9x.14 Low-Noise Isolated Power

Let's say you want to make sensitive measurements of low-level analog signals with a high-resolution ADC, and convey the results to a microcontroller; or perhaps going in the opposite direction, you want to generate stable dc voltages from a DAC, with low noise and microvolt stability. For these kinds of instrumentation challenges you'll want to isolate the low-level analog front-end from the noisy digital controller, using digital signal isolators (e.g., optocouplers, see §12.7) to separate the grounds. You'll need isolated dc supplies, also, especially because some of these applications may run the analog circuitry with its "ground" floating at a substantial voltage difference (tens or hundreds of volts offset) from the controller's ground.

Figure 9x.51 shows the basic idea, with some typical part numbers that permit data rates to 25 Mbps or more (we've listed both opto- and capacitively-coupled isolators, for variety). The figure shows a 2 W isolated power converter, intended for just this sort of application; it converts +5 Vdc at the driver side to an unregulated (and floating) 7 Vdc nominal output,[35] which is easily regulated down to 5 V with a low-dropout linear regulator, as shown.

So far, so good. The problem we've encountered in this tidy scheme is that the power isolator (a switching converter clocked at several hundred kilohertz) couples some of its clocking signal onto the isolated output. This appears as a spiky common-mode signal whose amplitude is typically 100 mV or more. Figures 9x.52 and 9x.53 show measured waveforms of the voltage impressed on the isolated ground (triangle symbol in Fig. 9x.51) with respect to the input-side ground (normal ground symbol), for two representative isolated power converters. These measurements

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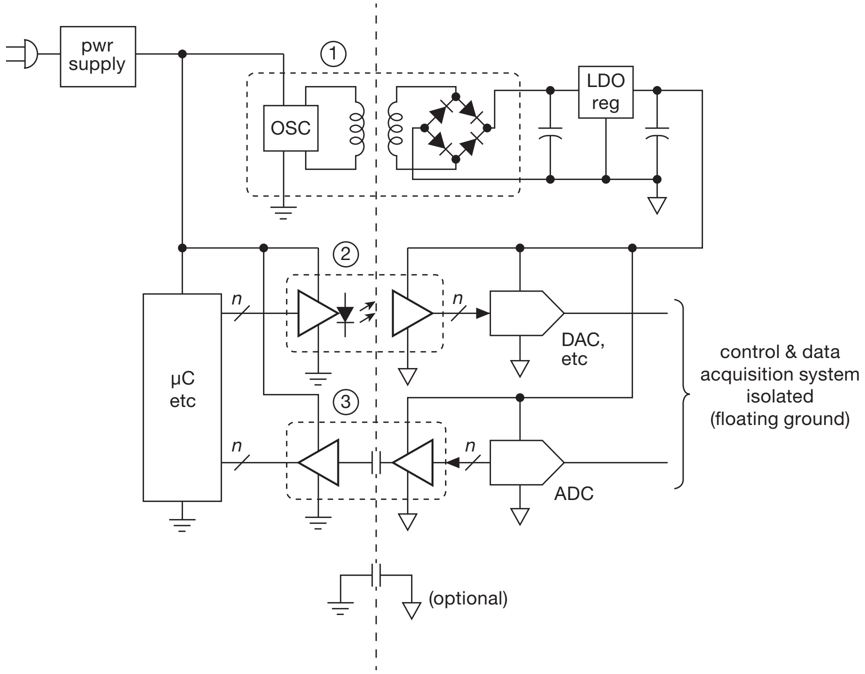
[35] Many other input and output voltage options are available, including models with dual ±5 V or ±15 V outputs.



(1) ISO-PWR: DCP0207P (+5 Vin, 7 V(unreg) out)
(2) opto: ACPL-772L, PC412S, etc
(3) capacitor: ISO7220, etc

Figure 9x.51. An isolated system with its own floating "ground" (▽) needs a thoroughly isolated dc supply. It's important that no signals associated with the power conversion (either on the isolated dc power or its ground) are coupled through to interfere with the low-level signals.

were made across a 50 Ω resistor bridging the two grounds, and with a 25 mA resistive load at the 12 Vdc isolated output; in each case we took a waveform with and without a bypass capacitor.

