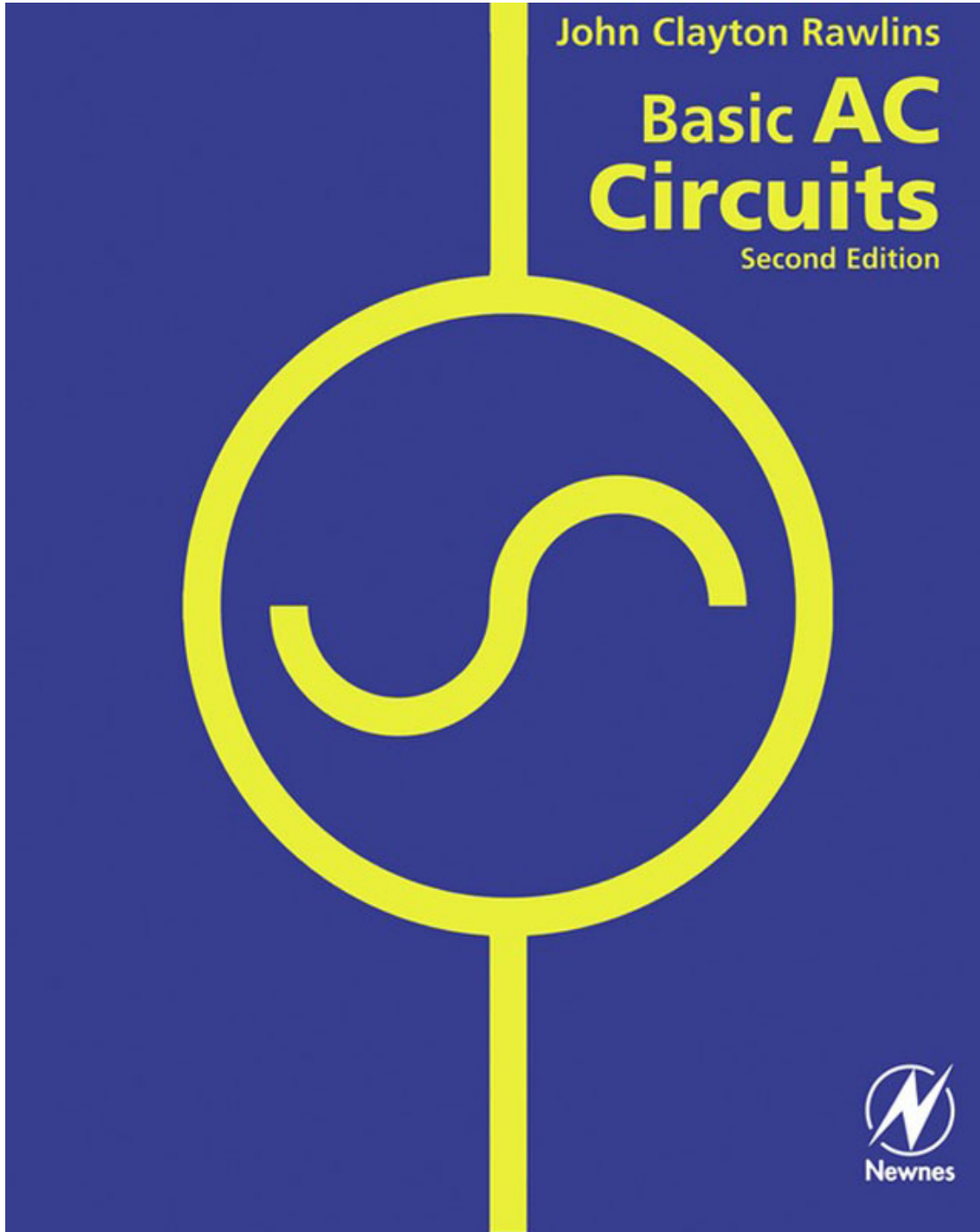




BASIC AC CIRCUITS

SECOND EDITION

John Clayton Rawlins, M.S.

