

APPLICATION NOTE

ANP047 | The Behavior of Electro-Magnetic Radiation of Power Inductors in Power Management

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01. INTRODUCTION

DC-DC converters are widely used in power management applications and the inductor is one of the key components (Figure 1).

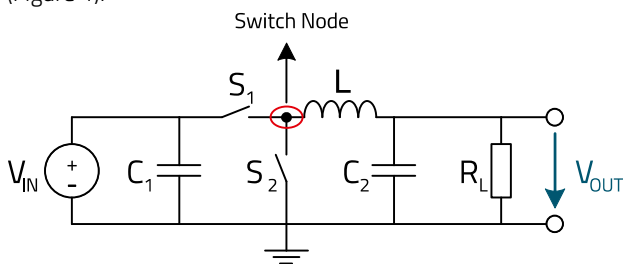


Figure 1: Typical DC-DC Converter.

The usual focus is on electrical performance characteristics such as R_{DC} , R_{AC} and core losses. But, the electro-magnetic radiation characteristics can often be overlooked. Power inductors in switch mode power supplies (SMPS) can be made of various core materials and different types of windings (coils). Inductors can also be classified into three types; unshielded, semi-shielded and shielded. Different types of inductor have advantageous and disadvantageous characteristics that permit or limit their range of application. Due to the switching action in SMPS, AC voltage/current is produced over the inductor. Since, an inductor can, in effect, operate as a transmitting loop antenna, the electromagnetic radiation depends on a number of factors. These include the source properties such as core material, shielding material and the orientation of the start of the winding amongst others.

Electromagnetic radiation of an inductor in the low frequency spectrum range (100 kHz to 30 MHz), which is caused by the switching frequency and harmonics, is dependent on whether the inductor is shielded and the winding properties. Whereas, in the high frequency spectrum range (30 MHz to 1 GHz), where emissions are caused by ringing frequencies and their harmonics, the electromagnetic radiation is more dependent on the shielding characteristics of the core material, switching frequency and transitions of the switching converter.

02. ELECTRO-MAGNETIC (EM) RADIATION

The inherent design and operation of inductor(s) in DC/DC converters leads to unfavorable attributes which are comparable to that of a loop antenna. The AC voltage and current in the inductor produces electric (E-field) and magnetic (H-field) fields which propagate away from the source at right angles to one another.

Near to the loop antenna (source), the characteristics of the fields (E and H) are determined by the behavior of the source characteristics (switching frequency, transitions). However, far from the source, the properties of the field are determined by the medium it propagates through. These separate yet interconnected phenomena can therefore be divided into two regions; the near-field and the far-field as shown in Figure 2.

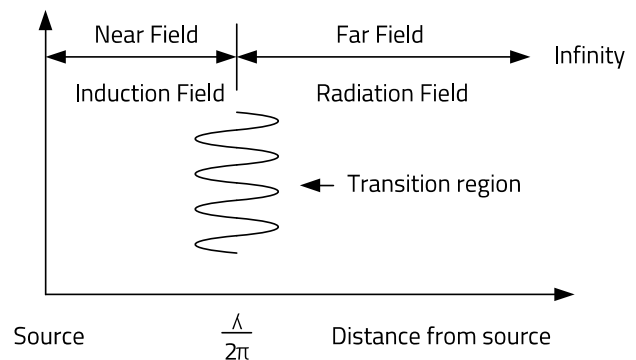


Figure 2: Near and far-field region(s) spread spectrum.

The area within $\lambda / 2\pi$ of the source is defined as the near-field whereas further than this is defined as far-field radiation.

In the near-field, the E and H-fields must be considered separately as the ratio between the two fields is not constant. The ratio E / H is also called wave impedance. However, in the far-field these fields combine to form a plane wave. Hence, individual electric (E) and magnetic (H) fields are only discussed in the context of near-field. If the source has high current and low voltage, the magnetic field is said to be dominant whereas if the source has low current and high voltage then the electric is said to be dominant.

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For a loop antenna, magnetic field near the source is high resulting in a low wave impedance near the antenna. As the distance from the source increases, the magnetic field declines simultaneously generating an electric field perpendicular to the direction of the H-field. The magnetic field attenuates at a rate of $(1/r)^3$ and the electric field attenuates at a rate of $(1/r)^2$ when moving away from the source where r is the distance.

For a straight wire antenna, the wave impedance is high, hence the electric field is dominant near the source and the attenuation characteristics are entirely opposite to that of loop antenna.

2.1 EM radiation behavior of Unshielded, Semi-Shielded and Shielded Inductors

As we have seen in the previous section 01, radiation from inductors in DC/DC converters is no triviality, especially when considering the type and proximity of surrounding components and their susceptibility to magnetic coupling. For further researches the test setup was used (see Figure 3). As engineers have become more mindful of this source of potential EMI, component manufactures have responded by offering ranges of inductors that are shielded and semi-shielded in addition to conventional unshielded inductors.

