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3D FEA Software Solves Tough Inductive Noise Problems

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A previous article on 3D electromagnetic finite element analysis (FEA) software explained how a new generation of these tools, which includes EMS from EMworks, can be used for optimization of high-frequency transformer design (see the reference.) In this article, I would like to show how the same software can help to solve difficult layout problems in electronics, especially power electronics.

Switched-mode power supplies are notorious for hard-to-eliminate noise problems simply because we cannot completely avoid proximity of high-power switching circuits and sensitive controls. Good engineering practices such as minimizing high-frequency current loops and voltage surfaces, perpendicular arrangement of potential source-target sets and using large copper planes for shielding are naturally a must. But without any way of quantifying problematic phenomena it is impossible to know if we are pushing our luck and if we did the best we could within the given constraints. In the end, we have to make a choice between unnecessarily conservative designs and risking costly, time consuming (and stressful!) fixing of prototypes.

However, dangerous noise can be reduced and many layout re-spins avoided if we model potential trouble spots with FEA software. In most cases it is necessary to use 3D modeling as practical geometries are not reducible to 2D-type problems. The latest-generation electromagnetic FEA software such as EMS from EMWorks, which was used to generate the examples for this article, combines modeling power and simplicity to the point where the tools can be used for low-noise design.

The most-important classes of difficult noise problems that can be modeled and minimized with 3D FEA are:

1. inductive coupling from a high-current loop into a low-voltage control circuit,
2. inductive coupling from a high-power current loop into EMI chokes (these chokes can "pick up" magnetic field and inject the noise, instead of attenuating it!),
3. capacitive coupling from high dv/dt areas into a low-voltage control circuit,
4. capacitive coupling of the noise via parasitic capacitance of the transformers and chokes,
5. parasitic inductance and resistance of the layout in high di/dt circuits (gate drivers, MOSFETs, current sensors, decoupling capacitors, etc.), and
6. ground-potential bouncing.

Of the two main noise mechanisms present in switched-mode power supplies, the magnetic type is the more difficult to predict. Here, designers rely mostly on engineering intuition or simple formulas because of complex but less immediately apparent 3D patterns of current loops and partially open shielding.

The basic mechanism can be described by Ampere's and Faraday's laws, see Fig. 1.

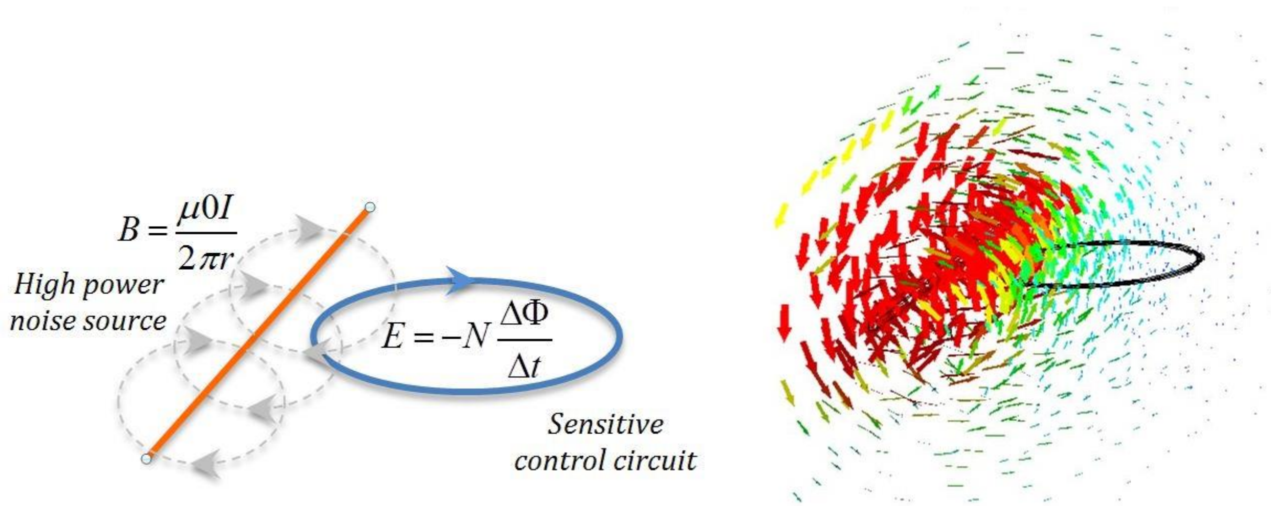

Fig. 1. Inductive noise as per Ampere's and Faraday's laws (shown on left) and simulated flux density (shown on right).

