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NOISE SOURCES IN APPLICATIONS USING CAPACITIVE COUPLED ISOLATED AMPLIFIERS

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Noise is a typical problem confronting many isolation applications. Isolation products such as analog isolation amplifiers, optocouplers, transformers and digital couplers, are used in applications to transmit signals across a high voltage barrier while providing galvanic separation between two grounds. Burr-Brown's isolated analog amplifiers and digital couplers use one of three coupling technologies in their isolation products, each having its own set of advantages and disadvantages in noisy environments. These technologies are inductive coupling, capacitive coupling and optical coupling. Isolation amplifiers and digital couplers are used for a variety of applications including breaking of ground loops, motor control, power monitoring and protecting equipment from possible damage. An understanding of the design techniques used to transmit signals across the isolation barrier, as well as an understanding of the sources of noise, allows the users to quickly identify design and layout problems and make appropriate changes to reduce noise to tolerable levels.

Noise is defined in this application note as a signal that is present in a circuit other than the desired signal. This definition excludes analog nonlinearities which may produce distortion. As shown in Figure 1, there are three primary types of noise endemic to isolation applications, each with their own set of possible solutions. The first noise source is device noise. Device noise is the intrinsic noise of the devices in the circuit. Examples of device noise would be the thermal noise of a resistor or the shot noise of a transistor. A second source of noise that effects the performance of isolation devices is conductive noise. This type of noise already exists in the conductive paths of the circuit, such as the power lines, and mixes with the desired electrical signal through the isolation device. The third source of noise is radiated noise. Radiated noise is emitted from EMI sources such as switches or motors and coupled into the signal. This application bulletin will cover these three noise classifications as they relate to capacitive coupled isolation amplifiers.

THEORY OF OPERATION OF THE CAPACITIVE COUPLED ISOLATION AMPLIFIERS

The capacitive coupled isolation amplifiers are designed with an input and output section galvanically isolated by a pair of matched capacitors. A block diagram of this type of

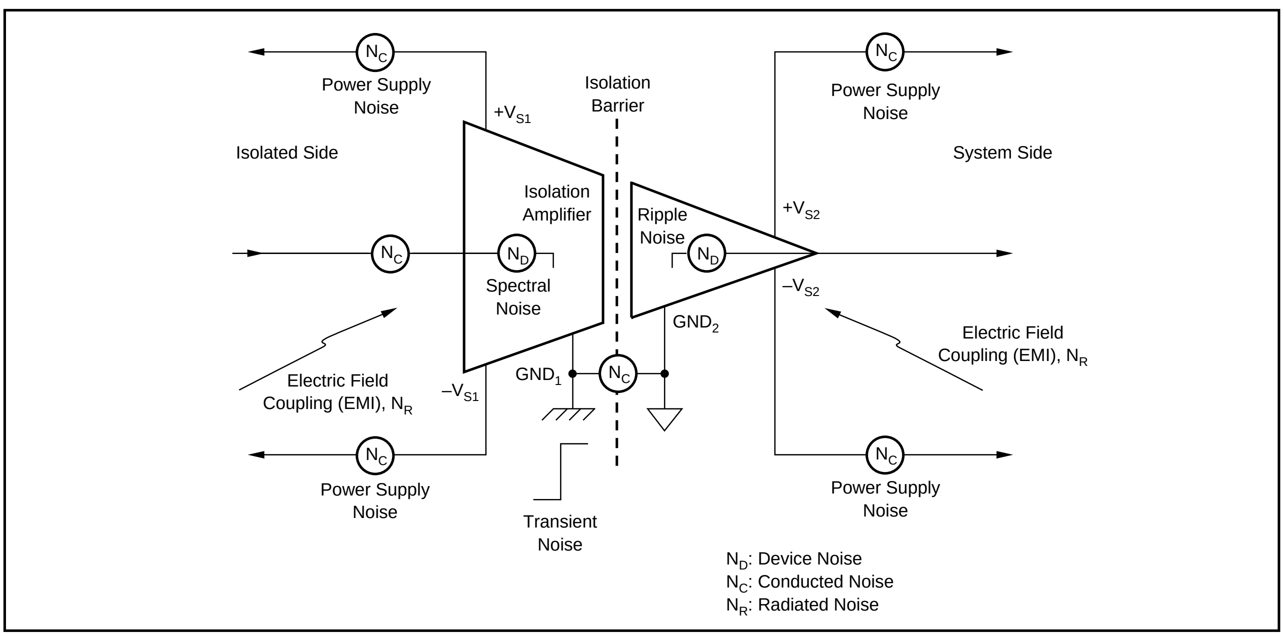


FIGURE 1. The Three Basic Types of Noise in Isolation Applications are Device Noise, Conducted Noise, and Radiated Noise.

isolation amplifier is shown in Figure 2. The capacitive coupled isolation amplifiers employ digital modulation schemes to transmit a differential signal across the isolation barrier. The modulation schemes used in the capacitive coupled isolation amplifiers are duty-cycle modulation or voltage-to-frequency, depending on the product. Both modulation schemes are basically voltage to time. An internal oscillator is used to modulate the analog input signal into a digital signal which is transmitted across the isolation barrier. Most capacitive coupled amplifiers (ISO103, ISO107, ISO113, ISO120, ISO121, ISO122), as shown in the block diagram in Figure 3, modulate the analog signal to a duty-cycle encoded signal; The remainder of the isolation amplifiers (ISO102 and ISO106), as shown in the block diagram in Figure 4, modulate the analog voltage to a frequency.

