Experiment 4: Grounding and Shielding

Power System

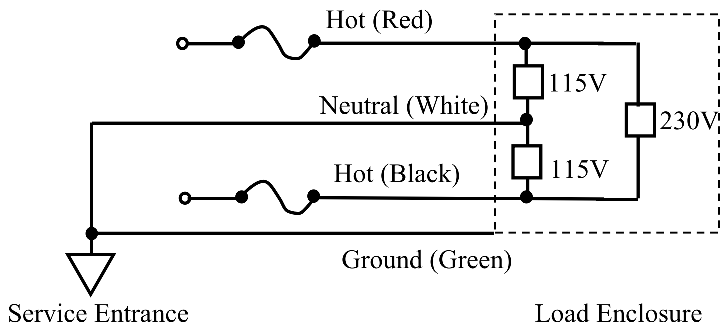


Figure 1 – Typical residential or commercial AC power system

One of the main sources of interference in a sensitive electronic circuit is the ac power system used to provide power in most stationary applications. Depending on the placement and electrical configuration of the electronic circuit, the power system can capacitively, inductively, or conductively couple 60 Hz noise into various electronic components. A major problem is the voltage drop on the neutral line. As shown in Figure 1, the neutral line is connected to earth ground at the service entrance, which can be a substantial distance from the point of use. Since most of the return current travels through this line, a voltage reference at this point will differ significantly in potential from the ground point. The ground line, however, to which all load enclosures (chassis) should be connected for safety purposes normally carries no current. Thus, this line serves as a better reference point for electronic circuits. Problems can occur with this ground reference, however, when it carries current.

Capacitive Interference

Problems

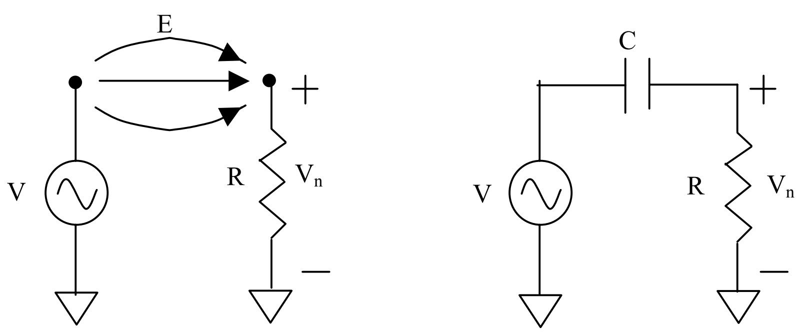


Figure 2 – Capacitive or electric field coupled interference

Capacitive, or electric field coupled interference occurs when a fringing electric field is large enough to produce a significant displacement current in an electronic circuit. Under these conditions the fringing electric field can be modeled as a capacitance with a value approximately given by

$$C = \frac{\pi\varepsilon}{\cosh^{-1}\frac{D}{d}} \tag{1}$$

where D is the distance between the noise source and the electronic circuit, d is the average wire diameter, and ε is the dielectric permittivity of the environment. Considering the equivalent circuit shown on the right hand side of Figure 2, the noise voltage in the electronic circuit is given by

$$V_n = \frac{R}{R + \frac{1}{j\omega C}} V \tag{2}$$

where V is the voltage of the noise source and R is the effective resistance of the electronic circuit. At low frequencies the rms magnitude of the interference in the electronic circuit is then

$$|V_n| = \omega RCV \tag{3}$$

So, the magnitude of the interference increases with the frequency of the source and the effective resistance of the electronic circuit.

Remedies

The remedies for capacitive or electric field coupling are relatively straightforward. From equation (1) it is clear and intuitive that the electronic circuit should be as far from the noise source as possible. Another remedy is to provide electrostatic or conductive shielding around the electronic circuit connected to a point of fixed potential such as ground. This terminates the fringing electric fields before they can interact with the relevant circuit. In this experiment we will use grounded aluminum foil for this purpose.

