ISOLATION AMPS HIKE ACCURACY AND RELIABILITY

Isolation Amplifiers Protect Critical Circuitry From Damage and Enhance Performance

by Tom Sommerville

Fault tolerance, transient protection, and interference rejection are valuable features that isolation amplifiers bring to critical circuitry. Two useful examples of how designers can employ isolation amplifiers to improve their systems' performance and reliability are process temperature controllers and electrocardiogram (ECG) amplifiers.

In the case of process control, isolation amplifiers galvanically isolate both the input channel and the current-loop output driver from the controller hardware. Consequently, neither accidental faults from line-powered manufacturing plant equipment to the control system circuitry nor ground loop voltages can compromise the process. In ECG amplifiers, a low-capacitance isolation barrier limits 60Hz leakage current to safe levels, and a high barrier voltage rating protects the monitoring equipment from defibrillator transients and electrosurgery (ESU) interference.

Process control loops, in particular, illustrate a number of ways that isolation amplifiers improve performance and reliability. In unisolated control systems, the long ground lines can develop error potentials across the common impedance that can cause component failure and/or inaccurate control. In contrast, isolating the distributed control systems (DCS) inputs and outputs close to the controller interrupts the dc path, replacing it with the large impedance of the isolation amp's high-voltage barrier (Figure 1).

Similarly, isolation protects the loop from interruption or damage. In the example loop, which is a temperature controller, isolation protects the circuit if the resistance-temperature detector (RTD), a PT100, is accidentally shorted to a grounded metal case or high-voltage conductor. Another possible problem is a fault from the high-potential wire of a twisted pair to earth ground. In addition, high current transients from motors and relays sharing an unisolated system ground can create voltages that exceed the ±1V maximum rating of the two-wire transmitter (XTR).

Isolated control loops also benefit from improved rejection of 60Hz line interference, because low-level transducers are especially susceptible to inductive-loop coupling to the 60Hz magnetic field and capacitive coupling to the electric fields. Not only can the isolation amp prevent system damage, but also the component's isolation-mode rejection (IMR) can attenuate the effect on the output by over 1 million to one.

High dv/dt from inductive current and from radiated electromagnetic interference (EMI) caused by relay arcing are
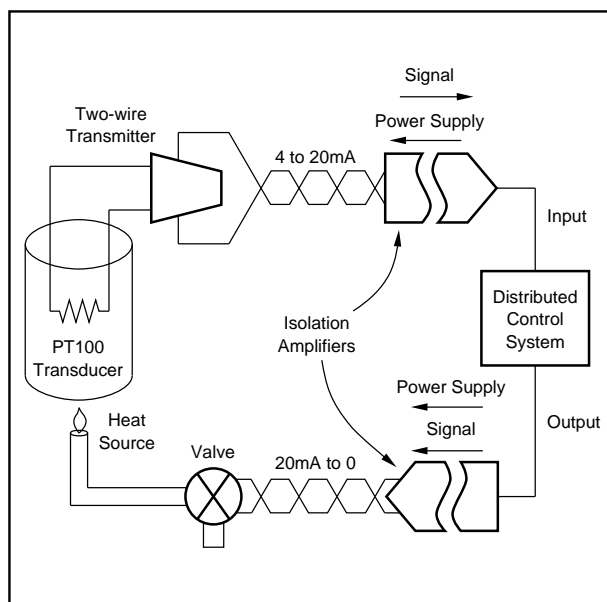

FIGURE 1. Isolating the Distributed Control System in a Process Control Loop Interrupts the DC Path, Blocking Possible Error Potentials that Could Cause Component Failure and Control Inaccuracy.

more difficult to deal with. An isolation amp, however, can reduce their effect on system accuracy, depending on the amplifier's transient immunity. This parameter is defined as the greatest dv/dt that can appear between isolated and unisolated ground before accuracy is lost at the amplifier's output. Few data sheets specify transient immunity, which can vary from 0.1 to 10,000V/µs.