*Instructor, Eastfield College, Dallas
County Community College District*



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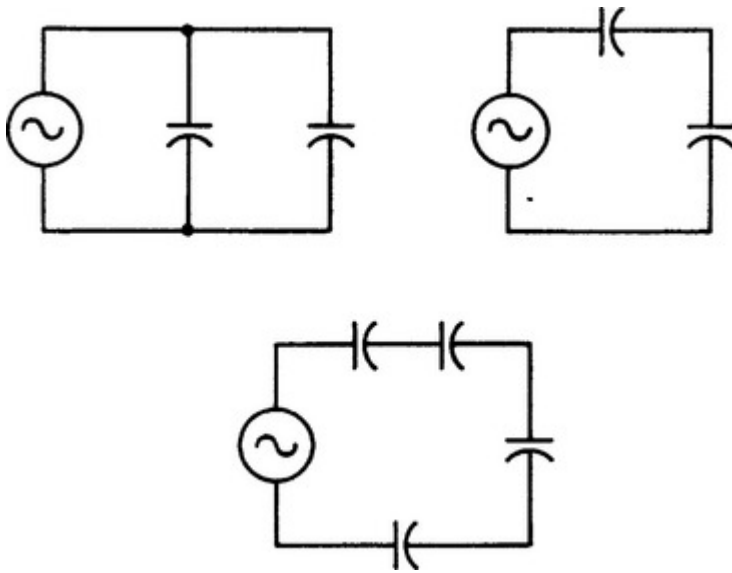
CHAPTER 6

Capacitance

In this chapter, the electrical property of capacitance and another electronic circuit component, the capacitor, are introduced. The physical and electrical properties of capacitors are discussed. Series and parallel capacitive ac circuits are described and analyzed. The capacitor and the effects of capacitive action in ac series and parallel circuits are described.

At the end of this chapter, you should be able to:

1. List the names of common types of capacitors and discuss the characteristics of each.
2. Define capacitance and the capacitive property.
3. Describe two effects of capacitors in ac circuits.
4. Describe the result of using different types of dielectrics, different sizes of plates, and increasing the distance between the plates of capacitors.
5. Given a schematic diagram of the types shown and typical circuit values, you should be able to calculate capacitance, capacitive reactance, current, voltage, and power for each capacitor and for the circuit total.



INTRODUCTION

In the previous chapter, discussion concerned the action of alternating current in resistive circuits. As you probably noted, this concept was very similar to an analysis of direct current in resistive circuits. Resistor series, parallel, and series-parallel circuits were analyzed. Total and individual values of current, voltage, resistance, and power were determined for each of these types of circuits.

In this chapter, capacitive properties and the effects of capacitance in ac circuits will be described and circuits containing capacitors connected in series and parallel will be analyzed.

Capacitors, like resistors, do not amplify or increase voltage or current. However, they perform a unique function by storing an electrical charge. This has the effect of opposing any changes in voltage.

PROPERTIES OF CAPACITANCE

Definition Of Capacitance

The ability of a nonconductor to store an electrical charge is called *capacitance*. This capability is particularly important for applications that require short bursts of relatively large amounts of current. For example, a

flash tube for a camera uses a burst of current to produce light for a fraction of a second. An electronic ignition system in a car has a capacitor in it to help provide interrupted current conditions that produce the high voltage for the spark discharge. Spot-welding equipment uses a capacitor to obtain peak current almost instantaneously. Capacitors are also used in medical equipment. For example, in a defibrillator used to revive a patient's heartbeat, a capacitor is discharged between two paddles that are applied to the patient's body. The paddles, thus, deliver a controlled amount of electrical energy to the patient.

PHYSICAL DESCRIPTION OF A CAPACITOR

Basic Schematic Symbol

Essentially, a capacitor is two conductive metal plates separated by an insulator. **Figure 6.1** shows a capacitor's schematic symbol. The straight and curved lines represent the two conducting plates of the capacitor. The space between the two lines is the *dielectric* of the capacitor. A dielectric is a nonconductor of electric current.

