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ABSTRACT

This study guide is part of a program of studies entitled the Science and Engineering Technician (SET) Curriculum developed for the purpose of training technicians in the use of electronic instruments and their applications. The program integrates elements from the disciplines of chemistry, physics, mathematics, mechanical technology, and electronic technology. This volume provides content related to the following topics: (1) basic electrical quantities; (2) test instruments; (3) resistors and resistance circuits; (4) operational amplifiers; (5) bridge circuits; (6) temperature transducers; (7) power amplifiers; (8) recorders; (9) strain gauge; (10) light transducers; (11) sound transducers; (12) linear variable differential transformers; and (13) differential amplifiers. (Author/SK)

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ELECTRONIC COMPONENTS, TRANSDUCERS, AND BASIC CIRCUITS

A STUDY GUIDE OF THE SCIENCE AND ENGINEERING TECHNICIAN CURRICULUM

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ELECTRONIC COMPONENTS, TRANSDUCERS, AND BASIC CIRCUITS

INTRODUCTION

This guide is designed for use by the student who is studying electronic components, transducers and basic circuits.

Electronic components are devices which affect the flow of electricity. Some of the components which will be discussed are:

Resistor	Transistor
Conductor	Meter
Rheostat	Battery
Linear Operational Amplifier	Inductor
Capacitor	Switch
Transformer	

Transducers are electronic components which convert physical parameters into electrical signals. Following are several of these physical parameters:

Temperature	Force
Pressure	Displacement
Sound	Light
Radiation	Flow

These components and transducers may be combined to produce these basic circuits:

Series Resistors	Inverting Op-Amp
Parallel Resistors	Wheatstone Bridge
Voltage Dividers	Electronic Thermometer
Power Amplifier	Differential Amplifier

Electronic test instruments such as voltmeters, ammeters, and oscilloscopes can be utilized to investigate these components and circuits.

SAFETY

Since electrical shock and burns cause severe injury, precautions should be taken to minimize this hazard. The following are a few of these precautions:

1. Disconnect circuits from power sources whenever possible while modifying or testing them.

2. Do not wear conductive objects such as rings and bracelets when working with electrical circuits.

3. Make certain that all equipment is properly grounded.

4. Do not replace blown fuses with fuses of higher current ratings than recommended.

GLOSSARY OF TERMS

An Ammeter is an instrument for measuring electric current.

A Circuit is any closed path through which current can flow.

A Conductor is a material, usually metal such as wire, through which current can flow easily.

The gain of an amplifier is the ratio of output signal to input signal.

An Ohmmeter is an instrument for measuring electrical resistance.

A Power Supply or voltage source provides the energy necessary to move charge through a circuit.

Resistance is an electrical quantity which provides opposition to the flow of electrical current and is measured in ohms (Ω).

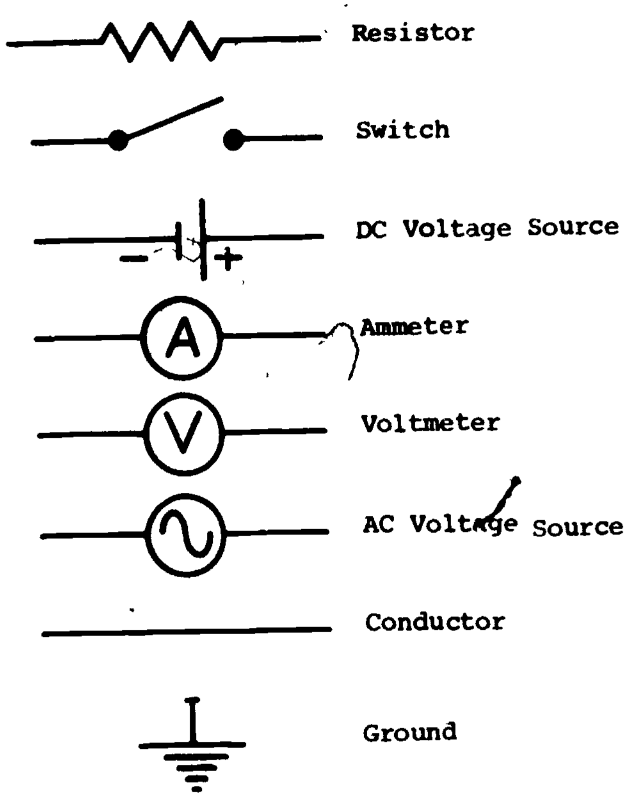
A Resistor is an electrical component which has a designated amount of resistance.

A Voltmeter is an instrument for measuring potential differences.

A circuit diagram, or schematic diagram, is a way of representing an electrical circuit, using standard symbols such as those in Table 1, to represent circuit components. Other symbols will be added as new components are encountered. Figure 1 is an example of a circuit diagram.

Table 1.

Schematic Symbols



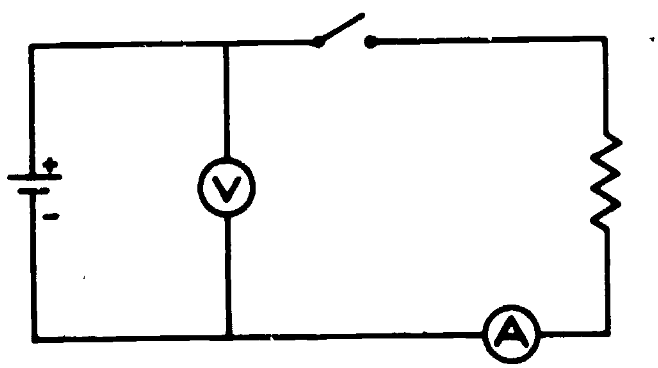


Figure 1.
Schematic Diagram

CHAPTER I

BASIC ELECTRICAL QUANTITIES

Electric Charge is a property of matter which causes objects possessing this characteristic to react with each other in certain ways. In particular, there are two types of electric charge - positive and negative. Objects having charges of the same type repel each other and objects having charges of different types attract each other.

The unit of electrical charge is the coulomb (C). The symbol, Q, is used to represent electrical charges.

Current refers to a flow of electrically charged particles. The symbol, I, is used to represent current.

Current is measured in amperes (A). If a coulomb of electric charge passes a point in 1 second, we say that the current is 1 ampere - i.e., $1\ A \doteq 1\ C/s$.

The electron has a charge of 1.60×10^{-19} C. Hence, 6.25×10^{18} electrons flow past a point each second when the current is 1 ampere.

$$I = \frac{Q}{t}$$

If this flow of electric charges is always in one direction, we speak of Direct Current (DC). If the flow periodically reverses itself, first flowing one way and then the other way, we speak of an Alternating Current (AC).

AC currents are usually sinusoidal functions of time as shown in Figure 2. The instantaneous value of current at time, t, is given by

$$I = I_o \sin(2\pi ft)$$

where I_o is the amplitude as indicated in Figure 2, and f is the frequency.

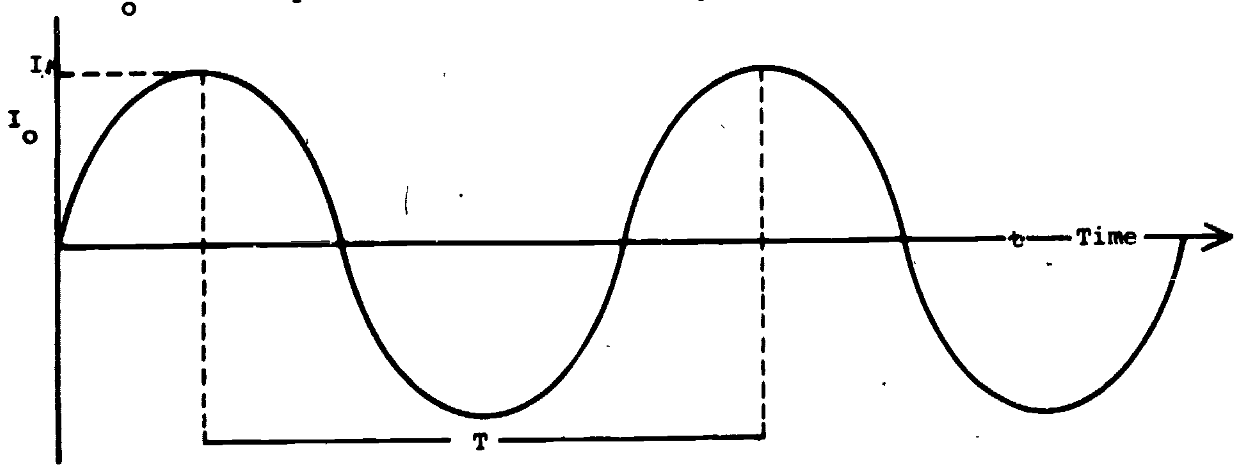


Figure 2
Sinusoidal Alternating Current

The period (T) of the oscillation is given by

$$T = \frac{1}{f}$$

The Potential Difference (Voltage) between 2 points in a circuit is measured by the work W required to move a unit positive charge from one point to the other.

Voltage is measured in volts (V). If one joule of work is needed to move 1 coulomb of charge between two points in a circuit, we say that the potential difference between these two points is 1 volt. That is, 1 V = 1 J/C

If a charge Q moves between 2 points in a circuit that differ in potential by V volts, then the work W done by the charge Q in moving from the higher to the lower potential point is W = QV.

If the polarity (+ - orientation) of a voltage remains the same, we speak of a DC voltage. If the polarity periodically reverses itself, we speak of an AC voltage.

AC voltages, like alternating currents, are usually sinusodial functions of time. The instantaneous voltage at time, t, is

$$V = V_o \sin (2\pi ft)$$

where V_o is the voltage amplitude as shown in Figure 3.

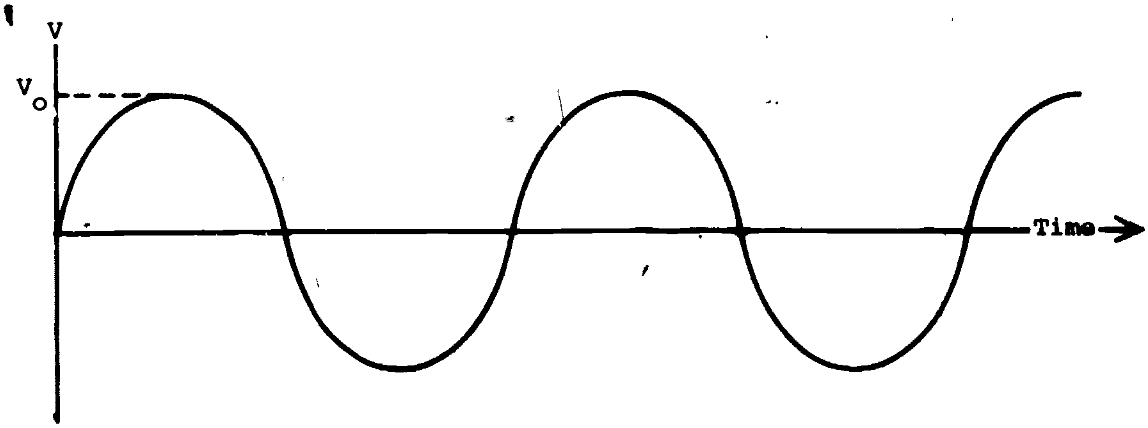


Figure 3
AC Voltage

Electrical Power P is the electrical energy per unit time and is measured in watts (W) or kilowatts (kW). In a DC circuit

$$P = IV$$

For example if a current of 100 mA moves through a potential of 12V the electrical power developed is P = IV = (0.1 A)(12 V) = 1.2 W.

In dealing with AC currents and potentials, it is often more meaningful to use the effective or root mean square (rms) currents and potentials. The rms current is the value of DC current which would produce the same heating effects in a resistor.

rms current is related to current amplitude by

$$I_{rms} = 0.707\ I_o$$

For example an AC current of amplitude 25 mA has an rms current of $I_{rms} = (0.707)(0.025\text{ A}) = 0.0177\text{ A}$.

Similarly rms potential is related to potential amplitude by

$$V_{rms} = 0.707\ V_o$$

For example an AC potential of 155.6 V in amplitude has an rms potential of $V_{rms} = (0.707)(155.6\text{ V}) = 110\text{ V}$.

In AC circuits containing only resistance, the electical power produced is given by

$$P = I_{rms} \cdot V_{rms}$$

For example an AC potential of 24 V rms produces a current through a resistor of 0.5 A rms. The electrical power developed is $P = I_{rms} V_{rms} = (24\text{ V})(0.5\text{ A}) = 12\text{ W}$.

Examples

1. What is the current if 75 μC of charge moves through a circuit in 5 ms?

$$I = \frac{Q}{t} = \frac{75\ \mu C}{5\text{ ms}} = \frac{7.5 \times 10^{-5} C}{5 \times 10^{-3} s} = 1.5 \times 10^{-2}\text{ A} = 15\text{ mA}$$

2. How much electrical charge flows through a circuit when a current of 1 A flows for 50 minutes:

$$I = \frac{Q}{t}$$

$$Q = It = (1\text{ A})(50\text{ min}) = (1\text{ A})(3000\text{ s}) = 3000\text{ C}$$

3. What electrical power is developed when a potential of 10 V produces a current of 150 mA?

$$P = IV = (150\text{ mA})(10\text{ V}) = (0.15\text{ A})(10\text{ V}) = 1.5\text{ W}$$

4. What AC voltage amplitude is necessary to produce an rms potential of 5 V?

$$V_{rms} = 0.707\ V_o.$$

$$V_o = \frac{V_{rms}}{0.707} = \frac{5\ V}{0.707} = 7.1\ V$$

5. What electrical power is developed in a resistor if an AC potential of 15 V rms produces an AC current of 25 mA rms?

$$P = I_{rms} V_{rms} = (25\ mA)(15\ V) = 375\ mW$$

6. What is the period of an AC current of frequency 60 Hz?

$$T = \frac{1}{f} = \frac{1}{60Hz} = 1.67 \times 10^{-2} s$$

Problems

1. A current of 45 mA flows for 2.5 s. How much electrical charge moves through the circuit?

(112.5 mC)

2. What is the current if an electrical charge of 3×10^4 C flows through a circuit in 1 hour?

(8.3 A)

3. What is the electrical power developed when a potential of 10 V DC produces a current of 25 mA?

(250 mW)

4. What is the rms current for an AC current of amplitude 50 mA?

(35.4 W)

5. What is the frequency of an AC potential of 2.5 ms period?

(400 Hz)

6. What is the electrical power developed in a resistor if an AC potential of 50 V amplitude produces an AC current of 0.10 A amplitude?

(2.5 W)

CHAPTER II

TEST INSTRUMENTS

A voltmeter is used to measure electric voltages. Some voltmeters are designed to measure DC voltages while some are designed to measure AC voltages, and others are designed to measure both DC and AC voltages. In any case, voltmeters are connected in parallel with (across) the desired voltage as shown in Figure 4.

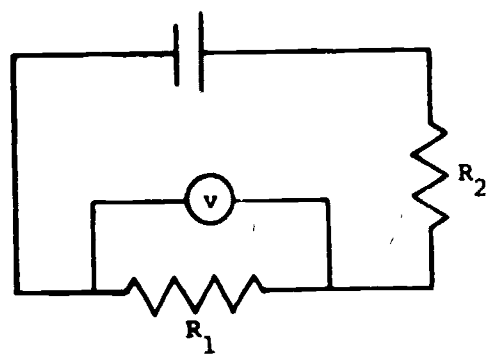


Figure 4
A voltmeter connected to measure the voltage across R_1

In order that the voltmeter not change the characteristics of the circuit, it is necessary that the voltmeter have a high resistance. The resistance of a voltmeter is usually given in terms of the sensitivity, S, such as 1000 Ω/V. When the sensitivity is multiplied by the full scale reading, V_{max}, of the voltmeter, the resistance of the voltmeter is determined. That is $R = SV_{max}$. For example, when a voltmeter with a sensitivity of 5000 Ω/V is set on the 50 V range, the resistance of the voltmeter is $R = SV_{max} = (5000\ \Omega/V)\ (50\ V) = 250\ k\Omega$.
When using a multirange meter, or any other type of meter, it is desirable to start with the meter on the highest range available, then reduce ranges until an acceptable reading is obtained.

Ammeters are used to measure electrical current. Ammeters are also available as DC, AC or AC/DC meters. As Figure 5 indicates, an ammeter must be placed in a circuit in series with the desired current.

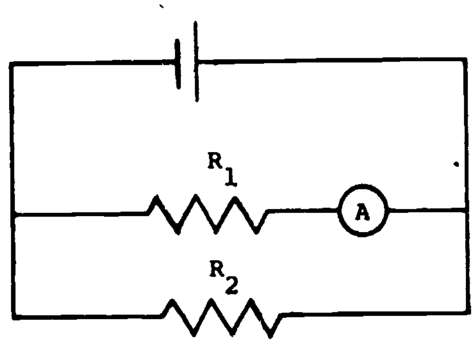


Figure 5
An ammeter connected to measure the current through R_1

Unlike the voltmeters, ammeters must have a low resistance in order not to disturb the circuit being measured. Like voltmeters, multirange ammeters should be used on the highest range first then the range reduced until a reading is obtained. This prevents damage to the meter.

Meters used to measure resistance are called ohmmeters. An ohmmeter must be connected to the device for which the resistance is desired. If that device is a component in a circuit, it must be removed from the circuit in order to insure accurate measurement of its resistance.

Multimeters are a combination voltmeter, ammeter, and ohmmeter contained in one package. Multimeters are usually multirange, combination AC/DC meters and may use either digital or analog readout. Although a multimeter can perform several different functions, it can perform only one at a time.

An oscilloscope is an instrument which displays a graph of an input voltage signal versus time (or another voltage). The oscilloscope is quite valuable in analyzing AC signals for such characteristics as wave shape, peak voltage, and period. Figure 6 illustrates the appearance of an oscilloscope.

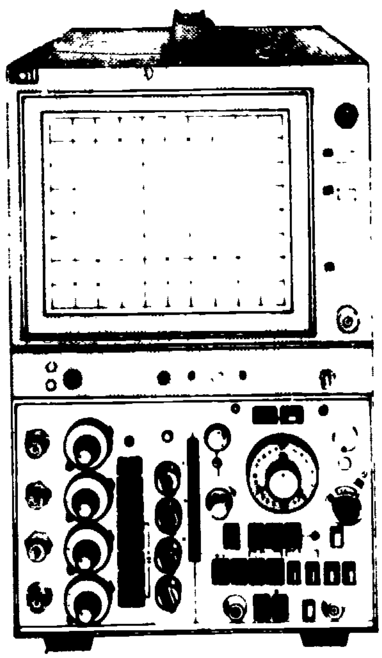


Figure 6
Oscilloscope

An oscilloscope usually has two primary sets of controls: one for vertical sweep; one for horizontal sweep. The vertical controls usually consist of gain controls which determine the relationship between the input voltage and the vertical scale of the screen (expressed in V/cm or V/div) and position controls which control the vertical zero position.

The horizontal controls consist of a position control and a time-base control. The time-base control determines the rate at which the beam moves across the screen (expressed in ms/cm or ms/div). There is also a trigger control which selects the source and level of the signal that starts the trace across the oscilloscope.

Another useful instrument that is valuable in testing AC circuits is the function generator. The function generator produces AC voltages of a variety of periodic waveforms, such as sine, triangular, or square waves, over a range of frequencies and amplitudes.

For many circuits it is necessary to provide a source of DC power. This is done utilizing a power supply. Power supplies may be regulated to maintain constant voltage or constant current. In any case, the manufacturer's specifications will state the maximum current, voltage, and power available from the power supply. The specifications should also give the ripple in the signal --that is the ratio of alternating current to direct current in the power supply output.

Laboratory

The student should be able to use a multimeter, oscilloscope, power supply, and function generator to determine DC and AC circuit parameters.

