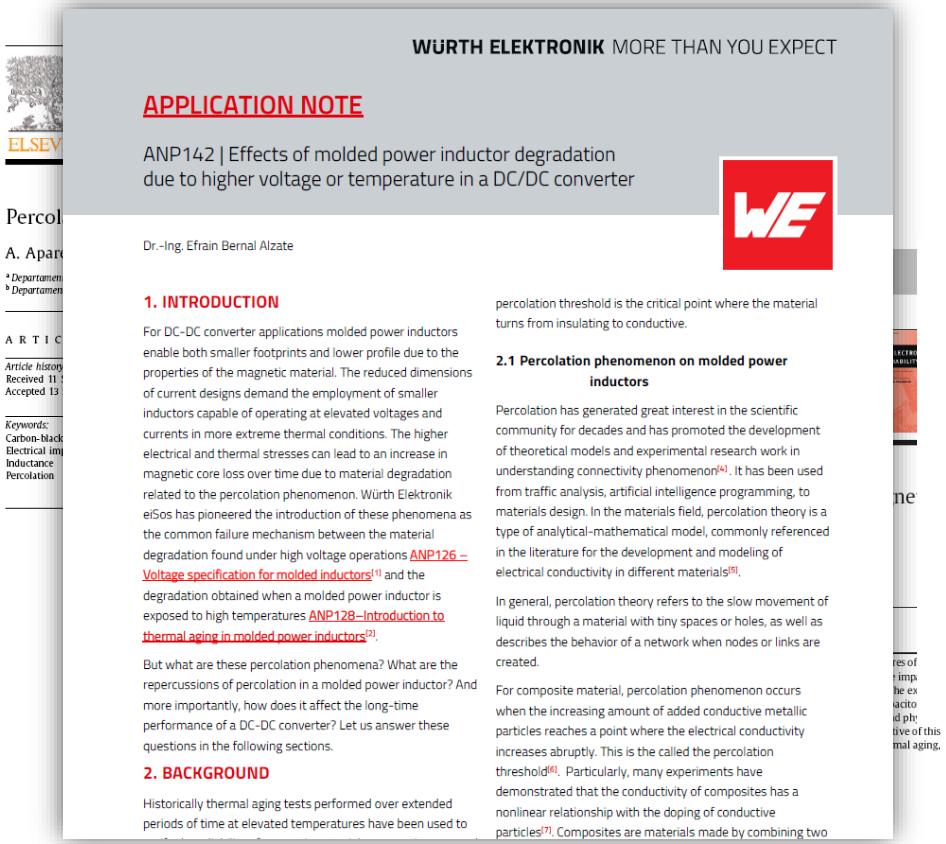
b. Threshold curve.

Fig.9. Percolation phenomenon in materials.

PERCOLATION PHENOMENON

Molded Power Inductors **degradation due to**:

- **High Voltage** ANP126: Voltage specification
- **High Temperature** ANP128: Thermal aging



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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. Efrain 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[1] and the degradation obtained when a molded power inductor is exposed to high temperatures ANP128–Introduction to thermal aging in molded power inductors[2].

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[4]. 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[5].

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 the called the percolation threshold[6]. Particularly, many experiments have demonstrated that the conductivity of composites has a nonlinear relationship with the doping of conductive particles[7]. Composites are materials made by combining two

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.

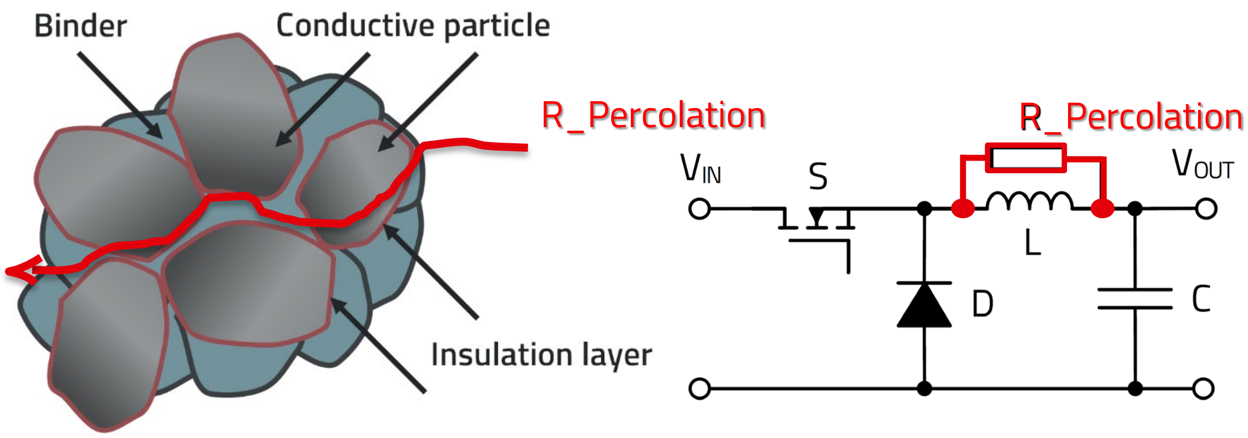
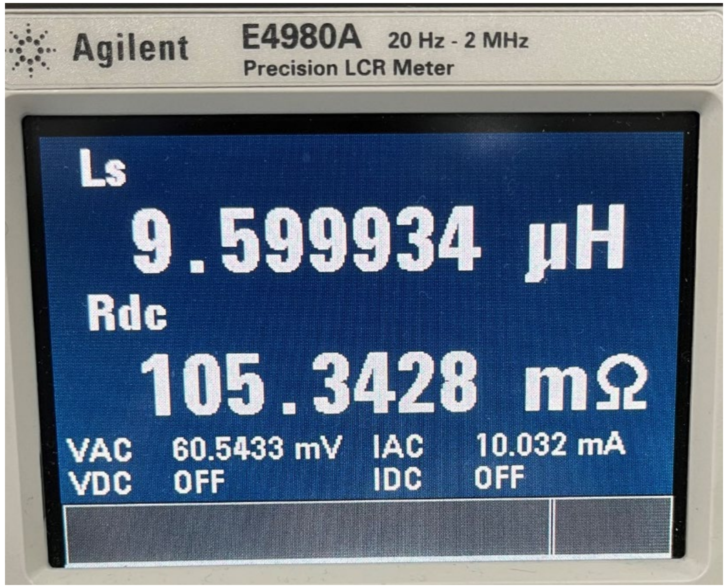


Fig. 10. Percolation on Molded Power Inductors.

PREVIOUS FINDINGS

ANP126: Voltage specification

Material degradation not detectable during standard AECQ200 qualification testing:



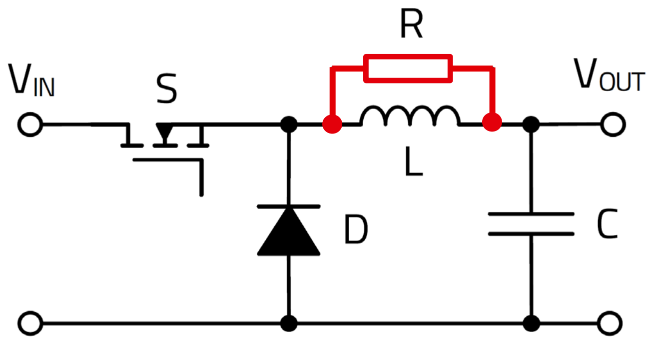
a. Good part

b. Compromised part

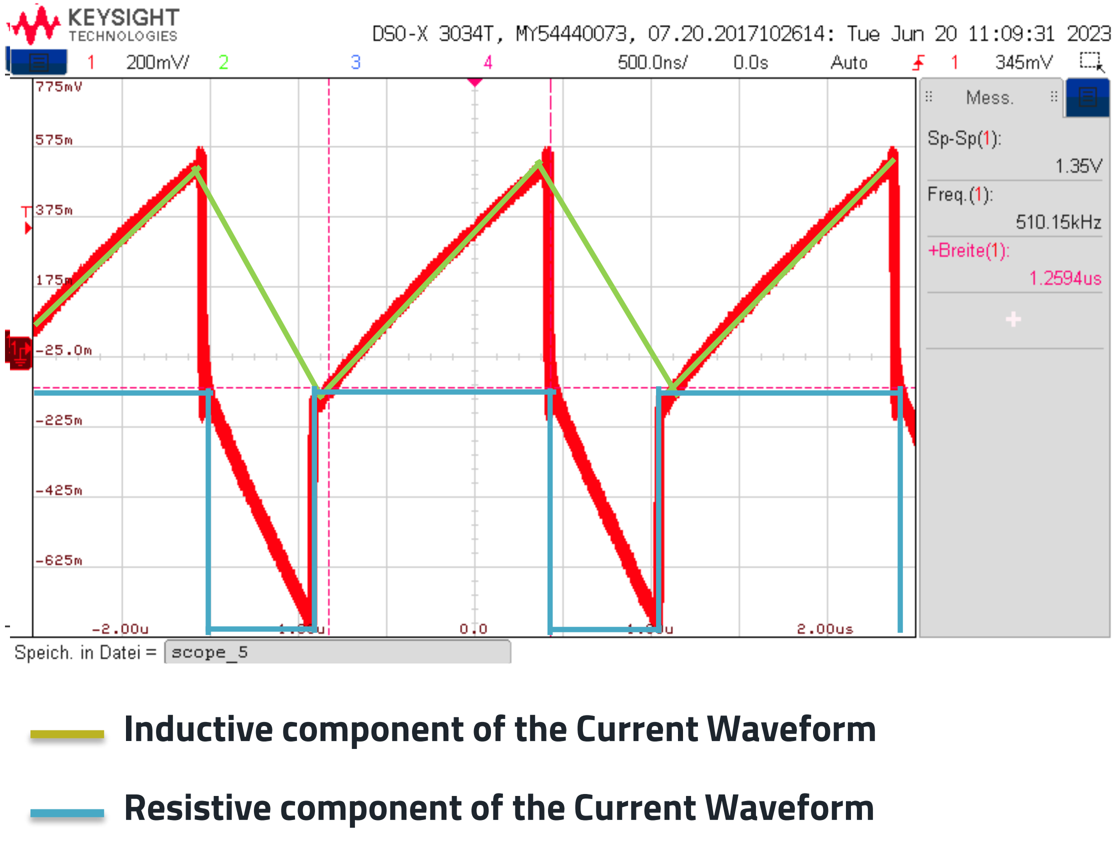
Fig. 11. LCR measurements at 100 kHz 10 mA.

