APPLICATION NOTE

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

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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 this phenomenon as the common failure mechanism underlying the material degradation found under high voltage operations (ANP126 – Voltage specification for molded inductors[1]) and the degradation observed when a molded power inductor is exposed to high temperatures (ANP128–Introduction to thermal aging in molded power inductors[2]).

But what are this percolation phenomenon? 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 verify the reliability of magnetic materials, magnetic cores and inductive components. The options for evaluating the operating voltage on power inductors are limited to burn-in testing or voltage impulse testing to assess the effects of transient voltages on insulation integrity. In the specific case of molded power inductors, a form of progressive degradation in terms of performance at higher frequencies has been found by Würth Elektronik eiSos, when testing them at higher voltages or higher temperatures. The failure mechanism refers to the appearance of some "micro conductive networks" between the metal powder particles of the core material. This is due to the increase of the material conductivity which causes an increase of core losses, eventually over time exhibiting a percolative behavior. The 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 originally refers to the slow movement of liquid through a material with tiny spaces or holes, as well as describing the behavior of a network when nodes or links are created. Percolation behavior occurs when interconnected pathways are formed within a material.

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 so-called 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 or more elements, natural or artificial, which are stronger together than individually.

In the case of molded power inductors, the preferred solution for better performance is Soft Magnetic Composites, or SMCs. These composites are advanced materials engineered for their magnetic properties. Unlike traditional magnetic materials, SMCs are comprised of iron alloy powder particles coated with a thin insulation layer dispersed in a non-conducting matrix, such as epoxy or polymer binder. Molded power inductors based on SMCs depend on the insulation layer and binders to reduce the overall amount of eddy current losses, i.e. conductivity between particles[2], as shown in the Figure 1:

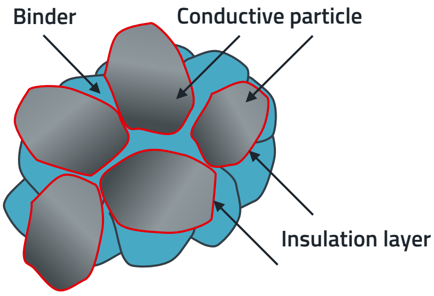


Figure 1: Typical components on SMCs[2]

However, researchers have found that at high voltages or high temperatures, the phenomenon of conductive percolation also occurs even when the amount of conductive materials added to a polymer is small[8]. The theory suggests that, under the action of a strong external environment, such as a high electric field, conductive particles collide with each other more frequently, leading to the movement of electric charges. This charge movement can generate electric currents and contribute to an emissive effect, allowing electrons to overcome the insulation layer in a material[9], and it can be associated with unfavorable or even a destructive effect[10]. In fact, we have found that with more current due to high voltages or with the continuous exposure to higher temperatures, the loss of the insulation properties of the binder and the coating layer itself induces the creation of more micro conductive networks, i.e. the percolation phenomenon in SMCs. A schematic illustration of the percolation network in composites[11] is used to clarify the concept, as show in Figure 2:

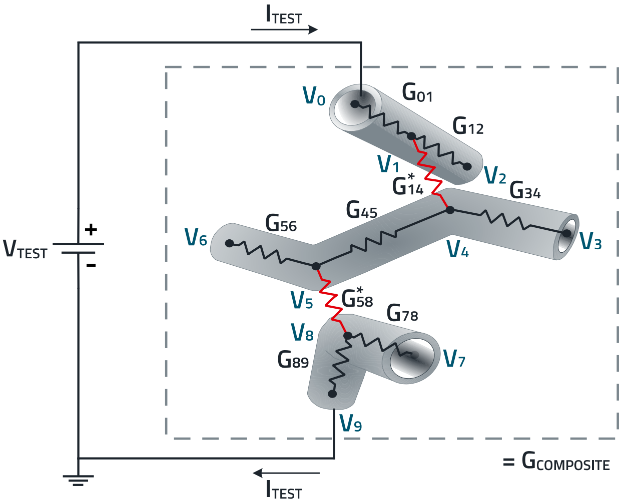
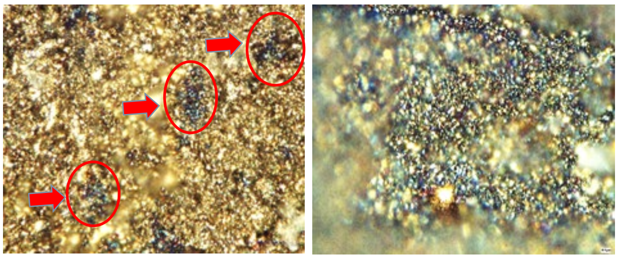