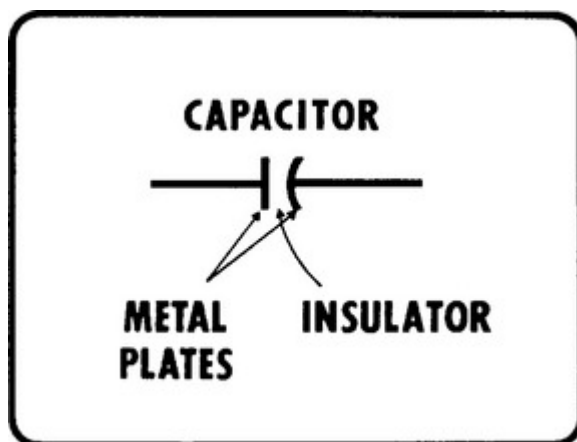


FIGURE 6.1 A Capacitor's Schematic Symbol

Types Of Capacitors

Different types of capacitors can be manufactured by using various materials for the dielectric, such as *paper*, *ceramic* (a porcelain or baked-clay material), *Teflon*^{*} (an inert, tough insoluble polymer), and *air*. Several

types of capacitors are shown in [Figure 6.2](#). More detail on various types of capacitors is presented later in this chapter.

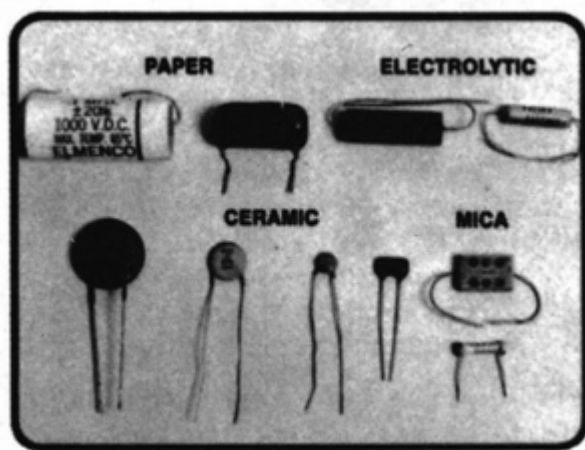


FIGURE 6.2 Several Types of Capacitors

Charging A Capacitor

How does a capacitor store a charge? In [Figure 6.3](#) two plates of a capacitor are shown in a circuit with a battery. Switch 1 is open. Therefore, the plates contain equal numbers of neutral atoms, positive ions, and free electrons that are associated with all conductive materials. This equality makes the plates electrically neutral. When a battery is connected between the two plates by closing switch 1, as shown in [Figure 6.4](#), current flows. (As in all other discussions in this book, current is *electron* current.) Current flows because the positive potential applied to plate A attracts free electrons from the neutral atoms of the plate. This action creates an excess of positive ions. The free electrons are pulled to the *positive* terminal of the battery. They are deposited on the *negative* terminal by the chemical action within the battery and repelled by the negative battery potential and then they collect on plate B of the capacitor. The creation of positive ions on plate A constitutes a net positive charge on the plate. The excess electrons on plate B creates a net negative charge on that plate. The difference between the charges on the two plates is a potential difference which is defined as voltage. If there is no restriction of current flow in the circuit, the voltage, or potential difference, between the plates of the capacitor becomes equal to the battery voltage very quickly.