CHAPTER III

Resistors and Resistance Circuits

SECTION 1: DC and AC Characteristics

Values of resistance are measured in ohms (Ω). An ohm is the resistance which will carry 1 ampere of current when the ends of the resistance differ in potential by 1 volt. The values of some resistors are indicated by a color code in which various colors stand for specific numbers as shown in Table 2.

Table 2
Resistor Color Code

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9
Gold	±5%
Silver	±10%

The first two color bands indicate two significant digits. The third band is the multiplier and indicates the power of ten by which the first two digits are multiplied. The color of the fourth band indicates the tolerance of the resistor. If there is no fourth band, the tolerance is 20%. A color coded resistor is shown in Figure 7.

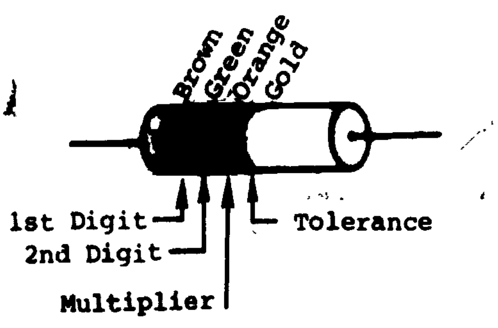


Figure 7.
Color Coded Resistor

(Stated Value: $15 \times 10^3\ \Omega \pm 5\%$)

For example, a resistor with a color code Brown-Green-Orange-Gold would have a value of 15,000 Ω ±5%.

Ohm's Law relates the voltage V across a circuit element which has a resistance R to the current I passing through it, as in Figure 8.

$$V = IR$$

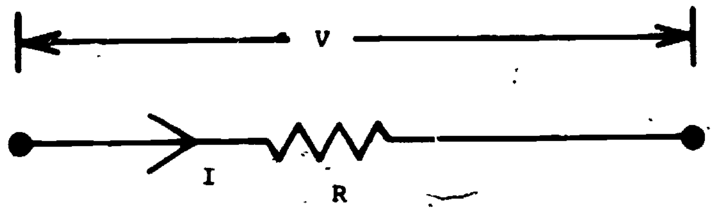


Figure 8.
Voltage and Current for a resistance

This relationship can be applied to most resistance in DC circuits.

Solved Problems

1. A potential difference of 120 V produces a current of 0.1 A through a resistor. What is the value of the resistor?

$$V = IR$$

$$R = \frac{V}{I} = \frac{120\ V}{0.1\ A} = 1200\ \Omega$$

2. A 50 Ω resistor carries a current of 2 amps. What is the potential difference across the resistor?

$$V = IR = (2\ A)(50\ \Omega) = 100\ V$$

Student Problems

1. What potential difference is necessary to produce a current of 0.01 A through a 250 Ω resistor? (2.5V)

2. A potential difference of 220 V is placed across a 1000 Ω resistor. What is the current through the resistor? (0.22 A)

3. A 100 V potential difference causes a 2.5 mA current through a resistor. What is the value of the resistor? (40 kΩ)

AC voltages are usually generated to produce a sine wave pattern. The instantaneous value of the voltage V as a function of time is

$$V = V_o \sin(2\pi ft),$$

where V_o is the amplitude as indicated in Figure 9, f is the frequency, and t is time. The period (T) of the wave (or oscillation) is related to the frequency by

$$T = \frac{1}{f}$$

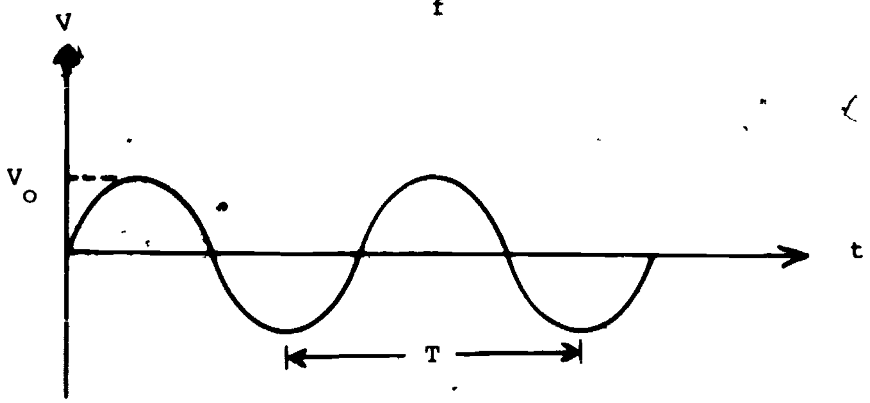


Figure 9.
AC Voltage

Since the current through a resistor is related to the applied voltage by Ohm's Law, the instantaneous current can also be written as a sinusoidal function of time.

$$I = I_o \sin(2\pi ft)$$

where I_o is given by

$$I_o = \frac{V_o}{R}$$

Solved Problem

3. What is the current through a 100 Ω resistor when an AC potential of amplitude 10 V and frequency 60 Hz is applied?

$$I = \frac{V_o}{R} \sin(2\pi ft)$$

$$I = \frac{10\ V}{100\ \Omega} \sin(2\pi \cdot 60\ Hz\ t)$$

$$I = 0.1 \sin(380 \quad \cdot t)\ A \qquad \text{where t is in seconds}$$

Student Problem

4. What is the current through a 250 Ω resistor when an AC potential of amplitude 1000 V and frequency 600 Hz is applied?

(4 sin (3800 t)A)

In dealing with AC currents and potentials it is often more meaningful to use the effective or root mean square (rms) currents and potentials. The rms current equals the value of DC current which would produce the same heating effects in the resistor.

rms current is related to current amplitude by

$$I_{rms} = 0.707\ I_o$$

Similarly rms potential is related to potential amplitude by

$$V_{rms} = 0.707\ V_o$$

Most AC meters read rms values.

The power (in watts) dissipated by a resistor is given by

$$P = IV \quad .$$

When combined with Ohm's Law, the above equation can be written as

$$P = I^2R$$

or

$$P = \frac{V^2}{R}$$

When dealing with AC circuits, the power must be calculated using rms values of current and potential.

Solved Problems

4. What is the power dissipated by a resistance which carries 0.5 A rms current when the applied rms potential is 120 V?

$$P = IV = (0.5\ A)(120\ V) = 60\ W$$

5. What power is dissipated by a 25 Ω resistor when an AC potential of amplitude 200 V is applied?

$$P = \frac{V_{rms}^2}{R} = \frac{(.707\ V_o)^2}{R} = \frac{(.707 \cdot 200\ V)^2}{25\ \Omega}$$

$$= \frac{20,000\ V^2}{25\ \Omega} = 800\ W$$

Student Problems

5. What power is dissipated by a 50 Ω resistor which carries a DC current of 2 A? (200 W)

6. What is the power dissipated by a 10,000 Ω resistor when a DC potential of 1,000 V is applied? (100 W)

7. What is the rms current through a 100 watt light bulb when the rms potential is 110 V? (0.91 A)

8. What power is dissipated by a 15 Ω resistor when an AC current of amplitude 0.05 A is passed through it? (19 mW)

Laboratory

The student should be able to determine the values of resistors using the color code, and/or ohmmeter and properly connect the resistors to an AC or DC voltage source. Using a meter and an oscilloscope, the student should.
be able to measure the current, and voltage in a DC circuit and calculate the power dissipated. In an AC circuit, the student should be able to use a multimeter and an oscilloscope to measure V_{rms}, I_{rms}, V_o, and T. The student should then be able to calculate frequency, f, current amplitude, I_o, and power dissipation.

SECTION 2: Series and Parallel Circuits

When resistors R_1, R_2, R_3... are connected in series as in Figure 10, the resulting resistance R is given by

$$R = R_1 + R_2 + R_3 + \ldots R_N$$

Figure 10.
Resistors in Series

Resistors in series all carry the same current as the equivalent resistance. Resistors in parallel as in Figure 11 have the same effect as a single resistance R given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \frac{1}{R_N}$$

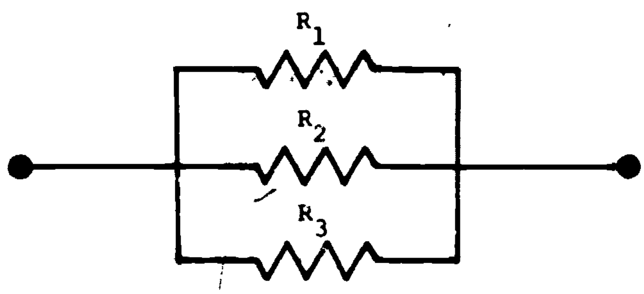


Figure 11.
Resistors in Parallel

Resistors in parallel all have the same potential difference.
Any number of series and parallel resistors can be added by these rules.

Solved Problems

1. Find the equivalent resistance of 50 Ω, 100 Ω, and 250 Ω resistors placed in series.

$$R = R_1 + R_2 + R_3 = 50\ \Omega + 100\ \Omega + 250\ \Omega$$

$$R = 400\ \Omega$$

2. A circuit contains 100 Ω, 200 Ω and 300 Ω resistors in parallel. What is the equivalent resistance?

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

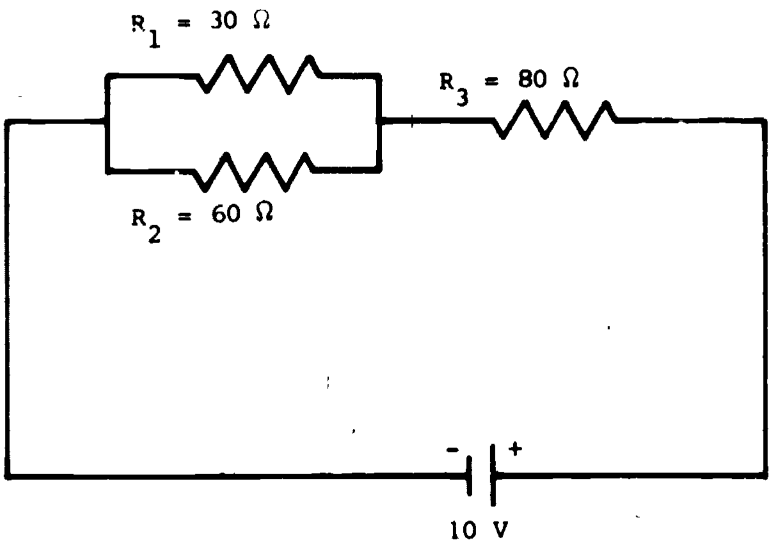
$$\frac{1}{R} = \frac{1}{100\ \Omega} + \frac{1}{200\ \Omega} + \frac{1}{300\ \Omega}$$

$$= \frac{6}{600\ \Omega} + \frac{3}{600\ \Omega} + \frac{2}{600\ \Omega}$$

$$= \frac{11}{600\ \Omega}$$

$$R = \frac{600\ \Omega}{11} = 54.6\ \Omega$$

3. A circuit contains 30 Ω and 60 Ω resistors in parallel. This combination is in series with an 80 Ω resistor. A 10 V D.C. potential is connected as shown. Find the current through each resistor.



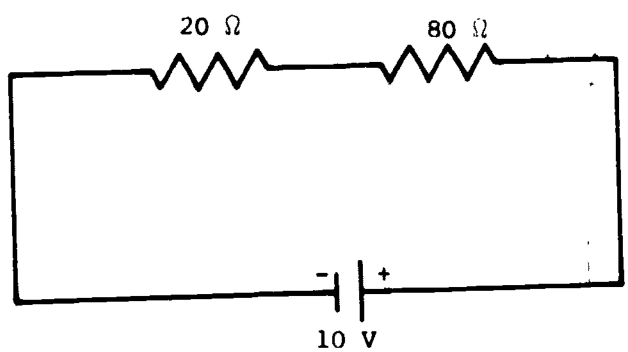
First replace the parallel circuit with its equivalent resistance.

$$\frac{1}{R_\rho} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{30\ \Omega} + \frac{1}{60\ \Omega}$$

$$= \frac{2}{60\ \Omega} + \frac{1}{60\ \Omega} = \frac{3}{60\ \Omega}$$

$$R_\rho = \frac{60\ \Omega}{3} = 20\ \Omega$$



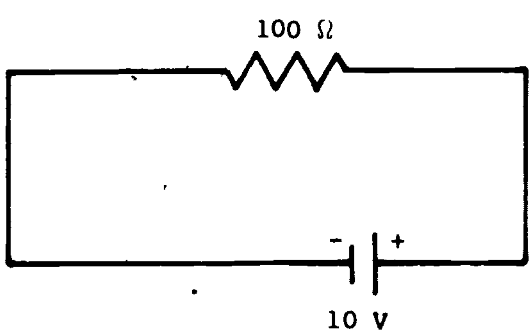
This series combination can be replaced by its equivalent

$$R = R_\rho + R_3$$

$$= 20\ \Omega + 80\ \Omega$$

$$R = 100\ \Omega$$

This equivalent circuit then becomes



By Ohm's Law the current through this circuit is then

$$I = \frac{V}{R} = \frac{10\ V}{100\ \Omega} = 0.10\ A$$

This is also the current through the 80 Ω resistor and the sum of the current through the parallel resistors.

The current through each of the parallel resistors can be found by first using the equivalent resistance of the parallel combination to calculate the voltage drop.

$$V_\rho = IR_\rho$$

$$= (0.10\ A)(20\ \Omega)$$

$$V = 2\ V$$

Now the current through the 60 Ω resistor is given by

$$I_2 = \frac{V_\rho}{R_2}$$

$$= \frac{2\ V}{60\ \Omega}$$

$$= 0.033\ A$$

Similarly the current through the 30 Ω resistor is given by

$$I_1 = \frac{V_\rho}{R_1}$$

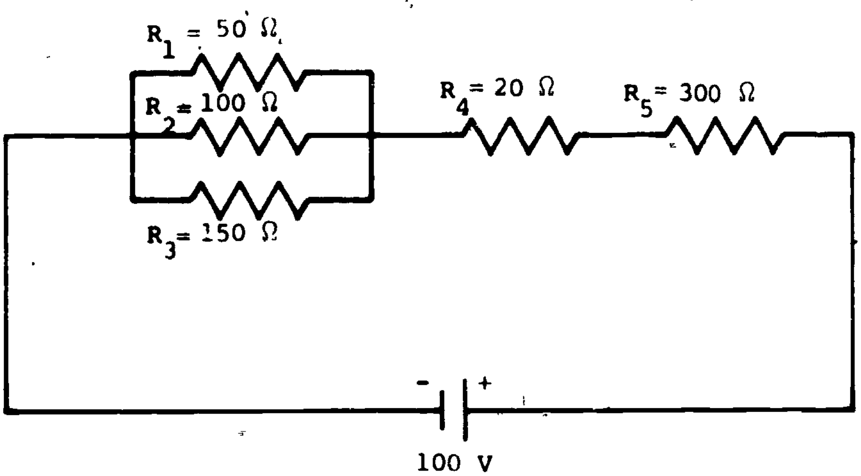
$$= \frac{2\ V}{30\ \Omega}$$

$$= 0.067\ A$$

Note that the sum of the currents through the parallel network equals the current through the circuit.

Student Problems

1. What is the equivalent of 30, 60, and 90 Ω resistors in series? (180 Ω)
2. What is the equivalent of 30, 60, and 90 Ω resistors in parallel? (16.4 Ω)
3. Three resistors of 50, 100, and 150 Ω are in parallel. This parallel combination is in series with resistors of 20 and 300 Ω. A 100 V D.C. source is connected as shown. Find the current through each resistor.



(I_1 = 157 mA, I_2 = 79 mA, I_3 = 52 mA, I_4 = I_5 = 288 mA)

SECTION 3: Voltage Dividers

One consequence of Ohm's Law is that when resistors are connected in series, as in Figure 12, the ratio of the voltage across a single component to the applied voltage is equal to the ratio of the resistance of the component to the total resistance.

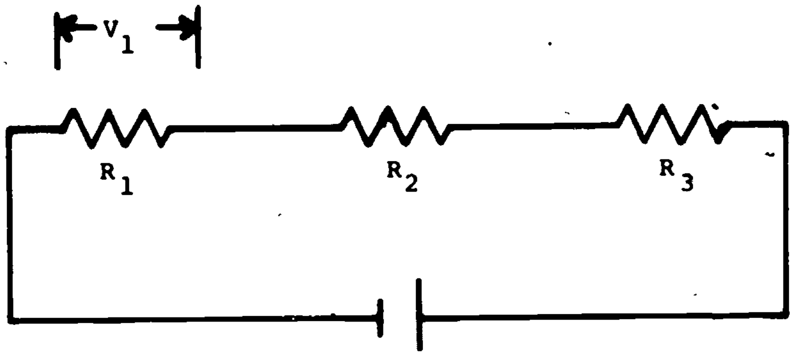


Figure 12.
Voltage Divider

$$\frac{V_1}{V} = \frac{R_1}{R_{total}} = \frac{R_1}{R_1 + R_2 + R_3}$$

A device or circuit which utilizes this concept to produce a voltage smaller than the applied voltage is known as a voltage divider circuit.

A special type of voltage divider is called a potentiometer. It uses a resistive element and a sliding contact to produce a continuously variable voltage divider. The schematics for two types (circular and linear) of potentiometers are shown in Figure 13.

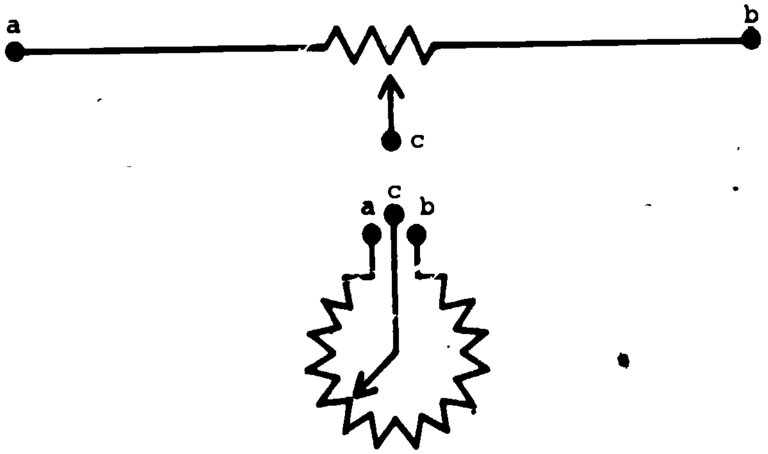


Figure 13.
Linear and circular potentiometer schematic symbols

Solved Problems

1. If a 100 V potential is applied to 200 Ω and 300 Ω resistors in series, what will be the potential across each resistor?

For the 200 Ω resistor

$$\frac{V_{200}}{V} = \frac{R_{200}}{R_{total}}$$

$$\frac{V_{200}}{100\ V} = \frac{200\ \Omega}{500\ \Omega}$$

$$V_{200} = \frac{200\ \Omega}{500\ \Omega}\ 100\ V = 40\ V$$

For the 300 Ω resistor

$$\frac{V_{300}}{V} = \frac{R_{300}}{R_{total}}$$

$$\frac{V_{300}}{100\ V} = \frac{300\ \Omega}{500\ \Omega}$$

$$V_{300} = \frac{300\ \Omega}{500\ \Omega}\ 100\ V = 60\ V$$

2. What resistor could be used in series with a 10,000 Ω resistor to produce a potential of 1 V when the applied potential is 12 V?

$$\frac{R_1}{R} = \frac{V_1}{V}$$

$$\frac{R_1}{R_1 + 10,000} = \frac{1\ V}{12\ V}$$

$$R_1 = 0.0830\ (R_1 + 10,000)$$

$$R_1 - 0.0830\ R_1 = 830$$

$$0.92\ R_1 = 830$$

$$R_1 = \frac{830}{0.92}$$

$$= 900\ \Omega$$

Student Problems

1. What potential would be produced across a 250 Ω resistor in series with a 500 Ω resistor when the applied potential is 6 V? (2 V)

2. What resistor in series with 25,000 Ω will produce a potential of 0.5 V when the applied potential is 10 V? (1320 Ω)

SECTION 4: Kirchoff's Laws

Circuits containing more than one voltage source may be resolved using Kirchoff's Laws:

Kirchoff's Current Law:

The algebraic sum of currents flowing into a junction is equal to the algebraic sum of currents flowing away from the junction.

