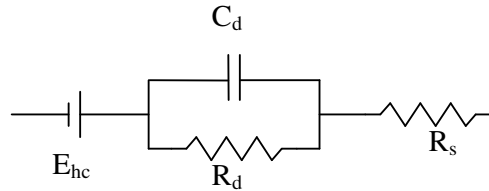


## BIOELECTRIC AMPLIFIERS

### Ag/AgCl Electrodes



Total electrode impedance is

$$Z_T = R_s + R_d // \left( \frac{1}{j\omega C_d} \right)$$

$E_{hc}$  : Half-cell potential (contact potential) generated at the metal-liquid interface (junction)

$R_s$  : Series resistance associated with the metal-liquid interface and due to resistance in liquid (electrolyte) between metal and body.

$R_d$  : Leakage resistance metal-liquid interface

$C_d$  : capacitance of the metal-liquid interface

The total electrode impedance,  $Z_T$  is obviously frequency dependent. In addition

$C_d$  and  $R_d$  have frequency dependence. For Ag/AgCl electrodes dependence of  $C_d$  and  $R_d$  on frequency can be neglected for up to 100 KHz.  $C_d$  and  $R_d$  also depend on the current passing through the electrode. Modern amplifiers have very high input impedances and therefore the current passing through the electrode is negligible. In any case, up to  $1 \frac{mA}{cm^2}$  current density on the electrode surface, dependence of  $C_d$  and  $R_d$  on the current is negligible.

Typical values for electrode parameters:

$$E_{hc} = 0.24mV, R_d = 20K\Omega, R_s = 300\Omega, C_d = 100nF.$$

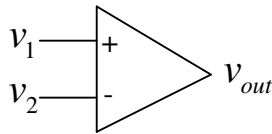
At 10 Hz the impedance of the capacitance is

$$\frac{1}{j\omega C_d} = -\frac{j}{2\pi \times 10 \times 100 \times 10^{-9}} = -\frac{j}{2\pi \times 10 \times 100 \times 10^{-9}} = -159j K\Omega \text{ which is much larger than}$$

$R_d$  in magnitude, and at 100 KHz it is  $-15.9j \Omega \ll R_d$  which is much smaller than  $R_d$  in magnitude.

Thus at low frequencies (up to 100 Hz) total electrode impedance is about  $R_d + R_s \approx R_d$  in magnitude, and at high frequencies it is about  $R_s$ . Recommendation of AHA for diagnostic ECG instruments is that ECG must be recorded in a band of 0.05 Hz to 100 Hz. Therefore in this band electrode impedance is high. Usually it is between  $5 - 20K\Omega$ .

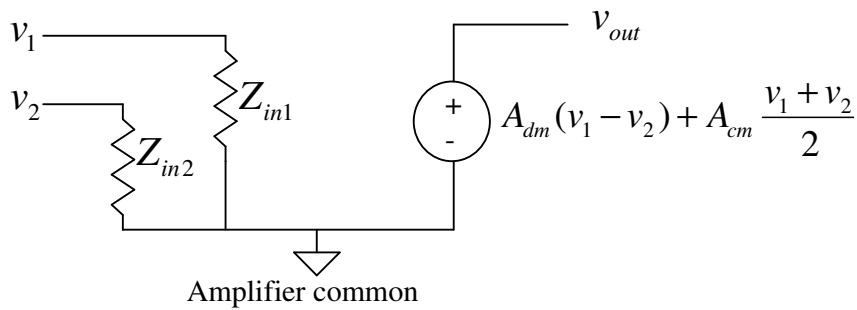
## Instrumentation Amplifiers



$$v_{out} = A_{dm}(v_1 - v_2) + A_{cm} \frac{v_1 + v_2}{2} \text{ where}$$

$A_{dm}$  is the differential mode gain and  $A_{cm}$  is the common mode gain. An ideal differential amplifier has  $A_{cm} = 0$ .

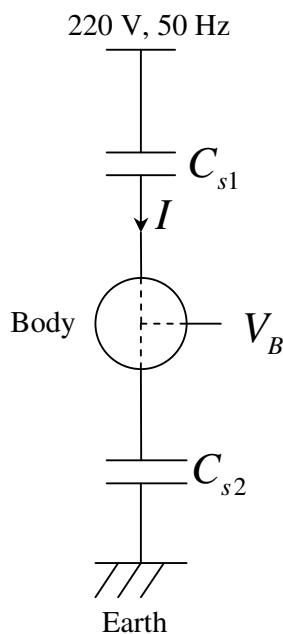
The internal equivalent circuit of an instrumentation amplifier is



where  $Z_{in1}$  and  $Z_{in2}$  are input common mode impedances. An ideal instrumentation amplifier has  $Z_{in1} = Z_{in2} = \infty$  and  $A_{cm} = 0$ .

There are also other non-idealities such as input bias currents, and offset voltages which are negligible for the analyses we shall undertake in these notes.

## Common Mode 50 Hz interference



Due to unavoidable stray capacitances the body has a large 50 Hz common mode voltage.

Assuming the body is highly conductive and equipotential the body voltage with respect to earth is

$$V_B = 220 \frac{\frac{1}{j\omega C_{s2}}}{\frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}}} = 220 \frac{C_{s1}}{C_{s1} + C_{s2}}$$

With  $C_{s1} = C_{s2}$ ,  $V_B = 110V(50Hz)$ .

Fortunately  $C_{s1}$  and  $C_{s2}$  are small enough that low currents flow through the body. Say  $C_{s1} = C_{s2} = 100pF$ , in which case

$$|I| = \frac{220}{\left| \frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}} \right|} = \frac{220}{\frac{2}{\omega C_{s1}}} = 110\omega C_{s1} = 110 \times 2 \times \pi \times 50 \times 100 \times 10^{-12} = 3.46\mu A$$

This value is much smaller than the safety limit of  $100\mu A$  at 50 Hz.