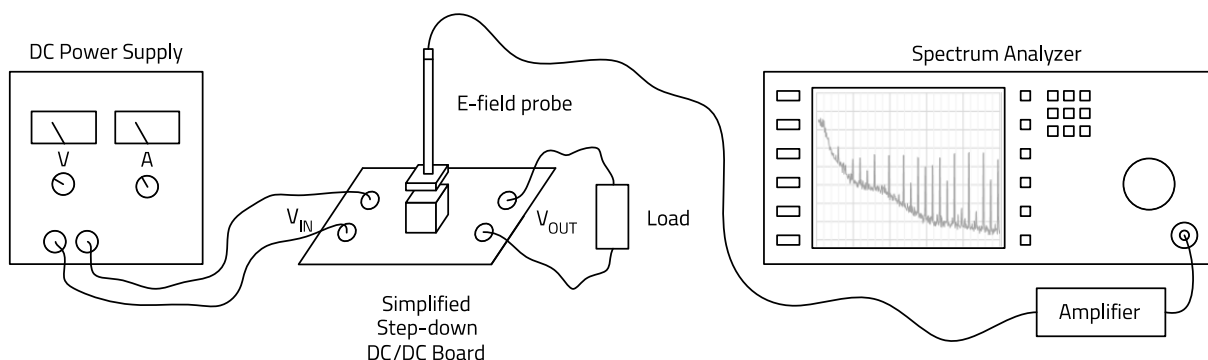
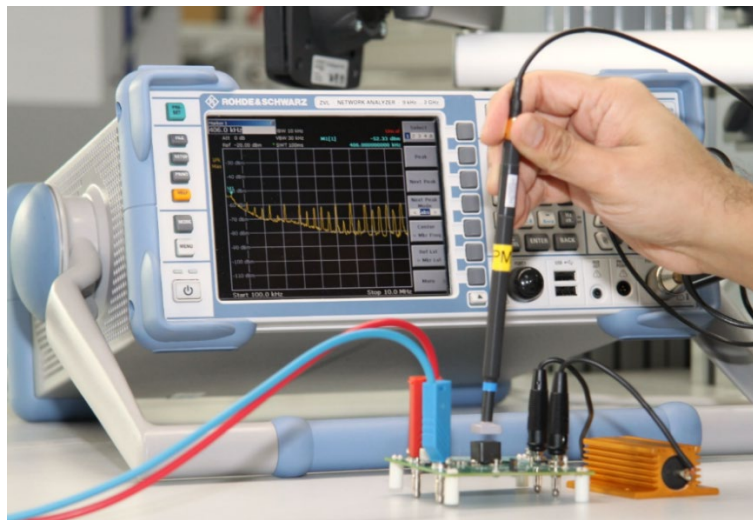


Figure 3: Test setup and block diagram.

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Shielded inductors are manufactured to fully encapsulate the coil in a form of magnetic shielding. With unshielded inductors, the coil windings are typically exposed or otherwise magnetically not shielded. These are generally the worst offenders from an EMI perspective due to the unhindered propagation of EM fields. In semi-shielded inductors magnetic materials are usually glued over the exposed windings with epoxy resin.

Each type of inductor has its own advantages and disadvantages. The main advantage of the shielded inductor is its relatively low emissions when compared to semi-shielded or shielded inductors (Figure 4).

But as most electrical engineers know, a fine balancing act must be maintained when a new design is in development. Increasing a desirable characteristic can often increase undesirable characteristics which are ultimately restrained by the overall project requirements. One of those restraints is unescapably size. Shielded inductors, when compared to the same Inductance value required of unshielded inductors and of the same dimensions, have lower DC-resistance and lower saturation. Naturally, this would direct the less experienced engineer to select an unshielded inductor which is smaller and has higher saturation current capability. But this will ultimately lead to a myriad of electromagnetic interference and compatibility issues which cannot be compromised.

Würth Elektronik is one of the few companies to offer semi-shielded inductors which walk the fine balancing line between space requirements, electrical characteristics and EMI. Semi-shielded inductors are particularly suited to applications where components close to the inductor are not severely sensitive to radiation. The excellent saturation characteristics of the **WE-LQS** semi shielded inductor size 8040 (**74404084100**) are presented in Figure 5 and compared with shielded inductor WE-PD size 7345 (**74477710**) and unshielded inductor WE-PD2 size 7850 (**74477510**).

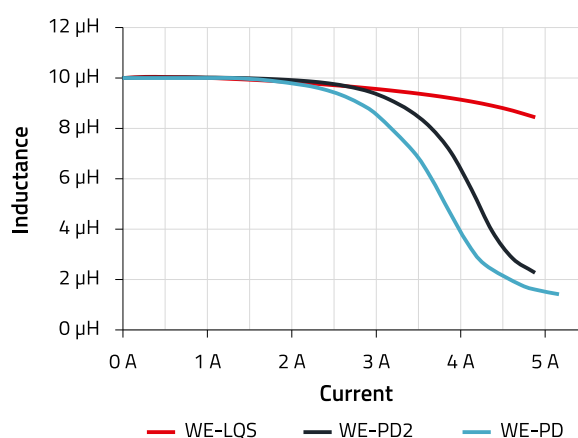


Figure 5: Saturation characteristics of shielded, semi-shielded and unshielded inductor.

