Coreless power design for high magnetic field environments

Steve Taranovich - January 25, 2018

In this article, I want to use an MRI (magnetic resonance imaging) medical scanner design as a familiar example for what needs to be done in a power supply design architecture to allow it to function properly in a high magnetic field environment.

An MRI room is a very harsh electromagnetic (EM) environment for electronics. Shielding may be used to enclose electronic devices to attenuate the strength of magnetic fields down to a level at which the devices can function properly and not be destroyed. Without proper shielding, the magnetic fields produced by the MRI scans will damage electronics and may also pull ferromagnetic objects into the bore of the MRI.

In the other direction, interference from electronics can cause false images to be obtained from the MRI, so that aspect of the power supply design must be addressed.

Until recently, power supplies designed into the MRI environment have had limited functionality depending upon how close they are placed near the MRI unit. The magnetic field that is present typically causes power supply failure. An object made from ferromagnetic material will be pulled into the MRI machine, and become attached to the MRI magnet—not a good thing. A power supply with iron-core based transformers and inductors are candidates for this disastrous situation.

In the past, power supplies were prevented from being drawn into the MRI machine via Velcro strips to keep them attached to the floor or other anchors in the room. In this case, a long, shielded cable is used to connect the power supply to the patient monitor being powered. This method goes against two key features of an MR patient monitor. Cost needs to be kept down, but the shielded cable is expensive. Mobility is necessary, and the range of the patient monitor is limited by the shielded cable it is attached to. The best design is to have the power supply attached to the patient monitoring unit. This would lower the cost of the shielded cable, because it can be much shorter. The mobility of the patient monitor is also increased, because the power supply is not attached to a fixed anchor.

Creating an optimum power supply

Designing a power supply board takes many resources, and a great deal of testing needs to be performed. A custom power supply would need to be produced pretty quickly for the completion of the MRI scanner project, and may not be at the same quality of an off-the-shelf one, which had years of resources deployed in its development. In addition, the power supply would also have to comply with safety regulations regarding patient monitoring systems, such as IEC60601. Because such a power supply would have already gone through the regulation process, it would just need to be qualified for the purposes of the particular project architecture.
MRI equipment and its surrounding environment

MRI uses a magnetic field and pulses of radio wave energy in order to create images of organs and structures inside the body. The magnetic field generated by the coil is typically in the range of 1 to 4 Tesla, which is a huge magnetic field that will have a detrimental effect on some of the electrical equipment such as power supplies that may get their transformers saturated and will not be able to function in such an environment. For safety and patient comfort during the MRI session, some equipment requires the power supply to be as close as possible to the load, meaning the power-unit must operate safely while exposed to the high magnetic field generated by the coil.

MRI uses a large magnet and radio waves to look at organs and structures inside the human body. There are numerous challenging design requirements when designing a power supply for an MRI architecture. Because of the sensitivity of the measurements made by an MRI machine, the oscillator frequency of the power supplies need to be precisely placed at a frequency that will not corrupt the MRI image.

A Powerbox solution to MRI power

Challenges

The greatest challenge in developing the GB350, a new coreless power supply, did not emerge until Powerbox designers started realizing the project complexity. Since the power supply unit is used in a MRT (magnetic resonance tomography) system, it is exposed to a very strong magnetic field. This meant that developers could not use an inductive unit with a magnetic core for this product as mentioned above.

The solution for this problem consisted of a new technology. Newly developed coreless induction units allowed the power supply to operate flawlessly even in a strong magnetic field. In addition, designers integrated an 80-dB shielding on the front panel connectors that shields the MRT system from interference from the measuring system.
This power supply has a DSP-regulated converter as well as ventilation with integrated speed control. Designers have developed a new technology with magnetic coreless inductivity and four-phase switching at 600kHz, a total of 2.4MHz, allows the air-cores to work, and a digital processor manages everything from switching parameters to output voltage characterization. The 2.4 MHz switching frequency can be synchronized to an external clock in an MRI or other external equipment. This frequency reduces the size of air-core inductors and keeps the switch-mode power supply switching frequency outside the sensitive ranges of MRI equipment which allows for accurate processing of the measured signals in MRI equipment, the key to obtaining high quality images.

This power supply has an input voltage of +13 VDC with output voltages as follows:

+6.90 VDC / 60 A
+3.45 VDC / 50 A
+1.65 VDC / 50 A

The architecture of this supply, the first building block in its category, is a buck converter module able to operate safely right within an MRI scanner where it is exposed to high radiation magnetic fields. The supply has an output power of 350W and when higher power levels are required it can be paralleled using an interleaving mode thus reducing EMI. Modern MRI systems usually generate 1 to 4 Tesla, making conventional power supplies, using ferrite material, useless due to inductance saturation as a result of the MRI magnet disturbing the energy transfer.

