Engineering Measurements

Chapter three

Basic Electrical Measurements and Sensing Devices

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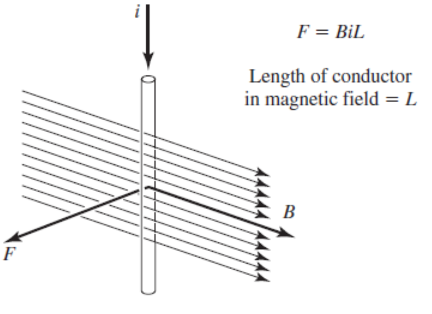
Basic Electrical Measurements and Sensing Devices

Forces of Electromagnetic Origin

- **Assume that we have a conductor in a magnetic flux as shown. If a current (i) passes through the wire, a magnetic force (F) will be generated and affect the wire. The value of this force is:**

$$F = BiL \qquad (1)$$

Where:
B is the magnetic flux density; Weber/m^2
i is the current, Ampere.
L is the length of conductor in the magnetic filed, m.



When using N of coils, the force become

$$F = NBiL \qquad (2)$$

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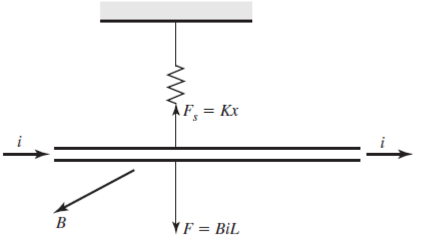
Forces of Electromagnetic Origin

❑Consider the apparatus shown in Fig. the relation between the spring displacement (x) and the current an be derived as:

$$Kx = BiL \qquad (3)$$



Rearrange Eq(3):

$$x = \frac{BL}{K} i$$

Or:

$$i = \left(\frac{K}{BL}\right) x$$

As you can see, we can measure the current passing a conductor by letting this current pass through the above configuration. Knowing B, L and K, what we have to do is measure (x) and relate it to the current.

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Analog and digital wave form

❑In many cases, the measured is a variable value with respect to time.

❑If the variation of the variable is continues all other the period of measuring, the measured waveform is called analog (i.e. continuous reading)

❑If the measuring is done at discrete points of time, then the wave form is called digital.

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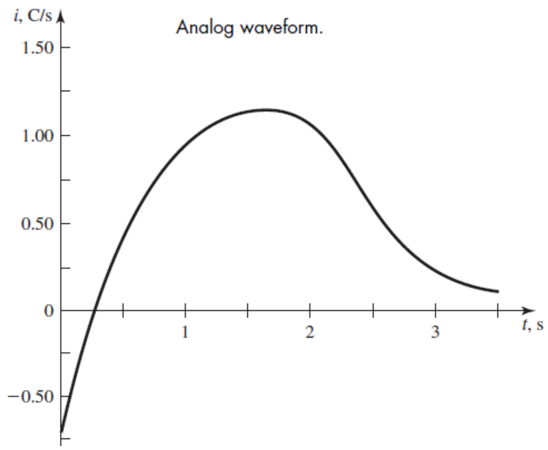
Analog and digital wave form



Analog waveform.

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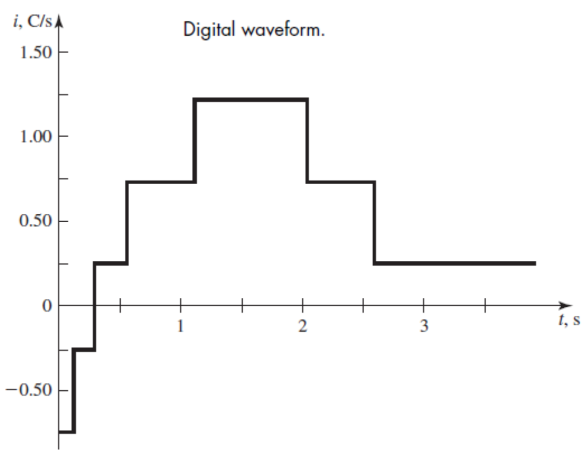
Analog and digital wave form



Digital waveform.