It is worthwhile to notice some immediate consequences of these relationships: noise coupling improves with the frequency and all spectral components are shifted by 90 degrees. As a result, rectangular pulses at the noise source are converted into "spikes" at the receiving end as shown in Fig. 2.

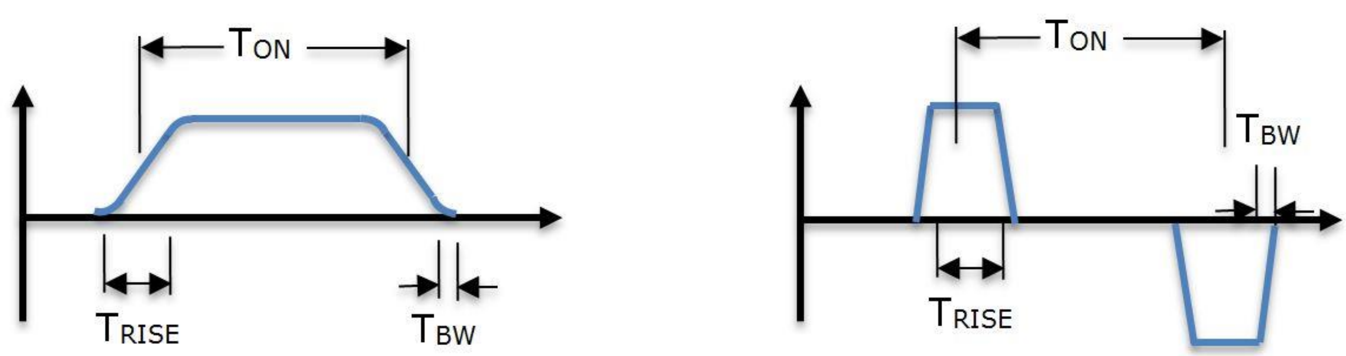

Fig. 2. Timing relationships between the source of the noise and the target.

The rise time of the noise source corresponds to the width of the spike and higher-order bandwidth limitations determine the sloping of the induced noise. A trapezoidal noise shape will occur with the receiving loop terminated with the dominant resistance. But in real circuits there are always some explicit or parasitic capacitances and inductances that change the shape of the received signal to a more "spike-like" shape. With the noise analysis, however, we are not interested in the exact shape of the received noise, just the magnitude.

It is useful to take a look at the spectral characteristics of the signals as shown in Fig. 3.

