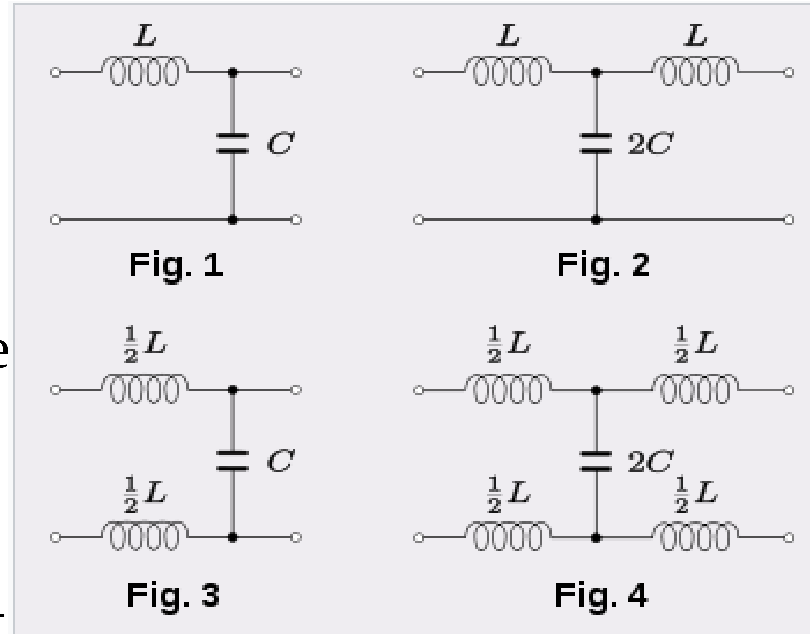
Balancing and Filtering

BALANCING

- A **balanced circuit** is a two-conductor circuit in which both signal conductors, and all circuits connected to them, have the same nonzero impedance with respect to a reference (usually ground) and all other conductors.
- The purpose of balancing is to make the noise pickup equal in both conductors; in which case, it will be a common-mode signal, which can be made to cancel in the load.
- If the impedances of the two signal conductors to ground are unequal, then the system is unbalanced.
- For a balanced circuit to be most effective in reducing common-mode noise, not only must the terminations be balanced, but also the interconnection (cable) must be balanced.



Example of 4 different circuit configurations, using a low-pass filter, to demonstrate. **Fig. 1.** Unbalanced, asymmetrical circuit. **Fig. 2.** Unbalanced, symmetrical circuit. **Fig. 3.** Balanced, asymmetrical circuit. **Fig. 4.** Balanced, symmetrical circuit.

BALANCING

- An excellent example of the effectiveness of a balanced system in reducing noise is the **telephone system**, where signal levels are typically a few hundred millivolts.
- Telephone cables, which consist of unshielded twisted pairs, often run parallel to high-voltage (4 to 14 kV) ac power lines for many miles, and it is seldom that any 50/60-Hz hum is heard in the telephone system.
- This is the result of the telephone system being a balanced system; both the source and the load are balanced.
- On the rare occasion that hum is heard, it is because something has caused an unbalance (e.g., water getting into the cable) to occur to the lines, and the problem will go away once the balance is restored.

BALANCING

- Consider the circuit shown in Fig. 4-1.
- If R_{s1} equals R_{s2} then the source is balanced, and if R_{L1} equals R_{L2} then the load is balanced.
- Under these conditions, the circuit will be balanced because both signal conductors have the same impedance to ground.
- Notice, that it is not necessary for V_{s1} to be equal to V_{s2} for the circuit to be balanced.
- One or both of these generators may even be equal to zero, and the circuit is still balanced.