Kirchoff's Voltage Law:

In any circuit loop, the algebraic sum of the voltage sources is equal to the algebraic sum of the IR voltage drops.

Suggestions for applying Kirchoff's Laws:

1. Assume an arbitrary direction for the current through each branch in the circuit and indicate these on the schematic diagram. (The selection of direction is not critical since negative values in the solution will indicate currents opposite the assumed direction.)

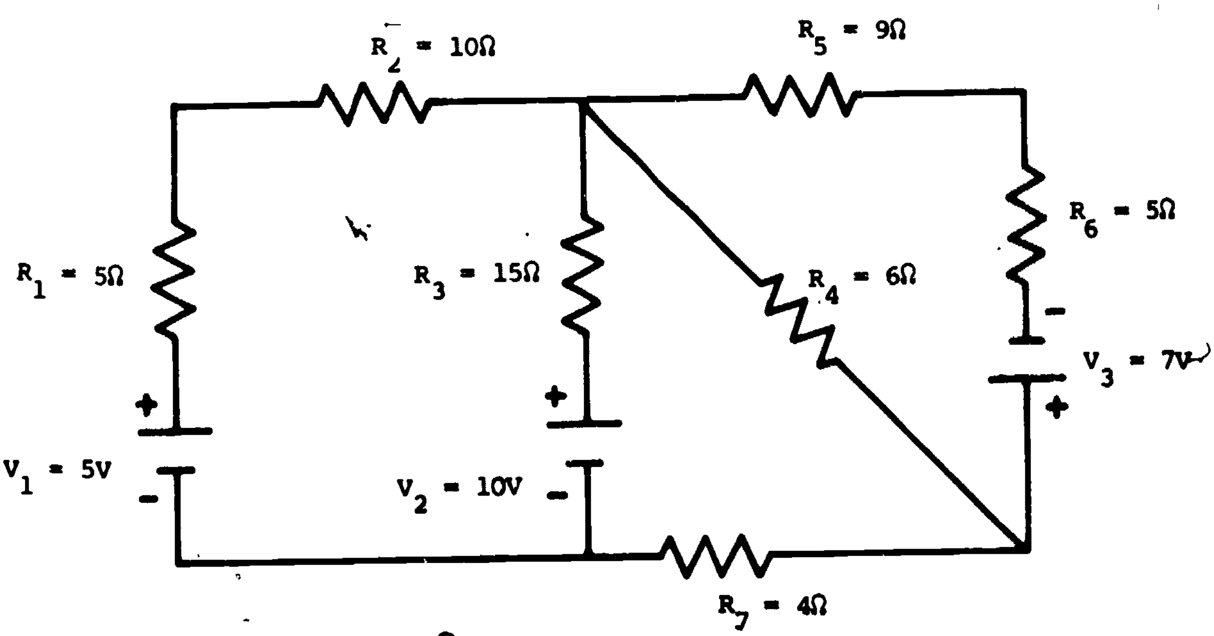
2. Apply Kirchoff's Current Law to each junction in the circuit.

3. Arbitrarily select a direction for the loops and apply Kirchoff's Voltage Law.

4. Simultaneously, solve the equations resulting from Steps 3 and 4.

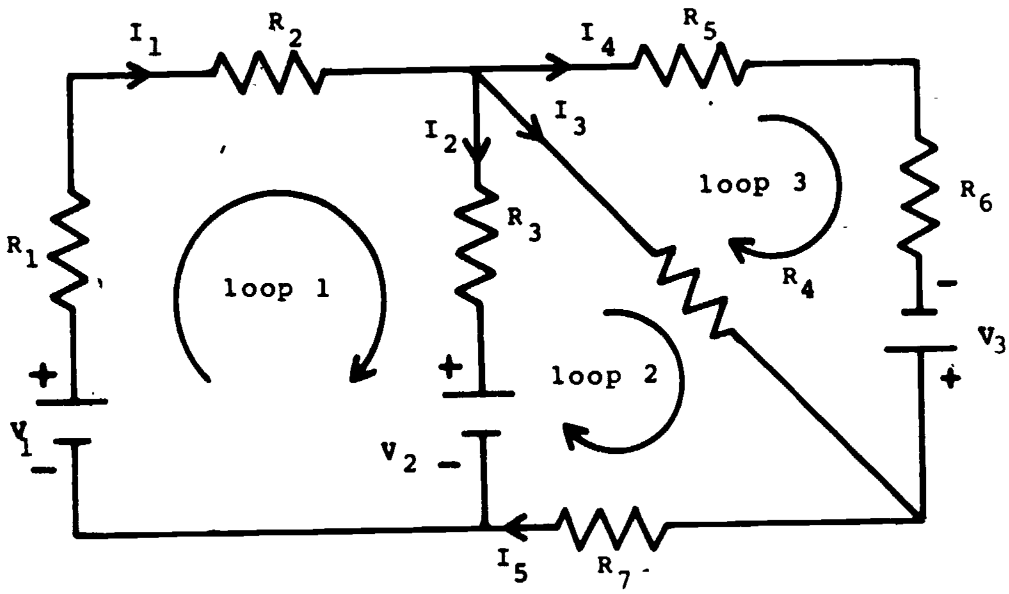
Solved Problem

Find the currents in the following circuit.



Solution:

1. Assume branch currents I as shown.



2. Apply Kirchoff's Current Law:

(1) $I_1 = I_2 + I_3 + I_4$

(2) $I_3 + I_4 = I_5$

(3) $I_2 + I_5 = I_1$

3. Apply Kirchoff's Voltage Law to the loops indicated.

loop 1

(4) $V_1 - V_2 = R_1I_1 + R_2I_1 + R_3I_2$
(V_2 is negative due to + to - polarity)

loop 2

(5) $V_2 = -R_3I_2 + R_4I_3 + R_7I_5$
(R_3I_2 is negative due to the direction of I_2 relative to loop 2)

loop 3

(6) $V_3 = -R_4I_3 + R_5I_4 + R_6I_4$

Reordering and combining terms in the above equations yields

(1) $I_1 - I_2 - I_3 - I_4 = 0$

(2) $I_3 + I_4 - I_5 = 0$

(3) $I_2 + I_5 - I_1 = 0$

(4) $(R_1 + R_2)I_1 + R_3I_2 = V_1 - V_2$

(5) $- R_3I_2 + R_4I_3 + R_7I_5 = V_2$

(6) $-R_4I_3 + (R_5 + R_6)I_4 = V_3$

Substituting the values and rewriting so that Cramer's Rule* may be applied.

(1) $(1)I_1 + (-1)I_2 + (-1)I_3 + (-1)I_4 + (0)I_5 = 0$

(2) $(0)I_1 + (0)I_2 + (1)I_3 + (1)I_4 + (-1)I_5 = 0$

(3) $(-1)I_1 + (1)I_2 + (0)I_3 + (0)I_4 + (1)I_5 = 0$

(4) $(15)I_1 + (15)I_2 + (0)I_3 + (0)I_4 + (0)I_5 = -5$

(5) $(0)I_1 + (-15)I_2 + (6)I_3 + (0)I_4 + (4)I_5 = 10$

(6) $(0)I_1 + (0)I_2 + (-6)I_3 + (14)I_4 + (0)I_5 = 7$

*See study guide "Algebraic & Trigonometric Equations with Applications."

This system of equations may be solved by applying Cramer's rule or one of the many computer or calculator programs available to any five of the above equations.

This yields the following values for the branch currents.

$I_1 = 0.139$ A

$I_2 = -0.472$ A (in opposite direction as indicated)

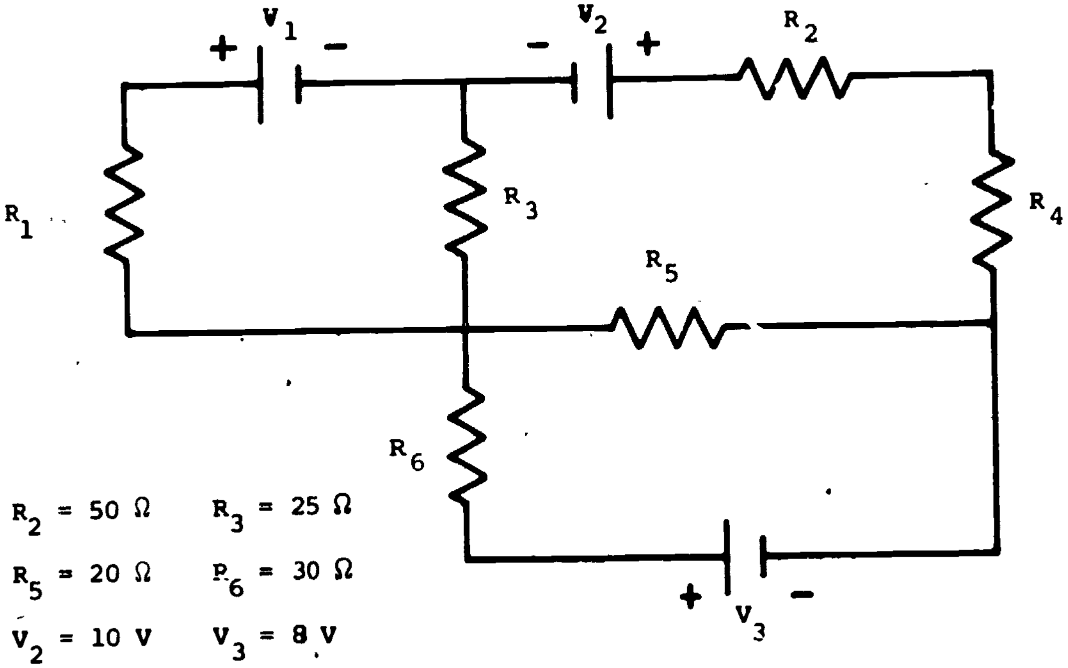
$I_3 = 0.078$ A

$I_4 = 0.533$ A

$I_5 = 0.611$ A

Student Problem:

Find the currents in the circuit below.



$R_1 = 100\ \Omega$ $R_2 = 50\ \Omega$ $R_3 = 25\ \Omega$

$R_4 = 75\ \Omega$ $R_5 = 20\ \Omega$ $R_6 = 30\ \Omega$

$V_1 = 12$ V $V_2 = 10$ V $V_3 = 8$ V

($I_{R_1} = 82$ mA $I_{R_2} = 69$ mA, $I_{R_3} = 151$ mA, $I_{R_4} = 69$ mA, $I_{R_5} = 119$ mA, $I_{R_6} = 188$ mA)

Laboratory

In the laboratory the student should be able to connect a multiloop circuit and measure the currents through each branch in order to verify Kirchoff's Laws.

CHAPTER IV

Operational Amplifier

SECTION 1: The Op-Amp

The operational amplifier or op-amp is a direct-coupled, high voltage gain (10^3 - 10^9) amplifier characterized by high input resistance and low output resistance. These are available as integrated circuits. The symbol for the op-amp is a triangle pointing in the direction of signal flow as shown in Figure 14. It has two input terminals called the inverting (-) and non-inverting (+) inputs.

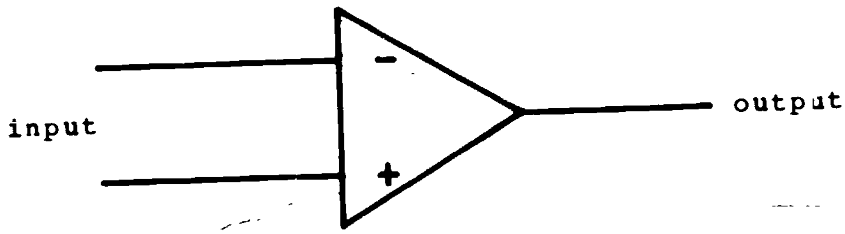


Figure 14.
Op-Amp Symbol

Power for the op-amp is supplied by a DC power supply connected as shown in Figure 15.

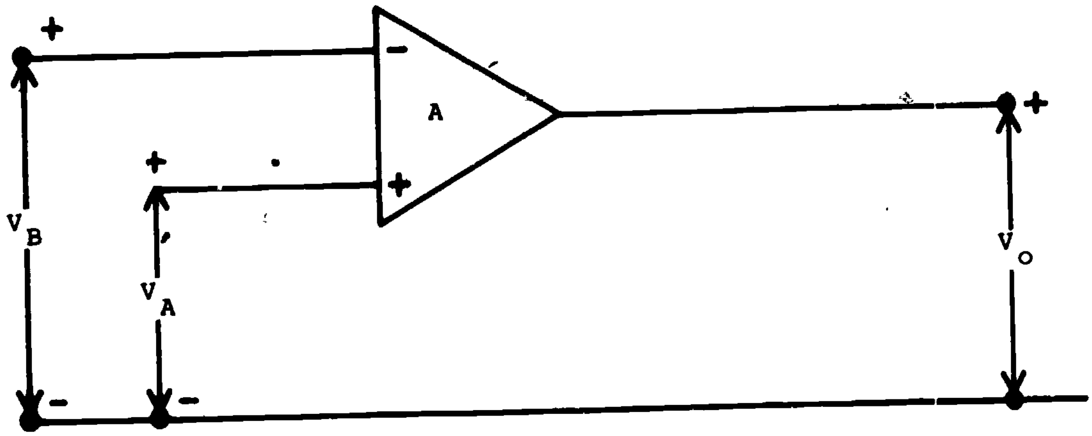


Figure 15.
Basic Op-Amp Circuit

The amplifier amplifies the voltage difference between the inverting and non-inverting inputs by a large constant factor A. For this reason the op-amp is also called a differential amplifier. This relation between the output voltage V_o and the input voltage (V_A and V_B) is

$$V_o = A(V_A - V_B)$$

where A is the open loop gain which can vary from 10^3 to 10^9 depending on the device.

The range of possible output voltages is determined by the power supply voltages so that

$$- V < V_o < + V$$

where -V and +V are the power supply voltages.

Power supply voltages are typically ±9 to ±15 volts. Thus the voltage difference (V_A - V_B) can only be fractions of a millivolt without exceeding the maximum allowable output voltage.

SECTION 2: Inverting Amplifier

Most commonly, op-amps are used with feedback circuits - a portion of the circuit which connects or feeds the output back to the input. The result is called a closed-loop op-amp circuit. In this connection the gain is essentially independent of the open loop gain of the op-amp. The simplest of these circuits is the inverting amplifier shown in Figure 16. In this circuit the feedback resistor, R_f, provides a current loop connecting the output back to the inverting input.

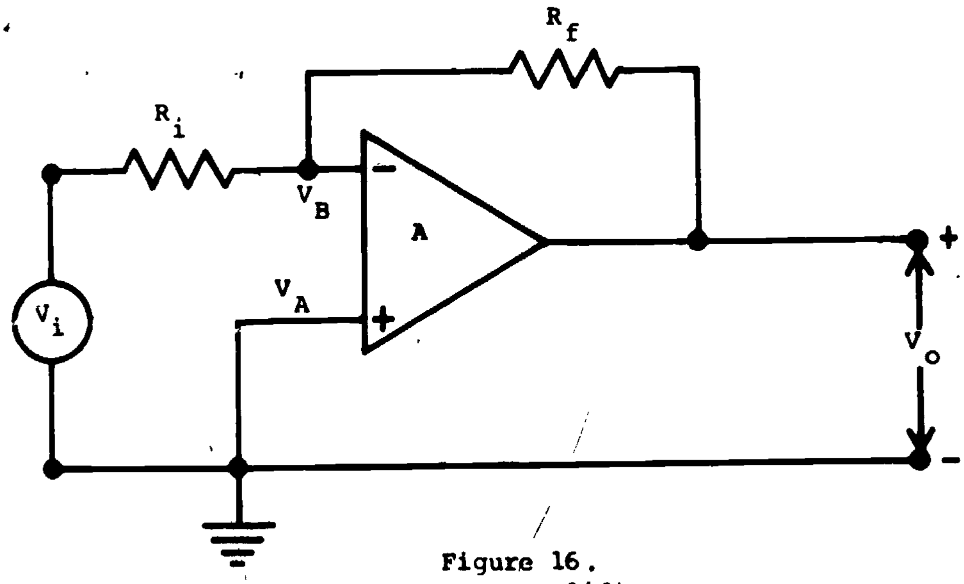


Figure 16.
Inverting Amplifier

The closed-loop gain (G) of the inverting amplifier is determined by the fraction of the output voltage that appears at the inverting input. In the circuit of Figure 16, this is determined by the values of the voltage divider, resistors R_f and R_i.

$$G = \frac{V_o}{V_i} = -\frac{R_f}{R_i}$$

The negative voltage gain is the result of a polarity inversion between the input and the output.

The input resistance (the resistance between the input connections) of the inverting amplifier is determined by the value of R_i.

$$R_{in} = R_i$$

Solved Problems

1. What is the input resistance and closed-loop gain of an inverting amplifier with $R_i = 10{,}000\ \Omega$ and $R_f = 50{,}000\ \Omega$?

$$R_{in} = R_i = 10{,}000\ \Omega$$

$$G = -\frac{R_f}{R_i} = -\frac{50{,}000\ \Omega}{10{,}000\ \Omega} = -5$$

2. What values of R_i and R_f will produce an inverting amplifier with an input resistance of 250 Ω and a closed-loop gain of -1000?

$$R_i = R_{in} = 250\ \Omega$$

$$G = \frac{-R_f}{R_i}$$

$$R_f = -G\ R_i$$

$$= -(-1000)(250)$$

$$R_f = 2.50 \times 10^5\ \Omega = 250\ k\Omega$$

Student Problems

1. What are the input resistance and closed loop gain of an inverting amplifier with R_i = 1,000 Ω and R_f = 250,000 Ω? (1 kΩ, -250)

2. What values of R_i and R_f will produce an inverting amplifier with an input resistance of 10,000 Ω and a gain of -100? (10 kΩ, 1 MΩ)

SECTION 3: Non-Inverting Amplifier

An op-amp can be used to produce an amplifier which does not cause a polarity inversion. This circuit, called a non-inverting amplifier, is shown in Figure 17.

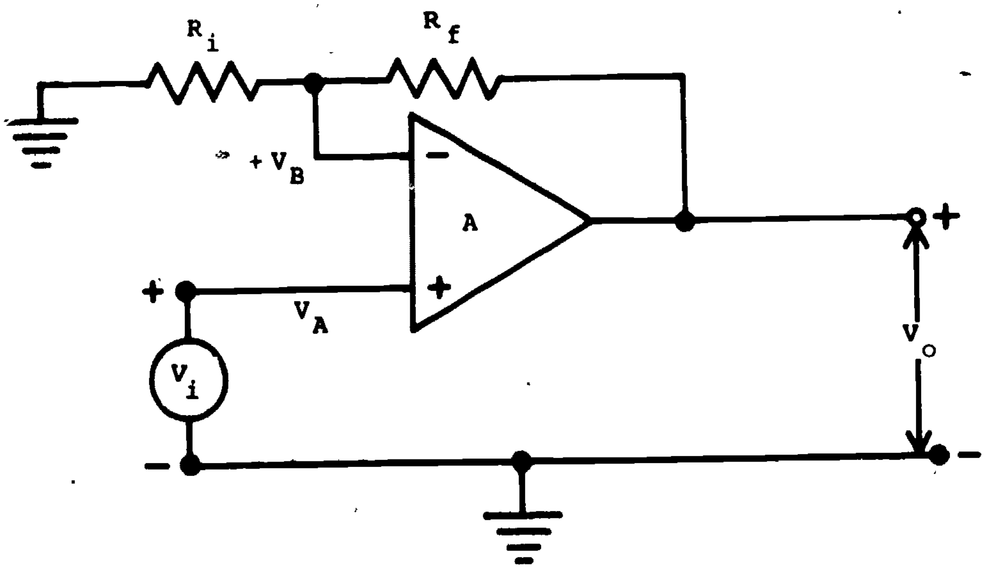


Figure 17.
Non-Inverting Amplifier

The closed-loop gain for this amplifier is given by

$$G = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_i}$$

For most circuits R_f/R_i is large and the gain is approximately $G \simeq \frac{R_f}{R_i}$.

