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Magnetic-field measurements hold the key to reducing dc/dc EMI

POWER CONVERTERS FREE SYSTEM DESIGNERS FROM UNWIELDY CONSTRAINTS, BUT THE DEVICES RADIATE UNSPECIFIED FIELDS THAT CAN DESTROY THE SIGNAL/NOISE PERFORMANCE OF SENSITIVE CIRCUITS NEARBY. MAGNETIC-FIELD MEASUREMENTS HOLD THE KEY TO FINDING AND CORRECTING THESE PROBLEMS.

Performance-driven measurement instrumentation requires low-noise, high-bandwidth linear front-end circuits that combine with equally well-performing A/D converters and clocking (Figure 1). Designers work to quantize the measurement of interest into a digital signal early in the processing chain to keep out unwanted noise. Look at your favorite instrumentation Web sites. A brief scan of dc-measurement and ac-source-and-measurement instrumentation turns up instruments with dynamic ranges of 120 dB or more. Engineering for dynamic range is a search for the source of every spurious signal. High-performance-instrument designers must be aware of all of the potential noise sources—not just the usual culprits, such as power supplies and digital activity. As dynamic range exceeds 100 dB, engineering for high SNR leads to investigating the charge pump running in the FPGA, the thermal gradient that occurs when the processor starts and stops, and the magnetic coupling from the other instrument that someone set on top of your instrument. A significant part of the design is isolating precision analog circuits from internal and external electromagnetic activity.

Today's instrumentation-and-measurement industry is undergoing a transformation. After years of performance-based engineering, market forces are leading to new open architectures (Figure 2). With customers wanting the advantages of open architecture without performance compromise, the new environment brings new engineering challenges.

For example, consider the semiconductor-test industry, in which the test requirements of SOC (system-

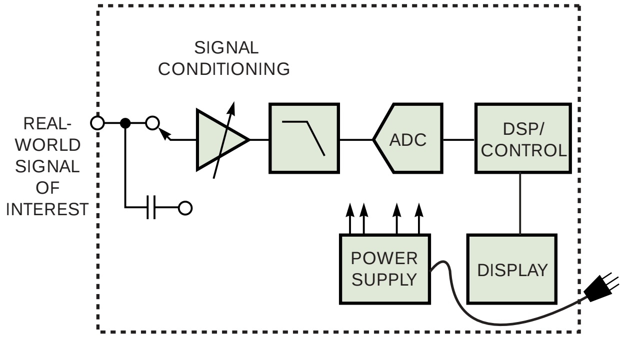


Figure 1 Performance-driven measurement instrumentation requires low-noise, high-bandwidth linear front-end circuits coupled to equivalent-performing A/D converters and clocking. It also requires a power supply, sometimes line-powered, as shown, but often a dc/dc converter.

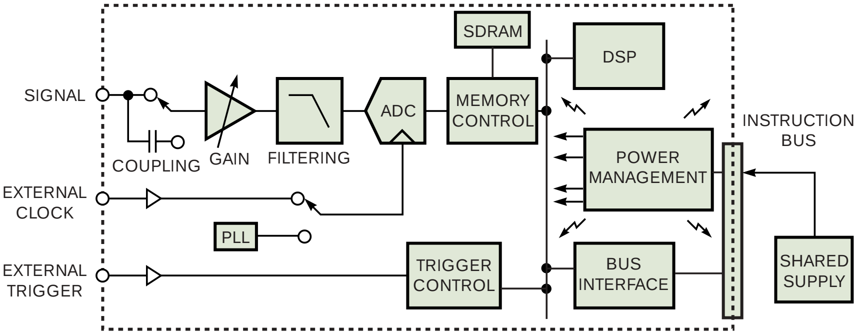


Figure 2 After years of performance-based engineering, market forces are leading to new open architectures. At the block-diagram level, open and proprietary architectures are similar, but, at the implementation level, the differences can be significant.

on-chip) ICs drive up the breadth of instrumentation that test systems must contain. Time to market and the cost of ownership of large ATE (automatic-test-equipment) systems have combined to define a critical need for an open-test-system architecture (**Reference** 1). The trend exceeds the bounds of just ATE, however. A growing need exists for high-performance, modular VXI and PXI instrumentation for production testing and characterization. Test-equipment architectures are opening up as a strategy to reduce cost through greater flexibility, which leads to higher efficiency, greater reuse, and lower barriers to competition among suppliers.