Figure 2: Equivalent electrical circuit used to illustrate the growth of a percolation network on composite materials based on[11]

In the figure the red resistors represent the new conductive connections between the exposed iron particles of the material itself. This connection leads to the creation of clusters that can deteriorate the molded power inductor, from small areas to the complete material, as illustrated in the Figure 3.



a. Left Column: first percolated cluster formations.

b. Right Column: material with strong percolation.

Figure 3: Pictures show some burned areas obtained with a microscope reference zoom at 1000X after a stressful test on a molded power inductor.

As summary, **we define the percolation phenomenon in a molded power inductor as the material degradation that transitions from an insulating to a conductive state, due to higher voltage or higher temperature, increasing the core losses due to larger eddy currents.**

The non-linear relation between the loss of insulation and the increase of electrical conductivity (due to appearance of yellow networks) in a SMC is shown in Figure 4.

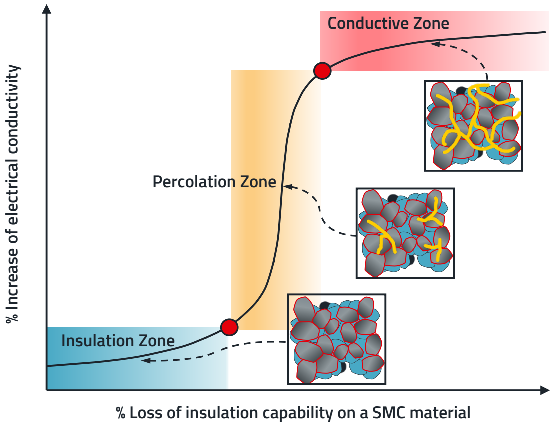


Figure 4: Percolation threshold on molded power inductors.

When the loss of insulation is below the threshold, the conductivity of the composite material increases slowly with the increase of the temperature or the applied voltage. However, when the material is exposed to higher voltages or higher temperatures, the conductivity increases leading to the percolation threshold. At this point, the percolative path passes through overlapping the binder, around iron particles, by creating the clusters shown in Figure 3a. Over time, the conductive paths of the material increase dramatically, and change it from an insulating material to a conductive material.

It is a non-reversible phenomenon and compromises the performance of the affected inductor.

3. REPERCUSSION OF PERCOLATION IN THE MOLDED INDUCTOR PERFORMANCE

As has been presented, the percolation phenomenon appears during the lifetime of a molded power inductor, and it is difficult to identify at early stages. A molded power inductor with AEC-Q200 qualification for higher temperatures, over 125 °C, can suffer from percolation, which cannot be detected with the usual pre and post measurements as the standard recommends. This has been explained by Würth Elektronik eiSos in our previous two application notes ANP126 and ANP128.

The common findings in those application notes reveal that a compromised part does not change the inductance or resistance value when measured at lower frequencies (i.e. 100 kHz). However, when an impedance analyzer is used at high frequencies (i.e. 2 MHz), the Q value reveals a performance decrease.

To corroborate the percolation phenomenon due to higher voltage or higher temperatures, a new test setup has been prepared for this application note. A total of 20 samples of a 4.7 µH molded power inductor were taken from the same production lot number, all with similar electrical properties. For the series of tests, ten chokes were subjected to a high-voltage test and another ten to a thermal aging test. The measurements were carried out at an ambient temperature of 20 °C in each case.