Choosing the best isolation amplifier from process-control applications isn't a simple matter. The common use of 4-to-20mA current loop transmitters and receivers requires an isolated power supply that can supply at least 25mA for the loop and any signal conditioning circuitry. Another consideration is the input supply-voltage range. Some isolation amps need a regulated 15V supply, while others can tolerate sharing an unregulated system supply. The IMR needed depends on the 60Hz line voltage encountered. Most isolation amps specify greater than 100dB rejection at 60Hz, which is adequate for the majority of process-control applications.
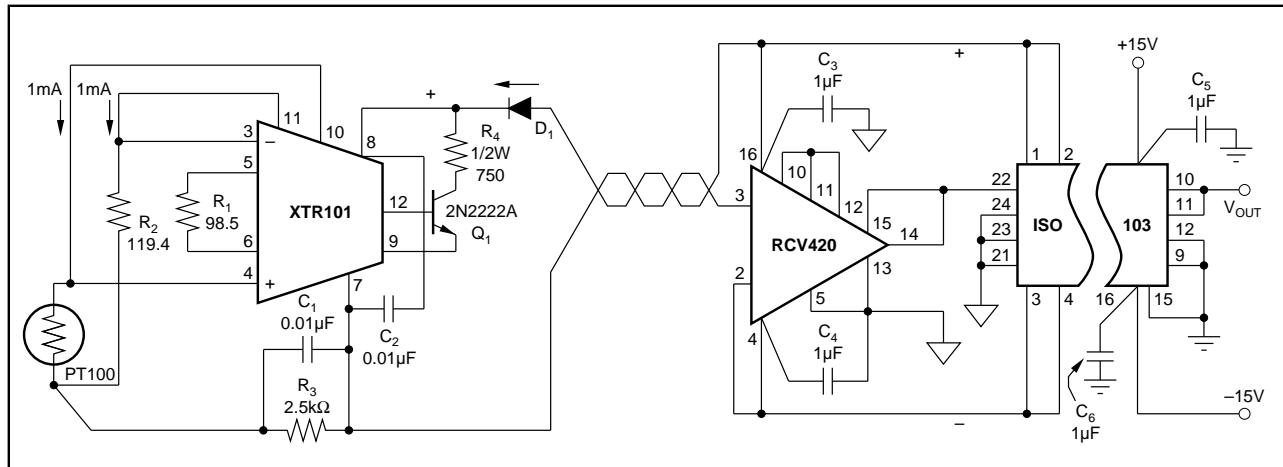
FIGURE 2. In an Example Process Temperature Controller, the Isolated Input Channel Runs from the PT100 Transducer to the XTR101 Two-Wire Transmitter.

TESTS MAY BE NEEDED

As noted, transient immunity is important in process control, with the character of the ground noise determining the level required. If the immunity isn't specified, or is specified at a low barrier voltage, designers must test the amplifier to determine its suitability.

Reliability testing of the barrier integrity varies between manufacturers and their products. For process-control applications, the UL1244 standard calls for 100%, 60Hz ac breakdown testing at the rated voltage for 1 minute. By comparing the isolation amp's test-voltage condition with its continuous rating voltage, designers can judge how conservative the rating is.

Accuracy specifications, however, are relatively uniform. At one time, only expensive discrete modules or in-house custom designs offered better than 0.05% linearity. But recently, small and inexpensive (less than $30) hybrids with comparable performance became available. In some cases, surface-mounting techniques have reduced size and cost. Other designs include custom ICs and high-frequency ferrite transformers that reduce complexity, as well as size and cost.

The isolated input channel of the example control loop runs from the PT100 transducer to the DCS input, beginning with the XTR101 two-wire transmitter configured for the required process temperature of 50°C to 150°C (Figure 2). The PT100 temperature resistance table indicates a resistance of 119.4Ω at 50°C and 157.31Ω at 150°C. One of the XTR101's two 1mA current sources flows through the PT100, so the input amplifier voltage span is 37.9mV.

The span resistor, R_1, is calculated from the input voltage and output current span (4 to 20mA from 50°C to 150°C):

$$R_1 = 40/[(20mA - 4mA)/37.91mV - 0.016m\Omega] = 98.5\Omega$$

The offset resistor, R_2, is equal the PT100's resistance at 50°C: 119.4Ω. The 5V common-mode bias needed for the XTR101's inputs is supplied by R_3 (2mA x 2.5kΩ).

