Agilent Technologies
Innovating the HP Way

Linear Applications of Optocouplers

Application Note 951-2

Introduction

Optocouplers are useful in applications where analog or DC signals need to be transferred from one module to another in the presence of a large potential difference or induced noise between the ground or common points of these modules.

Potential applications are those in which large transformers, expensive instrumentation amplifiers or complicated A/D conversion schemes are used. Examples are: sensing circuits (thermocouples, transducers ...), patient monitoring equipment, power supply feedback, high voltage current monitoring, adaptive control systems, audio amplifiers and video amplifiers.

Agilent Technologies Optocouplers

Agilent's optocouplers have integrated photodetector/ amplifiers with speed and linearity advantages over conventional photo-transistors. In a phototransistor, the photodetector is the collector-base junction so the capacitance impairs the collector rise time. Also, amplified photocurrent flows in the collector-base junction and modulates the photo-response, thereby causing non-linearity. The photodetector in an Agilent optocoupler is a separately integrated diode so its photoresponse is not affected by amplified photocurrent and its capacitance does not impair speed. Some linear isolation schemes employ digital conversion techniques (A/D-D/A, PWM, PCM, etc.) in which the higher speed of the integrated photodetector permits better linearity and bandwidth.

The 6N135/6N136 is recommended for single channel AC analog designs. The HCPL-2530/31 is recommended for dual channel DC linear designs. The 6N135/6 series or the 6N137 series are recommended for digital conversion schemes.

If the output transistor is biased in the active region, the current transfer relationship for the 6N135 series optocoupler can be represented as:

$$I_C = K\left(\frac{I_F}{I_F'}\right)^n$$

where I_C is the collector current; I_F is the input LED current; I_F' is the current at which K is measured; K is the collector current when $I_F = I_F'$; and n is the slope of I_C vs. I_F on logarithmic coordinates.

The exponent n varies with I_F, but over some limited range of ΔI_F, n can be regarded as a constant. The current transfer relationship for an optoisolator will be linear only if n equals one.

For the 6N135 series optocoupler, n varies from approximately 2 at input currents less than 5 mA to approximately 1 at input currents greater than 16 mA. For AC coupled applications, reasonable linearity can be obtained with a single optocoupler. The optocoupler is biased at higher levels of input LED current where the ratio of incremental photodiode current to incremental LED current ($\delta I_D / \delta I_F$) is more nearly constant.

For better linearity and stability, servo or differential linearization techniques can be used.

The servo linearizer forces the input current of one optocoupler to track the input current of the second optocoupler by servo action. Thus, if $n_1 \cong n_2$ over the excursion range, the nonlinearities will cancel and the

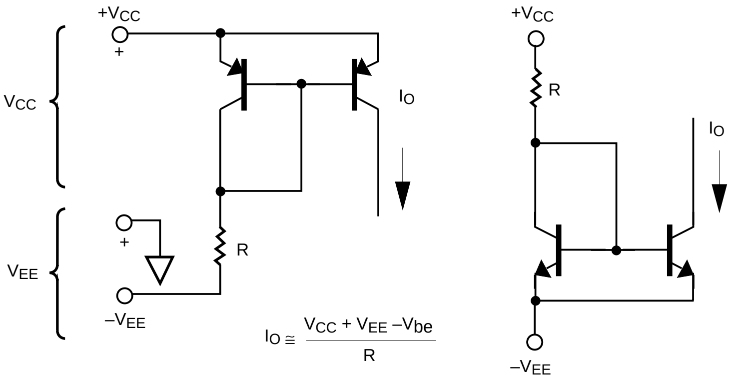


Figure 1.