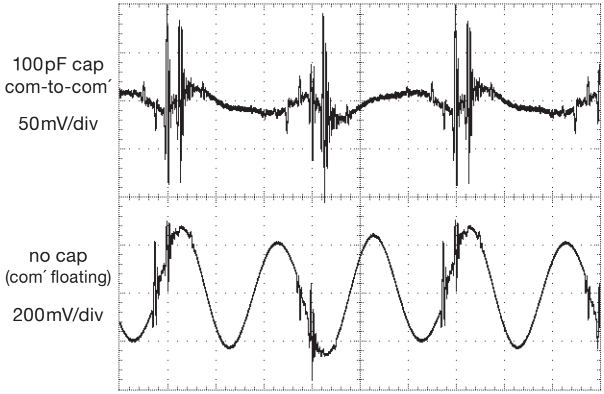


Figure 9x.52. Noise coupled to the isolated ground (com′) with respect to driver-side ground (com), measured across a 50 Ω bridging resistor, both with and without an optional common-to-common bypass capacitor. Dc–dc converter: DCP021515P. Horizontal: 400 ns/div.

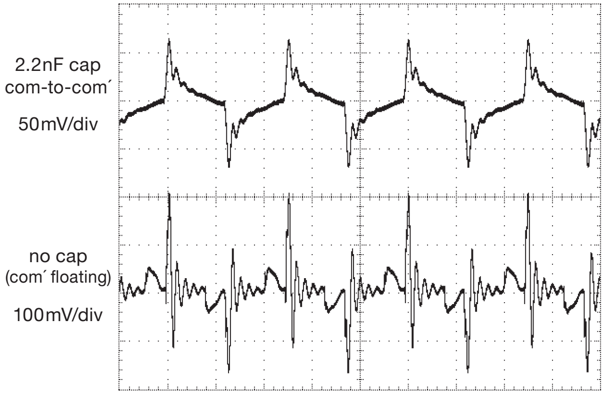


Figure 9x.53. Same setup as Fig. 9x.52, for the LT3999 "Low Noise Isolated Power Supply." Horizontal: 400 ns/div.

These switching-noise signals are *common-mode* – they appear on both the isolated common and its corresponding regulated dc voltage. If shielding and grounding in the isolated system were perfect, so that the power common and all signal commons joined in a single point, well-bonded to the shield (if any), they might not be of serious concern. But in real life there is inductance and resistance in the grounding paths, allowing a portion of common-mode noise to appear at sensitive inputs; and so, as one user of research instrumentation put it, "common-mode noise, if left to its own devices, will find a way to become normal-mode noise."

In practice these converter-noise voltages coupled onto the sensitive analog circuitry have proven quite troublesome, amounting to some 1000 LSBs of a 16-bit conversion. And this induced noise extends to many megahertz, as can be seen in the spectra in Figure 9x.54. What is needed is a dc–dc converter whose output acts like an isolated battery.

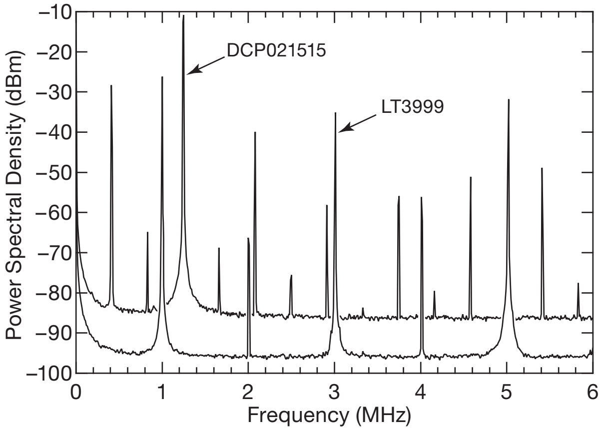


Figure 9x.54. Power spectra for the two dc–dc converters of Fig. 9x.52 and 9x.53, measured with the same configuration as used for their lower traces.