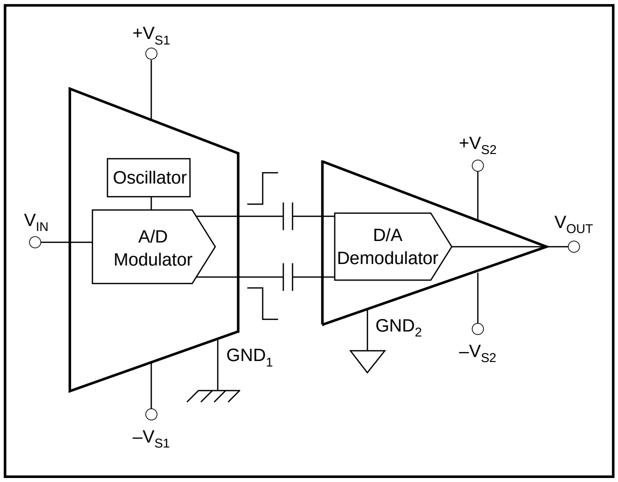


FIGURE 2. A Block Diagram of a Capacitive Coupled Isolation Amplifier.

The modulated signal is transmitted to the other side of the isolation barrier through a pair of matched capacitors built into the plastic or ceramic package. The value of these capacitors varies from lpF to 3pF depending on the device. The resulting capacitor is simple and reliable by design.

After the modulated signal is transmitted across the isolation barrier, it is demodulated back to an analog voltage. The output section of the isolation amplifier detects the modulated signal and converts it back to an analog voltage by using averaging techniques. Most of the undesired ripple voltages inherent in the demodulation process is then removed.

DEVICE NOISE AND CAPACITIVE COUPLED ISOLATION AMPLIFIERS

Device noise is generated by the devices in the circuit. Examples of device noise generators would be a discrete resistor, which generates thermal noise, or an operational amplifier, which would generate 1/f noise, etc. Specifically, with Burr-Brown's capacitive coupled isolation amplifiers, there are two device noise specifications of consequence.

Ripple Noise

A by-product of the demodulation scheme for the duty-cycle modulated isolation amplifiers is a ripple voltage on the output of the isolation amplifier. A large part of the ripple voltage is filtered by the output stage, however, a small amount is still present at the output. This ripple voltage varies from product to product (5mVp-p to 25mVp-p [typ]), and is dominated by the sample-hold droop and capacitive feed through in the output stage of the isolation amplifier. An example of ripple voltage noise is shown in Figure 5.

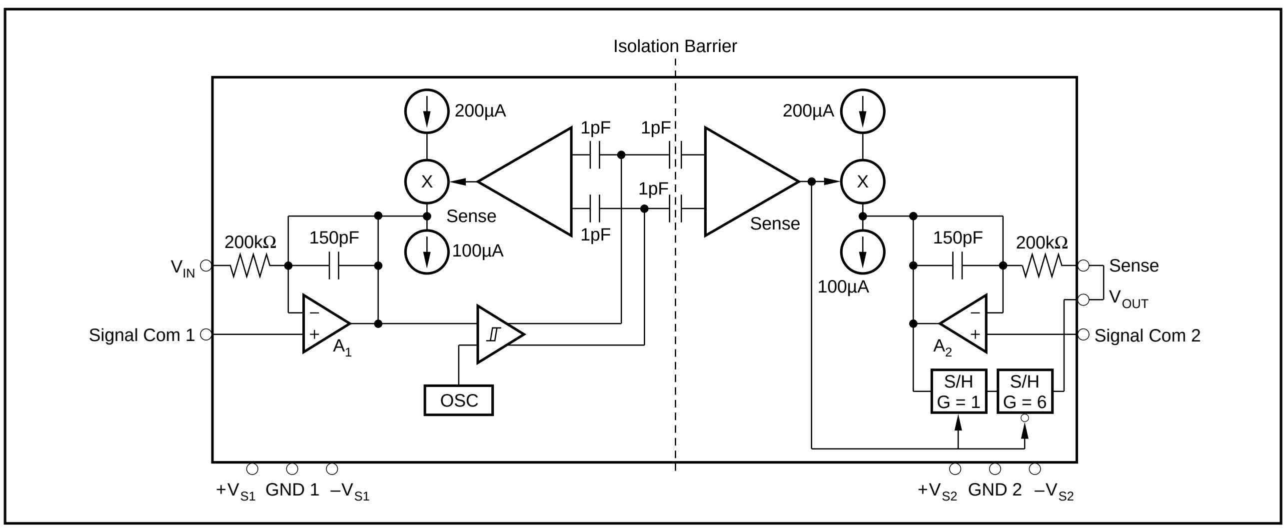


FIGURE 3. The Basic Block Diagram of the ISO103, ISO107, ISO113, ISO120, ISO121, and ISO122 Isolation Amplifiers, which use Duty-Cycle Techniques to Transmit Signal Across the Isolation Barrier.

