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Magnetically Isolated Digital Coupling Circuit Solves Gate Drive and Communications Dilemmas

by Andrew Ferencz, Ferencz Consulting, Southborough, Mass.

Power engineers often need digital isolation and for a variety of reasons. They might need to control switches on the other side of an isolation barrier or to drive high-side switches. In other cases, they might need to pass communication signals, or to use digital methods to encode analog signals such as a PWM signal.

A number of solutions for implementing digital isolation exist in packaged form including optical isolators, magnetic isolators, and even capacitive isolators. When choosing among these various options, typically designers will look at characteristics of the digital isolation devices such as their drive requirements, delay, immunity to common-mode noise, operating temperature range, safety agency approvals, and capabilities of the output drive stage. Each solution has some type of tradeoff in performance or a key technology that differentiates it from the alternatives. Nevertheless, better performance often comes at some cost.

In 1991 I was managing the group at Computer Products developing the Basix full brick dc-dc converter. As part of this design, John Bassett designed a secondary-side-controlled converter that was based on his patented topology. The Basix converter required both a standard 48-Vdc telecom input and a 300-Vdc input for offline applications. Thus this product needed a way to transmit the control signal from the secondary feedback to the primary gate drive. Computer Products teamed up with a small group of engineers at Alliance Microsystems and one of their contributions was a tiny digital isolation circuit based on a one-turn pulse transformer. The safety isolation was created by using safety-approved triple-insulated wire and an appropriate spacing between the terminals.

In this application, the board was very crowded with parts as the custom design used a discrete controller. So in seeking an isolation circuit, we needed the smallest low-profile solution. I cannot go back in time to report on alternative solutions but I do remember the space was much too small for anything but a tiny toroid. Fortunately, we only needed one signal (the duty-cycle for the main switch) to cross the isolation barrier.

Since then, I have been developing power converters using digital control. In these designs, the best performance is often gained by using secondary-side control where the controller can directly measure the output voltage and current and thereby avoid the delays associated with an optical isolator. However, these designs still required that certain signals be passed across an isolation barrier. To that end, I have successfully reused the 1991 isolation circuit a number of times to perform functions such as safety-isolated serial communication, secondary-side control of primary MOSFETs, and high-side control of MOSFETs for active-clamp applications.

A New Twist On Transformer Isolation

Of course magnetic isolation itself is not new. Transformer-isolated gate drives have a long history and, depending on the particular requirements, one can find a reasonable solution that covers some range of operation. As best I know, no perfect transformer-isolated gate drive has yet to be developed. But for many applications, transformer gate drives are still used today, even in high-volume products. That said, most gate-drive transformers are significantly larger and more expensive than a single-turn pulse transformer. For this reason I have been reusing the digital isolation circuit concept developed by Alliance Microsystems for size, simplicity, and (most important) low cost.

The digital isolation circuit described below has been developed to cover some specific requirements that are often encountered in power supplies (Fig. 1.) Specifically, it enables transmission of a digital signal that has very little delay (<10 ns), high immunity to noise, low cost, and the ability to meet a very high isolation test voltage (>8 kV) with only changes to spacing or wire type.

Although I do not have copies of the original schematic, I do remember the pulse transformer driving the npn and pnp transistors as shown. I have worked out the values of capacitance, inductance, and loading that have worked well for my needs. One of the key components, the pulse transformer, was not available as a standard part. So I worked with Xfrms, Inc. to develop an off-the-shelf pulse transformer that uses triple-insulated wire on both sides and meets 6.8 mm creepage and clearance. This transformer is model XF0056-PT1.

Since the transformer is the critical element in achieving safety isolation, it's worth taking a moment to discuss the physical requirements for transformer construction. In order to meet the requirements of safety from hazardous voltages, there are several methods that can be applied and often more than one is needed.

One method is physical distance. One type of distance is called creepage, or distance along a surface. The other type is called clearance, or distance through air. Creepage requirements depend on the type of material and are usually equal to or greater than clearance requirements.

Another method to achieve safety is distance through insulation. For example, typically 0.4 mm (or 0.016 in.) of solid insulation is enough to be considered "reinforced insulation." This is a simplification as the type of material including the flammability and operating temperature range has to be suitable to the application too.