Taking our cue from the "ultra-isolated" powerline transformers that come from manufacturers like Topaz,[36] we developed a converter design with far better isolation. The tricks are (a) using sinusoidal drive, to eliminate those pesky edge transients, (b) using balanced (differential) drive, to eliminate common-mode primary signal, (c) surrounding the output winding of the transformer with an electrostatic shield, to suppress capacitive coupling, and (d) using a common-mode choke at the isolated output, to add common-mode series impedance at signal frequencies.

Figure 9x.55A shows the scheme, with a custom transformer wound on an RM10-size ferrite core. For shielding we used copper foil tape with an insulating layer of Kapton: both primary and secondary windings are 22 turns each (2 mH), with a layer of foil on both sides of the secondary. The foil layers are each a bit more than one turn, overlapped but insulated so they do not form shorted turns. The transformer is "inside-out": the primary surrounds the shielded secondary. We wound the output choke on another

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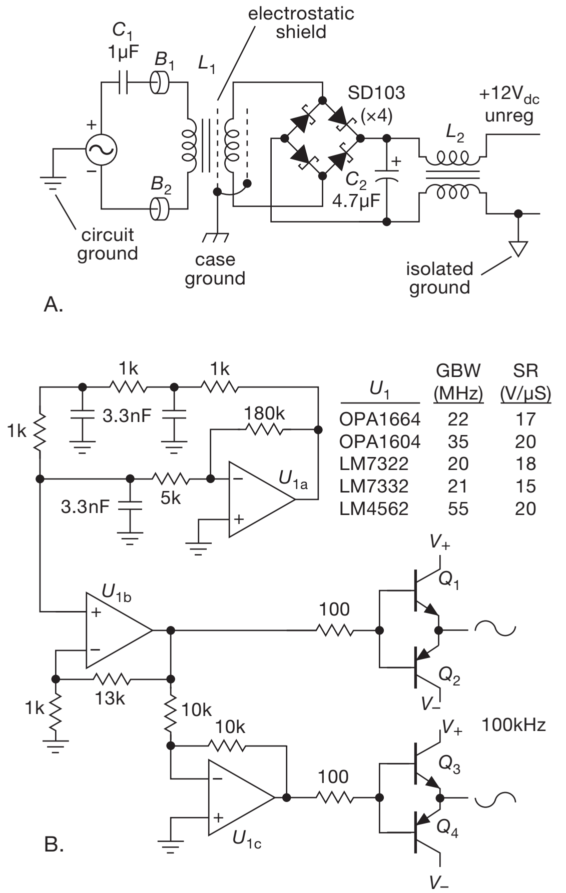
[36] Whose transformers specify an inter-winding mutual capacitance of 0.003 pF: the capacitive coupling is blocked by the grounded shield.

RM10 core, 161 bifilar turns of #28 magnet wire (110 mH). The inductance was chosen so that its self-resonant frequency matched the 100 kHz fundamental drive frequency (100 kHz), to further suppress coupled energy.



U_1	GBW (MHz)	SR (V/µS)
OPA1664	22	17
OPA1604	35	20
LM7322	20	18
LM7332	21	15
LM4562	55	20

B_1, B_2: Toshiba AB4X2X8W
L_1: EPCOS (TDK) RM10/N87 core, A_L = 4200, p/n B65813JR87
$N_P = N_S$ = 22t #30, primary over shielded secondary
L_2: same core, 161t #28, bifilar
Q_1, Q_3: BD139-16
Q_2, Q_4: BD140-16

Figure 9x.55. Suppressing converter noise with sinewave drive through a shielded transformer. A. Circuit. B. Buffered phase-shift oscillator adequate for the job. See Fig. 9x.59 for a triangle-wave or trapezoidal-wave alternative, and Fig. 9x.61 for a clocked square-to-sine converter. Fig. 9x.60 shows what the cores look like.