So where does this trend leave instrument-development teams? During the era of performance-driven design, development teams had control over a large part of the system architecture. That's not the case in open, card-modular architectures, such as VXI. In such architectures, the backplane interface and physical-packaging limits highly constrain design engineers. Engineers need to place more emphasis on environmental issues, such as cooling, power conversion, and EMI (electromagnetic interference). One of the more significant of these challenges is EMI from power-conversion components within the instrumentation system. A dc/dc converter within the system relieves a combination of space and power-supply constraints, but it also generates noise, which could be the factor that limits your spurious-free dynamic range. This scenario can occur whether this

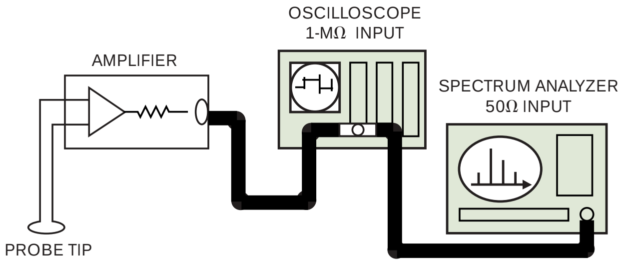


Figure 4 A wideband amplifier amplifies the pickup-loop output and drives an oscilloscope and a spectrum analyzer. Wiring the signal to the amplifier and from the amplifier to the instruments requires care to avoid introducing spurious signals that can reduce the measurement accuracy.

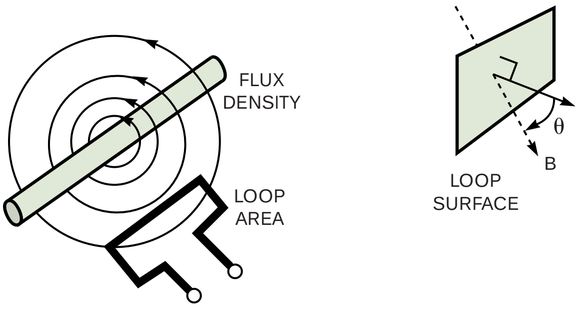


Figure 3 A varying magnetic field induces in a pickup loop a voltage proportional to the loop area and rate of change of the field component normal to the plane of the loop.

Figure 5 The intent is to place the pickup loop 1 in. above the plane that would represent the surface of the motherboard if the converter were mounted in an appropriate through-hole design.