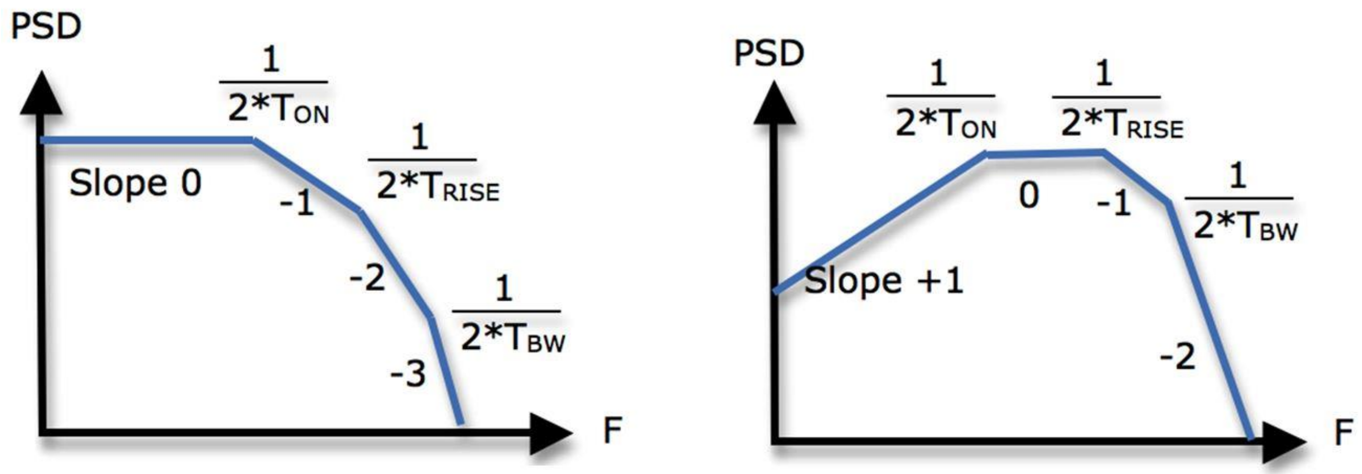

Fig. 3. Spectral characteristics of a noise source and induced voltage at the noise receiver.

The flat spectral density between $1/2T_{ON}$ and $1/2T_{RISE}$ has a very important practical implication. It means that *we can comfortably run an ac magnetic analysis at a single frequency and extrapolate the amplitude results to the whole pulse.*

With a very simple geometry like the one shown in Fig. 1, an analytical solution for the noise injected into the control circuit would be possible. But with any realistic 3D arrangement, FEA software is the only way to obtain a solution.

It is still worthwhile to keep in mind the principles of Ampere's and Faraday's laws as they improve our ability to prepare simple but accurate models, help to grasp the meaning of the results and then optimize the design. If that sounds like a more-intuitive approach, it is not one that is at odds with performing finite element analysis. FEA is very useful for developing correct intuition regarding magnetic and electric fields and the associated design choices.

Up until this point our discussion about noise has been rather abstract. We have not said anything about the type of noise levels we might experience in real applications. So, just how much of a noise problem are we talking about? That will depend on a number of circuit and operating conditions.

Let's take a look at some simulation results from five different case studies. In each of these examples, we have the following conditions:

- noise source: I = 10 A, T_{RISE} = 25 ns, loop = 25 mm x 1 mm,
- noise target: loop = 16 mm x 0.75 mm,
- shield = 0.2 mm under the loops,
- distance between loops = 6 mm (except 1.2 mm in case 2).

Figs. 4 through 8 depict the configurations used in the five cases. TO-220 and SO-8 packages are included in the drawings to show scale.

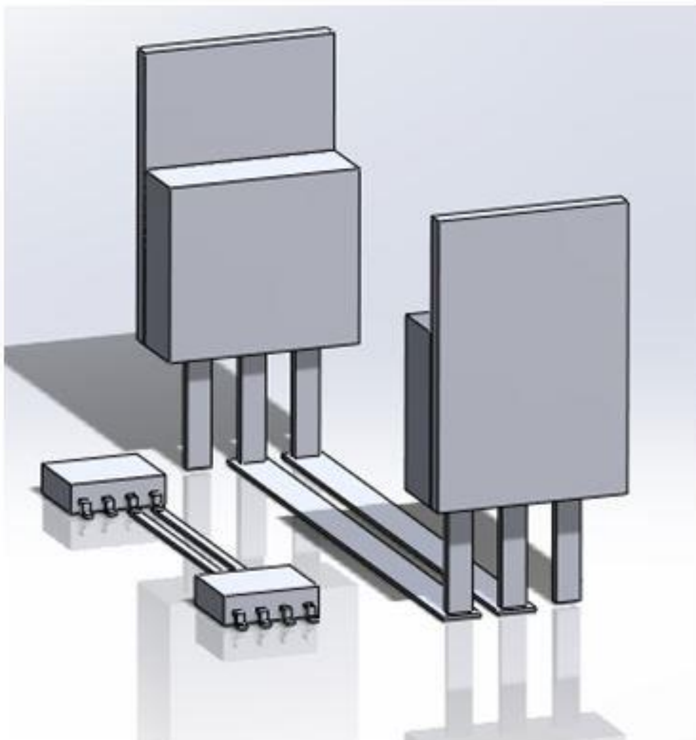

Fig. 4. Case 1: Parallel loops with no ground plane. Induced noise = 70 mV. In this case, the parallel orientation facilitates strong coupling. If this arrangement is unavoidable, it should be accompanied by good shielding.