This ripple voltage noise can easily be eliminated by using a low pass R-C or active filter at the output of the isolation amplifier as shown in Figure 6. This two-pole, unity-gain, Sallen-Key type filter is designed with a Q = 1 and a 3dB bandwidth = 50kHz. The OPA602 is selected to preserve DC accuracy of the ISO122. In Figure 6, the dynamic range of the ISO122 is changed from a typical 9-bit resolution to 11-bit resolution (see AB-023). The ISO102 and ISO106 isolation amplifiers have an active filter built into their outputs. This low pass filter provides a significant reduction in the ripple voltage. The remaining noise at the output of the isolation amplifier is spectral noise. If the ripple noise of the isolation amplifier is sufficiently reduced, the spectral noise will begin to dominate.

Spectral Noise

The spectral noise, or wideband noise, is the second type of isolation amplifier device noise. This noise is generated by the jitter of the modulation process. In the case of the ISO102 and ISO106, the jitter is dominated by the time uncertainty of the one-shot. With the ISO103, ISO113 and ISO107 the jitter noise is dominated by the translation of voltage noise in the comparator. Spectral noise can be reduced by reducing the signal bandwidth, or again using a low pass filter at the output of the isolation amplifier. Another method of reducing the noise contribution from spectral noise as well as the ripple voltage noise is to use a pre-gain stage to the isolation amplifier. This technique is shown in Figure 7. By gaining the signal before it is transmitted across the isolation barrier, the signal-to-noise ratio will be improved.

CONDUCTIVE NOISE AND ITS EFFECT ON ISOLATION AMPLIFIER SIGNALS

The second source of noise, conductive noise, can be coupled into the signal path through the three paths as shown in Figure 8. Noise on the power supply lines is coupled into the signal through the supply pins and eventually to the signal path. Noise coming from the input of the isolation amplifier is transmitted directly across the barrier. And finally, a fast change in the voltage difference between the grounds of the isolated system can corrupt the signal and in some cases give an erroneous output.

Power Supply Noise

Noise on the power supply lines can be coupled into the isolation amplifier through the supply pins. Isolation amplifiers require isolated supplies, typically DC/DC converters. DC/DC converters utilize high-frequency oscillators/drivers to transmit voltage information across a transformer barrier. The output stage of the DC/DC converters rectify, filter and in some instances regulate the output voltage. The output voltage has the desired DC component as well as remnants of the switching frequency in the form of a complex ripple voltage. The DC/DC converter regulation (or lack there of) and switching frequency can have an effect on the performance of the isolation amplifier. In the cases where the isolation amplifier is self-powered (ISO103, ISO113, and ISO107), the DC/DC converter is synchronized with the isolation amplifier oscillator, however, it is unregulated. The system power supply performance should be evaluated and possibly a regulator chip added to the circuit on the system