To prevent parasitic saturation, power supplies are traditionally positioned outside the shielded operation room. Installing the power supplies remotely requires long cables with subsequent power losses, and it is also a big challenge to power the latest generation of measuring equipment that
require stable and tightly regulated voltages under fast transient load conditions.

This solution uses a 670W coreless design, using the principle of transferring energy from an inductance to inductance. To guarantee the highest performance, designers implemented a DSP control and advanced power topologies with paralleling and interleaving that simplifies power scaling and reduces EMI. To protect the complete power supply from electromagnetic leakage, the power unit is shielded with an 80dB screen.

Powerbox has won the Power System Product of the Year at the prestigious Elektra Awards for 2017, run by leading UK magazine Electronics Weekly, for this design. The award is presented to the power product that demonstrates technical capabilities and usefulness that differentiate it from competitive products. Judges looked for evidence of product performance presented in numbers and/or design applications, and for new topologies and architectures, use of materials, advanced semiconductor technologies, and packaging.

The GB350 is a very clever and elegant solution to a long-standing but never previously solved problem - a true first.

At a special awards evening in London on December 6, Powerbox’s Chief Marketing and Communications Officer Patrick Le Fèvre accepted the award from Hal Cruttenden, famous comedian, actor, and master of ceremonies on behalf of Electronics Weekly. (Photo credit: Leo Johnson Photography)

**Discrete power designs for MRI environments**

Some designers make an effort to do their own custom design. There are many applications that need a switch mode power solution that is totally immune to powerful magnetic fields that would saturate even a well-screened ferrite core-based transformer. They may use a switched capacitor voltage conversion technique. However, the RF field emanating from the MRI equipment also needs to be taken into consideration in a home-grown design. The designer needs to see how well their design should be shielded from that RF (Reference 3).

Typically, an air-cored transformer is not too efficient (20-30%), but can do the job. Questions a designer needs to ask are: How efficient is the typical air-core inductor I can get on the market? Is
that good enough for my design?

Also, how large are the coreless inductors that are readily available in the industry. It seems that Farnell only has them up to 0.5uH.

**Shielding materials**

Designers may want to use shielding materials for keeping out those high intensity magnetic fields. Relative permeability will not remain constant for all frequencies. Different shielding materials will have specific frequency ranges in which they are more effective due to their relative permeability. **Table 1** is a list of the electrical properties of shielding materials at 150 kilohertz.

**Table 1** Properties of shielding materials at 150 kHz (Hemming, 1992)

<table>
<thead>
<tr>
<th>Metals</th>
<th>Relative Conductivity ($\sigma_r$)</th>
<th>Relative Permeability ($\mu_r$)</th>
<th>Absorption Loss (dB) 1 mm</th>
<th>Absorption Loss (dB) 1 mil</th>
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<tbody>
<tr>
<td>Silver</td>
<td>1.05</td>
<td>1</td>
<td>51.96</td>
<td>1.32</td>
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<tr>
<td>Copper, annealed</td>
<td>1.00</td>
<td>1</td>
<td>50.91</td>
<td>1.29</td>
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<tr>
<td>Copper, hard-drawn</td>
<td>0.97</td>
<td>1</td>
<td>49.61</td>
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<tr>
<td>Gold</td>
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<td>1</td>
<td>42.52</td>
<td>1.08</td>
</tr>
<tr>
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<td>1</td>
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<td>1.01</td>
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<td>22.83</td>
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<td>Phosphor–bronce</td>
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<td>1</td>
<td>21.65</td>
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<td>1</td>
<td>665.40</td>
<td>16.90</td>
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<tr>
<td>Tin</td>
<td>0.15 1000</td>
<td>1</td>
<td>19.69</td>
<td>0.50</td>
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<tr>
<td>Steel, SAE 1045</td>
<td>0.10 1000</td>
<td>1</td>
<td>509.10</td>
<td>12.90</td>
</tr>
<tr>
<td>Beryllium</td>
<td>0.10</td>
<td>1</td>
<td>16.14</td>
<td>0.41</td>
</tr>
<tr>
<td>Lead</td>
<td>0.08</td>
<td>1</td>
<td>14.17</td>
<td>0.36</td>
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<td>Hypernick</td>
<td>0.06 80 000</td>
<td>1</td>
<td>3484.0 *</td>
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</tr>
<tr>
<td>Monel</td>
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</tr>
<tr>
<td>Mu–metal</td>
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<td>1</td>
<td>2488.0 *</td>
<td>63.20*</td>
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<td>Fermitloy</td>
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<td>1</td>
<td>2488.0 *</td>
<td>63.20*</td>
</tr>
<tr>
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</table>

*Assuming that the material is not magnetic flux saturated. Taken from MIL-HB-419A.

