

DESIGN AND APPLICATION OF TRANSFORMER-COUPLED HYBRID ISOLATION AMPLIFIER MODEL 3656

Hybrid-compatible toroid assembly in a flyback-modulated circuit achieves long-term stability, high frequency response, and superior breakdown ratings.

Whenever engineers who need or use isolation amplifiers get together and talk about the improvements they would like to see most, the big three—cost, size, performance—are likely to be mentioned. The industrial or medical equipment manufacturer often has to make a choice of either buying an isolation amplifier or building his own. Cost is the key criterion for such a decision, but there are others as well. For example, the multichannel analog system designer usually runs into printed circuit board space limitations, since he almost always requires a lot of data channels on each PC

board. On the other hand, the medical equipment manufacturer is not as concerned with size but encounters very-high breakdown voltages and requires low leakage at a reasonable price.

To meet the widely varying needs of these and other potential users, Burr-Brown has made a radical departure from established design and manufacturing techniques in developing its new isolation amplifier, model 3656. Among the key design features and the resultant benefits for the user are:

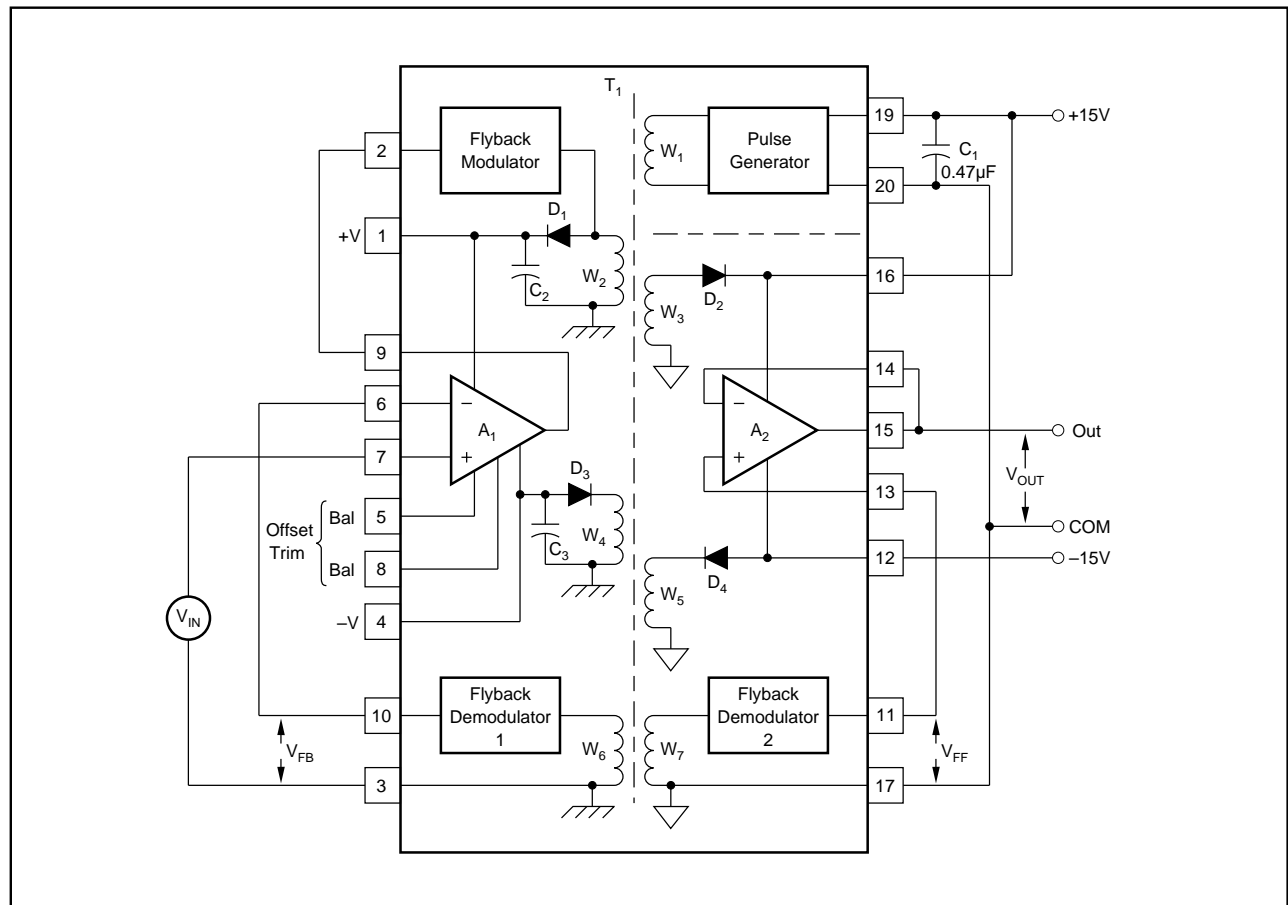


FIGURE 1. Self-contained By Design. Function diagram of hybrid isolation amplifier shows transformer T_1 at its heart and a minimum of external components. Switching rate of 750kHz results in high frequency response and eliminates external filter components.