The degradation mechanism was triggered by the continued exposure at a temperature of 160 °C for an extended period of 300 h for the aging test. The high voltage test was accomplished by using a modular impulse generator to expose the inductors to a series of controlled pulses.

In the high voltage test, the first sequence of voltage pulses was chosen to be 120 Vdc, which is the limit recommend by the manufacturer's datasheet. The applied pulses had a duration of 36 µs per pulse, following the recommendation of the IEC61000-4-5 standard for the rise and fall time of the pulses. In total 35 pulses were applied to each inductor to assess any impact.

After that validation, the inductors were subjected to an overvoltage round of pulses. The summary of pre and post test results is shown in Figure 5.

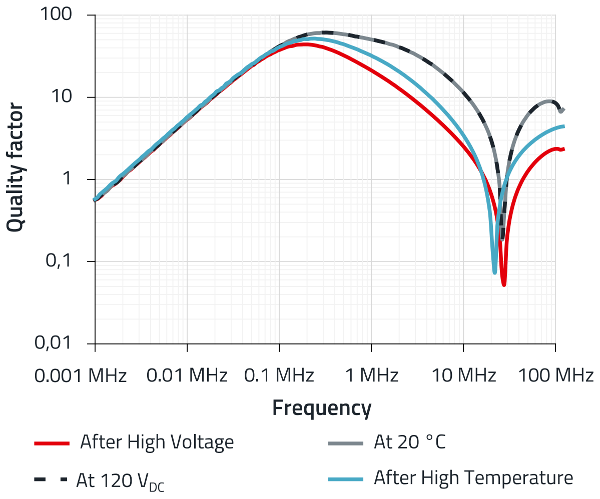


Figure 5: Change of the Q factor due to high temperature or high voltage exposure.

The gray line refers to the average quality factor Q vs. Frequency curve of the first 10 samples before exposure to higher temperatures, and the black dash line corresponds to the other 10 samples after the first round of pulses at 120 Vdc. As can be seen, both curves show the same behavior. The red line corresponds to the average of the Q value vs. Frequency after high voltage exposure with pulses around 190 Vdc and the blue curve to the 160 °C test.

The voltage of 190 VDC represents a 60% increase over the voltage limit supported by the non-conducting matrix mentioned earlier. From previous experience with the selected inductor, a voltage of 240 Vdc generates cracks on the component within the first few pulses.

A total of 10 pulses of 190 Vdc were applied. No cracks have been found, but there is an evident change on the Q curve. The blue line, the average Q after high temperature exposure, exhibits an impact, as expected. In general, it can be observed, both average values of the tests, i.e. the increased voltage and the increased temperature, have the same reduction of the quality factor at higher frequencies and a small change in the resonance frequency.

It is necessary to remark that percolation starts at different points inside the core of the inductor due to the physical effects induced by the test, which could be associated with either electrical or thermal percolation.

However, the trend is undeniable. Furthermore, with more exposure time the percolation will lead to a continuous decrease of the Q curve in a shorter time, as introduced in ANP128[2]. The results for the case or thermal aging degradation at 200 ^{0}C for 5000 h is presented in the following figure.

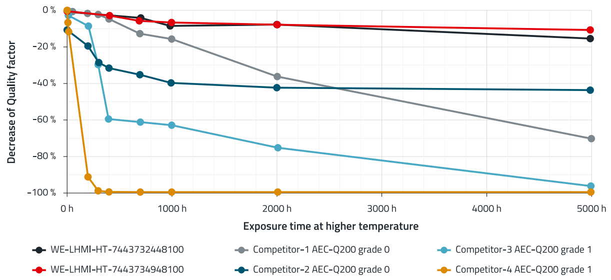


Figure 6: Decrease of Q value at 2 MHz during 5000 h at 200 °C.

The measurement results show that even the products of the best competitors shows a decrease of the Q value greater than 40% while the High Temperature version of our new family WE-LHMI 7443732448100 and WE-LHMI 7443734948100 show a minimal decrease in the performance.