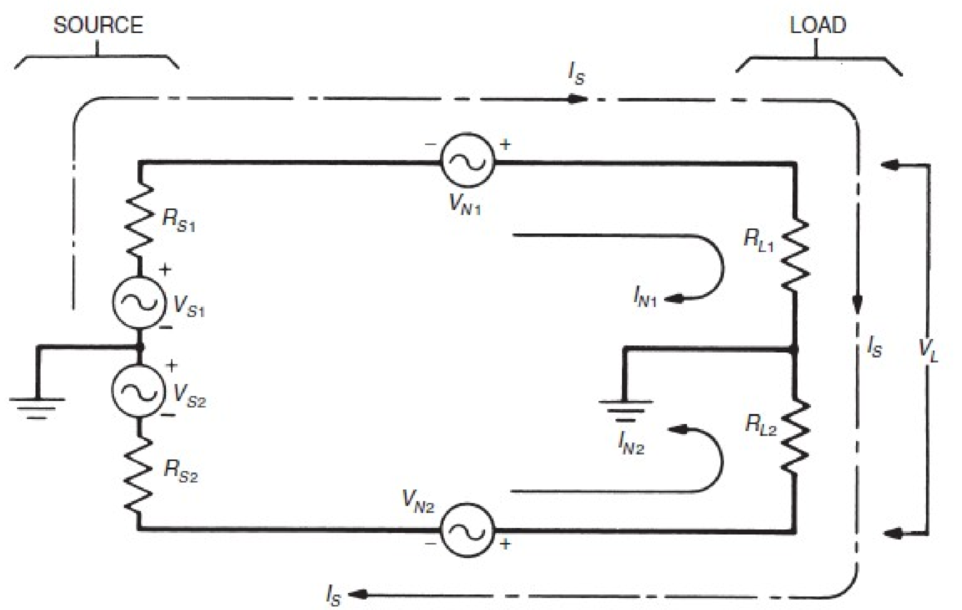


FIGURE 4-1. For balanced condition: $R_{s1} = R_{s2}$, $R_{L1} = R_{L2}$, $V_{N1} = V_{N2}$, and $I_{N1} = I_{N2}$.

BALANCING

- In Fig. 4-1, the two common-mode noise voltages V_{N1} and V_{N2} are shown in series with the conductors.
- These noise voltages produce noise currents I_{N1} and I_{N2}.
- The sources V_{s1} and V_{s2} together produce the signal current Is.
- The total voltage V_L produced across the load is then equal to:

$$V_L = I_{N1}R_{L1} - I_{N2}R_{L2} + I_s(R_{L1} + R_{L2}). \tag{4-1}$$

- The first two terms represent noise voltages, and the third term represents the desired signal voltage.
- If I_{N1} is equal to I_{N2} and R_{L1} is equal to R_{L2}, then the noise voltage across the load is equal to zero.
- Equation 4-1 then reduces to