- A single hybrid-compatible transformer (patents 4,006,974; 4,103,267; 4,082,908) in conjunction with a patented circuit, that couples both signal and power across the isolation barrier, resulting in the industry's smallest and lowest cost isolation amplifier having its own internal isolated power.
- A ceramic thick-film integrated circuit that uses the transformer to provide long-term stability and reliability at low cost.
- True three-port isolator design that achieves unprecedented voltage breakdown ratings and versatility.
- A 750kHz switching rate that results in the highest small-signal frequency response for any isolation amplifier and reduces external filtering requirements.
- A differential design concept that uses two demodulators, one for feedback and one for feedforward, producing accuracies comparable to those of higher priced transformer-coupled devices.

Figure 1 shows the functional diagram of the device in its unity-gain, noninverting configuration with a minimum of external components. A highly inductive transformer, T_1 , is excited by the pulse generator containing a solid-state switch that alternately applies an open circuit and the voltage present across filter capacitor, C_1 , to transformer winding, W_1 , as illustrated in Figure 2a. When the voltage (V) is applied to the winding, the current (i) in the inductance (L) of the winding increases as shown in Figure 2b according to:

$$di/dt = V/L$$

(Circuit resistances and capacitances have only secondary effects and can be ignored here). At the instant the switch opens, the voltage across the transformer reverses and reaches the magnitude necessary to maintain the current at its previous value. This effect is called flyback.

The flyback voltage (V_F) appears on all windings in the form shown in Figure 2c. Its amplitude is proportional to the instantaneous current and the equivalent resistance (R_p) shunting the transformer inductance:

$$V_F = iR_p$$

The magnitude of V_F can be varied by changing the parallel resistance across any winding of the transformer, resulting in a form of amplitude modulation. This is accomplished by the flyback modulator, which is controlled by input operational amplifier, A_1 . Power for A_1 is generated by rectifying the positive energizing pulse appearing across W_2 . Rectification is accomplished by diode D_1 , and the resultant direct current is smoothed out by C_2 to derive the positive supply voltage. Similarly, the negative supply voltage is derived by diode D_3 and capacitor C_3 from winding W_4 . If the isolation amplifier is to be used as a three-port isolator, isolated power voltages for output op amp A_2 can be derived by adding filter capacitors between pins 16 and 17 and between pins 12 and 17.

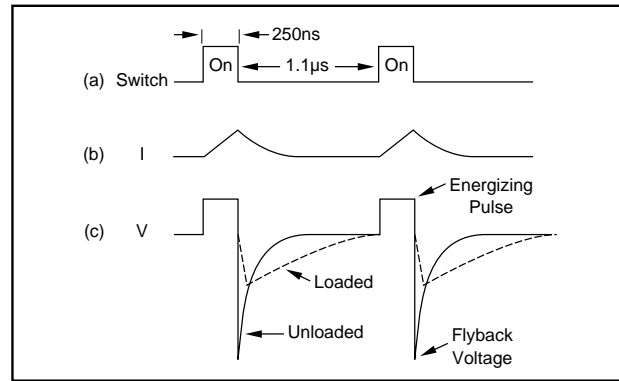


FIGURE 2. Flyback Modulation. The pulsed supply voltage is applied to transformer winding (a). As a result of voltage, V , across winding, current I increases as in (b) until switch opens, producing flyback shown in (c). Rectified positive-going pulses provide power to energize input op amp, A_1 , which controls flyback modulator.

At the heart of the isolation amplifier are two identical flyback demodulators. Both compare the positive-going flyback signal at the respective winding at which they are connected with the amplitude of the negative energizing pulse. At minimum modulation (load), they produce a positive output signal; as modulation increases, the demodulator output signal decreases until it is negative at maximum modulation.

Flyback demodulator 1 is used in a closed-loop system by connecting its output to the inverting (feedback) terminal of A_1 . This configuration causes A_1 to control the level of the modulator until the output of flyback demodulator 1 equals the signal at the noninverting input of A_1 , so that $V_{FB} = V_{IN}$. Flyback demodulator 2, identical to flyback demodulator 1, has the same output, and thus $V_{FF} = V_{IN}$. To prevent loading of demodulator 2, it is buffered by A_2 , which is configured as a unity-gain amplifier. As a result, $V_{OUT} = V_{FF} = V_{IN}$.

The accuracy of the transfer equation depends basically on the stability and tracking of the two op amps and the close matching of the demodulator components. With high grade op amps and components matched to within 0.5% or better initially, and a temperature coefficient of 25ppm/°C, a very high gain accuracy can be achieved. Nonlinearity caused by differences in demodulator outputs is very low because of the repeatable matching of the resistors and stray capacitances made possible by thick-film hybrid-circuit technology.

HYBRIDS AND TRANSFORMERS

Until now, transformers and large chokes were to be avoided in hybrid integrated circuits. The few hybrids manufactured with such components are hard to produce and very costly because of the difficulties with size, uneven mounting surfaces, and substrate-to-magnet-wire interconnections. When

Burr-Brown moved to enter the rapidly expanding market for isolation amplifiers and isolated DC/DC converters with low cost transformer-coupled hybrid circuits, it decided that these shortcomings had to be eliminated. As a result, it developed a new approach to implementing a toroidal transformer on a hybrid substrate that eliminates the manufacturing problems.

