

ROBERT BOYLESTAD and LOUIS NASHELSKY

***ELECTRICITY,
ELECTRONICS,
and
ELECTROMAGNETICS***
Principles and Applications

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Principles and Applications

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three), as shown in Fig. 2.53 with a photograph of a typical commercial bridge. The resistors, R_1 , R_2 , and R_3 are then adjusted until the current through the movement is zero. The equation can then be applied and the unknown resistor determined by $R_4 = R_{\text{UNK}} = R_2 R_3 / R_1$. As indicated in the figure the actual instrument is not made as basically simple as indicated by the network of Fig. 2.53, but the principle of operation is exactly the same. The bridge configuration will see further application in this chapter and in those to follow. For now, take note of its unique characteristics and appearance.

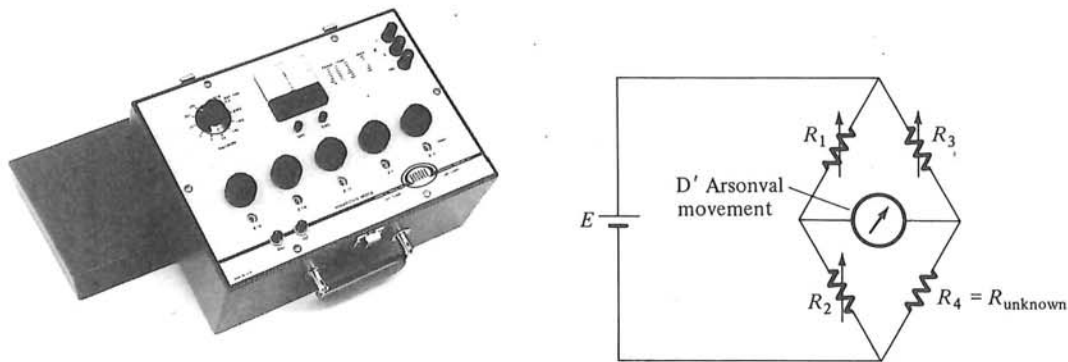


Figure 2.53 Wheatstone bridge. (Courtesy James G. Biddle Co.)

2.12 CAPACITORS

Thus far our interest has been solely in the basic dc sources and resistors. There are two other very important elements called the capacitor and inductor that we must now consider since they play a very important role in the behavior of electrical systems. This section will introduce the capacitor, while Section 2.13 will be devoted to the inductor.

The construction of each is basically quite simple. The capacitor in its most fundamental form has simply two conducting surfaces separated by a dielectric (a type of insulator) as shown in Fig. 2.54. The label capacitor comes from the *capacity* of the element to store a charge on its plates. The larger its capacitance, the more charge will be deposited on its plates for the same voltage across the plates. In equation form, capacitance is defined by

$$C = \frac{Q}{V} \quad \text{farads (F)} \quad (2.27)$$

Note that the unit of measurement is the *farad*, although microfarads (μF) and picofarads (pF) are more common values of capacitor values.

For the system of Fig. 2.54, we shall assume that the plates are initially uncharged

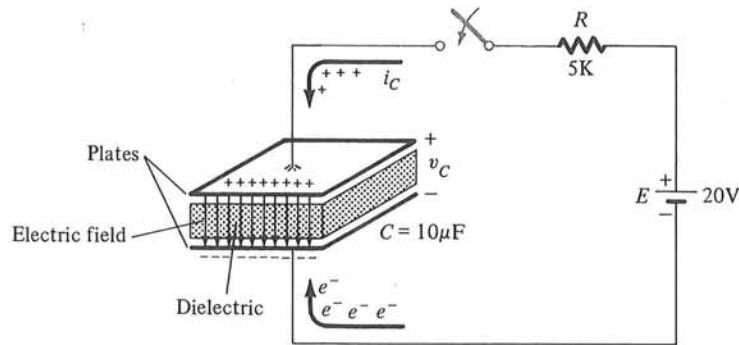


Figure 2.54 Charging capacitor.

