Galvanic Isolation of Logic Signals at Extreme Temperatures

Many extreme temperature applications such as power converters and motor drivers operate from power rails that are floating, noisy and have extremely high voltages. Typically the logic signal is only a few volts but is must be transmitted in an environment with hundreds or thousands of volts of common mode voltage. In some cases isolation is required for safety reasons to prevent leakage currents that could present an electrical shock hazard. For example the ground reference for a high side driver of an all N channel half bridge is referenced to the switch pin and switches between ground and the power rail within a few nanoseconds. At normal operating temperatures there are many specialized components such as opto-isolators, capacitive coupled devices and devices with integrated high frequency transformers that transmit logic signals across the isolation barrier. These specialized integrated circuits that provide isolation may not function reliably at elevated temperatures; those that do tend to be expensive. With special consideration of the system partitioning, it may be possible to avoid the need for galvanic isolation at extreme temperatures. It may be possible to provide the isolation in a remote more benign environment and send the isolated signal down a cable with appropriate impedance matching. When galvanic isolation at extreme temperatures is necessary, there must be temperature considerations for the components used. For example, when designing pulse transformers, the temperature effects on the magnetic core material properties such as permeability and frequency response must be considered as well as the Curie temperature. Modulation of the logic signals can help to reduce transformer size. Since the isolated driver functions typically require power, a novel method of winding the transformer is discussed; this method allows the drive signal to be transferred across the isolation barrier in the same transformer core that is used to provide isolated power to the driver. This paper addresses these topics and provides several alternative solutions to the problem of galvanic signal isolation at extreme temperatures.

Non-isolated power converters and motor drivers require control systems that provide galvanic isolation between the power lines and the earth ground referenced controller. This greatly reduces ground leakage currents that propose a shock hazard. Historically, galvanic isolation was provided by transformers and optical isolator integrated circuits. The isolation standards relating to integrated circuits are written for optical isolators but are also being applied to ICs with integrated modulators and isolation transformers. Applicable industry standards are UL1577 and EN60747-5. UL1577 requires a voltage isolation of at least 3.5kVrms for 60 seconds from the input side to the output side of the coupling device. In a half bridge or full bridge topology using N channel MOSFETs or NPN devices, the high side driver floats and uses the switch pin as a reference. The switch pin voltage represents a common mode voltage to the ground based controller. For these applications, it can be necessary for the level shifter or isolation technique to ignore common mode voltage transients in excess of 15kV/us.

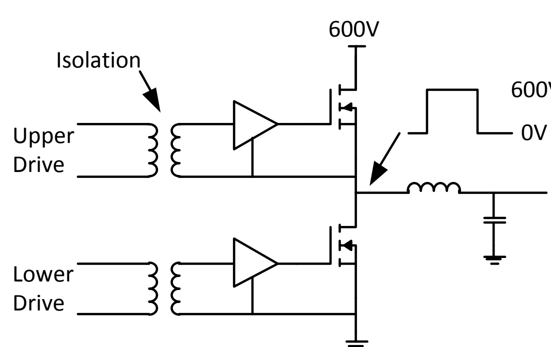

Figure 1: Isolated half bridge driver

There are two methods used to provide the galvanic isolation, optical coupling and transformer coupling. The electrical current is path is severed by conversion to magnetism or light and thus galvanic isolation is achieved. Some ICs can also achieve specification compatible coupling using capacitive coupling. IC manufacturers have developed full integrated transistor drivers that have isolation integrated inside the single component. These devices have impressive technology and are relatively inexpensive, but not suitable for extreme temperatures. The Infineon 1ED020I12-F, is an IGBT driver which provides an RF modulator and integrated transformer coupling implemented on a silicon die; its maximum operating junction temperature is 150°C. [1] The Avago ACPL-333J, is an IGBT driver which provides an integrated optical coupler operates to 125°C. [2] These integrated circuits drive the transistors with high currents to insure fast turn on and turn off times; because of this they would be located in close proximity to the transistors they drive. If the transistor is SiC and the environment is extremely high temperature, these integrated circuits are not a viable solution.