The input resistance is the resistance between the + and - inputs of the op-amp, and is generally quite large, several megohms.

Solved Problems

1. What is the gain of a non-inverting amplifier with $R_i = 1.5\ k\Omega$ and $R_f = 250\ k\Omega$?

$$G = 1 + \frac{R_f}{R_i}$$

$$= 1 + \frac{2.5 \times 10^5\ \Omega}{1.5 \times 10^3\ \Omega}$$

$$G \simeq 170$$

2. What must be the value of R_f to produce a non-inverting amplifier with a gain of 1000 when $R_i = 50\ \Omega$

$$G = 1 + \frac{R_f}{R_i}$$

$$G - 1 = \frac{R_f}{R_i}$$

$$R_f = R_i(G - 1)$$

$$= 50\ \Omega(1000 - 1)$$

$$\simeq 5.0 \times 10^4\ \Omega = 50\ k\Omega$$

Student Problems

1. What is the gain of a non-inverting amplifier with $R_i = 7.5\ k\Omega$ and $R_f = 150\ k\Omega$? (20)

2. What value of R_i is necessary to produce a non-inverting amplifier with a gain of 200 when $R_f = 100\ k\Omega$? (500 Ω)

A special case of the non-inverting amplifier is the voltage follower in which the output of the amplifier is connected directly to the inverting input with no feedback resistors as shown in Figure 18. This amplifier connection has a gain of one and is often used as a buffer stage when a high input resistance circuit is required.

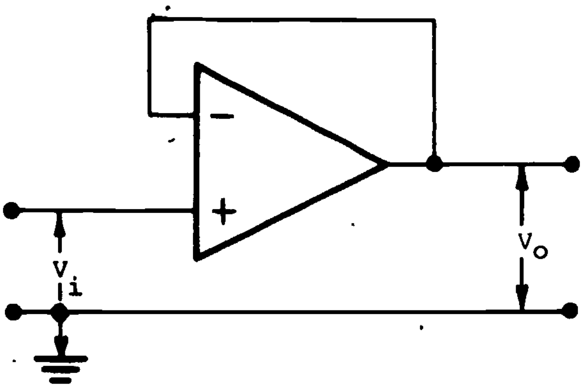


Figure 18.
Voltage Follower

SECTION 4: AC Characteristics

The op-amp can operate over a wide range of frequencies from zero to fairly high AC frequencies. The response of the amplifier is designated by the half-power point (or corner frequency) and the roll off. The corner frequency is the frequency for which the gain has dropped to 0.707 of the DC gain. The roll off describes the decrease in gain as frequency increases and is usually stated in dB/octave. The dB in this case is defined by

$$dB = 20 \log (G/G_{DC})$$

where G is the gain at a given frequency and G_{DC} is the DC gain. Most linear op-amps have a roll off of about 6 dB/octave. When the op-amp is connected to a feedback circuit, the closed-loop gain is considerably smaller than the open-loop gain; the corner frequency is, however, increased considerably.

Laboratory

In the laboratory the student should be able to connect an op-amp into circuits to produce an inverting and non-inverting amplifier. The characteristics of the amplifiers, such as closed-loop gain, input impedance, and AC response, should then be determined.

CHAPTER V

Bridge Circuits

SECTION 1: DC Bridge

The Wheatstone bridge is a circuit for measuring resistance. The circuit can be operated in two modes. The balanced condition results in zero output voltage, and the unbalanced condition uses the output voltage as a measure of the resistance. The basic bridge circuit is shown in Figure 19. It consists of two voltage dividers in parallel having a detector across the center connections.

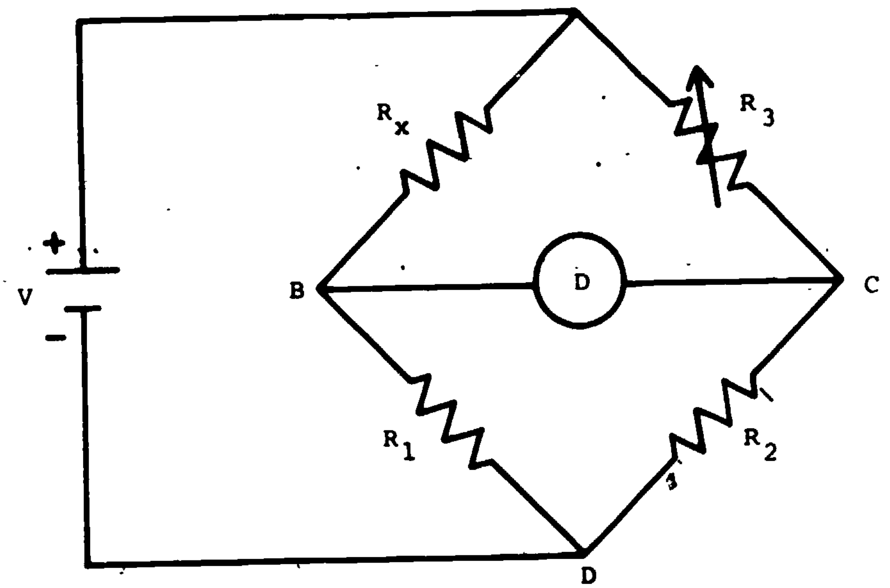


Figure 19.
Wheatstone Bridge

In Figure 18 R_x is the unknown resistance to be measured, R_3 is a variable, known resistance, R_1 and R_2 are fixed resistors.

The condition for bridge balance ($V_{BC} = 0$) is

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

In the balanced condition values of R_x can be determined to high precision (6 significant figures) provided that the values of R_1, R_2 and R_3 are accurately known to the same precision and the bridge detector D is sufficiently sensitive.

The sensitivity of the bridge is the ratio of the output voltage change Δ_{BC} to a small change in R_x, ΔR_x.

$$\text{Sensitivity} = \frac{\Delta V_{BC}}{\Delta R_x}$$

The sensitivity is greatest when $R_x = R_1$ and $R_3 = R_2$, the resulting maximum sensitivity is also dependent on the applied voltage:

$$\text{Sensitivity} = \frac{-V}{4R_1}$$

The sensitivity is given in volts/ohm.

In the unbalanced (off null) bridge the unknown resistance is determined from the output voltage. If R_x equals R_1 at balance, then a small change in R_x results in a voltage given by

$$V_{BC} = -V\,\frac{\Delta R_x}{4R_1}$$

The unbalanced bridge is quite useful when a resistive transducer (such as a thermistor, photoconductor or strain gauge) is used as the unknown resistor since the variation in output voltage is nearly linear with changes in ΔR_x over a small range. If the resistance change is also linear with changes in the physical variable (temperature, light, strain) then the bridge voltage is a direct measure of the change in physical variable.

Solved Problems

1. What is the value of the unknown resistance, R_x, when a bridge is balanced with $R_1 = 400\ \Omega$, $R_2 = 600\ \Omega$ and $R_3 = 1000\ \Omega$?

$$R_x = R_3\,\frac{R_1}{R_2}$$

$$= 1000\ \Omega\left(\frac{400\ \Omega}{600\ \Omega}\right)$$

$$R_x = 667\ \Omega$$

2. What is the maximum sensitivity for a bridge circuit if the applied voltage is 1.5 V and R_1 = 2.0 kΩ?

$$\text{Sensitivity} = \frac{-V}{4R_1}$$

$$= \frac{-1.5\ V}{4(2.0 \times 10^3\ \Omega)}$$

$$= -1.9 \times 10^{-4}\ V/\Omega$$

3. For an unbalanced bridge with an applied voltage of 6 V, what will be the output voltage if R_x changes from 1.5 kΩ at null to 1.6 kΩ?

$$V_{BC} = -V\,\frac{\Delta R_x}{4R_1}$$

$$= -6\ V\,\frac{.1 \times 10^3\ \Omega}{4(1.5 \times 10^3\ \Omega)}$$

$$V_{BC} = .1\ V$$

Student Problems

1. What is the unknown resistance, R_x, if a bridge is balanced when R_1 = 10 kΩ, R_2 = 8.0 kΩ and R_3 = 12 kΩ? (15 kΩ)

2. What is the maximum sensitivity for a bridge if the applied voltage is 1.0 V and R_1 = 10 kΩ? (-2.5×10^{-5} V/Ω)

3. A voltage of 1.5 V is applied to a bridge. The bridge is balanced for R_x = 800 Ω. What is the output voltage when R_x changes to 775 Ω? (12 mV)

SECTION 2: AC Bridge

The bridge circuit can also be used to measure the AC impedance of circuit components. The AC bridge circuit is shown in Figure 20.

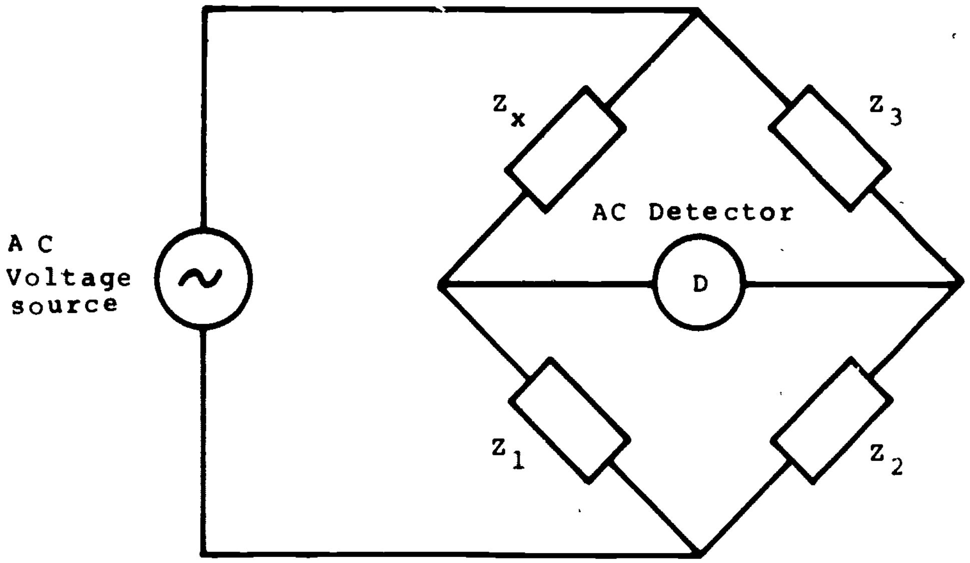


Figure 20.
AC Bridge Circuit

The condition for balance of this circuit is the same as for a DC circuit.

$$Z_x = Z_3 \frac{Z_1}{Z_2}$$

where Z is the AC impedance of the components. Most commonly this type of circuit is used to measure capacitance by inserting a known capacitance for Z_1, a known resistor for Z_2, and a variable resistor for Z_3 as in Figure 21.

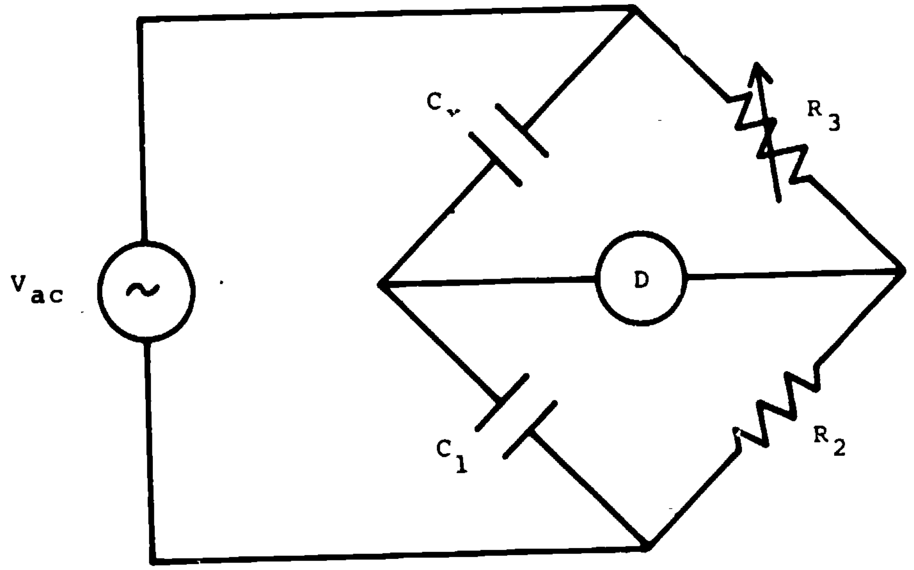


Figure 21.
Capacitance Bridge Circuit

Since the impedance for a capacitor is given by

$$Z = \frac{1}{2\pi fC}$$

where f is the frequency in hertz and C the capacitance in farads.

and the impedance for a resistor is

$$Z = R ,$$

the condition for balance of the capacitor bridge is

$$\frac{1}{2\pi fC_x} = \frac{R_3}{R_2} \frac{1}{2\pi fC_1}$$

or

$$C_x = C_1 \frac{R_2}{R_3}$$

Solved Problem

4. What is the value of the unknown capacitance when a capacitance bridge is balanced with C_1 = 1.0 microfarad, R_2 = 600 Ω and R_3 = 500 Ω?

$$C_x = C_1 \frac{R_2}{R_3}$$

$$= (1.0 \times 10^{-6}\ F) \frac{600\ \Omega}{500\ \Omega}$$

$$= 1.2 \times 10^{-6}\ F$$

Student Problem

4. What is the unknown capacitance when a capacitance bridge is balanced with C_1 = 2.5 nanofarads, R_2 = 1.5 kΩ and R_3 = 2 kΩ? (1.9nF)

CHAPTER VI

Temperature Transducers

SECTION 1: Resistance Thermometer

The resistance thermometer utilizes the fact that resistivity and thus resistance changes with temperature in a known and reproducible manner. The resistance of an element is related to temperature approximately by

$$R = R_o(1 + AT + BT^2)$$

where R_o is the resistance at 0^oC, and A and B are constants characteristic of the material from which the resistor is made. As can be seen from the equation, the resistance of a resistance thermometer increases as the temperature increases and vice-versa. The temperature for various values of R can be found from known values of R_o, A, and B, by solving the above quadratic equation, but are usually found from calibration graphs. The resistance of the resistance thermometer is generally determined by using some type of Wheatstone bridge. Some commonly used materials for resistance thermometers and their range of operation are given in Table 3.

	Temperature Range, C^o	
Material	Lower	Upper
Platinum	-260	650
Copper	-200	150
Nickel	- 70	150

Table 3
Common Resistance Thermometer Materials and Ranges

Solved Problem

1. For platinum $A = 3.96 \times 10^{-3}$ and $B = -5.83 \times 10^{-6}$. If a platinum resistor has a resistance of 130 Ω at 0^o C, for what temperature will the resistance be 180 Ω?

$$R = R_o(1 + AT + BT^2)$$

$$180\ \Omega = 130\ \Omega\left[1 + (3.96 \times 10^{-3})T - (5.83 \times 10^{-6})T^2\right]$$

$$180 = 130 + (5.15 \times 10^{-1})T - (7.58 \times 10^{-4})T^2$$

$$0 = -50 + 5.15 \times 10^{-1}T - 7.58 \times 10^{-4}T^2$$

A quadratic solving program gives 118 and 561 as the solutions for the equation. We select the value nearest 0 as the correct temperature.

Student Problem

1. A platinum thermometer has resistance of 130 Ω at 0° C. For what temperature is the resistance 210 Ω? (240°C)

SECTION 2: Thermistors

Thermistors are a type of resistance thermometer made from a mixture of metallic oxides. These mixtures are called semiconductors because their conductivity is less than that of most metals but greater than that of typical insulators. These semiconductor materials have high negative temperature coefficients of resistance. As a result their resistance decreases as temperature increases according to

$$\log R = 0.434\ \beta\ \frac{1}{T} + b$$

β is a constant characteristic of the semiconductor material of the thermistor and b is a constant characteristic of the particular thermistor at the time the temperature is measured. Although the log of the resistance varies as 1/T, for very small ranges of temperature R changes almost linearly with T.

The resistance of thermistors is best determined by the use of a Wheatstone bridge although an ohmmeter may be used. Once the resistance is measured, the temperature can be determined from a calibration curve or from the manufacturer's data. The range of operation of thermistors is typically from -60 C° to 300 C°.

SECTION 3: Thermocouples

Thermocouples are a pair of junctions of two dissimilar metals. When there is a temperature difference between the two junctions, a voltage is produced. The greater the difference in temperature the greater the voltage produced. In order to measure temperature, one junction is held at a reference temperature such as the ice point or room temperature, and the other junction is placed in contact with the temperature to be determined. Since the resulting voltage is only a few millivolts, it is necessary to measure this with a millivolt meter or a potentiometer. One can also amplify the voltages by a known amount and measure the amplified voltage with a conventional voltmeter. Once the voltage is determined a calibration table such as Table 4 can be used to find the temperature difference of the thermocouple junctions. For example, if copper-constantan thermocouple produces a voltage of 3.087 mV with one junction of 0°C, the other junction is at 74°C. Ranges of operation for some common thermocouples are given in Table 5.

COPPER-CONSTANTAN THERMOCOUPLE

REFERENCE JUNCTION 0°C

°C	0	1	2	3	4	5	6	7	8	9
	millivolts									
(+)0	0.000	0.038	0.077	0.116	0.154	0.193	0.232	0.271	0.311	0.350
10	0.389	0.429	0.468	0.508	0.547	0.587	0.627	0.667	0.707	0.747
20	0.787	0.827	0.868	0.908	0.949	0.990	1.030	1.071	1.112	1.153
30	1.194	1.235	1.277	1.318	1.360	1.401	1.443	1.485	1.526	1.568
40	1.610	1.652	1.694	1.737	1.779	1.821	1.864	1.907	1.949	1.992
50	2.035	2.078	2.121	2.164	2.207	2.250	2.293	2.336	2.380	2.423
60	2.467	2.511	2.555	2.599	2.643	2.687	2.731	2.775	2.820	2.864
70	2.908	2.953	2.997	3.042	3.087	3.132	3.177	3.222	3.267	3.312
80	3.357	3.402	3.448	3.493	3.539	3.584	3.630	3.676	3.722	3.767
90	3.813	3.859	3.906	3.952	3.998	4.044	4.091	4.138	4.184	4.230
100	4.277	4.324	4.371	4.418	4.465	4.512	4.559	4.606	4.654	4.701
110	4.749	4.796	4.843	4.891	4.939	4.987	5.035	5.083	5.131	5.179
120	5.227	5.275	5.323	5.372	5.420	5.469	5.518	5.566	5.615	5.663
130	5.712	5.761	5.810	5.859	5.908	5.957	6.007	6.056	6.105	6.155
140	6.204	6.254	6.303	6.353	6.403	6.453	6.503	6.553	6.603	6.653
150	6.703	6.753	6.803	6.853	6.904	6.954	7.004	7.055	7.106	7.157
160	7.208	7.258	7.309	7.360	7.411	7.462	7.513	7.565	7.616	7.667
170	7.719	7.770	7.822	7.874	7.926	7.978	8.029	8.080	8.132	8.184
180	8.236	8.288	8.340	8.392	8.445	8.497	8.549	8.601	8.654	8.707
190	8.759	8.812	8.864	8.917	8.970	9.023	9.076	9.129	9.182	9.235
200	9.288	9.341	9.394	9.448	9.501	9.555	9.608	9.662	9.715	9.769

Table 4.