An increase in the thickness of the insulation is not the only way to achieve reinforced insulation. Another means of meeting the reinforced insulation requirement is by insulating the wire with multiple layers of thin material such that each layer is capable of passing a high potential (hi-pot) test. Triple-insulated wire, like that used to build the transformer in this design, is a special wire that literally has three thin layers. These layers are often as thin as 0.001 in. but more typically 0.0015 in. thick, which allows primary and secondary wires to be in close proximity but still be safe.

A tiny pulse transformer needs to use this type of triple-insulated wire to be considered safe. A high-permeability ferrite core would be considered a conductor (at least not an insulator), so even if the core were large you could not directly wind magnet wire on a core and have it be considered safe from hazardous voltages. Since the pulse transformer needs to connect to a PCB the distance between the terminals also has to meet the requirements for reinforced insulation, hence the 6.8-mm distance mentioned above.

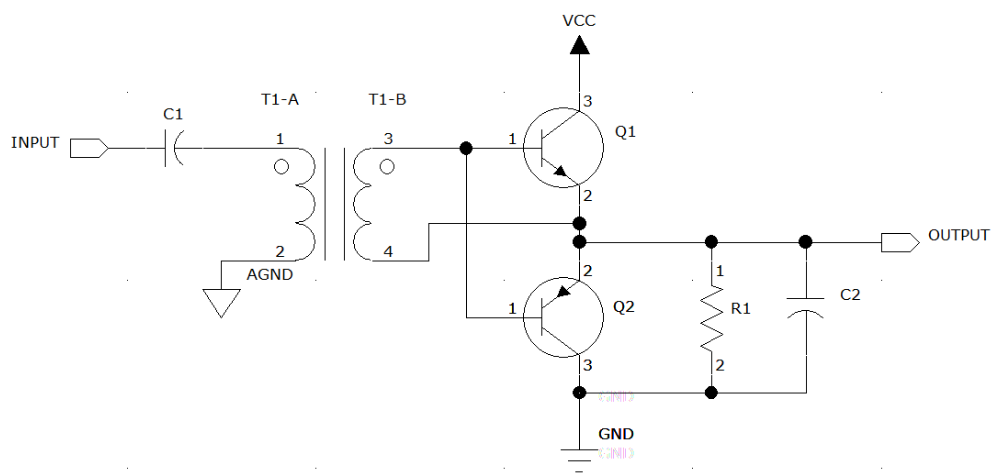

Fig. 1. Basic isolated digital coupler circuit. Input and output are fully isolated by T1, potentially across a safety isolation barrier if T1 is designed properly.

How It Works

The circuit in Fig. 1 operates as follows. Typically, the input to this circuit is a 3.3-V or 5-V digital signal. The critical requirement for this signal is that it be able to drive the pulse transformer T1 with a reasonably rapid dv/dt on the order of 20 ns or less. I have used standard 32-mA output rated logic gates (74LVC for instance) to buffer the microcontroller or DSP pins that generated this signal.

C1 differentiates the step in voltage, putting a pulse of current through T1-A , the transformer primary. T1 acts as a current transformer. The current induced in T1-B, depending on the direction, turns on either Q1 or Q2. C2 holds the signal, while R1 is used to establish a voltage in the absence of pulses. Fig. 2 shows current flow through the circuit at turn-on.

The input could be an asynchronous communication signal such as RS-232 or it could be the gate-drive signal from a DSP or even a PWM controller. The output could go to a microcontroller, RS-232 buffer, or gate-driver input.

For gate drives, it might be required to have the device off at the beginning of operation or during shutdown. That is the purpose of R1. Likewise, R1 could be connected to VCC so the default output is high. Or the output signal could be put into a circuit with positive feedback to latch it in a particular state as a 1-bit memory.