Let us consider another numerical example: Let us assume that the body is closer to earth compared to some 220 V lines. In such a case say  $C_{s1} = 10\text{pF}$  and  $C_{s2} = 100\text{pF}$ . Then

$$V_B = 220 \frac{10}{10+100} = 20\text{V}, \text{ and}$$

$$|I| = \frac{220}{\left| \frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}} \right|} = \frac{220}{\frac{1}{\omega C_{s1}} + \frac{1}{\omega C_{s2}}} = 220\omega \frac{C_{s1}C_{s2}}{C_{s1} + C_{s2}} = 220 \times 2\pi \times 50 \times \frac{1000}{110} \times 10^{-12} = 0.628\mu\text{A}$$

For later use let us find the impedances of the two capacitors

$$\frac{1}{\omega C_{s1}} = \frac{1}{2\pi \times 50 \times 10 \times 10^{-12}} = 318\text{M}\Omega$$

$$\frac{1}{\omega C_{s2}} = \frac{1}{2\pi \times 50 \times 100 \times 10^{-12}} = 31.8\text{M}\Omega$$

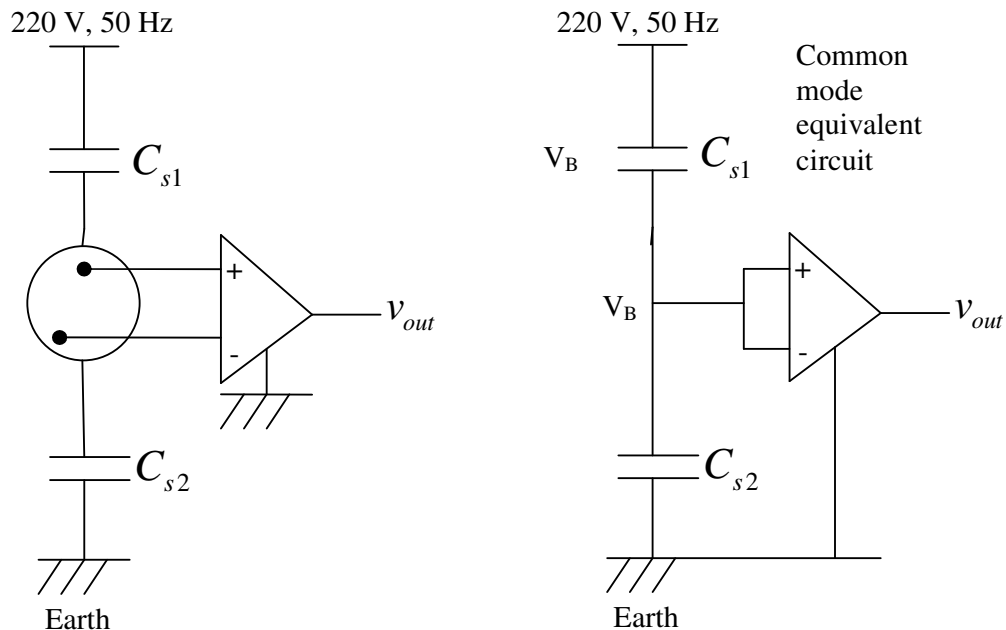
## ECG Amplifier Configurations

ECG amplifiers are to be designed in the isolated configurations. However we shall first study the non-isolated configurations to analyze their disadvantages, then we shall study the preferable isolated configurations.

Isolated means that the amplifier's common is different than (isolated from) the real earth. Non-isolated means that the amplifier's common is the same as the real earth.

### Non-isolated configuration:

#### The 2-electrode non-isolated configuration:



Assuming that  $Z_{in1} = Z_{in2} = 10\text{M}\Omega$ ,  $C_{s1} = 100\text{pF}$  and  $C_{s2} = 100\text{pF}$

$$V_B = 220 \frac{\frac{1}{j\omega C_{s2}} // Z_{in1} // Z_{in2}}{\frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}} // Z_{in1} // Z_{in2}} = 220 \frac{-j31.8 // 5}{-j31.8 - j31.8 // 5}$$

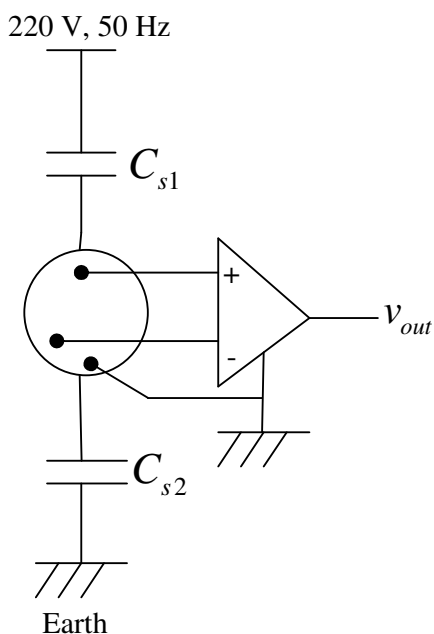
$$= 9.8813 + 31.4532j = 33V \angle 1.27 = 33V \angle 73^\circ$$

For  $A_{cm} = 1/3000, A_{dm} = 25$

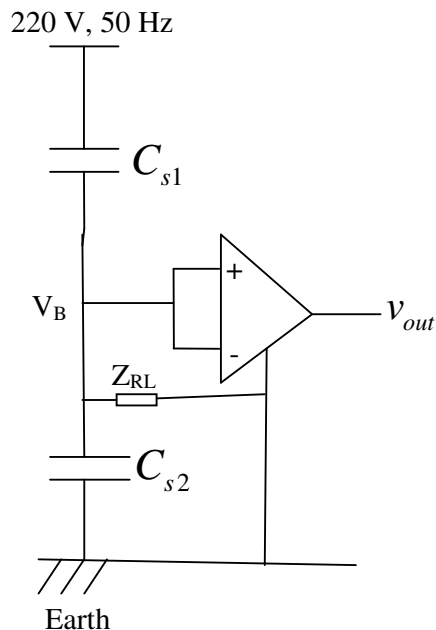
$$v_{out} = \frac{33}{3000} \cos(2\pi \times 50t + 1.27) + 25v_{ecg} = 11mV \cos(2\pi \times 50t + 1.27) + 25v_{ecg}$$

Thus ecg signals less than  $\frac{11}{25} mV$  will be buried in 50 Hz interference. Considering that the peak of ecg is 1-2 mV, this amount of interference is not tolerable.

### The 3-electrode non-isolated configuration:



In order to decrease the common mode voltage  $V_B$  we can connect the amplifier common to the body (usually the right leg, RL). Thus we are effectively grounding the body and  $V_B$  should be identically equal to zero. However due to finite electrode impedance of the RL electrode this is not achieved but  $V_B$  is significantly reduced. The equivalent common mode circuit is given below:



where  $Z_{RL}$  is the RL electrode impedance. In this case since  $Z_{RL} \ll Z_{in1}$  and  $Z_{in2}$

$$\text{and } Z_{RL} \ll \frac{1}{j\omega C_{s1}} \text{ and } \frac{1}{j\omega C_{s2}}$$

$$V_B = 220 \frac{Z_{RL} // \frac{1}{j\omega C_{s2}}}{Z_{RL} // \frac{1}{j\omega C_{s2}} + \frac{1}{j\omega C_{s1}}}$$

$$V_B = 220 \frac{Z_{RL}}{1 + j\omega C_{s1} Z_{RL}} = 220 \times j\omega C_{s1} \times Z_{RL} = 0.069Vj = 69mVj$$

if  $Z_{RL} = 10K\Omega$  and  $C_{s1} = 100pF$ .