To minimize the temperature rise in the XTR101, the external 2N2222A conducts all but 4mA of the transmitter current. The 750Ω, 1/2W resistor limits the worst-case power dissipation in the transistor to 19.6 x 16mA = 314mW, where 19.6V is V_{CE} and 16mA is determined by the transistor and XTR. Thus, the dissipation is below the TO-18 limit of 400mW at room temperature. For applications at higher ambient temperatures, a 2N6121 in a TO-220 package is a more reliable substitute. This small, current-mode transmitter can be located close to the RTD, with signal and power conducted through one twisted-wire pair from the remote monitoring point to the central controller. At the controller, a proportional analog voltage is reconstructed.

The RCV420 current-loop receiver has an output of 0 to 5V for a 4-to-20mA output. The maximum voltage drop across the receiver's input is 75Ω (the internal resistance between pins 2 and 3) times 20mA, or 1.5V.

ERROR COMPENSATION

The isolation amp, an ISO103, creates both an isolated signal buffer and an isolated dc-dc converter power supply that energizes the XTR101 and RCV420, as well as the ISO103's internal input amplifier. By adjusting R_1 and R_2 for input-temperature-to-voltage accuracy, designers can compensate for gain and offset-voltage errors in the ISO103 and RCV420. The ISO103's high continuous-voltage rating means that the circuit can tolerate line voltages to 1500Vrms. The amplifier's isolation-mode rejection is 130dB at 60Hz, high enough to limit the interference of a 1500Vrms fault to 0.5mVrms, or an error of 0.014°C referred to the input.

Designers can verify the input-channel linearity by measuring the temperature-to-voltage error. The resulting 0.2% error, which equates to a maximum 0.2°C error, is due almost entirely to the temperature-to-resistance nonlinearity of the PT100. If greater accuracy or a wider temperature range is needed, designers can apply an RTD resistance
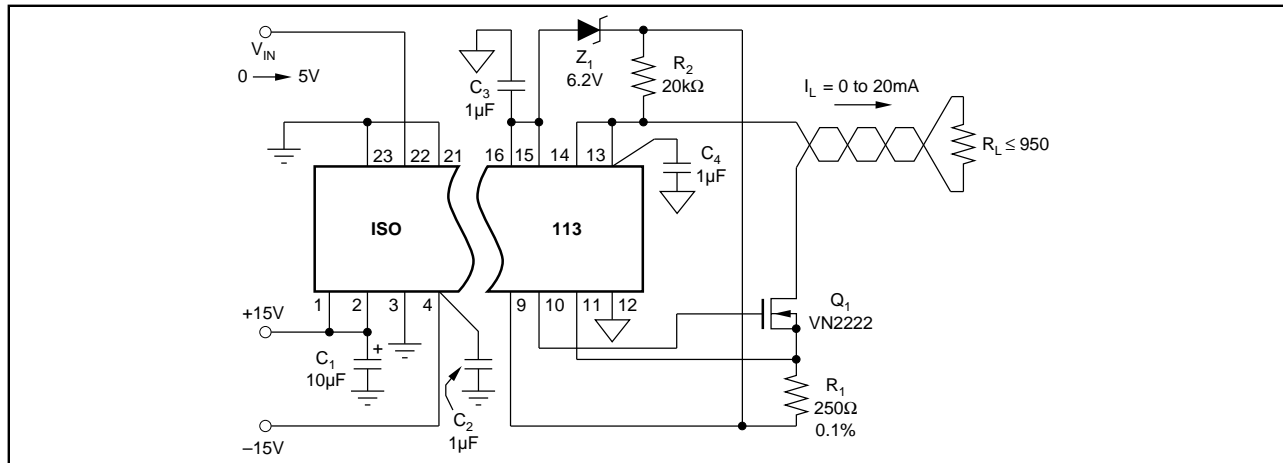
FIGURE 3. On the Output Side, the Process Control Loop Includes an Isolated 0-20mA Loop Driver.

correction factor in the controller, leaving only the 0.04% error from the ISO103.

The output half of the process control loop consists of the isolated 0-to-20mA loop driver (Figure 3). The circuit receives a 0-to-5V input from the controller in the DCS. The driver output current energizes an actuator valve that controls the steam pressure, which regulates the process temperature. Thus, the process control loop is closed by an isolated current-to-pressure converter built around the ISO113 internally powered output isolation amp.