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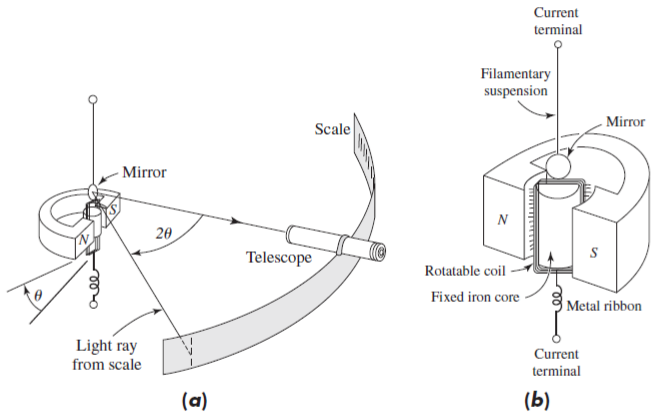
Basic Analog Meters

Galvanometer

This device is used mainly to measure DC (direct current)



(a) Optical system; (b) D'Arsonval movement.

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Basic Analog Meters

Galvanometer

Working principle:

- **A permanent magnet is used to produce the magnetic field**
- **the telescope arrangement and expanded scale improve the readability of the instrument.**
- **When the measured current passes through the coil, it will produce magnetic flux . The interaction between this flux and the flux from the permanent magnet produce a force – moment system which rotate telescope. The telescope position on a scale represent the value of the measured current.**

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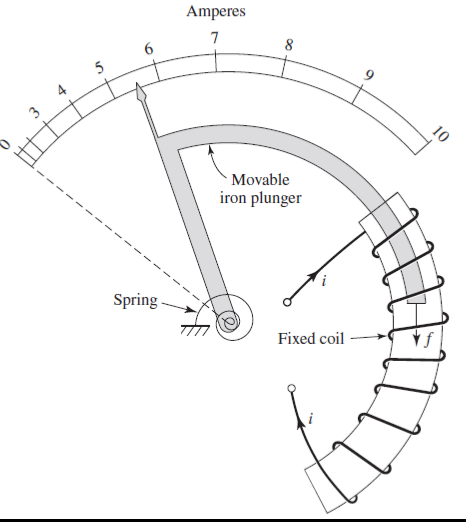
Basic Analog Meters

iron-vane or moving-iron instrument

This device is used mainly to measure AC (alternating current)



Working principle:

When the AC is given to the fixed coil, it produces a magnetic field. This field exert a force on the movable iron vane. The displacement of the vane is proportional to the magnitude of the current.

E n g i n e e r i n g m e a s u r e m e n t s

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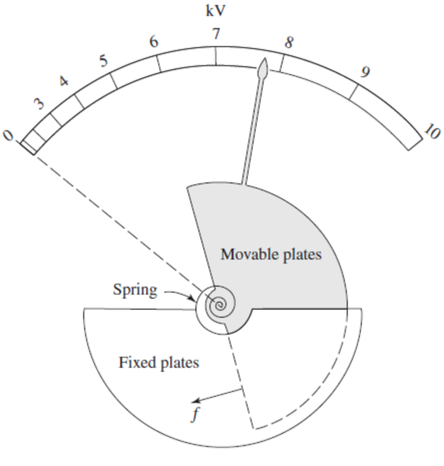
Basic Analog Meters

DC voltmeter

Working principle:

a large resistor is placed in series with the movement; thus, when the instrument is connected to a voltage source, the current in the instrument is an indication of the voltage.



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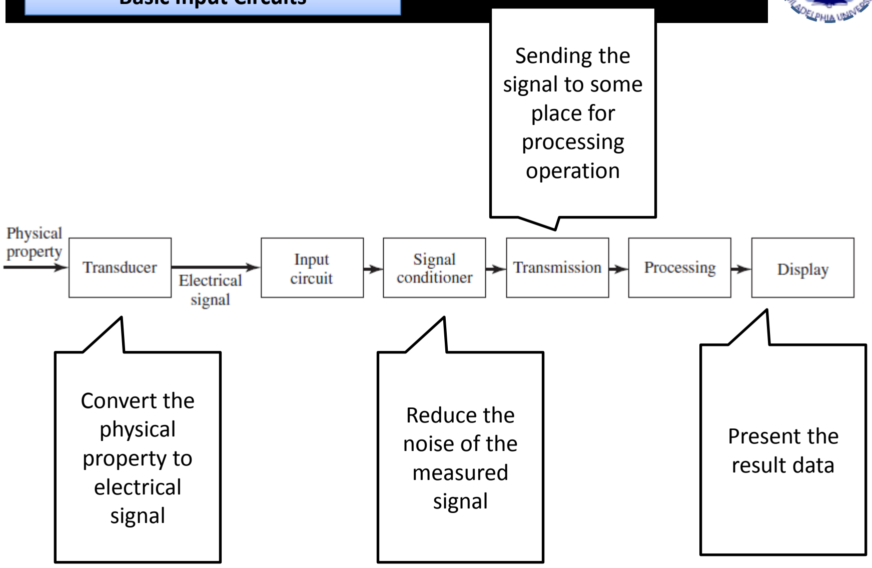
Basic Input Circuits



