Unit 51 Recovery of small signals from noise

- **Instrumentation amplifiers** use a three op-amp configuration to obtain high input resistance and improved common mode rejection. The gain is set by a single gain setting resistance which can be chosen for high thermal stability.
- **Isolation amplifiers** have no galvanic connection between input and output and can operate with common mode voltages up to thousands of volts. They are also used for protecting patients from danger of electrical shock in medical applications of electronics.
- **Phase sensitive detectors** use the fact that the frequency and phase of a signal are known and that a reference signal is available to gain-switch from $+1$ to -1 and obtain synchronous detection of a signal which may be buried in noise.

There are many situations in electronics where signals are present but are partially masked by noise. It is not enough to increase the amplification since the noise is also amplified with the signal and the signal to noise ratio remains unchanged. There are three techniques or types of circuits which are frequently used when the signal is very small. The general aim is to obtain as good a signal as possible to start with and then to use the fact that the signal is at a known frequency and phase in order to improve the detection of the signal.

Instrumentation amplifier. The ordinary op-amp has good common mode rejection; that is, it is insensitive to signals which are present at both the inverting and noninverting inputs. However, when the signal is a small difference voltage in the presence of a large common mode signal then an instrumentation amplifier should be used. An example of such a signal would be two voltages from a bridge circuit, $V_1 = 1.000000\,\text{V}$ and $V_2 = 1.000001\,\text{V}$. If we wish to measure the difference between V_1 and V_2, which in this case is $1\,\mu\text{V}$ in the presence of the $1\,\text{V}$ common mode signal, then an amplifier using a single op-amp would have to have the two inputs matched to one part in a million, which is not possible.

The traditional instrumentation amplifier uses three op-amps in the circuit configuration shown in Figure 51.1.

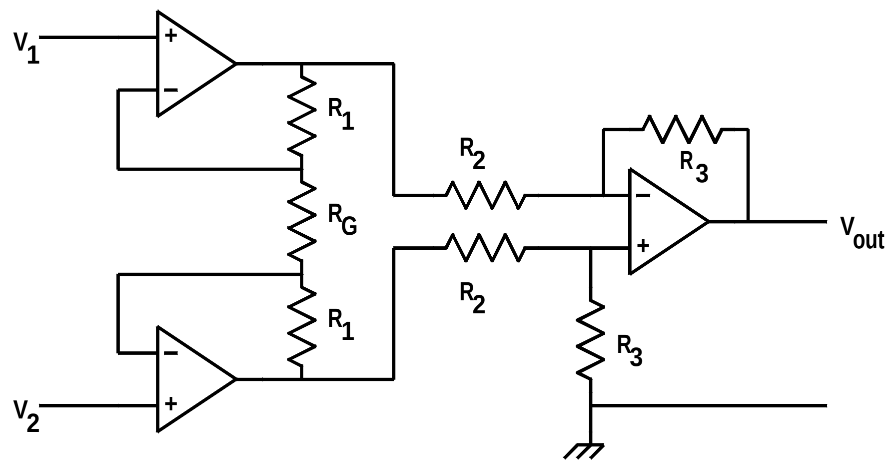

Figure 51.1: The three op-amp instrumentation amplifier.

Two op-amps are used symmetrically for the input amplifier followed by the differential amplifier which was analyzed in Unit 43. In the circuit in Figure 51.1, consider the resistor chain R_1, R_G and R_1. (Note the convention that resistors with the same labels have the same values.)

Using the rules for op-amps from Unit 39, the voltage across the gain setting resistor, R_G, is $V_1 - V_2$ and therefore the current in the resistor chain is:

$$I = \frac{V_1 - V_2}{R_G}$$

The voltage applied to the input to the differential amplifier is then:

$$V_{diff} = \frac{V_1 - V_2}{R_G} \times (R_1 + R_G + R_1)$$

The differential amplifier has a gain of $\frac{R_3}{R_2}$ and therefore the output from the instrumentation amplifier is:

$$V_{out} = \frac{2R_1 + R_G}{R_G} \times \frac{R_3}{R_2} \times (V_2 - V_1)$$

Typically an instrumentation amplifier having this configuration would be manufactured as a hybrid integrated circuit by specialist companies such as Analog Devices, using selected low noise, ultra stable op-amps. You would not normally construct an instrumentation amplifier from discrete components. The gain of the instrumentation amplifier is set by a single, external gain setting resistor having a high thermal stability. The instrumentation amplifier is usually supplied in a metal can rather than plastic package so as to have better shielding from interference. Such a device is capable of operating close to the inherent noise limits discussed in Unit 50.