Inductive Interference

Problems

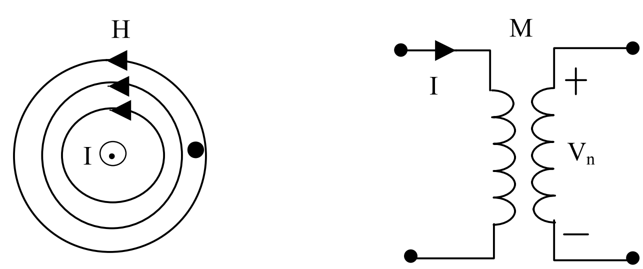


Figure 3 – Inductive or magnetic field coupled interference

According to Faraday's law of induction, a voltage will be induced in a circuit which is linked by the fringing magnetic flux lines of a wire with a time varying electric current. From an electric circuit point of view, this can be represented by a mutual inductance and the noise voltage is given by

$$V_n = \frac{d\lambda}{dt} = M\frac{dI}{dt} \tag{4}$$

where λ is the flux linkage and M is the mutual inductance. If the interference source is sinusoidal in time, the magnitude of the induced noise voltage is

$$|V_n| = \omega MI. \tag{5}$$

As with capacitive coupling, in the absence of metallic shielding around the circuit, we expect inductively coupled interference to increase with the frequency of the noise source.

Remedies

One obvious remedy is to make the circuit as small as possible by using shorter connections. A smaller circuit is linked by fewer fringing magnetic flux lines. Orientation is also important. If the portion of the electronic circuit that is picking up the magnetic interference is parallel to the magnetic flux lines, the linkages will be small and less voltage will be induced in the circuit. Magnetic shielding of the interference source or the electronic circuit is also an effective remedy at low frequencies. In this experiment we will examine all of these remedies.

At higher frequencies coaxial cable will reduce interference due to skin effect in the shield. The mutual inductance then has the form

$$M = M_0 \exp\left(-\frac{d}{\delta}\right) \tag{6}$$

Where d is the thickness of the shield and

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} \tag{7}$$

is the skin depth. In equation (7), σ is the conductivity of the shield material and μ is its magnetic permeability. If we calculate skin depth for copper at 60 Hz we obtain

$$\delta = 0.86 \text{ cm} = 0.34 \text{ in.} \tag{8}$$

which does not reduce the coupling very much at 60 Hz for any normal shield thickness.

Conductive Interference

Common Power Supply and Common Ground

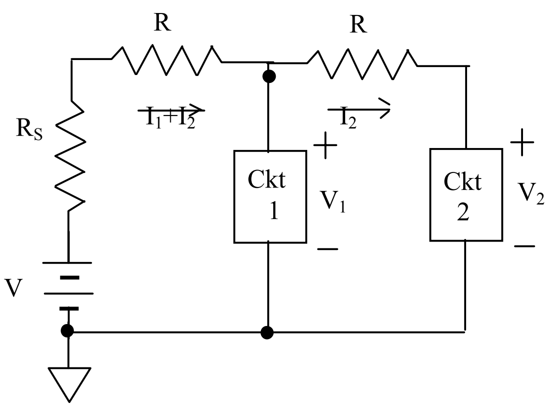


Figure 4 – Circuit showing the effects of common power supply

The problems associated with conductive interference are the most difficult to remedy. Figure 4 indicates a potential problem that will be encountered using a common power supply. For example, if we look at the voltage across circuit 2, we find that

$$V_2 = V - (R_S + R)(I_1 + I_2) - RI_2 \quad . \tag{9}$$

That is, the voltage across circuit 2 depends upon the current through circuit 1 because of the resistance, R, of the connecting wire between the circuits and the source resistance, R_S. If Circuit 1 is a typically noisy digital circuit and circuit 2 is a sensitive analog circuit, there is a problem.