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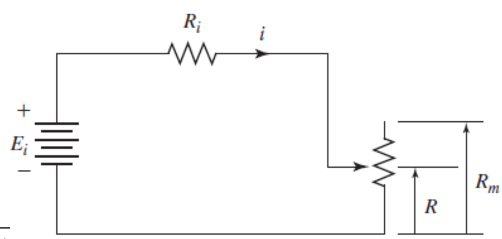
Basic Input Circuits

- Consider a gas sensor, the resistance of which changes as a function of the gas concentration surrounding the sensor.
- Let the sensor be in series with a battery
- The relation between the current, voltage and the resistance connection is:

$$i = \frac{E}{R + R_i}$$

- The maximum resistance of the transducer is R_m, *and the current may be written in* dimensionless form as

$$\frac{i}{E_i / R_i} = \frac{1}{(R/R_m)(R_m/R_i) + 1}$$



Current-sensitive input circuit.

- As you can see, the relation between the transducer resistance and the current is none linear

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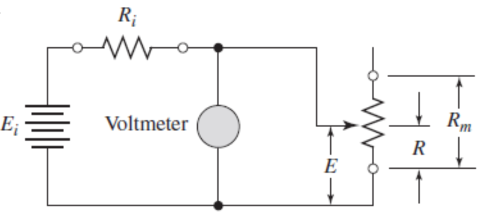
Basic Input Circuits

A modified circuit is shown in the figure. If the internal impedance of the voltmeter is very large compared with the resistance in the circuit can be represented as:

$$i = \frac{E}{R + R_i}$$

This circuit is called ballast circuit
And with some dimensionless manipulation we can find:

$$\frac{E}{E_i} = \frac{iR}{i(R_i + R)} = \frac{(R/R_m)(R_m/R_i)}{(R/R_m)(R_m/R_i)+1}$$



➢the We can relate the voltage to resistance by the previous equation.

➢It is more easy to measure voltage than the current. However, the relation here is also none linear.

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Basic Input Circuits

The sensitivity (S) of a ballast circuit is defined as the rate of change in transducer voltage (E) with respect to transducer resistance(R) and is given as:

$$S = \frac{dE}{dR} = \frac{E_i R_i}{(R + R_i)^2}$$

➢The maximum sensitivity is found when

$$\frac{dS}{dR} = 0 \Rightarrow \frac{E_i(R - R_i)}{(R + R_i)^3} = 0 \Rightarrow R = R_i$$

for maximum sensitivity we should take $R_i = R$. *But since R is a* variable, we may select the value of R_i *only for the range of R where the sensitivity* is to be a maximum.

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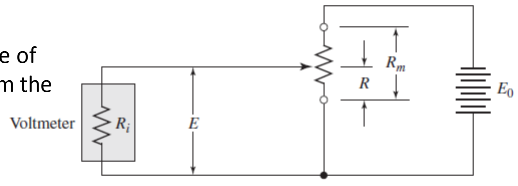
Simple voltage divider

If the impedance of the meter is sufficiently high, the indicated voltage *E will be directly* proportional to the variable resistance *R; that is,*

$$\frac{E}{E_o} = \frac{R}{R_m} \qquad for\ R_i >> R$$

Considering the internal resistance of the meter, the current drawn from the voltage source is



$$i = \frac{E_o}{R_m - R + R_i R/(R + R_i)}$$

$$\frac{E}{E_o} = \frac{R/R_m}{(R/R_m)(1 - R/R_m)(R_m/R_i) + 1}$$

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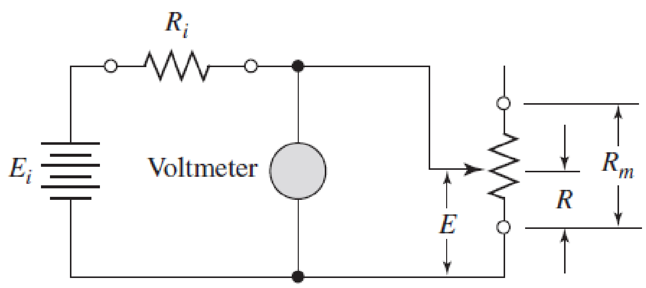
Example [1]