Table I is a step-by-step comparison of the new technique with the conventional (but rarely used) approach. At present, the hybrid-compatible transformer is well suited for low-cost, low-power transformers, with the overall cost of the transformer assembly about 60% to 80% of the mounted transformer. However, it does not yet provide the same performance as the conventional transformer in all respects. Although coupling capacitance is lower and accuracy is better, the resistive losses are higher and the achievable inductance is lower.

COMPARING PAST AND PRESENT

Table II is a comparison of features and specifications of the new isolation amplifier with previously available component-type units. (Note that previously available transformer-coupled isolation amps were built as printed circuits most often housed in plastic modules.) Amplitude-modulated isolation amplifiers were the first to appear. High accuracy pulse-width-modulated types were introduced in 1973, and optical ones have been available since 1976.

It can be seen that the single-transformer, flyback modulated amplifier performs well in most areas. Its nonlinearity is in line with that of all the other types and exceeds that of the low-cost amplitude-modulated types. Its isolation-voltage pulse rating is higher than that of any other amplifier and conforms with the requirements specified in medical applications for protection against defibrillator pulses.

Also, its isolation barrier capacitance is the lowest of any transformer-coupled device available today—a highly desirable feature in medical applications where the leakage from the standard 115VAC equipment power outlets to the patient must be kept at a minimum. Actually, the single transformer design keeps the leakage current below 0.5μA, 20 times lower than the limit specified by Underwriters Laboratories.

Another big advantage of low barrier capacitance is that the isolation-mode rejection degradation is kept at a minimum in applications where the source impedance is high and the isolation amplifier does not have a balanced front end. The isolation-mode rejection of the new unit also compares well with that of previous designs. Another strong point of this device is its small-signal frequency response—an order of magnitude better than any other transformer-coupled isolation amp and even better than optically coupled devices.

CONVENTIONAL TRANSFORMERS	HYBRID-COMPATIBLE TRANSFORMERS
To be mounted into a hybrid package, a small toroid transformer not only must be wound by hand, but all wire must be accurately placed and dressed.	Turns are completed using a manual or automatic wire bonder, cutting labor by 50% to 90%.
The mounting surface of a toroid transformer is formed by the magnet wire, causing problems of tolerance and flatness.	The flat surface of the toroid itself is used for mounting, giving a high degree of uniformity.
The magnet wire bonded to the substrate must hold the core in place and take g stress.	The core is bonded directly to the substrate, resulting in better adhesion and device integrity.
Magnet wire is hard to position accurately on small pads for soldering. The difficulty in making connections and required substrate area increases with the number of connections.	Connections are made with wire bonds. The number of connections does not affect complexity or cost.
Magnet wire must be held in place and soldered.	No soldering is required.

TABLE I. Comparison of Conventional and Hybrid-Compatible Transformers.

INSULATION METHOD	SINGLE TRANSFORMER	DUAL TRANSFORMER	DUAL TRANSFORMER	DIFFERENTIAL OPTICAL
Package	Ceramic-IC	Plastic - Module	Plastic - Module	Ceramic - IC
Modulation	Flyback	Amplitude	Pulse - Width	Light-Intensity
Nonlinearity max. specified (%)	0.05 - 0.1	0.03 - 0.3	0.005 - 0.025	0.05 - 0.2
Isolation voltage pulse rating (kV)	8	up to 7.5	up to 5	5
Isolation barrier capacitance (pF)	6.0	20 - 100	16	1.8
Isolation-mode rejection (dB) at 60Hz and Gain = 10V/V	125	115 - 130	140 - 150	120
Frequency response small signal (kHz)	35	1 - 2.5	1.5 - 2.5	15
Size (in ³)	0.33	1.4 - 10	5.6	0.44

TABLE II. Comparison of Isolation Amplifiers.

The innovation that makes it economically feasible to put this isolation amplifier into a ceramic hybrid package is the hybrid-compatible transformer design. Figure 3, a photograph of an uncapped isolation amplifier, shows the location of the transformer, the rest of the components (the op amps, resistors, capacitors, and diodes) and the gold-plated pins. The toroid transformer assembly is the dominant feature in

the center. Its turns are made of gold rather than magnet wire—a sharp departure in construction from the state-of-the-art until now. To further illustrate the construction details of the transformer, Figure 4a gives an X-ray type view through the transformer structure from the top, and Figure 4b shows a sectional cut of the assembly.