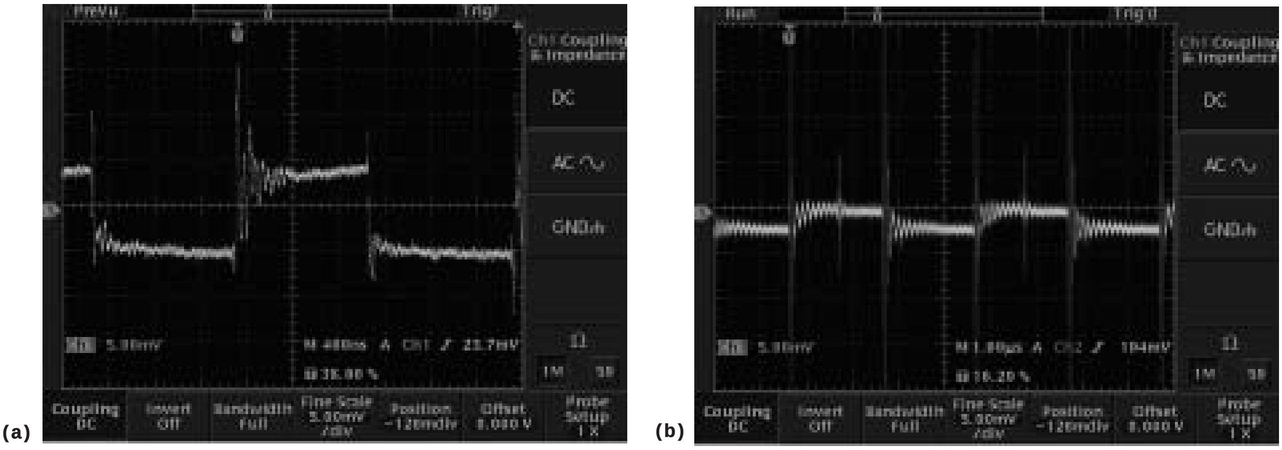
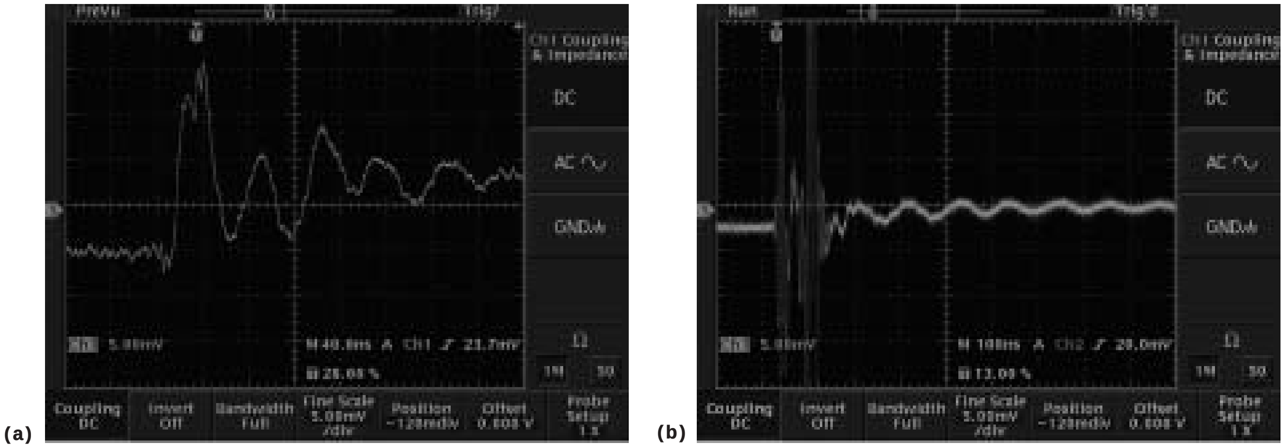


Figure 6 Although the two tested dc/dc converters, Brand X (a) and Brand Y (b), are equal in size, have the same basic architecture, and have nearly identical published specifications, the magnetic fields above them differ considerably.



(a)

(b)

Figure 7 Whereas both converters, Brand X (a) and Brand Y (b), have similar switching characteristics, a faster sweep reveals that, although Brand Y's magnetizing inductance keeps emissions lower overall, the unit's leakage inductance resonates at a higher frequency and couples greater peak voltage at the switching transient.

TABLE 1 DATA FROM SAMPLES

Characteristic		Brand X	Brand Y
Switching frequency (kHz)		420	250
Time domain	Switching field (mV p-p)	9.5	2
	Switching field (µtesla p-p)	14.1	4.94
	Transient field (mV p-p)	20	160
	Transient field (tesla/sec)	24.7	197
Frequency domain	Fundamental field (dBm)	−36	−48
	Fundamental field (µtesla)	3.5	1.4
	Resonance (MHz)	20	9.1
	Resonant field (dBm)	−56	−55
	Resonant field (ntesla)	7	17.1