and the switch open. When the switch is closed positive charges from the battery will be deposited on the top plate of the capacitor and negative charges on the lower plate. The result of this charge flow from source to capacitor is a current i_C that initially jumps to a value limited by the resistor R and then decreases toward zero. In other words, the charging rate of the plates is initially very heavy and then decreases quite rapidly to zero. The result of the deposited charge is an *electric field*, shown between the plates of the capacitor in Fig. 2.54, that extends from the positive to the negative charges. Since the voltage is directly related to the charge on the plates through Eq. (2.27) and the charging of the plates cannot occur instantaneously, the *voltage of a capacitor cannot change instantaneously*. It takes a definite amount of time determined by the circuit elements, which will be examined later in this section.

A plot of the current i_C vs. time would result in the exponential curve of Fig. 2.55. Note that the current jumped to a peak value of $E/R = 20/5\text{ K} = 4\text{ mA}$ and then decreased to zero exponentially. For most practical applications the time required to decay to zero is approximately 5τ , where τ (tau), called the *time constant* of the circuit, is determined by

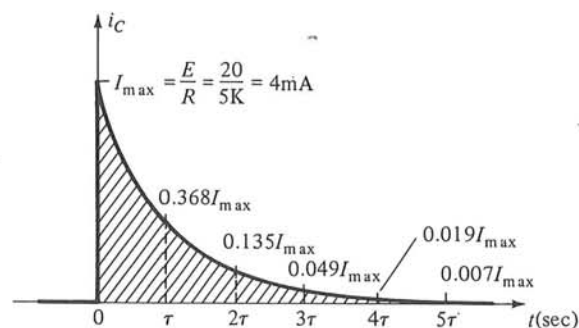
$$\tau = RC \quad (\text{seconds}) \quad (2.28)$$

For the network of Fig. 2.54,

$$\tau = RC = (5\text{ K})(10\text{ }\mu\text{F}) = (5 \times 10^3)(10 \times 10^{-6}) = 50 \times 10^{-3} = 50\text{ ms}$$

and the discharge time is

$$5\tau = 5(50\text{ ms}) = 250\text{ ms} = 0.25\text{ sec} = \frac{1}{4}\text{ s}$$

Figure 2.55 Charging current i_C of Fig. 2.54.

In equation form, the current i_C is the following:

$$i_C = \frac{E}{R} e^{-t/\tau} \quad (2.29)$$

Since the exponential function in the form e^{-x} , or $1 - e^{-x}$ appears quite frequently in the analysis of electrical systems, a plot of the function and its value at each time constant appears in Fig. 2.56. Note that after one time constant, the curve, and therefore i_C above, drops to 36.8% of its peak value, while at five time constants it is down to 0.7% of its peak value (less than 1%).

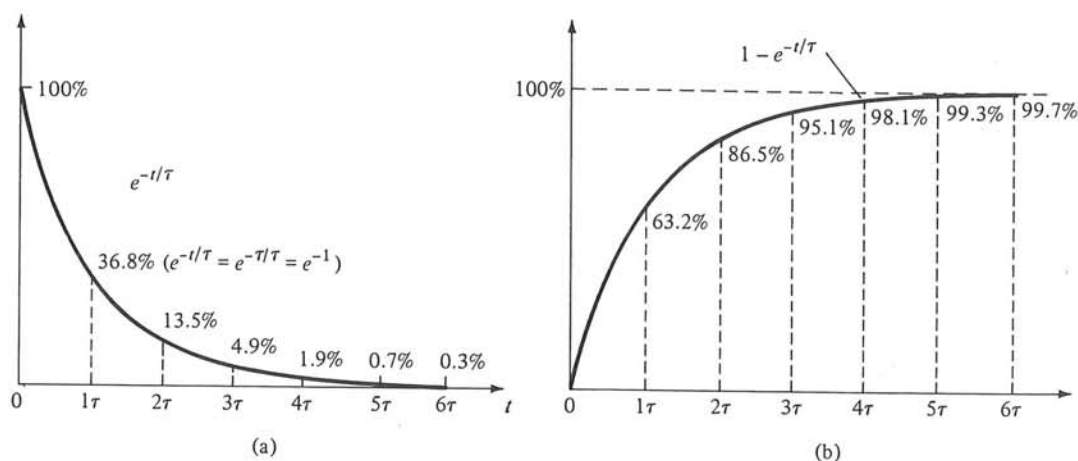


Figure 2.56 Functions: (a) $e^{-t/\tau}$, (b) $1 - e^{-t/\tau}$.