The output of a transducer with a total resistance of 150 is to be measured with a voltage-sensitive circuit like that shown in Fig. . The sensitivity is to be a maximum at the midpoint of the transducer. Calculate the sensitivity at the 25 and 75 percent positions, assuming a voltage source E_i of *100 V.*



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Example [1]

Solution

For maximum sensitivity at the midpoint of the range, we take

$$R_i = R = \frac{1}{2} R_m = 75\Omega$$

At the 25 percent position R = (0.25)(150) = 37.5, and the sensitivity is calculated from

$$S = \frac{dE}{dR} = \frac{E_i R_i}{(R + R_i)^2} = \frac{(100)(75)}{(37.5+75)^2} = 0.592\, V/\Omega$$

At the 75 percent position the corresponding sensitivity is

$$S = \frac{(100)(75)}{(112.5+75)^2} = 0.213\, V/\Omega$$

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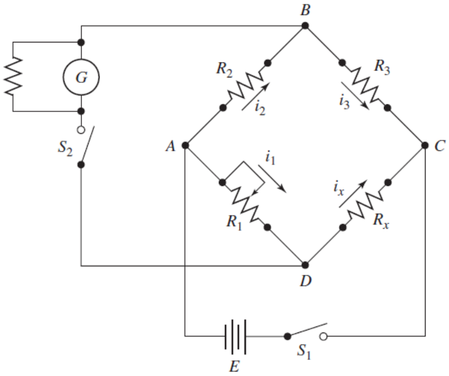
Wheatstone bridge

- The Wheatstone bridge is normally used for the comparison and measurement of resistances in the range of 1Ω *to 1 MΩ.*
- The figure to the right shows an example of typical Wheatstone.
- the bridge consists of the four resistances (*R1, R2, R3, Rx*), *which are arranged in a diamond shape. R2 and R3 are normally known resistors, R1 is a variable resistance, and Rx is the unknown resistance value associated with* the transducer output.



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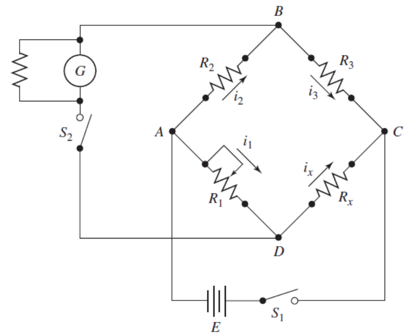
Wheatstone bridge

Balanced and unbalanced bridge



➢Balanced bridges means that the potential between points B and D equal Zero when the voltage E is applied to the circuit by closing switch S1.

➢To examine the balanced bridge condition, we can close switch S2 and if the sensing device (G) reads no current then, the bridge is balanced and if it reads some current then the bridge is unbalance

➢We can balance the bridge by varying R1 until (G) reads zero current.

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Wheatstone bridge

Resistances relations

➢If the bridge is balanced bridge, then:

$$V_1 = V_2 \Rightarrow i_1 R_1 = i_2 R_2 ---(1)$$

➢Also $i_2 = i_3 = \dfrac{E}{R_2 + R_3}$ and $i_1 = i_x = \dfrac{E}{R_1 + R_x} ---(2)$

➢Rearrange Eqs (1) and (2)

$$\frac{R_2}{R_3} = \frac{R_1}{R_x} \Rightarrow R_x = \frac{R_1 R_3}{R_2} ---(3)$$

➢Now we can determine the value of the unknown resistance Rx if

1. We guarantee that the bridge is balanced (G reading is zero)
2. The values of R_1, R_2 and R_3 are known

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Wheatstone bridge

Ratio arms

➢In bridges the term ratio arm is a used to describe two adjacent resistances (for example R_2 and R_3 or R_1 and R_x)

Alternating current (AC) measurement

➢There are some bridge arrangements used to measure AC current.

➢In these bridges, the inductance and the capacitive elements are used to balance the fluctuating in the signal.

➢Table 4.1 represent some of these circuits.

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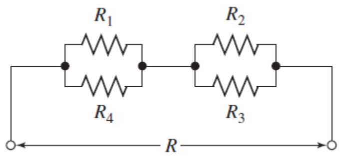
Unbalanced bridges

➢Again, unbalanced bridge is the bridge that has a current reading measured by the sensing device G (Galvanometer).