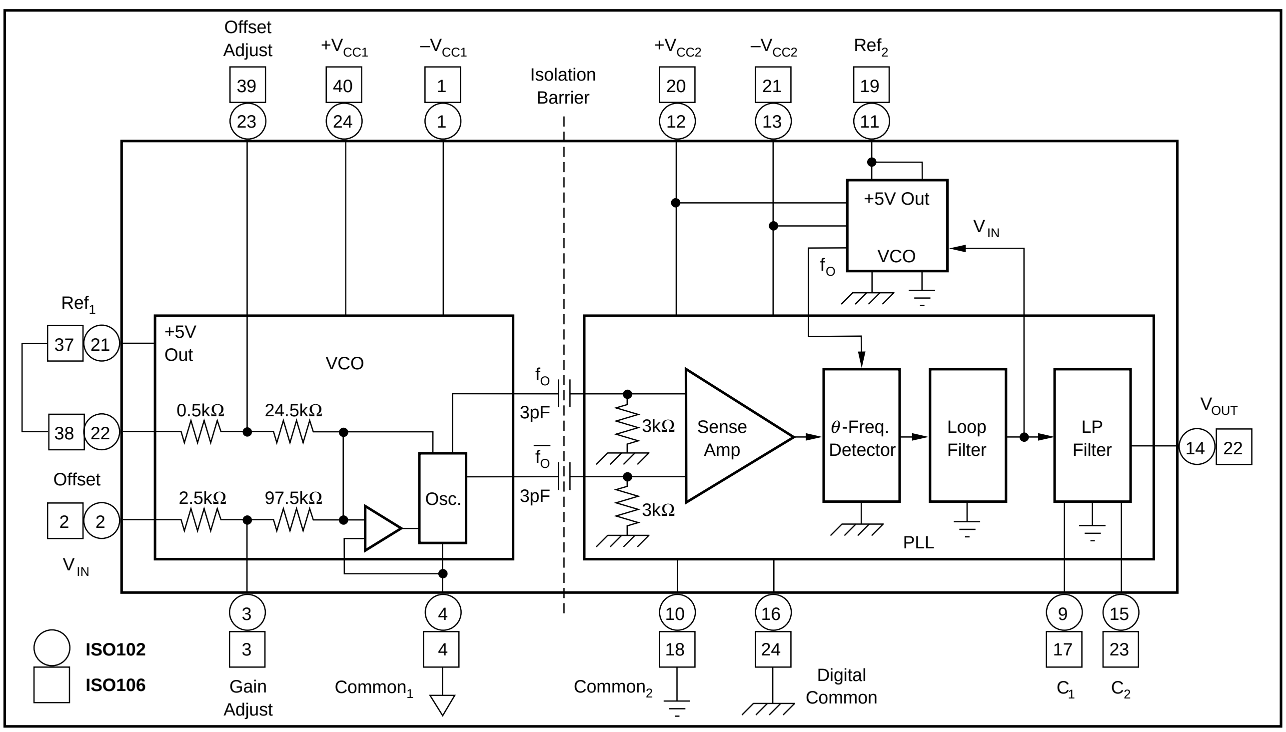


FIGURE 4. The Basic Block Diagram of the ISO102 and ISO106, Isolation Amplifiers, which use Voltage-to-Frequency Modulation Techniques to Transmit Signal Across the Isolation Barrier.

side. The isolation amplifiers that are not self-powered (ISO102, ISO106, ISO120, ISO121, and ISO122) require power be supplied by an external DC/DC converter or a battery.

In the case where the noise on the power supply line is less than the bandwidth of the isolation amplifier, the noise manifests itself as a small signal offset voltage. The magnitude of this error is specified in the data sheets of the

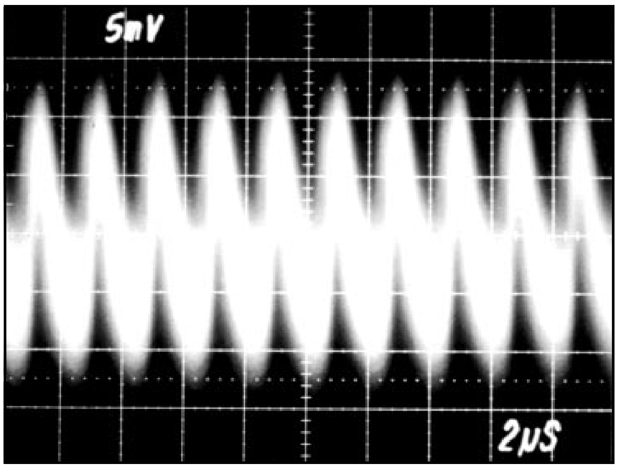
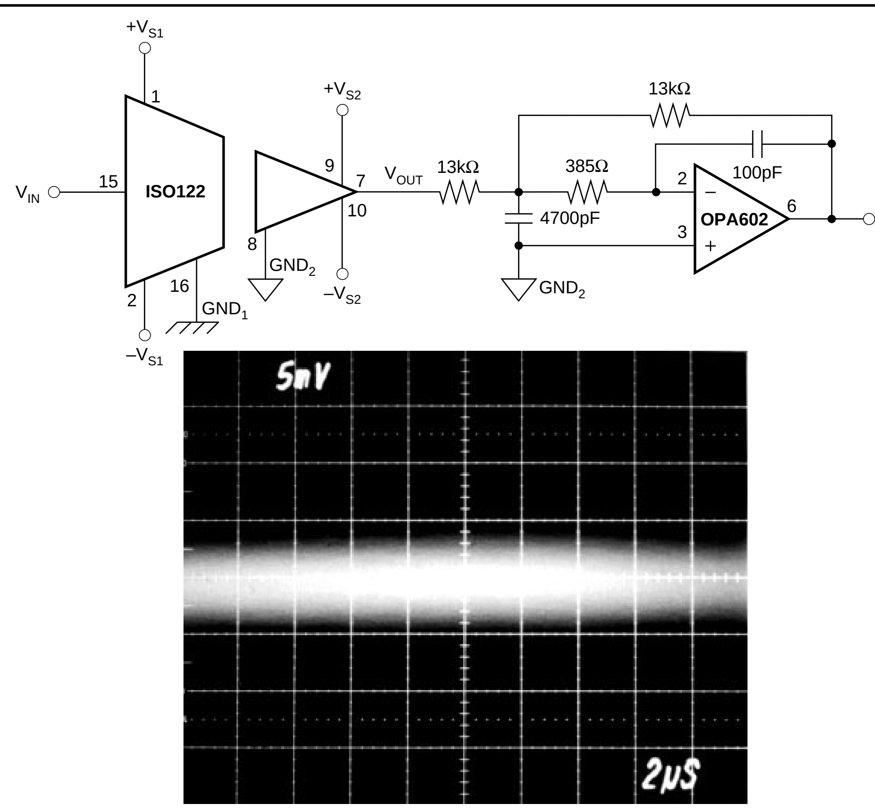


FIGURE 5. The Unfiltered Output of the ISO122 Isolation Amplifier Showing Approximately a 20mVp-p Output Ripple.

isolation amplifiers as power supply rejection (PSR). Usually the contribution of a power supply rejection error is less than the ripple voltage that is generated by the demodulation process mentioned above.