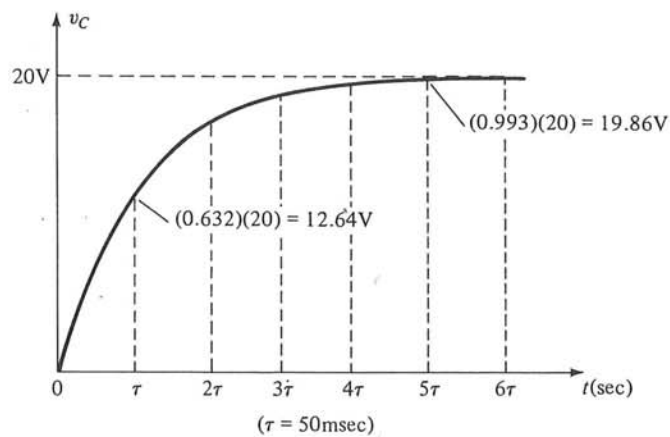
The voltage v_C will build up to a maximum value of $E = 20$ V at a rate directly related to the rate in which charge is deposited on the plates. Note from the plot of v_C in Fig. 2.57 that it reaches 63.2% of its final value in only one time constant and 99.3% in five time constants. The curve of Fig. 2.57 can be described by the following equation:

$$v_C = E(1 - e^{-t/\tau}) \quad (2.30)$$

Note the presence of the same experimental function which will dictate that v_C reach its final value of E volts at the same instant i_C decays to zero. Consider the importance of the following statement, which will be used to full advantage in the chapters to follow: When $v_C = E = 20$ V and $i_C = 0$ A (after approximately five time constants) the capacitor has the characteristics of an *open circuit*. In electronic systems this characteristic can be used to *block* dc from reaching certain points in the network.

Since $v_R = i_R R = i_C R$ and R is a constant, the voltage of v_R will have the same shape as the i_C curve and a peak value of 20 V.

The general behavior of the capacitor in a simple dc switching situation is thus described. The factors that affect the capacitance of a capacitor appear in the following equation:

Figure 2.57 Increasing voltage v_C of Fig. 2.58.

$$C = \epsilon_0 \epsilon_r \frac{A}{d} \quad (2.31)$$

where ϵ_0 = permittivity of air (8.85×10^{-12})

ϵ_r = relative permittivity

A = area in square meters

d = distance between plates in meters

The equation indicates quite clearly that the larger the area of the plates or the smaller the distance between the plates, the larger the capacitance. The factor ϵ , called the permittivity of the material, is a measure of how well the dielectric between the plates will "permit" the establishment of field lines between the plates. The insertion of these insulators between the plates will increase the capacitance above that with simply air between the plates by a factor of ϵ_r , the *relative permittivity*, given by $\epsilon_r = \epsilon/\epsilon_0$. Table 2.8 lists a few dielectrics with their ϵ_r values.