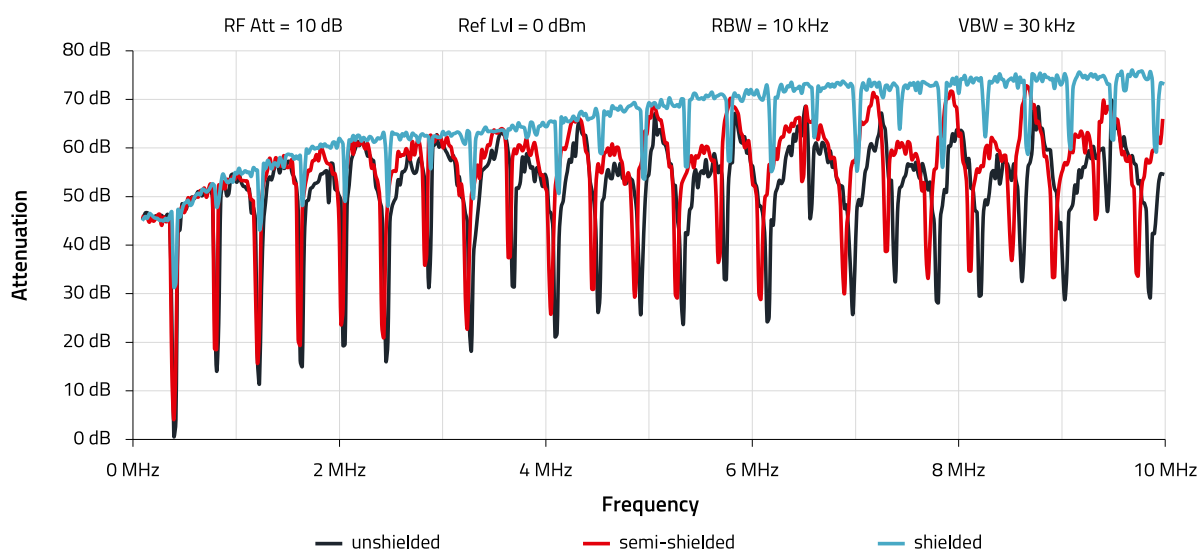


Figure 4: Magnetic radiation of unshielded, semi-shielded and shielded inductors.

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2.2 EM Radiation due to the Influence of Start of the Winding in an Inductor

One EMI consideration that can easily be overlooked is the orientation of the start of the coil winding. The 'dot' on the inductor package represents the start of winding (Figure 6).

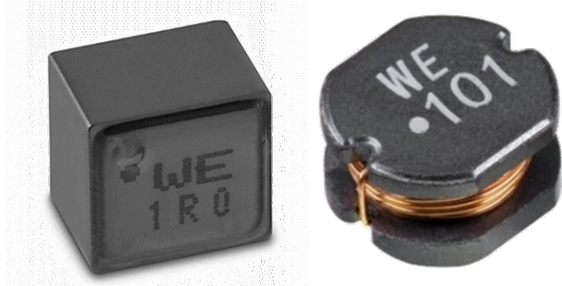


Figure 6: [WE-XHMI](#) and [WE-PD2](#) with the 'dot' identifying the location of the start of the winding.

It is important to connect the dotted end of the inductor closest to the switch node as this is the end that will undergo the most dV/dt and thus generate the most interference. In this way, the AC flux from switch node switching will be shielded by the outer windings.

If the non-dot end is connected to the switch node, AC flux voltages are present on the outside winding layer which can cause unacceptable levels of electric or capacitive coupling. Magnetically shielded inductors are effective at shielding H-field dominant radiation but may not be able to shield E-field dominant radiation in all conditions. Effective E-shielding depends on the material properties and complex permeability. The higher the thickness and permeability of the core material, the more effective the inductor will be at shielding the E-field.

As an example, the E-field emissions of a Würth Elektronik shielded inductor was measured with a WE-LHMI ([74437368022](#)). The transistor of the converter was operating at 400 kHz producing the fundamental resonance and subsequent harmonics. The spectrum clearly shows that emissions from the inductor are up to 8 dB lower when the dotted end of the inductor is connected to the switch node (Figure 7). It is, therefore, highly recommended to use the inductor in the correct orientation. The H-field emissions, however, are unaffected by the change of orientation of the inductor (Figure 8).

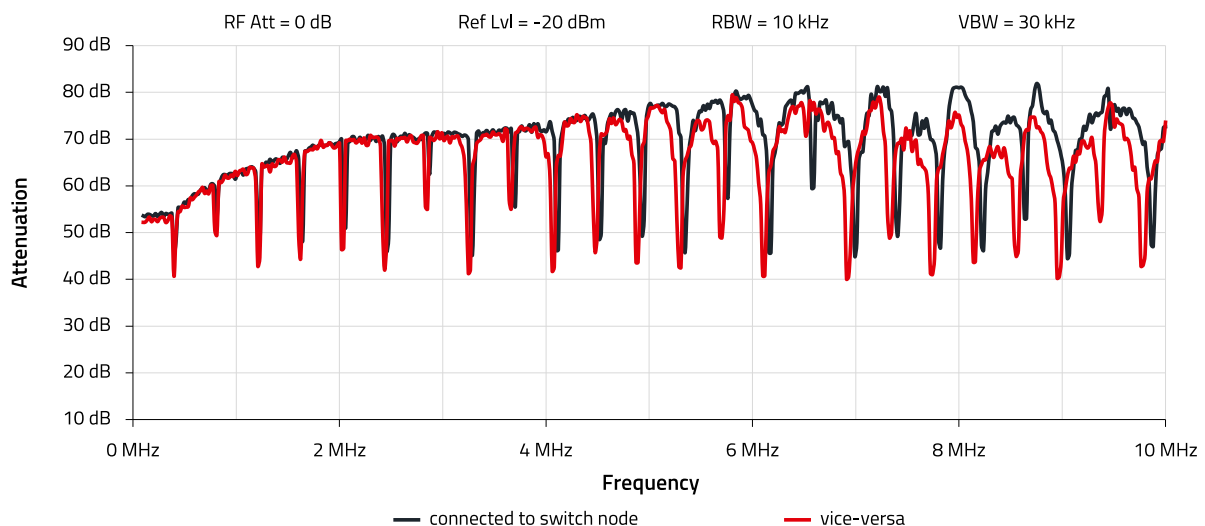


Figure 7: E-field of the inductor's start of winding connected to the switch node and vice-versa.