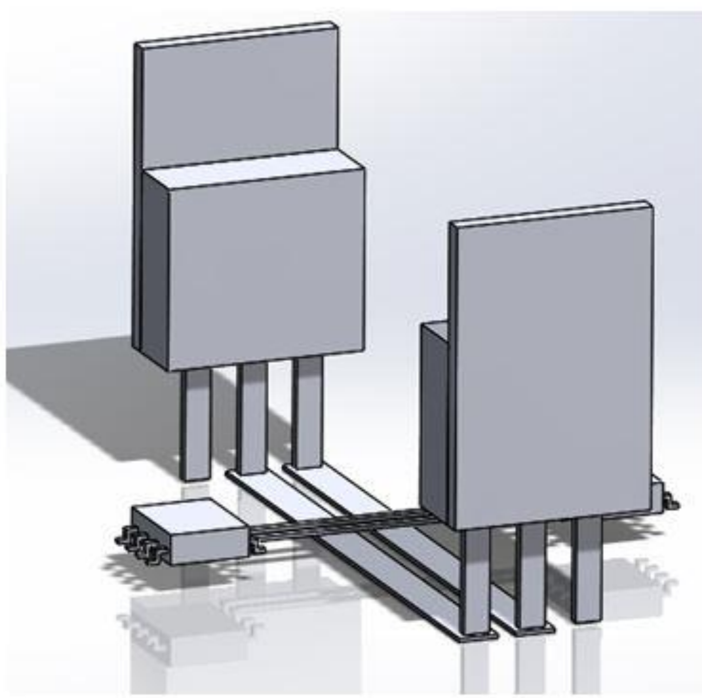

Fig. 5. Case 2: Perpendicular loops with 1.2 mm of separation (1.2 mm = board thickness). Induced noise = 50 mV. As the results illustrate, a perpendicular orientation is better, but with the separation reduced to the board thickness, the net improvement is only 3 dB.

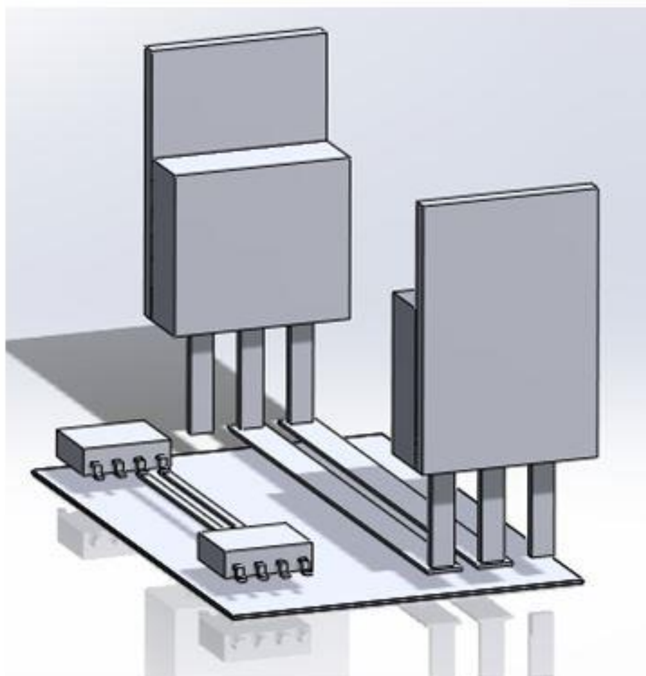

Fig. 6. Case 3: Parallel loops with the ground plane shield. Induced noise = 11 mV, (-19 dB) for a shield on the opposite side of the board (1.2-mm distance). The shields work similarly under both loops, and their effects are cumulative, so both should be used if possible. The shields should be thick, especially for devices with lower di/dt. A 1-oz. ground plane is effective for switching harmonics above 1 MHz, while 6-oz works down to 25 kHz.