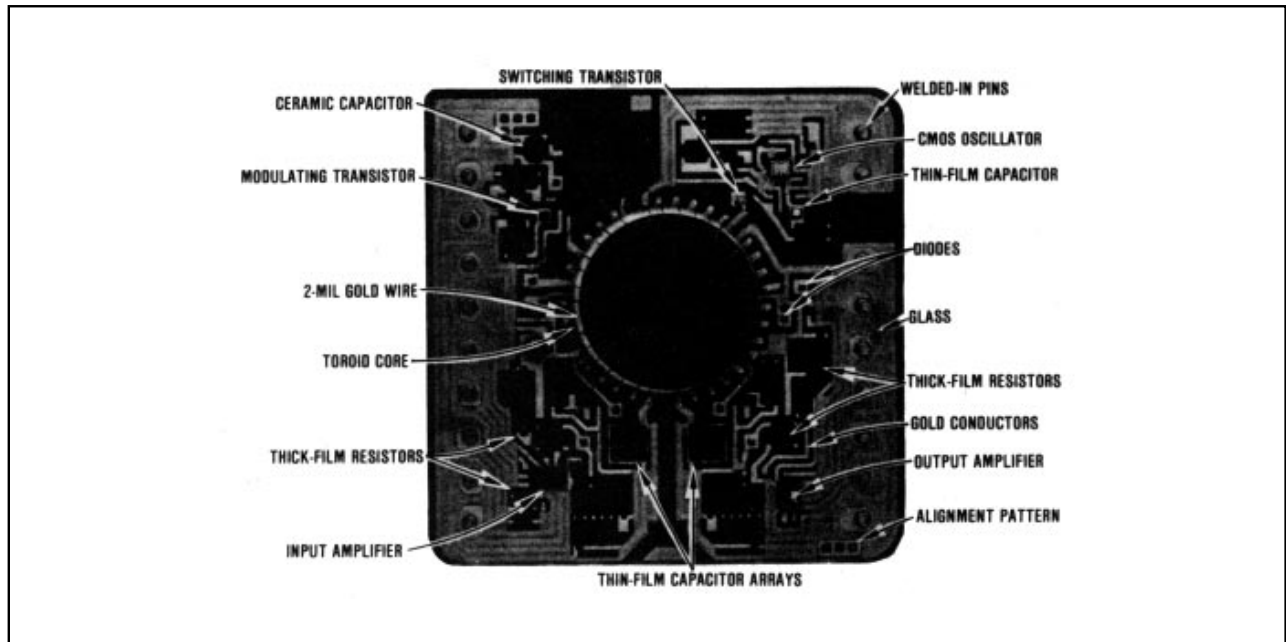


FIGURE 3. Dominant Feature of This Hybrid Integrated-Circuit Isolation Amplifier is Compatible Transformer, Which in Conjunction with the Flyback-Modulation Technique, is Used to Achieve Isolation of Signal and Power with a Single Transformer.

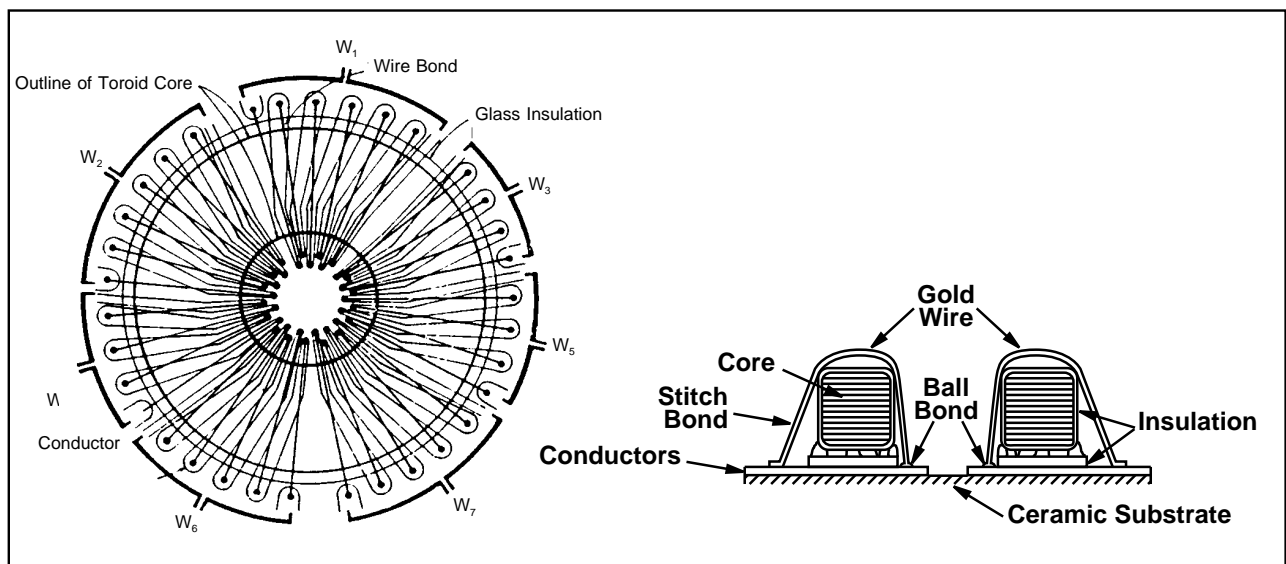


FIGURE 4. Transformer Views. Top X-ray view (a) and cross section (b) show construction of toroid assembly, which provides coupling of signal and power across amplifier's isolation barrier. Turns are of gold wire instead of usual magnet wire and are bonded to screened gold interconnection pattern on ceramic substrate.

MANUFACTURE

Manufacture of the isolation amplifier begins by screening gold conductors onto the ceramic substrate to provide circuit interconnection patterns and the transformer conductor patterns shown in Figure 4a. The gold conductor is then fired in accordance with Burr-Brown's standard thick-film process. The layer of glass insulation is also screened on and fired using thick-film technology. Further processing completes the substrate, which contains 20 laser-trimmed cermet resistors and 19 gold-plated pins, swaged and welded in place.