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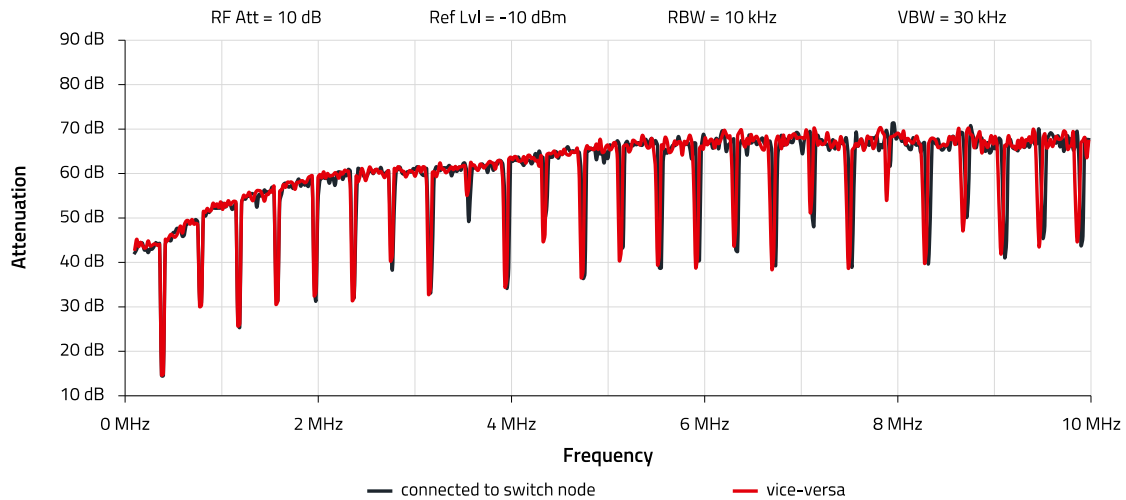


Figure 8: H-field of the inductor's start of winding connected to the switch node and vice-versa.

2.3 EM radiation due to the Influence of switching transitions

There cannot be electromagnetic interference if either the source, medium or the victim is not present. As switching frequencies increase, DC/DC converters also employ faster

rise and fall times of the switching device to keep switching losses low. But this creates steep switch-node transitions, accompanied by switch-node ringing and spikes (Figure 9). The resulting switch-node ringing and the inductor voltage waveform is shown in Figure 10.

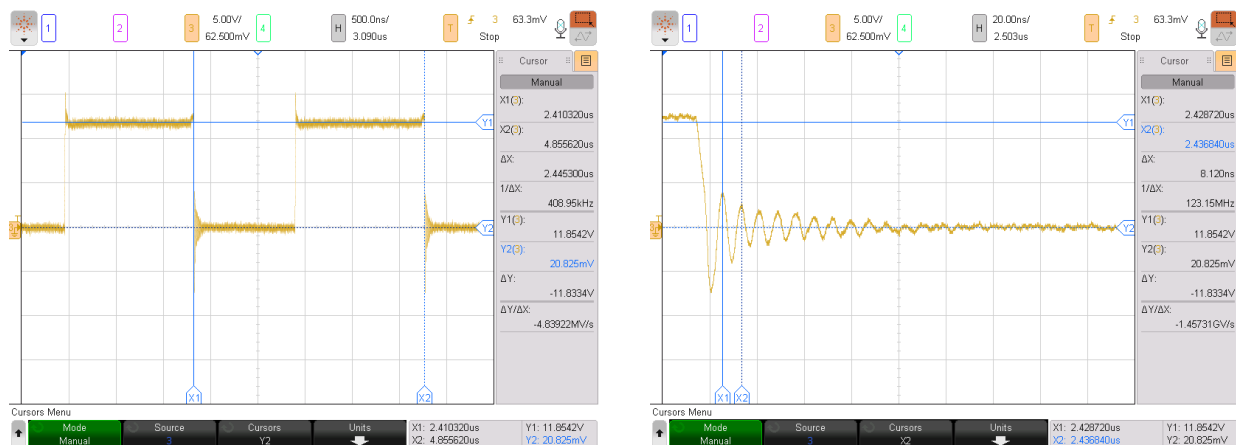


Figure 9: V_{DS} of Buck converter on the left and switch node ringing during turn on of S1 on the right.