Calibration Table for Copper-Constantan

Thermocouple Pair	Temperature Range, C° Lower	Upper
Copper-Constantan	-200	400
Iron-Constantan	- 20	800
Chromel-Alumel	- 20	1300
Platinum/Rhodium Platinum	- 20	1500

Table 5.

Thermocouple materials and ranges

SECTION 4: Applications

In the use of any temperature transducer it is important to keep in mind that the temperature indicated is the temperature of the transducer; not necessarily the temperature desired. Also, a certain amount of time, the response time, is necessary for the transducer to indicate any change in temperature. It is also desirable that the method used for measuring the electrical signal produced not change the temperature of the transducer. This means that care must be taken in using resistance thermometers and thermistors to keep the current through these devices to a minimum as greater currents produce self-heating effects. Another important consideration is to select a transducer appropriate for the range of temperatures to be measured. One of the most important considerations in selecting a temperature transducer is accuracy. Approximate values of accuracy, response time, and range of operation for the various types of temperature transducers are given in Table 6.

Transducer Type	Range, C°	Response Time	Accuracy
Resistance Thermometer	-250 to 800	1 second	±0.2 C°
Thermistor	- 60 to 300	several seconds	depends on temperature
Thermocouple	-260 to 900	2 seconds	±0.2 C°

Table 6.

Temperature Transducer Characteristics

LABORATORY

The student should be able to use any of the above transducers with appropriate devices to determine temperatures. By inserting a thermistor into one arm of a Wheatstone bridge circuit and amplifying the output with a non-inverting amplifier the student should construct and calibrate an electronic thermometer.

CHAPTER VII

Power Amplifier

SECTION 1: Transistor Basics

Transistors are solid state devices made of two types of materials. The "P" type material has an excess of positive charge carriers (holes) and the "N" type material has an excess of negative charge carriers (electrons). These materials are combined as in Figure 21 to produce a PNP transistor.

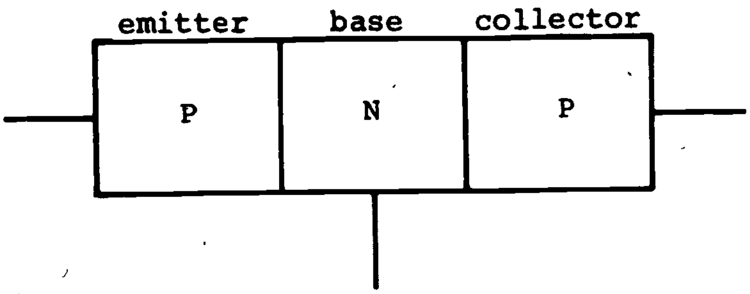


Figure 22.
PNP Transistor

The parts of the transistor are identified as the emitter, base and collector. The schematic symbol for the PNP transistor is shown in Figure 23a.

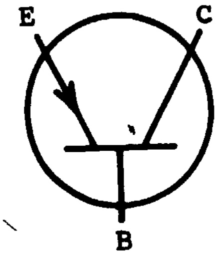


Figure 23a.
Schematic PNP Transistor

A second type of transistor is produced by reversing the types of materials of the emitter, base, and collector. This produces an NPN transistor as shown schematically in Figure 23b.

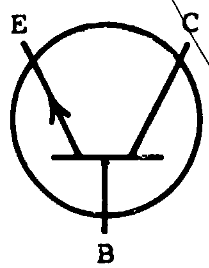


Figure 23b.
Schematic NPN Transistor

Both types of transistors act much like a valve. A small current from the base to emitter (I_B) can control relatively large currents from the collector to the emitter (I_C). This process of current amplification makes the transistor quite useful. The DC current gain (β_F) is given by

$$\beta_F = \frac{I_C}{I_B}$$

The only major difference between PNP and NPN transistors is that voltage supply polarities must be reversed and thus current flow is reversed.

Transistors are usually connected in one of three ways: common base, common collector, or common emitter. The most frequently used method is the common emitter as shown for NPN and PNP transistors in Figure 24.

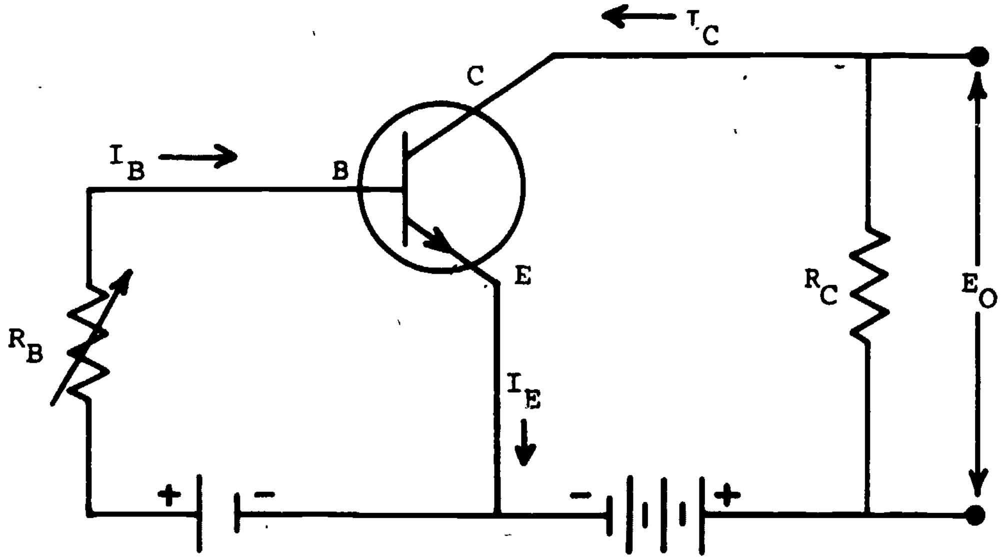


Figure 24a.
NPN Common Emitter

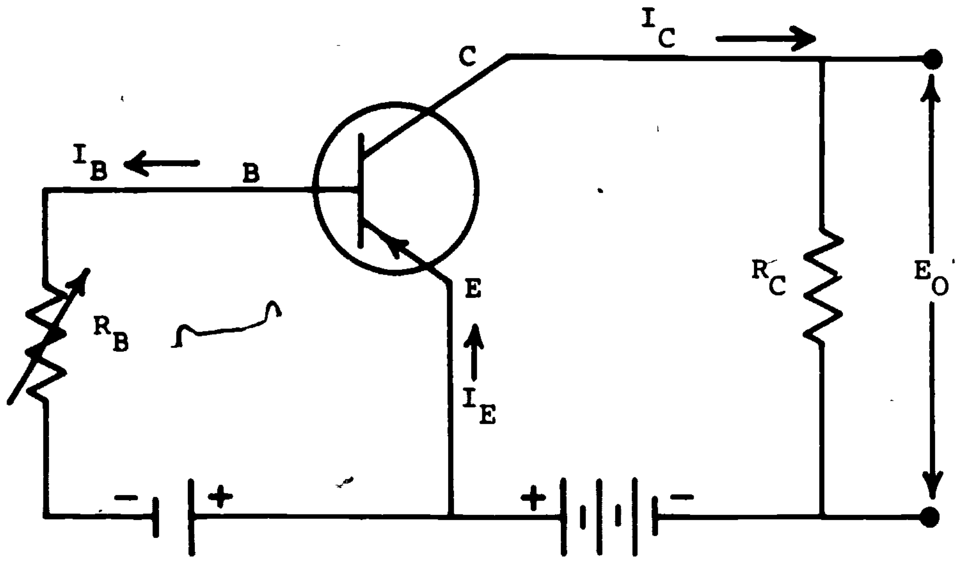


Figure 24b.
PNP Common Emitter

The output characteristics of transistors in common emitter configuration are usually presented graphically by plotting collector current (I_C) against collector-emitter voltage for various base currents (I_B) as in Figure 25.

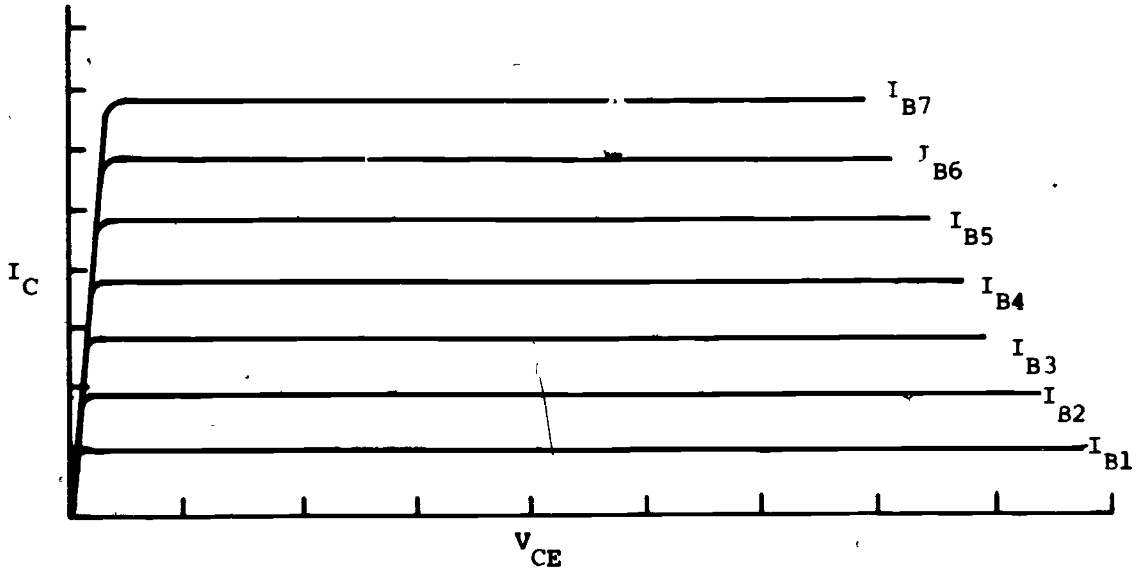


Figure 25.
Common Emitter Characteristic Curves

The specifications of a transistor are usually found on the manufacturers "spec sheet". These include such general specifications as the uses and physical dimensions of the transistor and specific characteristics such as maximum ratings and thermal characteristics. Figure 26 is a spec sheet for an NPN power transistor.

NPN SILICON POWER TRANSISTOR

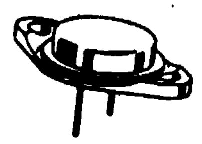
. . . designed for general-purpose, moderate speed, switching and amplifier applications.

- DC Current Gain –
  h_{FE} = 20-70 @ I_C = 4.0 Adc
- Collector-Emitter Saturation Voltage –
  $V_{CE(sat)}$ = 1.0 Vdc (Max) @ I_C = 4.0 Adc
- Excellent Safe Operating Area

15 AMPERE POWER TRANSISTOR

NPN SILICON

60 VOLTS
115 WATTS



*MAXIMUM RATINGS

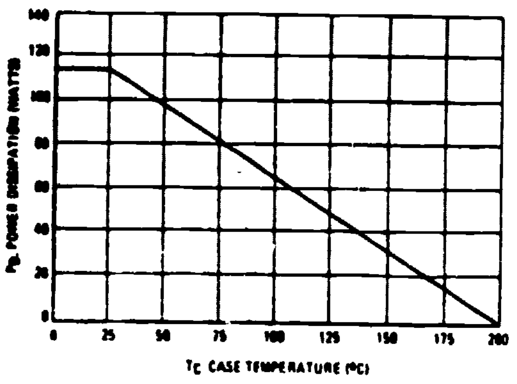
Rating	Symbol	Value	Unit
#Collector-Emitter Voltage	V_{CEO}	60	Vdc
Collector-Emitter Voltage	V_{CER}	70	Vdc
Collector-Base Voltage	V_{CB}	100	Vdc
Emitter-Base Voltage	V_{EB}	7.0	Vdc
Collector Current – Continuous	I_C	15	Adc
Base Current – Continuous	I_B	7.0	Adc
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	115 0.657	Watts W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-65 to +200	°C

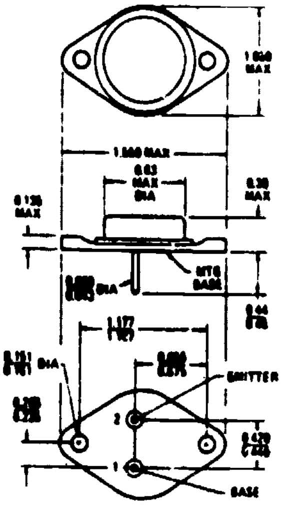
THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	θ_{JC}	1.52	°C/W

*Indicates JEDEC Registered Data.
#Motorola guarantees this value in addition to JEDEC Registered Data.

FIGURE 1 – POWER TEMPERATURE DERATING CURVE





CASE 11
(TO 3)

Collector Connected to Case

Figure 26.
Transistor Spec Sheet

Although the transistor is rapidly being replaced in most applications by integrated circuits (ICs), in cases where large amounts of power must be dissipated, such as the power amplifier, power transistors are used. One problem with transistors in such applications is that as temperature increases, so does the gain of the transistor. This can result in "thermal runaway," a process in which the transistor is quickly damaged. One method of preventing thermal runaway is to insert a resistor (R_E) into the emitter circuit. If the emitter current increases the voltage drop across R_E increases. This causes a decrease in current and thus prevents runaway. Figure 27 shows a typical common emitter amplifier circuit which controls thermal runaway, designed for operation with a single power supply.

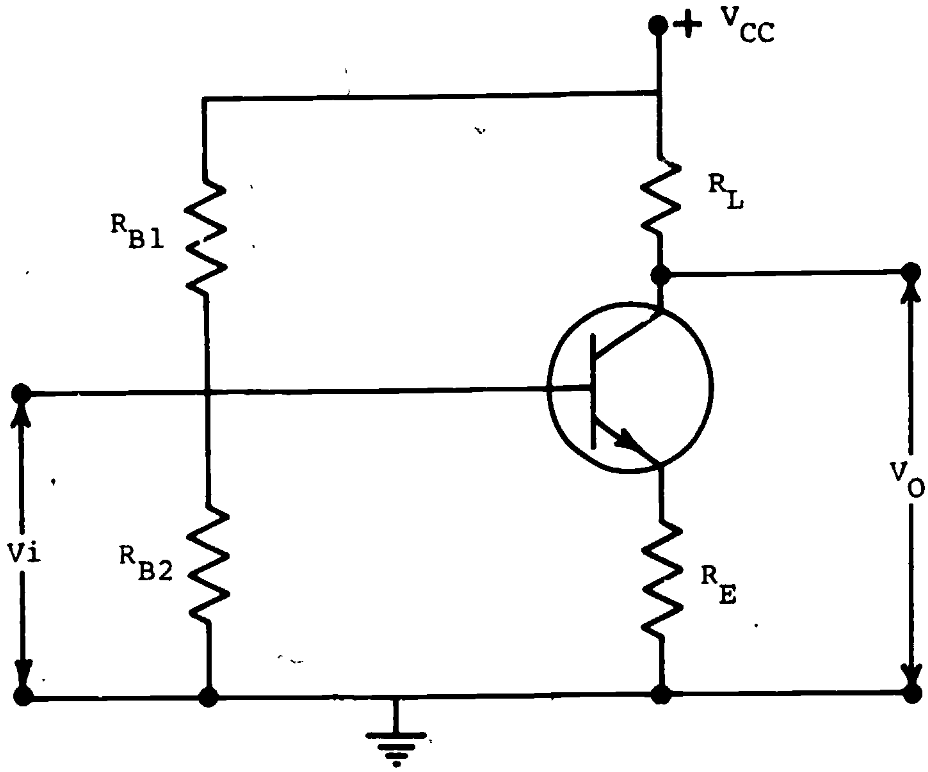


Figure 27.
Common Emitter Amplifier With Temperature Compensation

LABORATORY

In the laboratory, the student should be able to connect a common emitter amplifier using an NPN or a PNP transistor. The student should be able to determine characteristics of these circuits such as gain, power dissipation, phase relationship for AC signals and distortion of signals.

SECTION 2: Power Amplifier

Currently transistors are used in power amplifiers where large amounts of power must be transferred. In most applications a high input impedance is required to prevent distortion of the signal source. At the same time a low output impedance is frequently required in order to operate certain readout devices. These two requirements are best met by using the emitter-follower (common collector) transistor circuit shown in Figure 28.

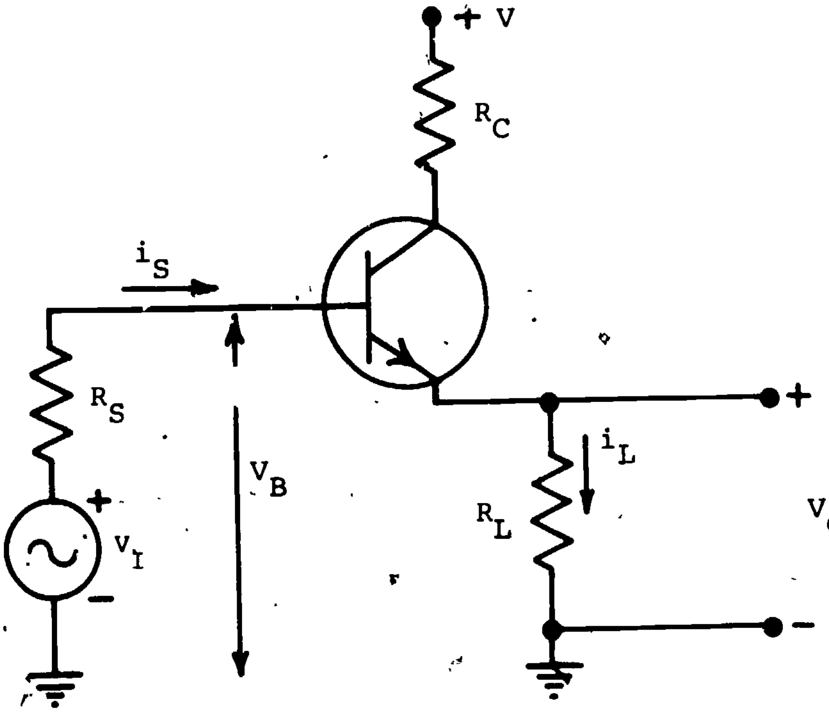


Figure 28.
NPN Emitter Follower

The maximum output voltage of the emitter-follower is given by

$$V_{L_{max}} = \left(\frac{R_L}{R_C + R_L}\right)V$$

where V is the power supply voltage.

and the maximum load current is

$$i_{L_{max}} = \frac{V}{R_C + R_L}$$

The input resistance is given by

$$R_{in} = (1 + \beta_F)R_L$$

and the power gain is approximately given by

$$G_P \quad \beta_F$$

The voltage transfer characteristics of an emitter-follower are best presented by graphing output voltage (V_O) against voltage (V_I) as in Figure 29.

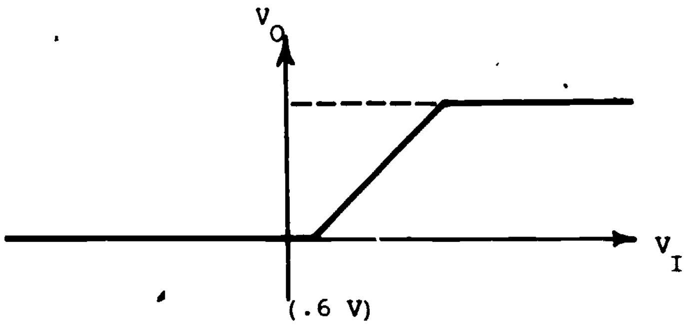


Figure 29.
NPN Emitter-Follower
Voltage Transfer Characteristics

The "dead" region of the voltage transfer is caused by the fact that the NPN transistor does not "turn on" until the input voltage is greater than 0.6 volts.