At this point, it is necessary to remark that the post test curves presented on Figure 5 do not correspond to the final conductive phase. If a molded power inductor has reached its limit, as the case of the competitors in the Figure 6, even if the part presents some cracks, the coil will still conduct as a power inductor, however, with significantly different electrical properties compared to the original specification, affecting the application where it is used.

In order to relate the percolation level on the quality factor curve vs. frequency curve, the measurement results for the same inductor of 4.7 µH under a long-term stress condition are presented in Figure 7:

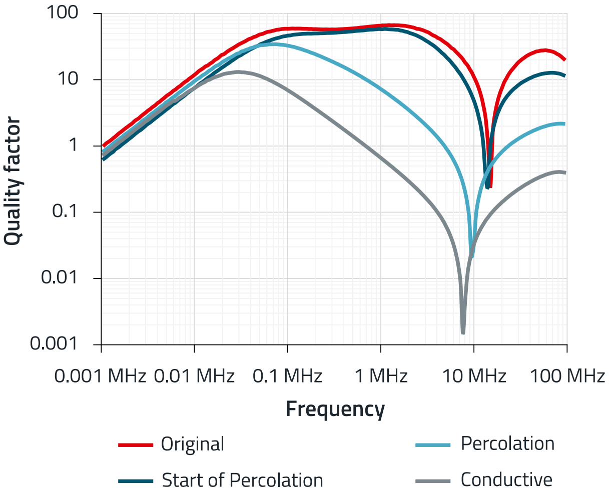


Figure 7: Decrease of Q value due to percolation phenomenon.

In summary, **the percolation in molded power inductors could be identified as the decrease of the quality factor and inductance at high frequencies as well as the decrease of the resonance frequency depending on the progress of the phenomenon per se.**

As a designer and/or end user, you may be questioning at this moment, how long a molded power inductor with percolation problems can work without failure if used at high temperatures or high operating voltages?

To solve this doubt, an Arrhenius Plot, presented in Figure 8, has been built following the recommendations found in IEC 60216-1 Electrical insulating materials, Thermal endurance properties, Part 1: Ageing procedures and evaluation of test results; in combination with the equivalent ASTM D 2307 standard. As the end point criteria, a decrease of 40 % in the measured Q value at 5 MHz was established, which represents a critical increase of 100% of the AC losses for a competitor molded power inductor of 5.6 µH.

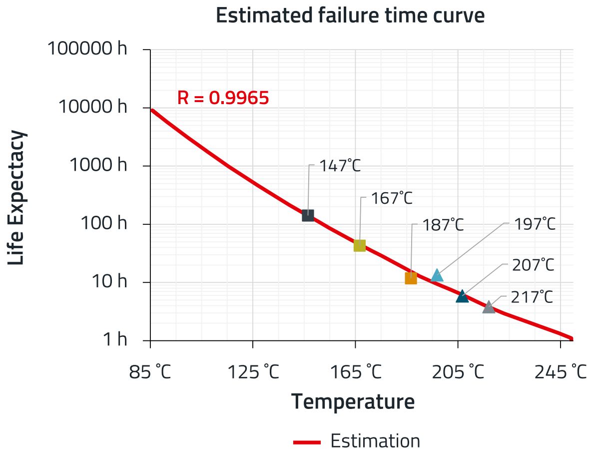


Figure 8: Arrhenius diagram to estimate the percolation over time at different temperatures on the tested molded power inductor.

The curve in Figure 8 shows that the competitor part fails after the first 100 hours of continuous exposure at a high temperature of 147 ^{0}C. One might assume that by using the inductor at a moderately high temperature, slightly above the reported maximal temperature 125 ^{0}C, it will not fail.

However, as the estimation in the Arrhenius plot demonstrates, with a robust confidence interval in R, even if the inductor is used at 85 ^{0}C it will fail after 10 000 hours of continuous service, this is little more than one and half years. Moreover, most industrial applications are designed to work for least 10 to 20 years. Our next question will be, how does the percolation phenomenon affect a real application?

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

Today, semiconductors like GaN and SiC switching transistors with very short switching times and high maximum voltage capability get more interest from designers[12].