Power supply noise greater than the bandwidth of the isolation amplifier can come from several sources. Some of these sources can be the DC/DC converter switching frequency, switching noise from digital logic, switching noise from motors, or from the oscillator used in the isolation amplifier, to name a few. It is easy to assume that the isolation amplifier will filter out noise that is greater than its own bandwidth. That assumption is erroneous, because of aliasing between the power supply noise and the isolation amplifier's own oscillator.

To illustrate this point, refer to the performance curve from the ISO122 data sheet shown in Figure 9. The x-axis represents the power supply noise frequency. The left y-axis represents the ratio between voltage out to supply voltage in. The right y-axis represents the frequency of the output signal generated by the aliasing effect. As illustrated, if a supply line has a switching frequency of 750kHz, there will be a noise ripple contribution at the output of the ISO122 of about –33dBm and the frequency component of that noise will be 250kHz, which can easily be filtered using methods illustrated in Figure 6. If the supply line has a switching frequency noise of 900kHz, there will be a noise ripple



Output of OPA602

FIGURE 6. The ISO122 Isolation Amplifier with a Two-Pole, Low Pass Filter to Reduce Ripple Voltage Noise.

contribution at the output of the ISO122 of about –20dBm with a frequency component of 50kHz. Since the typical bandwidth of the ISO122 is 50kHz, this aliased noise will be difficult to filter without effecting the signal bandwidth.

A danger zone for the power supply switching frequency noise in this example is a frequency band of ±50kHz around 500kHz and multiples of 500kHz. This is because the ISO122's bandwidth is 50kHz and the modulation/demodulation oscillation frequency for the ISO122 is 500kHz. To complicate matters further, a DC/DC converter ripple voltage will never have the frequency content of a simple sine wave, but rather a fairly complex summation of several frequencies, usually multiples of the fundamental frequency. If the DC/DC converter switching frequency is selected to be exactly the same frequency (or a multiple) of the modulation/demodulation oscillator frequency of the isolation amplifier, the aliasing phenomena will not be a problem. This, of course, is unrealistic because of lot to lot variances

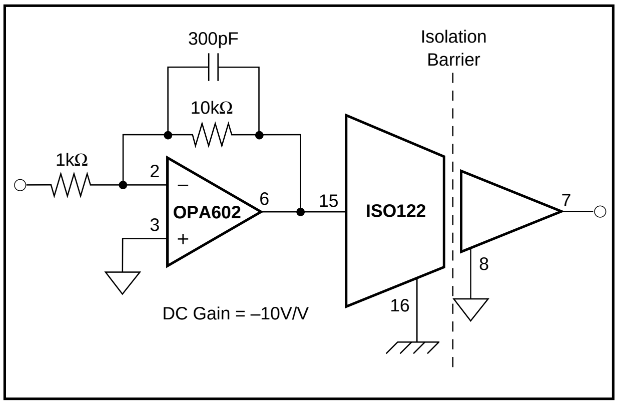


FIGURE 7. By Using a Pre-Gain Stage the Signal-to-Noise Ratio is Improved. In this Example the Signal-to-Noise Ratio is Improved by 20dB.

and variations in temperature performance of both the DC/DC converter and the isolation amplifier. A small difference between the two switching frequencies will generate low frequency noise in the signal path that is impossible to filter.

There are two design issues taken into consideration when selecting the DC/DC converter switching frequency for a specific isolation amplifier. As an example, in the case of the ISO122, an acceptable DC/DC switching frequency would be 400kHz. In this case, the difference between the DC/DC switching frequency and the isolation amplifier's oscillating frequency is l00kHz. The aliased noise will have a fundamental frequency content of l00kHz, which is easily filtered by the isolation amplifier. Additionally, the 5th harmonic of the DC/DC converter and the 4th harmonic of the ISO122 are equal. Generally, the amplitude of the DC/DC converter ripple having the frequency content of a higher harmonic is considerably smaller than that of lower harmonics. Signals aliased back from higher harmonic elements of the DC/DC converter's ripple voltage will be less.

In cases where the isolation amplifier has voltage-to-frequency modulation topology (ISO102 and ISO106), the selection of the DC/DC converter becomes more difficult. The frequency modulation range of the ISO102 and ISO106 is 0.5MHz (V_{OUT} = –10V) to 1.5MHz (V_{OUT} = +l0V). In these applications, proper by-pass designs can help reduce noise caused by the switching frequency of the DC/DC converter.