The circuit operates by closing a voltage feedback loop, such that V_{IN} is developed across R_1. This is done by connecting the common pin to one end of R_1 and the sense pin to the other, with V_{OUT} connected to the gate of the VN2222 MOSFET.

To use the maximum compliance voltage at the output, the common pin voltage is referenced off the negative supply with a 6.2V zener diode, Z_1. To keep the zener active when the output current is zero, the driver output current flows through the diode to the negative supply, along with a 1.5mA current from the positive supply through R_2. For the 30V supply in the example, 19V remains across the MOSFET and load, allowing for a maximum load resistance of 950Ω.

The ISO113's input offset voltage, which can be compensated by the controller's transfer function, determines the accuracy of the output offset current ($I_{OS} = V_{OS}/R_1$). Gain accuracy depends on the accuracy and stability of R_1. If adequate care isn't taken, power dissipation in R_1 can degrade the transfer function's linearity.

For example, the temperature change in R_1, for a resistor thermal resistance of 300°C/W is 30°. Consequently, a resistor temperature coefficient of 50ppm/°C causes a 0.15% nonlinearity. To reduce this error, either the resistor thermal resistance or temperature coefficient must be reduced. The thermal resistance can be lowered by connecting four separate 1kΩ resistors in parallel to form the 250Ω resistance, or by using a large wire-wound resistor.

As with the ISO103, the ISO113 is rated for 1500Vrms continuous isolation voltage. Under this maximum interference condition at 60Hz, the 130dB isolation-mode rejection results in a 2μA output-current error, only 0.01% of full-scale and negligible in this application.

Medical instrumentation, although a totally different class of application from process control, illustrates an extreme example of isolation protection that may also be needed in process control, automated test equipment, and data acquisition systems. An ECG amplifier, for instance, is designed to accurately amplify the heart muscle's action potential sensed by surface skin electrodes. A specific design example is an amplifier configured for measuring the difference between the left arm (LA) electrode and the right arm (RA) electrode while driving the right leg (RL) with a small current. This is referred to as the "Lead I" configuration (Figure 4).

AVOIDING INTERFERENCE

Corrupting interference from nearby 60Hz line-operated equipment is minimized by the RL drive amplifier (IC_{2A}), the high input impedance and common-mode rejection ratio (CMRR) of the instrumentation amplifier (IC_1), and the low barrier capacitance of the isolation amp (IC_3). The barrier capacitance, 13pF, also ensures patient safety by limiting 60Hz leakage current from 240Vrms power-line coupling to below 2μArms, which is one-tenth of the Underwriters Laboratories' standard for medical and dental equipment. The electrode input-current limiting resistors (R_1-R_3), the transistor clamps (Q_1 and Q_2, both 2N3904s), and the isolation amp's internal insulation protect the amplifier from defibrillator and ESU high-voltage transients.