It is popular to find DC-DC applications performing with switching frequencies over 1 MHz, for example, in Power Supply on Chip (PwrSoC) aiming for higher efficiency with compact embedded designs for artificial intelligence applications[13][14]. All of these show a trend in maximum power demand, high-frequency voltage stress and inductor energy. However, many molded power inductors from well-known manufacturers will fail under these new operating conditions due to percolation phenomenon. To demonstrate the possible effects of percolation, a conventional buck converter (step-down converter) with Vin = 14V, Vout = 5 V @ 1.3 A, operating at 1020 kHz has been selected as presented in the following picture:

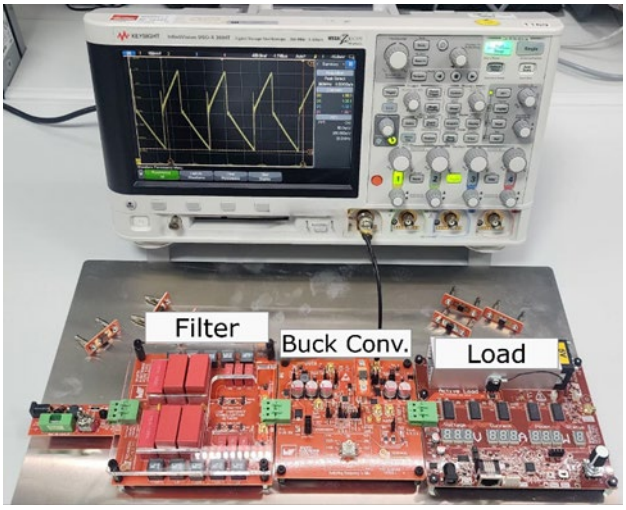


Figure 9: Buck DC-DC Converter to test impacts of percolation.

Among the switched-mode power supplies, the buck converter is certainly the most widely used topology[15]. A typical molded power inductor of 10 µH was selected. The demo board includes the possibility of interchanging the power inductor without affecting the setup by soldering and desoldering the power inductors, as can be seen in the figure below.

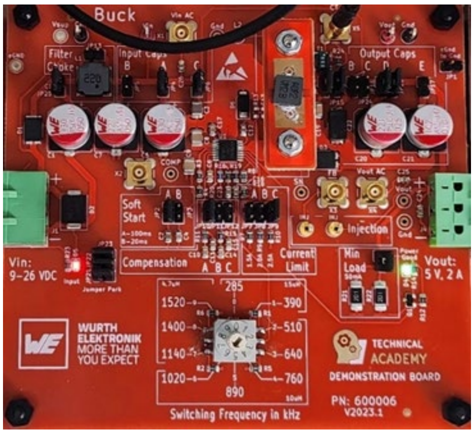


Figure 10: Buck Converter for the test.

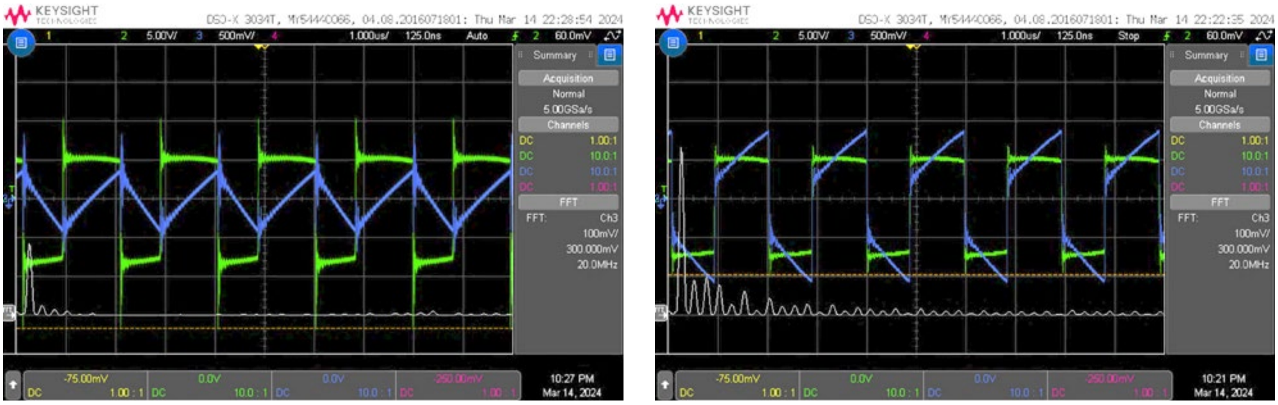
This property allowed us to test different samples affected by the percolation phenomenon in a short time. The level of percolation in the samples ranges from the early stages to the percolation threshold where the samples performance is closer to the conductive zone. Additionally, a line impedance stabilization network (LISN) demo board is employed to reduce influences of electromagnetic noise from the external power supply, although its use is not strictly necessary.