PREVIOUS FINDINGS

ANP126: Voltage specification



a. Simplified Buck Converter with parallel Resistor R



b. Buck Converter Current Waveform with Resistor R

Fig. 12. Interpretation model for percolation losses.

PREVIOUS FINDINGS

ANP128: Thermal aging

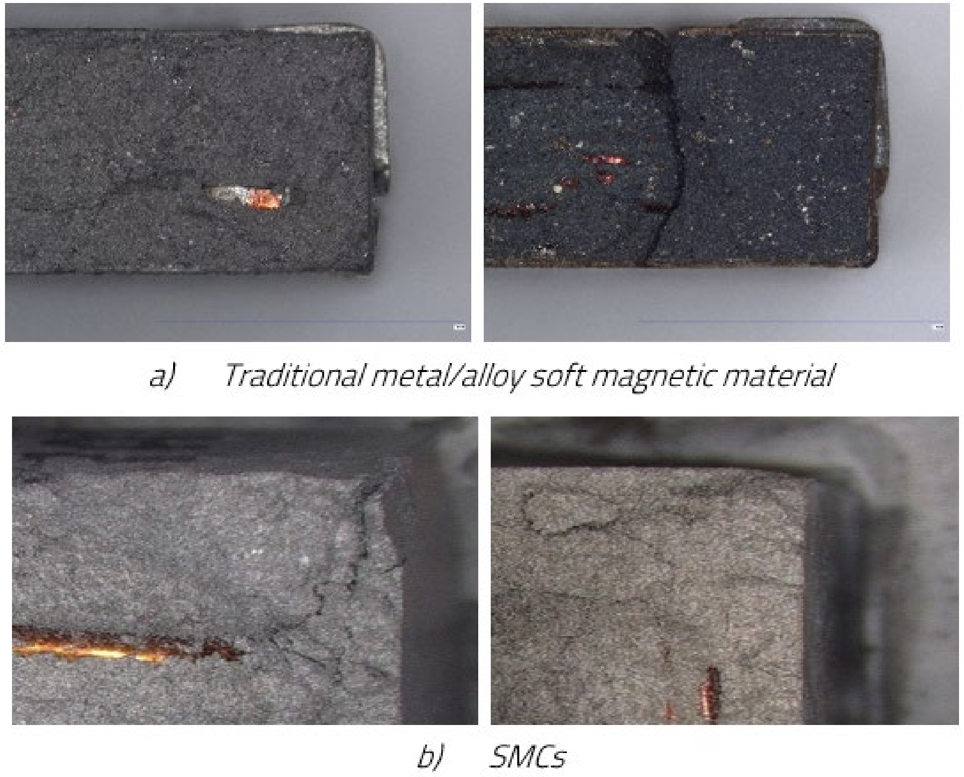


Fig. 13. Molded Power Inductors before test (left column) and after test (right column) zoom at 10X.

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

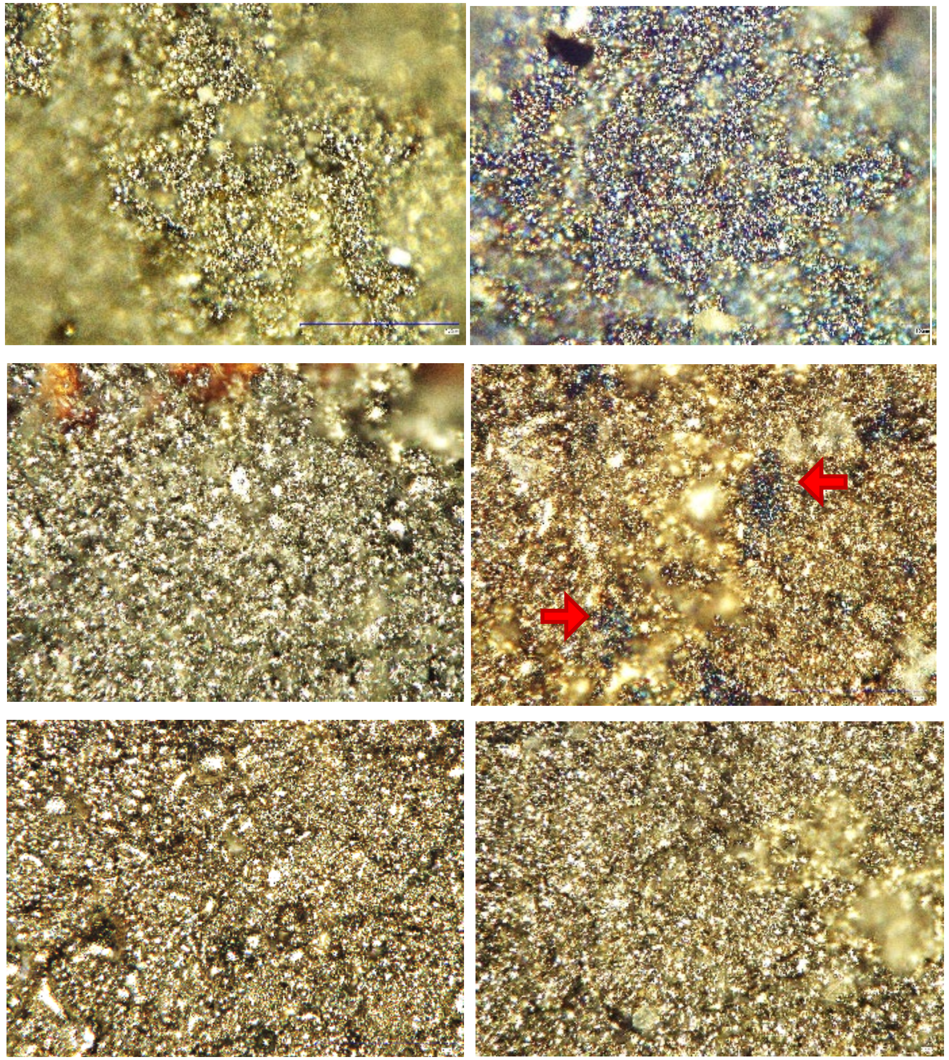
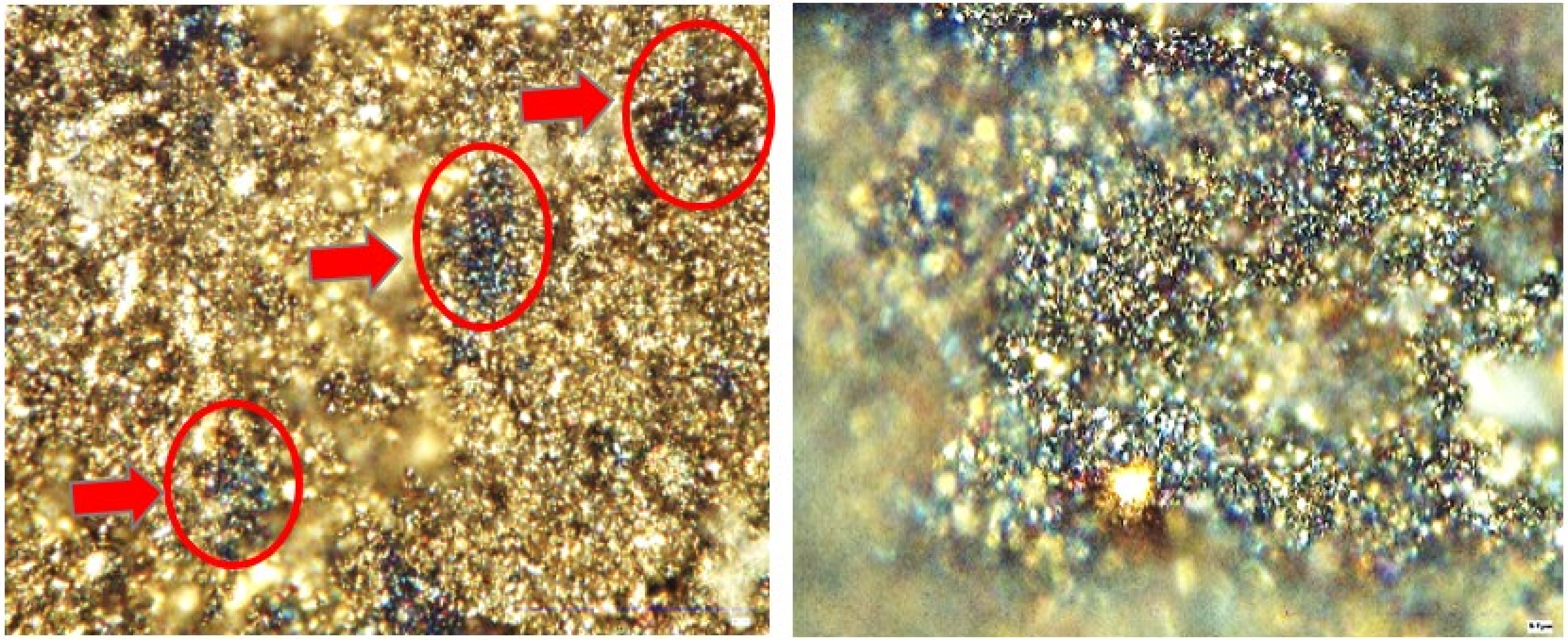


Fig. 14. Molded Power Inductors before test (left column) and after test (right column) zoom at 1000X, Test setup: 1000 h @ 200 °C.