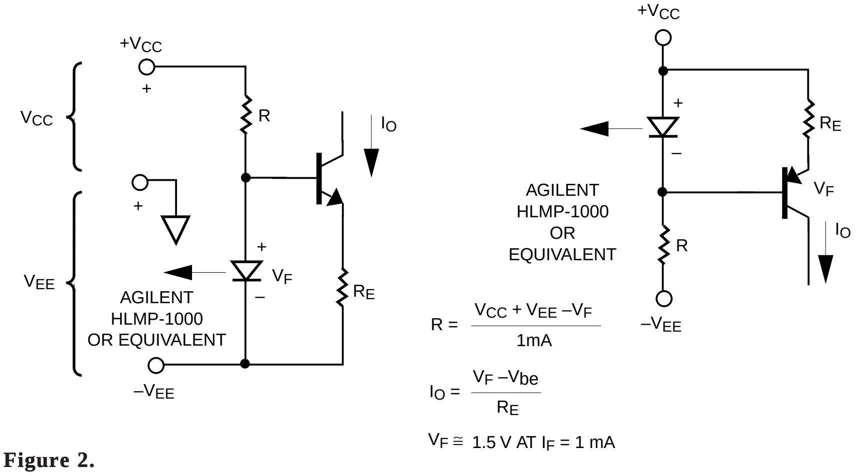


Figure 2.

overall transfer function will be linear. In the differential linearizer, an input signal causes the input current of one optocoupler to increase by the same amount that input current of the second optocoupler is decreased. If $n_1 \cong n_2 \cong 2$, then a gain increment in the first optocoupler will be balanced by a gain decrement in the second optocoupler and the overall transfer function will be linear. With these techniques, matching of K will not effect the overall linearity of the circuit but will simplify circuit realization by reducing the required dynamic range of the zero and offset potentiometers.

Gain and offset stability over temperature is dependent on the stability of current sources, resistors, and the optocoupler. For the servo technique, changes of K over temperature will have only a small effect on overall gain and offset as long as the ratio of K_1 to K_2 remains constant. With the differential technique, changes of K over temperature will cause a change in gain of the circuit. Offset will remain stable as long as the ratio of K_1 to K_2 remains constant. In the AC circuit, since $(\delta I_D / \delta I_F)$ varies with temperature, the gain will also vary with temperature. A thermistor can be used in the output amplifiers of the Differential and AC circuits to compensate for this change in gain over temperature.

There are also several digital techniques to transmit an optocoupler analog signal. Optocouplers can be used to transmit a frequency- or pulse-width-modulated signal. In these applications, overall circuit bandwidth is determined by the required linearity as well as the propagation delay of the optocoupler. The 6N137 series optocoupler features propagation delays typically less than 50 ns and the 6N135 series optocoupler features propagation typically less than 300 ns.

In several places the circuits shown call for a current source. They can be realized in several ways. If V_{CC} is stable, the current source can be a mirror type circuit as shown in Figure 1.

If V_{CC} is not stable, a simple current source such as the ones shown in Figure 2 can be realized with an LED as a voltage reference. The LED will approximately compensate the transistor over temperature since $\Delta V_{be} / \Delta T \cong \Delta V_F / \Delta T = -2$ mV/°C. See Figure 2.

Servo Isolation Amplifier

The servo amplifier shown in Figure 3 operates on the principle that two optocouplers will track each other if their gain changes by the same amount over some operating region. U_2 compares the outputs of each optocoupler and forces I_{F2} through D_2 to be equal to I_{F1} through D_1. The constant current sources bias each I_F at 3 mA quiescent current. R_1 has been selected so that I_{F1} varies over the range of 2 mA to 4 mA as V_{IN} varies from -5 V to +5 V. R_1 can be adjusted to accommodate any desired range. With $V_{IN} = 0$, R_2, is adjusted so that $V_{OUT} = 0$. Then with V_{IN} at some value, R_4 can be adjusted for a gain of 1. Values for R_2 and R_4 have been picked for a worst case spread of optocoupler or current transfer ratios. The transfer function of the servo amplifier is:

$$V_{OUT} = R_4 \left[(I_{F'2}) \left(\frac{K_1 R_2 (I_{CC_1})^{n_1}}{K_2 R_3 (I_{F'1})^{n_1}} \right)^{1/n_2} \left(1 + \frac{V_{IN}}{R_1 I_{CC_1}} \right)^{n_1/n_2} - I_{CC_2} \right]$$

After zero adjustment, this transfer function reduces to:

$$V_{OUT} = R_4 I_{CC_2} \left[(1 + x)^n - 1 \right],$$

$$\text{Where } x = \frac{V_{IN}}{R_1 I_{CC_1}}, \quad n = \frac{n_1}{n_2}$$

The non linearities in the transfer function where $n_1 \neq n_2$ can be written as shown below. For example, if $|x| \leq 0.35$, $n = 1.05$, then the linearity error is 1% of the desired signal.