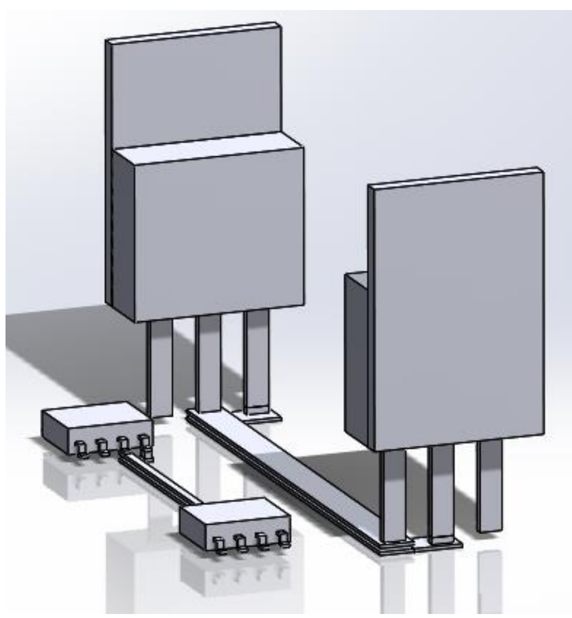

Fig. 7. Case 4: Loops with return path directly beneath the forward path. Induced noise = 9 mV, (-21 dB). A two-layer arrangement allows us to reduce the effective loop area while keeping good voltage isolation. It also helps with the skin effect, reducing the effective resistance of the traces. Adding a horizontal ground plane underneath the whole structure yields little further improvement because of the direction of the magnetic field—a vertical shield would work better.

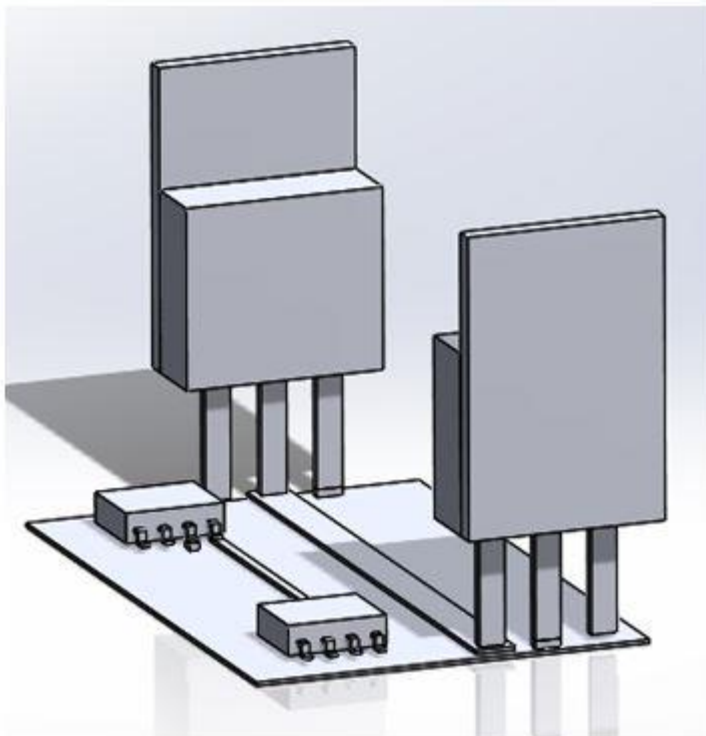

Fig. 8. Case 5: Common ground plane as a return path and a shield. Induced noise = 20 mV (-11 dB). This is frequently the most practical arrangement but moderately effective. It also injects the noise into the ground plane. On the other hand, if the ground plane is used as a shield only (without a direct conductive path like in Case 3) the noise from the eddy current is also present in the ground plane. A shield under two-layer arrangement (Case 4) results in the least noise in the ground.

It is important to keep in mind that due to the complexity of practical systems we are not looking for exact results. What we really want to achieve is to assign the noise situation to one of three main categories:

A. Absolutely no problem, forget about the noise.

B. A potential problem, try to improve without major redesign, pay special attention during prototype testing.

C. Big problem, redesign radically or be prepared for a severe noise problem.

A practical methodology for modeling inductively coupled noise in power electronics may look as follows.

Step 1. Simplify the problem to one pairing of noise source and noise target.