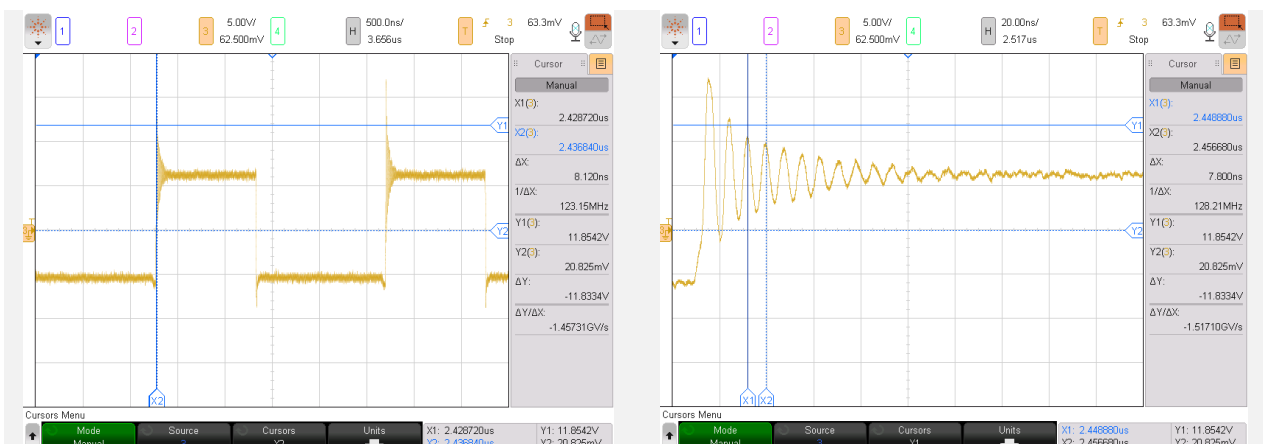


Figure 10: Voltage waveform over the storage inductor of buck converter on the left and resulting ringing on the inductor during turn on of S1 on the right. Note: Input: 12 V, Output: 5 V, 5 A, Switching Frequency: 400 kHz, Ringing Frequency: 128 MHz.

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Because of switch node ringing, fast transitions and high switching frequency, it is necessary to choose an appropriate inductor for achieving electromagnetic compatibility. Typically, the ringing frequency is in the 100 to 200 MHz range. The effectiveness of attenuating emissions at these frequencies very much depends on the inductors properties, most notably, the core material (Figure 11) and thickness.

Usually, iron powder and metal alloy powder inductors have less E-field shielding effectiveness at frequencies above 1 MHz. Here MnZn and NiZn have better performance at higher switching frequencies.

The effect on the radiation of H and E-fields when changing the core material may be seen below (Figure 12 and Figure 13).

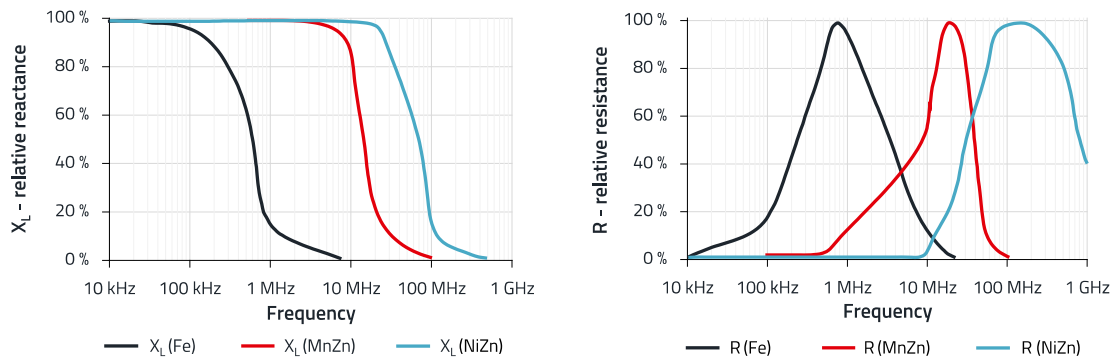


Figure 11: Resistive and inductive characteristics of widely used core materials- Iron powder, MnZn and NiZn.

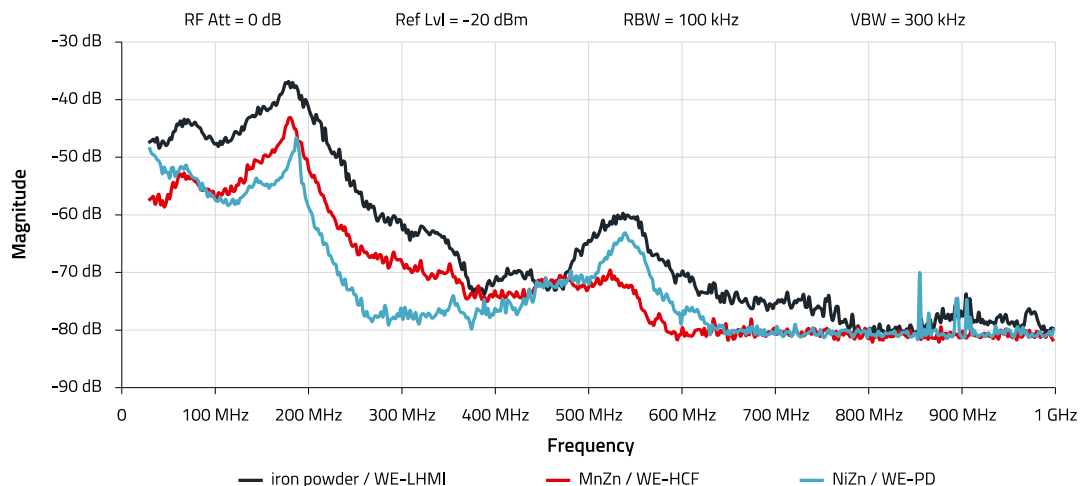


Figure 12: H-field comparison of iron powder (WE-LHMI), MnZn (WE-HCF) and NiZn (WE-PD) core material.

