Unit 43 Sensors and interfacing

- The output from a current to voltage converter is given by:

$$V_{out} = -I \times R_f$$

- A bridge is said to be in balance when:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

- The output from a differential amplifier is given by:

$$V_{out} = \frac{R_2}{R_1} \times (V_2 - V_1)$$

A transducer or sensor can be described as a device which responds to an external environment or stimulus and gives an output signal which is a function of one parameter of the environment or stimulus. An example might be a pressure sensor which gives an output voltage proportional to the pressure in a container or a platinum metal resistor whose resistance increases in proportion to the temperature.

While some commercial transducers contain embedded electronics which give output voltages proportional to the parameter being sensed, the signals from many sensors need conditioning or amplification or conversion to voltage signals before the signals can be used. In this unit we examine some common sensors and common signal conditioning techniques.

Photodiodes and current to voltage conversion. Photodiodes or solar cells are large area silicon pn junction diodes, mounted on supporting substrates and encapsulated in housings which allow light to fall on the pn junction region. The light is absorbed in the silicon and generates electron-hole pairs. In the dark, the photodiode behaves just like a normal pn diode but when light falls on the device the electron-hole pairs generated give minority carriers and a significant reverse bias diode current. The characteristics of the device are shown in Figure 43.1.

In the top right and the bottom left quadrant of operation, an external voltage drives current through the device. When the diode is in reverse

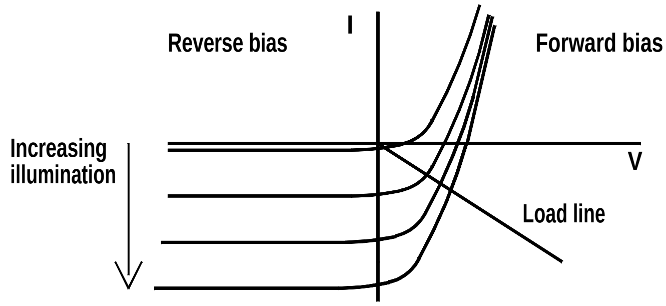

Figure 43.1: Photoconductive and photovoltaic response of photodiode.

bias, the current is proportional to the intensity of illumination. In the bottom right hand quadrant, the signs of the current and the voltage are opposite. This implies that the device can drive current through an external load which is represented by the load line in Figure 43.1. This is the quadrant of operation of the solar cells used to power satellites and also used to power electrical equipment in isolated locations.

We wish to use the photodiode as a light detector, so we can use it in the reverse bias mode and then we get a current which is proportional to the light falling on the device or we can use it in the forward bias mode and then we measure the output voltage from the device. In this second configuration, the output voltage is not proportional to the intensity of the light.

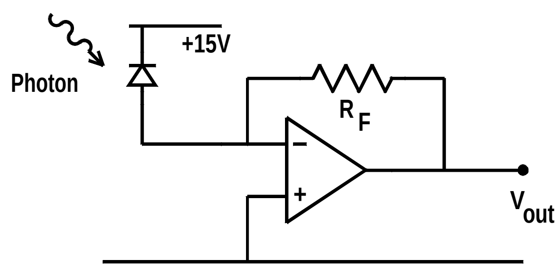

Figure 43.2: Photodiode in photoconductive mode used with a current to voltage converter.

Figure 43.2 shows a circuit which applies a reverse bias to the photodiode so that the diode cathode is at +15 V. The anode is at 0 V (because of Rule 1 of Unit 39). The photodiode current, I_{pd}, also flows in R_f. The voltage across R_f is $0\,\mathrm{V} - V_{out}$ and therefore we get:

$$V_{out} = -I_{pd} \times R_f$$

so we have an output voltage which is proportional to transducer current with the scaling determined by the feedback resistor, R_f. This circuit configuration is called a current to voltage converter or I–V converter. The current through a reverse biased photodiode is proportional to the illumination of the photodiode and this circuit then gives an output voltage which is proportional to the intensity of the light falling on the photodiode.

Bridge circuits. There are many sensors whose response to a stimulus takes the form of a change in resistance. However, many of these sensors also show some sensitivity to other ambient stimuli. A common method of dealing with this cross sensitivity is to use a bridge system of two resistive sensors in series. One sensor is exposed to the stimulus to be measured, the other dummy sensor is either made insensitive to the stimulus or shielded from the stimulus. Both sensors are exposed to the environment. Any environmental effects balance out but the stimulus to be measured remains.

A flammable gas sensor for detecting hydrogen or methane in the atmosphere is a good example. A current is passed through a palladium coated filament, heating the filament. If the heated filament is exposed to a low concentration of flammable gas, catalytic combustion occurs on the filament, raising the filament temperature and causing the resistance of the filament to increase. A single coated filament would not give a satisfactory gas sensor since the filament temperature and resistance also change with ambient temperature, power supply variations, ambient humidity and local air flow. The small effect due to the flammable gases would not be resolvable and spurious alarms would result.