$$v_{out} = \frac{69mV}{3000} \cos(2\pi \times 50t + 1.57) + 25v_{ecg} = 23\mu V \sin(2\pi \times 50t) + 25v_{ecg}$$

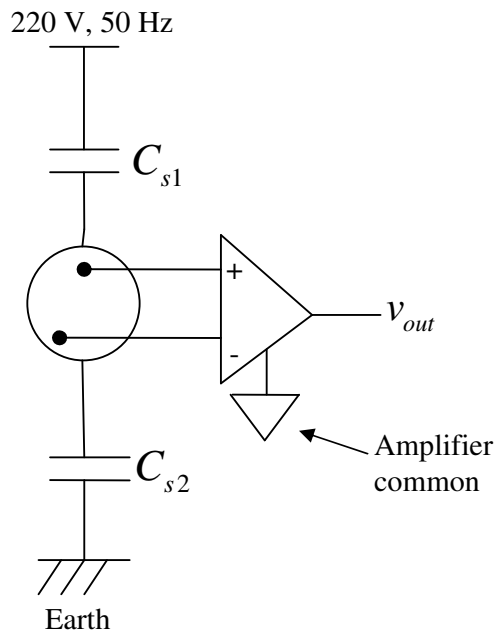
Obviously in this case the common mode interference  $\frac{23\mu V}{25}$  is much less than  $v_{ecg}$ .

This is nice but there is yet another very serious problem: SAFETY!

If the person, by accident, touches 220 V then the current which will flow through the body is  $\frac{220V}{10K} = 22mA$  which is much larger than the acceptable limit of  $100\mu A$ . Therefore the above configuration is not safe. The solution is to use an isolated amplifier.

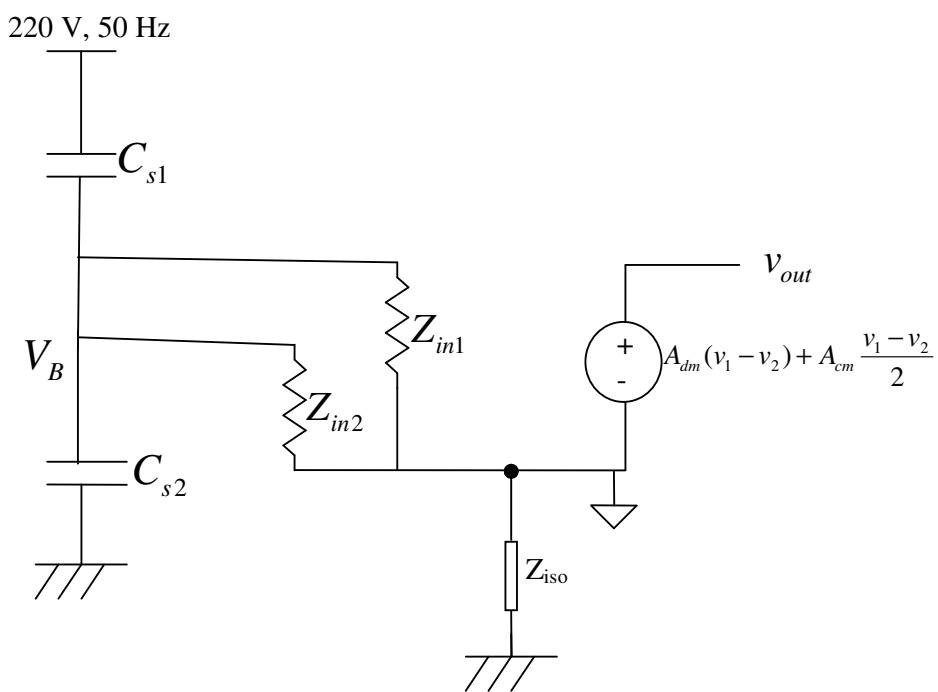
### Isolated configuration:

The 2-electrode isolated configuration:

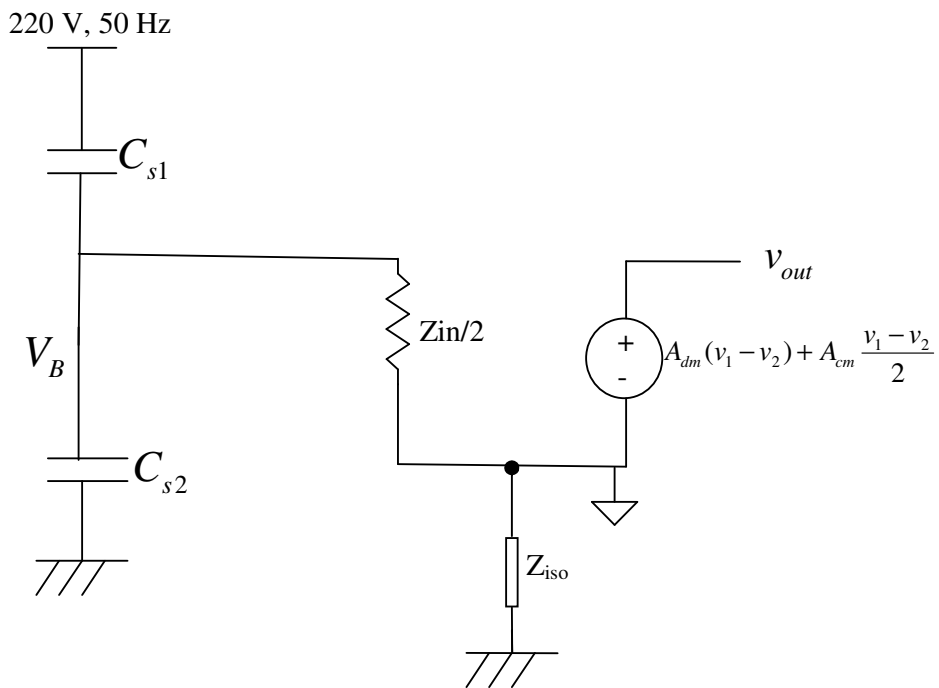


In reality between the amplifier common and real earth there is a large impedance,  $Z_{iso}$  (isolation impedance), which is mainly due to stray capacitance. To find  $V_{out}$  due to common mode voltage seen on the body w.r.t. real earth, we must first find the common mode voltage seen by the amplifier itself w.r.t. its own common.