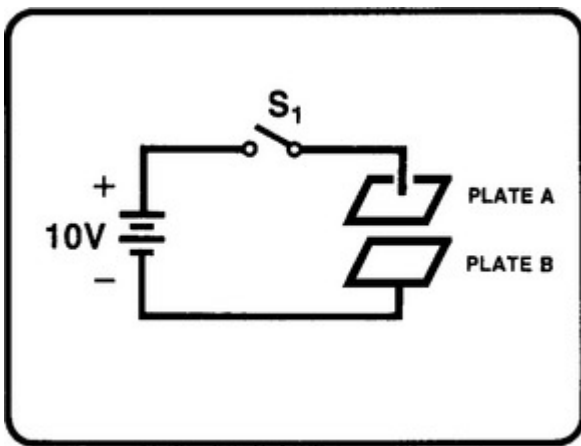


FIGURE 6.3 Plates of a Capacitor Normally Are Electrically Neutral

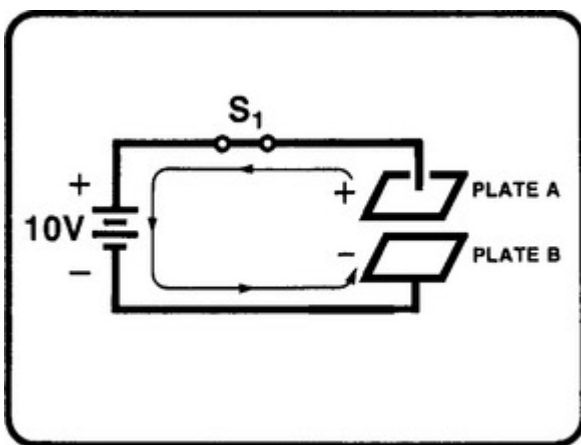


FIGURE 6.4 Capacitor Connected to a Battery and Charging

In [Figure 6.5](#), the positive potential on plate A is equal to the positive potential on the battery. Therefore, no more electrons are removed from the positive plate, A. The negative potential on plate B is equal to the negative potential on the battery. Therefore, the B plate cannot collect any more electrons. At this point the current in the circuit stops. The charges have been distributed on the positive and negative plates until the voltage across the capacitor is equal to the battery voltage, and the capacitor is fully charged. The amount of time necessary for the capacitor to charge and the values of voltage across the capacitor after different time periods are discussed in Lesson 10 of this book and in Lesson 13 of the TI Learning Center textbook *Basic Electricity and DC Circuits*.

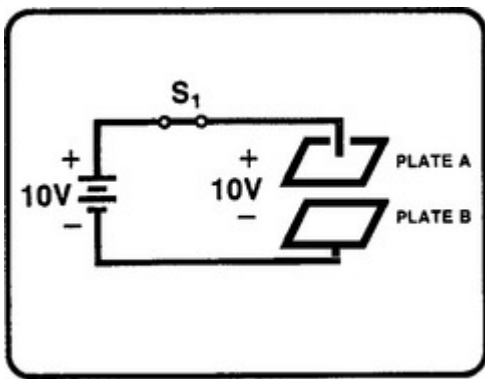


FIGURE 6.5 Capacitor Is Fully Charged
Storing A Charge

If the capacitor is disconnected from the battery by opening the switch as shown in [Figure 6.6](#), the attraction of the charges on the two plates maintains the potential difference between the two plates. Also, the dielectric (insulator) material prevents electrons from moving from plate B to neutralize the positive ions on plate A. Therefore, the charge is stored. By storing a charge equal to the applied battery voltage, the capacitor opposes any change in voltage which normally occurs when the battery is disconnected from the circuit.

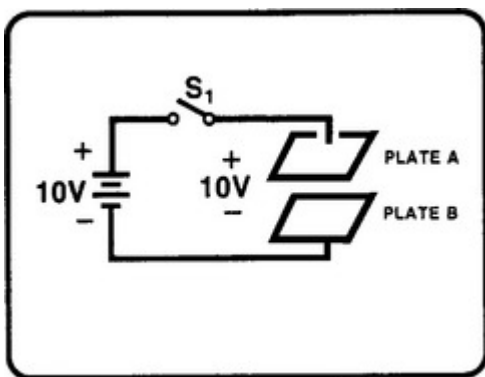


FIGURE 6.6 Charged Capacitor Disconnected from Battery

Discharging A Capacitor

To discharge the capacitor, a wire can be connected between the two plates, as shown in [Figure 6.8](#). Current flows for a short period of time, and the excess electrons from plate B flow back to plate A and neutralize the positive ions on plate A. Both plates return to their original neutral

condition, and current flow then stops as shown in **Figure 6.9**. The discharge time is related to the charge time. This also is discussed in **Chapter 10**.