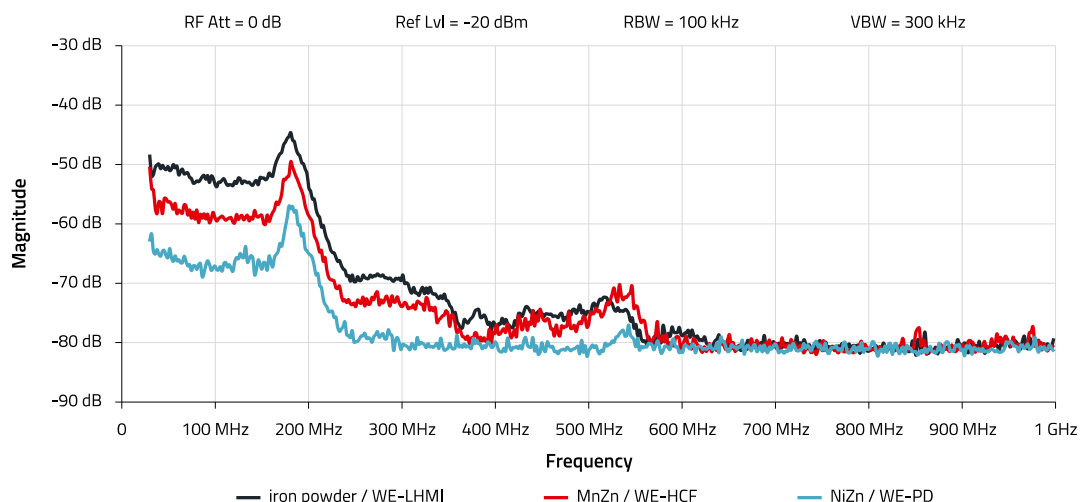


Figure 13: E-field comparison of iron powder (WE-LHMI), MnZn (WE-HCF) and NiZn (WE-PD) core material.

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The DC-DC converter used for the testing is switching at 400 kHz and ringing frequency on the switch node is about 180 MHz. As demonstrated, an inductor with a NiZn core (WE-PD [7447714022](#)) is much more successful at limiting H- and E-field radiation at higher switching frequencies than an Inductor with MnZn core ([7443630220](#)).

03. SHIELDING

Every core material has inherent advantages and disadvantages which are particularly suited to a specific application. In these circumstances where a core **WE-HCF** material cannot be substituted, external solutions may be necessary to mitigate emissions. For example, inductors made of iron powder/metal alloy core material have excellent saturation characteristics and can be made in extremely small sizes but have limited shielding characteristics at frequencies above 1 MHz. Hence, to shield the emissions caused by the ringing frequency caused by a fast switching transition time, external shielding may be required to ensure electromagnetic compatibility. Metal and magnetic shielding solutions can be optimized based on the application.

Metal shielding materials are made of copper, aluminum, metal alloys and composite mixtures. Metal shielding usually consists of an enclosure that is attached over the source to reflect or absorb the noise. The thickness and type of material can be chosen based upon shielding effectiveness, frequency (Figure 14) and cost.

Interestingly, some iron powder inductor manufacturers are integrating a metal bridge on the top of the inductor to improve shielding performance. However, this approach is less advantageous as it may first appear as these inductors are not as flexible to design and emission requirements as they have a limited effect at a constrained range of switching frequencies and fixed source properties.

Alternatively, magnetic shielding can be achieved using magnetic materials or μ -metals and their effectiveness are dependent on material permeability, impedance and thickness. The material characteristics are similar to those shown in Figure 10.

3.1 Effect of Shielding in the near-field

As mentioned earlier, the switch node ringing frequency on one demo-board is ≈ 130 MHz and on the other demo-board it is ≈ 180 MHz. Since the advantages of iron powder and metal alloy inductors cannot be compromised most of the time, Würth Elektronik offers a huge variety of metal and μ -metal shielding materials such as copper tape, various composite metal shielding cabinets with and without vents, NiZn and ferrite plates, etc. These products offer flexible and adaptable solutions that are suitable for specific design restraints and can be selected for the particular range of frequencies where attenuation is required (Figure 14).

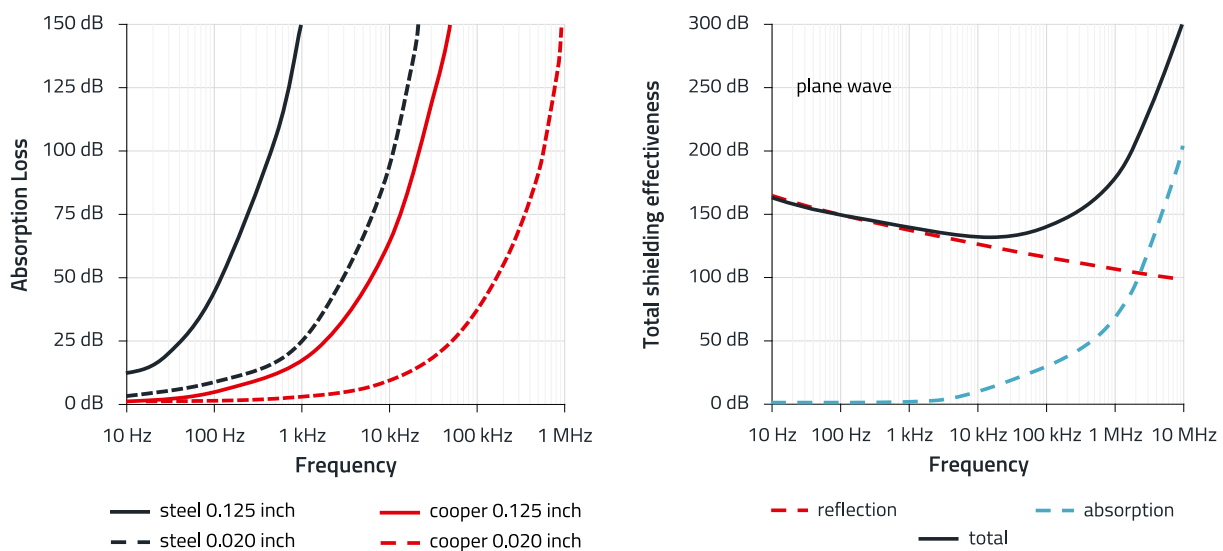


Figure 14: Absorption and reflection characteristics of metal shielding.