Figure 10 illustrates resistor-capacitor and inductor-capacitor decoupling networks that can be used to isolate devices from power supply noise. These networks are used to eliminate coupling between circuits, keep power-supply noise from entering the circuit and to suppress the reflected ripple current of the DC/DC converter caused by the dynamic current component at its switching frequency. When the

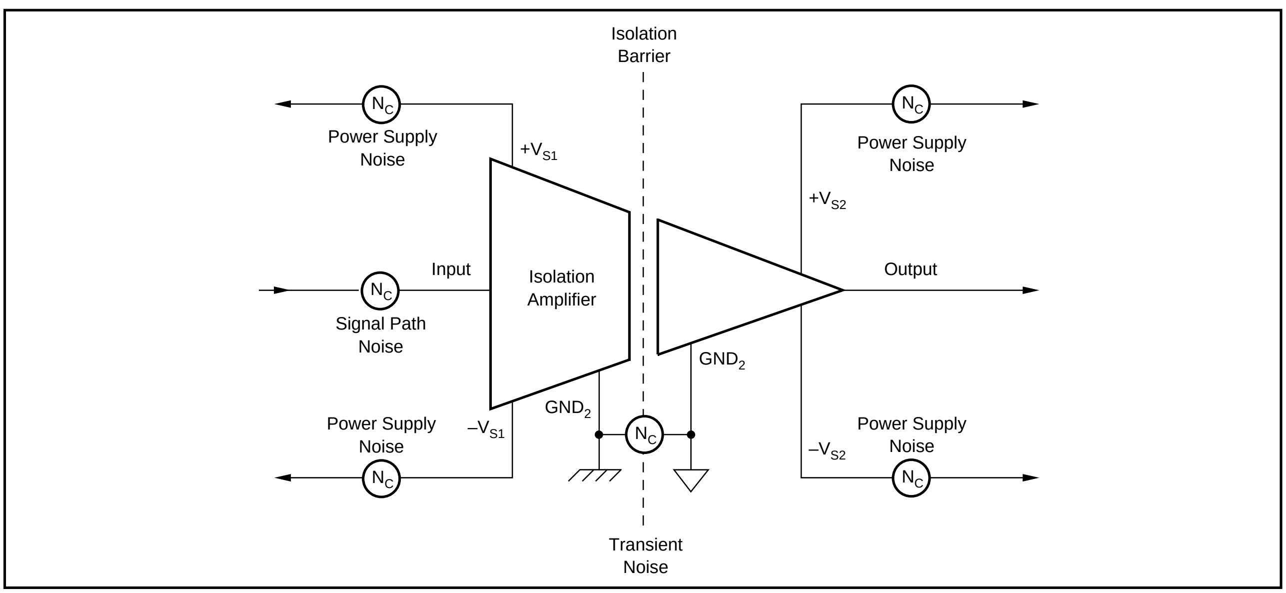


FIGURE 8. The Three Sources of Conductive Noise in an Isolation Application are from the Power Supply Lines, the Signal Path and Between the Isolated Grounds.

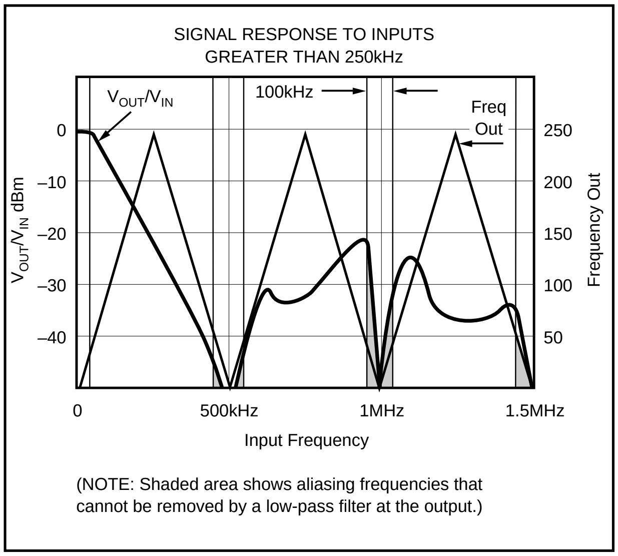


FIGURE 9. Noise Rejection Performance Curve of the ISO122.

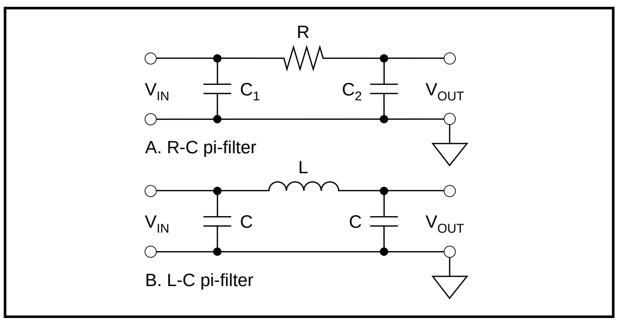


FIGURE 10. Suggested Pi-Filter Designs to Eliminate Power Supply Noise.

R-C filter is used, the voltage drop in the resistor causes a decrease in power-supply voltage (see AB-024 for more details). The L-C circuit provides more filtering, especially at high frequencies, however, the resonant frequency of the network can amplify lower frequencies. If a resistor is placed in series with the inductor, this resonant frequency is attenuated. See Figure 11 for the frequency response and design equations of the L-C network. This by-pass design approach is known as a pi-filter. The filter should be positioned on the PCB as close to the noise source as possible.

Power supply noise can be reduced by one or a combination of four methods. First, the designer should carefully select the DC/DC converter according to its power performance and switching frequency. Second, filter the output of the isolation amplifier to eliminate high frequency noise. Third, use a pi-filter on the supply lines as close to the switching source as possible. And fourth, in some instances, an external synchronization pin on the isolation amplifier makes it possible to synchronize multiple channels of isolation amplifiers to each other and the DC/DC power supplies.