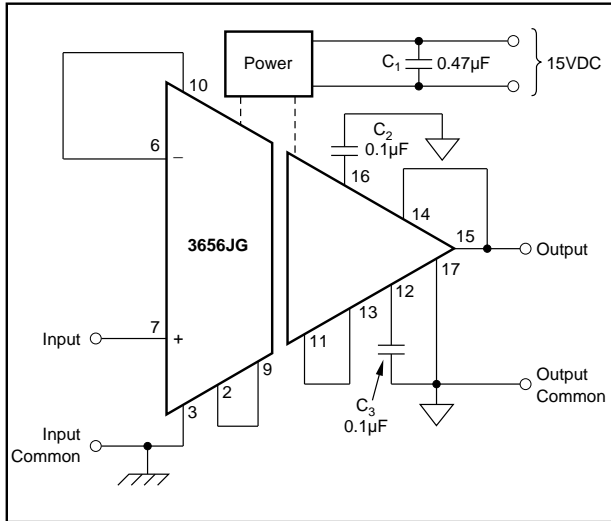


FIGURE 5. Three-port. The 3656, shown here in unity-gain configuration, has a dynamic input and output range of 5V with internally generated power. With external dual-polarity supply, capacitors, C_2 and C_3 , can be eliminated.

The first step on the assembly line is the bonding of the insulation-coated toroid to the glass insulation layer. All the other circuit components are then bonded to the substrates. Chip-to-conductor interconnectors are made with 1-mil gold wire and transformer turns are completed with 2-mil gold wire in accordance with the pattern shown in Figure 4a.

Next, the unit is actively laser-trimmed, tested, and insulation-coated with a high dielectric constant insulating material.

The integrity of the transformer under high voltage stress is ensured by the use of several insulation steps. The glass layer on top of the conductors and the insulator coating on the toroid core each have a minimum dielectric strength of 8kV.

Finally, the package is sealed by applying a ceramic cap over the top of the unit under pressure and heat in a nitrogen atmosphere. The heat cures an epoxy ring prescreened onto the ceramic cap to form an airtight seal.

APPLICATIONS

In the two-port unity-gain isolator of Figure 1, only one external filter capacitor (C_1) and a $\pm 8V$ to $\pm 15V$ supply are required. With a standard $\pm 15V$ supply and at unity gain, this circuit provides a dynamic input and output voltage range of $\pm 5V$. With two additional resistors, A_2 can be programmed for a noninverting gain of 2, providing a minimum dynamic output voltage range of $\pm 10V$.

Figure 5 shows the 3656 connected as a unity-gain, three-port isolator. All isolated supplies are internally generated. C_2 and C_3 filter the internal supplies for output buffer op amp, A_2 . If a dual-polarity supply is available at the output port, these capacitors can be eliminated. With the internal supplies as configured, the dynamic input and output voltage range is $\pm 5V$.

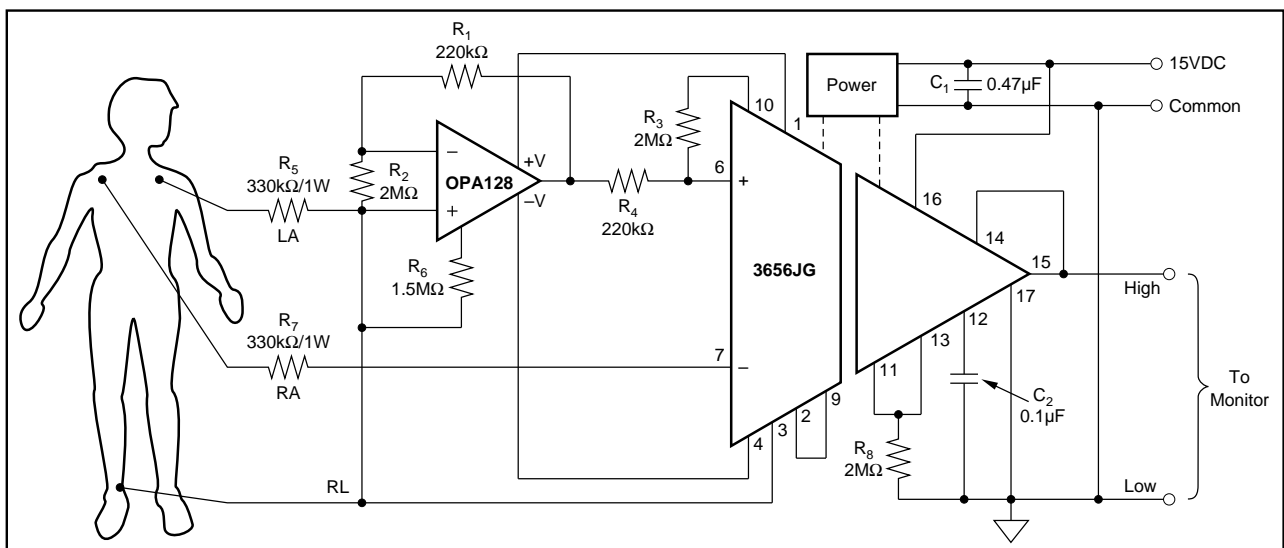


FIGURE 6. Medical Beat. Because of its high isolation, the 3656 is ideal as an electrocardiograph amplifier. It can withstand inadvertent applications of defibrillation pulses while the patient is being monitored. Heart pulses are accurately amplified with a frequency response of DC to 3kHz.