➢The unbalanced bridges is helpful when measuring the dynamic signal behavior specially when there is no time to achieve balanced condition.

➢If we are looking from the point of view of the galvanometer, the effective resistance of the bridge (R) will be



$$R = \frac{R_1 R_4}{R_1 + R_4} + \frac{R_2 R_3}{R_2 + R_3}$$

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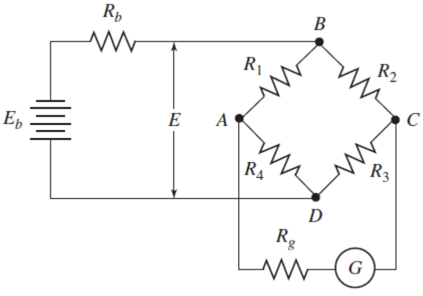
Unbalanced bridges

➢If the unbalance is very small, the resistance R_b will not affect the effective resistance of the bridge fro m the point of view of the galvanometer. So:

$$i_g = \frac{E_g}{R + R_g}$$



➢Where:

1. i_g is the current detected by the galvanometer
2. E_g is the galvanometer voltage and its found as:

$$E_g = E\left[\frac{R_1}{R_1 + R_4} - \frac{R_2}{R_2 + R_3}\right]$$

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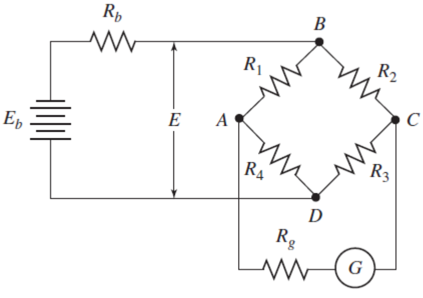
Unbalanced bridges

➢For small unbalance we can also assume that the galvanometer is not connected and the resistance of the total bridge circuit as seen from the battery point of view is designated as Ro and equal to:

$$R_o = \frac{(R_1 + R_4)(R_2 + R)}{R_1 + R_4 + R_2 + R_3}$$



➢Now the voltage of the bridge circuit (E) determined as:

$$E = E_b \frac{R_o}{R_o + R_b}$$

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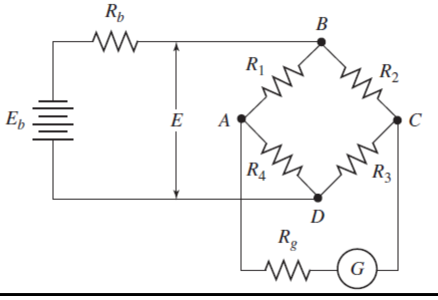
Example [2]

Example 4.4

DEFLECTION BRIDGE. The Wheatstone bridge circuit of Fig. 4.24 has ratio arms (R_2 and R_3) *of 6000 and 600 . A galvanometer with a resistance of 70 and a sensitivity of* 0.04 *μA/mm is connected between B and D, and the adjustable resistance R1 reads 340 . The* galvanometer deflection is 39 mm, and the battery voltage is 4V. Assuming no internal battery resistance, calculate the value of the unknown resistance *R. Repeat for R2 and R3 having values* of 600 and 60 , respectively.



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Example [2]

Solution

- the bridge is operated on the deflection principle
- The galvanometer current is calculated from the deflection and sensitivity as

$$i_g = (39)(0.04\times10^{-6}) = 1.56\ \mu A$$

- *Now the resiatance are*

$$R_b = 0\ R_1 = 340\ R_2 = 6000\ R_3 = 600\ R_4 = R_x\ R_g = 70$$

- *Also we have the voltage*

$$E = 4.0V.$$

- *To find R4, combine* $i_g = \dfrac{E_g}{R + R_g}$ *and* $E_g = E\left[\dfrac{R_1}{R_1 + R_4} - \dfrac{R_2}{R_2 + R_3}\right]$

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Example [2]

Solution

- The relation become

$$R_4 = \frac{ER_1R_3 - i_g\left[R_gR_1(R_2+R_3)+R_1R_2R_3\right]}{i_g(1+R_1+R_G)(R_2+R_3)+ER_2}$$

$$R_4 = \frac{(4)(340)(600)-1.56x10^{-6}[(70)(340)(6000+600)+(340)(6000)(600)]}{1.56x10(1+340+70)(6000+600)+(4)(6000)}$$

$$R_4 = 33.93\Omega$$

- now when we take R_2 = *600 and* R_3 = *60, we have* $R_4 = 33.98\Omega$

E n g i n e e r i n g m e a s u r e m e n t s

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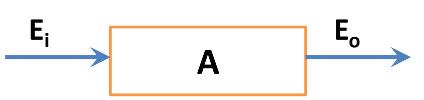
Basic electrical elements