Table 2.8
Relative Permittivity

DIELECTRIC	ϵ_r
Vacuum	1.0
Air	1.0006
Teflon	2.0
Paper, paraffined	2.5
Rubber	3.0
Transformer oil	4.0
Mica	5.0
Porcelain	6.0
Bakelite	7.0
Glass	7.5
Water	80.0

The most common types of capacitors are the mica, paper electrolytic, ceramic, and air, all of which appear in Fig. 2.58(b) with the symbol for the fixed and variable device in Fig. 2.58(a). The basic construction of every commercial capacitor leans toward making the capacitance its largest value while still limiting its size. For the ceramic type, two conducting surfaces are "rolled" together (with a ceramic dielectric between them) to make the area factor a maximum. For the mica capacitor, maximum area is obtained by "stacking" the plates (with the mica dielectric between them) and connecting the proper plates together. For the air capacitor the common area between

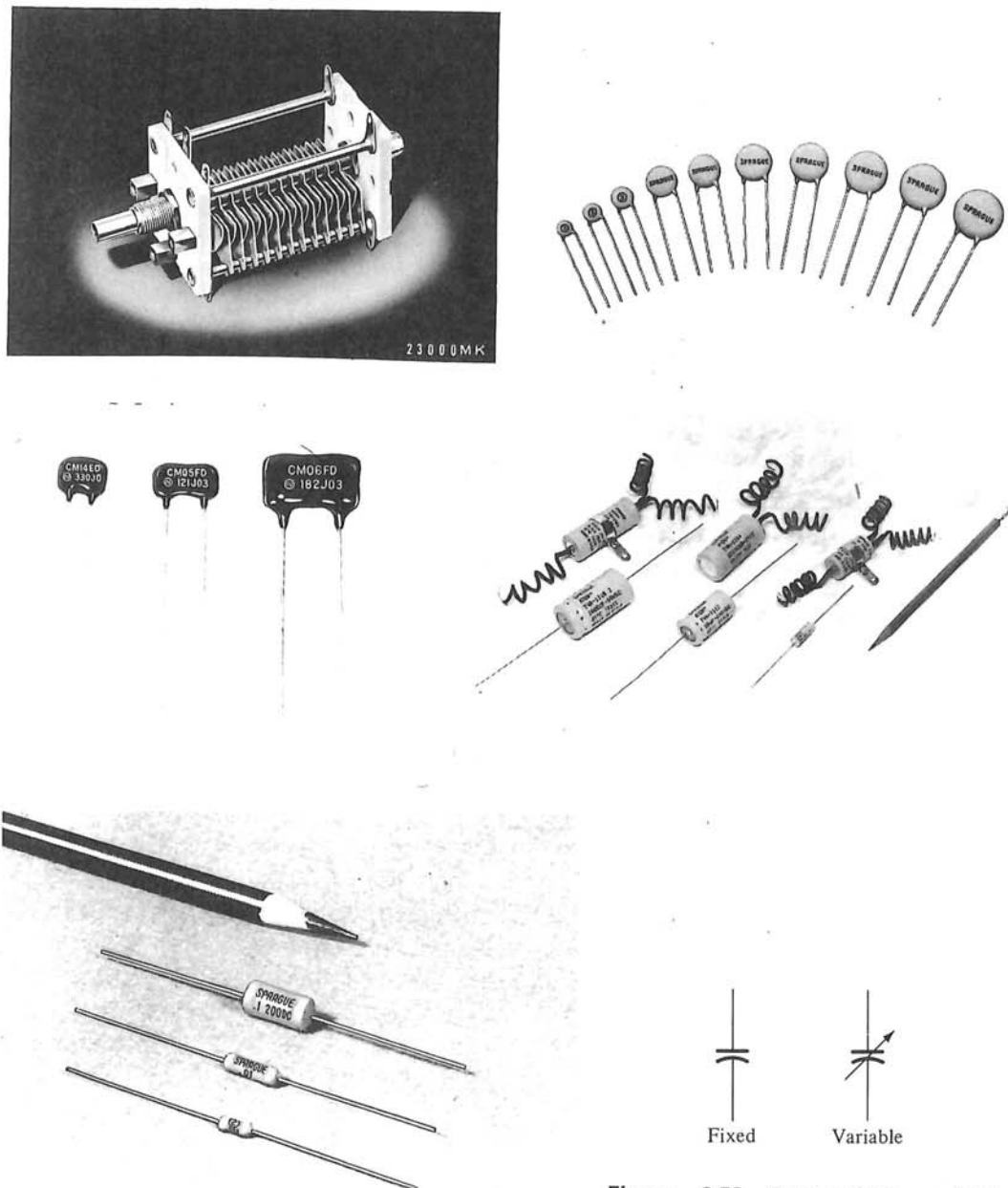


Figure 2.58 Commercially available capacitors with their graphic symbols.

the stacked plates is made adjustable (for various values of capacitance) by a control knob that can move one set of plates.