The solution is to use a dummy filament, which is not coated with palladium and therefore does not show a temperature rise and resistance increase due to catalytic combustion of flammable gas. The two filaments show similar temperature and resistance changes due to fluctuations in supply voltage, ambient temperature and cooling due to ambient air flow. The two filaments are mounted in the same metal gauze covered flameproof housing and are wired in series in a bridge circuit as shown in Figure 43.3. The gauze covering serves to cool any flame which occurs within the sensor due to ignition of gases within the housing and prevent the flame from escaping and causing ignition of the gases external to the sensor. The gauze permits a free diffusion of ambient gases into the sensing region.

The voltage at the centre of the two filaments is compared to the voltage at the centre of the potential divider of two $1\,\mathrm{k\Omega}$ resistors. If there is no flammable gas present then the differential bridge output voltage, marked V_{out}, is zero. This should be true even if the sensor supply voltage of $3\,\mathrm{V}$ drifts from its nominal value. The output voltage should also be zero even if the ambient temperature changes or there is a moderate air flow near the filaments because the two filaments are affected equally and the bridge remains in balance. However, a small concentration of flammable gas changes the sensing filament but not the dummy filament and the bridge then gives

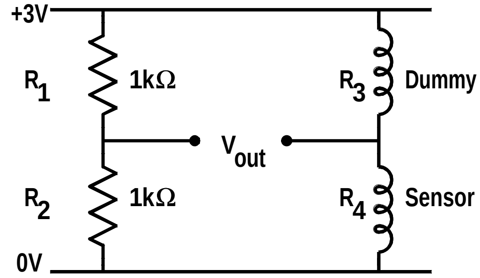

Figure 43.3: Bridge circuit for flammable gas detector.

a nonzero output. The output of such a bridge is usually very small and the signal requires amplification. The bridge output signal is usually amplified with a differential amplifier or difference amplifier.

The differential amplifier. A typical application of the differential amplifier is to measure small voltage difference signals which occur in circuits such as the bridge circuit. In a bridge circuit there is a usually large common mode signal, about 1.5 V in the case of the flammable gas sensor bridge in Figure 43.3, which is applied to both inputs. A small difference voltage is to be measured in the presence of this large common mode signal. The circuit which is usually used is the differential amplifier such as that shown in Figure 43.4 (a). To analyze the operation of this differential amplifier circuit, we

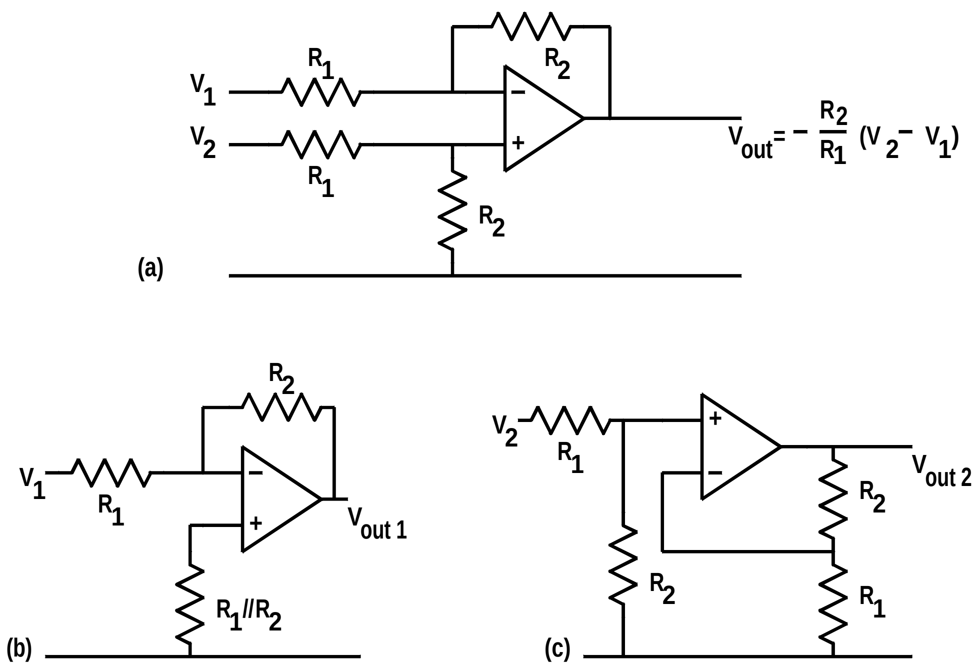

Figure 43.4: The differential amplifier.

apply the principle of superposition (Unit 21).