$$\frac{\text{linearity error}}{\text{desired signal}} = \frac{(1 + x)^n - n\,x - 1}{n\,x}$$

Typical Performance for the Servo Linearized DC Amplifier:

- 1% linearity for 10 V p-p dynamic range
- Unity voltage gain
- 25 kHz bandwidth (limited by U_1, U_2)
- Gain drift: – 0.03%/°C
- Offset drift: ±1 mV/°C
- Common mode rejection: 46 dB at 1 kHz
- 500 V DC insulation (3000 V if two single couplers are used)

Differential Isolation Amplifier

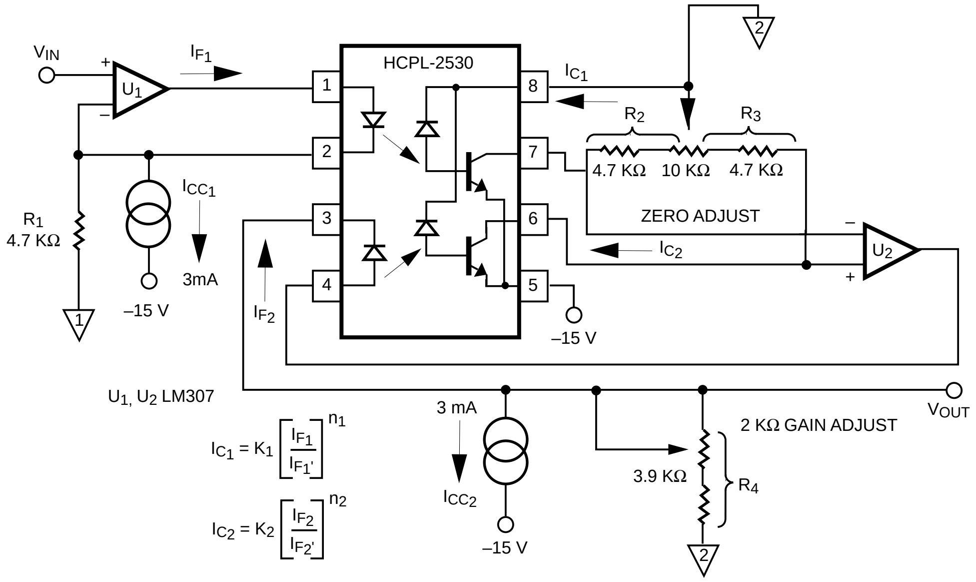
The differential amplifier shown in Figure 4 operates on the principle that an operating region exists where a gain increment in one optocoupler can be approximately balanced by a gain decrement in the second optocoupler. As I_{F1} increases due to changes in V_{IN}, I_{F2} decreases by an equal amount. If $n_1 = n_2 = 2$, then the gain increment caused by increases in I_{F1} will be balanced by the gain decrement caused by decreases in I_{F2}. The constant current source biases each I_F at 3 mA quiescent current. R_1 and R_2 are designed so that I_F varies over the range of 2 mA to 4 mA as V_{IN} varies from -5 V to +5 V. R_1 and R_2 can be adjusted to accommodate any desired dynamic range. U_3 and U_4 are used as a differential current amplifier:

$$V_{OUT} = R_5 \left[(R_3 / R_4)\, I_{C1} - I_{C2} \right]$$

R_3, R_4, R_5 have been picked for an amplifier with a gain of 1 for a worst case spread of coupler current transfer ratios. The transfer function of the differential amplifier is:

$$V_{OUT} = R_5 \left[\left(\frac{K_1 R_3}{R_4} \right) \left(\frac{I_{CC}}{2 I_{F'1}} \right)^{n_1} \left(1 + \frac{V_{IN}}{R I_{CC}} \right)^{n_1} - K_2 \left(\frac{I_{CC}}{2 I_{F'2}} \right)^{n_2} \left(1 - \frac{V_{IN}}{R I_{CC}} \right)^{n_2} \right]$$