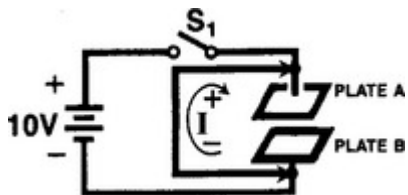


FIGURE 6.8 Capacitor Plates Discharging

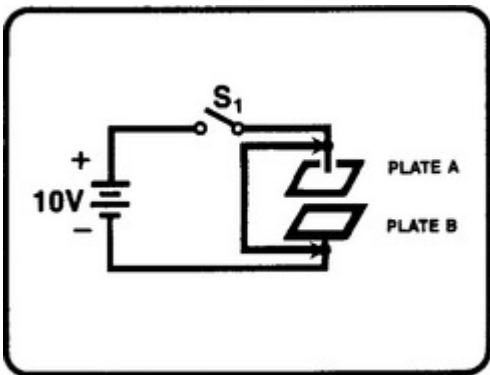


FIGURE 6.9 After Discharge Both Plates Are Once Again Electrically Neutral

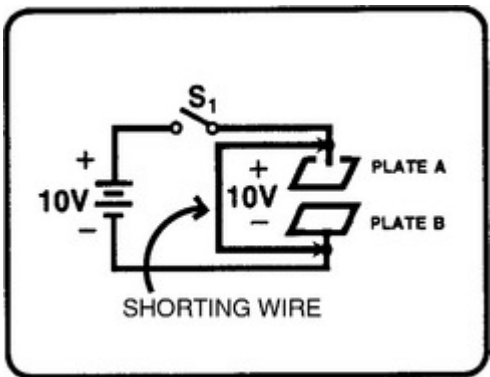


FIGURE 6.7 A Wire Connected Between the Two Plates

VALUES OF CAPACITORS

The Farad

The value of capacitance in a circuit is described by the capacitive unit, the *farad*, named for Michael Faraday. Faraday, a British physicist who lived during the 19th century, is credited with developing the method of measuring capacitance. Faraday stated a capacitor has a value of *one farad* of capacitance if *one volt* of potential difference applied across its plates moves *one coulomb* of electrons from one plate to another. This is illustrated graphically in **Figure 6.10**, and it is expressed in the equation:

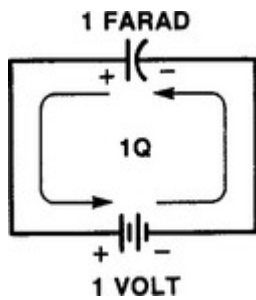


FIGURE 6.10 Circuit Factors for Measuring One Farad of Capacitance

$$C = \frac{Q}{E} \quad (6-1a)$$

Where

Q = the charge transferred in Coulombs. (One Coulomb = 6.25×10^{18} electrons)

C = value of capacitor in farads

E = voltage applied across the capacitor plates in volts

Rearranging terms, this equation may also be written in the form.

$$Q = C \times E \quad (6-1b)$$

As an example of its application, if you have a capacitor of 20 μF that is charged to 12 volts with a battery as shown in **Figure 6.11**, the quantity of electrons transferred from the positive to the negative plate of the capacitor stated in coulombs of charge is calculated as follows.

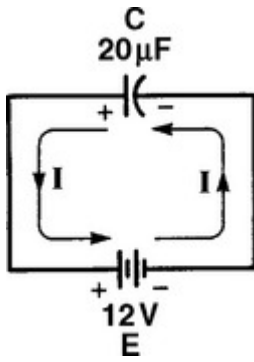


FIGURE 6.11 Charge Transfer in Charging a 20-μF Capacitor to 12 V

$$Q = C \times E$$

$$Q = (20 \mu\text{F}) \times (12 \text{ V})$$

$$Q = (20 \times 10^{-6} \text{ F}) \times (12 \text{ V})$$

$$Q = 240 \times 10^{-6} \text{ C}$$

or

$$Q = 240 \mu\text{C}$$

Recall that one coulomb of charge is equivalent to the amount of charge possessed by 6.25×10^{18} electrons. So the result above suggests that the number of electrons transferred in charging the capacitor is equivalent to 6.25×10^{18} electrons per coulomb times 240 μC.

$$\begin{aligned} \text{Number of Electrons} &= (6.25 \times 10^{18} \\ &\text{electrons/coulomb}) \times (240 \mu\text{C}) \end{aligned}$$

$$\begin{aligned} \text{Number of Electrons} &= (6.25 \times 10^{18} \\ &\text{electrons/coulomb}) \times (240 \times 10^{-6} \text{ C}) \end{aligned}$$

$$\begin{aligned} \text{Number of Electrons} &= 1,500 \times 10^{12} \\ &= 1.5 \times 10^{15} \text{ electrons} \end{aligned}$$

The number of electrons transferred in charging the 20 μF capacitor to 12 V is 1,500 million-million or 1.5×10^{15} electrons.