For the sinusoidal drive (Fig. 9x.55B) we used a phase-shift oscillator (see §7.1.5C), whose paired outputs of opposite phase are buffered by simple push–pull BJT followers. The op-amps listed are appropriate: their supply voltage range extends to ±16 V, and they have enough bandwidth (note U_{1a}'s inverting gain of ×36 requires $f_T \gg 4$ MHz) and slew rate (100 kHz at 10 V peak amplitude requires at least SR=6.3 V/μs) to do the job. However, by actual measurement (see below) a triangle-wave drive[37] is equally effective in reducing coupled ground signals. Figure 9x.59 shows a simple implementation, which, owing to ratiometric design, exhibits an oscillation frequency independent of supply voltage: $f = R_3/4R_1R_2C_1$. By clamping the output you could generate a trapezoidal waveform of the same frequency.

Figure 9x.56 shows the coupled ground noise, for three choices of bypass capacitor, measured with the same setup and loading as for the lower traces in Figures 9x.52 and 9x.53. The shielded sinewave converter improves on the latter by about 50 dB in peak amplitude; the reduction in *peak spectral power* is comparable or greater – some 50–70 dB, as seen in the spectra of Figure 9x.57.

A few additional notes: (a) The push–pull driver stages are outside the op-amps' feedback loops, which avoids problems of feedback stability; we did not bias them into crossover-free class-AB conduction, having found no improvement with the latter. (b) The Toshiba "Amobeads" (B_1 and B_2; see also §1x.4.3E) were effective in suppressing some minor ringing at a few MHz, which was seen at portions of the waveform (e.g., at onset or termination of diode conduction). (c) With power supplies (V_+, V_-) of ±12 V, the circuit of Figure 9x.55 delivered an isolated 12 Vdc (unregulated) output when loaded to 50 mA, rising another volt when loaded only to 25 mA. For other output or supply voltages, change the turns ratio of L_1 accordingly to set the nominal unregulated $V_{\rm out}$; the gain of U_{1b} can be altered for minor trimming. (d) We tried substituting some commercial common-mode chokes for L_2, to see whether it's worth winding your own resonated version; for this we tried an Eaton CMT3-1-R (5.4 mH), a Coiltronics CMS3-14-R (1.3 mH), and a Würth #74429 (6.5 mH). With each of these the common-mode suppression was poorer than with our optimized L_2 by some 20 dB, i.e., no improvement over the performance with no choke at all.

Which suppression tricks matter the most?

We threw the kitchen sink at this problem, combining suppression measures of (a) sinusoidal drive, (b) symmetrical push–pull drive, (c) electrostatic shielding of transformer windings, and (d) resonant common-mode choke. To see how effective each of these are, we measured coupled signal amplitudes and spectra for various reduced configurations. The data is summarized in Figure 9x.58, which

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[37] Probably also a trapezoidal waveform, i.e., a slew-rate-limited square wave.

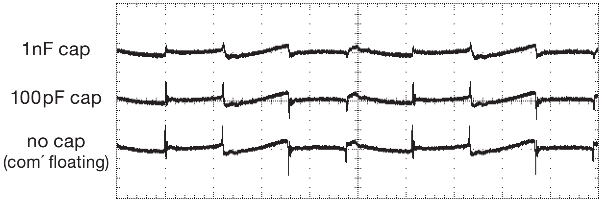

Figure 9x.56. Coupled ground noise for the shielded-transformer converter of Fig. 9x.55, measured across a 50 Ω bridging resistor (with three values of bypass capacitor), with its 12 Vdc output loaded to 25 mA. Note greatly expanded vertical sensitivity (50× to 200×), compared with Figs. 9x.52 and 9x.53. Horizontal: 2 μs/div; Vertical: 1 mV/div.