Theoretically it is possible to simulate the whole thing at once but it would require a supercomputer. With predominantly linear relationships, weak coupling and negligible feedback loops, a "pair by pair" analysis should not lead to any significant error. Geometrical information can be transferred via a dxf file and simple extrusion. Simplification can be done either in layout software or in SolidWorks.

It makes sense to purge the model of everything not important for the coupling between the two main loops. Later, some details can be added back for more-refined checking in a borderline case. Pay attention to the ground arrangement as it may play an important role. It is useful to check the coupling with no shielding surfaces first to establish a starting point.

Step 2. Set both source and target loops as voltage-driven coils.

The noise source coil should have a voltage set at the level that generates a current approximately equal to that in the actual circuit. The exact value of the current during simulation is not critical as we are looking for a degree of coupling. However, a level similar to the one present in an actual circuit helps us to intuitively grasp the results immediately.

The receiving coil should have a voltage amplitude set to zero as it serves only to measure the induced voltage. The internal impedance of the transmitting coil should be set to zero. Meanwhile, the internal impedance of the receiving coil should be set as resistive and to a value several times higher than the impedance of the self inductance of the receiving loop. The exact value is not important as it is used only to capture the full value of the induced voltage without the mitigating impact of the induced current.

Step 3. Run the analysis at a frequency equal to ½T_{ON} and an amplitude of I_{SOURCE}.

One analysis should be a sufficiently good proxy for the whole pulse. Current induced in the receiving loop multiplied by the coil voltage source resistance represents the voltage noise amplitude.

Multiply the result by the number of odd harmonics from $1/2*T_{ON}$ to $1/2*T_{RISE}$ to obtain the amplitude of the whole induced noise spike (all harmonics combined.)

Step 4. Check the attenuation of the receiving loop.

The noise amplitude obtained in step 3 represents the voltage induced in the receiving loop. In many cases the impedances present will attenuate this noise, especially the high-frequency components. On the other hand the resonance may amplify some frequencies. Standard circuit analysis has to be used to include the impact of these factors.

Step 5. Consider the impact of the ground planes and shields.

The method presented above assumes that there are no shields covering the loops (source and/or target.) If the shields are present we have to remember several additional factors:

- Accurate simulation may require a finer mesh, usually with a fine mesh air box around the receiving loop.
- Geometry has to be simplified as much as possible, especially for the loops separated by a large distance.
- Incomplete shields with constrained induced currents change the direction of the magnetic field, which may have unexpected influence on the noise (even to the point of making it worse in some rare cases).

Shields are ineffective below a certain minimum frequency. This frequency is equal to the frequency at which the skin depth is equal to twice the thickness of the shield, let's call it F_{skin}. This will change the spectral characteristic at the receiving end, which may look like that shown in Fig. 9.

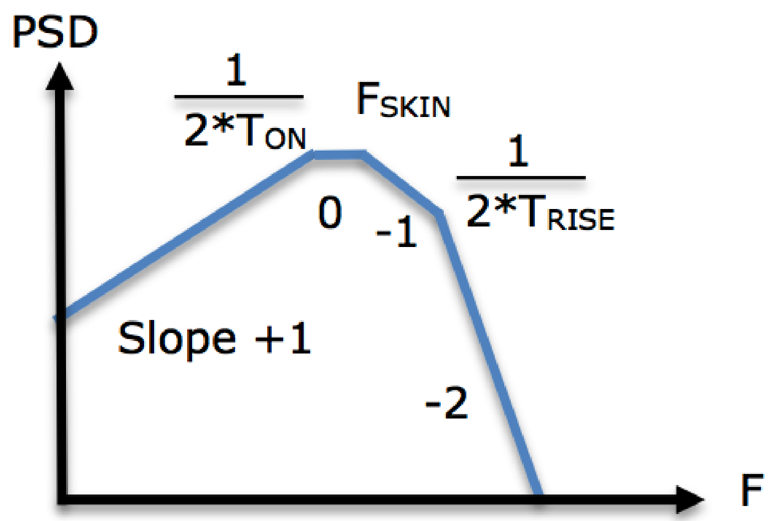

Fig. 9. Power spectral density on the receiving side when a highly effective shield is present.