Isolation amplifier. The ultimate in common mode rejection is achieved by an isolation amplifier which has zero common mode response because there is no galvanic connection between the input and output. These circuits are not normally constructed from components by the user but are also bought as complete devices from specialist manufacturers such as Analog Devices.

The most common configuration of isolation amplifier is a low power consumption instrumentation amplifier followed by a voltage to frequency converter in which the frequency output is proportional to the input differential voltage. This signal is then coupled through an isolating transformer which passes the high frequency signal but blocks any DC or low frequency AC. The secondary of the transformer is then fed to a frequency to voltage converter and to a low pass filter and the output. The basic configuration is shown in Figure 51.2.

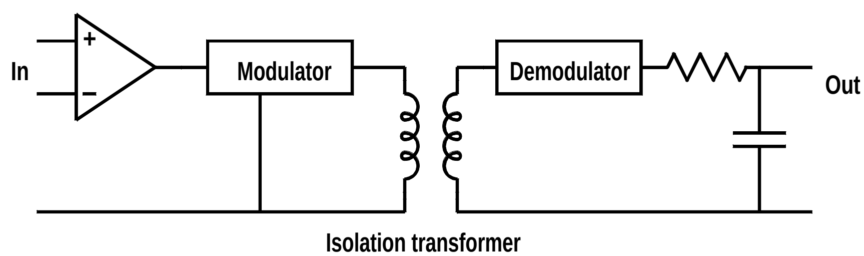

Figure 51.2: Isolation amplifier using a transformer for isolation.

There is usually a second transformer in the system which couples AC power to a rectifier which powers the input stage, again without having any galvanic connection with the input stage. This second transformer is not shown in the diagram.

One very important application for these isolation amplifiers is for providing isolation between the electrodes connected to patients and the mains powered equipment in hospitals. These electrodes are connected for electrocardiography, ECG (heart monitoring), and electroencephalography, EEG (brain wave monitoring). In the event of a fault in the mains powered equipment, the isolation amplifier prevents the patient receiving a shock. Also, because of the isolation, it is possible to use heart resuscitation, electro shock equipment without burning out the sensitive amplifiers.

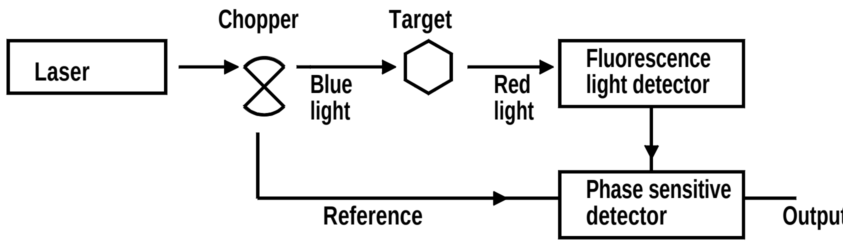

Figure 51.3: Chopper and phase sensitive detector configuration.

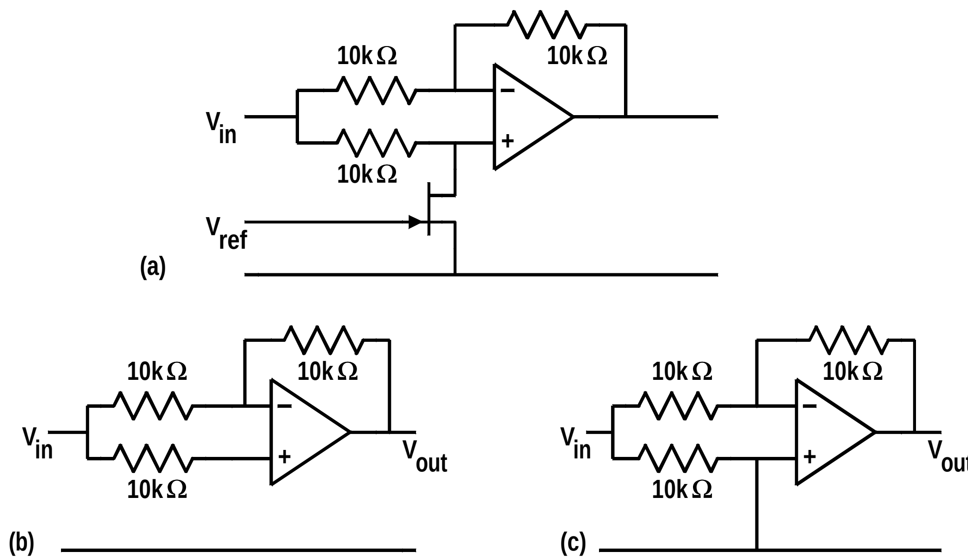

Figure 51.4: Basic phase sensitive detector circuit.