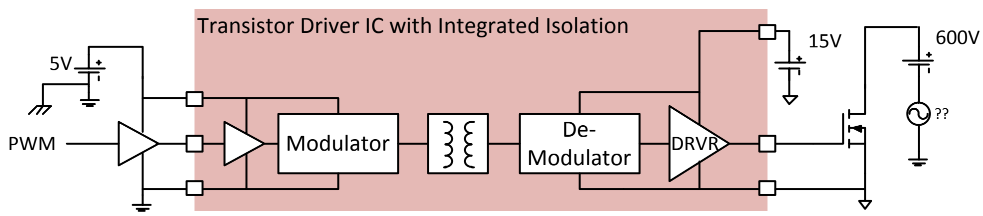

Figure 2: Fully Integrated Driver plus Isolator

There are digital galvanic isolators that provide just the signal isolation, but not the low impedance transistor driver. These devices can work in conjunction with a non-isolated power driver IC that provides the drive strength to turn on the switching transistor. The Analog Devices ADuM5010, is a transformer coupled device, that operates up to 105°C. [3] The IXYS CPC5001, an optically coupled device, operates to 85°C. [4] There are many other ICs from other vendors that have similar performance. These devices may be suitable for extreme temperature systems provided the controller electronics and isolator can be located in a more thermally benign environment and transmit the logic signal over a controlled impedance cable to the driver and transistor which are operating at a much higher temperature. Transmission delay for twisted pair is about 5ns/meter and signal attenuation is tolerable for cables less than 30 meters making a remotely located controller feasible. The majority of interference in a twisted cable is common mode so using a differential signal is less susceptible to a noisy environment. The driver should be differential, which may require the use of two channels of a galvanic isolated logic IC.

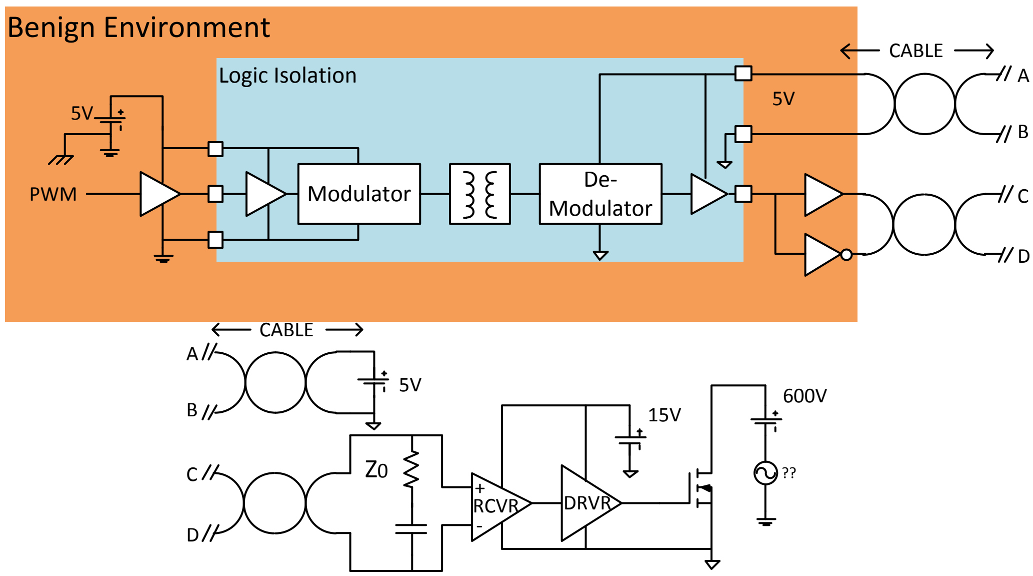

Figure 3: Logic Isolator remotely located in benign environment

Disadvantages to using a logic isolator is the cable itself must be referenced to the high common mode signal will have high voltage transients that will be an EMI and safety concern. Another disadvantage is the remotely located isolator requires power referenced to the transistor driver which must be cabled back. A simple solution that overcomes these disadvantages is to utilize a pulse transformer to provide the isolation. If a pulse transformer is used instead of a logic isolator, the transformer can be located at the high temperature and high voltage end of the cable; in this case the cable carries a safe voltage and does not have common mode transients producing EMI. The transformer does not require a power supply from the driven transistor back to the benign environment. To minimize reflections the transmission line should be properly terminated. Using a capacitive coupled terminator reduces the loading on the driver for longer duration pulses. [5]