The NPN emitter-follower allows amplification of only positive signals. It is necessary to use a PNP emitter-follower as in Figure 30 to amplify negative signals

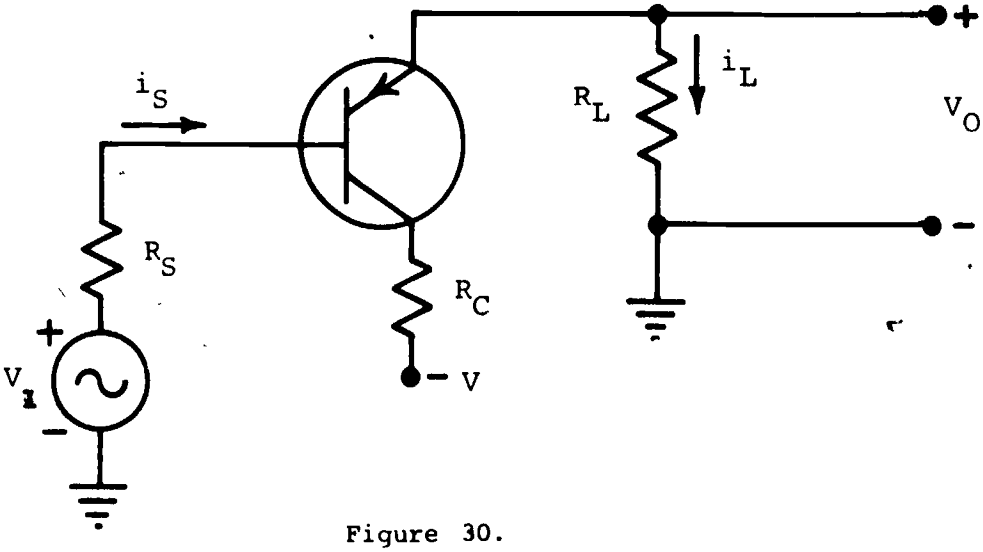


Figure 30.
PNP Emitter-Follower

The voltage transfer characteristic for the PNP emitter-follower is shown in Figure 31.

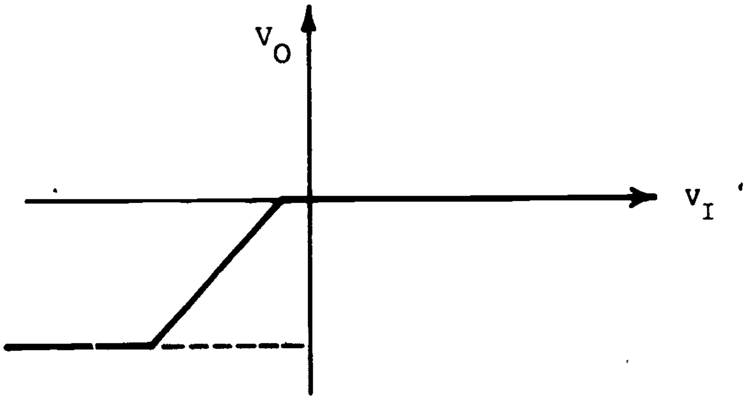


Figure 31.
PNP Emitter-Follower
Voltage Transfer Characteristics

The PNP emitter-follower circuit amplifies only negative signals. Since it is often desirable to amplify both positive and negative signals, a combination of NPN and PNP emitter-follower circuits must be used. Such a circuit, called a complimentary emitter-follower amplifier is shown in Figure 32.

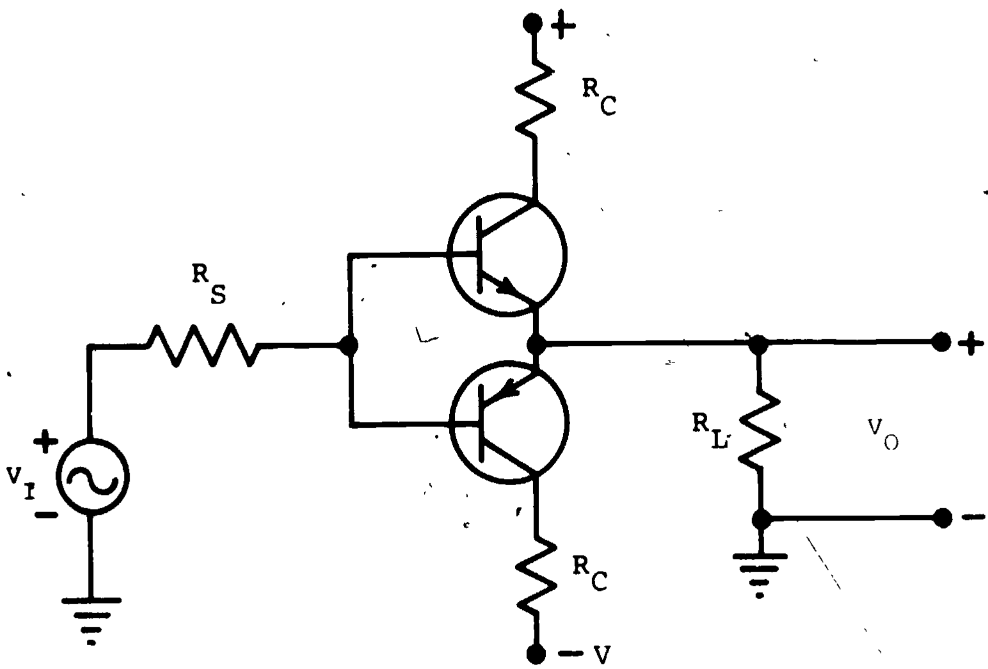


Figure 32.
Complimentary Emitter-Follower Amplifi

When the signal voltage is positive, the NPN transistor conducts and the PNP has no effect. When the signal voltage is negative, the PNP transistor conducts and the NPN has no effect. The voltage transfer characteristic is a combination of the NPN and PNP characteristics as in Figure 33.

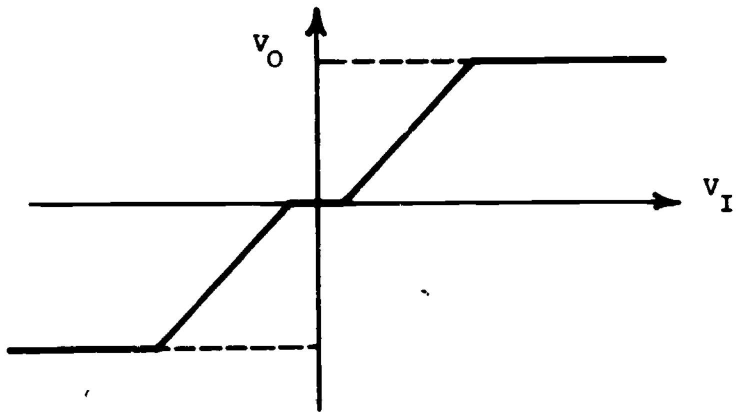


Figure 33.
Complimentary Emitter-Follower Voltage Transfer Characteristic

The result of the dead region of the complimentary emitter-follower is that for an AC signal, the output suffers from "crossover distortion" as in Figure 34.

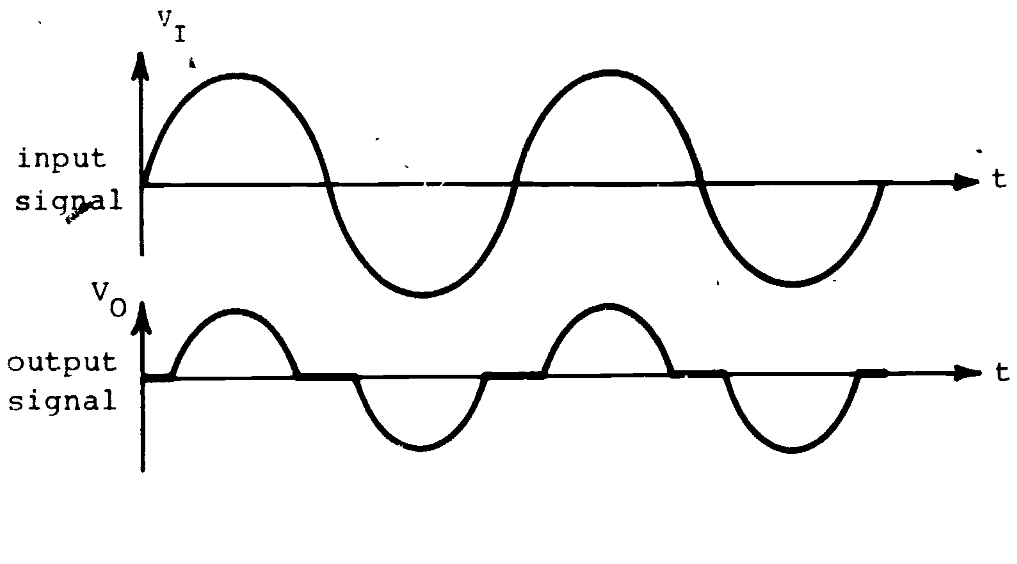


Figure 34.
Crossover Distortion Caused by Dead Region in
Complimentary Emitter-Follower

This crossover distortion can be nearly eliminated by the addition of an op-amp in the non-inverting mode as in Figure 35.

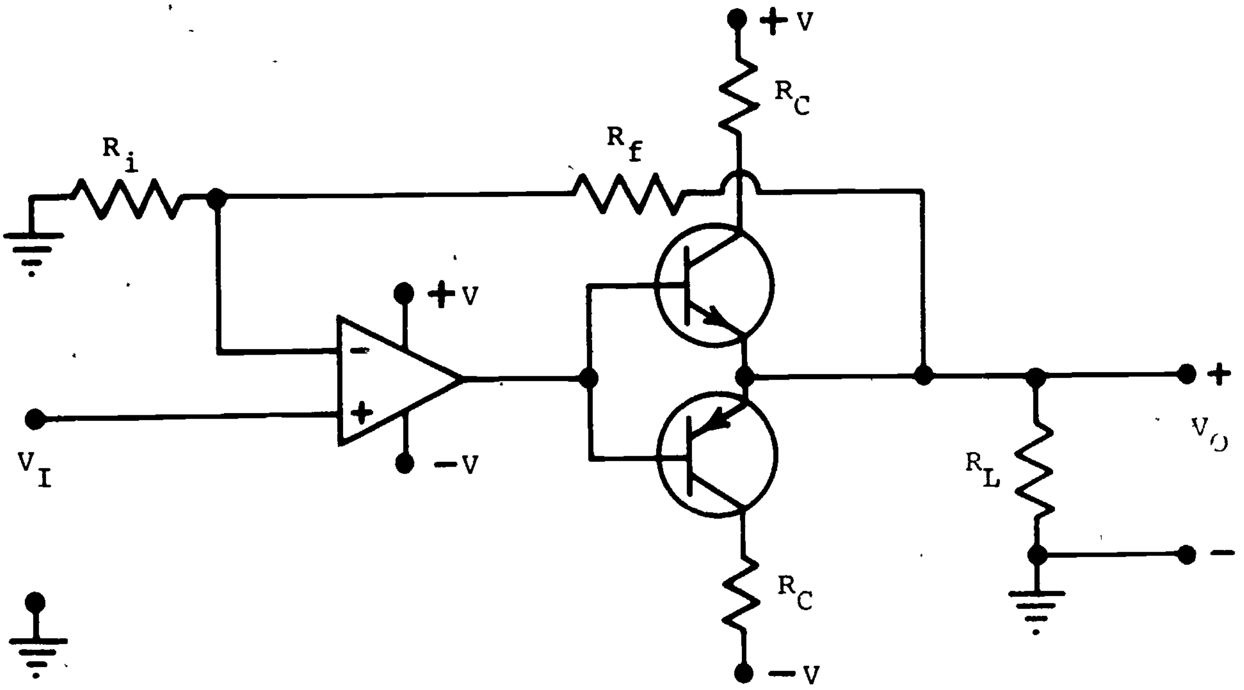


Figure 35.
Op-Amp and Complimentary Emitter-Follower Amplifier

The resistor R_f provides feedback from the emitter-follower output to the op-amp input. This feedback loop is open when the emitter-follower is not conducting. The result is that the dead region is reduced by a factor of approximately 1/A where A is the open-loop gain of the op-amp. The voltage gain of such a power amplifier is the same as the gain of the non-inverting amplifier:

$$\frac{V_O}{V_I} = \frac{R_f + R_i}{R_i}$$

In practical applications it is desirable to be able to control the gain and DC offset of the power amplifier. This can be accomplished by including two potentiometers in the circuit as in Figure 36.

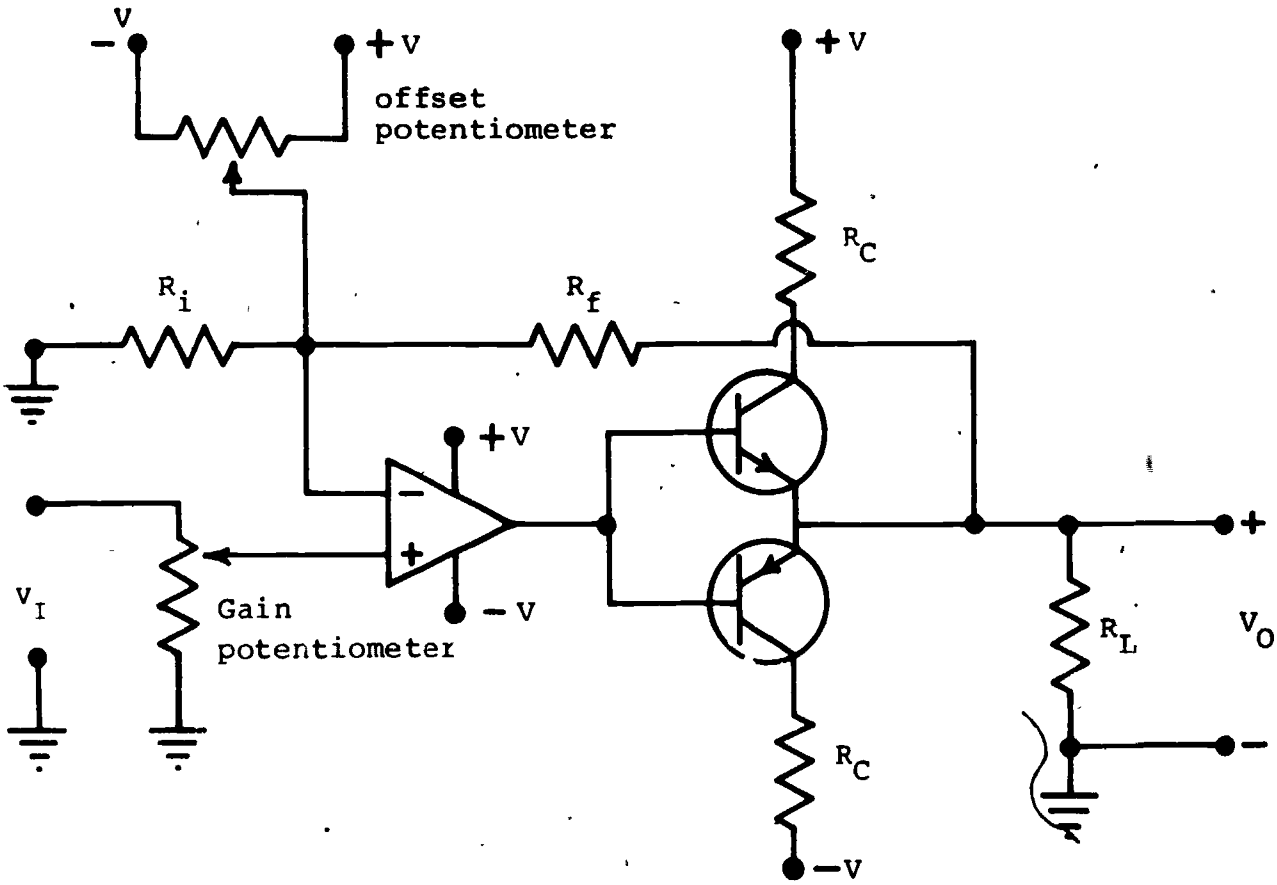


Figure 36.
Power Amplifier with Gain Control and DC Offset Control

The power amplifier is characterized by the following parameters:

maximum output voltage $V_{O_{max}} = (\frac{R_L}{R_C + R_L})V$

maximum load current $i_{L_{max}} = \frac{V}{R_C + R_L}$

input impedance at transistor base $R_{in} = (1 + \beta_F)R_L$

input impedance of op-amp. approximately 10 MΩ

maximum voltage gain $\frac{V_O}{V_I} = \frac{R_f + R_i}{R_i}$

LABORATORY

In the laboratory the student should be able to assemble a power amplifier with gain and DC offset controls. The student should then determine its characteristics; gain, crossover distortion and maximum operating range.

CHAPTER VIII

Recorders

Recorders are devices which produce graphical representations of electrical signals. There are two main types of recorders: Chart recorders and X - Y recorders.

SECTION 1: Chart Recorders

Chart Recorders will draw a graphical representation of an electrical signal as a function of time. This is accomplished by pulling a paper chart at a constant speed under a pen. The displacement of the pen is determined by the input signal. There are two types of chart recorders. Linear chart recorders utilize a servo motor and resistance feedback to drive the pen in such a manner that pen displacement is linearly related to input signal. A linear chart recorder and the type of chart it uses are shown in Figure 37.

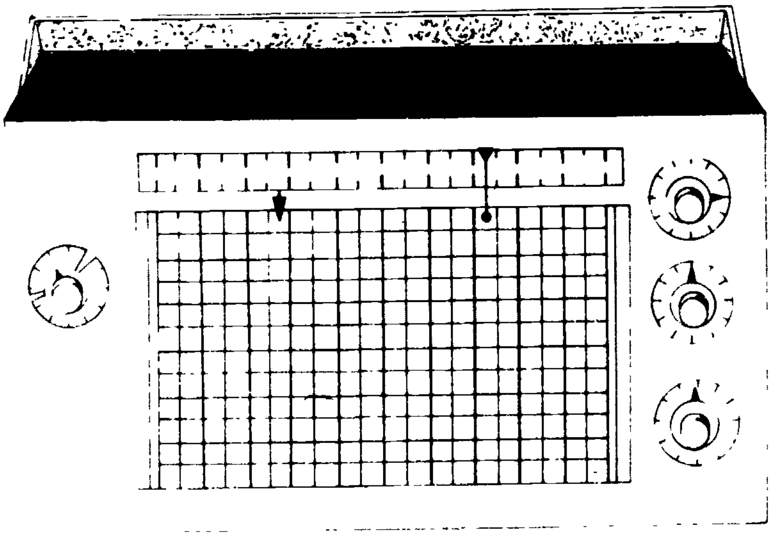


Figure 37. Linear Chart Recorder

Non-linear chart recorders use a galvanometer movement to cause the pen to pivot about some point. While this type of recorder is less expensive to build than a linear recorder, the deflection of the pen is not linearly related to input signal and a non-linear chart must be used. Figure 38 shows a non-linear chart recorder.

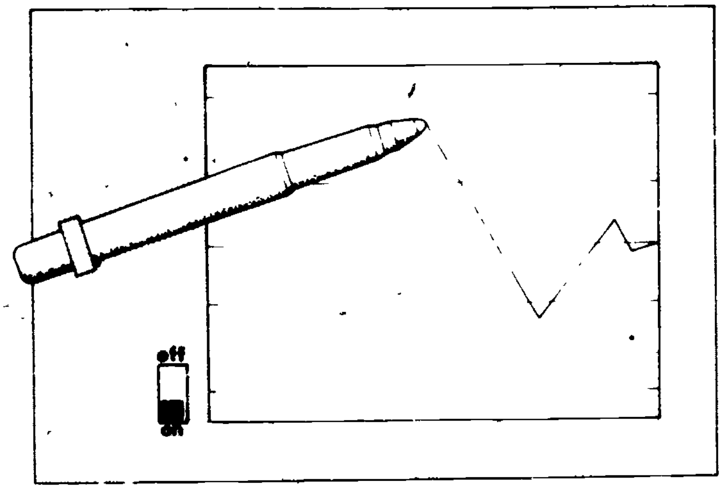


Figure 38. Nonlinear Chart Recorder

Chart recorders are available with a wide selection of sensitivities ranging from a few millivolts to several hundred volts for full scale deflection. There is also a wide selection of chart speeds typically from several centimeters per minute to a few centimeters per day. The sensitivity and chart speed required depend on the magnitude of the signal to be plotted and the rate at which it changes. Some chart recorders have the capability of recording more than one signal at a time. These are referred to as multi-channel chart recorders. Chart recorders are often used to monitor physical parameters (such as temperature or pressure) over periods of time and are often used as the output device in physical, chemical, and medical instruments.