The bandwidth needed to faithfully amplify the ECG waveform is 0.05Hz to 100Hz. The low-frequency limit is needed to attenuate slowly varying potentials caused by chemical reactions at the electrode-skin interface. Therefore, the gain of the dc-coupled instrumentation amplifier is set at 10 to prevent the amplified electrode potentials from creating an
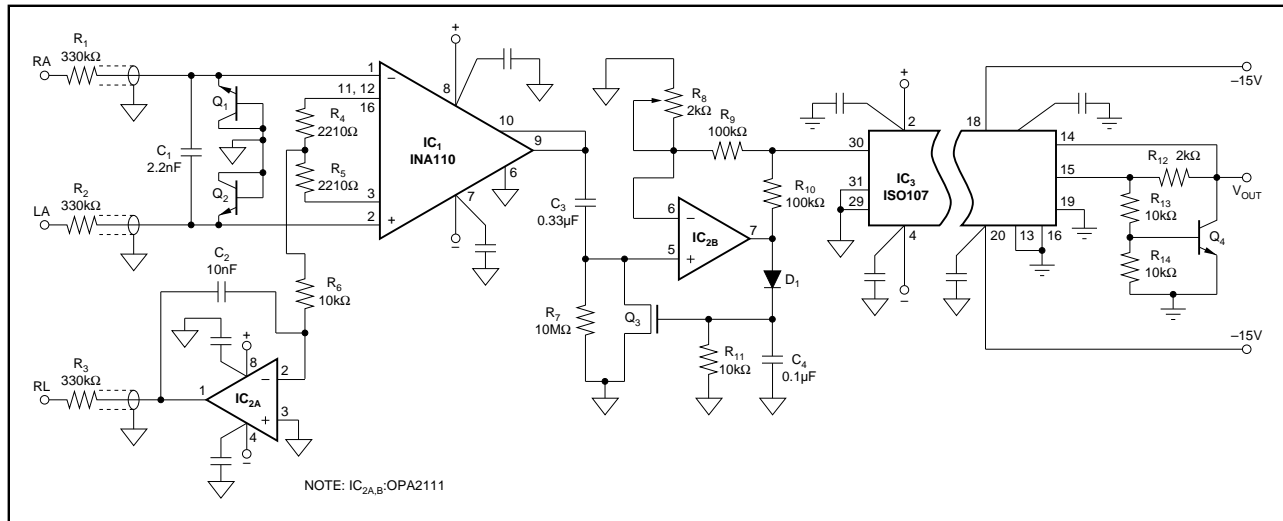
FIGURE 4. In an ECG Amplifier, an Isolation Amplifier Protects the Circuitry and the Patient from Leakage Current from 60Hz Line Operated Equipment and From High-Voltage Transients Caused By Other Equipment.

overload. Input low-pass filtering for differential inputs is performed by R_1, R_2 and C_1. The upper 3dB frequency:

$$= (1/2\pi)/[R_1 + R_2)(C_1)]$$

$$= (0.159)/[(600k\Omega)(2.2nF)] = 110Hz$$

An important consideration is the ECG amplifier's common-mode input impedance. Because the LA and RA electrode impedances can be imbalanced by as much as 100kΩ, the differential signal seen by IC_1 may be in error if the impedance is below 10MΩ. However, the common-mode input impedance of the instrumentation amplifier used, an INA110, is large enough, $2 \times 10^{12}\Omega$, so the cable shield's capacitance of 100pF dominates the ECG amplifier's common-mode input impedance. The resulting reactance of 26MΩ at 60Hz is high enough to prevent errors due to electrode impedance mismatching.

The RL amplifier reduces the 60Hz noise resulting from the magnetic and electric fields surrounding line-voltage sources. Typically, this noise voltage is 0.1 to 1Vp-p, about 100 to 1000 times the ECG signal. The RL amplifier helps reject the noise by reducing the common-mode voltage with negative feedback through the op amp integrator (IC_{2A}).

The amount of loop gain available at 60Hz depends on the compensation needed to stabilize the loop. The isolation supplied by IC_3 reduces the required compensation by adding series barrier capacitance between the patient and earth ground, thereby maximizing the available 60Hz noise rejection.

A pair of gain-setting resistors (R_4 and R_5) create an ac common-mode voltage sense point for the RL drive amplifier. The dc voltage at this point is 1V lower than the inputs, so the driver amplifier floats the patient to +1V relative to isolated ground as a consequence of forcing the common-mode point to zero. The design aims to maximize the RL drive amplifier's gain at 60Hz while maintaining the feed-back loop's stability. Using the INA110's gain equation, the gain-setting resistance for a gain of G is:

$$R_4 = R_5 = [20k\Omega/(G - 1) - 25]\Omega.$$

The second amplifier stage (IC_{2b}) is an ac-coupled, variable gain, noninverting amplifier. The lower 3dB frequency is 0.05Hz. The unit used is an OPA2111 JFET input op amp with a $10^{14}\Omega$ input resistance and a 3pA input bias current. These values allow the use of a 10MΩ input resistor without introducing dc errors. With the variable gain feature, designers can set a nominal 1V/mV gain or adjust the output waveform amplitude for patient ECG variations.

This stage includes an automatic-gain-control feedback loop that ensures a rapid recovery from ESU interference. The loop caps the amplifier's output at 2V, a level determined by the MOSFET's threshold voltage (0.8 to 3V), the diode peak detector, and value of R_9. By limiting the output to 2V, the input is kept below 20mV, so C_2 can quickly discharge during transient recovery.

