Digital Isolators Offer Performance Advantages in Industrial Motor Drive Applications

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IDEA IN BRIEF

Electronic controls used in industrial motor drives must be capable of delivering high system performance in a very demanding electrical environment. The power electronic circuits produce sharp voltage edges on motor windings that can be capacitively coupled into the low voltage circuits. The nonideal behavior of the power switches and parasitic elements in the power circuit also generates inductively coupled noise. The long cables between the control circuits and the motor and sensors provide multiple paths to couple noise into control feedback signals. High performance drives require high fidelity feedback control and signals that must be isolated from the very noisy power circuits. In a typical drive system this includes isolation of gate drive signals to drive the power inverter, current, and position feedback signals to motor controller and isolation of communication signals between various subsystems. The signal isolation must be delivered without compromising the bandwidth of the signal path or without adding significant system cost. Optocouplers have been the traditional method to create safety isolation across the isolation barrier. Even though optocouplers have been used for decades, they have limitations that affect the system level performance.

The widespread adoption of variable speed motor drives in industrial applications has been enabled by the availability of highly efficient power electronic switches and cost effective electronic control circuits. The design challenge is to couple the high power switching circuits with the low voltage control circuits without trading off noise immunity or switching speed.
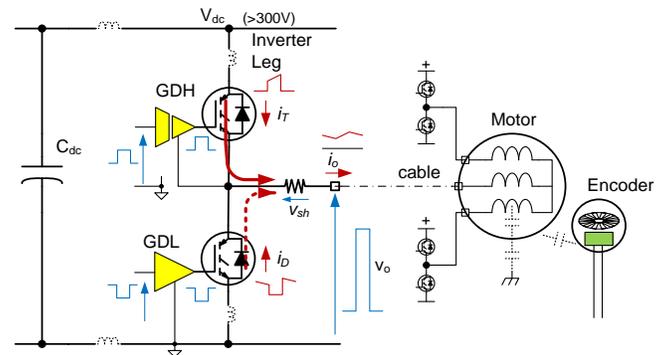

Figure 1. Power inverter circuit including parasitic elements.

The efficiency of a modern switching power inverter typically exceeds 95% using power transistor switches that alternatively connect the motor windings between upper and lower rails of a high voltage dc rail. This process minimizes the losses in the inverter because the power transistors operate in a fully saturated mode which minimizes the voltage drop and power loss when conducting. There are additional power transistor losses while switching because during this period there is a large voltage across the transistor while the load current switches between upper and lower power devices. Power semiconductor companies design transistors such as IGBT's with short turn on and turn off times to minimize this switching power loss. However, this higher switching speed has some unwanted side effects, such as an increase in switching noise.

On the drive control side, continuing advances in VLSI processing has improved the cost and performance of mixed signal control circuits to enable the widespread adoption of advanced digital control algorithms for improved efficiency of ac motors. The price of this improved performance is a reduction in IC operating voltages from 12 V to 5 V and now to 3.3 V with the consequential increased sensitivity to noise. The traditional approach of filtering this noise is very often not available because of the need to maintain drive system bandwidth which is typically a key performance parameter.

MOTOR DRIVE INVERTER ENVIRONMENT

A three phase inverter is a power electronics switching circuit that controls the flow of power from dc power rails to three ac motor windings. The inverter has three identical legs and each includes two IGBT transistors and two diodes as shown in Figure 1. Each motor winding is connected to the common node connecting the high and low side transistors via a current shunt. The inverter switches the motor windings between the upper and lower voltage rails of the dc bus to control the average voltage. The windings are highly inductive and will oppose a change in the current flow so when a power transistor is switched off current starts to flow in the diode connected to the opposite rail. This allows continuous current to flow to the motor windings even if there is discontinuous conduction through the inverter power devices and dc link capacitor. The motor winding impedance acts as a low pass filter for the high voltage pulse width modulated square wave output voltage from the inverter.

There are significant challenges when connecting the low voltage control circuits to the power inverter. A very basic problem is that the high side transistor emitter node is switching between the upper and lower rails of the high voltage bus. First of all, the high side driver must be capable of driving the gate signal relative to an emitter that could be 300 V or more above the input signal common. Secondly, the motor current signal across the shunt (v_{sh}) must be extracted from a 300 V or more common-mode voltage. Additional problems are introduced by parasitic elements in the power circuit. PCB trace inductances of even 10 nH can introduce significant voltages (>10 V) when power transistors or diodes turn on or off at rates more than 1 A/ns. Parasitic and component capacitances will result in ringing that extends the duration of the noise pulse generated by the device switching. Even the high frequency impedance of the motor power cables can introduce problems because for safety reasons the power board may be located a long distance from the motor. Other effects include noise coupled into feedback sensor signals from the motor because of the fast switching winding voltage waveforms. The problem grows in magnitude as the power rating of the drive circuit increases the physical size of the circuit board resulting in even higher parasitic inductances along with even higher current and voltage switching rates.