As a result of increased public awareness and increasing government involvement in patient safety, isolation amplifiers have become a must for most electrical patient-monitoring devices marketed today. The 3656 is well suited to such applications because of its low noise, low isolation capacitance, and a high isolation breakdown.

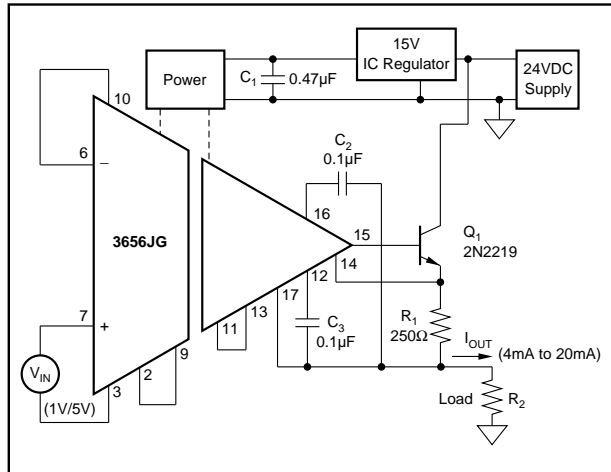


FIGURE 7. Industrial Control. Current-mode signal transmission, often used in industrial control loops, is conveniently implemented with the 3656, here used as a three-port isolator to control current-source transistor, Q_1 . Circuit converts 1V or 5V input into a 4mA or 20mA signal.

The electrocardiograph amplifier in Figure 6 is implemented with an instrumentation input stage by using a second low power, low noise op amp (OPA128) in addition to the internal device. Resistors R_3 and R_4 set the noninverting gain of the internal op amp to 10, and resistors R_1 and R_2 provide matching of the external op amp inputs in accordance with standard practice for designing instrumentation amplifiers.

Resistors R_5 and R_7 protect against the peaks of defibrillation pulses, which might be inadvertently applied to the input if a defibrillator is used to restore the patient's heart function while he is being monitored. These resistors must be carbon composition types, because film types of the same rating cannot survive defibrillator impulse energy, which can range up to 2W/s (8kV).

Resistor R_6 sets the quiescent current of A_1 , and R_8 equalizes the load of the output demodulator with that of the input demodulator for maximum gain accuracy. Capacitor C_2 filters the internal negative supply for the output buffer op amp, but if a $\pm 15V$ supply is connected to the output buffer op amp, C_2 can be eliminated.

This circuit accurately amplifies heart pulses with a frequency response of DC to 3kHz. A bandpass filter between amplifier and monitor can select out the desired frequency range.

For electroencephalography, or brain wave monitoring, where defibrillator protection is not required, R_5 and R_7 can be eliminated, resulting in lower noise. But in order for the frequency band to be monitored, the gain must be increased,