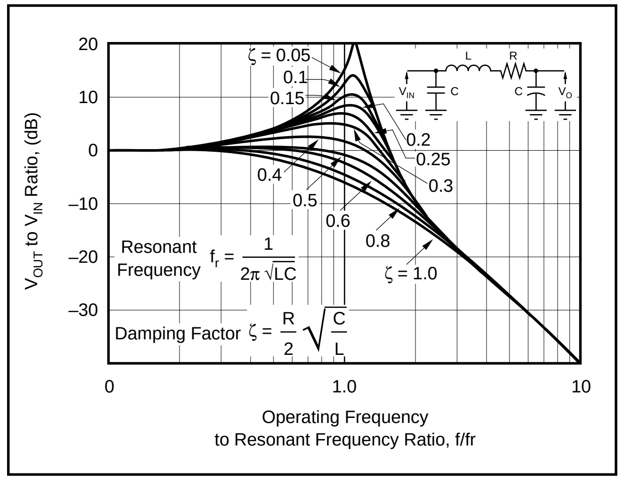


FIGURE 11. The L-C Pi-Filter Response and Design Formulas

Input Signal Noise

Noise in the signal path at the input of the isolation amplifier that is within the bandwidth of the isolation amplifier will be transmitted across the barrier with the desired signal. This type of noise is impossible to eliminate with a filter before or after the isolation amplifier and should be eliminated at its source. Typically, noise is coupled into the signal path where there is a metal trace with a high impedance node next to a metal trace where noise is present.

Signal path noise that is above the bandwidth of the isolation amplifier may or may not be transmitted across the barrier. Using the performance curve of the ISO122 in Figure 9, it is easy to deduce how much noise will be transmitted. In this instance, the x-axis represents the input noise frequency. The left y-axis represents the ratio between voltage out to input voltage. The right y-axis represents the frequency of the output signal generated by the aliasing effect. If there is concern that there will be high frequency noise at the input of the isolation amplifier, usually a low pass filter before the isolation amplifier will reduce the effects of input noise aliasing into the signal bandwidth.

High dV/dt Changes Between The Ground References Of The Isolation Barrier

A third source of conductive noise for isolation applications is caused by the transients between the two ground references across the isolation barrier (as shown in Figure 12). The isolation mode voltage (IMV) is the voltage that appears across the isolation barrier between the input common and output common. A fault condition may directly apply high voltage AC to the isolated common, forcing AC current through the barrier capacitors. Finite isolation mode rejection results in small output AC noise. Another specification that describes the ability of an isolation product to reject high transients between the grounds is called Transient Immunity (TI). These transients most commonly occur in motor control applications. Transient Immunity is specified in volts per seconds. A high Transient Immunity indicates a

MODEL	Isolation Function	Isolation Barrier-Type (Signal/Power)	Signal Modulation Method	Isolation Barrier Test Voltage(6) kV	Isolation Barrier Impedance(1) Ω/pF	Isolation Mode Rejection Ratio at 60Hz dB	Transient Immunity(1) kV/µs	Wide-band Noise Density(1) µV/Hz	Signal Output Ripple(1) mVp-p	Full Scale Bandwidth/ Small Signal Bandwidth kHz/µs	Number of DC/DC Channels	DC/DC Output Ripple/External Filter Capacitor/ Frequency(1) mVp-p/µF/kHz
ISO103	Buf-DC/DC	Cap/Mag	Duty Cycle	4rms	10E12/9	130(1)	1	4	25	20/75	1	5/1/1600
ISO107	Buf-DC/DC	Cap/Mag	Duty Cycle	8 peak	10E12/13	100(1)	0.006	4	20	20/75	1	10/0/1600
ISO113	Buf-DC/DC	Cap/Mag	Duty Cycle	4rms	10E12/9	130(1)	1	4	25	20/75	1	5/1/1600
ISO212	Amp-DC/DC	Mag	Balanced AM	1.2rms(2)	10E10/12	115(1)	0.6(3)	0.02	8	2/400	1	10/10/25
3656	Amp-DC/DC	Mag	Flyback	8DC	10E12/6	112	0.1(3)	0.117	5	1.3/500	1	100/.47/900
ISO100	Amp	Opto	Linear	2.5DC	10E12/2.5	108(1)	1(3)	6	0	5/100	—	—
ISO102	Buffer	Cap	Frequency	4rms	10E14/6	115	0.1	16	3	5/100	—	—
ISO106	Buffer	Cap	Frequency	8 peak	10E14/6	125	0.1	16	3	5/100	—	—
ISO120	Buffer	Cap	Duty Cycle	2.5rms(2)	10E14/2	115(1)	1	4	10	20/50	—	—
ISO121	Buffer	Cap	Duty Cycle	5.6rms(2)	10E14/2	115(1)	1	4	10	20/50	—	—
ISO122	Buffer	Cap	Duty Cycle	2.4rms(2)	10E14/2	140(1)	1	4	10	20/50	—	—

NOTES: (1) Typical. (2) Conforms with VDE884 partial discharge test methods. (3) Value based on limited evaluation; should be used for comparison purposes only.

greater ability to reject isolation mode voltage transients. If transient voltages between the grounds exceed the capabilities of the isolation amplifier, the input of the sensor amplifier may start to false trigger and the output will display spurious errors. Transient immunity is defined as the maximum rate of change of IMV voltage that does not interfere with the normal transmission of information across the barrier. Errors due to high transients that are less than 1% of the full scale range of the isolation amplifier are deemed to be within the normal transmission range.