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For example, the effectiveness of metal shielding of a Würth Elektronik **WE-LHMI** iron powder inductor is demonstrated by the H-field comparison in Figure 15 and a 10 dB reduction in E-field emissions in Figure 16.

3.2 Effect of Shielding in the far-field

The effectiveness of shielding is not only limited to near field radiation. Notable reductions in far-field emissions can also be achieved using metal and ferrite solutions. The same demo-board was tested in the EMI chamber for far-field radiation.

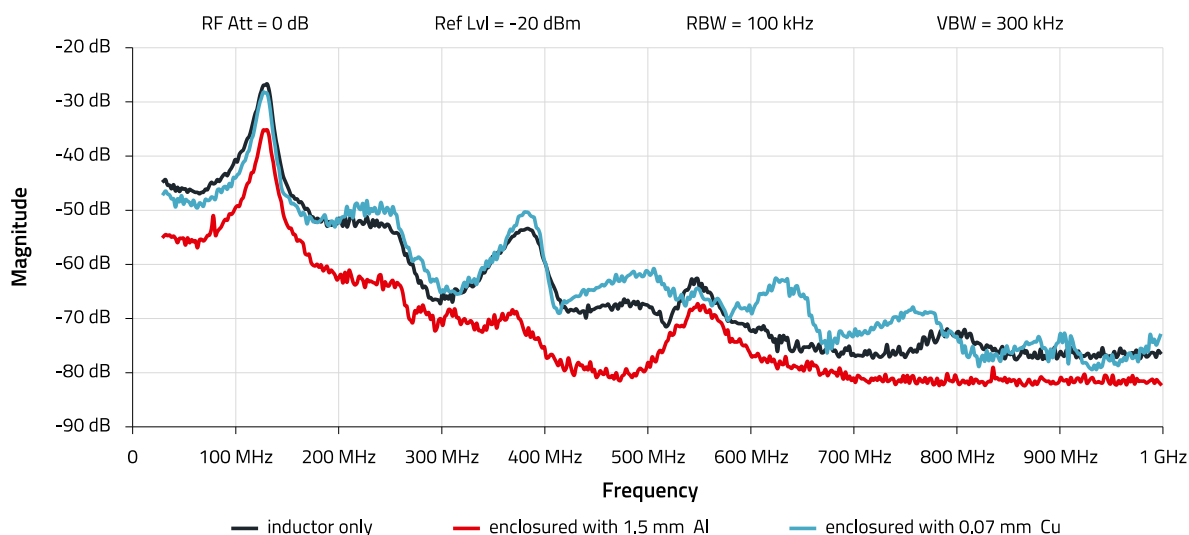


Figure 15: H-field comparison of iron powder (**WE-LHMI**) without additional shielding, with 1.5 mm Aluminum enclosure and with 0.07 mm copper tape.

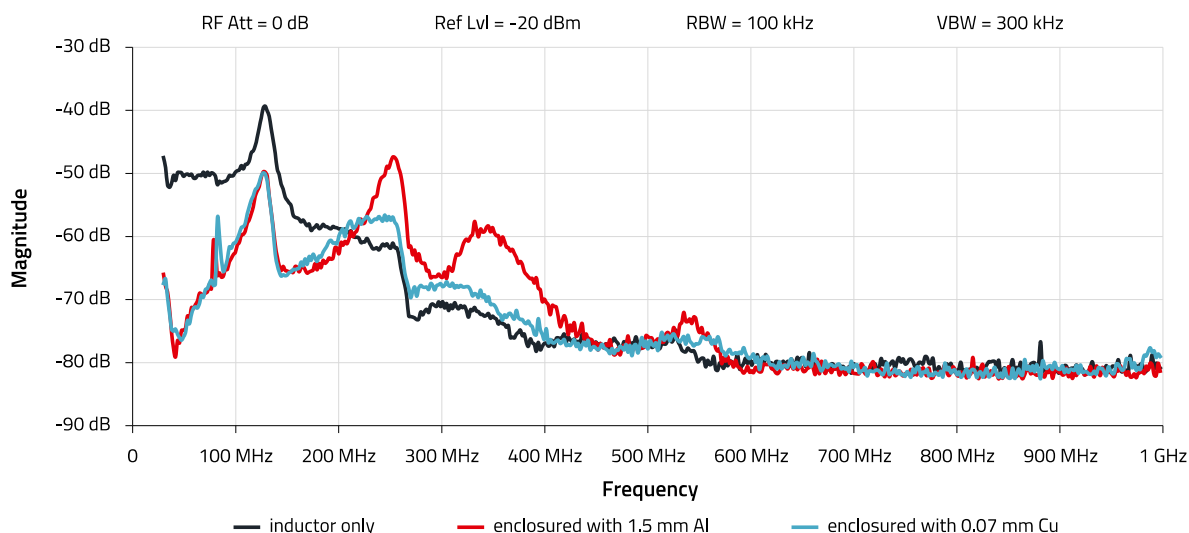


Figure 16: E-field comparison of iron powder (**WE-LHMI**) without additional shielding, with 1.5 mm Aluminum enclosure and with 0.07 mm copper tape.