You might also notice that if you were to increase the applied voltage above 12 V, more electrons (coulombs of charge) would be transferred. Conversely, if the applied voltage were less than 12 V, fewer electrons would be transferred. The delta (Δ) symbol is often used to indicate a

change in a quantity. For example, a change in voltage could be written as ΔE . So if a change in voltage causes a change in the amount of coulombs of charge transferred, **equation 6-1b** might be written again to account for changes in voltage as

$$\Delta Q = C \times \Delta E \quad (6-1c)$$

This equation might be interpreted as saying that the amount of change in coulombs transferred equals the amount of capacitance being charged times the change in applied voltage.

Notice in **Figure 6.11** that when charging a capacitor, current flows and electron transfer take place. Recall that current may be defined as the “rate of flow of electrons” and that quantities of electrons may be measured in terms of coulombs of charge.

A simple way to state this in an equation is

$$I = \frac{Q}{t} \quad (6-1d)$$

where

I = current (measured in amperes)

Q = quantity of electrons past a point within

a conductor (measured in coulombs)

t = time for a number of electrons to pass a point within a conductor
(measured in seconds)

equation 6-1d reiterates the well known fact that one ampere of current is equivalent to a charge flow rate of one coulomb per second. Another way to state this is to rearrange **equation 6-1d** as

$$Q = I \times t \quad (6-1e)$$

This equation indicates that if a given amount of current flows for a certain length of time in a conductor, the total number of coulombs of charge that will have flowed through the conductor is equal to the product of the current and time.

For example, if a current of 2A flows through a conductor for 15 seconds, then 30 coulombs of charge will have passed through the conductor.

$$Q = I \times t$$

$$Q = (2A) \times (15 \text{ sec})$$

$$Q = 30 \text{ C}$$

Similarly, if a capacitor is charged with a current that is maintained constant at a given level for a specified amount of time, the capacitor will accumulate an amount of charge as calculated by this same equation. For example, if a capacitor is charged for 15 seconds with a constant current of 2 A, it will accumulate 30 coulombs of charge.

It is easy to see that if the amount of time is changed, the amount of charge accumulated will also change. Using delta notation

$$\Delta Q = I \times \Delta t \tag{6-1f}$$

Now we get to where all this discussion has been leading. If you take [equation 6-1c](#) for a capacitor

$$\Delta Q = C \times \Delta E$$

and [equation 6-1f](#)

$$\Delta Q = I \times \Delta t$$

and substitute $I \times \Delta t$ for ΔQ in [equation 6-1c](#) you get

$$I \times \Delta t = C \times \Delta E \tag{6-1g}$$

If you rearrange this equation to solve for I in terms of all other values you get

$$I = C \times \frac{\Delta E}{\Delta t} \quad (6-1h)$$

This equation has the term, $\Delta E/\Delta t$, which is the change in voltage, ΔE , in a given amount of time, Δt . This is usually referred to as the “rate of change of voltage” in volts per second. If the voltage across a capacitor of value C is changed at a rate of so many volts per second, the amount of current that will flow to charge the capacitor is given by this equation.

As an example, suppose the voltage across a 40- μ F capacitor is be changed at the rate of 50 V/sec, the amount of current that will flow to charge this capacitor will be 2 mA.

$$I = (40 \mu\text{F}) \times (50 \text{ V/sec})$$

$$I = (40 \times 10^{-6} \text{ F}) \times (50 \text{ V/sec})$$

$$I = 20 \times 10^{-3} \text{ A}$$

$$I = 2 \text{ mA}$$

equation 6-1h describes the behavior of a capacitor in a circuit with changing voltage conditions, and therefore is most useful in analyzing how a capacitor will respond electrically to varying dc as well as ac voltage sources.

Standard Values Of Capacitance

6.25×10^{18} electrons is a very large number of electrons; therefore, a one farad capacitor is very large electrically and physically. Practical units of capacitance vary from a small capacitor of one picofarad (1 pF = 0.000000000001 farads = 10^{-12} farads) to 1,000 microfarads (1,000 μ F = 0.001 farads = 1×10^{-3} farads), for a large capacitor. Typical capacitors of these values are shown in **Figure 6.12**.