if $R \equiv R_1 \equiv R_2$



$$I_{C_1} = K_1 \left[\frac{I_{F1}}{I_{F1'}} \right]^{n_1}$$

$$I_{C_2} = K_2 \left[\frac{I_{F2}}{I_{F2'}} \right]^{n_2}$$

Figure 3. Servo Type DC Isolation Amplifier

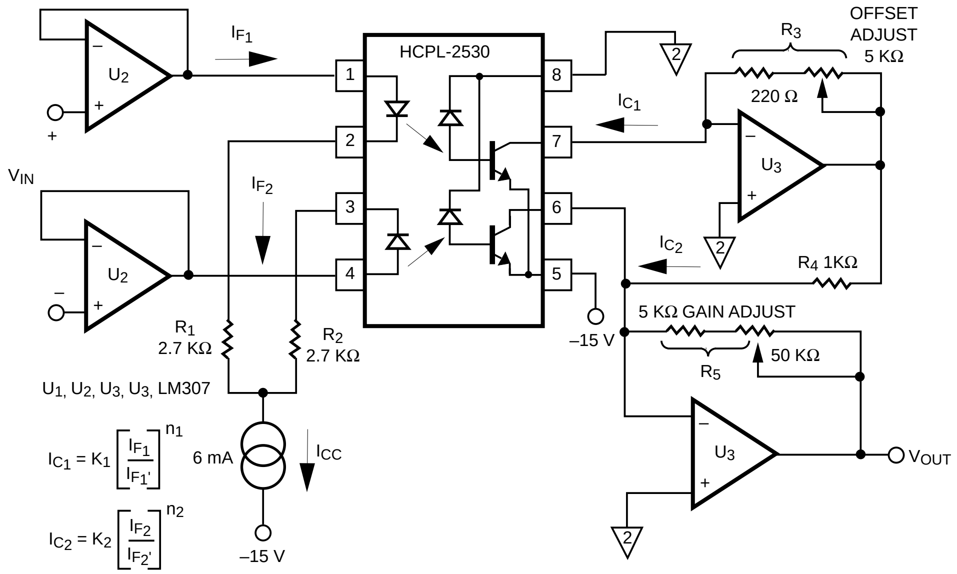


Figure 4. Differential Type DC Isolation Amplifier

After zero adjustment, this transfer function reduces to:

$$V_{OUT} = R_5 K' \left[\left(1 + \frac{V_{IN}}{R\,I_{CC}}\right)^{n_1} - \left(1 - \frac{V_{IN}}{R\,I_{CC}}\right)^{n_2} \right]$$

$$\text{Where } K' = \left(\frac{K_1 R_3}{R_4}\right) \left(\frac{I_{CC}}{2\,I_{F\,'1}}\right)^{n_1}$$

$$= K_2 \left(\frac{I_{CC}}{2\,I_{F\,'2}}\right)^{n_2}$$

The non linearities in the transfer function when $n_1 \neq n_2 \neq 2$ can be written as shown below. For example, if $|\,x\,| \leq 0.35$, $n_1, = 1.9$, $n_2 = 1.8$, then the linearity error is 1.5% of the desired signal.

$$\frac{\text{linearity error}}{\text{desired signal}} =$$

$$\frac{(1 + x)^{n_1} - (1 - x)^{n_2} - (n_1 - n_2)x}{(n_1 + n_2)x},$$

$$\text{where } x = \frac{V_{IN}}{R\,I_{CC}}$$

Typical Performance of the Differential Linearized DC Amplifier:

- 3% linearity for 10 V p-p dynamic range
- Unity voltage gain
- 25 kHz bandwidth (limited by U_1, U_2, U_3, U_4)
- Gain drift: – 0.4%/°C
- Offset drift: ±4 mV/°C
- Common mode rejection: 70 dB at 1 kHz
- 3000 V DC insulation