4.1 Measurements for different level of percolation in the example application

In this subsection, the results of different levels of percolation from the same lot number of molded power inductors are presented. The samples correspond to competitor-1 used in the test of the Figure 6

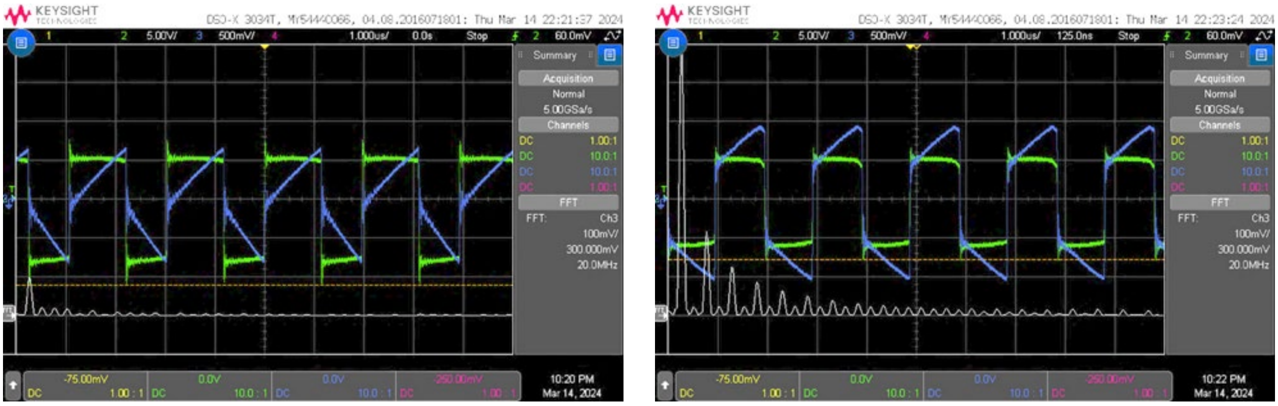
The oscilloscope screen captures of the ripple current for the different molded power inductors are presented in Figure 11. The voltage through the inductor is represented in blue, the ripple current in green and with gray the FFT of the waveform thought the inductor. What can be seen is that the shape of the ripple current has changed compared to the good part. The evolution of the change leads to very interesting findings. The first corresponds to the increase of the core material losses caused by the percolation phenomenon, equivalent to a resistor in parallel to the inductor, for the initial steps of the percolation, as already explained in our ANP126, and shown in Figure 12. However, when the percolation threshold is reached and is close to the conductive zone, as presented in Figure 11-d, the gradient of the ripple starts decreasing as well, and the parallel resistor model is no longer appropriate.

The second observation corresponds to the increase of the harmonics. The harmonics cannot be attributed to external noise sources, thanks to the filter used between the power source and the buck converter.



a. Current/voltage Inductor waveforms with no percolation.

c. High level of percolation phenomenon



b. Begin of percolation phenomenon.

d. Waveforms for the inductor closer to conductive zone.

Figure 11: Evidence impacts on the ripple current due to percolation.