The common mode equivalent circuit is given below:.



which can be simplified as (assuming  $Z_{in1}=Z_{in2}=Z_{in}$ )



$$V_B = 220 \frac{\frac{1}{j\omega C_{s2}} \parallel \left(\frac{Z_{in}}{2} + Z_{iso}\right)}{\frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}} \parallel \left(\frac{Z_{in}}{2} + Z_{iso}\right)} = 95 + 0.65j$$

$$\approx 95V \angle 0.007^\circ \approx 95V$$

Then, the common voltage seen by the amplifier w.r.t. its own common is

$$v_{cm} = V_B \frac{\frac{Z_{in}}{2}}{\frac{Z_{in}}{2} + Z_{iso}} = 0.2043 + 4.7360j = 4.74V \angle 1.53^\circ = 4.74V \angle 87.5^\circ$$

assuming  $Z_{in1} = Z_{in2} = 10 \text{ M}\Omega$  and  $Z_{iso} = -j100 \text{ M}\Omega$ .

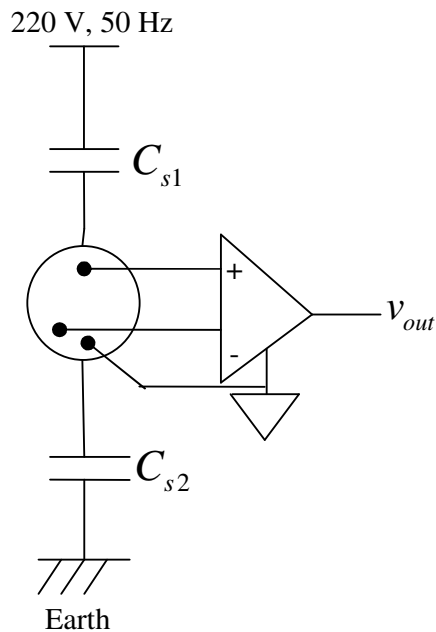
$$v_{out} = \frac{4.74V}{3000} \cos(2\pi \times 50t + 1.53) + 25v_{ecg} = 1.58mV \cos(2\pi \times 50t + 1.53) + 25v_{ecg}$$

To have small  $v_{cm}$  we need very high  $Z_{iso}$  and very small  $Z_{in}$ .  $Z_{iso}$  cannot be made infinitely large because of unavoidable stray capacitances and  $Z_{in}$  cannot be made very small because in the differential mode circuit the diff signal seen by the amplifier will be attenuated.  $Z_{in1} = Z_{in2} = 10$  Mohms is the minimum acceptable by international standards for ECG.  $Z_{iso} = -j100$  Mohm is a practically achievable isolation impedance.

Still 1.58 mV is much better than the 11mV we had before.

It would be nice to further decrease  $v_{cm}$ . This is achieved by the RL connection to the amplifier common as in the next configuration

**The 3-electrode isolated configuration:**



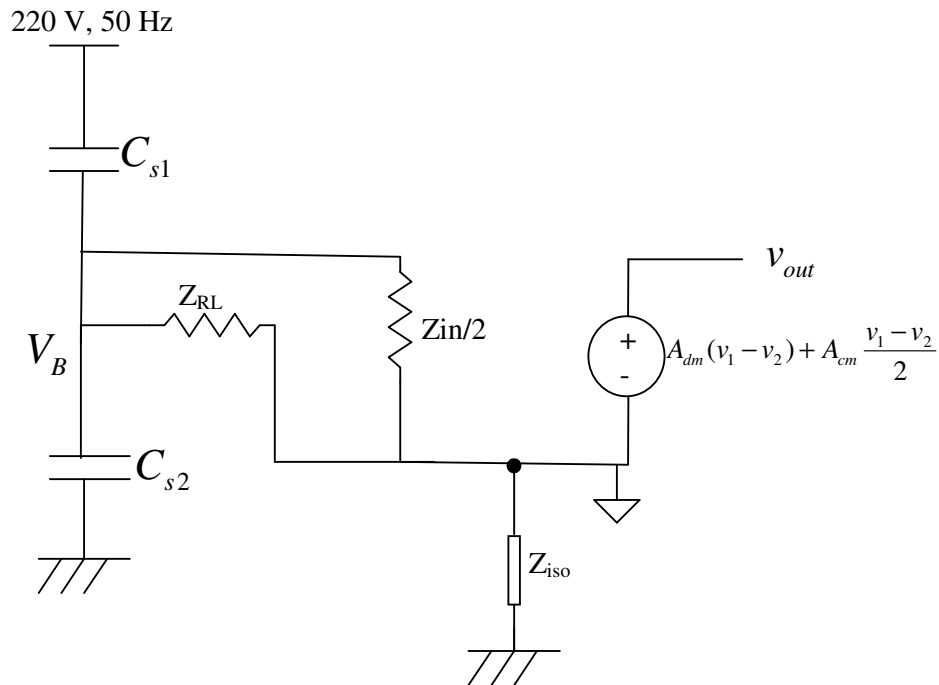
Assuming  $Z_{RL}$  is much less than  $Z_{in}/2$ ,

$$v_{cm} = V_B \frac{Z_{RL}}{Z_{RL} + Z_{iso}}$$

and

$$V_B = 220 \frac{\frac{1}{j\omega C_{s2}} \parallel (Z_{RL} + Z_{iso})}{\frac{1}{j\omega C_{s1}} + \frac{1}{j\omega C_{s2}} \parallel (Z_{RL} + Z_{iso})} \approx 95V$$

and  $v_{cm} = 9.5mVj$ .



Thus the whole output is

$$v_{out} = \frac{9.5mV}{3000} \sin(2\pi \times 50t) + 25v_{ecg} = 3.2\mu V \sin(2\pi \times 50t) + 25v_{ecg}$$

Safety consideration: If the person touches 220 V by accident, current through the body is

$$\left| \frac{220}{Z_{RL} \parallel \frac{Z_{in}}{2} + Z_{iso}} \right| \approx \left| \frac{220}{Z_{iso}} \right| = \frac{220}{100M\Omega} = 2.2\mu A \text{ which is OK.}$$

### Summary of results

	$V_B$	$v_{cm}$	50 Hz interference referred to input	Safety
Non-isolated 2-electrode	33V	33V	11mV/25	Safe
Non-isolated 3-electrode	69mV	69mV	23μV/25	Not safe
Isolated 2-electrode	95V	4.74V	1.58mV/25	Safe
Isolated 2-electrode	95V	9.5mV	3.2μV/25	Safe