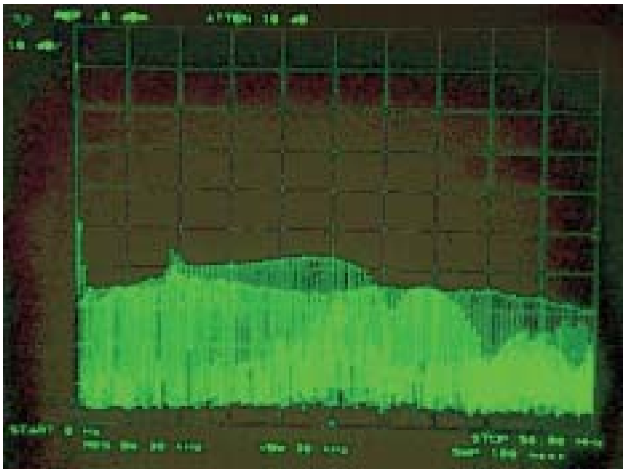


Figure 8 A broad look at the spectrum of Brand Y's field shows a resonance near 10 MHz with components peaking at 20 to 25 MHz.

noise originates in the affected instrument or from a noisy neighbor whose design did not require the same attention to dynamic-range requirements.

Instrumentation for an open architecture must comply with system specifications regardless of whether the instrument in the next slot is a highly dynamic power supply or a bank of 200-MHz digital-pin drivers. In this environment, every instrument must be tested to demonstrate compliance with a field-emission profile that imposes the same emission and susceptibility requirements on all instruments.

MAGNETIC COUPLING

Near-field, radiated EMI can create noise problems for sensitive instrumentation. Near fields contain both electric and magnetic fields in proportion to the impedance of the source (Reference 2). Low-impedance circuits—that is, low relative to the 377Ω impedance of free space, or air—emit predominantly magnetic fields, whereas high-impedance circuits emit predominantly electric fields. Coupling includes capacitive and mutually inductive coupling depending upon fields present and the configuration of the victim circuitry. Because circuit impedances in switch-mode power-supply circuits tend to be low and electric fields are relatively easy to shield, this article focuses on magnetic coupling Figure 3).

Faraday's Law leads to an understanding that the electromotive force—essentially voltage plus any resistive losses—in a circuit is proportional to the rate of change of the magnetic flux within the circuit. No voltage is induced if the rate of change is zero. Magnetic interference is an ac issue with a higher degree of coupling as frequency increases.

Magnetic flux, Φ_M, can be self-induced, as with the product of inductance and current, or mutually induced, as with the product of flux density and loop area (see sidebar "Magnetic circuits"). The relationship in the following equation is interesting: $E=-d\Phi_M/dt=d(LI)/dt=-d(BA\cos\theta)/dt$, where I is current, B is

(continued on pg 64)

MAKING YOUR OWN MAGNETIC-FIELD-MEASUREMENT PROBE

A high-bandwidth amplifier provides approximately 20 dB of gain to a signal that a small magnetic loop produces (Figure A). You can observe the probe output on a spectrum analyzer or an oscilloscope depending upon the application requirements. Many ac-source or -measurement instruments need to describe performance in terms of SFDR (spurious-free dynamic range) and would tend toward spectral data. However, dc instrumentation may be more concerned with total rms noise energy and would examine field measurements in the time domain. These component measurements look at both.

Figures B and C show the layout of the amplifier and probe tip. The probe tip provides a circular area with 0.4 in. diameter perpendicular to the circuitry on the pc board. An additional design consideration is to provide a balanced input to cancel any electric fields coupling to the probe tip.

This circuit uses high-bandwidth current-feedback op amps because the dc/dc converters that are most interesting for instrumentation development have resonant components of 25 to 60 MHz.