Phase sensitive detection. If the amplitude of an AC waveform is to be measured, a very simple technique is to use a diode rectifier and measure the DC voltage at the output of the rectifier (see Unit 28). However, if there is noise present as well as signal then the noise will also be rectified and contribute to the output. There is no way a simple rectifier can distinguish between signal and noise and a signal to noise ratio of at least 10:1 is necessary for valid detection of a signal using a diode detector.

There are many situations where a signal at a particular frequency is present but is partially or fully masked by noise and where the signal frequency is available for reference. An example of this situation is shown in Figure 51.3 where a laser beam is chopped at frequency, f_R, by a rotating chopper blade. The laser beam subsequently causes a weak fluorescence in a target material and the fluorescent light is then detected by a photodetector. In fluorescence, short wavelength light is absorbed in a target. This causes excitation of the molecules in the target. The excited molecules rapidly release some of this energy as lower energy, longer wavelength light. The signal from the photodetector may be noisy but it is known that if a valid fluorescence signal is present then it will be at a frequency f_R because this is the frequency at which the exciting laser light is modulated. This is the type of situation where a phase sensitive detector would be used. The phase sensitive detector essentially uses the information that the signal is at a particular frequency to pull the signal out of the noise background.

The basic electronic configuration of a phase sensitive detector is shown in Figure 51.4 (a).

A reference square wave signal from 0 V to -5 V is available from the chopper which is synchronized with the signal to be detected. This signal is applied to the gate of the FET.

When the reference is at -5 V the FET is off or nonconducting and the effective circuit is that shown in Figure 51.4 (b). No current flows into the noninverting input of the op-amp and the noninverting input is at the signal voltage. The output is fed back to the inverting input and the amplifier therefore has a gain of $+1$.

When the reference voltage is at 0 V the FET conducts and the effective circuit is that shown in Figure 51.4 (c). This is an inverting amplifier with a gain of -1. (The 10 kΩ resistor from the signal input to the noninverting input and ground does not affect the operation of the amplifier.)

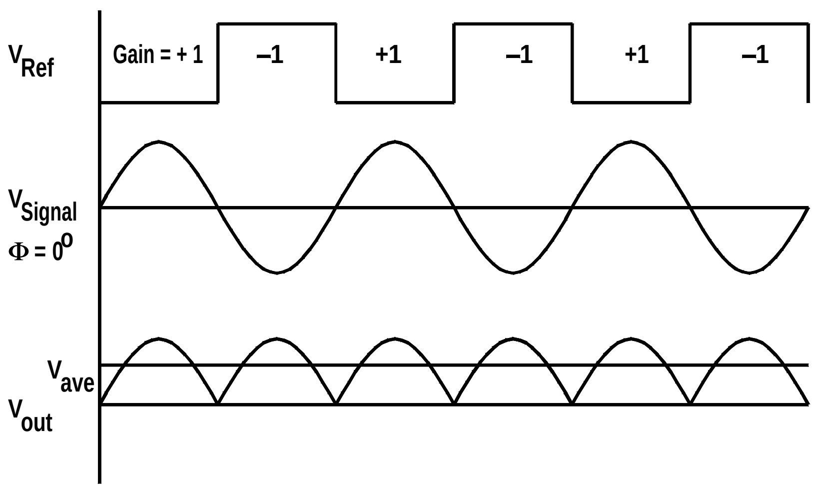

Figure 51.5: Reference and signal in phase.

The circuit for the phase sensitive detector is therefore an amplifier which is switched between a gain of $+1$ and -1 by the application of the reference square wave.

Now consider what happens when there is a sinusoidal input signal which is at the same frequency as the reference and which is in phase with the reference, that is $\phi = 0°$. This situation is shown in Figure 51.5.

The upper waveform is the reference from the chopper. The corresponding value of the gain of the amplifier is shown for each half cycle of the reference. The signal is then multiplied by this value of the gain to give the output in the third waveform. It can be seen that the negative half of the signal waveform is inverted to give a positive half cycle. The net effect is similar to having a diode rectifier with one important difference. Any noise will be uncorrelated with the reference waveform and therefore a pure noise input will give an average output of zero whereas a signal at the reference frequency and having zero phase difference will give an average output as shown on the diagram as V_{ave}. Typically this averaging is carried out using an RC low pass filter or an op-amp integrator.