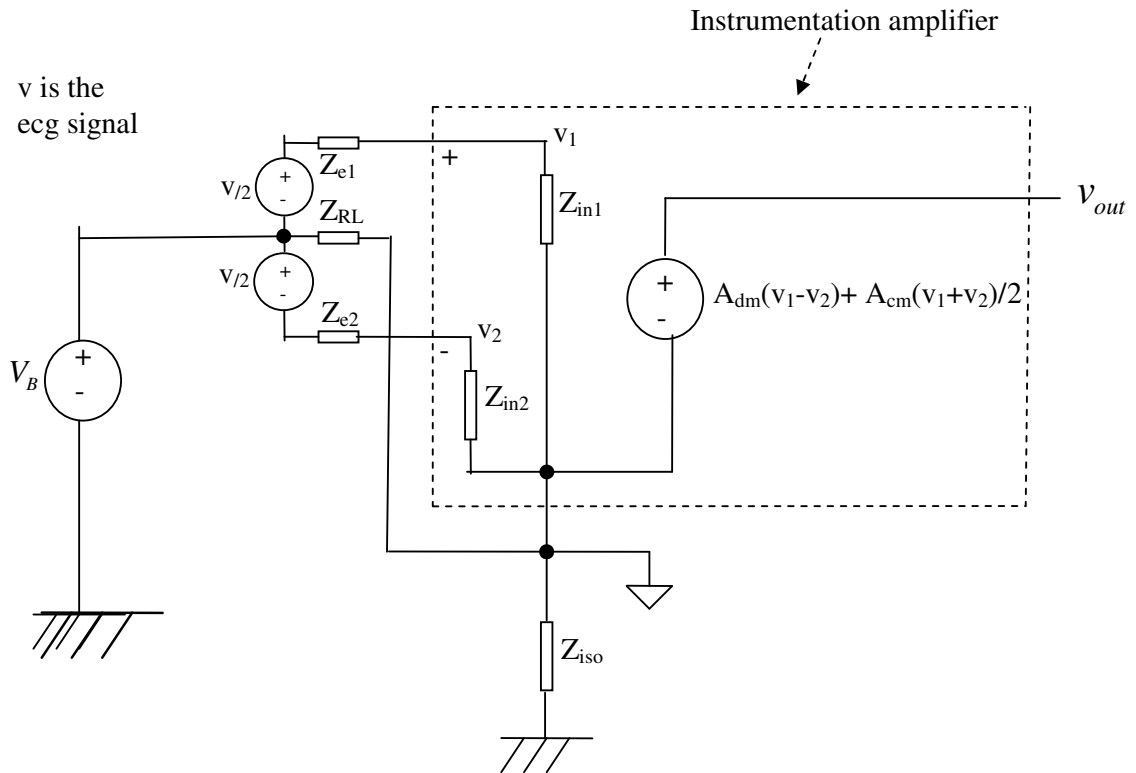
### Right-Leg-Drive Circuit:

This technique can be used to further decrease  $v_{cm}$  by effectively lowering  $Z_{rl}$ . This technique is used with the 3-electrode isolated configuration and is explained in Webdsater page 256.

**Complete analysis of the isolated 3-electrode ECG amplifier including imbalance in electrode impedances:**

It is shown above that the 3-electrode isolated amplifier is best for ECG amplification. However in practice there is another problem which is due to the unbalance between the impedances of the two electrodes ( $Z_{e1}, Z_{e2}$ ) other than the RL electrode.

The equivalent circuit including all electrode impedances is given below:

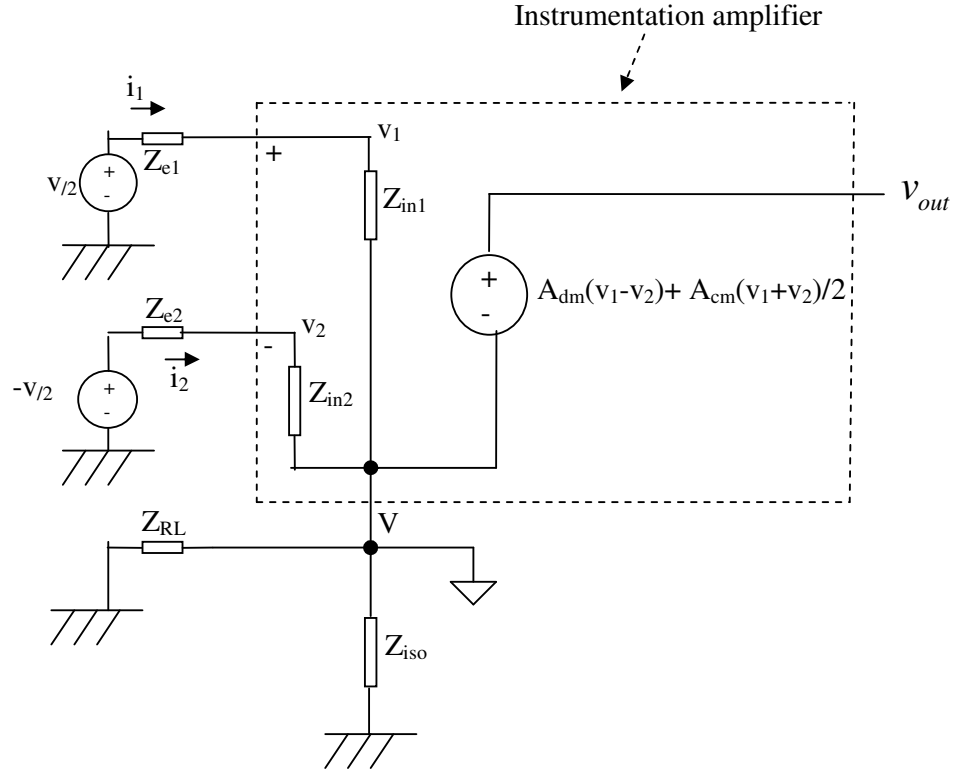


We can assume  $Z_{in1}=Z_{in2}=Z_{in}$ . In general  $Z_{e1}$  is not equal to  $Z_{e2}$ . say  $Z_{e2} - Z_{e1} = \Delta Z_e$

We can use superposition (i) Differential input only i.e.  $V_B = 0$  and  $v_{ecg} \neq 0$

(ii) Common mode input only i.e.  $V_B \neq 0$  and  $v_{ecg} = 0$

(i) Differential input only



If  $Z_{e1}=Z_{e2}$ , then  $i_1=-i_2$  and  $V=0$ .