A high transient phenomena is easy to identify by tracking the difference between the grounds and correlating it to errors at the output of the isolation amplifier. If the transients are predictable, this error can be filtered from the signal by timing data collection at the output of the isolation amplifier to when the data is known to be valid. In addition, selecting an isolation amplifier with a high Transient Immunity specification will reduce the errors caused by IMV transients.

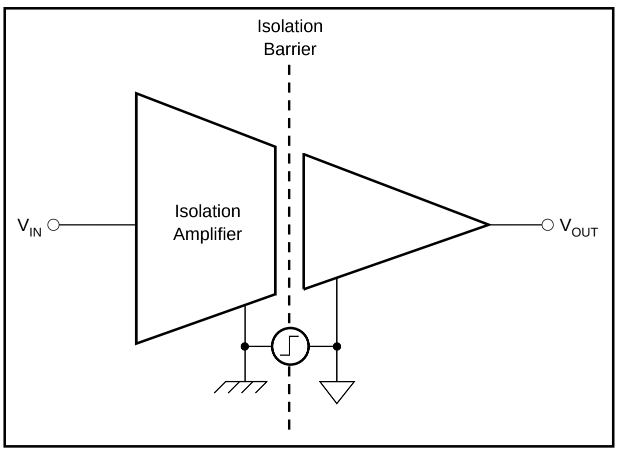


FIGURE 12. Transient Noise is Caused by High dV/dt Transients Between the Grounds of the Isolation Application.

RADIATED NOISE

Radiated noise is transmitted through air into high impedance nodes. Some isolation technologies are more sensitive to radiated noise interference than others. Radiated noise, also called EMI interference, can easily be identified as a problem by experimenting with the proximity of a circuit to a radiating device or by experimenting with shielding techniques. There are numerous sources for radiated noise such as ground planes, power planes, metal traces in close proximity, switching networks, inductors, toroids, etc. The E-field or the B-field portion of the radiated field can have an effect on isolation amplifiers. Specifically, a high E-field in the vicinity of the capacitively coupled isolation amplifiers can effect the performance of the device. In near-field emission areas, transmission of radiated sources is proportional to the inverse cube distance.

Radiated noise can transmit directly into the signal, usually through the capacitive barrier of the isolation amplifier. If the frequency content of the radiated noise is a multiple of the oscillating frequency of the isolation amplifier (plus or minus the bandwidth of the amplifier) the radiated noise will appear in the signal bandwidth. As an example, refer to Figure 9, using the left y-axis equal to the ratio of the output voltage of the isolation amplifier and the field strength of the radiate noise at the point of entry. Although it is difficult to quantify the field strength of a radiated signal at the point of entry, the concepts in Figure 9 still apply. In heavy fields, isolation amplifiers can produce signals outside of its linear region.

Radiated noise can be identified as a problem by experimenting with shielding or using a l0X scope probe to identify hot spots. Various metallic materials can be used for shielding as long as the metal is connected to a ground in the circuit. The most effective shielding material found in experimentation is Mumetal, however, copper and even conductive tape have been used to identify and eliminate problem areas.

CONCLUSION

Noise problems in any application can be difficult to solve, particularly if the causes and effects are not known. When investigating a noise problem in an isolation application, one or a combination of three noise sources can be identified as responsible for a noisy output of the isolated amplifier. By understanding the source of noise, steps can be taken in layout and circuit design to significantly reduce noise errors to acceptable levels.

REFERENCES

(1) Ott, Henry W., *Noise Reduction Techniques in Electronic Systems*, John Wiley & Sons, NY, 1976.

(2) Morrison, Ralph, *Noise and Other Interfering Signals*, John Wiley & Sons, NY, 1991.

(3) Zirngast, Mark F., *Isolation Amplifiers-Design and Implementation: Isolation, Transformer and Optical Techniques, Part 1*, Electronic Engineering, April, 1989, pp. 37-40.

(4) Zirngast, Mark F., *Isolation Amplifiers-Design and Implementation: Capacitive Isolation , Part 2*, Electronic Engineering, May, 1989, pp. 33-45.

(5) Burt, Rod, *Cut Noise in Isolated Circuits with Variable Carrier Amplifier*, Electronic Design, April 14, 1988, pp. 101-104.

(6) Baker, Bonnie, *Improved Device Noise Performance for the 3650 Isolation Amplifier*, Application Bulletin AB-044, Burr-Brown Corporation.

(7) Stitt, Mark, *Very Low Cost Analog Isolation with Power*, Application Bulletin AB-024, Burr-Brown Corporation.

(8) Stitt, Mark, *Simple Filter Eliminates ISO Amp Ripple and Keeps Full Bandwidth*, Application Bulletin AB-023, Burr-Brown Corporation.