Partial Remedy

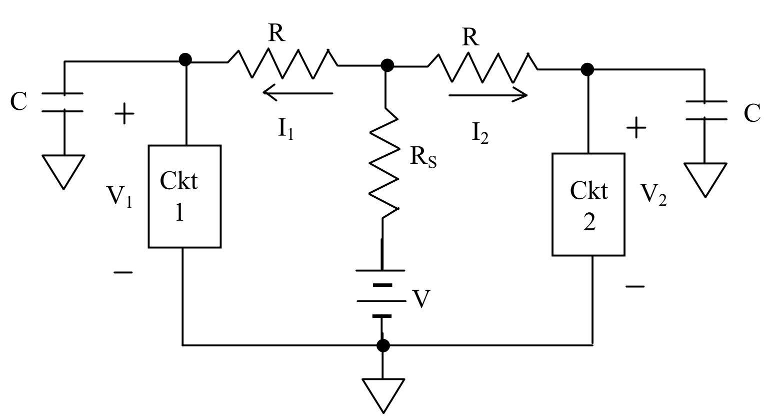


Figure 5 – Stellate connection to power supply and ground

Figure 5 shows a partial solution to the problem. In this circuit there is a single point or stellate connection to the power supply and a single point connection to ground. In this connection the interference due to the resistance R of the connecting wire is eliminated but the interference due to R_S remains. The effect of R_S could be further reduced by connecting a capacitor, C, across each circuit to ground, as shown in the figure.

Ground Loop or Common Mode Interference

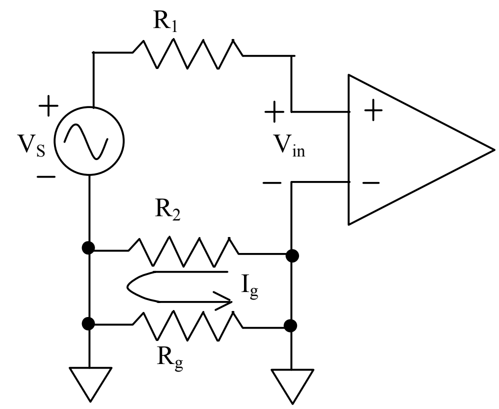


Figure 6 – Ground loop

Figure 6 indicates the kind of problem that can occur when there is more than one ground connection in an electronic circuit. More than one ground connection provides a current path or ground loop through the ground resistance that results in one apparent ground being at a different potential than another one. In Figure 6, for example, we see that the input voltage to the amplifier is given by

$$V_{in} = V_S + I_S R_g \quad (10)$$

To avoid this problem we can eliminate one of the ground connections. As indicated in Figure 7 it is still possible, however, to have a virtual ground loop with only one ground connection. This

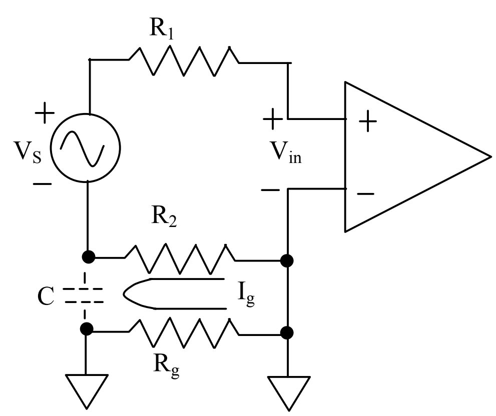


Figure 7 – Virtual ground loop

can be caused by capacitive coupling. Stellate grounding is the preferred mode for electronic circuits operating at frequencies less than about 1 MHz. Above about 10 MHz the self inductance of long ground lines becomes a problem and multi-point grounding using a ground plane is usually preferred.