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:

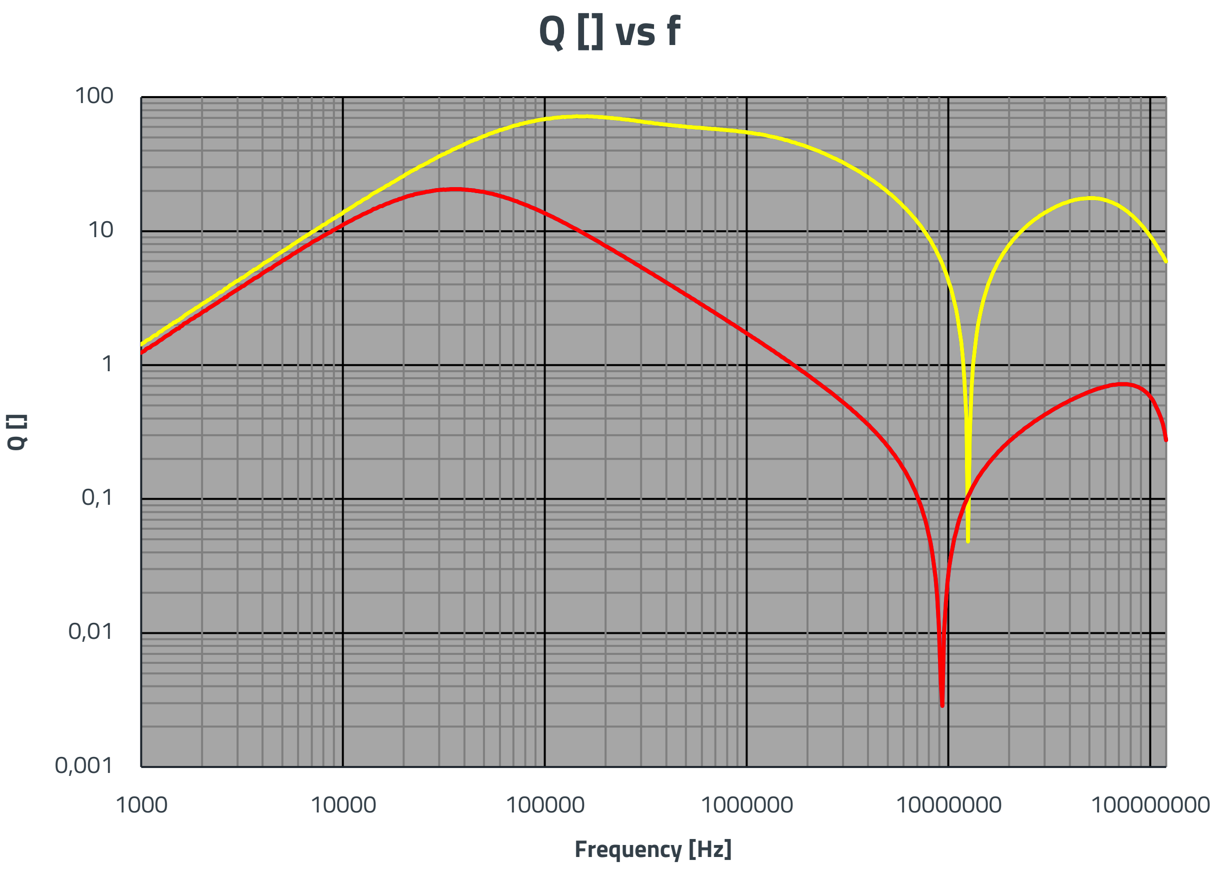


a. First percolated cluster formations. **b. Material with strong percolation.**

Fig. 15. 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.



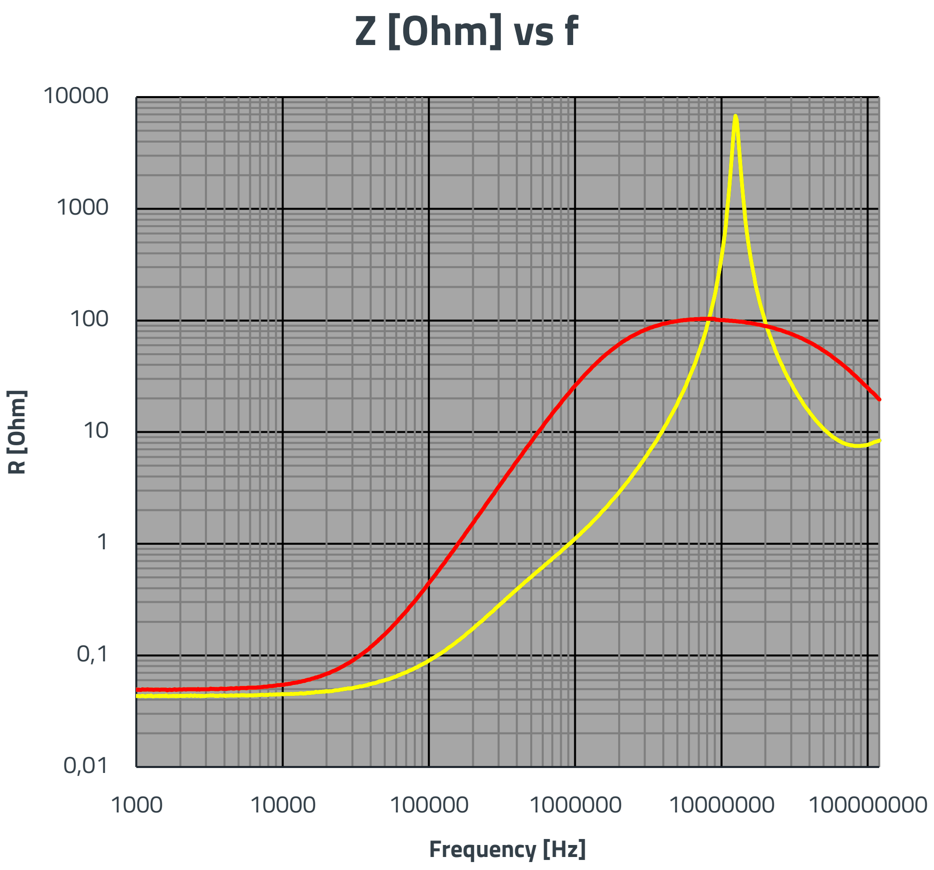
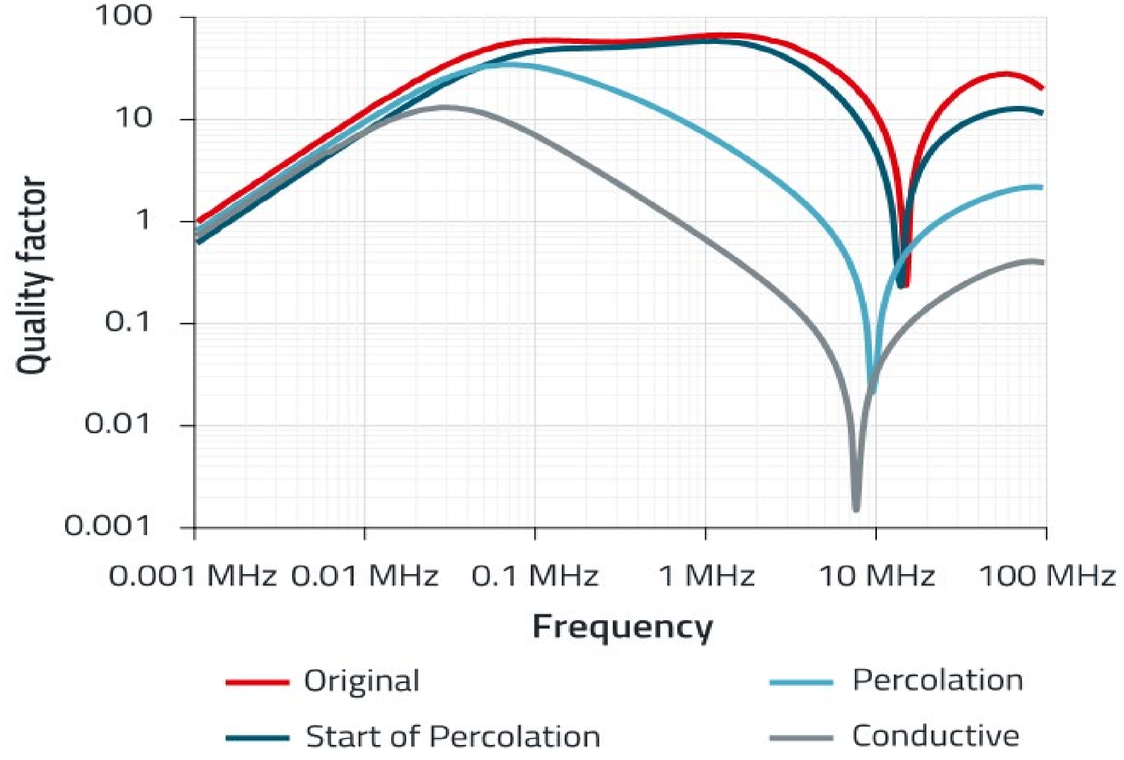


Fig. 16. A decrease in the Q factor corresponds to an increase in core losses..