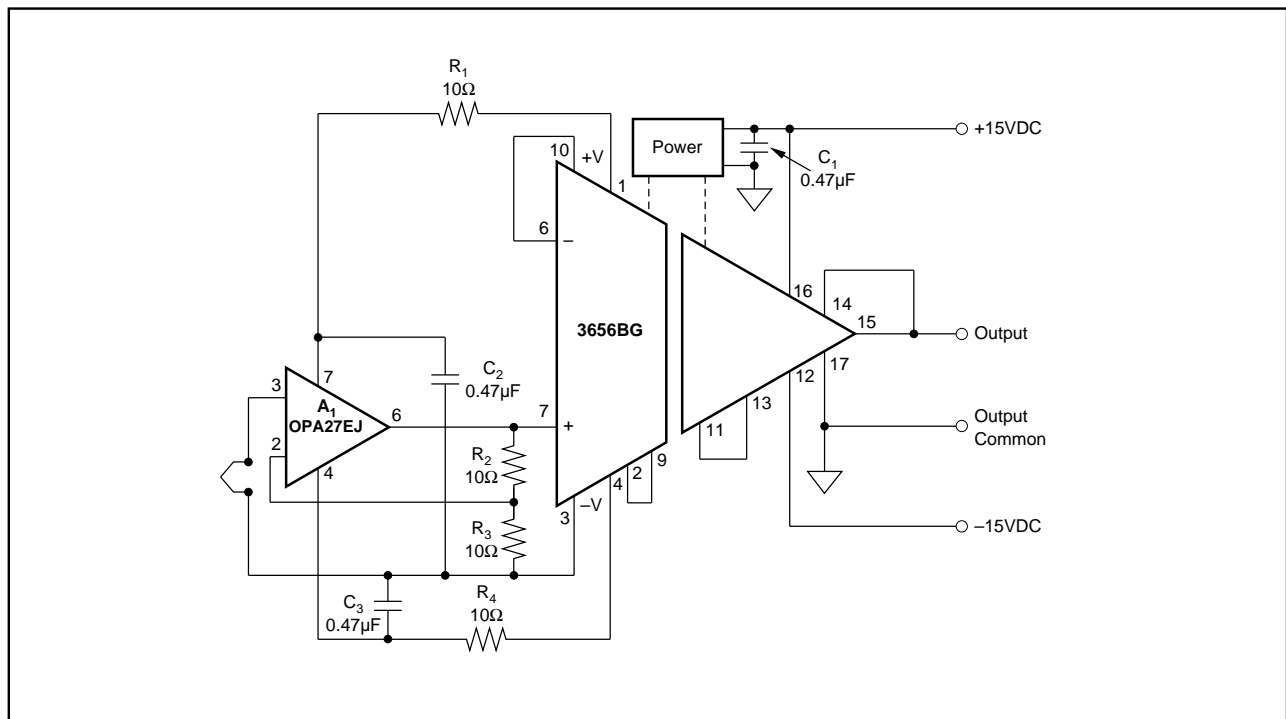


FIGURE 8. Stability. For applications like this thermocouple, where DC stability is important, the isolation amplifier can be supplemented with a high-performance op amp, using the internal isolated power supply, for which capacitors C_2 and C_3 provide additional filtering.

since brain waves are an order of magnitude smaller in amplitude than heart pulses. Increasing the gain is accomplished by bypassing both R_1 and R_4 with an appropriate RC series network. For example, to monitor alpha and theta waves (4Hz to 13Hz) with a gain of 200, two 10k Ω resistors and two 10 μ F capacitors should be used.

INDUSTRIAL CONTROL LOOPS

Analog signal transmission for industrial control circuits is typically done with 4mA to 20mA loops, where 4mA represents zero or quiescent level and 20mA represents maximum signal. Current-mode signal transmission eliminates inaccuracies that are caused by attenuation in cables, intrinsic safety barriers, and multiple sensors. The shifted zero inherent in the 4mA to 20mA range also makes it easy to recognize abnormal operating conditions such as power down or open circuits. If the transmitted current is not between 4mA and 20mA, an error condition is generally assumed.

Figure 7 shows an isolated 1V-5V to 4mA-20mA converter. All power is derived from a single 24VDC supply. The voltage for the isolation amplifier is regulated to 15V using a standard three-terminal regulator. The isolation amplifier is used with a floating output (three ports) to control current-source transistor, Q_1 , and feed its emitter current into grounded load resistor, R_2 . The feedback voltage for the internal output buffer is derived across sense resistor R_1 and is proportional to the output current.

For increased DC stability when required in applications like a thermocouple amplifier, the front end of the 3656 can be supplemented with a high performance op amp by using the available isolated supply. Figure 8 shows such a configuration. Resistors R_2 and R_3 set the gain of the front end amplifier to 1000. Capacitors C_2 and C_3 provide additional filtering for the isolated supply—recommended if A_1 draws more than 0.1mA of supply current.

GETTING FULL ISOLATION-MODE REJECTION

A recent analysis of an isolation amplifier to determine the effect of internal- and external-component and stray capacitances on isolation-mode rejection shows that only the capacitances of the input wires to the output circuits are critical. Thus, the major factors for the user are specified isolation-barrier capacitance (C_{ISO}), and the external capacitance between any of the input and output pins.

Designing for high isolation-mode rejection becomes very simple if the isolation amp includes an instrumentation or balanced front end or one is added externally. The balanced front end makes it easy to maintain the full isolation-mode rejection specified because the barrier capacitances from each input-to-output common can be easily balanced. To maintain an isolation-mode rejection close to 120dB with a capacitance unbalance of 0.5pF, a source impedance unbalance of up to 50k Ω can be tolerated.

Maintaining full isolation-mode rejection with a single-ended or unbalanced front end is more difficult. The source resistances in this case must be no more than a few hundred ohms. With large source impedances, degradation can occur in degrees that depend on the circuit, the isolation capacitance, and external stray capacitances.

A simple model of an isolation amplifier with an operational amplifier input stage is shown in Figure 9. Amplifier, A_1 , represents the input op amp, and A_2 the unity-gain isolation stage. Specified isolation-mode rejection is achieved if common-mode signal V_{CM} produces no differential input signal between the inputs of A_1 , A_2 , or both. This is the case if both R_2 , R_4 , and R_5 , and C_1 , C_2 , and C_{ISO} , are zero. However, when these resistors and capacitors have finite values, they form three low-pass filters, each with the general attenuation function:

$$A = [R + (1/j\omega C)]j\omega C$$

For example, if $R_5 = 1k\Omega$ and $C_{ISO} = 6pF$, the calculated attenuation A at 60Hz is 2.2×10^{-6} or 2.2ppm. Though a few ppm of attenuation seems trivial, note that 1ppm is equivalent to 120dB ($20 \log 1ppm$).