Remedies

The obvious solution to ground loop problems is to use only one ground point reference in an electronic circuit. As a general rule this is best placed at the most sensitive part of the circuit: usually at an amplifier input. Avoid the inappropriate use of coaxial cables since they ground everything to everything else. Differential amplifiers were designed and developed to reduce the effects of common mode signals in electronic circuits. A high common mode rejection ratio (CMRR) can take care of many of these interference problems. When all else fails one can always try an optoelectronic isolator or an isolation transformer.

Experiment:

Equipment List

1	Printed Circuit Board with AD521 Instrumentation Amplifier
1	Printed Circuit Board Fixture
1	Screw Driver
1	Specially Mounted Inductor, 47 mH, 316 Ω, 200 kHz Self Resonance
1	Cylindrical Magnetic Shield

Procedure

Plug the circuit board into the test fixture. Connect the circuit shown in Figure 8 with an R of 100 Ω. This should result in a gain of 1000 (see table in AD521 data sheet). R should be a ¼ watt resistor mounted using a double banana-to-binding-post adapter and other adapters to minimize circuit area. Run a short jumper from jack 21 to 11. Power up the board and confirm

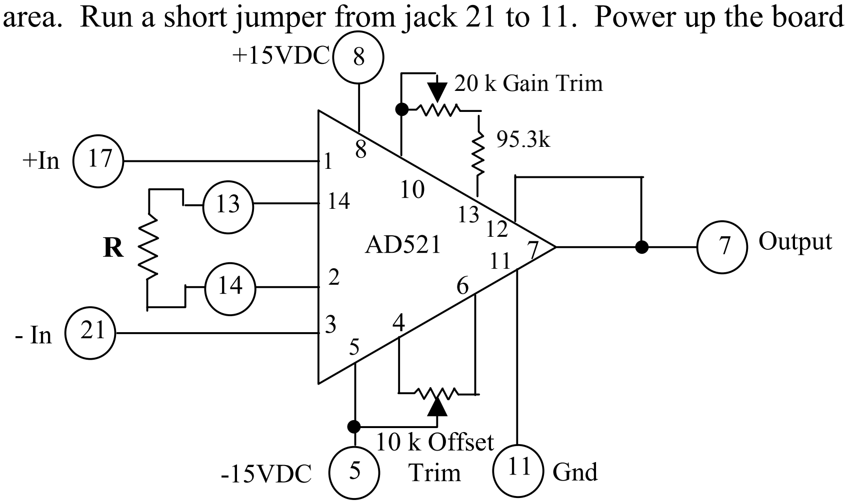
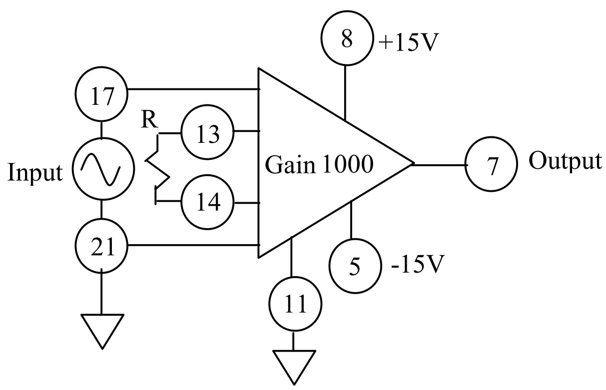
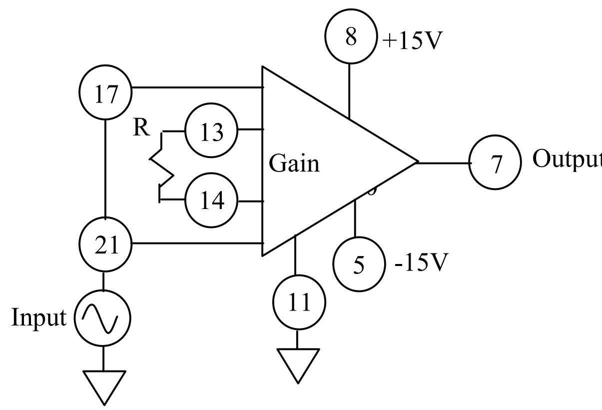


Figure 8 – Instrumentation amplifier circuit

that you get a differential gain of 1000 at 1kHz. You may have to adjust the 20k potentiometer to achieve a gain of 1000. Adjust the 10 kΩ potentiometer (offset null) to set the DC level of the output to zero; check this null from time to time. Be careful to avoid ground loops in wiring this setup. Make sure the contacts of the PC board are clean and that the banana plugs are securely connected to their wires.