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The value of enclosing an iron powder core inductor with a 1.5 mm thick aluminum shield is demonstrated below (Figure 17 and Figure 18) where the ringing frequency has been substantially reduced. In addition, attenuation was also notable over the whole frequency range including harmonics. Similarly, the addition of adding a 3 mm thick ferrite plate has a similar effect when placed on the iron powder inductor (Figure 19).

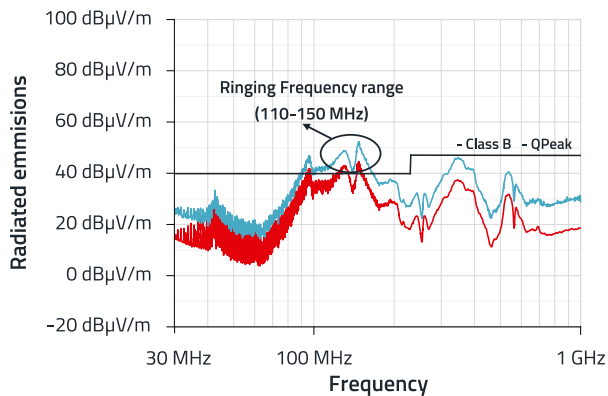


Figure 17: Far-field electro-magnetic radiation of the system, where the iron powder inductor is part of it.

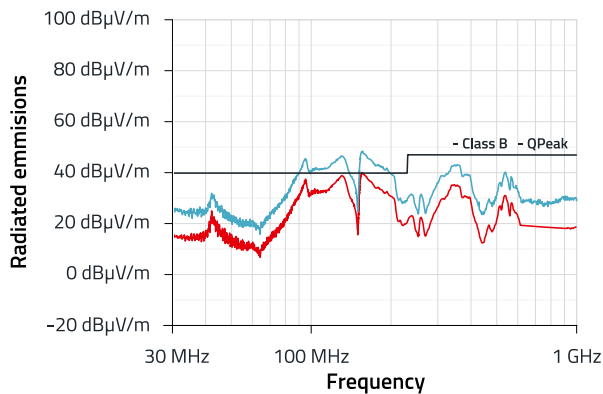


Figure 18: Far-field testing of the system with Aluminum enclosure on the inductor.

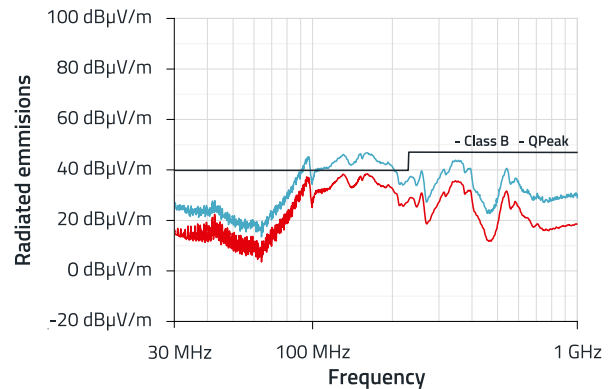


Figure 19: Far-field testing of the system with 3 mm ferrite plate on the top of the inductor.

04. SUMMARY

EM radiation is an incredibly vast and intricate topic as seemingly small variations in any one parameter can influence emission sources and therefore the near-field and far-field characteristics. The characterization of the near-field can be a complicated and lengthy process because of the necessity of many experiments and observations to fully comprehend and resolve EMI issues. Additionally, the move towards high switching frequencies for higher power densities and better efficiency, as the availability of new technologies in Mosfets becomes readily available (GaN, SiC), further necessitates consideration and control of emissions. When switching at higher frequencies the usual approach for power magnetics is no longer valid. Würth Elektronik completely understands the necessity to address and is fully prepared to support with issues that arise due to changing technologies, designs and parameters. Designing one specific inductor which is valid for only few conditions is not the WE way. A small change in the switching device can affect the source characteristics of the inductor dramatically. Specific components for a specific design for a specific application is required. For this reason, WE offers a wide variety of products together with unparalleled levels of support and technical assistance to ensure your device meets EMI standards.

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A Appendix

A.1 BOM

Description	Size	Value	Order Code
WE-PD SMD Shielded Power Inductor	7345	L: 10 μ H, I _R : 2 A, R _{DC} : 45 m Ω (typ)	74477710
WE-LQS SMD Power Inductor	8040	L: 10 μ H, I _R : 3.3 A, R _{DC} : 29 m Ω (typ)	74404084100
WE-PD2 SMD Power Inductor	7850	L: 10 μ H, I _R : 2.3 A, R _{DC} : 45 m Ω (typ)	74477510
WE-PD SMD Shielded Power Inductor	1050	L: 2.2 μ H, I _R : 8.6 A, R _{DC} : 6.8 m Ω (typ)	7447714022
WE-HCF SMD High Current Inductor	2013	L: 2.2 μ H, I _R : 28 A, R _{DC} : 1.5 m Ω (typ)	7443630220

A.2 References

- [1] Electromagnetic Compatibility Engineering by Henry W. OTT
- [2] <http://www.we-online.com/app-notes>

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