Set $V_2 = 0$ and short this input. The circuit then becomes an inverting amplifier as shown in Figure 43.4 (b) which has an output due to input signal V_1 of:

$$V_{out1} = -\frac{R_2}{R_1} \times V_1$$

Now find the response due to input V_2 alone by shorting V_1 input to ground. This gives the circuit in Figure 43.4 (c). The circuit is the same as Figure 43.4 (a) but has been redrawn with a different layout while maintaining the same topology or interconnections. It can be seen that this circuit is really a potential divider of R_1 and R_2 which gives a signal of $\frac{R_2}{R_1+R_2} \times V_2$ at the +input to the noninverting amplifier configuration. The noninverting amplifier has a gain of:

$$A_V = 1 + \frac{R_2}{R_1} = \frac{R_1 + R_2}{R_1}$$

The output signal due to input signal V_2 acting alone is therefore:

$$V_{out2} = \frac{R_2}{R_1 + R_2} \times \frac{R_1 + R_2}{R_1} \times V_2 = \frac{R_2}{R_1} \times V_2$$

We then use the principle of superposition to obtain the response when both input signals V_1 and V_2 are present and get an output from the differential amplifier of:

$$V_{out} = \frac{R_2}{R_1} \times (V_2 - V_1)$$

Self balancing bridge. If one resistor of the four in a bridge is a sensing element, as shown in Figure 43.5, for which the resistance is given by an

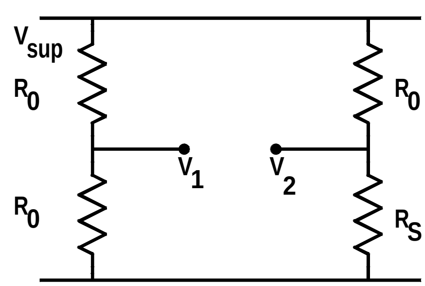

Figure 43.5: Out of balance bridge.

equation of the form $R_S = R_0(1 + \alpha)$, then it is found that the differential bridge voltage is given by:

$$\begin{aligned} V_{Bridge} = V_1 - V_2 &= \frac{V_{sup}}{2} - \frac{R_S}{R_0 + R_S} \times V_{sup} \\ &= V_{sup}\left(\frac{1}{2} - \frac{R_0(1+\alpha)}{2R_0 + \alpha R_0}\right) \end{aligned}$$

which is a nonlinear function of α.

This means that a linear resistive sensor, when used in a fixed or out of balance bridge circuit, gives a nonlinear output voltage response.

A very useful way of maintaining linearity is to use a self balancing bridge where the op-amp acts in such a way as to restore the bridge to balance. A suitable circuit is shown in Figure 43.6 (a). The bridge is in balance and the output from the op-amp $V_{out} = 0$ when $\alpha = 0$ in $R_S = R_0(1 + \alpha)$.

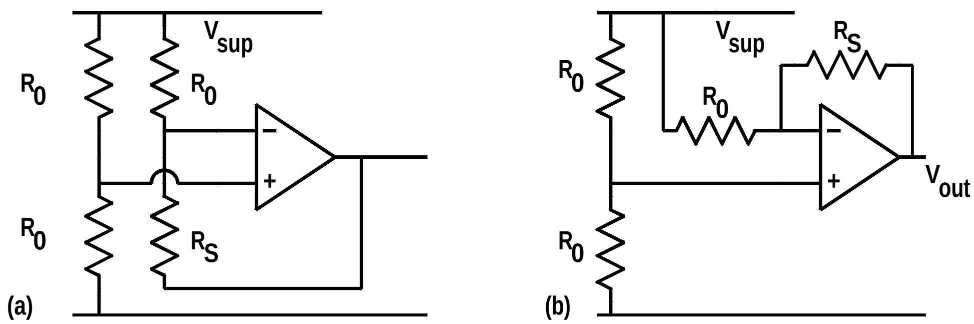

Figure 43.6: Self balancing bridge circuit.

This circuit is best analyzed by redrawing the circuit with a different topology as shown in Figure 43.6 (b). The input to the noninverting, +input, is now $\frac{V_{sup}}{2}$. This gives a fixed offset voltage, V_{off}. The input to the inverting amplifier comprising the op-amp, R_0 and R_S is:

$$V_{sup} - V_{off} = V_{sup} - \frac{V_{sup}}{2} = \frac{V_{sup}}{2}$$

The gain of the inverting amplifier is $-\frac{R_S}{R_0}$. So we get the output voltage of:

$$V_{out} = -\frac{R_S}{R_0}\left(\frac{V_{sup}}{2}\right) = -(1+\alpha) \times \frac{V_{sup}}{2}$$

which is a linear function of α.