(a) Differential gain circuit



(b) Common mode gain circuit

Figure 9 - Common Mode Rejection Ratio (CMRR) Measurement

1. Common Mode Rejection Ratio: First measure the differential gain of the circuit of Figure 9(a) at frequencies from 10 Hz to 100 kHz; use a 1, 2, 5 frequency step sequence. The differential mode input voltage should normally be about 10 mV peak-to-peak.

Next measure the common mode gain of the circuit of Figure 9(b) (run a short jumper from jack 21 to 17) at frequencies from 10 Hz to 100 kHz; use a 1, 2, 5 frequency step sequence. The common mode input voltage should be about 5 V peak-to-peak.

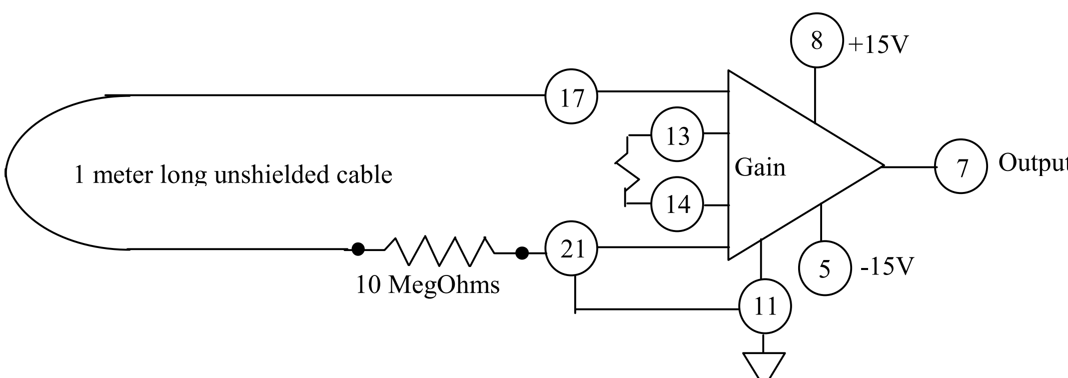


Figure 10 - Capacitive Coupling Circuit

2. <u>Capacitive Coupling:</u> In this part you will study the effects of electric interference by capacitive coupling into the circuit of Figure 10. Connect the circuit shown in Figure 10. Set the differential gain to 10 by changing the value of R from 100 Ω to 10 kΩ. Plug a 10 MΩ resistor into banana jack 21, shorted to 11; and connect it by way of a 1 m long unshielded cable to jack 17; allow the cable to make a broad loop on the bench top. Examine the 60 Hz picked up. Look at the output in both the time and frequency domain. Now take a large sheet of aluminum foil, ground it to jack 11 at one corner, and observe the 60 Hz pickup as you move the foil near the loop. Finally, wrap the loop and observe the 60 Hz pickup with the foil grounded.