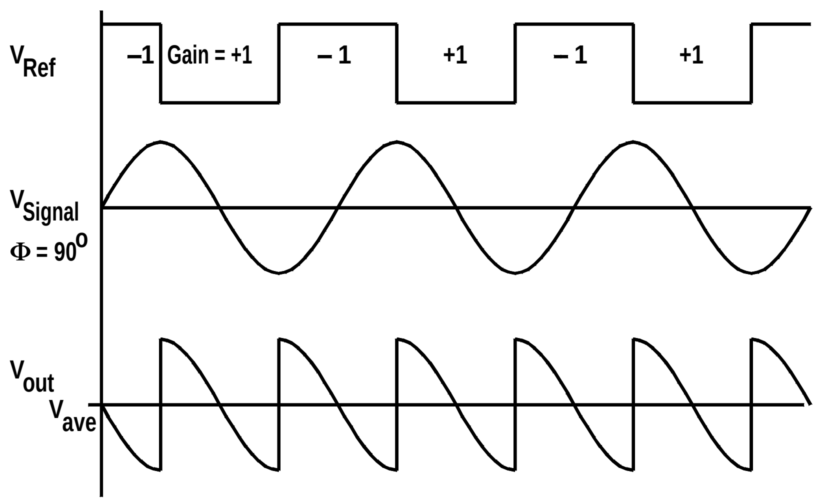

Figure 51.6: Reference and signal 90° out of phase.

The phase sensitive aspect of the circuit becomes apparent when we look at the situation when the phase difference between the reference and the signal is $\phi = +90°$ as is shown in Figure 51.6.

Again the signal is multiplied by either $+1$ or -1 depending on the phase of the reference waveform and the resultant waveform is shown at the bottom. In this case when the phase difference is 90° it can be seen that the output averages to zero. This is the phase sensitive aspect of the detection system.

The case when the phase difference is $\phi = 180°$ is shown in Figure 51.7. The output voltage now averages to a negative value.

So the output goes from full positive output to full negative output as the relative phase of the reference and the signal varies from 0° to 180°.

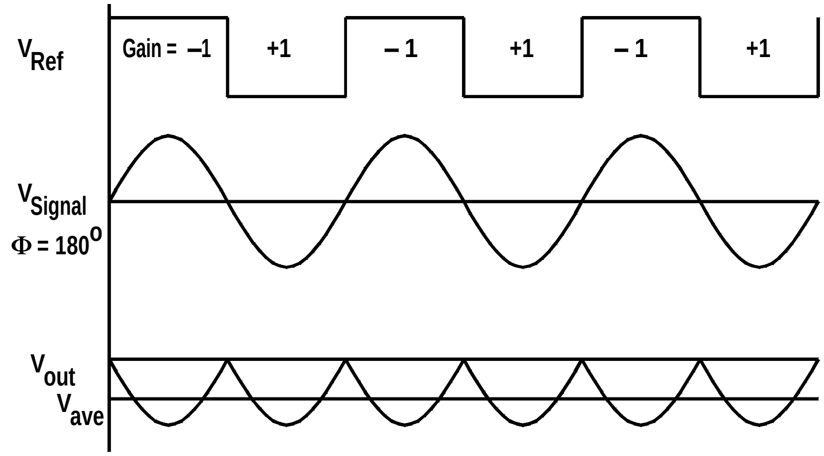

Figure 51.7: Signal and reference 180° out of phase.

In a commercial phase sensitive detection system there is usually a control on the front panel which allows you to vary the phase electronically over a range of 360° so as to obtain signal maxima when the phase is 0° and 180°. No maximum will be obtained for noise or for signals at frequencies different from the reference frequency. It is therefore possible to measure signals which are buried in noise. In other words, it is possible to operate with fractional signal to noise ratios. The commercial implementations of combined amplifiers and phase sensitive detectors are usually called lock-in amplifiers and these systems are capable of measuring voltage signals down to levels of nanovolts (10^{-9} V)

51.1 Problems

51.1 What is the bandwidth of a low pass filter having an RC time constant of 2 seconds?

51.2 If the noise at the input to an amplifier is $740\,\mu$V per $\sqrt{\text{Hz}}$, what would be the RMS noise voltage measurement if the signal were passed through a low pass filter having a time constant of 5 seconds?

51.3 The input signal to a lock-in amplifier consists of a signal of $23\,\mu$V mixed with a noise signal of $120\,\mu$V per $\sqrt{\text{Hz}}$. Calculate the signal to noise ratios for filter time constants of 0.1 seconds and 2 seconds.