PERFORMANCE REPERCUTION OF PERCOLATION

Q Factor change



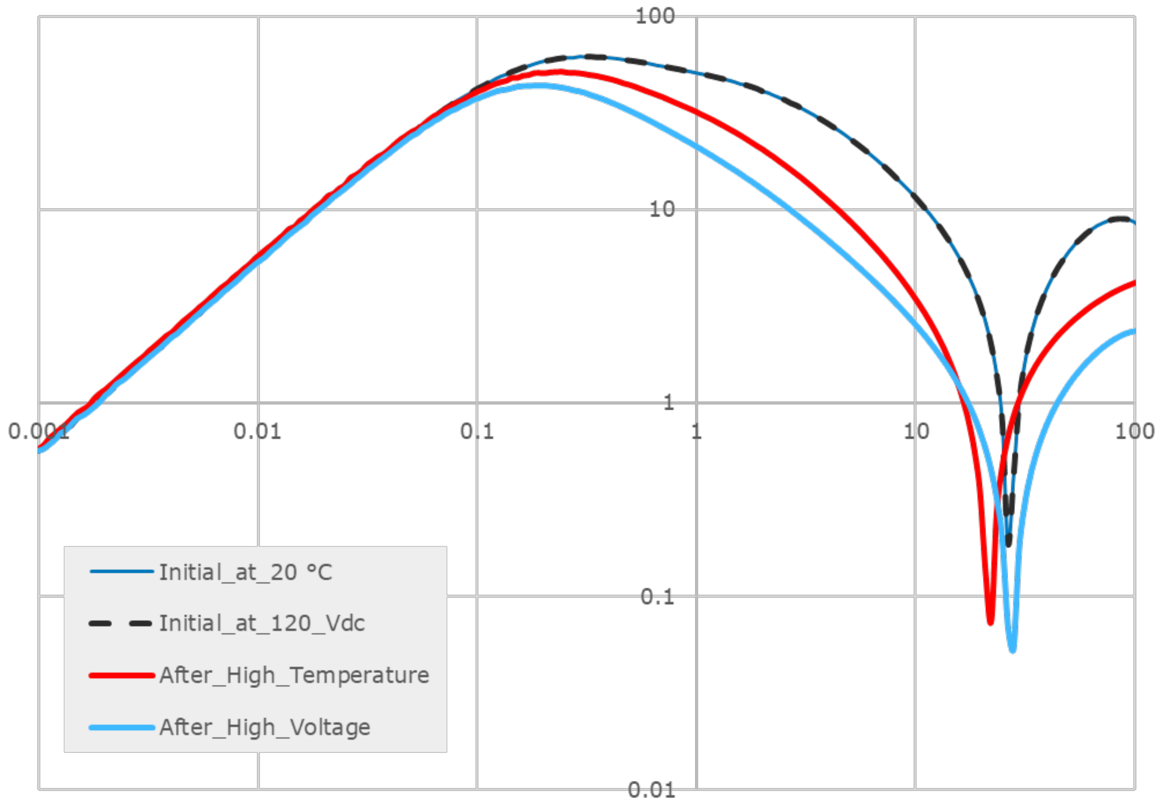


Fig. 17. Change of the Q factor due to high temperature or high voltage exposure.

PERFORMANCE REPERCUTION OF PERCOLATION

Reliabilty

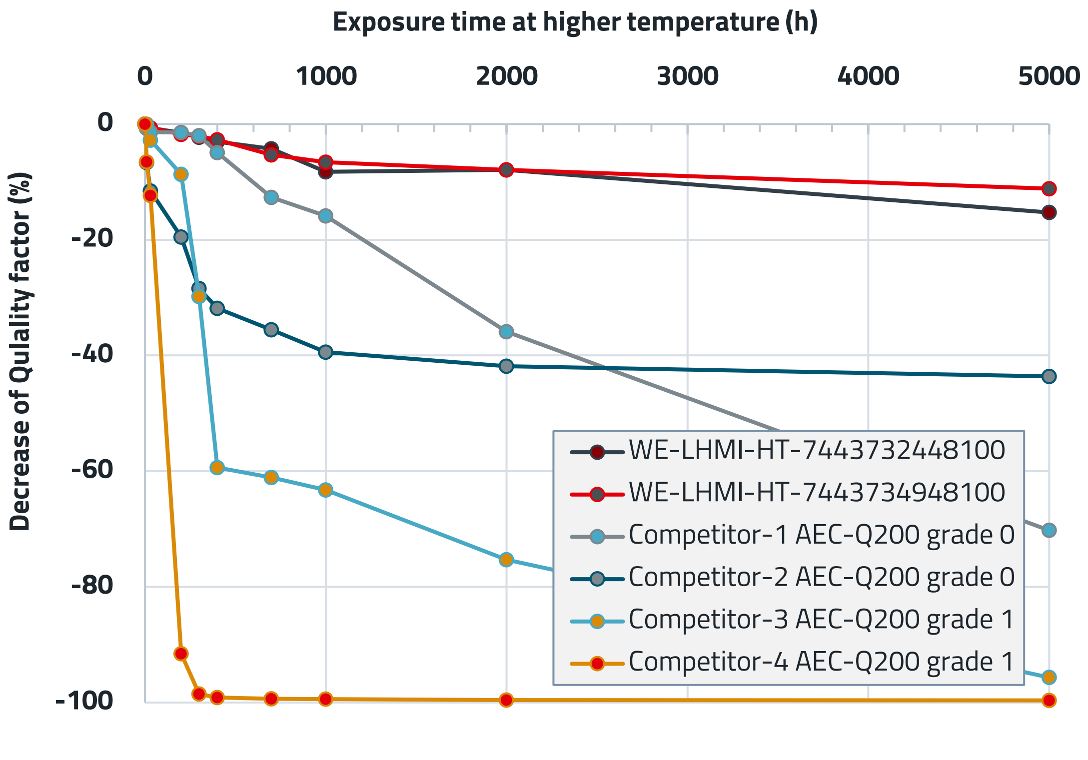


Fig. 18. Decrease of Q value at 2 MHz during 5000 h at 200 °C.

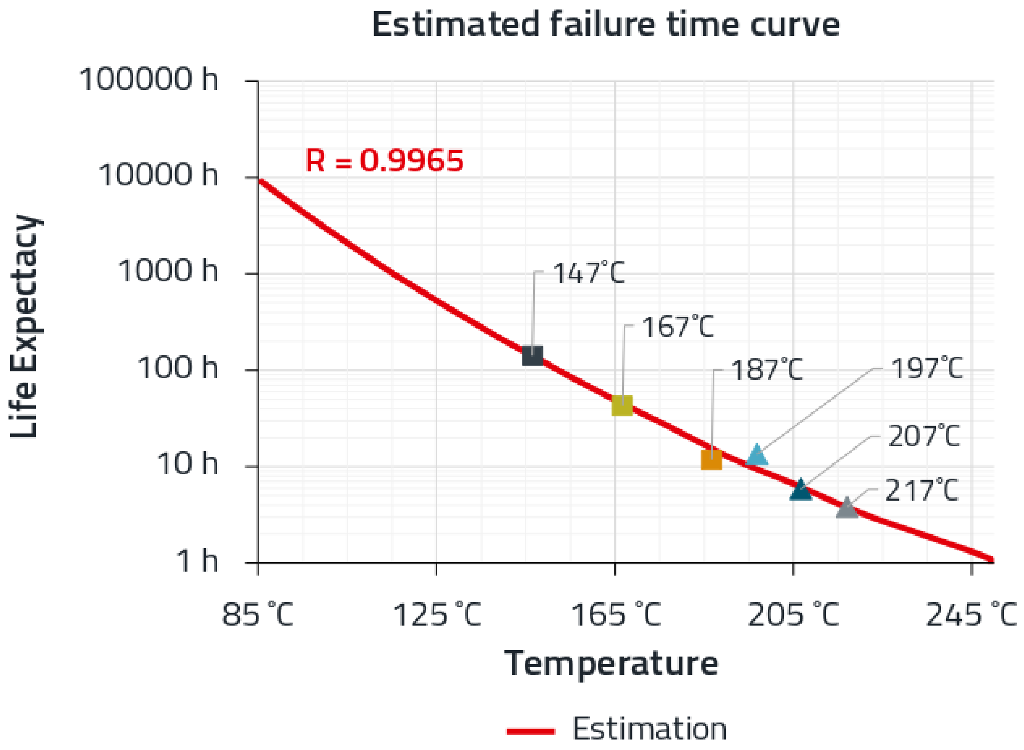


Fig. 19. Arrhenius plot to analyze the percolation at different temperatures on the tested molded power inductor.

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

Example setup

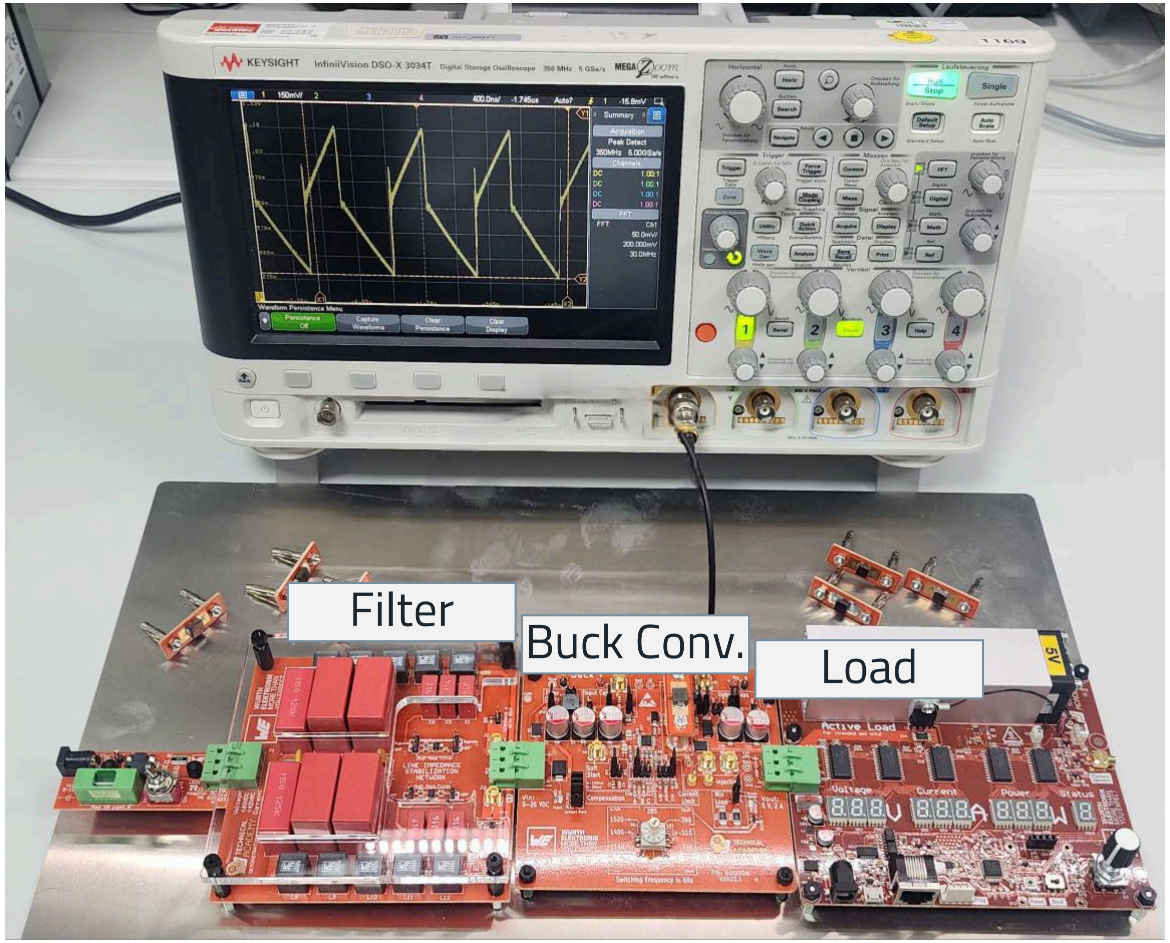


Fig. 20. WE DC-DC converter for test setup.