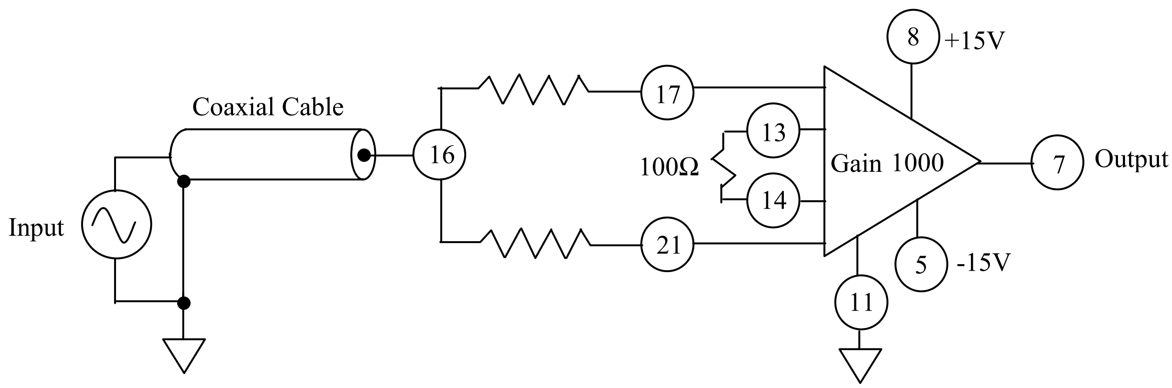


Figure 11 - Differential Unbalance Circuit

3. <u>Differential Unbalance:</u> Now you will study the effects of differential unbalance (unequal input impedances). Connect the circuit of Figure 11. Switch back to a gain of 1000 (change R back to 100 Ω). Run a coax from the signal generator to banana jack 16 taking care that it is grounded only at the generator (this will require creative plugging on your part!). Connect 16 to 21 via roughly 2 kΩ and 16 to 17 via a sequence of fixed resistors, R. Set the generator to 1 V pk-pk at 1 kHz and study $|V_{out}|$ as a function of R as the latter is varied from 10 Ω to 20 kΩ in an approximate 1, 2, 5 sequence; take additional points as needed to resolve any fine structure you suspect or discover.

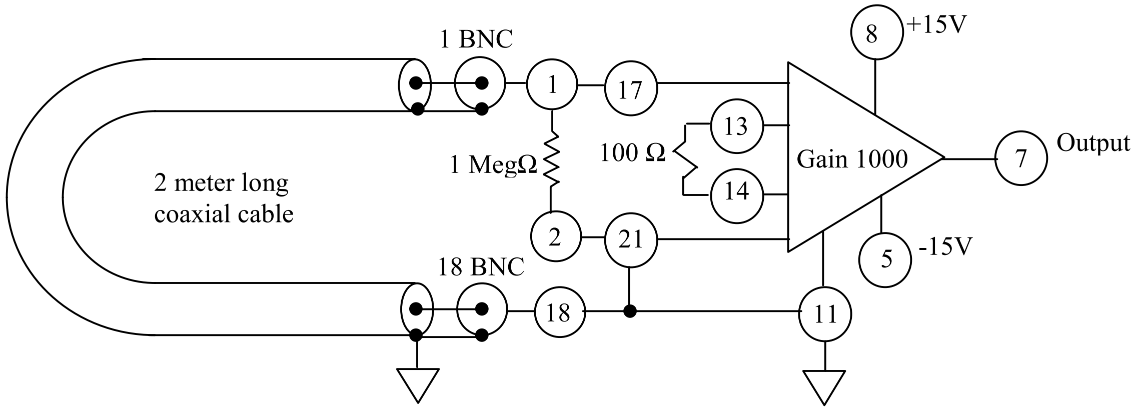


Figure 12 - Magnetic Interference and Shielding Circuit

4. Magnetic Interference: Finally, you will study magnetic interference and shielding. Connect the circuit of Figure 12. Set the AD521 to a gain of 1000 and power it up. Connect the BNC plugs 18 and 1 with 2 m of coax. Then jumper jacks 21 and 11. Connect 1 and 2 via 1 MΩ jumper 2 and 21; jumper 18 and 21; jumper 1 and 17. Connect jack 7 to the scope. This gives a preamplification of 1000 with an input impedance of 1 MΩ. Now set the frequency to 1 kHz, connect the function generator with a 20 V pk-pk output to the plastic mounted, 47 mH inductor, and observe V_{out} as:

(a) The secondary loop orientation is maintained and its area altered with the inductor both inside and outside the secondary loop.