Also, the typical switching overshoot evident in the Figure 11a can be ruled out as a cause. In fact, those effects start decreasing when the percolation phenomenon increases. The increase in harmonics is linked here to a considerable rise in DC offset. In terms of Fourier series, this corresponds to a step function, which is represented by an infinite number of harmonics. In this context, it is important to emphasize the overall distortion of the triangular waveform of the power inductor. This distortion impacts the ratio between the peak current and the output current of the converter. Consequently, the cycle-by-cycle current limit of the control IC is triggered at a lower output current than intended by the designer. Under certain conditions, this can coincide with the nominal current required by the application.

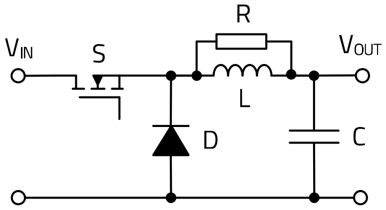


Figure 12: Illustration of the schematic resistor in parallel to the inductor[1]

This situation results in a drop in the output voltage. Ideally, the power IC detects this issue and shuts down. However, in the worst-case scenario, the application continues to operate with insufficient voltage, potentially leading to unintended conditions.

4.2 Percolation as efficiency killer in DC-DC Converter.

The cause of losses in a buck converter are well documented and straightforward, leading to buck converters with efficiencies higher than 95 %. The main losses are the switching losses, conduction losses, diode losses and in a lower proportion to the inductor core losses[16] [17].

Once a converter design has been defined, the developers focus on the ageing of capacitors and switching regulators as the main cause of failure in a real application.[18] [19].

However, our close relationship with clients has made it feasible to discover power inductor-related issues, when using some competitor components, in terms of reduced efficiency during the useful life of their applications.

To validate the level of influence in the example application, the increased input power demand has been measured and compared in terms of percentage of efficiency relative to levels of percolation. The results as illustrated in the following Figure 13.

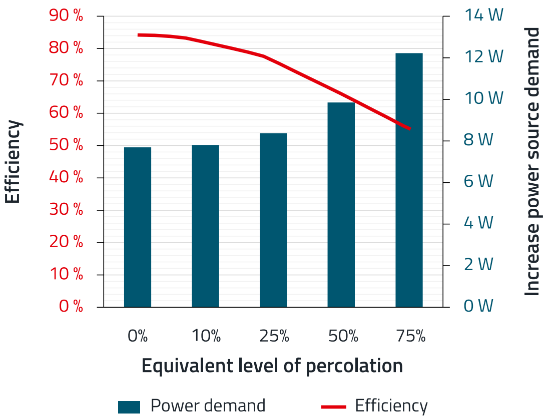


Figure 13: Efficiency decreases due to percolation of the molded power inductor.

It is observable how the efficiency of the buck converter decreases to low levels when the molded power inductor performs close to the conductive zone. It was not possible to measure values for higher level of percolation as the self-heating is faster, and the buck converter fails in few seconds.

In Figure 13, an efficiency of 85% is registered when there is a no percolation in the power inductor, with an input power demand of 7.6 W for a fixed load of 6.5 W. Initially, when percolation begins, the efficiency drop is less than 10%. However, once percolation reaches approximately 40%, the required input power increases to 10 W. Over time, the input power rises to 12.5 W in a strong percolation scenario of 75%, resulting in a 60% drop in efficiency from the original setup.

The initial drop in efficiency is primarily due to core losses. However, beyond the inductor core losses, the varying current wave shapes and increased AC ripple contribute to additional losses in the winding and semiconductors.

Furthermore, with a strong percolation level the correct operation of the feedback control loop in current mode systems may also be compromised. The DC-DC converter may become less stable, leading to oscillations or erratic behavior in the output voltage or current. Components such as capacitors, and semiconductors may experience higher stress, potentially reducing their lifespan, if the harmonics apparition are considered as well.