The elimination of noise coupling by isolating control and power circuits is a major tool in combating this problem. The performance of the isolating circuits is a key element determining drive performance. The shaft position encoder generates a digital pulse stream at frequencies of 100 kHz or more as the shaft rotates. However, in many cases, a circuit mounted on the encoder improves the precision of the device and increases the data rate over 10 Mbps. Also, the feedback signal across the shunt can be isolated by first converting the data to a digital bit stream and then isolating the bit stream from the low power circuits. In this case, the data rates are 10 Mbps to 20 Mbps.

The switching performance required for the gate drive circuits does not seem demanding considering motor drive inverter switching rates rarely exceed 20 kHz. However, there is a requirement to introduce a dead time between the switching signals for the high and low side devices to prevent shoot through. This dead time is a function of the delays in the turn on/off of the power switches and the uncertainty in the delay introduced by the isolation circuits. An extended dead time introduces further nonlinearity into the power inverter transfer function that will generate unwanted current harmonics and potentially reduce the drive efficiency.

Thus, it is critical that the method of sending data across the isolation barrier between the power circuits and control circuitry not introduce timing uncertainty in the switching and be immune to noise.

COMPARISON OF ISOLATOR TECHNOLOGY TRANSMISSION SPEEDS

The isolation should not contribute any appreciable timing uncertainty or timing errors to the overall system performance. Standard optocouplers have propagation delays in the order of microseconds, which can vary considerably from part to part, over temperature and lifetime. Optocoupler technology has fundamental limitations in timing performance whereas modern digital isolators use a completely different principle of operation with inherently higher speeds.

Increasing the speed of the optocoupler can be done with trade-offs. Optocouplers work by sending light from an LED across an optically clear isolating material and detecting the light with a photodiode on the other side. The speed of an optocoupler is a directly related to the speed of the detector photodiode and the time that it takes to charge its diode capacitance. One way to reduce the propagation delay is to increase the amount of light transmitted. The delay could be reduced by a factor of 2 or 3 by increasing the LED current at the cost of increasing the power consumption of the device, up to 50 mW per data channel.

Another way to increase the speed is to reduce the light transmission losses by making a thinner isolation barrier. To retain the same isolation capability requires an additional layer of material with the trade-off of higher prices. Higher speed optocouplers are many times more expensive than standard low cost optocouplers.

In contrast, digital isolators work using standard high-speed CMOS processes with isolated on chip microtransformers. The transmission speed is inherently much faster than opto-couplers. The higher speeds are inherent in the circuitry and design and do not require more complex and costly isolation materials for higher speeds. The transformers can pass data at transmission speeds of up to 150 Mbps with propagation delays as low as 32 ns with <5 mW of power consumption for switching speeds of 25 kHz or more. Another benefit of the faster speeds is that the matching between channels is better than 5 ns, more than an order of magnitude better than standard optocouplers and still 3 to 4 times better than the fastest optocouplers at about half the price per channel.

ISOLATION NOISE IMMUNITY

Within the motor drive system, the isolation provides an opportunity to separate noise sources as well by galvanically isolating the noise from the power switching circuitry and the control circuitry. There is a need for safety isolation between all of the following: high voltage bus, line voltages, and the user interface to protect both people and other equipment. There is also a need for functional isolation between the high and low side switches and control circuitry. The isolation components must be able to provide the necessary isolation, but also must be insensitive to a noisy environment.

The measure of an isolator's ability to separate high speed noises between ground domains is usually specified as the common-mode transient immunity (CMTI). The CMTI is a measure of how well an isolator will reject voltage noises across the barrier without the isolator data communications being disrupted by the noise. This is measured in units of kV/µs transients.
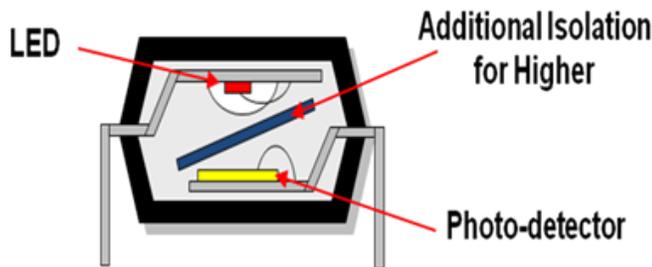