If  $Z_{e1}, Z_{e2} \ll Z_{in}$ , then  $i_1 \approx -i_2$  and  $V \approx 0$ .

$$v_1 \approx \frac{v_{ecg}}{2}, \quad v_2 \approx -\frac{v_{ecg}}{2}$$

$$v_1 - v_2 = v_{ecg}$$

$$v_{out} = A_{dm} v_{ecg}$$

(i) Common mode input only

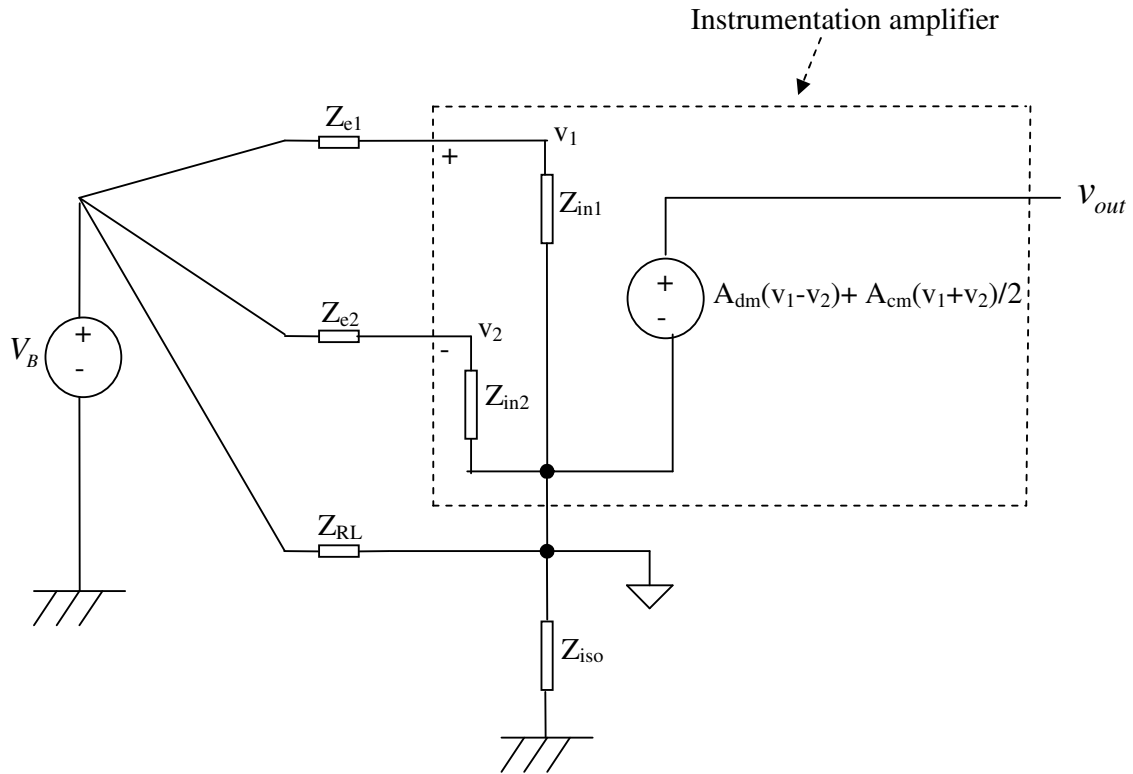
$$v_{cm} \approx V_B \frac{Z_{RL}}{Z_{RL} + Z_{iso}} \approx V_B \frac{Z_{RL}}{Z_{iso}}$$

$$v_1 = v_{cm} \frac{Z_{in}}{Z_{e1} + Z_{in}}, \quad v_2 = v_{cm} \frac{Z_{in}}{Z_{e2} + Z_{in}}$$

$$v_1 - v_2 = v_{cm} \left( \frac{Z_{in}}{Z_{e1} + Z_{in}} - \frac{Z_{in}}{Z_{e2} + Z_{in}} \right) \approx v_{cm} \frac{\Delta Z_e}{Z_{in}}$$

$$v_1 + v_2 = 2v_{cm} \frac{Z_{in}}{Z_{e1} + Z_{in}} \approx 2v_{cm}$$

$$\frac{v_1 + v_2}{2} \approx v_{cm}$$



$$v_{out} = (v_1 - v_2)A_{dm} + \frac{v_1 + v_2}{2}A_{cm}$$

$$= v_{cm} \frac{\Delta Z_e}{Z_{in}} A_{dm} + v_{cm} A_{cm}$$

$$= v_{cm} A_{dm} \left( \frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right)$$

$$\text{where } CMRR = \frac{A_{dm}}{A_{cm}}$$

$$\text{Since } v_{cm} \approx V_B \frac{Z_{RL}}{Z_{iso}}$$

$$v_{out} = V_B \frac{Z_{RL}}{Z_{iso}} \left( \frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right) A_{dm}$$

Combining the two cases, the total output is:

$$v_{out} = V_B \frac{Z_{RL}}{Z_{iso}} \left( \frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right) A_{dm} + v_{ecg} A_{dm}$$

For  $\Delta Z_e = 1K\Omega$ ,  $Z_{iso} = -j100M\Omega$ ,  $Z_{in} = 10M\Omega$ ,  $CMRR = 10^5$ ,  $V_B = 110V$ ,  $Z_{RL} = 10K\Omega$

$$v_{out} = 100 \frac{10}{100000} \left( \frac{1}{1000} + \frac{1}{100000} \right) A_{dm} + v_{ecg} A_{dm}$$

$$\approx \frac{1}{100} \left( \frac{1}{1000} \right) A_{dm} + v_{ecg} A_{dm}$$

$$= 1\mu V \times A_{dm} + v_{ecg} A_{dm}$$

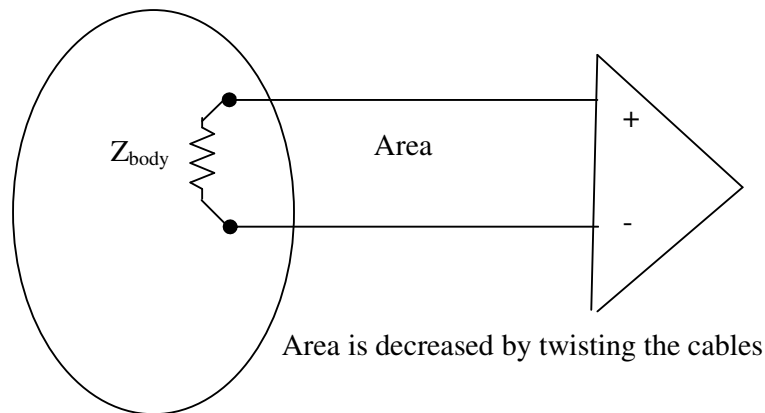
$1\mu V \times A_{dm}$  is the output voltage due to 50 Hz interference. The input referred value of this interference (i.e. divided by  $A_{dm}$ ) is  $1\mu V$  which is much smaller than  $v_{ecg}$ .