Beware that ferromagnetic materials should never be saturated; this causes them to lose their ability to attenuate the magnetic field. A solution from Reference 3 suggests creating a double-layered shield where the outer layer has low relative permeability and low susceptibility to saturation which will enable the inner shield to work well in shielding the magnetic field.

**A Texas Instruments discrete solution for MRI power**

Texas Instruments also has a good commentary on this synchronization issue on their site: [Create a power supply for an MRI application](https://www.ti.com). The switching frequency of the power supply must be synchronized to a 2.488MHz clock because as the MRI is scanning, it radiates a high magnetic field, typically in the range of 1-4 Tesla. Because traditional magnetic-core materials used in power supplies would saturate under such levels, air-core inductors must be used to replace the magnetic cores. However, for an inductor having no ferromagnetic core material, the air-core approach provides very low inductance values.

Texas Instruments suggests a solution to the MRI power supply with the **LM5140-Q1**, an automotive-
qualified dual-channel synchronous buck controller. One of the features of this IC that make it desirable for a MRI application is its ability to be synchronized to an external clock up to 2.6MHz. This frequency allows for smaller air-core inductors and keeps the switch-mode power supply switching frequency away from sensitive ranges of the MRI equipment. This enables accurate processing of the measured signals in an MRI for high quality images.

**MRI inductor design steps**

The inductance required for an MRI power supply is proportional to the switching frequency, as shown in Equation 1:

$$L = \frac{V_{OUT}}{\Delta I \times F_{SW}} \times D \quad (1)$$

where $L$ is inductance in microhenries, $V_{OUT}$ is the output voltage, $\Delta I$ is the inductor ripple current, $F_{SW}$ is the switching frequency, and $D$ is the duty cycle.

Once you have calculated the required inductance, you can use Equation 2 to determine the air-core inductor size:

$$L = \frac{(d^2 \times n^2)}{(18d + 40l)} \quad (2)$$

where $L$ is inductance in microhenries, $d$ is the coil diameter in inches, $I$ is the coil length in inches, and $n$ is the number of turns.

Looking at Equations 1 and 2, you can see that a higher switching frequency will result in a lower inductor value. A lower inductance value yields a smaller air-core inductor.

**Table 2** lists the typical power-supply requirements for MRI equipment. The highest power rail is 12V at 20.5A, from a 48V (nominal) input. The combination of MOSFETs $R_{DS(ON)}$ and switching losses (which dominate MOSFET losses when operating at 2.488MHz) make thermal management extremely challenging.

The solution is to replace the MOSFETs with gallium nitride (GaN) FETs. GaN FETs provide significant efficiency improvements over MOSFETs because they have nearly zero reverse recovery, lower $R_{DS(ON)}$ and a lower gate charge ($Q_G$), reducing the losses to a more manageable level. GaN FETs have critical gate-drive requirements, so the LM5113 GaN FET driver is also necessary.

**Table 2 MRI power rails (Image courtesy of Texas Instruments)**
There are air core inductor examples from AVX and Coilcraft has Air Core Springs and tools for designers.

The need for a negative voltage output at high current

One of the more challenging design requirements for MRI applications is the need for a negative output voltage at high output currents. This presents another challenge to overcome. Table 1 shows the power requirements for an MRI inverting buck-boost power supply, 48V to −15V (and 48V to −8V), at 15.84A. The inverting buck-boost topology transfer function (Equation 3) requires the LM5140-Q1 to be able to withstand $V_{\text{IN}} + V_{\text{OUT}}$, $50V_{\text{MAX}} + 15V = 65V$.

$$V_{\text{OUT}} = -V_{\text{IN}} \times \frac{D}{1-D} \quad (3)$$

The LM5140-Q1 is able to operate with an input voltage of 65V (70V absolute maximum), overcoming the danger of overvoltage stresses.

In essence, it is up to the designer to decide which type of architectural solution to employ in their specific system. I hope that I have provided a bit of insight to help you to choose the right path for your particular project.

Steve Taranovich is a senior technical editor at EDN with 45 years of experience in the electronics industry.

References

1. Create a power supply for an MRI application, Texas Instruments website.

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