AC Coupled Amplifier

In an AC circuit, since there is no requirement for a DC reference, a single optocoupler can be utilized by biasing the optocoupler in a region of constant incremental CTR ($\delta I_D / \delta I_F$). An example of this type of circuit is shown in Figure 5. Q_1 is biased by R_1, R_2 and R_3 for a collector quiescent current of 20 mA. R_3 is selected so that I_F varies from 15 mA to 25 mA for V_{IN} of 1 V p-p. Under these operating conditions, the 6N136 operates in a region of almost constant incremental CTR. Linearity can be improved at the expense of signal-to-noise ratio by reducing I_F excursions. This can be accomplished by increasing R_3, then adding a resistor from the collector of Q_1 to ground to obtain the desired quiescent I_F of 20 mA. Q_2 and Q_3 form a cascade amplifier with feedback applied through R_4 and R_6. R_6 is selected as V_{be}/I_3 with I_3 selected for maximum gain bandwidth product of Q_3. R_7 is selected to allow maximum excursions of V_{OUT} without clipping. R_5 provides DC bias to Q_3. Closed loop gain ($\Delta V_{OUT}/\Delta V_{IN}$) can be adjusted with R_4. The transfer function of the amplifier is:

$$\frac{V_{OUT}}{V_{IN}} \cong \left(\frac{\partial I_D}{\partial I_F}\right) \left(\frac{1}{R_3}\right) \left(\frac{R_4\,R_7}{R_6}\right)$$

Typical Performance of the Wide Bandwidth AC Amplifier:

- 2% linearity over 1 V p-p dynamic range
- Unity voltage gain
- 10 MHz bandwidth
- Gain drift: – 0.6% /°C
- Common mode rejection: 22 dB at 1 MHz
- 3000 V DC insulation