$$V_L = I_s(R_{L1} + R_{L2}) \tag{4-2}$$

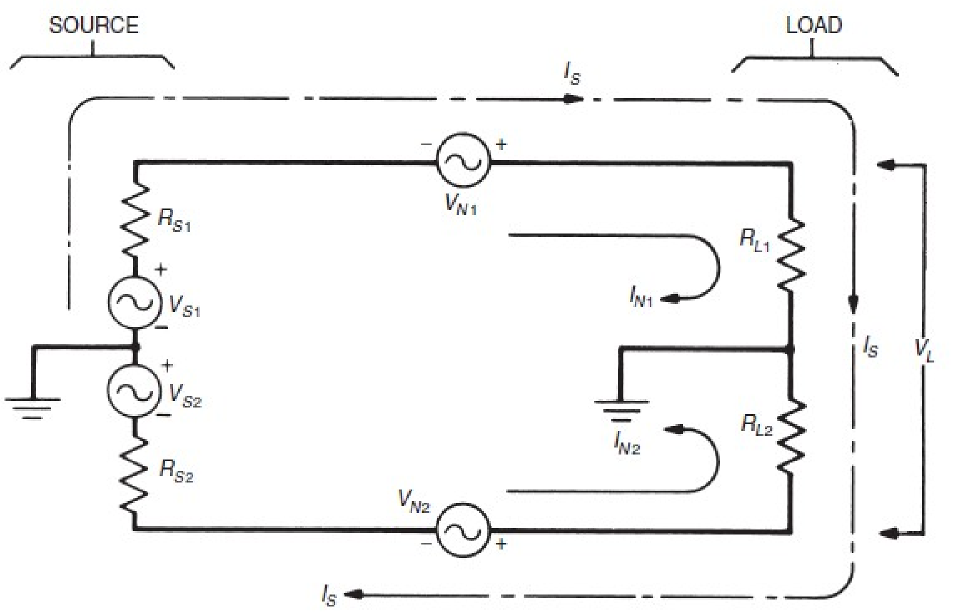


FIGURE 4-1. For balanced condition: $R_{s1} = R_{s2}$, $R_{L1} = R_{L2}$, $V_{N1} = V_{N2}$, and $I_{N1} = I_{N2}$.

BALANCING

- Figure 4-1 just shows resistive terminations to simplify the discussion. In reality, both resistive and reactive balance are important as shown in fig.4.2.
- In the balanced circuit shown in Fig. 4-2, V1 and V2 represent inductive pickup voltages, and current generators I1 and I2 represent noise that is capacitively coupled into the circuit.
- The difference in ground potential between source and load is represented by Vcm.
- If the two signal conductors 1 and 2 are located adjacent to each other, or better yet twisted together, the two inductively coupled noise voltages V1 and V2 should be equal and cancel at the load.

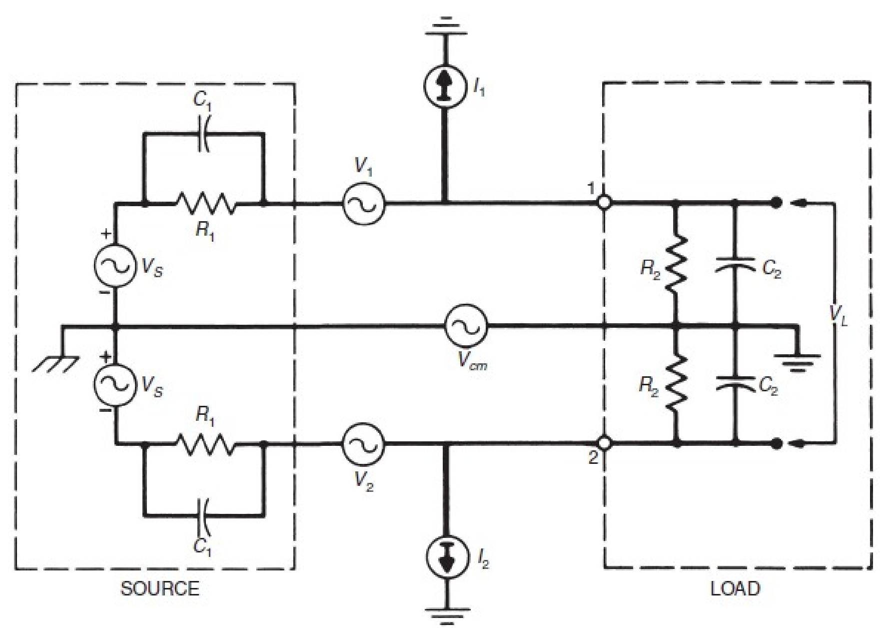


FIGURE 4-2. A balanced circuit that shows inductive and capacitive noise voltages and a difference in ground potential between source and load.

BALANCING

- The noise voltage produced between load terminals 1 and 2, resulting from to capacitive coupling, can be determined by referring to Fig. 4-3.
- Capacitors C31 and C32 represent capacitive coupling from the noise source, in this case conductor 3.
- Impedances Rc1 and Rc2 represent the total resistance to ground from conductors 1 and 2, respectively.
- The capacitive coupled noise voltage VN1 induced into conductor 1 because of the voltage V3 on conductor 3 is

$$V_{N1} = j\omega R_{c1} C_{31} V_3.$$

- The noise voltage induced into conductor 2 because of V3 is:

$$V_{N1} = j\omega R_{c2} C_{32} V_3.$$

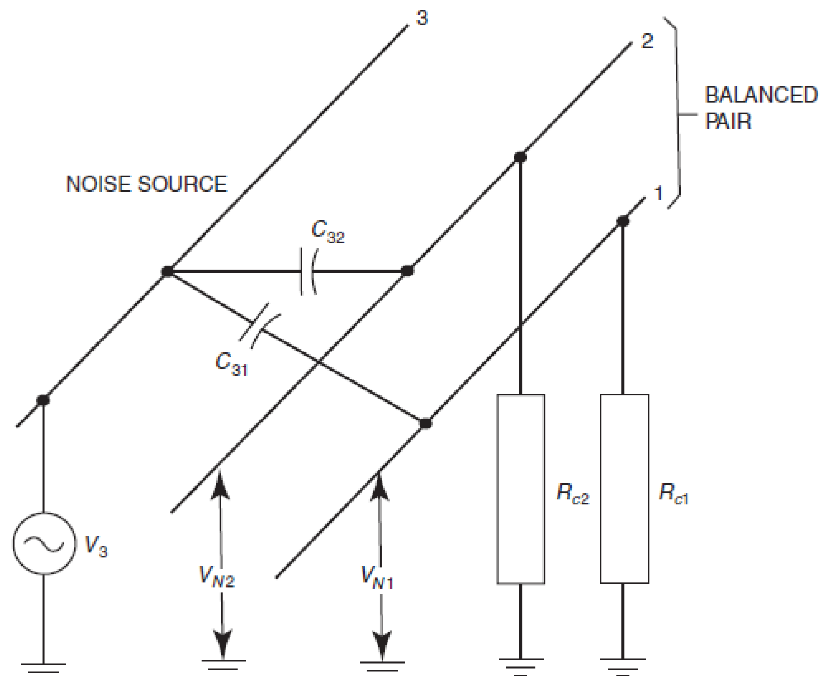


FIGURE 4-3. Capacitive pickup in balanced conductors.

BALANCING

- If the circuit is balanced, then resistances Rc1 and Rc2 are equal.
- If conductors 1 and 2 are located adjacent to each other, or better yet are twisted together, capacitance C31 should be nearly equal C32.
- Under these conditions, VN1 approximately equals VN2, and the capacitively coupled noise voltages cancel in the load.
- A balanced circuit using a twisted pair will therefore protect against both magnetic and electric fields, even without a shield over the conductors.
- Shields may still be desirable, however, because it is difficult to obtain perfect balance, and additional protection may be required.

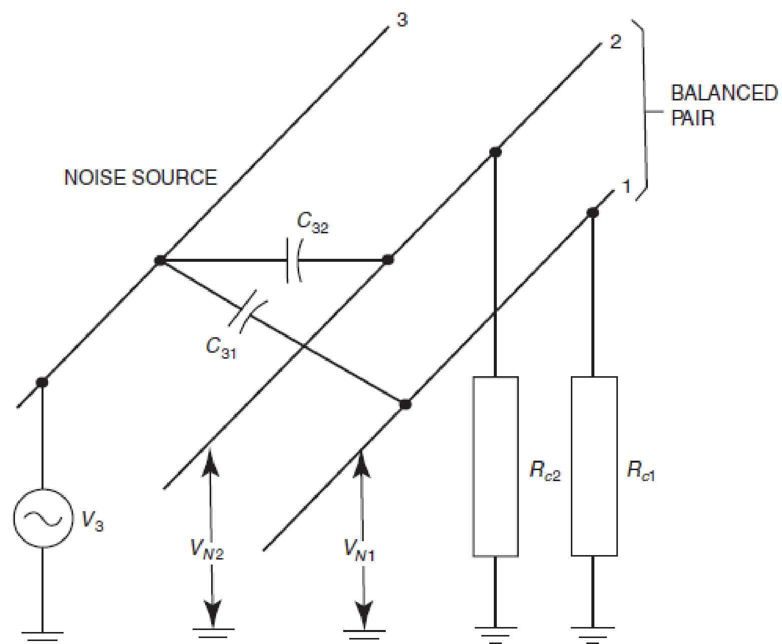


FIGURE 4-3. Capacitive pickup in balanced conductors.