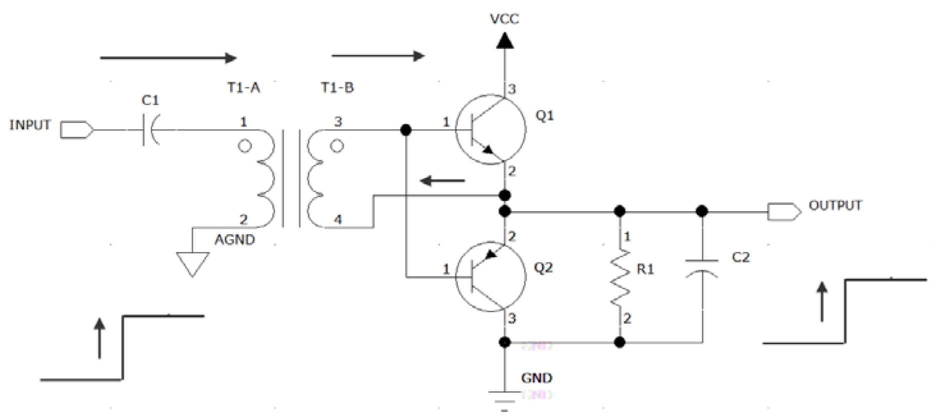

Fig. 2. Turn-on details showing current flow.

A typical implementation uses a value of 1000 pF to 2200 pF for C1, a toroid with 4 µH or more of inductance for T1, two 2N3904s or equivalents for Q1 and Q2, 4700 pF for C2, and 100 kΩ for R1. But these values can change so long as you understand the subtle requirements of this circuit.

First, a wideband pulse transformer often appears as a resistive impedance over a broad range of frequencies. This resistance works against the output impedance of the input driver. For instance, if the impedance looks to be about 50 Ω and the output impedance of the drive is 50 Ω, only half of the voltage signal is available. Thus, adding turns to the primary can compensate for high drive impedance or lower drive voltage by raising the load impedance. A typical core material has a permeability of 3000 or greater as high inductance is desired. I have used very small toroids or small balun cores successfully.

Second, the drive signal on the secondary must be high enough to exceed the base-emitter voltage of the transistors; nothing happens if the secondary voltage is too low. So, the reflected drive voltage must be measured and can also be increased with more turns on the secondary but at a cost of secondary drive current.

Third, the system must be critically damped. The LC network on the primary should not ring back or else one of the secondary transistors would turn on and then the other, which was not intended. Ideally, the magnetizing inductance would not be excited at all and this would just be a current transformer. But we need some voltage to turn on Q1 and Q2. This requirement is easy to meet, particularly if you use a blocking capacitor C1 that is just big enough to work with margin but not much bigger. You need a small hammer, not a sledge.

The Xforms device (XF0056-PT1) was designed to work from 3.3 V to 5 V and uses two turns on the primary and two turns on the secondary.

One recent implementation of this digital isolation circuit was in a secondary-side-controlled full-bridge converter, which was controlled by a DSP. The drive circuit for this converter is shown in Fig. 3.

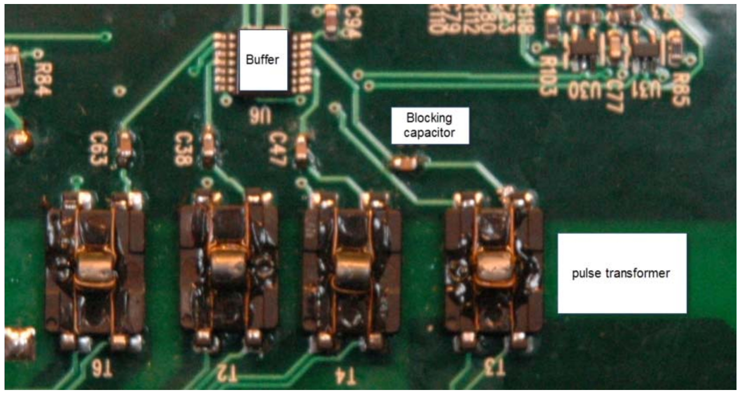

Fig. 3. Pulse drive circuit for secondary-side-controlled full-bridge converter.

The waveforms for input and output are shown in Figs. 4 and 5. As can be seen in these oscilloscope images, the delay is less than 30 ns. With higher pulse current it is possible to get the delay under 10 ns.