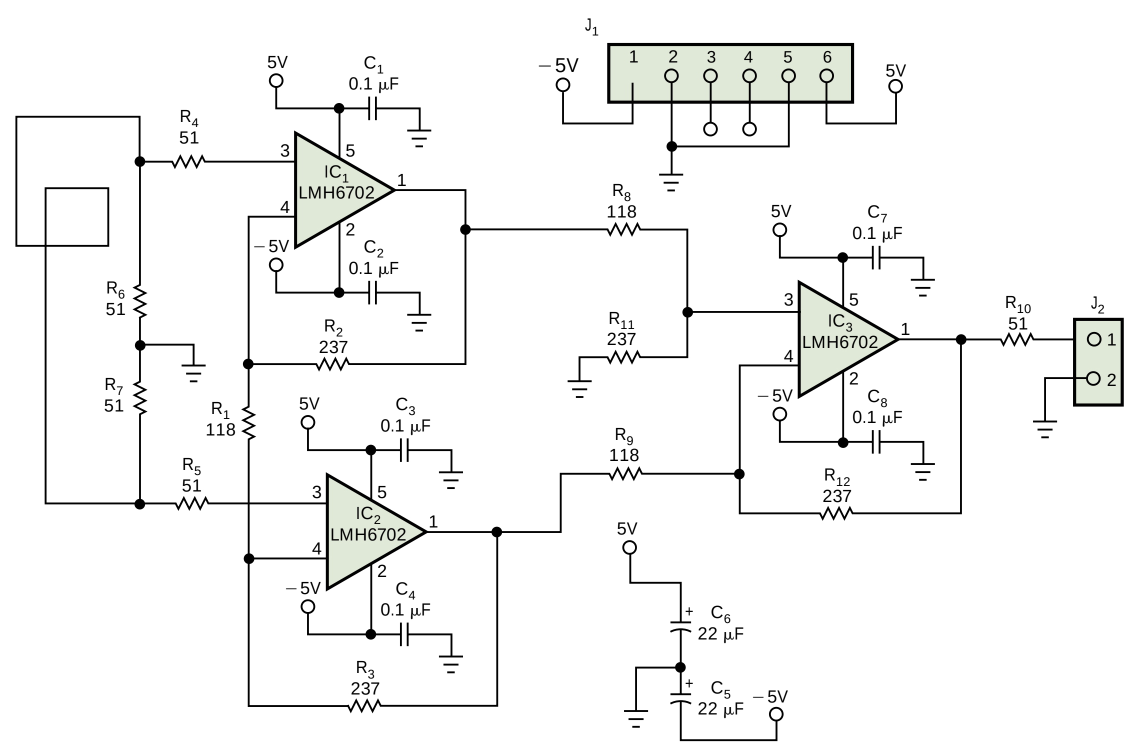


Figure A This high-bandwidth, 20-dB preamplifier amplifies the small signals that the magnetic loop picks up.

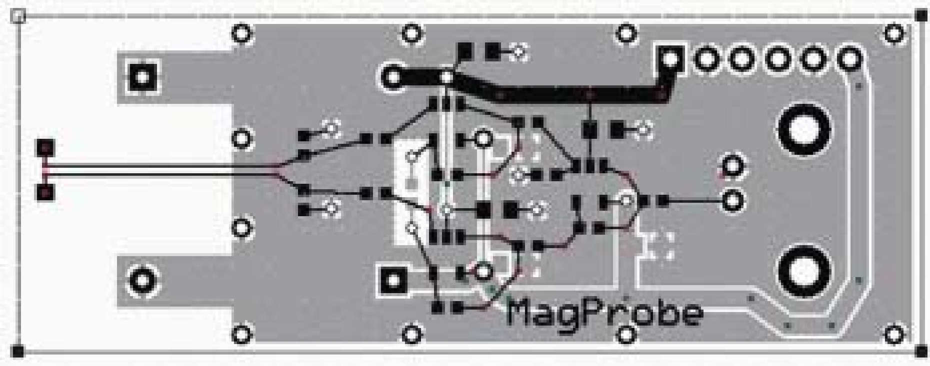


Figure B The amplifier layout is orthogonal to the probe tip and as balanced as possible.

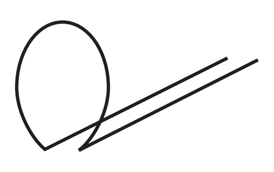


Figure C The probe tip provides a circular area 0.4 in. in diameter perpendicular to the circuitry on the pc board. A balanced input cancels any electric fields that couple to the probe tip.

magnetic-flux density, and L is inductance. The equation says that you can induce an error voltage into a circuit by changing any one or more of the parameters. A given percentage change in current, magnetic field, or inductance (loop area) produces the same effect on induced voltage. Therefore, the design practice of reducing loop areas in high-performance circuits to eliminate errors from conducted emissions also reduces errors from magnetic coupling.