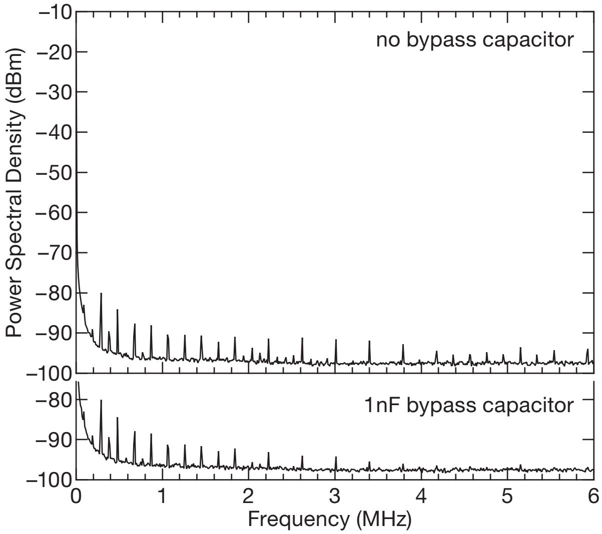

Figure 9x.57. Power spectrum for the shielded-transformer converter running at 100 kHz, measured with the same configuration as used for Fig. 9x.56 (and plotted on the same scale as Fig. 9x.54), showing a reduction in peak spectral power by some 50–70 dB.

SQUARE	SINE	TRIANGLE	SINGLE-ENDED	PUSH-PULL	SHIELDED	COMMON-MODE CHOKE	Vpp across 50Ω (mV)	Peak Spectral Line (dBm)
-	●	-	-	●	●	●	1.0	−80
-	-	●	-	●	●	●	1.0	−80
-	●	-	-	●	●	-	16	−60
-	●	-	-	●	-	-	26*	−34
-	●	-	●	-	-	-	62*	−29
●	-	-	-	●	●	●	24	−72
●	-	-	-	●	-	-	1400	−34
●	-	-	●	-	-	-	2200	−33

Figure 9x.58. “What matters?” Approximate ground-coupled clocking noise: signal level at the isolated common, measured across 50 Ω with respect to driver-side ground. Those marked with an asterisk exhibited wide pulse-like waveforms, all the rest were narrow spikes.

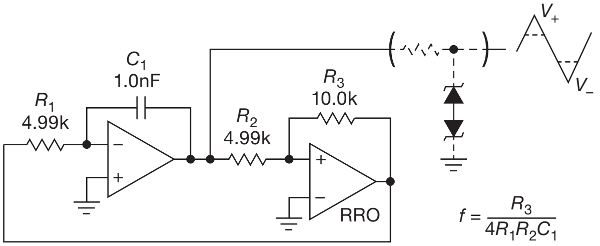

Figure 9x.59. Triangle-wave oscillator circuit, simpler than the sinewave version of Fig. 9x.55B yet retaining equivalent performance. This replaces U_{1a} and associated components in that circuit. The optional clamp creates a more efficient trapezoidal waveform without compromising performance (adjust subsequent gain appropriately).

demonstrates that, well, almost *everything* matters, if you want optimum suppression of clock signal. However, the drive waveform need not be sinusoidal, as long as it does not have discontinuities – it’s OK to use a triangle wave (or a slew-rate-limited square wave), as in Figure 9x.59. Parts like LTC’s LT1533 exploit this property (though their literature[38] does not address coupled common-mode clock noise, only switching noise as seen across the dc output (i.e., normal-mode noise).

For some applications it’s important to synchronize the various clocking signals in a system, so you don’t get beat notes and mixing products. For such applications you can use the circuit in Figure 9x.61 to create a very clean sinewave from a logic-level square wave of 50% duty cycle (use a toggling flip-flop, if needed, to ensure equality of HIGH and LOW durations). Here we used an LVC gate to drive a series-resonant *LC*, the latter forming a bandpass filter at 100 kHz for killing the harmonics; the additional shunt capacitance and *RC* section removed narrow spikes coupled through the inductor’s parasitic shunt capacitance. With this sinewave source the isolated power supply re-

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[38] See especially Jim Williams’ LTC App Note 70, “A Monolithic Switching Regulator with 100 μV Output Noise,” October 1997.