Common-Mode Rejection Ratio

- The common-mode rejection ratio (CMRR) is a metric that can be used to quantify the degree of balance or the effectiveness of a balanced circuit in rejecting common-mode noise voltages.
- Figure 4-4 shows a balanced circuit with a common-mode voltage Vcm applied to it.
- If the balance were perfect, then no differential-mode voltage Vdm would appear across the input of the amplifier.
- Because of slight unbalances present in the system, however, a small differential-mode noise voltage Vdm will appear across the input terminals of the amplifier.
- The CMRR, or balance, in dB, is defined as

$$\mathrm{CMRR} = 20 \log\left(\frac{V_{cm}}{V_{dm}}\right) \mathrm{dB}$$

- The better the balance, the higher the CMRR and the greater the common-mode noise reduction obtainable.

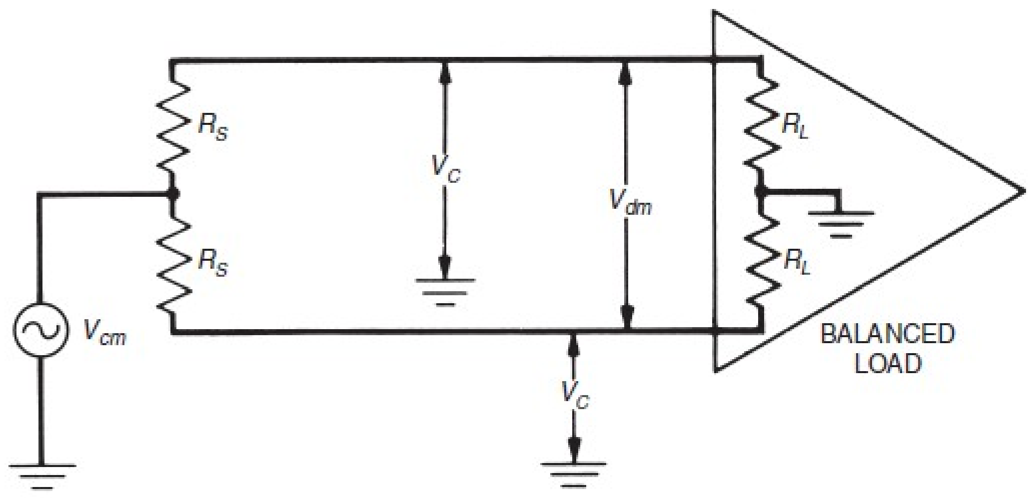


FIGURE 4-4. Circuit used to define CMRR.

FILTERING

- Filters are used to change the characteristics of, or in some cases eliminate signals.
- Filters can be differential mode or common mode.
- Signal line, or differential-mode filters are also well understood.

<u>Common-Mode Filters</u>

- Common-mode filters are usually used to <u>suppress noise</u> on cables while <u>allowing the intended differential-mode signal</u> to pass undisturbed.
- Why are common-mode filters more difficult to design than differential-mode filters?

<u>Basically there are three reasons:</u>

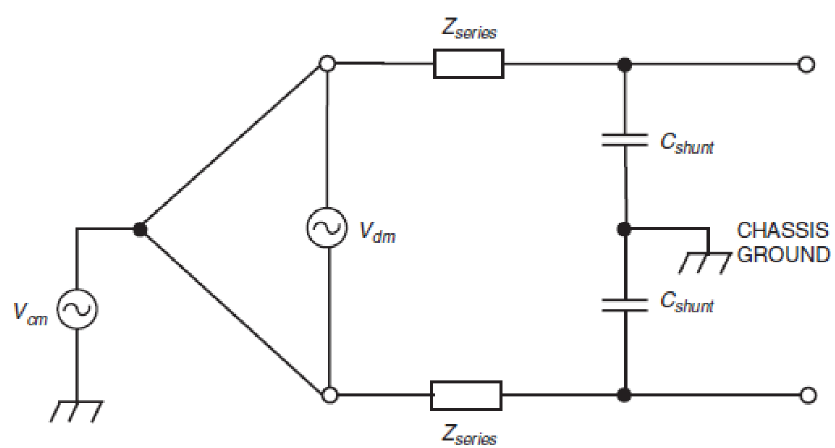
- We usually do not know the source impedance.
- We usually do not know the load impedance.
- The filter must not distort the intentional signal (the differential-mode signal) on the cable.