Although high-performance design practice dictates that you minimize loop area and shield necessarily susceptible components, such as filter inductors, it's always better to stop noise emissions at their source. Toward that end, instrument design-

CONVERTING VOLTAGE MEASUREMENTS TO MAGNETIC-FIELD DATA

An instrument designer characterizing various sources of magnetic interference might find satisfaction with the relative-voltage measurements that a standard loop produces–assuming that the loop represents the loop area and orientation that an instrument might experience. But, because the loops and amplification can differ, it is helpful to convert these voltage measurements into field data.

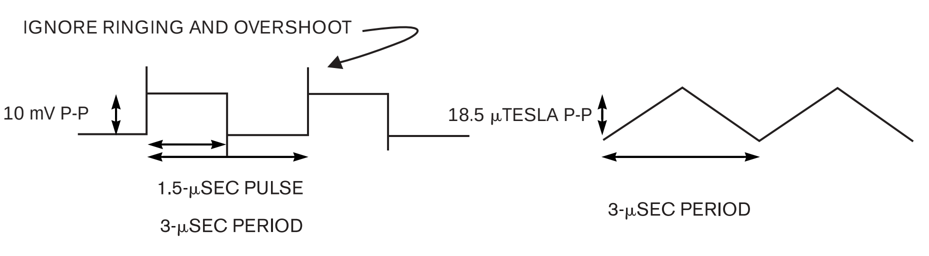


Figure A This typical time-domain measurement converted to the B-field is a 3-µsec, 50%-duty-cycle switching waveform. The 5-mV peak measurement equates to a 12.3-tesla/sec rate of change in flux density.

Current in the emitting circuit creates magnetic flux that cuts through the test loop. The test loop is held stationary, including its angle to the field, θ, but the flux density, B, is changing to induce a voltage: $|V_{MEASURED}|=K_A A_L \cos\theta dB/dt$, where K_A is the gain of the amplifier, A_L is the area of the loop in square meters, dB/dt is the rate of change of the flux density in webers per square meter, or teslas. Plugging in the values and noting that the termination into the spectrum analyzer reduces the gain by a factor of two yields: $|dB/dt|\cos\theta=2467\times V_{MEASURED}$ (teslas).

Consider a reading of 10 mV p-p for the switching component in Figure A. Ignore the peak deviations at the switch transients because they do not add appreciably to the rms energy. This example has a 3-µsec, 50%-duty-cycle switching waveform. The 5-mV peak measurement equates to a 12.3-tesla/sec rate of change in flux density. Given that this rate remains 1.5 µsec, the flux density (B-field) in the direction of the pickup loop is 18.5 µtesla p-p.

You measure the magnetizing force, or H-field, in amps per meter, and you can determine it from the B-field by dividing by the permeability of free space, or $4\pi\times10^{-7}$. The 37-µtesla-p-p flux density is equivalent to 29.4A/m in an air-core circuit.

A spectrum analyzer can provide an alternative view of noise coupling. You can examine the issues of ringing and resonance. Reference A provides a derivation that takes advantage of a sinusoidal B-field: $V_N(\omega)=\omega K_A A_L B_R(\omega)\cos\theta$, where V_N and B_R are rms quantities at the frequency of interest, K_A is the amplifier gain, A_L is the loop area, and θ is the angle between the field vector and the area perpendicular to the loop area. Plugging in the previously determined values yields: $B_R \cos\theta=393 [V_N(f)/f]$ 2. For general application, you can convert this formula into a chart (Figure B).

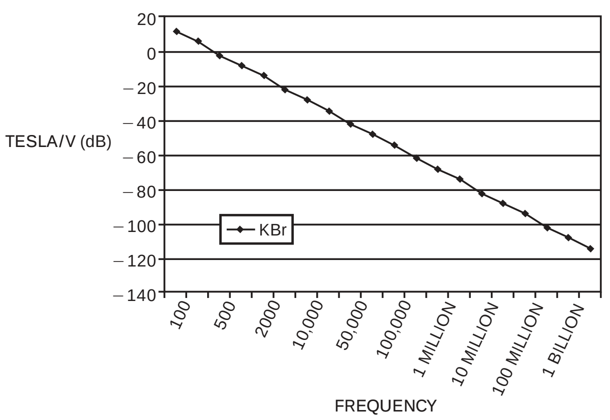


Figure B This chart shows the field-conversion factors for the magnetic probe.