SECTION 2: X - Y Recorders

X - Y recorders draw a graphical representation of one electrical signal (Y) as a function of another electrical signal (X). A typical X - Y recorder is shown in Figure 39.

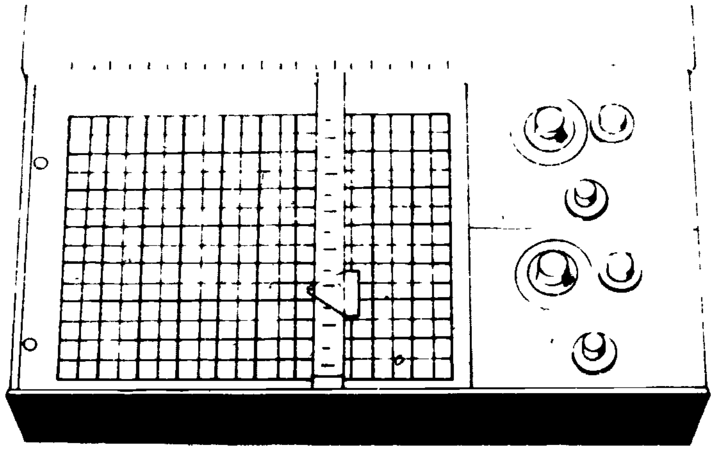


Figure 39. X-Y Recorder

X - Y recorders are also available with a variety of sensitivities and are usually calibrated in V/cm or V/in. By choosing the proper transducer and necessary auxiliary circuits the X - Y recorder can be used to plot one physical parameter as a function of another, such as pressure as a function of temperature. Some X - Y recorders also provide the option of plotting time on one of the axis. This allows the plotting of one physical parameter as a function of time over time intervals of a few seconds.

LABORATORY

In the laboratory the student should be able to connect a chart or X - Y recorder to obtain a plot of one physical parameter as a function of another or as a function of time.

CHAPTER IX

Strain Gauge

The strain gauge is a force displacement transducer. Strain gauges are commonly made of wire or metal foil arranged as in Figure 40.

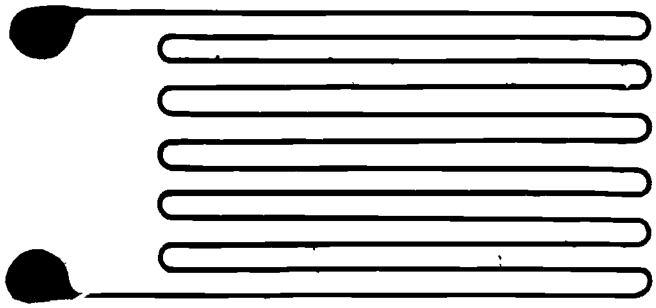


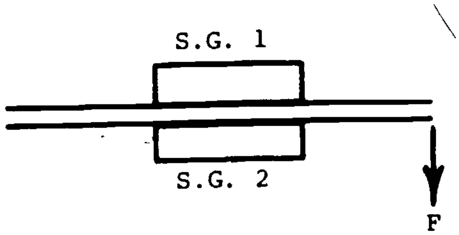
Figure 40.
Typical Strain Gauge Configuration

Changes in the length of the wire or foil of the strain gauge cause changes in the resistance of the gauge according to

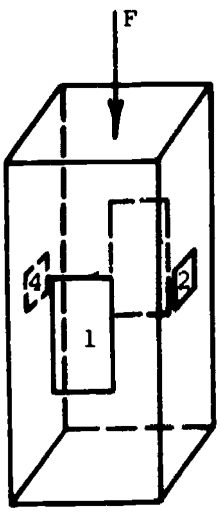
$$\frac{\Delta R}{R} = K \frac{\Delta L}{L}$$

where ΔR is the change in resistance, R is the original resistance, ΔL is the change in length, L is the original length, and K is the gauge factor. The gauge factor is a characteristic of the strain gauge and is usually supplied by the manufacturer.

Strain gauges can be cemented to the surface of the object in which strain is to be measured in a variety of configurations as shown in Figure 41.

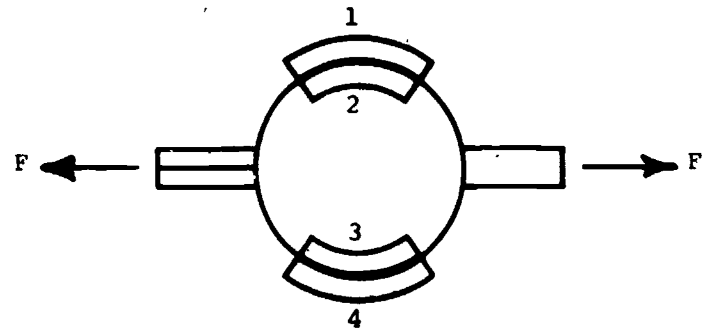


a.
Two strain gauges on a thin beam



b.
Four strain gauges on a load cell

Figure 41.



c.
Four strain gauges on a force ring

Figure 41.

Strain gauges are usually mounted in opposing pairs so that strain produces an increase in resistance of one gauge and decreases in resistances of the other. The use of pairs of gauges also decreases the effect of temperature changes. These changes in resistance are measured by use of a Wheatstone bridge as in Figure 42.

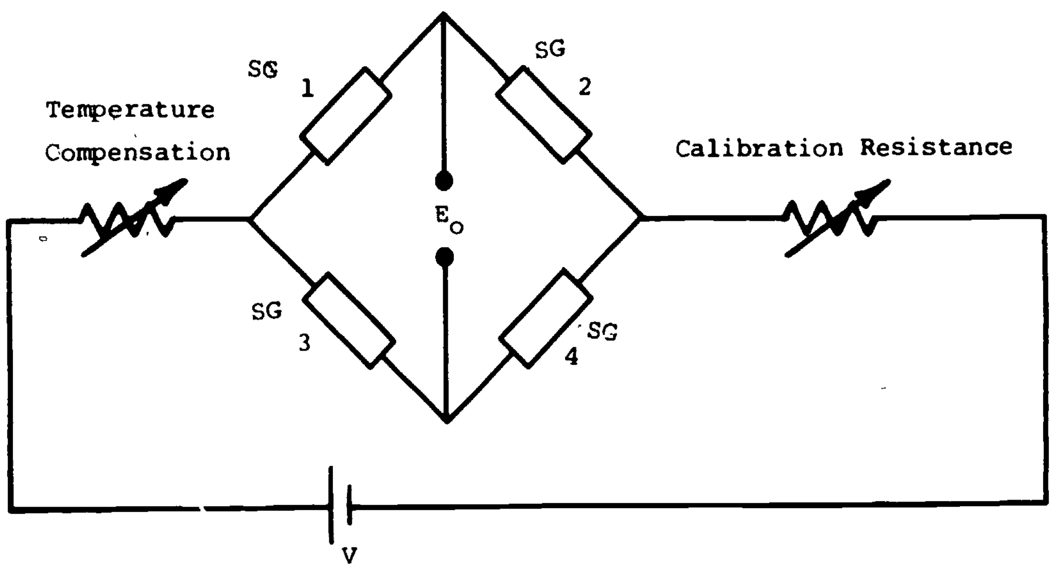


Figure 42.
The Strain Gauge Wheatstone Bridge

The use of two or four opposing strain gauges in the Wheatstone bridge produces greater output signals than does a single gauge.

Strain gauges can also be used to measure physical quantities which cause resulting strains such as force, pressure, and acceleration. Figure 43 shows a circular diaphragm with strain gauges attached for measuring pressure.

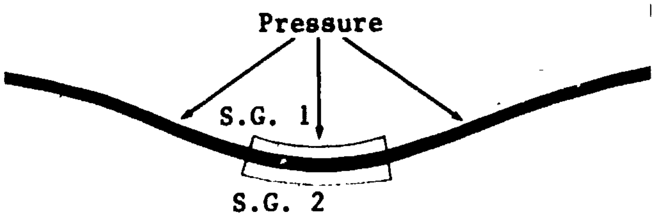


Figure 43.
Circular Diaphragm for Pressure Measurement

The disadvantage of this type of arrangement is that it is linear only for a small range of pressures. For a greater range of linearity a cantilever spring and bellows arrangement as in Figure 44, may be used.

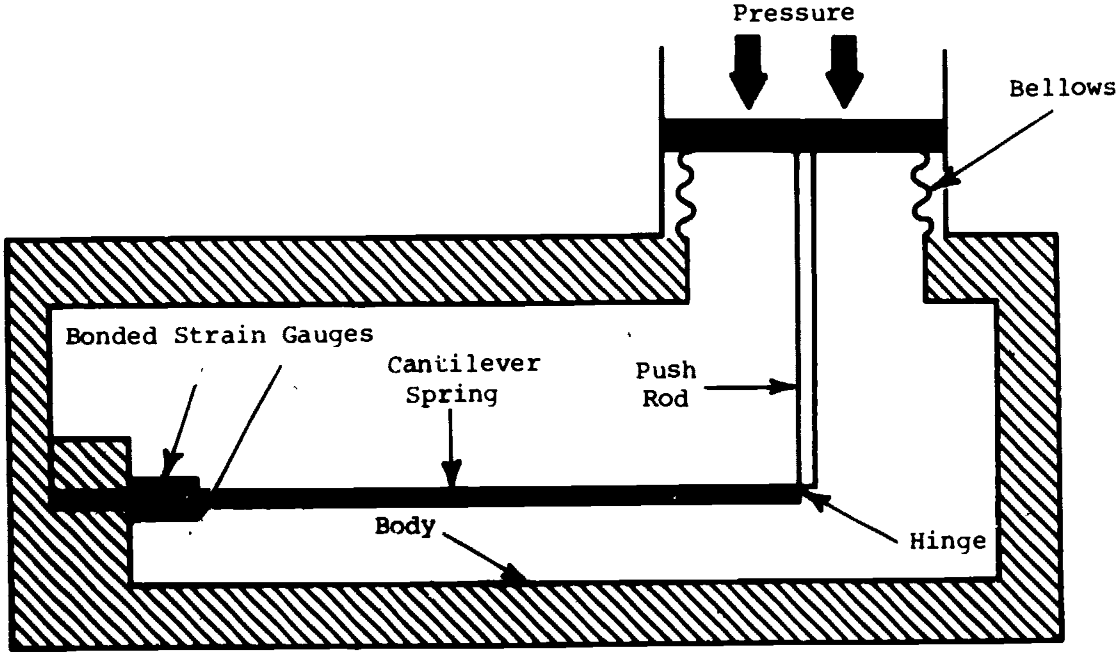


Figure 44.
Cantilever-type Pressure Transducer

LABORATORY

The student should be able to connect strain gauges in a bridge circuit with linear op-amp to measure stress in a load cell or force ring. Using a strain gauge pressure transducer in a bridge with the output amplified by a power amp and fed to a strip-chart recorder, the student should be able to build a recording pressure gauge.

CHAPTER X

Light Transducers

Light transducers are devices which convert electromagnetic radiation to electric signals. There are three major types of light transducers: photoemissive, photovoltaic, and photoconductive.

SECTION 1: Photoemissive Tubes

Photoemissive transducers are vacuum tubes which rely on the principle of electrons being emitted by some materials when light strikes the surface. This surface is the cathode of the tube and the emitted electrons are moved to the anode by the potential provided by a power supply. Figure 45 illustrates a photoemissive (photoelectric) tube.

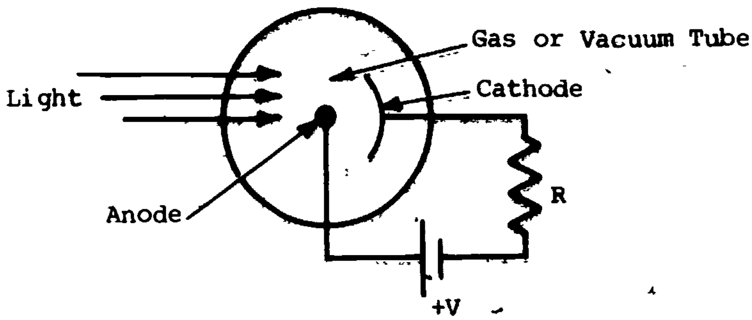


Figure 45,
The Photoemissive Tube

Each photosensitive material has a threshold wavelength. It is necessary for the wavelength of light to be shorter than this threshold in order to emit electrons. For most materials the threshold wavelength is in the ultraviolet region (200-400 nm) of the spectrum. For potassium and cesium oxide, however, the threshold wavelength is in the visible region (400-700 nm) of the spectrum.

For the photoemissive tube, the saturation current is a function of the luminous flux striking the cathode. Since the currents in the tube are small (about 10 µA), the photoemissive tube is best connected to an op-amp as in Figure 46.

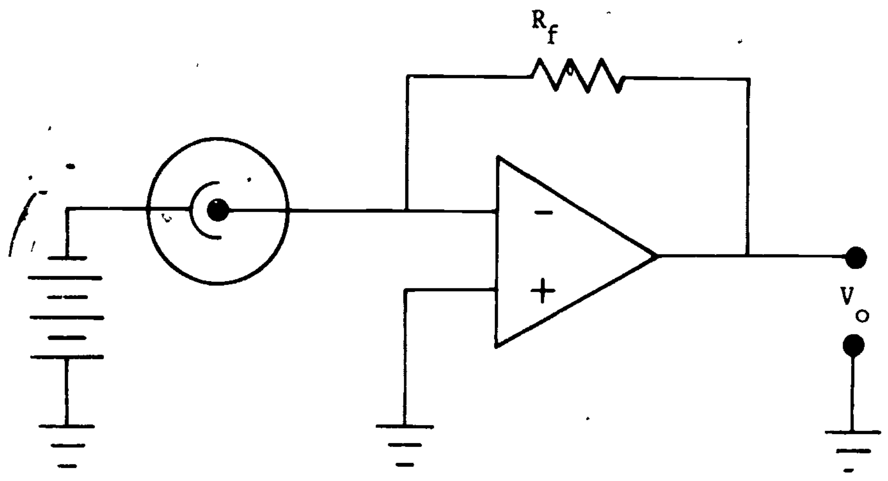


Figure 46.
Photoemissive Tube in an Op-amp Circuit

SECTION 2: Photovoltaic Cells

Photovoltaic cells are solid-state, semiconductor devices which convert radiant energy directly into a voltage. These devices are more commonly called "solar cells" since they are frequently used to convert radiation from the sun into electrical power. Silicon and selenium are the materials most often used in photovoltaic cells.

The potential produced by the cell is small (approximately 0.6 V for silicon in full sunlight) and is not a linear function of illumination for an open circuit. For a low resistance circuit, such as a microammeter, however, the current is a nearly linear function of illumination as in Figure 47.

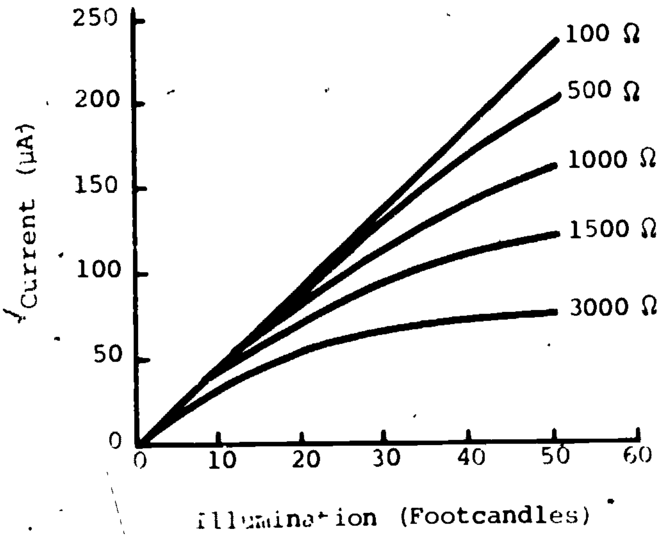


Figure 47.
Output Current for a Typical Photovoltaic Cell

After a period of continually drawing current from the photovoltaic cell, the fatigue effect reduces the amount of current produced by a constant illumination. In the measurement of radiation, this can be avoided by drawing very small currents or by limiting measurements to short time intervals. In the production of electrical power, however, the fatigue cannot be avoided.

SECTION 3: Photoconductive Cells

Photoconductors (or photoresistors) are devices for which the resistance changes depending on illumination. The resistance of these cells decreases as illumination increases. This change is non-linear as seen in Figure 48.

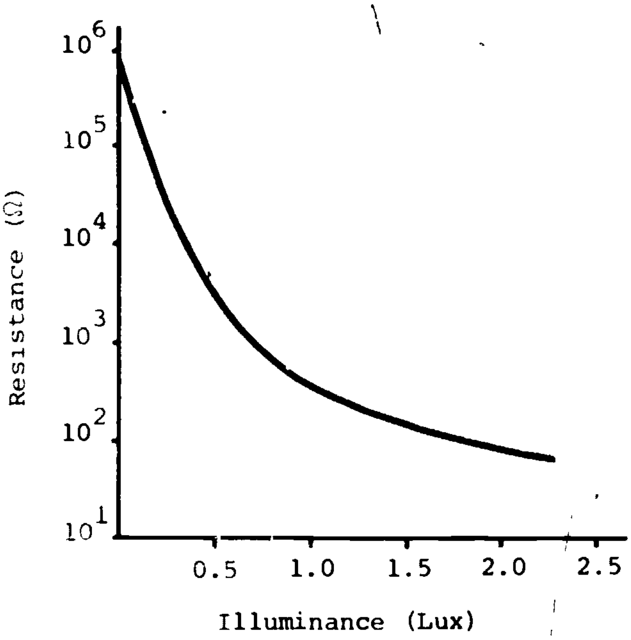


Figure 48.
Photoconductor Response

Cadmium sulfide (CdS) is commonly used in photoconductive cells to produce dark resistance up to 100,000 times greater than light resistance. Photoconductors using CdS also have spectral responses which very closely match that of the human eye and can be used to measure illumination without the photometric filter necessary for other light transducers. Because of their low cost, low power consumption, and spectral response, CdS cells are often used in photographic light meters.

A pair of these cells, with one sealed from the light for temperature compensation, can be used in a Wheatstone bridge (Figure 49) for photometric measurement.

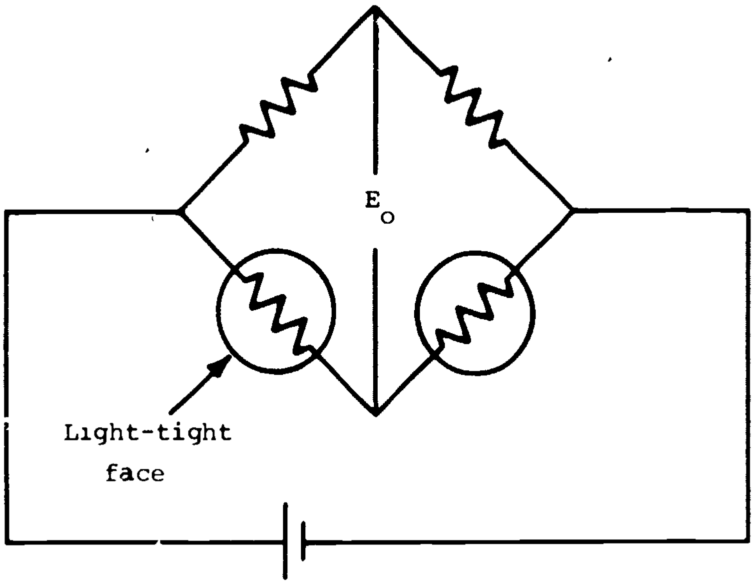


Figure 49.
Wheatstone Bridge with Pair of Photoconductors for Temperature Compensation

Although photoconductors can be used for photometry, their non-linearity has led to their wider use in chopping and triggering circuitry such as in some electronic automobile ignition systems.