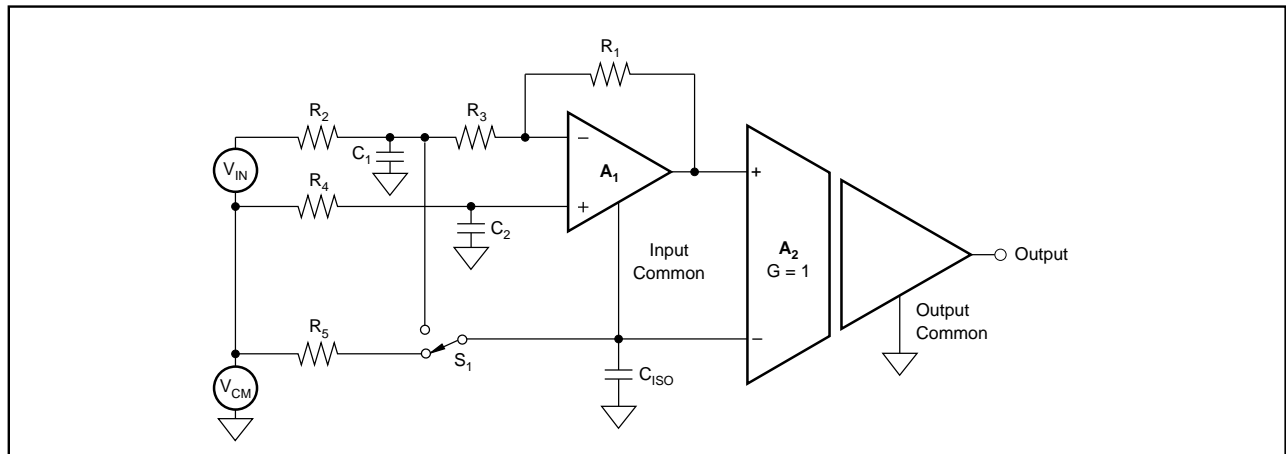


FIGURE 9. Isolation Amplifier Model For Analyzing Isolation-Mode Rejection.

Any differential signal appearing at the input of A_1 , because of unequal attenuation of V_{CM} by network C_1 - R_2 loaded with R_5 on the one hand, and C_2 - R_1 loaded with the noninverting input of A_1 on the other, will be amplified the same as an input signal (V_{IN}). Thus, unequal attenuation can be directly translated into a limit on isolation-mode rejection referred to the input. Any attenuation of V_{CM} caused by low-pass filter R_5 - C_{ISO} with respect to the common portion of V_{CM} across the input of A_1 appears across the input of A_2 . The gain for this signal is only unity regardless of gain of A_1 , causing an isolation-mode rejection degradation with reference to the output.

The three-wire input system in the figure maximizes the isolation-mode rejection of the 3656 or other isolation amplifiers with an unbalanced input, because C_{ISO} becomes less critical with high gain and C_1 and C_2 can be kept small. But, the value of R_2 affects the circuit gain.

If a two-wire system is chosen and the input common is connected to the junction of R_2 and R_3 (S_1 switched), the gain is no longer affected by R_2 , but the degradation of balance caused by network C_1 - R_2 loaded by R_3 in conjunction with the largest capacitance C_{ISO} is amplified by A_1 and causes much poorer isolation-mode rejection at gains higher than unity.

WHAT IS AN ISOLATION AMPLIFIER?

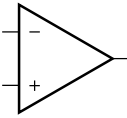
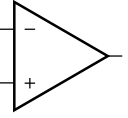
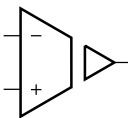
Isolation amplifiers resemble operational amplifiers but are designed to have a galvanic discontinuity between their input and output pins. This discontinuity, called an isolation barrier, must have high breakdown voltage, low DC leakage (high barrier resistance), and low AC leakage (low barrier capacitance).

The isolation barrier sets the isolation amplifier apart from operational and instrumentation amplifiers in cost and complexity, as well as in application. So called three-port isolation amplifiers have an additional isolation barrier between the power supply connection and the signal connections. This feature increases versatility, because it allows the user to connect power in common with either the amplifier's input or its output. In some cases, it may be advantageous to isolate the power supply from the input or the output and thereby eliminate additional error sources that may be present in a system.

Isolation amplifiers generally serve the following functions not achievable with operational or instrumentation amplifiers:

- Sensing small signals in the presence of very high (>10V) or unknown common-mode voltages.
- Protecting patients undergoing medical monitoring or diagnostic measurements.
- Completely breaking ground loops.

Below is a comparison of the three basic amplifier types. The isolation amplifier, as well as offering isolation, increases accuracy because of its floating input. In contrast to the instrumentation amplifier, it not only eliminates ground loop errors, but further reduces the total system error because its isolation mode rejection ratio is generally one or two orders of magnitude higher than the common-mode rejection of an instrumentation amplifier.

	OP AMP	INSTRUMENTATION AMP	ISOLATION AMP
SYMBOL			
FEEDBACK CONFIGURATION	User defined feedback such as voltage, current dV/dt ; $\int V dt$, $\log V$, etc.	Committed feedback. Gain adjustable within fixed limits.	
BASIC APPLICATION	1. General purpose gain element. 2. Buffer. 3. Analog computer.	High accuracy analog sense amplifier when common-mode potentials are smaller than the supply voltage.	1. High accuracy analog sense amplifier for common-mode potentials in excess of supply voltage. 2. Analog safety isolator. 3. Break ground loops.
MAJOR ERRORS	Offset, noise, and common-mode errors independent of gain.	Input and output offset and noise. Total error depends on gain. One set of common-mode specifications.	Input and output offset and noise. Separate common-mode and isolation mode errors except for single-ended input devices.

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