REFERENCE

A Ott, Henry W, *Noise Reduction Techniques in Electronic Systems, Second Edition*, pg 38, John Wiley & Sons, 1988.

ers would like to compare near-field performance in the time and the frequency domains before they select power converters for use in instruments. Magnetic-field specifications are not yet at this level of maturity, however, so device characterization is necessary.

MEASUREMENT EXAMPLE

For example, two similarly specified dc/dc converters have been characterized for magnetic-field emissions with a small loop antenna. Both converters are one-eighth-brick, wide-input-range devices using the same input voltage, 48V; output voltage, 5V; and load resistance, 4Ω. Both share the same conversion architecture—a fixed-ratio isolation stage following a regulation stage to support a 35 to 75V input range. These converters have two power magnetic sections within the design, but both run at the same frequency. Neither converter provides magnetic-emission data within the specification sheet.

In this characterization setup (Figure 4), a small pickup loop senses magnetic fields in the area above the dc/dc converters (see sidebar "Making your own magnetic-field-measurement

MAGNETIC CIRCUITS

Electrical engineers appear to be most comfortable working with circuits in which ideal conductors make signal connections. Inductors are OK for helping with frequency-domain issues, such as filtering, but there is a tendency to ignore the magnetic component.

Do not fear a magnetic circuit. Observing the similarities between inductors and capacitors is helpful in developing an understanding of the circuit operation (figures a and b and Reference A). The intensity of the electric field between the plates of a capacitor depends only on the voltage and the physical distance, d, between the plates: $E=V/d$ in volts per meter.

The intensity of the magnetic field surrounding a conductor depends only on the current and the physical width of the conductor, w: $H=I/w$ in amps per meter. The magnetic-field strength is sometimes called the magnetizing force.

Capacitance is a function of the plate area, the distance between the plates, and the dielectric material between the plates. The capacitance is $C=(\epsilon wl)/d$. The dielectric constant has units of farads per meter. A high dielectric constant produces more capacitance in a given plate area, holding plate separation constant, than a low dielectric constant.

A conductor forms a loop, creating an inductor. The inductance is a function of the area of the loop, the width of the conductor, and the permeability of the material surrounding the conductor: $L=(\mu dl)/w$. The core's permeability has units of henries per meter. Similar to the capacitor, high permeability produces more inductance in a given loop area, holding conductor width constant, than a material with low permeability.

In a capacitor, flux is a measure of the stored charge in coulombs. As the capacitor discharges, this charge becomes the source of current. Electric flux in a capacitor is a function of capacitance and voltage: $\Phi=CV$.

Magnetic flux in an inductor is analogous to the electric charge stored in a capacitor. Magnetic flux has units of webers and becomes the source of electromotive force (open-circuit voltage) as the inductor discharges. Magnetic flux is a function of the inductance and voltage: $\Phi M=LI$.

The dielectric that influences capacitance per unit also impacts flux density–or charge per unit area. Imagine flux lines between the positive and negative charges on the plate of the capacitor. The number of lines passing through a unit of area represents the flux density: $D=\Phi/(wl)=\epsilon E$. The flux density is directly proportional to the dielectric constant of the material between the capacitor plates.

The permeability of the core influences inductance and therefore magnetic-flux density. You measure flux density in flux per unit area: $B=\Phi M/(dl)=\mu H$.