Now, with the shield, most of the energy will be coupled in the frequency range between $1/2*T_{ON}$ and F_{SKIN}. We can still run the simulation at $1/2*T_{ON}$ but the result should be corrected to reflect that spectral components above F_{SKIN} are suppressed. In the first approximation we can assume that the noise amplitude reduction is proportional to the ratio of the number of harmonics below F_{SKIN} to the number of harmonics between $1/2*T_{ON}$ and $1/2*T_{RISE}$.

For frequencies below F_{SKIN} the shield is simply too thin for eddy currents to develop freely, which is necessary to cancel an external field. One look at the induced eddy current patterns can tell us if the shield is effective at a given frequency (see Figs. 10 and 11.) The impact of the geometrical arrangement can also be viewed with a current density plot but usually it is difficult to interpret and it is better to rely on the induced voltage.

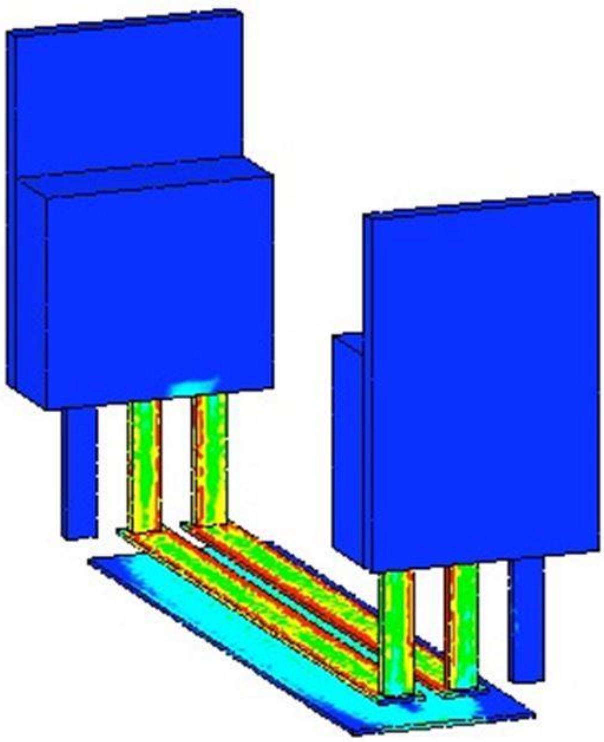

Fig. 10. Current density plot from 3D FEA simulation indicates shield effectiveness as it depends on the skin depth and the distance from the loop for Case 3. The visibly lower magnitude of the current induced in the shield suggests reduced effectiveness and higher noise. A similar picture will be obtained with a shield that is too thin.

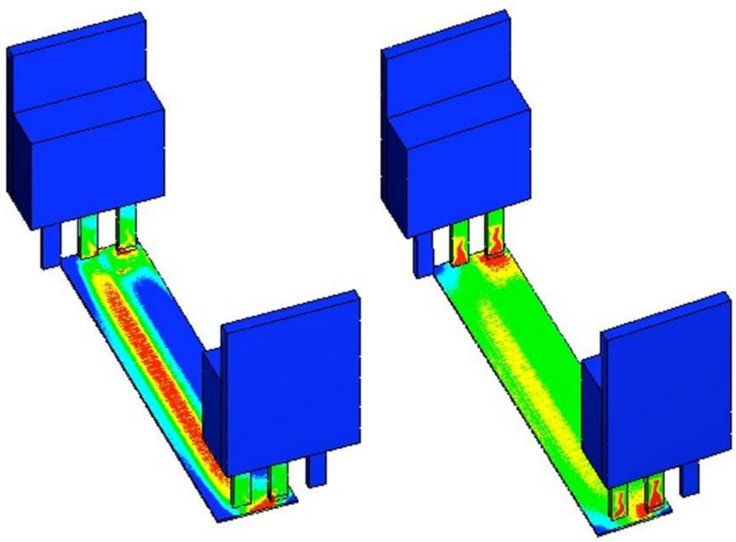

Fig. 11. Return current in the ground simulated for Case 5. In the result shown on the left, the ground thickness is sufficient, which allows eddy currents to form the return path directly under the forward path, creating good shielding and minimum noise. Meanwhile, in the result shown on the right, the ground plane is too thin so that current flows widely with reduced attenuation of the magnetic field (the forward path trace has been removed for a good view of the shield.)