If possible, the capacitance value is stamped right on the capacitor. However, some very small mica and ceramic capacitors require the use of a color-coding system, described in Fig. 2.59. Note that the numerical values associated with each color are exactly the same as applied to the color coding of resistors.

Capacitors connected in parallel are treated like resistors in series when it comes to determining the total capacitance. That is, for the parallel capacitors of Fig. 2.60, the total capacitance is determined by

$$C_T = C_1 + C_2 + C_3 + \cdots + C_N \quad (2.32)$$

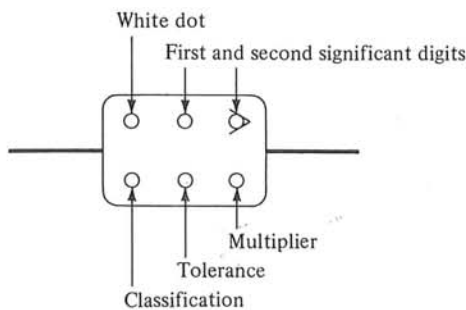


Figure 2.59 Capacitor color coding.

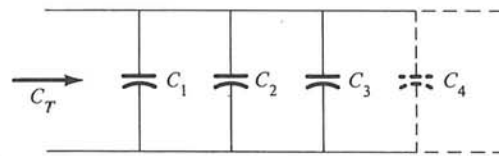


Figure 2.60 Parallel capacitors.

For capacitors in series, the equation relates directly to that obtained for parallel resistors. That is, for the capacitors of Fig. 2.61, the total capacitance is determined by

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_N} \quad (2.33)$$

For two series capacitors,

$$C_T = \frac{C_1 C_2}{C_1 + C_2} \quad (2.34)$$

The above equations can understandably be quite useful if a particular capacitance value is not available and must be obtained through a combination of available values.

Although an insulator (the dielectric) is placed between the plates, there is a

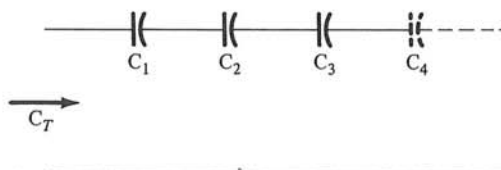


Figure 2.61 Series capacitors.

very small flow of charge between the plates called *leakage current*. If a capacitor is fully charged and then removed from the network and set aside, it will only be able to hold onto its charge for a limited amount of time due to the resulting leakage current through the dielectric that will deplete the plates of their charge. Keep in mind, however, that this leakage current is usually very very small and can be ignored for most practical applications.

In addition to the capacitance obtained through commercial design, there is a measure of capacitance between any two conducting or charged surfaces in an electronic system. This usually undesirable capacitance is called *stray capacitance* and can have, if not carefully considered, a pronounced effect on the performance of some electronic systems. In both the transistor and tube the stray capacitance between the elements of each can severely limit the range of operation of each in an electronic system unless properly considered.

For networks in which the value of R and C to be used in determining τ are not so evident an application of Thevenin's theorem can often be quite helpful, as demonstrated in Example 2.18.

EXAMPLE 2.18

Determine the mathematical expression for v_C if the switch is closed at $t = 0$ in Fig. 2.62.