REFERENCE

[A] **Walker, Charles S, *Capacitance, Inductance and Crosstalk Analysis*, Artech House, 1990.**

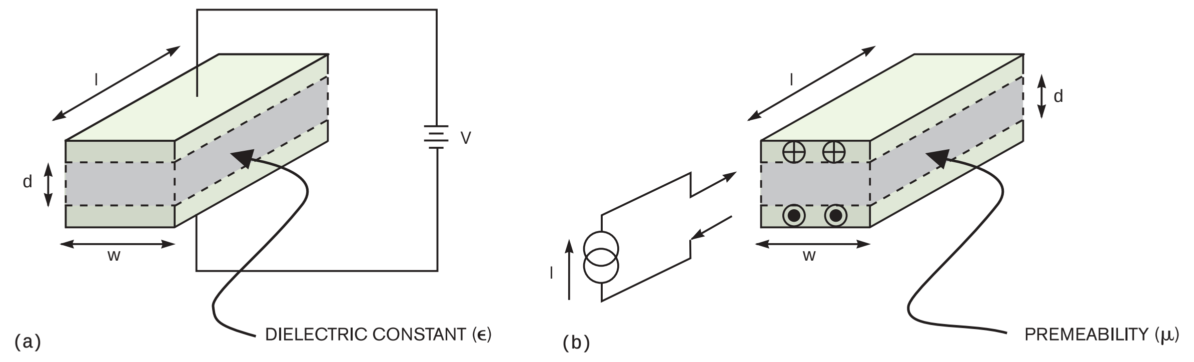


Figure A The electric field between the plates of a capacitor depends on the voltage and the distance between the plates (a). The inductance is a function of the area of the loop, the width of the conductor, and the permeability of the material surrounding the conductor (b).

probe"). The amplified-loop output connects to an oscilloscope and a spectrum analyzer. The magnetic emission of the dc/dc converters contains a broad band of energy from the fundamental switching frequency that reaches to 50 MHz or more. It is important to treat the measured signal's distribution network as a high-frequency transmission line. The signal runs past the high-impedance oscilloscope input with a BNC tee at the scope input. The line terminates at the spectrum-analyzer input.

To best represent a victim circuit in a neighboring slot, orient the probe tip in a plane parallel to the converter's pc-board substrate. Scan the surface of the board for maximum output; the strongest field is above the isolation transformer (second stage). The intent of the measurements, which take place about 0.65 in. above the top surface of the transformer, is to place the pickup loop 1 in. above the plane that would represent the surface of the motherboard if you mounted the converter in an appropriate through-hole design (**Figure 5**).

Viewing measurement results in the time domain, you can see the converter's fundamental frequency and ringing frequency, and you can get a sense of the magnetic-field intensity (**Figure 6**). These converters demonstrate a trade-off in the converter's magnetic design. The isolation transformer's leakage and magnetizing inductance mutually couples to the measurement probe. Brand X has a significantly lower magnetizing inductance in its isolation transformer, as the higher fundamental field in the measurement shows. Brand Y has lower leakage inductance and therefore higher ringing frequency. The ringing that occurs around the switching transient is the result of leakage inductance and the switch's parasitic capacitance.

You can make two observations based on the derivative relationship of the earlier **equation**: A square-wave response means that the magnetic flux is changing linearly. The magnetic component is operating in a linear region, and current is increasing linearly. In broad terms, the magnetic field for Brand X is an 18-μtesla p-p triangular wave (see **sidebar** "Converting voltage measurements to magnetic-field data").

Although lower leakage inductance is better for reduced emission, the higher frequency resonance couples greater peak voltage at the higher frequency (**Figure 7**). A closer observation of the switching transient provides some insight into the resonance within the dc/dc converter.

If your main concern is for spectral interference in an ac-source or -capture instrument, you may be more interested in the information the spectrum analyzer provides. Taking a broad look at Brand Y's magnetic-field spectrum, you can see the resonance near 10 MHz and the components peaking at 20 to 25 MHz (**Figure 8**). **Table 1** summarizes the data from these samples.

Open-instrumentation architectures offer an important role for dc/dc converters. If the converters are not the sources of performance-limiting noise, they open a platform to a large set of applications. This article examines two similar converters using a high-bandwidth magnetic probe and finds different results. Because a system is only as quiet as its noisiest neighbor, anyone wishing to participate in open-instrument development should carefully evaluate to ensure a performance-compatible environment.EDN

AUTHOR'S BIOGRAPHY

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