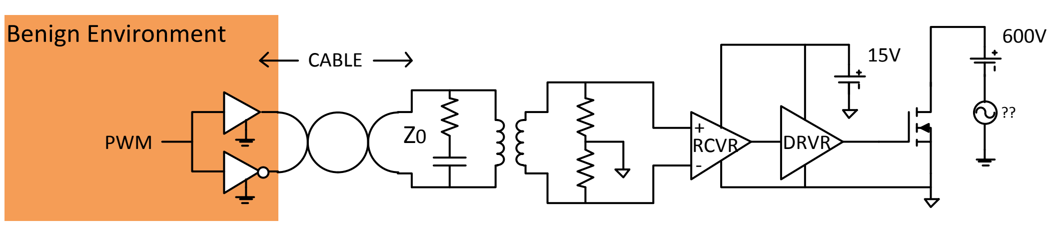

Figure 4: Pulse transformer at the driven device end of the cable

The rule of thumb for capacitive termination is to set the terminator RC time constant to twice the down and back transit time. For the scope traces below a 30 ft length of 24 AWG twisted pair cable was used. The characteristic impedance for the cable is 100 ohms. The transit time down and back was 125ns. The termination used was 100 ohms in series with 270pf. The transformer used for the measurements had a 1 to 1 turns ratio, a primary inductance of 1.65mH, a leakage inductance of 9.36uH, and <5pf primary to secondary capacitance. The driver was a HC CMOS logic device. The differential transformer output used 2k resistors. The trace on the left shows the differential cable drive as pink and green and the differential transformer output as dark and light blue.

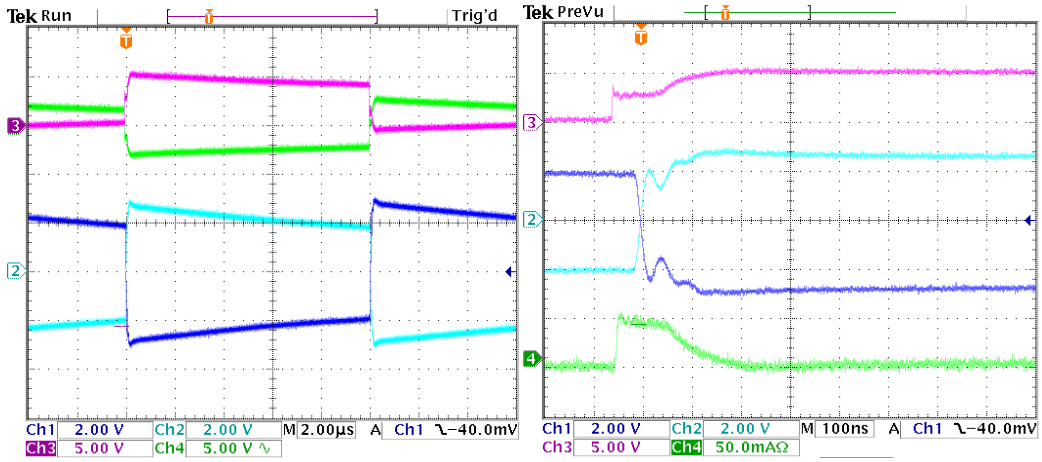

Figure 5: Output of pulse transformer at the end of 30 feet of 26AWG twisted pair.

A close up of the rise time (Figure 5 on the right) shows the effect of the termination. In this case the green trace shows the transformer primary current. This current is a pulse that drops to zero after the termination capacitance charges.

For the transformer to function in the high temperature environment it must be composed of wire with insulation and magnetic core properties that that can handle the elevated temperature. For high temperature applications magnet wire with a polyimide insulation is rated for continuous operation at 240^{o}C and thermoplastic flow to 400^{o}C. [6] Polyimide-ML coated wire conforms to EN60317-46 and 47 and is readily available and can be purchased with insulation ranging from single layer to quadruple layer; the advantage of more layers is an increase in the insulation thickness. A single layer for AWG 46 has an insulation thickness of 0. 13 mils between adjacent conductors and a quad layer has similar thickness of 0.8 mils. Dupont polyimide 1mil HN film insulation has 7kVrms at 0^{o}C and degrades to 4.2kV at 240^{o}C. [7] The increased quad insulation properties translates to an increase in the breakdown voltage between the primary and secondary windings and more flexibility in transformer clearances.