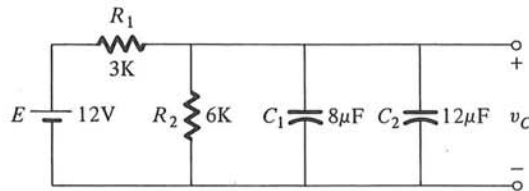


Figure 2.62

Solution:

The total capacitance of the parallel capacitors is given by

$$C = C_1 + C_2 = 8 + 12 = 20 \mu\text{F}$$

The value of R to be used is not evident. Applying Thevenin's theorem to the network of E , R_1 , and R_2 we find that $R_{Th} = R_1 \parallel R_2 = 3 \parallel 6 = 2 \text{ K}$ (remember that the source E is set to zero when R_{Th} is determined).

$$E_{Th} = \frac{R_2(E)}{R_2 + R_1} = \frac{6(12)}{6 + 3} = \frac{2}{3}(12) = 8 \text{ V}$$

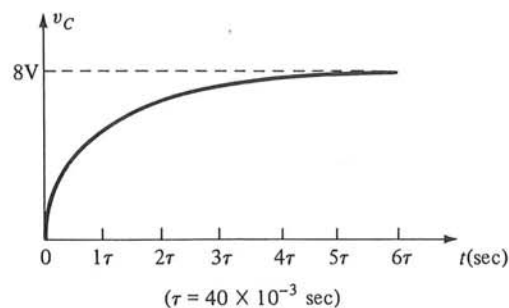


Figure 2.63 Voltage v_C of Fig. 2.62.

and

$$\tau = R_{Th}C = (2\text{ K})(20 \times 10^{-6}) = 40 \times 10^{-3} = 40\text{ ms}$$

with

$$v_C = E(1 - e^{-t/\tau}) = E_{Th}(1 - e^{-t/\tau})$$

or

$$v_C = 8(1 - e^{-t/40 \times 10^{-3}})$$

A plot of v_C appears in Fig. 2.63.

One very interesting characteristic of the capacitor is that the current i_C is not related directly to the magnitude of the voltage across the capacitor but to its *rate of change* of voltage across the capacitor. That is, the faster the rate of change of voltage across the capacitor, the greater the resulting i_C . An applied dc voltage of 100 V would (after 5τ of switching the network on) result in effectively zero current since the voltage does not change with time. In equation form, i_C and v_C are related by

$$i_C = C \frac{dv_C}{dt} \quad (2.35)$$

where dv_C/dt is a measure of the instantaneous rate of change of v_C with time. The notation d is employed in *differential calculus*, which most college-level students have had some exposure to but which will not be a prerequisite for the material to follow. The equation clearly indicates that if v_C fails to change, $dv_C/dt = 0$ and hence i_C will be zero.

The capacitor and the inductor (to be described in the next section) are quite different from the resistor when we consider the transfer of energy to these elements. We have learned in the previous sections that the resistor dissipates the energy delivered to it in the form of heat. The ideal capacitor, however (if we ignore the leakage current), *does not dissipate* the energy delivered to it but simply stores it in the form of the electric field that through design can be returned to the system as electrical energy. In other words, the capacitor, unlike the resistor, is an energy-storing element and not a dissipative one like the resistor.

2.13 INDUCTORS

The inductor, or coil, as it is often called, has terminal characteristics that are in many ways similar to those of the capacitor, although the roles of the voltage and current are interchanged. Fundamentally, the inductor is a coil of wire such as shown in Fig. 2.64 with or without a core in the center. When the switch is closed in the circuit of Fig. 2.64 the current i_L will pass through the wire of the coil and establish a magnetic field *linking* (passing through) the coil as shown in the figure. Magnetic effects will be discussed in detail in chapter 4. Suffice it to say here that magnetic flux lines are continuous lines that indicate through their density the strength of a magnetic field in a particular region. For the inductive network there is an interchange between the electrical energy of the network and the magnetic field of the inductive elements. Like the capacitor, the inductor (ideally speaking) *does not dissipate electrical*

For the complete cycle of Fig. 3.14(a),

$$G = \frac{A_1 - A_2}{T} = \frac{(8)(5) - 2(5)}{10} = \frac{40 - 10}{10} = \frac{30}{10} = 3 \text{ V}$$

indicating that the square wave of Fig. 3.14(a) could be generated using the two components of Fig. 3.14(b).