TWO SOURCES OF TRANSIENTS

The ECG amplifier must deal with two sources of high-voltage transients. One is the ESU, essentially a high-voltage RF generator. The other is the defibrillator, which generates electrical pulses.

The ESU has two modes: coagulate and cut. In the coagulate mode, the unit applies a gated 1MHz damped sinusoid to close small ruptured blood vessels with RF heating. In the cut mode, a lower frequency (300kHz) sinusoid with less damping is applied to tissue with a scalpel electrode, facilitating "bloodless" surgery (Figure 5).

The patient lies on a large electrode, supplying a return path for the high-frequency current. Another current path is created by the stray capacitance coupling the primary and secondary windings of the power-supply transformer, which
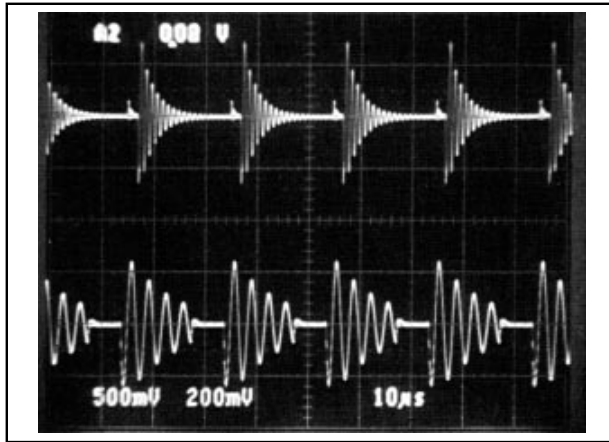
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FIGURE 5. An Electrosurgery Unit Generates Two Damped Sinusoids that Can Cause Transients in the ECG Amplifier. The coagulate waveform is at 1MHz (top), and the cut waveform is at 300kHz (bottom).

is connected to line voltage. The isolation amp completes this second path through its power-supply winding capacitance and barrier capacitance.

The defibrillator, on the other hand, charges a 16μF high-voltage capacitor to an adjustable voltage level calibrated in terms of energy (watt-seconds). The capacitor is discharged against the patient's chest through a 100mH inductor and two large metal electrodes, or paddles. The result is an underdamped transient known as the Lown waveform.

The value of this transient is derived by completing the LCR circuit with a 50Ω resistor model for the human body. The voltage that appears between the paddles is the voltage across the 50Ω resistor. For a setting of 400Ws, the capacitor is charged to 7kV, and the frequency of the damped sinusoid

is 126Hz. The peak current and voltage turn out to be 69A and 3460V. Some fraction of this transient appears at the ECG electrodes and between the isolated patient ground and the output (earth) ground.

During ESU and defibrillator operation, the two 2N3904 transistors clamp the INA110's inputs at +8V and –0.7V. With no overvoltages present, the transistor's leakage current is less than 100pA. The 330kΩ input resistors limit the peak defibrillator input current to less than 10mA, but they must dissipate 41W of instantaneous power. Fortunately, the defibrillator charges slowly enough to avoid significant resistor heating and damage.

Larger ESU generators, however, can deliver 300W of RF power to the patient. The result is a worst case of 300mW dissipated in the 1/2W input resistors.

The ISO107 supplies an isolated gain of one for the ECG signal and an isolated supply for the INA110 and OPA2111. Besides limiting the 60Hz leakage current, the unit's barrier capacitance limits barrier RF current during ESU operation. The path of the RF leakage current is through the 50pF stray capacitance of the ESU line transformer, the amplifier's power-supply transformer capacitance, and the ISO107 isolation barrier (Figure 6).

The 13pF barrier capacitance conducts a transient current of 57mA peak. Though this level doesn't damage the isolation amp, it corrupts the output signal, because the slew rate of the interference is 4400V/μs. As a result, an output latch is used to ground the output during the interference. When the output exceeds 1.4V, Q_4 (also a 2N3904) conducts, forcing the output to V_{SAT}, which the output sense sees as positive feedback. To release the clamp, the input voltage of the isolation amp must go below ground.