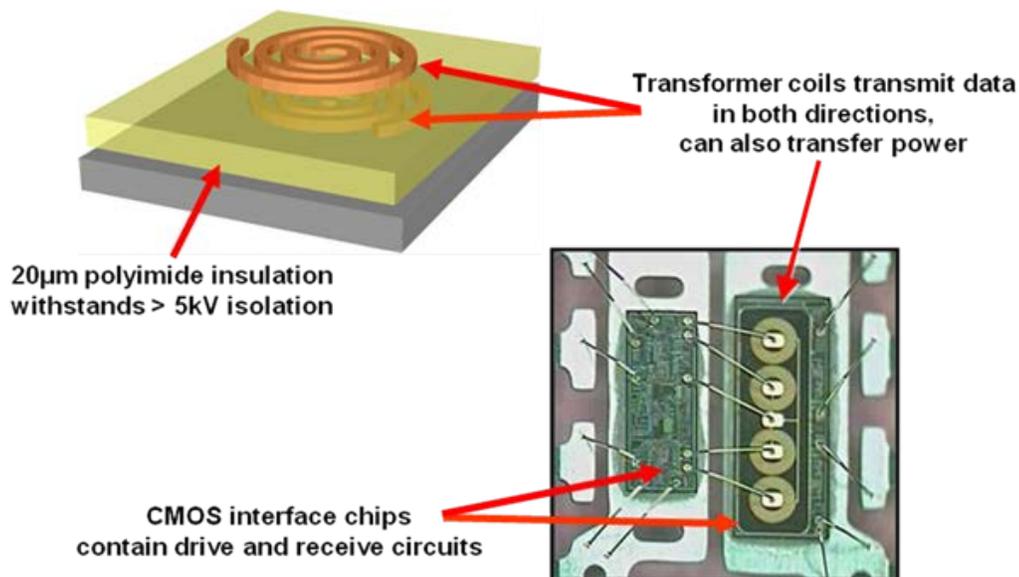*Figure 2. Optocoupler internal structure.*

Figure 3. Structure of a transformer based digital isolator.

The path for voltage transient noise to cross the barrier is generally parasitic capacitances across the barrier within the isolator. Optocouplers typically have a relatively poor CMTI of 15 kV/µs. Some modern digital isolators use capacitively coupled data isolation which has the same path for signals and common mode noise. Transformer based isolators, such as Analog Devices *i*Coupler digital isolators, have a signal path that is different than the noise path and typically have CMTI values of 50 kV/µs or greater.

INSULATION MATERIAL AND RELIABILITY

Digital isolators use foundry CMOS processes and are limited to materials commonly used in foundries. Nonstandard materials complicate production, resulting in poor manufacturability and higher costs. Common insulating materials include polymers such as polyimide (PI), which can be spun on as a thin film and silicon dioxide (SiO2). Both have well known insulating properties and have been used in standard semiconductor processing for years. Polymers have been the basis for many optocouplers, giving them an established history as a high-voltage insulator.

Safety standards typically specify a one minute voltage withstand rating (typically 2.5 kV rms to 5 kV rms) and working voltage (typically 125 V rms to 400 V rms). Some standards also specify shorter duration, surge voltage (for example, 10 kV peak for 50 µs) as part of certification for reinforced insulation. Polymer/polyimide-based isolators yield the best isolation properties (see Table 1).

Polyimide-based digital isolators are similar to optocouplers and exceed motor working lifetimes at typical working voltages with a 50-year rated lifetime. SiO2-based isolators provide a similar working lifetime, however, weaker protection against high energy surges.

Under continuous use at high temperatures optocouplers can have their lifetime limited not by a breakdown in the isolation material but by a wear out of the LED. For 10,000 hours of operation at elevate temperatures >85°C, the current transfer ratio (CTR) of the optocoupler will degrade by 10% to 20%. For 100,000 hours the CTR can drop by half or more.

Table 1. Comparison of Isolation Material Capability

	Polymer-Based Optocoupler	Polyimide-Based Digital Isolator	SiO2-Based Digital Isolator
Withstand Voltage [1 Minute]	7.5 kV rms	5 kV rms	5 kV rms
Lifetime at 400 V rms Working Voltage	50 Years	50 Years	50 Years
Surge Voltage Level for Reinforced Rating	20 kV	12 kV	6 kV
Distance Through the Insulation	400 µm	20 µm	8 µm

INTEGRATION POSSIBILITIES

Optocoupler LEDs and optimized photo-detectors are not compatible with low cost CMOS technology. Any integration of other features such as gate drivers with desaturated detection, isolated current detection using Σ-Δ ADCs, and multi-directional data flow requires multichip solutions making optocouplers with these features very expensive. Digital isolators using CMOS technology with isolated transformers can add these functions as a natural progression of increased integration. Because transformers can also be used to transmit isolated power, the high-side power can be transmitted from the same package without the need for boot strapping, which is problematic in some applications. Transformer-based digital isolators are available today with integrated dc/dc converters, Σ-Δ ADCs, gate drivers, I²C, RS-485 transceivers, RS-232 transceivers, and CAN transceivers in single packages which optimize both size and cost of the motor control system.