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 µH
- 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

Animation of percolation levels

Four different levels of percolation detected::

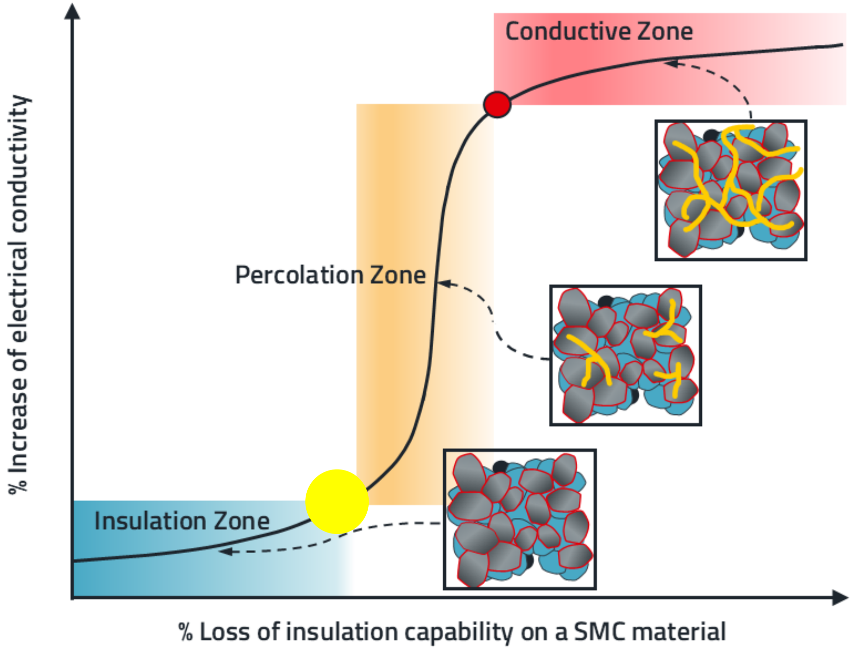
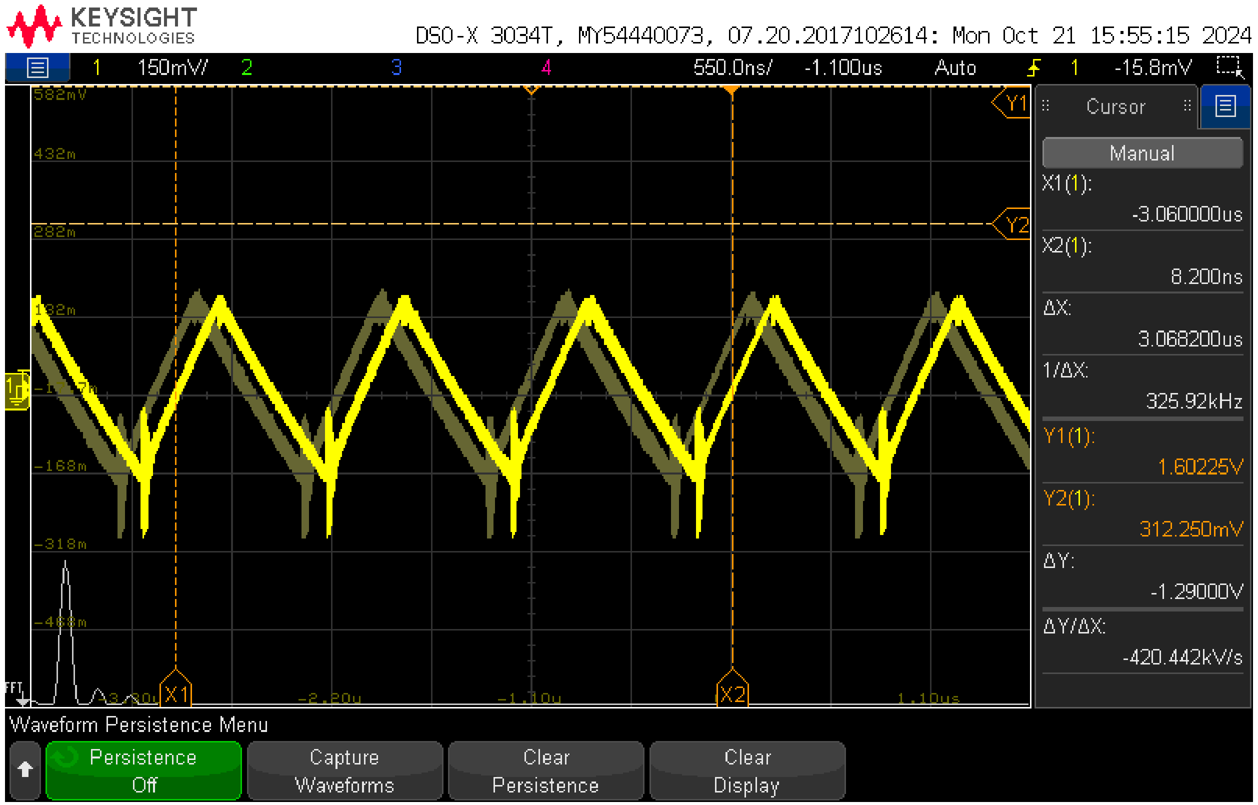


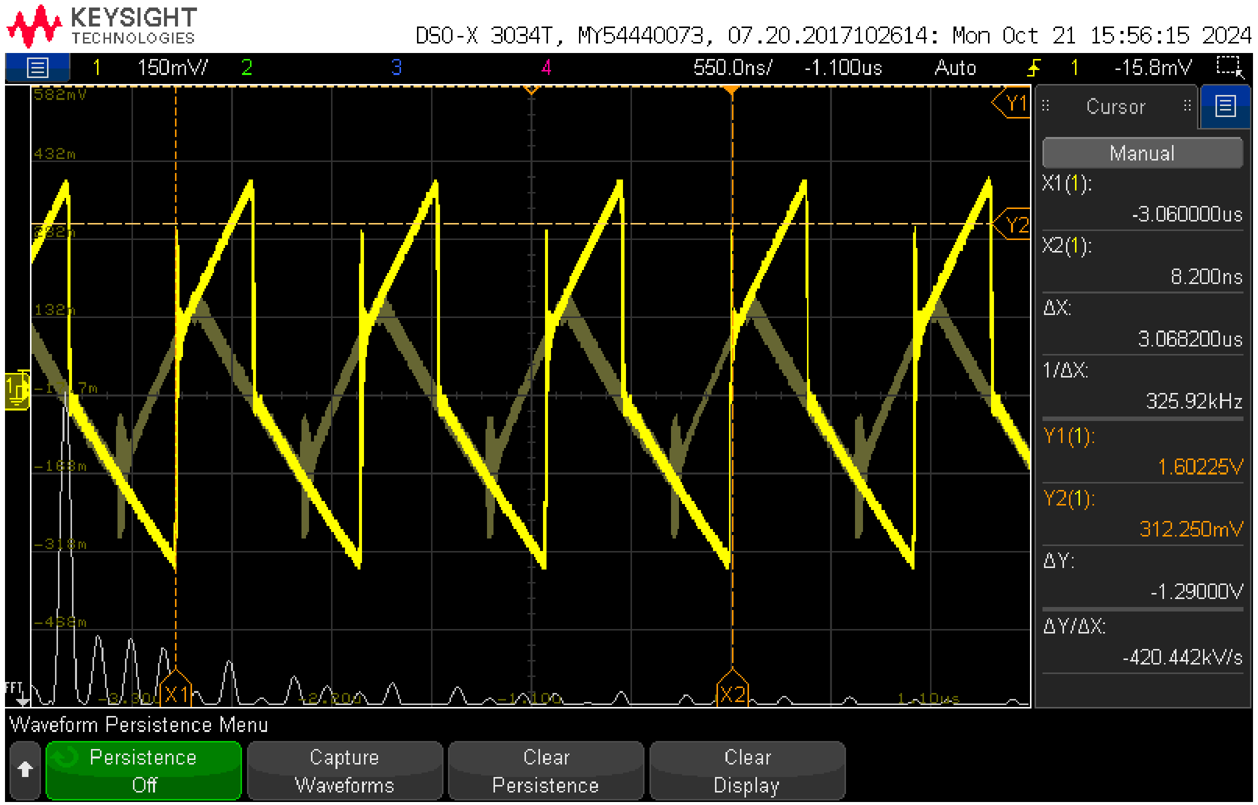
Fig. 21: . Affectation of a percolated molded power inductor in a DC-DC converter..

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.