Amplifier

- Amplifiers are electrical devices used to amplify the signal measured by the transducer to reach a sufficient level of power

- The value of the amplification is called the gain (A)



$$E_o = AE_i$$

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Amplifier

Types

There are two types of amplifiers:

1. Differential amplifier
2. Operational amplifier

Differential amplifier

- A *differential or balanced amplifier is a device that provides for two inputs and an* output proportional to the *difference in the two input voltages*
- is particularly useful for amplification and measurement of small signals subjected to stray electric fields (typically line voltage at 60 Hz and 115 V).

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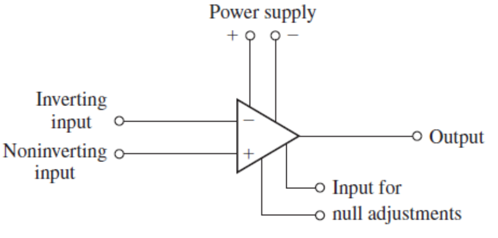
Amplifier

Operational amplifier (op-amp)

is a dc differential amplifier incorporating many solid-state elements in a compact package and shown schematically in Fig



The (+) input is called the *noninverting input because the output from this source is in phase* with the input. The *inverting input (−) has the opposite behavior; that is, the output* resulting from that source is 180° out of phase with the input

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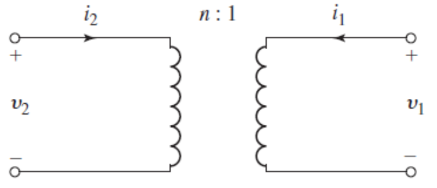
Transformers

Transformers are used to match impedance in many experimental situations.
Fig. show an ideal *n-turn transformer*



Mathematical relations

$$v_2 = nv_1 \; and \; i_2 = \frac{1}{n} i_1 \Rightarrow \frac{v_2}{i_2} = n^2 \frac{v_1}{i_1} \Rightarrow Z_2 = n^2 Z_1$$

v is the voltage
i is the current
Z is the impedance

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Signal Conditioning

- Noise is present in all physical situations in which measurements are attempted or information is conveyed.
- In general, the noise in measurements is represented as a range of frequency that is not related to the range of frequency of the measured variable.
- To reduce the noise, the range of measurement frequency must be defined and the other ranges where the noise may lie is eliminated.
- The elimination process is called filtering and the device used for this prepuce is called filter.

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Filters

- Filters are electrical devices that pass a certain desired range or band of frequencies.

- The unwanted parts of the signal can be characterized as noise, but in addition, there is also noise present in the frequency band of interest

Filter types

- Low-pass circuits
- High-pass circuits
- Band-pass circuits

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Filter types

Low-pass circuits: **permits the transmission of signals with frequencies below a certain cutoff value with little or no attenuation**

High-pass circuits: **allows the transmission of signals with frequencies above a cutoff value**

Band-pass circuits: **permits the transmission of signals with frequencies in a certain range or band while attenuating signals with frequencies both above and below the limits of this band**

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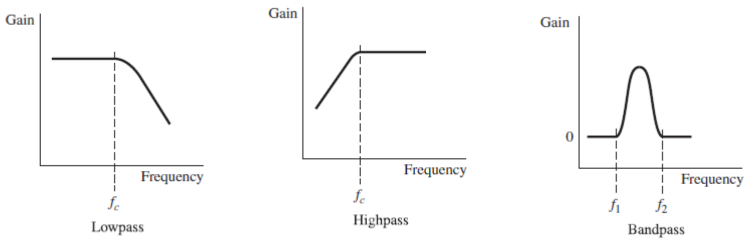
Filter types



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The gain

A measurement of the degree of amplification or attenuation provided by a circuit is given by its gain or amplification ratio.

$$Gain = \frac{output}{input}$$

In engineers language, we give the gain the decibel unit in spite of its dimensionless nature .

$$Decibel(dB) = 10\log\frac{P_2}{P_1}$$

where P_1 and P_2 are the input and output powers

Decibel in term of voltage and current

$$dB = 20\log\frac{E_2}{E_1} = 20\log\frac{I_2}{I_1}$$