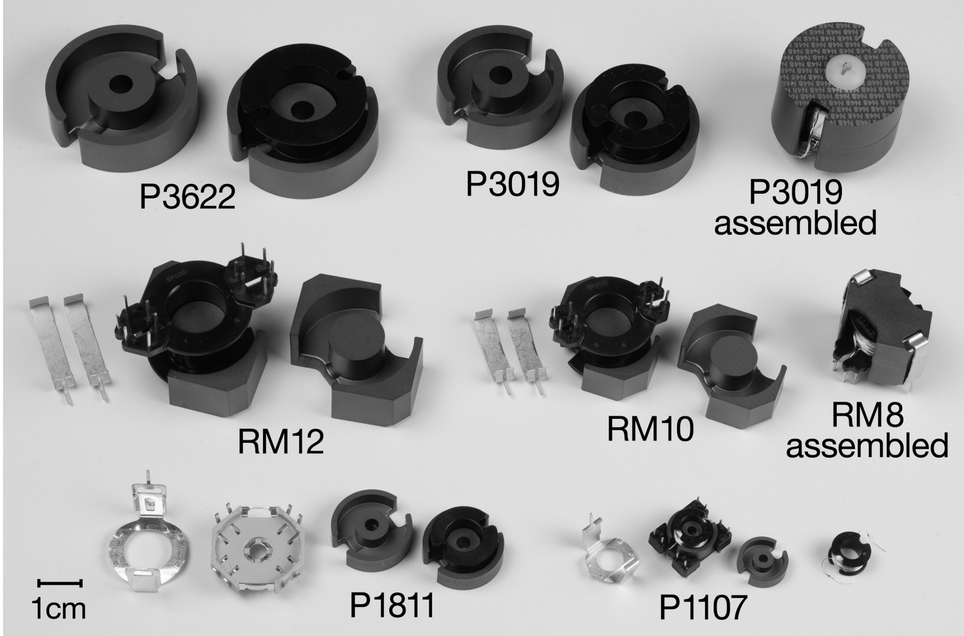

Figure 9x.60. Several sizes and styles of ferrite cores. Pot cores are sized by outer and inner diameter; e.g., a P3019 is 3 cm OD by 1.9 cm assembled height. The core halves are pictured with their matching "coil former" bobbins; note also the clamps and (for the two smallest pot-cores) the "terminal carriers." We used an RM10 core for L_1 and L_2 of Fig. 9x.55.

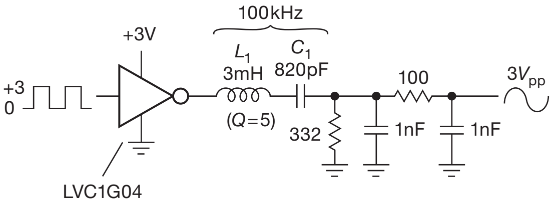

Figure 9x.61. A series resonant *LC* converts a logic-level square wave into a clean sinewave, so good you can't tell it's not a genuine sinewave when viewed on a 'scope (Fig. 9x.62). Trim C_1 to resonance (maximum sinewave amplitude) at the switching frequency.

tained its excellent common-mode isolation, as can be seen in the traces of Figure 9x.62.

This circuit design, combining symmetrical push–pull sinewave drive, electrostatically shielded transformer, and resonated common-mode choke, is really effective in suppressing common-mode switching noise – a 60 dB improvement over commercial modules is nothing to sneeze at. But for perspective keep in mind that many applications are rather insensitive to common-mode coupled noise on their power rails, particularly with robust grounding paths and shielding. You may need to resort to the kind of measures we've described only in unusual circumstances (for example, the delicate physics experiment that provided inspiration, in which programmable voltages are required, stable and quiet at the microvolt level, and they must ride on top of another programmable voltage, all this at the end of a 10 m length of cable).

Figure 9x.62. Measured waveforms when driving the converter of Fig. 9x.55 with sinewaves from the square-to-sine circuit of Fig. 9x.61. For L_1 we used a TDK 1433507C 3.3 mH inductor resonated with a 820 pF series capacitor (a Pulse Engineering PE-50502NL with 680 pF works identically). Horizontal: 2 μs/div.