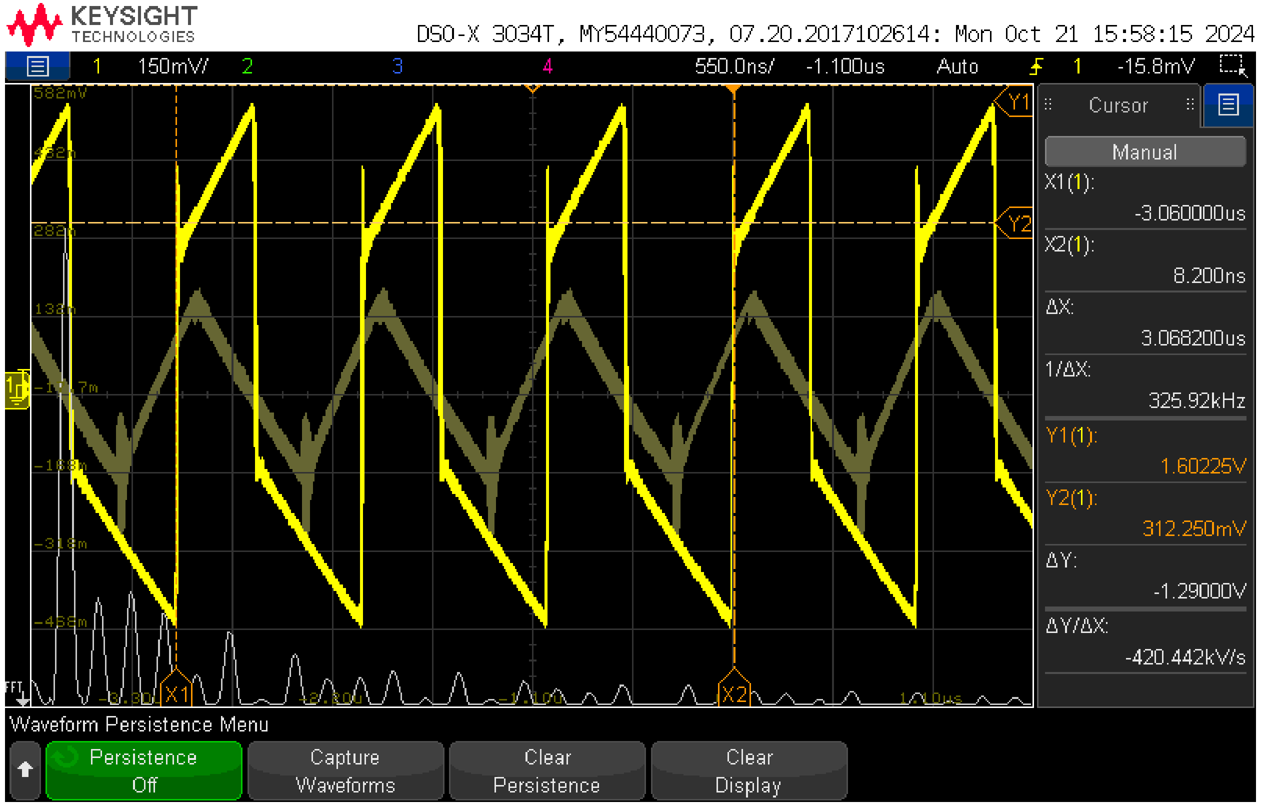


b. Evidence of percolation phenomenon.

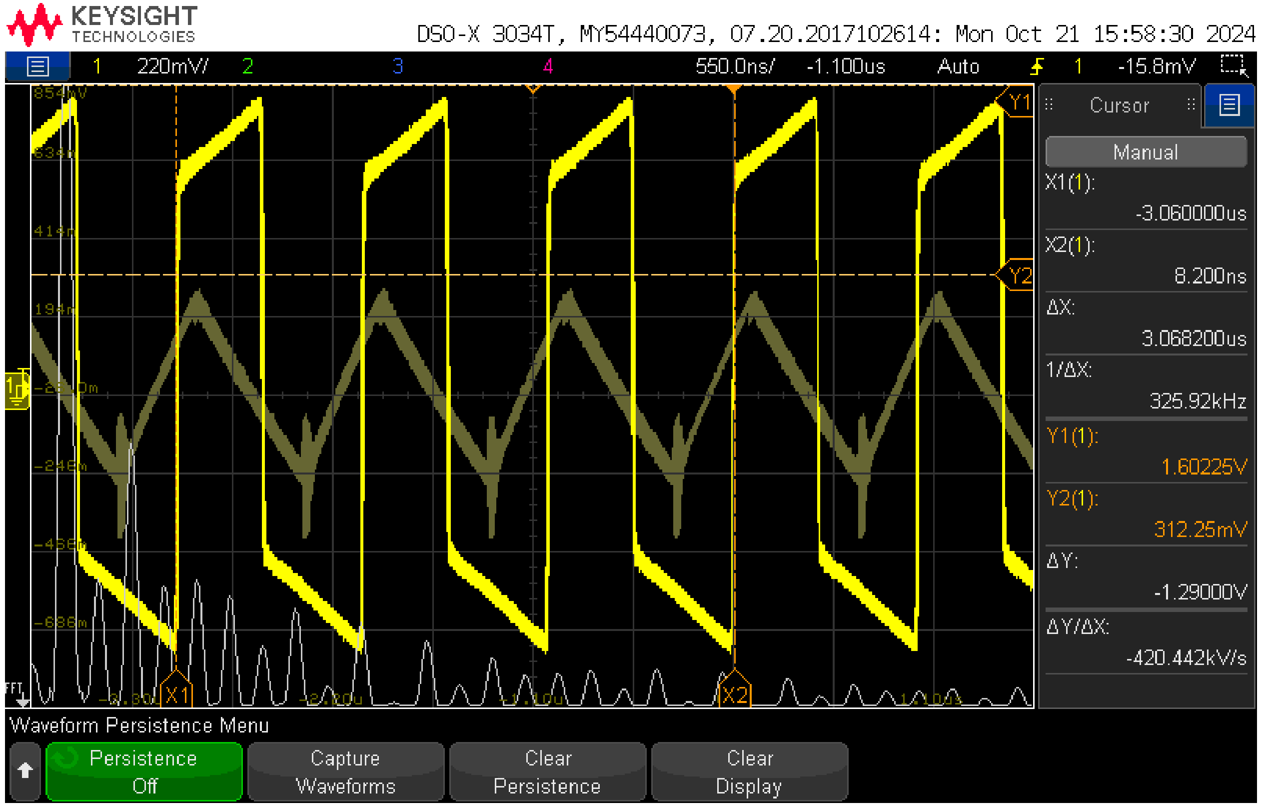
Fig. 22. Oscilloscope captures at beginning percolation test.

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.

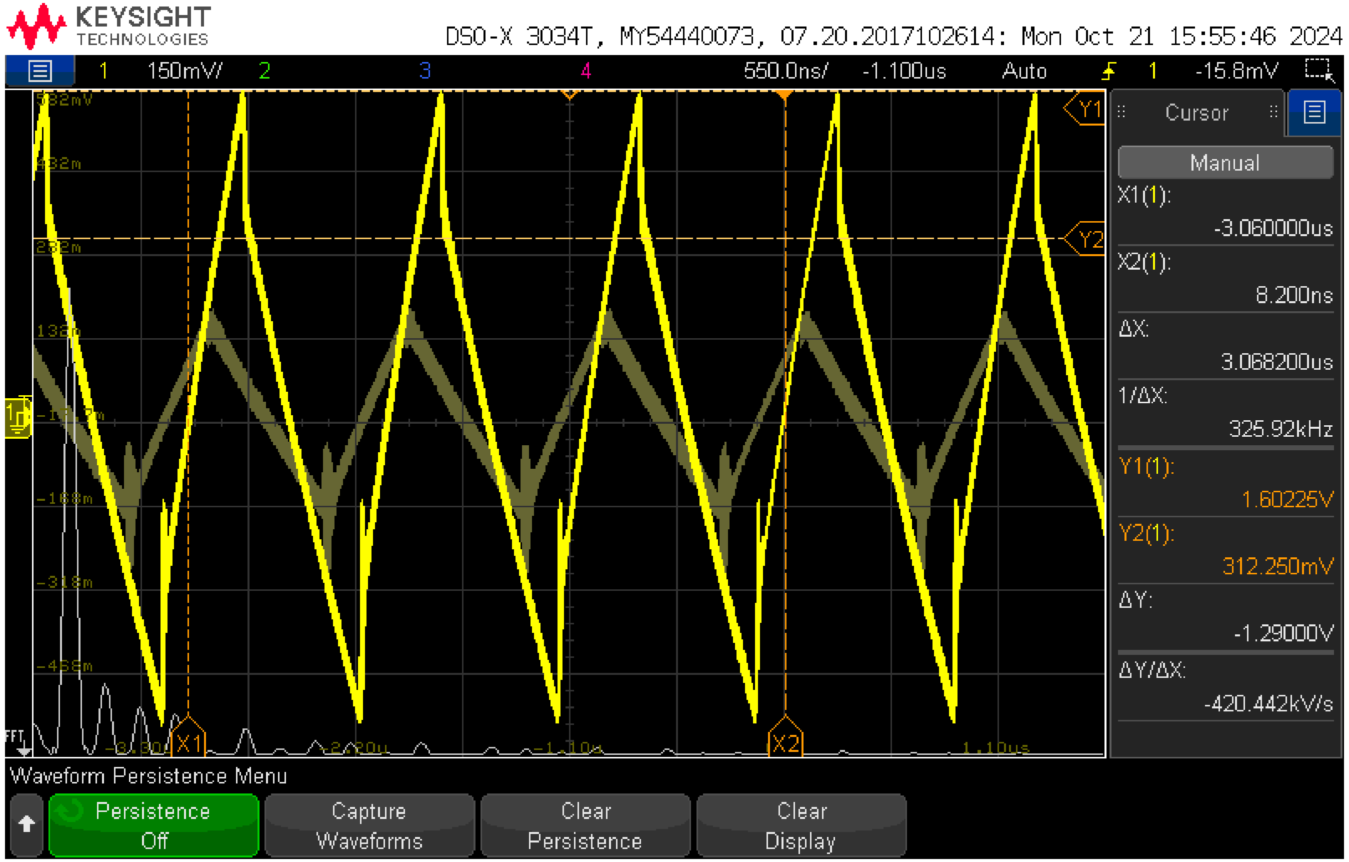


d. Waveforms for the inductor closer to conductive zone.

Fig. 23. Oscilloscope captures at the end of percolation test.

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

Different levels of percolation



d. Waveforms for the inductor in conductive zone.