In practical layout geometries, shields never cover the loops perfectly. There are always some "openings" that let some portion of noise through. In this case, we may overestimate the effectiveness of the shield and get a nasty surprise later.

This is where 3D FEA simulation is the real savior as applying intuition or simple calculations with partial shielding is impossible. For accurate results it is necessary to obtain more-accurate spectral density by running simulations at several frequencies and extrapolating the results across the frequency range of interest. Combining spectral components will complete the investigation.

Step 6. Set mesh size in proportion to the skin depth and receiving loop dimensions.

Mesh in the conductor. Theoretically, for the most-accurate results it is necessary to run the simulation with the mesh size substantially smaller than the skin depth, otherwise electromagnetic fields are polluted with noise-like, apparently random components (this phenomenon appears to be similar to images created by the sampling frequency below Nyquist, known from digital signal processing). The problem is that with the structures, which are large compared with the skin depth, we may be forced to simulate the system with a very large number of elements and a long simulation time. In the noise-coupling investigation, however, the error introduced by a larger mesh is usually acceptable, typically within 15% to 30%, as random components tend to cancel each other.

To minimize the "eddy noise" it is good to:

- Make the mesh finer only in the area of the loops.
- Make the finest mesh in the receiving loop.
- Keep the mesh in the receiving loop significantly smaller than the "width" of the loop.
- Avoid simulations where the net-coupled current is very small compared with the eddy.
- Repeat the simulation with a slightly different mesh to check, the result should be similar.

Mesh in the air. Because the noise is coupled through the air, the air mesh is more important than in many other simulations. The air mesh has to be fine near the loops, especially the receiving loop. Usually one half of the smallest dimension of the loop should be OK and it should grow only gradually with increasing distance. A separate air box for the receiving loop is usually the best approach.

It is also important to make sure that the simulation converges on a reasonable result. On rare occasions, with a particular combination of conditions, a coarse mesh leads to a significantly erroneous result. But we can easily handle this problem by making a practice of repeating the simulation at a different mesh. If the results are very similar, we can assume they are OK.

Conclusion

Noise analysis with 3D finite element analysis looks a bit complicated. But luckily, in the great majority of cases, we will find that that the noise belongs to case A (no problem at all) and a single run with coarse mesh will end the analysis. We will have confirmation that no major mistake was made.

In other cases, the discovery of the problem will be all that is needed as a radical improvement will become instantly apparent. It will be very rare, indeed, that a very detailed analysis will be necessary as all simple means fail. But when such rare situations do occur, good FEA software will prove to be very valuable.

An equally important benefit of applying 3D FEA will be the engineer's development of intuition based on viewing many real-life 3D electromagnetic field configurations and their impact on the circuit. After a while, FEA will be needed for only the truly tough cases.

Naturally the same methodology will apply to simulating the impact of the field originating from magnetic components, coupling to the cables, buss bars, etc. In an upcoming article, we will take a look at some interesting simulations regarding EMI problems.

Reference

"Latest Generation Of 3D Electromagnetic Finite Element Analysis Software With Breakthrough Simplicity Facilitates Magnetic Component Design," by Peter Markowski in Focus on Magnetics column in the September 2014 issue of How2Power Today.

About The Author

Peter Markowski has been involved with power supply design since graduating in 1990 with an advanced degree in power electronics. Most of his career he worked for Emerson, formerly Artesyn and Computer Products as a product designer and advanced technology engineer. Recently, Peter has been involved in high-performance FPGA digital controllers and very high bandwidth, purely switched-mode envelope tracking voltage modulators as well as advanced magnetic design. This year he started the consulting business Envelope Power LLC offering complete power supply design and 3D electromagnetic simulation. Peter is the author of 16 U.S. patents and several applications encompassing various aspects of the power conversion engineering.

For more on power supply simulation topics, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category, and select "Modeling and Simulation" in the Design Area category. For more on issues relating to power supply noise, select "Noise Performance" in the Design Area category.