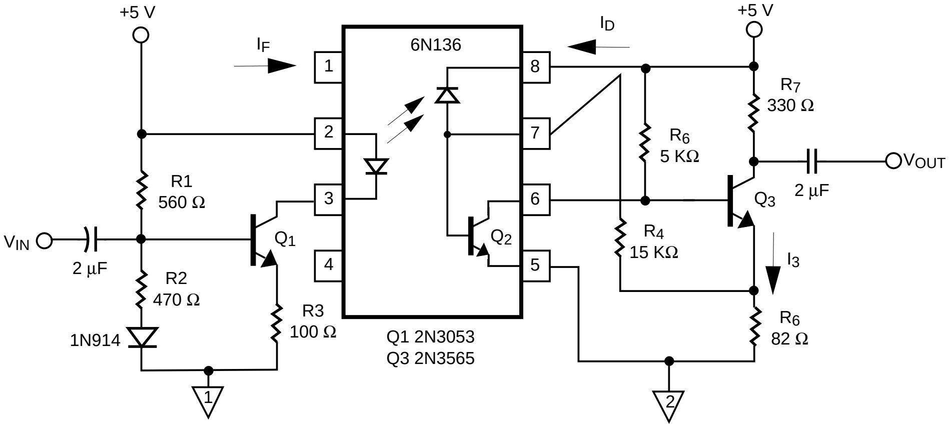


Figure 5. Wide Bandwidth AC Isolation Amplifier

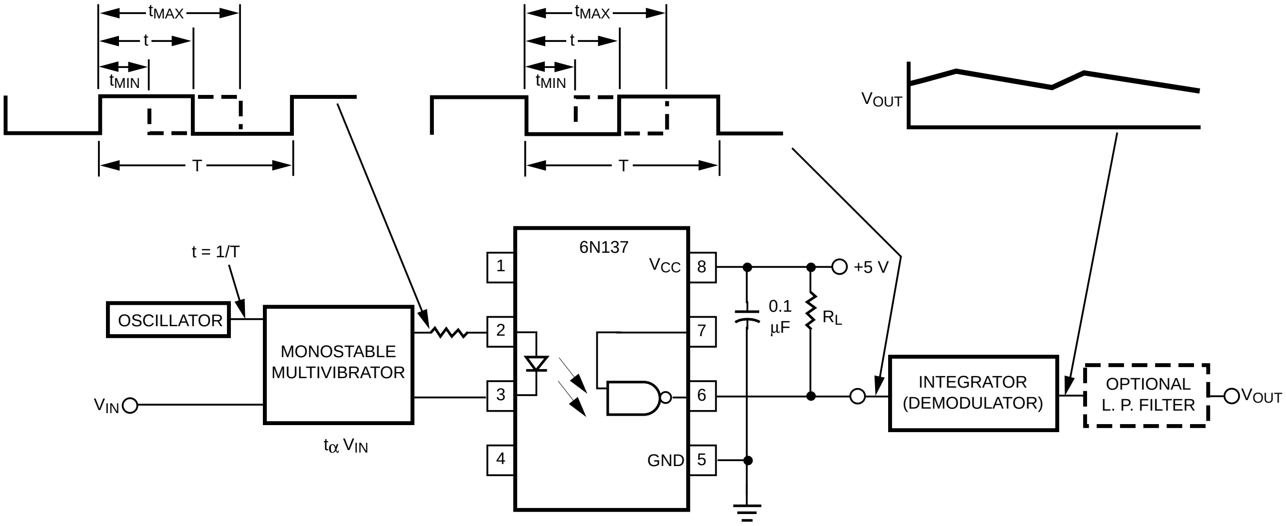


Figure 6. Pulse Width Modulation

Digital Isolation Techniques

Digital conversion techniques can be used to transfer an analog signal between two isolated systems. With these techniques, the analog signal is converted into some digital form and transmitted through the optocoupler. This digital information is then converted back to the analog signal at the output. Since the optocoupler is used only as a switch, the overall circuit linearity is primarily dependent on the accuracy by which the analog signal can be converted into digital form and then back to the analog signal. However, the overall circuit bandwidth is limited by the propagation delays of the optocoupler.

Figure 6 shows a pulse width modulated scheme to isolate an analog signal. The oscillator operates at a fixed frequency, f, and the monostable multivibrator varies the duty factor of the oscillator proportional to the input signal, V_{IN}. The maximum frequency at which the oscillator can be operated is determined by the required linearity of the circuit and the propagation delay of the optoisolators:

$$(t_{max} - t_{min})\ (\text{required linearity}) \geq |t_{PLH} - t_{PHL}|$$

At the output, the pulse width modulated signal is then converted back to the original analog signal. This can be accomplished with an integrator circuit followed by a low pass filter or through some type of demodulator circuit that gives an output voltage proportional to the duty factor of the oscillator.

Figure 7 shows a voltage to frequency conversion scheme to isolate an analog signal. The voltage to frequency converter gives an output frequency proportional to V_{IN}. The maximum frequency that can be transmitted through the optocoupler is approximately:

$f_{max} \cong 1 / t$,

where $t = t_{PLH}$ or t_{PHL}, whichever is larger.

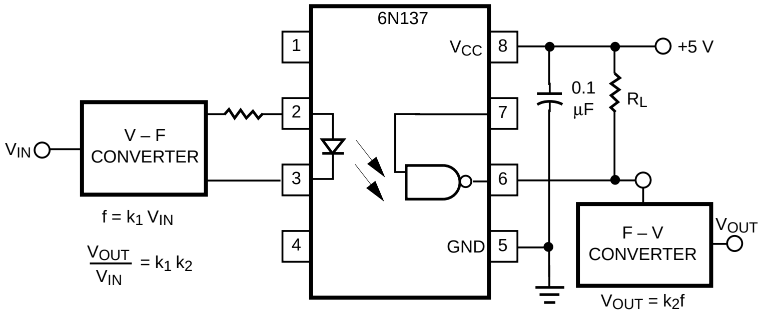


Figure 7. Voltage to Frequency Conversion

At the output, the frequency is converted back into a voltage. The overall circuit linearity is dependent only on the linearity of the V-F and F-V converters.

Another scheme similar to voltage to frequency conversion is frequency modulation. A carrier frequency, f_o, is modulated by Δf such that $f_o \pm \Delta f$ is proportional to V_{IN}. Then at the output, V_{OUT} is reconstructed with a phase locked loop or similar circuit.

One further scheme to isolate an analog signal is to use A-D and D-A converters and transfer the binary or BCD information through optocoupler. The information can be transmitted through the optocoupler in parallel or serial format depending on the outputs available from the A-D converter. If serial outputs are not available, the A-D outputs can be converted into serial form with a PISO shift register and transmitted through one high speed optocoupler. This scheme becomes economical especially where high resolution is required allowing several optocouplers to be replaced with one high speed optocoupler. Refer to Agilent Application Note 947 for further discussion of digital data transmission techniques.

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