For waveforms where the area cannot be obtained as directly as in the above example, try to approximate the odd shape using figures such as rectangles and triangles for which the area can easily be obtained. This technique will at least result in a numerical value that will permit further examination of the network at least on an approximate basis. Some mathematics texts list the areas under some of the more complicated mathematical functions, or if you are so versed, integral calculus can be employed.

3.5 THE R , L , AND C ELEMENTS

The effect of an ac sinusoidal signal on the basic R , L , and C elements can now be examined. Although certain statements of fact will have to be made without full derivation or explanation, be assured that the material will be more than complete to permit a full understanding of the more advanced material to follow.

In Fig. 3.15, a sinusoidal voltage has been applied across the resistor. As shown by the resulting current in the same figure, the peak values are related directly by Ohm's law. In addition, there is no phase shift introduced by the resistor, so v_R and i_R are said to be *in phase*. Note that the frequency of both v_R and i_R is also the same.

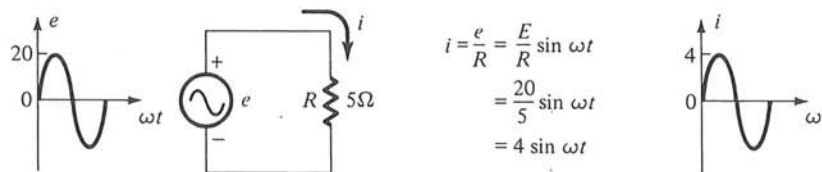


Figure 3.15 Simple ac resistive network.

The power to the resistor can be determined from the *effective* values of the voltage and current in the following manner:

$$P_R = I_R^2 R = \frac{V_R^2}{R} = V_R I_R \quad (\text{watts}) \quad (3.17)$$

For the case of Fig. 3.15,

$$P_R = V_R I_R = \left[\frac{20}{\sqrt{2}} \right] \left[\frac{4}{\sqrt{2}} \right] = \frac{80}{2} = 40 \text{ W}$$

Note the similarities between the forms of Eq. (3.17) and those used for dc networks. The *only* difference is that here we have effective values to determine from the sinusoidal functions.

The reaction of a coil or capacitor to an ac signal is quite different from the reaction of a resistor. Both elements react to the sinusoidal signal in a manner somewhat similar to the resistor in the sense that they can limit the current but neither (ideally speaking) will dissipate any of the electrical energy delivered to it. It will simply store it in the form of a magnetic field for the inductor, or electric field for the capacitor, with the ability to return it to the electrical system as required by design.

For the inductor the *reactance* to an ac signal is determined by

$$X_L = \omega L = 2\pi fL \quad (\text{ohms}) \quad (3.18)$$

Although reactance is similar to resistance in its ability to limit the current, always keep in mind that it is not an energy-dissipating form of opposition as noted in the previous paragraph.

Note that inductive reactance is directly proportional to the frequency of the applied signal. Increasing frequencies result in an increasing reactance magnitude. Recall that the ideal inductor had a short-circuit equivalent in dc networks. Certainly for dc, $f = 0$, and we find that the reactance of the inductor is $X_L = 0L = 0 \Omega$, corresponding to that conclusion.

A sinusoidal voltage has been applied across a 0.5 H inductor in Fig. 3.16. First, the reactance of the inductor at the applied frequency is 188.5Ω . Ohm's law can be applied to determine the peak value of the current. That is,

$$I_{\text{peak}} = \frac{V_{\text{peak}}}{X_L} = \frac{20}{188.5} = 106 \times 10^{-3} = \underline{106 \text{ mA}}$$