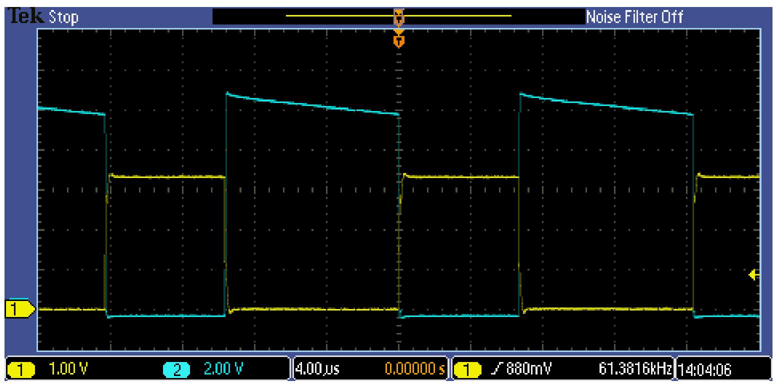

Fig.4. Input and output signals for digital isolation circuit shown in Fig. 3. Yellow trace is the 3.3-V drive. Blue trace is the secondary signal.

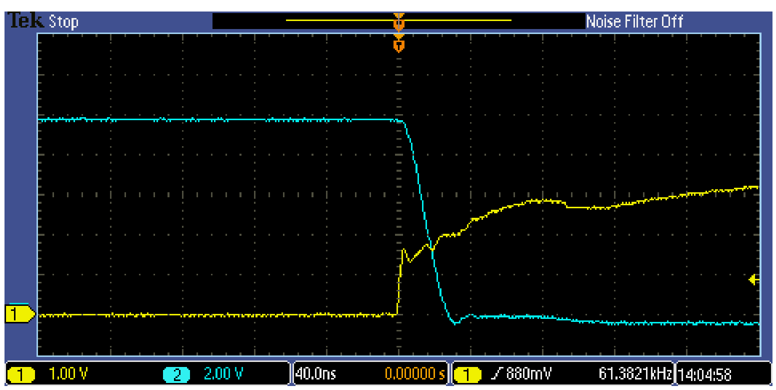

Fig. 5. Input and output waveforms from Fig. 4 magnified to show details of the delay.

The digital isolation circuit described in this article can be used as the basis for an isolated RS-232 interface or—with an extra part—for an isolated I^2C interface.

What differentiates this circuit from typical gate-drive transformer circuits is that the magnetizing inductance is not excited so that the pulse transformer is ideally "stateless." Some gate-drive circuits suffer in that, under some conditions, the residual energy in the magnetizing inductance must be dissipated. Solutions to this problem exist, and are sometimes as simple as just a diode clamp or other method.

One benefit of the standard gate-drive circuit is that both signal and power are delivered at the same time or during the "on" or "off" interval. However, in this circuit no attempt is made to transmit power, just the signal. The VCC power must come from someplace else such as a bias circuit or bootstrap supply.

As can be seen from the circuit diagram, excluding the pulse transformer, the component cost is on the order of just $0.10 to $0.15. Furthermore, even the cost of the transformer can be kept very low as it is possible to make the pulse transformer using planar technology. Cores for such transformers are on the order of $0.10 or less.

Contrast those costs with that of a typical digital isolator that costs about a $1.00 per channel (based on web-based pricing from distributors) and does not meet safety requirements. Optical digital isolators can be less expensive but usually have a more limited temperature range, more delay (the less expensive ones anyway), and take more power to drive.

There are a few caveats to keep in mind when using this isolation circuit. The circuit must be bread boarded and proven. The weakness in the design is its potential to “swallow up” small pulses where a very narrow on-pulse, for instance, does not reset the dc blocking capacitor and a proper signal does not cross the barrier. One must test for this possibility. I have done implementations where this is not a problem and at other times I have used a minimum pulse-width function in the DSP to prevent this from happening.

About The Author

Andrew Ferencz received his SB and SM degrees from MIT in 1987 and 1989. He was previously the VP, Technology at Galaxy Power in Westborough, Mass., developing high power density dc-dc converters. Prior to that, Andrew was the VP, Engineering at Acumentrics in Westwood, Mass. For the last eighteen months he has been self-employed, working on various projects as a turnkey design engineer and consultant in the medical, military, commercial, and industrial markets. Andrew can be reached at andrew[at]ferenczconsulting.com.