LABORATORY

By varying the distance from a standard lamp, the student should be able to measure input-output characteristics for photoemitters, photovoltaic cells, and photoconductors. With these input-output characteristics and auxillary circuits (op-amp, power amp, counter, etc.) the student should be able to measure light levels, or build light controlled devices.

CHAPTER XI

Sound Transducers

SECTION 1: Crystal Microphone

One of the most versatile sound transducers is the crystal microphone which uses the piezoelectric effect to transduce vibrations into electric signals. In piezoelectric crystals, such as quartz and Rochelle salt, elastic strain along the mechanical axis of the crystal results in a proportional electric potential between opposite sides of the crystal.

In the crystal microphone, vibrations in the air strike a diaphragm which is mechanically connected to the crystal as shown in Figure 50. This results in a potential difference between the electrodes which is proportional to the strength of the vibration. The crystal microphone can be used to detect frequencies from a few hertz to several megahertz. The impedance of a crystal microphone is rather high, which makes it a good input device for an amplifier.

The piezoelectric effect can also be used in other types of transducers where forces are produced, such as an accelerometer.

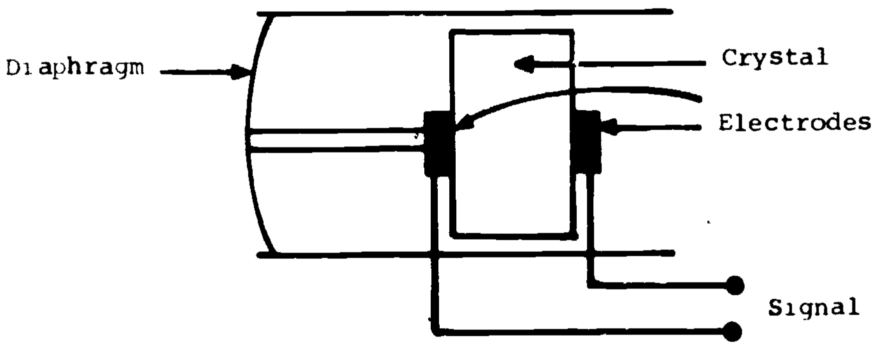


Figure 50.
Crystal Microphone

[illegible] Loudspeaker

The loudspeaker is most frequently used to transduce electric signals into sound vibrations although the reverse can be done. The loud speaker consists of a magnet (either permanent or an electromagnet) and a "spider" with a coil, the voice coil, around it. The spider is made of a soft fabric and is attached to the speaker cone. Figure 51 shows the arrangement of the magnet, voice coil, spider and speaker cone.

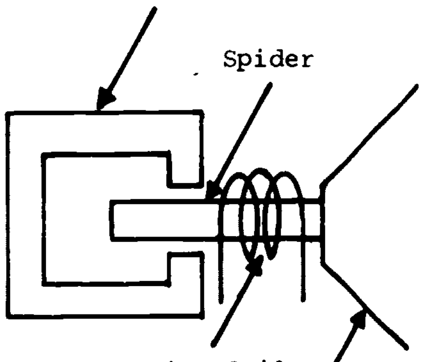


Figure 51.
Permanent Magnet Loud Speaker

As a current is passed through the voice coil, the resulting magnetic field interacts with that of the permanent magnet resulting in vibrations of the speaker cone which are the same frequency as the current to the voice coil. In speakers using an electromagnet, the magnetic field is produced by a steady current through the electromagnet rather than by a permanent magnet.

One major factor governing the amount of sound produced is the mechanical resonance of the speaker cone. As a result, large cones are used to produce low frequency sounds and small cones are used to produce high frequencies. Another factor is the impedance of the speaker which should be closely matched to the output impedance of the amplifier in order to produce the maximum power transfer. The impedance of a speaker is primarily the resistance of the voice coil and changes very little over the range of audio frequencies. Speakers are commonly available with impedances of 4, 8, 25, 50, 100, and 200 ohms over the range of audio frequencies.

Laboratory

The student should investigate the characteristics (particularly frequency response) of a crystal microphone and loud speaker.

CHAPTER XII

Linear Variable Differential Transformer

The linear variable differential transformer (LVDT) is a displacement transducer which relys on changes in mutual inductance to produce a signal. The LVDT consists of a transformer with a single primary coil (P) coupled to two identical secondary coils (S_1 & S_2) by a movable core as shown in Figure 52.

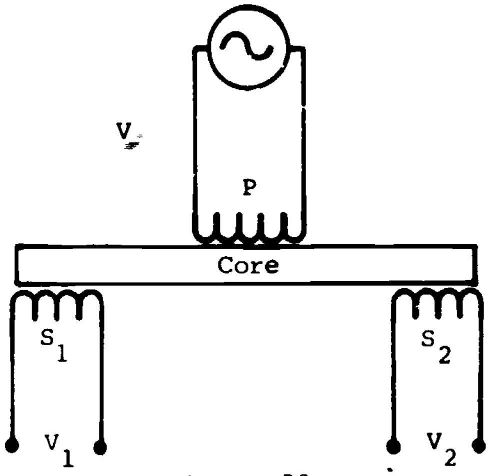


Figure 52.
Linear Variable Differential Transformer

The core is mechanically linked to the object for which the displacement is to be measured. With the core in its neutral (or null) position, the mutual inductance between P and S_1 is the same as between P and S_2. As a result, the voltages from the secondaries (V_1 and V_2) are the same. When the core is moved, one secondary voltage will increase while the other decreases. The amount of voltage change in each coil is proportional to the amount of displacement of the core. By connecting a spring of a known force constant to one end of the core, the LVDT can be used as a force transducer.

LVDTs are available with ranges from a few hundredths of an inch to several feet. The primary may be excited by the 60 Hz 110 V line voltage or from oscillators with frequencies from a few hundred to several thousand Hz. The linearity of the LVDT usually depends on the excitation frequency, which is usually specified by the manufacturer.

Laboratory

The student should be able to connect a LVDT to the appropriate circuit and determine the relationship between output voltages and core displacement.

CHAPTER XIII

Differential Amplifier

The linear op-amp can be used to amplify the difference between the two signals applied to the input terminal. This type of amplifier is referred to as a differential amplifier. The result of a signal +V applied to the inverting input and a signal -V applied to the non-inverting input is an output signal of -2V as in Figure 53.

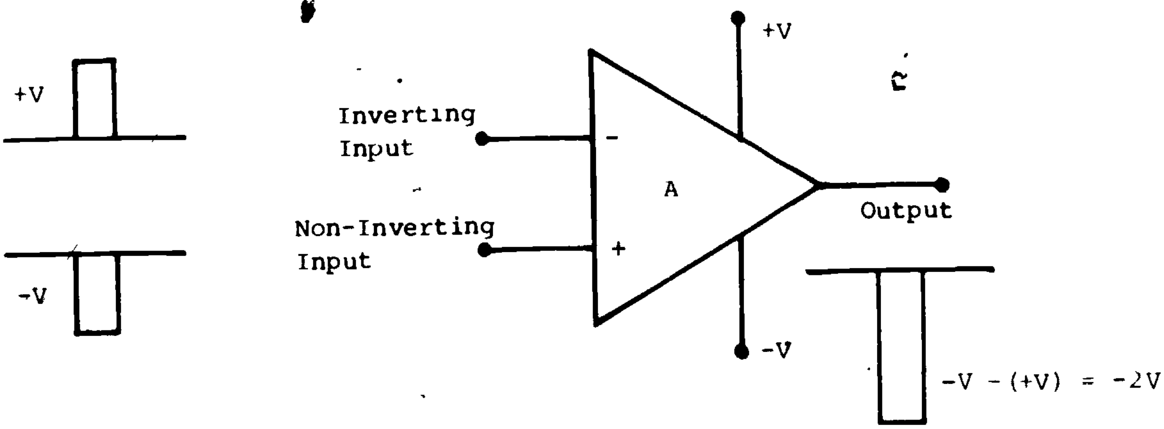


Figure 53.
Basic Differential Amplifier

One advantage of the differential amplifier is that any signal common to both inputs is not amplified. Such a signal is referred to as the common-mode signal.

As with the linear op-amp, the differential amplifier is most commonly used with a feedback loop as in Figure 54.

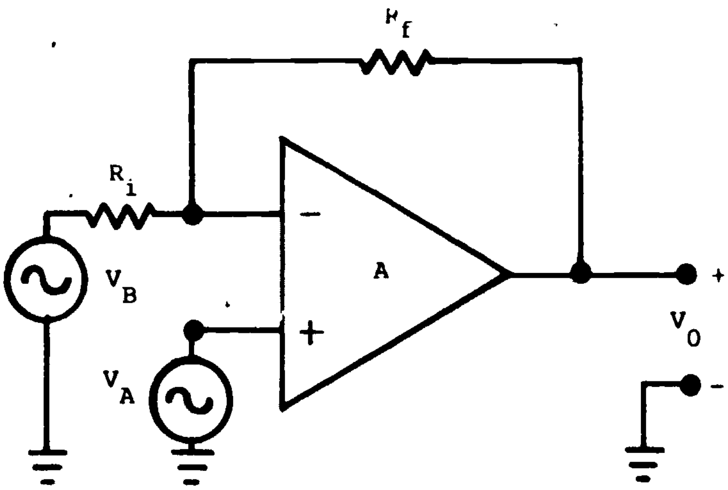


Figure 54.
Differential Amplifier with Feedback

For high closed-loop gain, the output voltage is given approximately by

$$V_0 = \frac{R_f}{R_i}(V_A - V_B)$$

The factor by which the difference in signals is amplified is called the differential gain.

When lower gains are used, the above approximation is not good enough. The differential gain is a combination of the inverting and non-inverting gains of the op-amp.

$$V_0 = (1 + \frac{R_f}{R_i}) V_A - (\frac{R_f}{R_i} V_B)$$

If R_f is not very much larger than R_i, the non-inverting gain is somewhat larger than the inverting gain and the true difference is not amplified faithfully. Also, the common-mode signal is not exactly cancelled out. These problems can be remedied by the use of a potentiometer to balance the gain as in Figure 55.

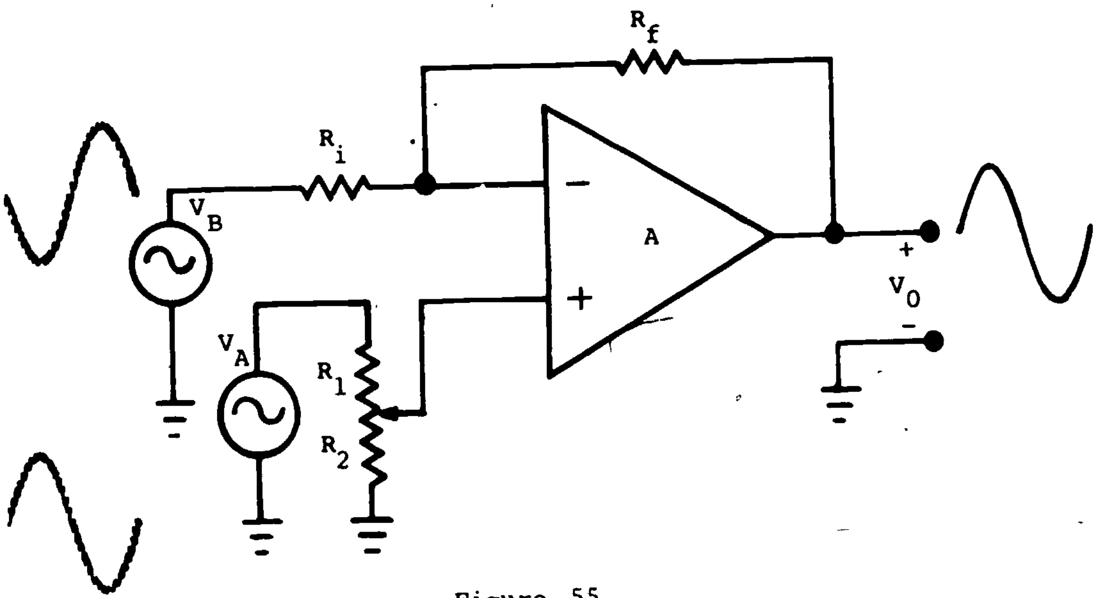


Figure 55.
Balanced Gain for Differential Amplifier

The condition necessary for balanced gain is

$$\frac{R_1}{R_2} = \frac{R_i}{R_f}$$

The gain is given by

$$G = \frac{R_f}{R_i}$$

and the output voltage is

$$V_0 = \frac{R_f}{R_i} (V_A - V_B)$$

The input impedance of the balanced gain differential amplifier is equal to R_i and is usually low. In cases where a high input impedance is desired, voltage followers can be used as buffers at the inputs. Figure 56 shows such a circuit. If a non-inverting amplifier is desired, the circuit in Figure 57 can be used.

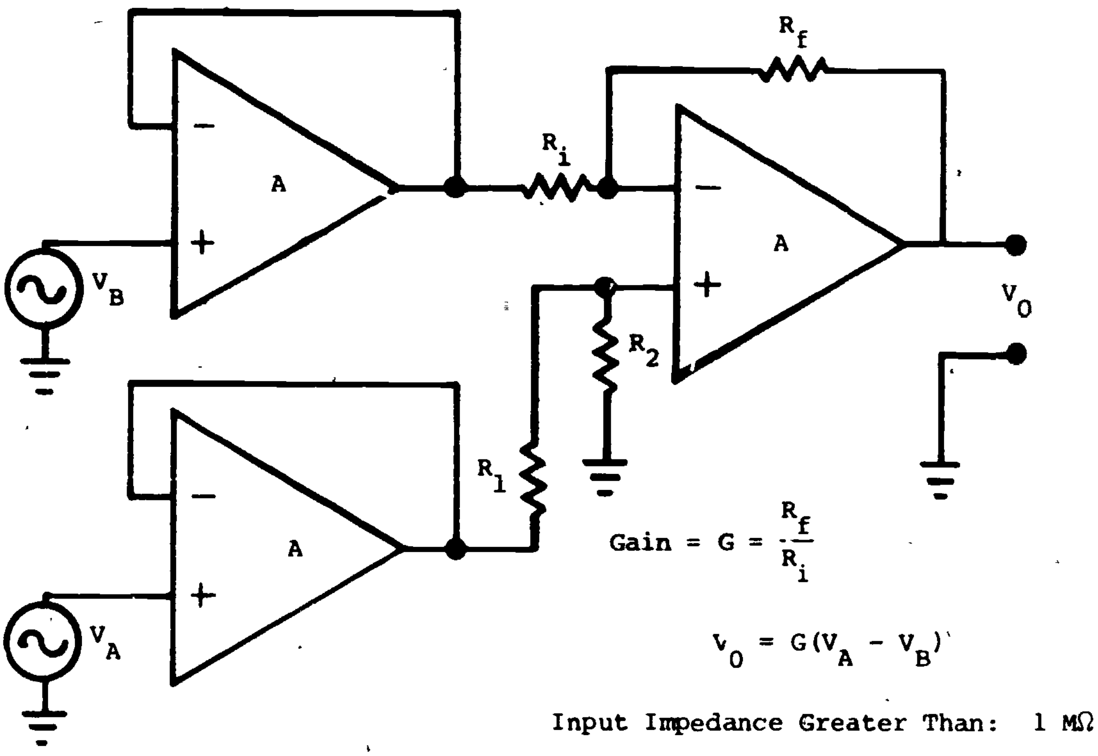


Figure 56.
High Input Impedance Differential Amplifier

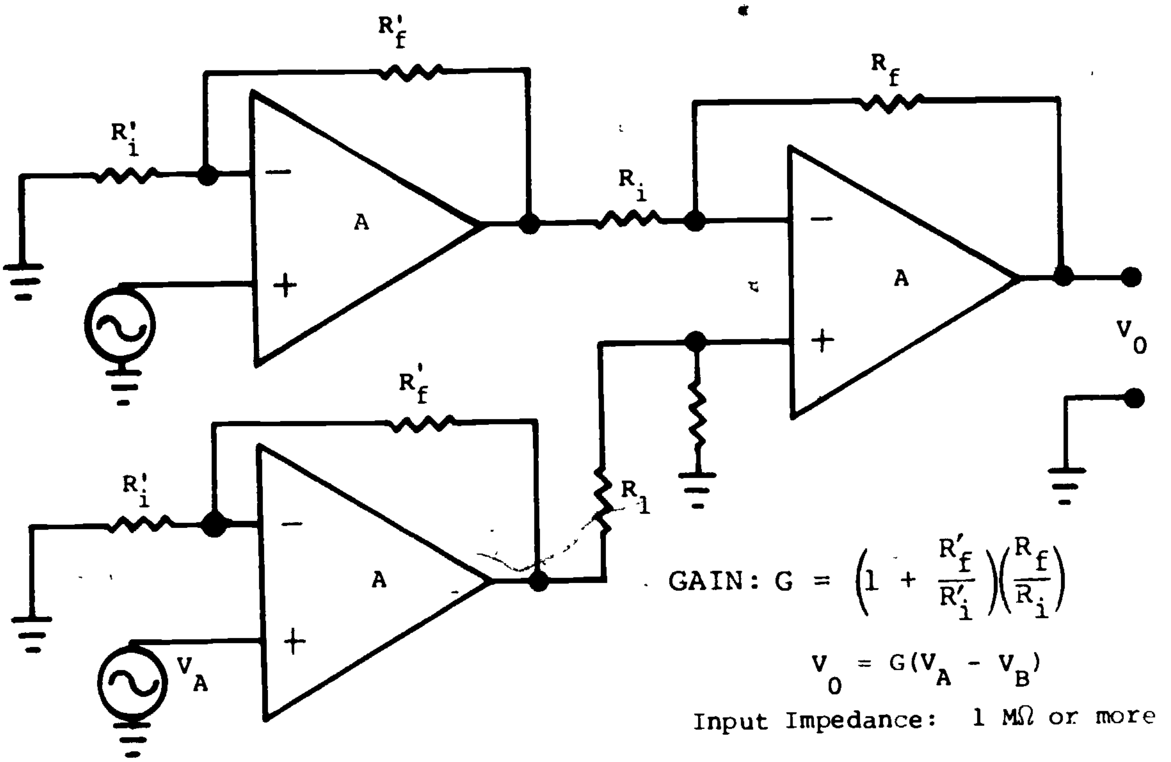


Figure 57.
Differential Amplifier with Non-Inverting Buffers

The term which is used to specify how well a particular differential amplifier rejects the common-mode signal is the common-mode rejection ratio (CMRR). The CMRR is defined operationally as follows: measure the output voltage with a signal applied at one input (inverting, for example) with the other input (non-inverting, for example) shorted to ground; then, measure the output voltage with the same signal applied to both inputs simultaneously, and take the ratio of these two numbers. In terms of the circuit of Figure 55 this gives:

$$\text{CMRR} = \frac{V_0\ (V_A \text{ shorted to ground})}{V_0 (V_a \text{ shorted to } V_B)}$$

This ratio is often quoted in deciBel units. The conversion is:

$$\text{CMRR(dB)} = 20 \log_{10} \text{CMRR}$$

In an ideal amplifier, the denominator of the equation would be zero, leading to an infinitely large CMRR.

A large CMRR is therefore the mark of a good differential amplifier (typical values are 1000 (60 dB) or better). In any given amplifier chip the ultimate CMRR is determined by the internal construction.

Laboratory

The student should be able to construct a differential amplifier of specified gain and use it to amplify signal differences.

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