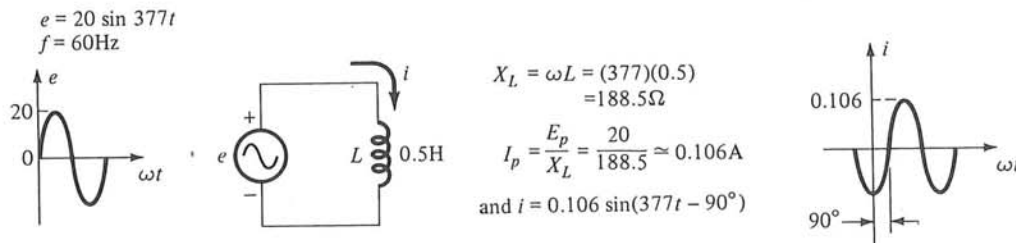


Figure 3.16 Simple ac inductive network.

as shown in Fig. 3.16. Note that the voltage applied across the inductor *leads* the resulting current by 90° . The inductor, therefore, introduces a 90° phase shift between the two quantities not present for the pure resistor.

For an ac system the basic equation for power becomes the following due to the effect of the reactive elements such as the inductor and capacitor:

$$P = \frac{V_p I_p}{2} \cos \theta = V_{\text{eff}} I_{\text{eff}} \cos \theta \quad (\text{watts}) \quad (3.19)$$

As indicated by Fig. 3.17, V_{eff} is the voltage across the elements or network to which the power is to be determined, while I_{eff} is the current drawn by the network.

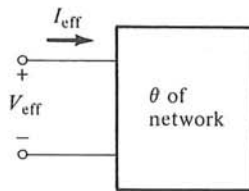


Figure 3.17 Power in an ac network.

The angle θ is the phase angle between V_{eff} and I_{eff} . For a pure resistor in the container, we found that v and i were *in phase* and that $\theta = 0^\circ$. Substituting into the equation will result in $P = VI \cos \theta = VI(1) = VI$ (from this point on the symbols V and I will refer to V_{eff} and I_{eff} , respectively), as indicated earlier. For the pure inductor $\theta = 90^\circ$ and $P = VI \cos 90^\circ = VI(0) = 0 \text{ W}$, indicating, as stated earlier, that the pure inductor does not dissipate electrical energy but simply stores it in the form of a magnetic field.

For the pure capacitor, the reactance is determined by

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} \quad (\text{ohms}) \quad (3.20)$$

indicating that as the frequency increases the reactance of a capacitor decreases (opposite to that of the inductor). In addition, for $f = 0$, corresponding with the dc condition, $X_C = 1/0C = \infty \Omega$ = very large value corresponding with an open-circuit equivalent as described for dc networks.

A sinusoidal voltage has been applied across a $10\text{-}\mu\text{F}$ capacitor in Fig. 3.18.

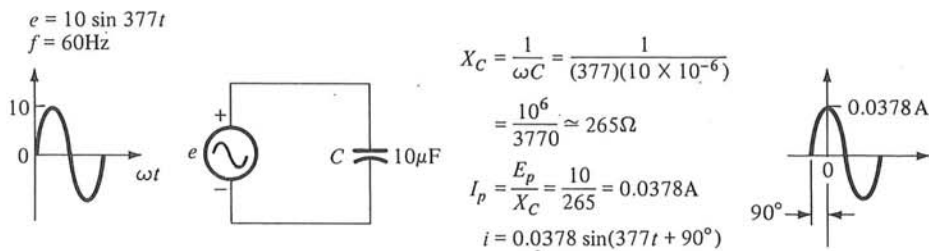


Figure 3.18 Simple capacitive ac network.

The reactance X_C as shown in the figure is 265Ω , and the peak value of the current can be determined through a simple application of Ohm's law. That is,

$$I_p = \frac{V_p}{X_C} = \frac{10}{265} = 0.0378 = \underline{37.8 \text{ mA}}$$

as shown in Fig. 3.18. Note in this case that a 90° phase shift has been introduced but that i_C *leads* v_C by 90° , which is the reverse of that encountered for the inductor. Substituting into the general power equation,

$$P_C = VI \cos \theta = VI \cos 90^\circ = VI(0) = 0 \text{ W}$$

substantiating the previous comments for the capacitor also.