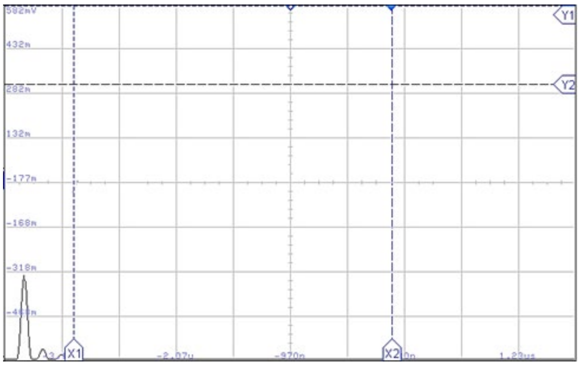
4.3 Percolation phenomenon from EMC point of view

The decreased efficiency in the example application is clearly related to the self-heating of the percolated molded power inductor resulting from increased core loss. It is important that a DC-DC converter operates as energy-efficiently as possible. However, an EMC behavior also deserves special attention, as a DC-DC converter should not interfere with other circuits in the environment from a EMC technical point of view[15].

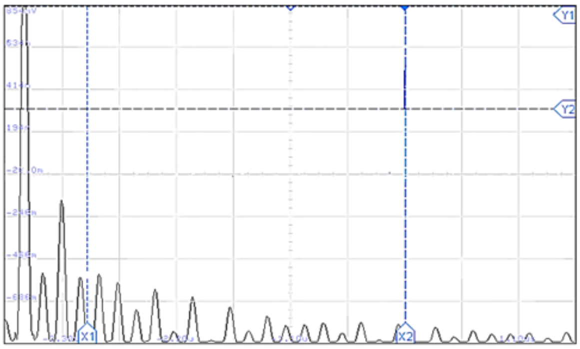
EMC test receivers are popularly used for electromagnetic interference (EMI) measurement in power electronics systems. Depending on the application, the EMI measurement could be very time consuming[20]. Pre-compliance can be inferred when using an oscilloscope with FFT capability.

It is very important to emphasize the significance of harmonics observed in the results, as they may create several EMC issues, both conducted and radiated.

The increase in core losses can be analyzed in the frequency domain, where it contributes to a spectrum consisting of harmonics [22], which is evident in our results. The FFT waveform obtained for a molded power inductor without percolation and the FFT waveform obtained for an affected one are presented in Figure 14.



a. Recorded FFT for initial set up without percolation.



b. Recorded FFT for a percolated molded power inductor.

Figure 14: Harmonic increase referred to the percolation phenomenon on the molded power inductor with a scale of 100 mV//div until 30 MHz

The graphs show clearly that the harmonics induced by a molded power inductor with percolation increase dramatically. These harmonics may lead to a slightly higher RMS current through the inductor, which will lead to higher losses on the Rdc.

However, there are two main concerns here in terms of performance of the overall design: will these harmonics, in terms of energy, be converted into heat and be dissipated, decreasing even more the efficiency of the converter? Will these harmonics be the source of EMI (Electromagnetic Interference) and transfer its undesired parts of interference currents to the load or will they create additional conducted and/or radiated emissions which can interfere with other areas of the device or even external devices, causing malfunctions?

There is no general answer to these questions as it depends on the application design itself, and the EMC measures included in the design. Still, you can contact us to evaluate your current design and answer any other doubts regarding the effects of molded power inductor degradation due to high voltage or temperature in your design.

5. SUMMARY

This application note introduced the percolation phenomenon in a Molded Inductor which refers to insulation material degradation when it transitions from an insulating to a conductive state, increasing the core losses due to higher eddy currents. This process starts after the exposure to high temperature or high voltage. It is distinctly measured as a critical decrease of Q Value at high frequencies; and it is evident from the change in the inductor ripple current, the increased harmonics, and consequently, the efficiency decreases when used in a DC converter over time.

It is clear from this paper that percolation influences the efficiency of the component, decreasing seriously the performance, and demonstrating that this should be a relevant factor to consider when selecting a power inductor.

And moreover, we have given a glimpse of the possible repercussions of percolation in terms of EMC compliance and the thermal management. All these directly affect the longevity and reliability of the device itself.

A APPENDIX

A.1 Literature

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