PRACTICAL APPLICATION CIRCUITS

A typical drive circuit that demonstrates the isolation of gate drive, communication, and feedback signals is shown in Figure 4. In this system, an isolated Σ-Δ ADC is used to measure the motor winding current and the digital bit stream is processed by digital filtering circuit on the motor control IC. The position encoder includes an ASIC that transmits position and velocity data to the motor control IC over an isolated RS-485 interface. Other isolated serial interfaces include the I²C interface to the PFC and the isolated RS-232 link to the front panel. In this instance, the PWM signals are isolated from the inverter module and the IGBT's are driven by a level shifting gate driver embedded in the module.

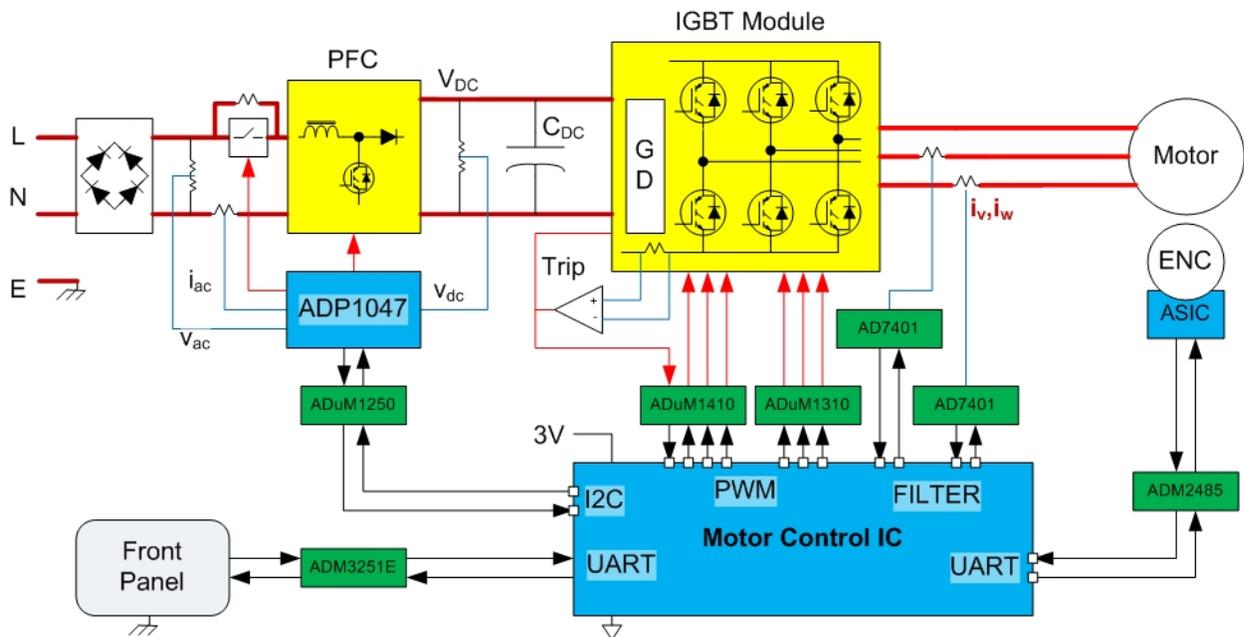For further information on the Analog Devices family of digital isolator products, visit www.analog.com/icoupler

Figure 4. Typical midsize industrial motor drive system.

RESOURCES

Products Mentioned in This Article

Product	Description
ADP1047	Digital Power Factor Correction Controller with Accurate AC Power Metering
ADuM1250	Hot Swappable, Dual I²C Isolator
ADM3251E	Isolated, Single Channel RS-232 Line Driver/Receiver
ADuM1410	Quad-Channel Digital Isolator
ADuM1310	Triple-Channel Digital Isolator
AD7401	Isolated Sigma-Delta Modulator
ADM2485	High Speed, Isolated RS-485 Transceiver with Integrated Transformer Driver

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