The performance of the ECG amplifier is determined by the frequency response, the common-mode rejection, and the
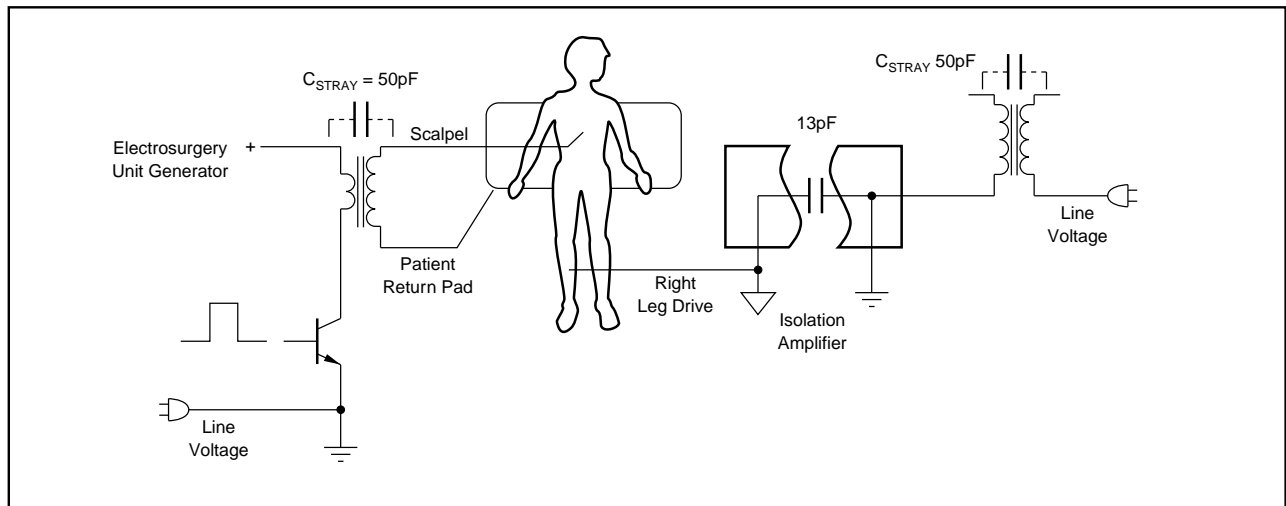

FIGURE 6. Stray Capacitances Coupling the Windings of the ESU and Amplifier Power Transformers Supply Paths for RF Leakage Current.

response to ESU interference and defibrillator pulses. Using the isolation circuitry described, the amplifier's 3dB bandwidth is 0.05 to 100Hz and CMRR ranges from 95dB at 0.05Hz to 80dB at 100Hz.

To simulate a patient load, a 50Ω resistor was placed across the defibrillator output. With a 400Ws defibrillator pulse applied directly between the amplifier's isolated and output grounds, the output clamps and briefly oscillates during the transient, but settles back before the transient ends.

To test the ESU interference response, an ECG simulator was used to apply a test input waveform of 1mV amplitude, and 240beats/min. The isolation barrier RF interference voltage and the ECG output were then displayed on an oscilloscope. The output clamp effectively zeroes the output during the transient, as expected, then releases during the first negative-going input once the RF ceases (Figure 7).
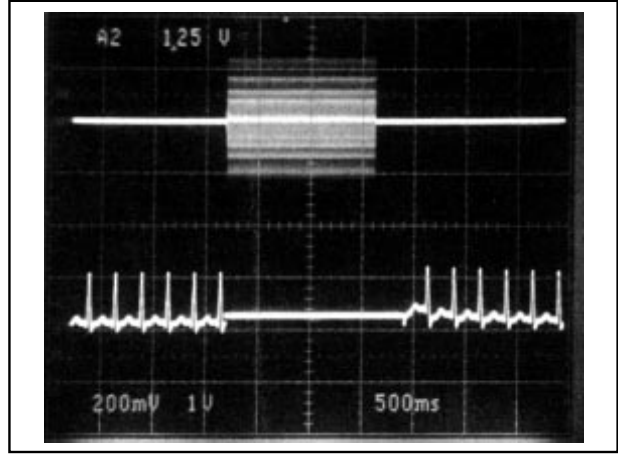

FIGURE 7. With an Isolation Barrier RF Interference Voltage Applied (top), the Amplifier's Output Clamp Zeroes the Output (bottom).

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