FILTERING

- The effectiveness of a filter depends on the source and load impedances between which the filter is working.
- For a differential-mode filter, it is usually easy to find information on the output impedance of the driver and on the input impedance of the load.
- However, for common-mode signals, the **source** is the noise generated by the circuit (not documented anywhere), and the **load** is usually some cable that acts as an antenna, the impedance of which is not generally known and varies with frequency, cable length, conductor diameter, and cable routing.
- In the case of a common-mode filter the **source** impedance is usually the printed circuit board (PCB) ground impedance (which is small and increases with frequency, because it is inductive), and the **load** is the impedance of a cable acting as an antenna.
- Differential-mode or signal line filters (e.g., clock line filters, etc.) should be placed as close to the source or driver as possible.
- Common-mode filters, however, should be located as close to where the cable enters or leaves the enclosure as possible.

FILTERING

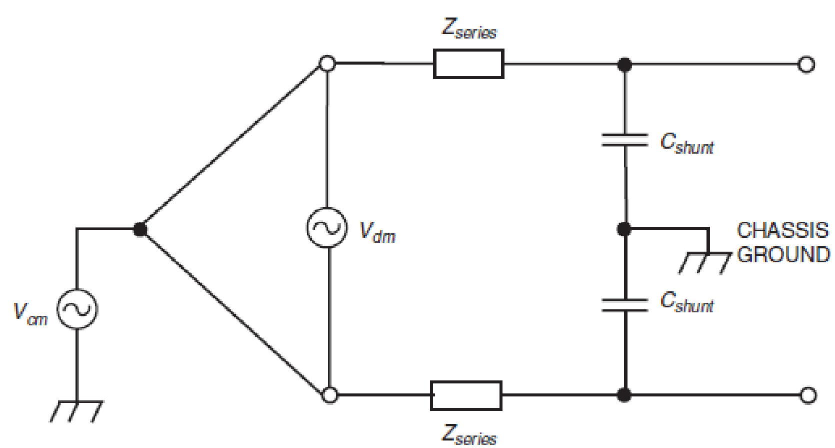
- Figure 4-12 shows a simple two-element, low-pass, common-mode filter that consists of a series element and a shunt element.
- The filter is inserted both in the signal conductor and in its return conductor.
- The figure also shows a common mode (noise) and a differential-mode (signal) voltage source connected to the filter.
- To the common-mode voltage source the two shunt capacitors are in parallel for a total capacitance of 2 C_{shunt}.
- To the differential-mode voltage source, the two capacitors are in series for a total capacitance of $C_{shunt}/2$.
- Therefore, the common-mode source observes four times the capacitance that the differential mode source observes.
- This result is good, because we want the shunt capacitance of the filter to have more effect on the common-mode signal than on the differential-mode signal.



A two-element common-mode filter in both the signal and return conductors.

FILTERING

- However, to the common-mode source the two series impedances are in parallel for a total impedance of $Z_{series}/2$.
- To the differential-mode source, the two series impedances are in series for a total capacitance of $2Z_{series.}$
- Therefore, the differential-mode source observes four times the series impedance that the common-mode source observes.
- This result is bad, because we want the series impedance of the filter to have more effect on the common mode voltage than on the differential mode voltage.
- As a result, the series element in a common-mode filter is usually configured as a common-mode choke, in which case the differential-mode impedance is zero, and the series impedance only affects the common-mode signal and not the differential-mode signal.



A two-element common-mode filter in both the signal and return conductors.