(b) The 47 mH inductor is centered at one point and slowly reoriented in the spherical coordinates Φ and Θ $(0 < \Phi < 2\pi\ ;\ 0 < \Theta < \pi)$. Take z along the inductor axis and perpendicular to the bench top.

(c) The inductor is moved about in the plane of the loop both inside and outside the loop.

(d) With the arrangement above, fix a multi-coiled secondary loop in a place where the pickup is large with the generator at 20 V pk-pk. Measure Vout as a function of frequency as f is increased in a suitable sequence from 10 Hz to 100 kHz; repeat with the shield in place over the inductor. (Take note that you may wish to explain the results from different frequency ranges by invoking different mechanisms. You may therefore wish to deviate from the standard 1, 2, 5 frequency sequence while taking data. Advance planning could prove useful here.)

Write Up

1. Provide on the same graph sheet plots of the differential gain $|a_d|$ and $|CMRR|$ as functions of frequency. How do these results compare with the specs in the AD521 data sheet?

2. Describe and discuss your results on electrostatic shielding.

3. Plot $|V_{out}| / |V_{gen}|$ as a function of R. Explicitly and unambiguously explain the variation noted.

4. Describe and qualitatively explain the area and orientation results. Plot the $|V_{out}| / |V_{gen}|$ vs. f data from part (d) of the experiment and qualitatively explain them. Be brief, but be very sure to set forth unambiguously a clear physical explanation of the observed phenomena; a simple recapitulation of the salient features of your plot will not suffice.

5. Consider the following problem: You are plagued by pure 60 Hz magnetic interference of the same magnitude as your desired signal. The power in the desired signal is spread uniformly over 40-90 Hz, thereby precluding normal filtering; and you can neither eliminate the noise source nor shield the experiment from it. Explain in detail how the circuit in Figure 13 can help. In particular, quantitatively evaluate the behavior of the circuit between points S and S'

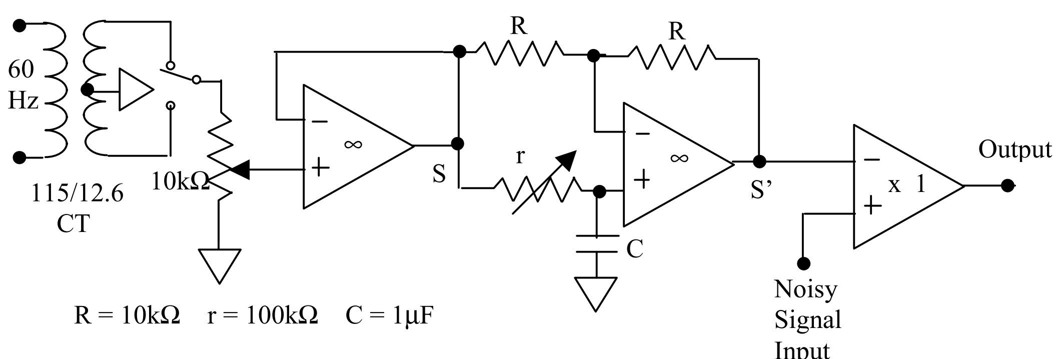


Figure 13 - 60 Hz interference circuit

Suggested Reading

R. A. Bartkowiak, **Electric Circuits**, (Intext, New York, 1973).
J. D. Kraus, **Electromagnetics**, (McGraw-Hill, New York, 1953).
R. Morrison, **Grounding and Shielding Techniques in Instrumentation**, (Wiley, New York, 1971).
H. W. Ott, **Noise Reduction Techniques in Electronic Systems**, (Wiley, New York,1976).