Note that this noise is primarily due to unbalance between  $Z_{e1}$  and  $Z_{e2}$ . Due to this unbalance  $v_{cm}$  is transferred into the two inputs of the instrumentation amplifier ( i.e.  $v_1$  and  $v_2$ ) unequally and a differential input appears at its input. As in the example above if

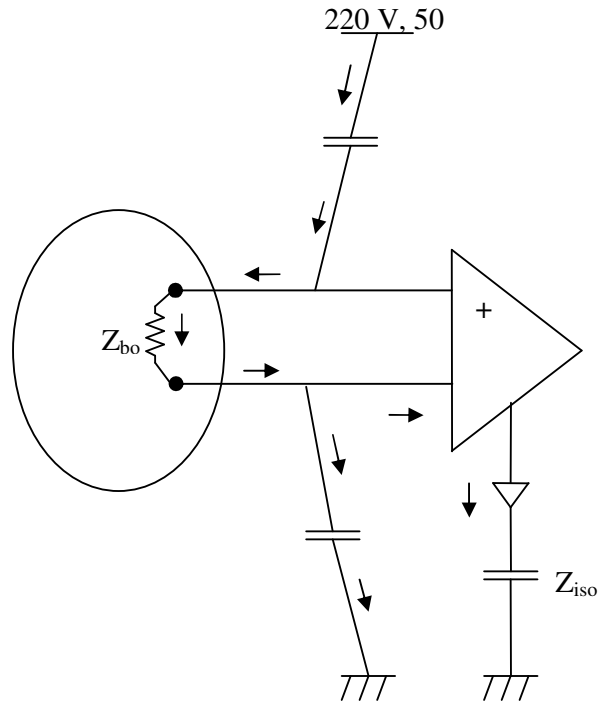
$\frac{\Delta Z_e}{Z_{in}} \gg \frac{1}{CMRR}$ , then conversion of  $v_{cm}$  to differential input has more pronounced effect than  $v_{cm}$  itself.

### **Other sources of 50 Hz interference:**

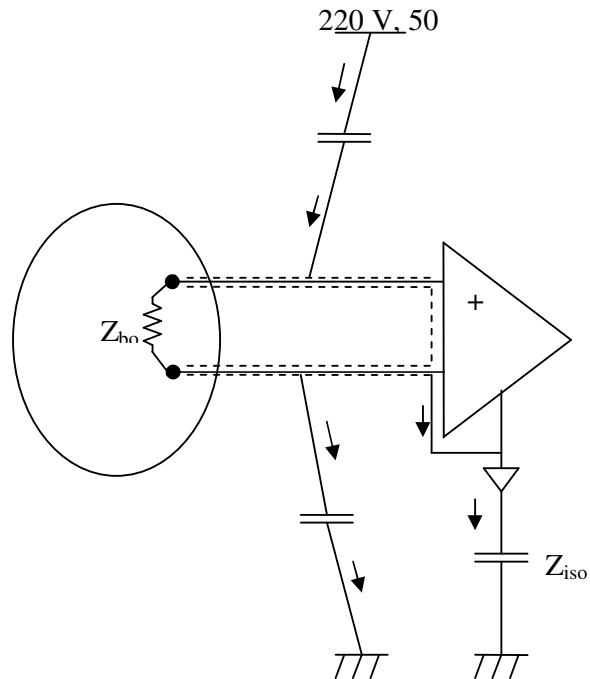
(i) Magnetic field generated by current carrying 220 V lines causes an induced voltage in the loop formed by the electrode leads(cables), the body, and the amplifier inputs. Reduction of this interference can be significantly achieved by twisting the electrode leads.



(ii) Due to stray capacitances to 220 lines, displacement current flows through the electrode leads via electrode impedances generating a differential input voltage. Remedy is shielding of the electrode leads. Without shielding we have



and with shielding we have



(iii) Currents flowing through the body induced by stray capacitances generate differential voltages on the body due to the resistivity of the tissues. Careful electrode placement and repositioning of the subject may remedy the problem.

## **Other interferences:**

EMG: EMG from muscles of the thorax, arms, and legs add on top of ECG. A low pass filter with 35 Hz cutoff significantly lowers this interference but also introduces some blunting of the ECG signal at an acceptable level.

It is best to record ECG while muscles are relaxed as much as possible like when the person is relaxed in supine (lying) position. In exercise ECG testing relaxation of muscles is not possible. In this case the method of signal-averaging is used to extract the PQRST waveform from the noisy recording.

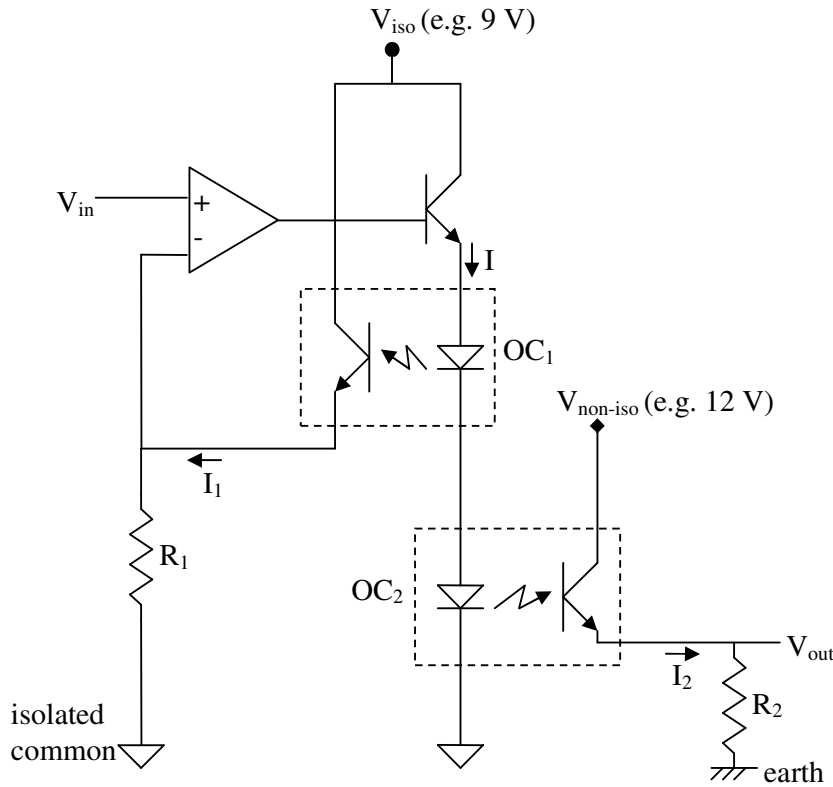
BASELINE WANDER: Motion alters ionic concentrations under electrodes' metal-solution interface and thereby changes the contact potential. Electrodes and leads must be attached and fastened firmly to the body to avoid motion. During rest ECG this motion artifact is minimal and is only caused by breathing which has a low frequency. A high pass filter with 0.05 Hz cutoff is sufficient to minimize this interference. The motion artifact may be abrupt during exercise ECG testing and a higher frequency interference is added to ECG. In exercise ECG a cutoff of 0.5 to 0.8 Hz is used. However of course ECG is also somewhat modified by such a filter.