Fig. 24. 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

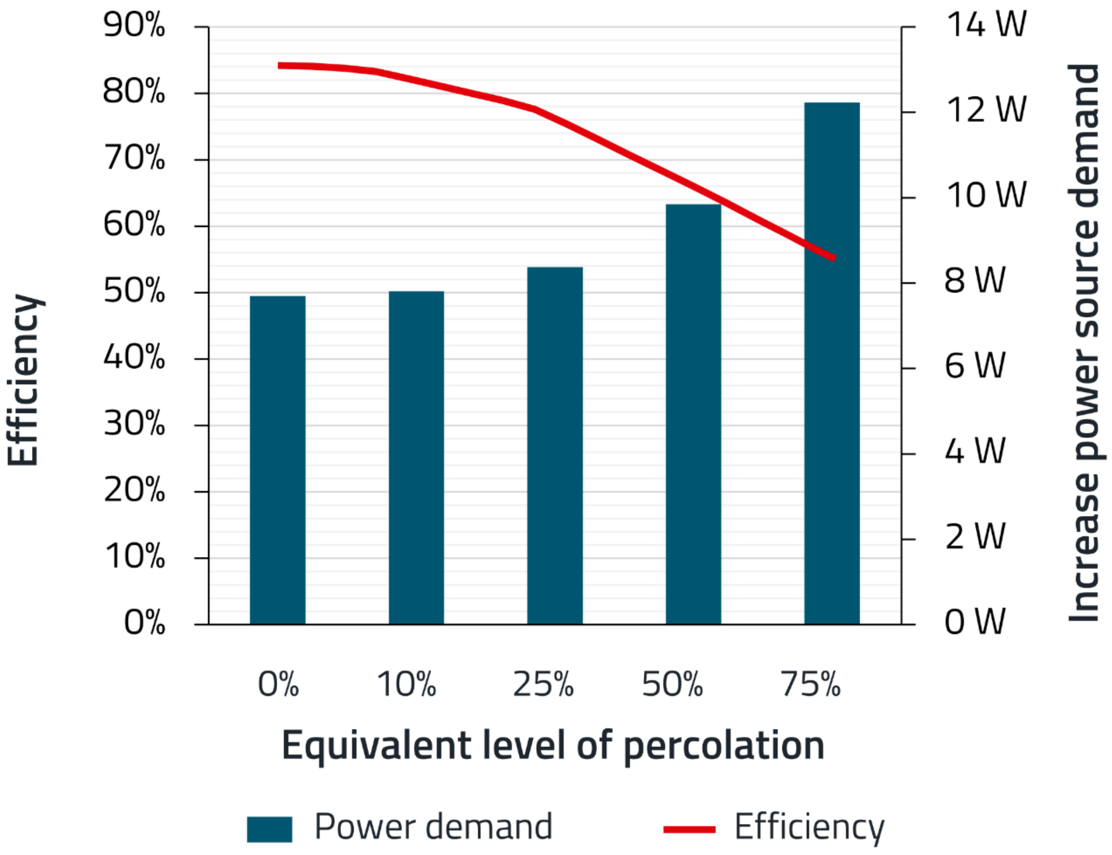
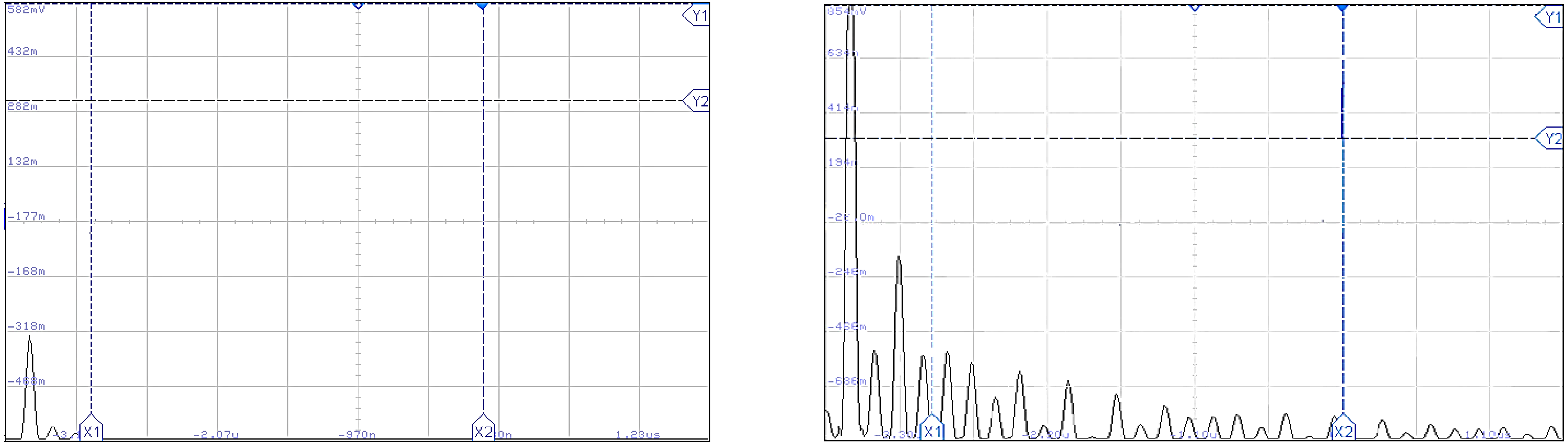


Fig. 25. Efficiency decrease due to percolation of the molded power inductor.

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?

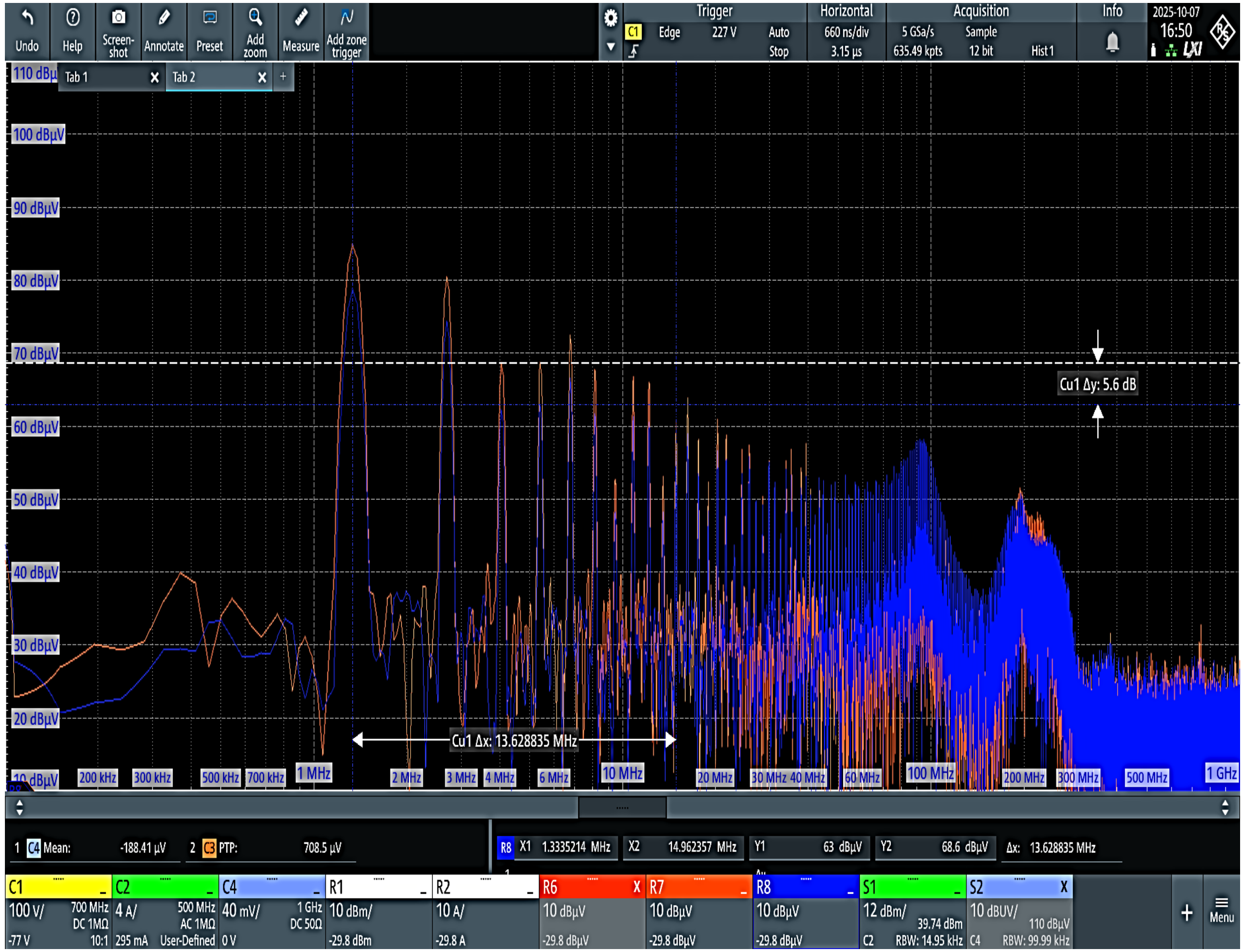


a. Recorded FFT for initial set up without percolation.