It is important to separate the primary and secondary windings to reduce primary to secondary coupling capacitance. At 15kV/us transient rates the current flow through one pF of capacitance from primary to secondary is 15mA. There is a downside, though, to separation to the separation of the primary and secondary windings in that it introduces leakage inductance into the coupling transformer. Leakage current can be modeled as a series inductance which attenuates the pulse and can introduce resonance with load capacitance.

The core material must have a high Curie temperature to operate at extremely high temperatures; the Curie temperature is the point a magnetic material loses its magnetic properties. Some ferrite materials such as NiZn exhibit Curie temperatures up to 380^{o}C and actually show an increase in initial permeability at high temperatures.[8] Increased permeability increases the primary inductance which reduces the current needed to drive the transformer. Another useful property of NiZn is it has a relatively flat permeability roll off out to 100Mhz and is suitable for 10MHz pulses. The downside to NiZn is its relatively low permeability which for a given primary inductance target will translate into a requirement for more turns and a higher leakage inductance as a result.

The goal for companies, like Microsemi, that manufacture high power transistor modules is to reduce the size of the coupling pulse transformer for possible module integration. One technique to accomplish this is to modulate the logic pulse with a higher frequency carrier. One technique for doing this is on off keying or OOK. With this technique, the transformer only needs to pass signals that are 10MHz and higher. This allows the transformer primary inductance to be quite low and therefore reduces the number of windings required and allows for a small core window area. The Microsemi LX4510 Extended Temperature SiC Device driver integrates the receiver and demodulator.

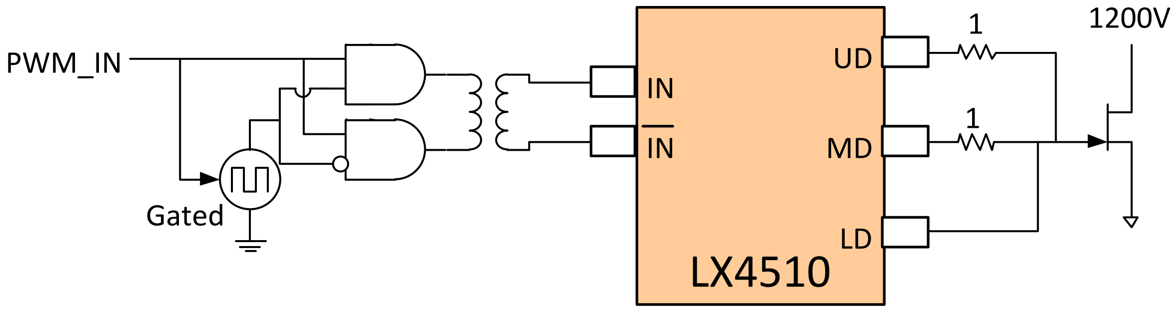

Figure 6: On off keying modulator and differential receiver/driver

The NiZn core material is available from several core manufacturers. Fair-rite makes several sizes of toroidal core using their NiZn material 61 and Epcos makes small pot cores using their NiZn material K1. A polyimide magnet wire is available from MWS in various gauges and voltage ratings. The transformer below was wound on a 5.95mm diameter toroid core made of Fair-rite 61 NiZn soft ferrite material (part number 5961000101). The primary and secondary were wound with 30 turns of AWG 46 polyimide magnet wire quad insulated from MWS (part number 46 QML-240).

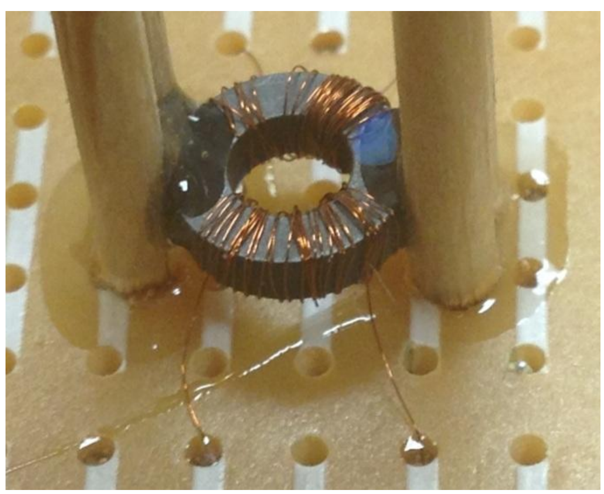

Figure 7: Miniature pulse transformer for 10MHz pulses

This transformer had the performance parameters:

Primary Inductance: 28.6uH
Leackage Inductance: 16.85uH

Primary to secondary capacitance: 0.25pF

This transformer was driven using the circuit of figure 6. The transformer was terminated in 2kΩ from each output to a common ground. The traces below show the performance at 25°C (left) and 250°C (right). Dark blue = PWM, Light blue = one side of primary, Pink and Green = transformer secondary. The scope pictures show very little performance change over temperature.

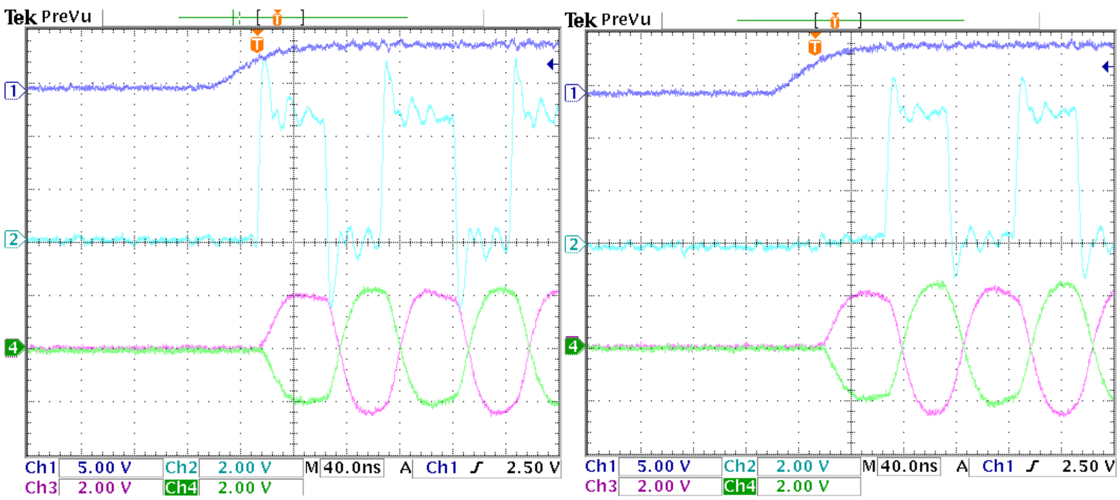

Figure 8: Miniature pulse transformer passing 10MHz OOK pulses

For most of the applications requiring a floating high side driver, it is also necessary to provide isolated power rails to power the high side driver. This technique typically requires a "DC transformer" which consists of a push-pull drive to one or more transformers. The resultant outputs are unregulated and are roughly the product of the primary voltage and the turns ratio.

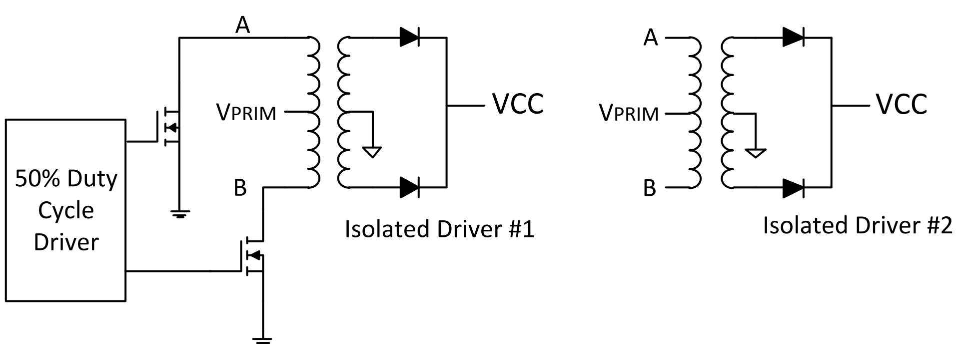

Figure 4: DC Transformer driving for two isolated driver power supplies

The power transformer core can simultaneously serve to implement a pulse transformer as well by using a unique winding technique. This patented winding technique involves winding the signal transformer such that the flux produced by the power transformer is common mode to the pulse transformer magnetic path. [9] This technique is well suited for planner magnetics. The winding technique is shown below:

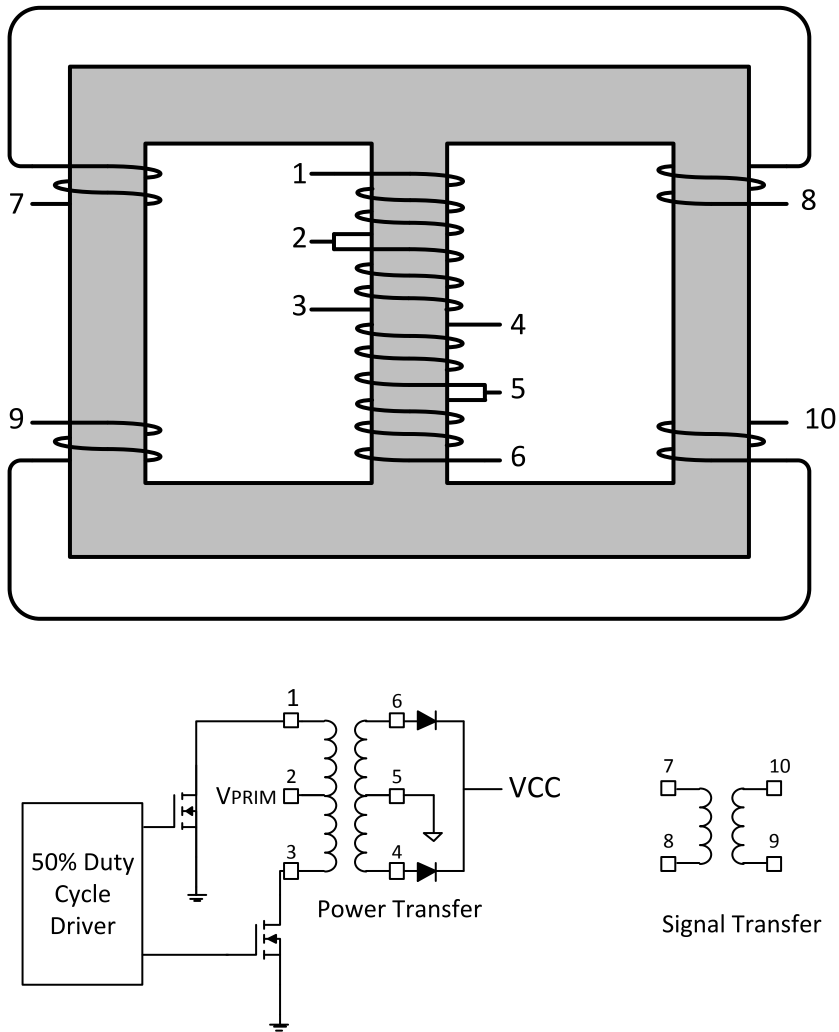

Figure 5: Power and pulse transformer on common core

In conclusion, high power applications typically require some form of galvanic isolation between the controller and the power switches. Several fully integrated isolated driver solutions are available but are not specified for extreme temperature operation. Several logic isolator integrated circuits are available and can be used if the driver can be kept in a remote temperature compatible environment. A pulse transformer can be used to provide isolation and can be placed at the end of a twisted pair cable if properly terminated; the transformer output can provide a control signal to an isolated device driver. A reduction in pulse transformer size is possible by using a carrier frequency to modulate the driver pulse. The LX4510 integrated circuit solution from Microsemi incorporates a demodulator for a high frequency OOK modulated signal. In the interest of a reduction in magnetic size, the winding technique presented can be used to add the pulse transformer to the power magnetic core without the need for an additional pulse transformer core.

References:

[1] The 1ED020I12-F datasheet V2.3, Infineon.

[2] The ACPL-333J datasheet, Avago, Oct 25, 2012.
[3] The ADuM5010 datasheet Rev A, Analog Devices.
[4] The DS-CPC5001-R02 datasheet, IXYS.
[5] AC Termination for Signal Busses; Ben Smith, AVX
[6] Magnet Wire Catalog, MWS Wire Industries
[7] Summary of Properties of Kapton Films, Dupont
[8] The 5961000101 dtatsheet, Fair-Rite Products Corp.
[9] US Patent 2009/0230776