## **SIGNAL AND POWER ISOLATION**

In order to protect the patient from dangerous current flow, biopotential amplifiers must be isolated from earth. Isolation must be achieved for both power and signals. Isolation, as we have seen before, also helps reduce 50Hz common mode interference.

### **Signal isolation**

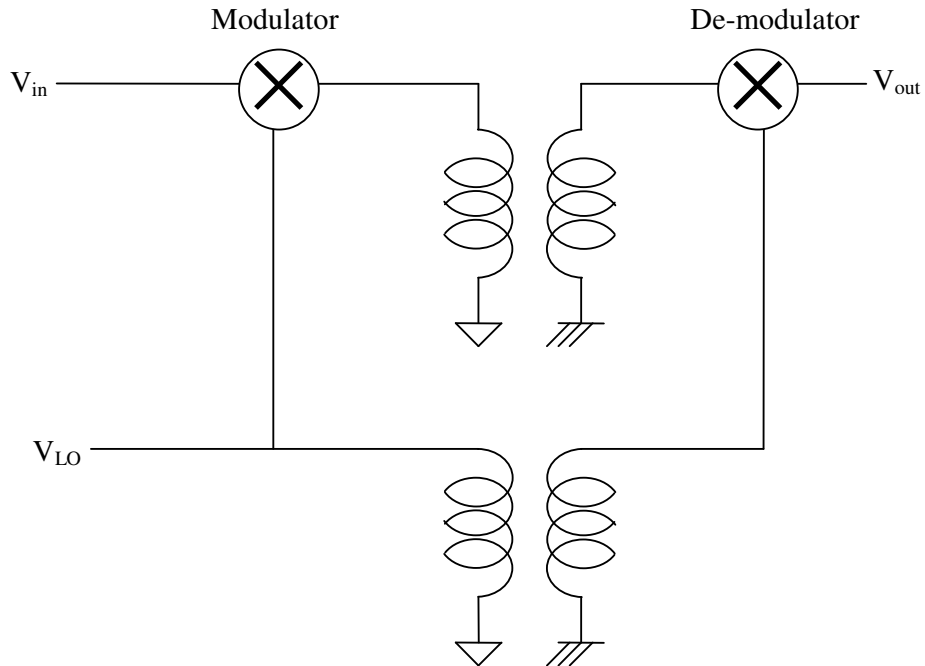
- (i) **Optical isolation:** Optocouplers or optical fibers can be used. These components have non-linearities and therefore precautions must be taken. Example for a low frequency linear optocoupler isolation is given below:



$$I_1 = K_1 \left( \frac{I}{I'} \right)^{n_1}, \quad I_2 = K_2 \left( \frac{I}{I'} \right)^{n_2} \quad \text{where } I' \text{ is a constant reference current.}$$

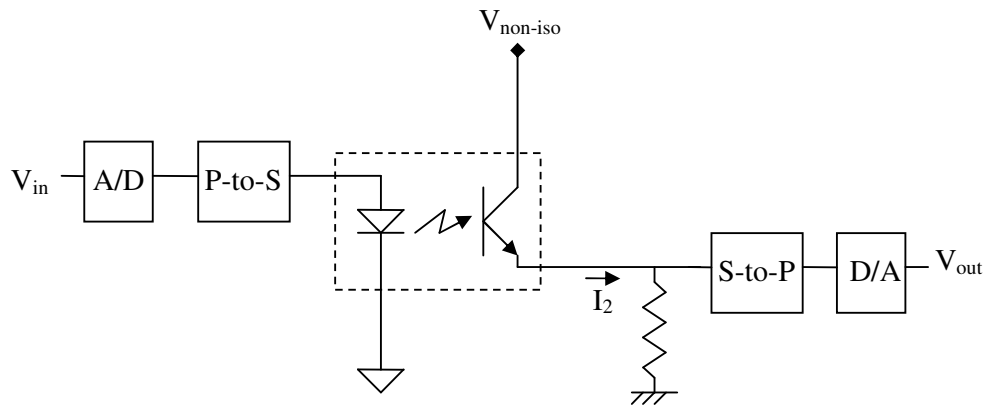
Because optocouplers, OC<sub>1</sub> and OC<sub>2</sub>, may not be matched, i.e.  $K_1 \neq K_2$  and  $n_1 \neq n_2$ , the relation between  $V_{in}$  and  $V_{out}$  will not be linear. However if they are matched (or nearly matched) we will get an almost linear relation. Assuming they are matched, i.e.  $K_1 = K_2$  and  $n_1 = n_2$ , we have  $I_1 = I_2$ ,  $I_1 = \frac{V_{in}}{R_1}$ ,  $I_2 = \frac{V_{out}}{R_2}$  and  $V_{out} = \frac{R_2}{R_1} V_{in}$ . In the above circuit  $V_{in}$  is referenced to the isolated common and  $V_{out}$  is referenced to earth which is the non-isolated common.

- (ii) **Magnetic isolation:** This is achieved using transformers. Since most bioelectric amplifiers have DC (or nearly DC) components, transformers must be used after shifting the signal from baseband to at least few KHz up.



$V_{LO}$  is the local oscillator ( $= \sin(\omega_0 t)$ )

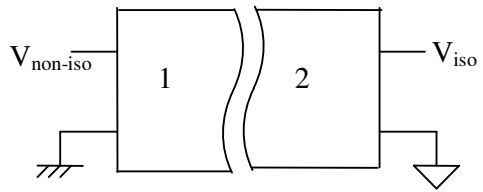
- (iii) **Digitization before isolation:** Because of the distortions due to non-ideal (and non-linear) analog isolators, one may digitize the signal beforehand using an A/D converter. After encoding (parallel-to-serial conversion) a bit stream is obtained which is then transferred to the non-isolated side using a single optocoupler. The signal is then S-to-P converted and fed out through a D/A converter.



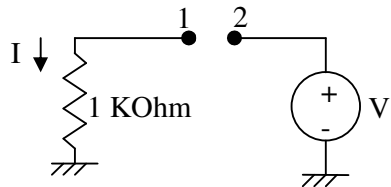
Instead of an opto-coupler, a pulse transformer can also be used.

## **Power isolation**

If a battery does not simply meet the power requirement, then power isolation may be used which is usually magnetic (using transformers). Isolated DC-DC converters are readily available (for < \$50.-).



Testing of an isolated DC-DC converter:



V is either a large DC voltage (5000 V) or 220 V (50 Hz). 1 and 2 are any conductive parts on the non-iso and iso sections of the converter respectively.

For V = 220 V (50 Hz) I must be less than 100 microA.

For V = 5000 V (DC) breakdown must not occur.