This bridge is called a self balancing bridge because the action of the op-amp maintains zero voltage difference between the two mid points of the bridge by varying the voltage applied across R_S.

43.1 Problems

43.1 The photodiode in the circuit shown in Figure 43.7 has a reverse current sensitivity to incident light of $0.3\,\mathrm{A\,W^{-1}}$ and has a sensitive area of $2.5\,\mathrm{mm^2}$.

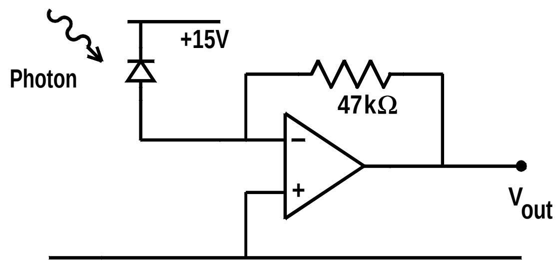

Figure 43.7: Problem 43.1.

Calculate the output voltages from the circuit when the photodiode is exposed to:

(a) Daylight having an intensity of $200\,\mathrm{W\,m^{-2}}$.

(b) Dusk light having an intensity of $5\,\mathrm{W\,m^{-2}}$.

43.2 A thermistor is a metal oxide semiconductor resistor whose resistance decreases with increasing temperature. The resistance of the MA473 thermistor used in the circuit shown in Figure 43.8 is given by:

$$R = 47\,\mathrm{k\Omega} \times \exp\left(\frac{3940}{T} - \frac{3940}{298}\right)$$

where T is the temperature in K.
Calculate the output voltages from the circuit for thermistor temperatures of 0 °C, 30 °C, 45 °C and 75 °C.

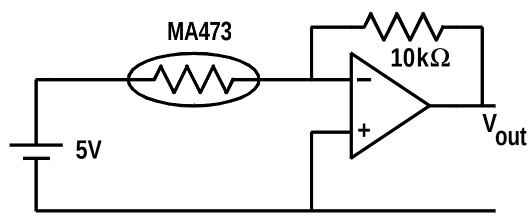

Figure 43.8: Thermistor thermometer.

43.3 The PRT_{100} is an industry standard platinum resistance thermometer having a resistance of $100\,\Omega$ at 0°C. The temperature coefficient of resistance of platinum metal is such that the resistance of a PRT_{100} varies linearly with temperature and is $138.5\,\Omega$ at 100 °C. A PRT_{100} is used in the bridge circuit shown in Figure 43.9.
Calculate the out of balance signal at temperatures of 20 °C, 35 °C, 75 °C and 100 °C.

If a differential amplifier, such as that in Figure 43.4 (a) and having a voltage gain of +10, is connected across the bridge, calculate the amplifier output at these four values of temperature.

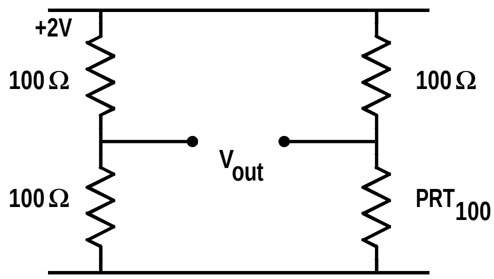

Figure 43.9: Problem 43.3. PRT_{100} temperature bridge.

43.4 A linear Hall effect I C, used for measuring magnetic fields, is shown in Figure 43.10. The device gives a differential output voltage between pins 2 and 3 when placed in a magnetic field. The sensitivity of the sensor is $8.2\,\mathrm{V\,T^{-1}}$ where the magnetic field is in tesla (T). Calculate the output voltage from the circuit in Figure 43.10 when the Hall effect IC is (a) in the magnetic field of the Earth ($\approx 6 \times 10^{-5}$ T) and (b) in the magnetic field of a permanent magnet (0.05 T).

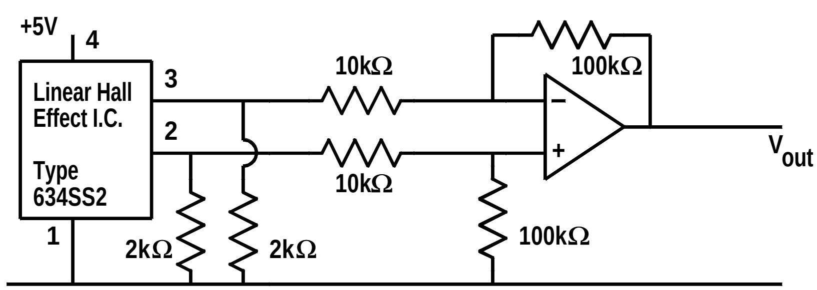

Figure 43.10: Problem 43.4. Hall effect probe.