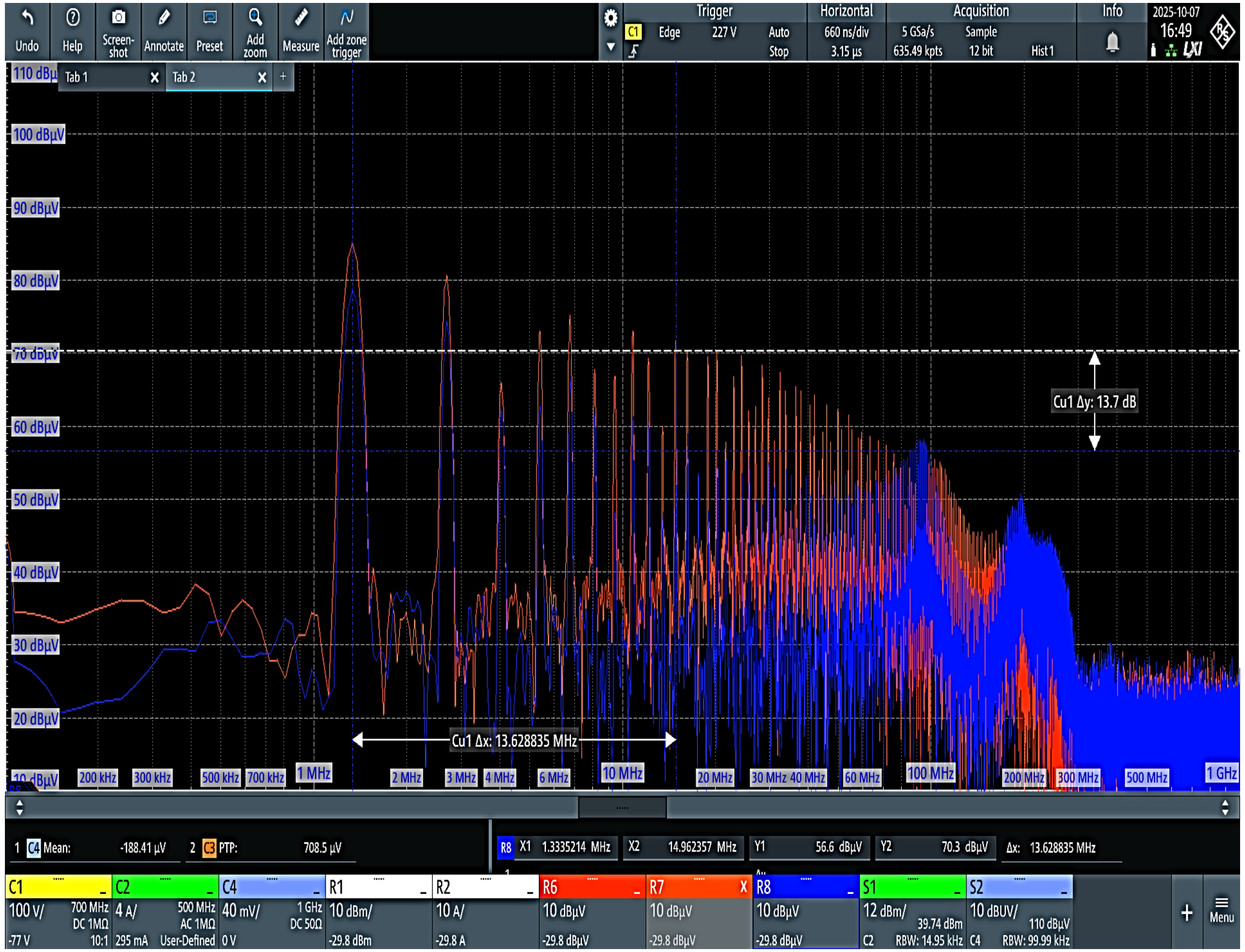
b. Recorded FFT for a percolated molded power inductor.

Fig. 26. FFT increase due to the percolation phenomena on the molded power inductor with a scale of 100 mV/div until 30 MHz.

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



a. Near radiation with small percolation.



b. . Near radiation with high percolation.

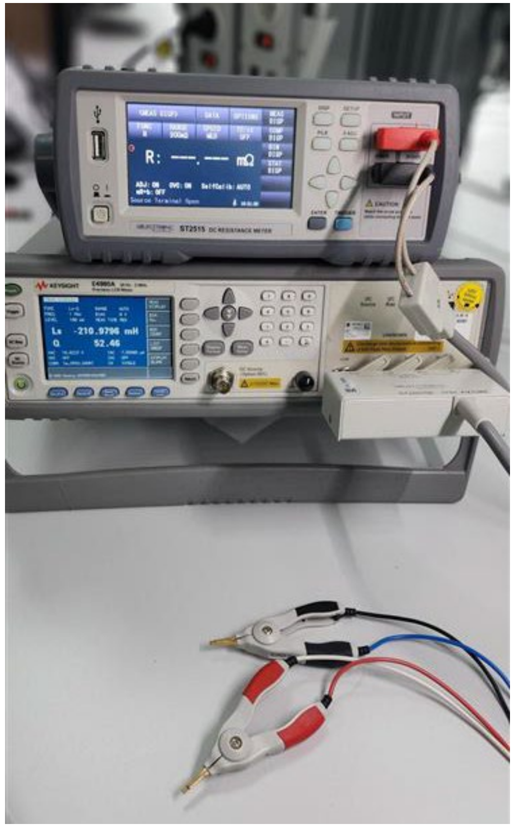
Fig. 27. Radiation increase due to the percolation phenomena on the molded power inductor.

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

LCR meter can be used as well to check percolation

Measurement conditions	100 kHz/10mA	500 kHz/10mA	1 MHz/10mA
Tested Samples		**Ls[µH]**	
No-Percolation	27.7956	27.6495	24.2351
Begin of Percolation	27.5408	22.5518	21.693
With Percolation	27.1151	16.90766	3.9945
Tested Samples		**Q[]**	
No-Percolation	45.2343	27.7864	15.3599
Begin of Percolation	45.1023	12.9543	6.57609
With Percolation	40.7112	0.889895	0.460104

a. Comparison measurements

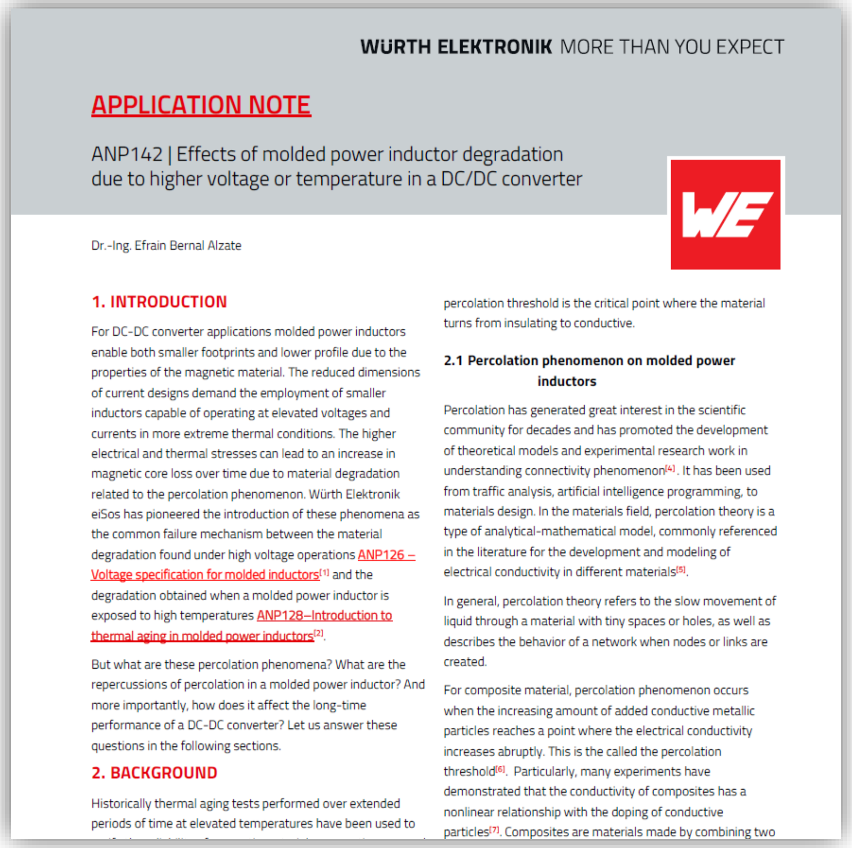


b. Equipment example at customer side

Fig. 28. LCR measurements for a 33 µH molded power inductors.

SUMMARY FINDINGS

- Percolation phenomenon starts after the exposition to high temperature or a high voltage.
- The percolation phenomenon in a Molded Inductor 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, increase of harmonic -EMI, and the eventual decrease of power converter efficiency over time.



WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

APPLICATION NOTE

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

Dr.-Ing. Efrain 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[1] and the degradation obtained when a molded power inductor is exposed to high temperatures ANP128–Introduction to thermal aging in molded power inductors[2].

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[4]. 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[5].

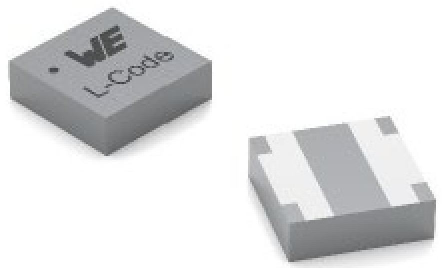
In general, percolation theory refers to the slow movement of liquid through a material with tiny spaces or holes, as well as describes the behavior of a network when nodes or links are created.

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 the called the percolation threshold[6]. Particularly, many experiments have demonstrated that the conductivity of composites has a nonlinear relationship with the doping of conductive particles[7]. Composites are materials made by combining two

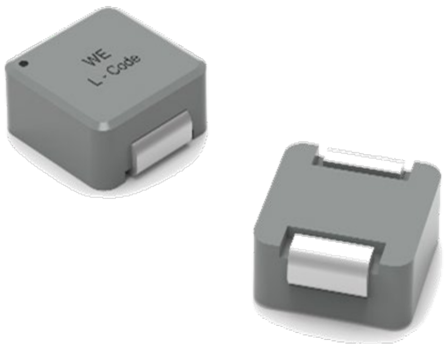
WÜRTH ELEKTRONIK: HIGH-TEMPERATURE MOLDED INDUCTORS

Molded Power Inductors for demanding applications

Industrial | **Automotive**



WE-MAPI HT



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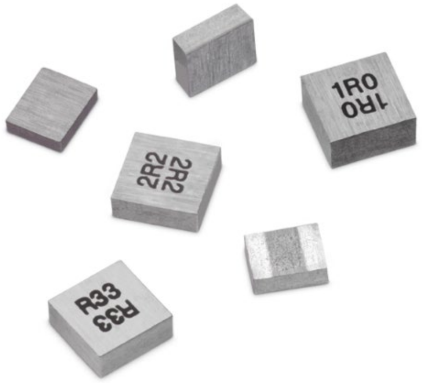

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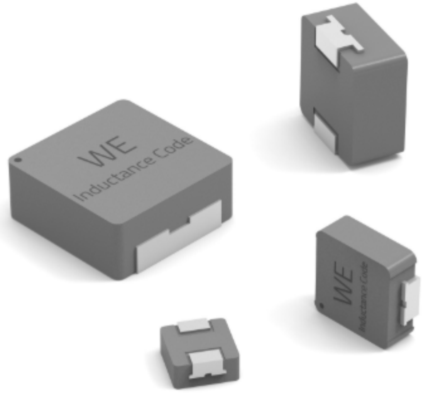

WE-LHCA HT

- 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.

Efrain.Bernal@we-online.de