FIGURE 6.12 Typical Small-Value and Large-Value Capacitors

Abbreviations Of Capacitive Unit

The capacitance value of most capacitors is in either microfarads or picofarads. There are many ways that these units can be expressed and abbreviated. For example, the value of a 0.001 microfarad capacitor can be written:

$0.001 \times 10^{-6}\text{F}$ or $1,000 \times 10^{-12}\text{F}$

or 1,000 picofarads or 1,000 pF or 1 kpF

or 1,000 micromicrofarads or 1,000 $\mu\mu\text{F}$

or $1,000 \times 10^{-6} \times 10^{-6}\text{F}$

or 1 nanofarad or $1 \times 10^{-9}\text{F}$

All other capacitance values can be expressed and abbreviated in as many ways. Although the capacitance value of a capacitor is usually printed on it, it can be in any one of many different abbreviations because all manufacturers have not established a standard abbreviation code for capacitance units. This can pose some deciphering problems. However, as a rule of thumb, remember that practical values of capacitance are fractions of one farad, and they typically range from one picofarad to several thousand microfarads.

Equation For Calculating Capacitive Values Based On Physical Parameters

Capacitors of different values are manufactured by varying several factors, such as the area of the plates, the distance between the plates, and the type of dielectric material used. An equation that relates these factors is

$$C = k_e \left(\frac{A}{d} \right) \epsilon_0 \quad (6-2)$$

Where

C = the value of the capacitor in farads

k_e = the dielectric constant of the

dielectric material (no units)

A = the area of either plate

(square meters)

d = the distance between the plates

(meters)

ϵ_0 = the permittivity of dry air

(8.85×10^{-12} farads per meter)

Area Of The Plates

If the area of the plates is increased, the capacitor will be able to store more charge for every volt applied across its plates. Thus, if the dielectric and the distance between the plates remain constant, capacitance will be increased if the plate area is increased.

Distance Between Plates

If the distance between the plates of a capacitor is increased, then the capacitor stores less charge for every volt applied across its plates.

Therefore, if the dielectric and the plate area remain constant, capacitance will be decreased if the distance between plates is increased.

Dielectric Constant

The dielectric constant of a dielectric material is a ratio of the permittivity of a dielectric material to the permittivity of a vacuum, or more practically, dry air. The permittivity of a material is its ability to concentrate the flux density of an electric field. For example, the dielectric constant of glass is 8. Therefore, glass has a permittivity of 8 times that of air. The ratio of the permittivity of glass to the permittivity of air is 8:1, the air having an assigned constant of 1.

The larger the value of dielectric constant, the greater the concentration of the electric field between the two charged plates. Therefore, assuming that the area of the plates and the spacing between plates remain constant, the value of a capacitor will be increased if the dielectric constant is increased, and it will be decreased if the dielectric constant is decreased.

A table of typical dielectric constants of various materials used in the construction of capacitors is shown in ***Figure 6.13***.

DIELECTRIC MATERIAL	DIELECTRIC CONSTANT
AIR	1
CERAMICS	80-1200 VARIES WITH TYPE
GLASS	8
MICA	3-8 VARIES WITH TYPE
TEFLON	2.1
OIL	2-5 VARIES WITH TYPE
PAPER	2-6 VARIES WITH TYPE

FIGURE 6.13 Dielectric Constant of Various Materials

Voltage Ratings Of Capacitors

In addition to their capacitance values, all capacitors are also rated as to the maximum allowable dc voltage that may be applied across the plates without arc-over and subsequent damage to it and the circuit. This rating is called the working voltage dc, usually abbreviated WVDC or simply VDC when printed on a capacitor. For example, if a capacitor is rated at 100 WVDC, no voltage greater than 100 volts dc should be applied across its plates.

If a capacitor is used in an ac circuit, the peak value of the ac voltage should be compared to WVDC rating of the capacitor to be sure that the voltage will not exceed that rating and cause the capacitor to arc between its plates. In a circuit in which the voltage across the capacitor is 40 volts peak-to-peak, the peak value of this voltage is 20 volts and therefore, the WVDC rating of the capacitor should be a minimum of 20 volts.

Dielectric Strength

The WVDC rating of a capacitor is related to the dielectric strength (breakdown voltage) of the type of dielectric material used in the capacitor's construction. The dielectric strength is different for different materials. The dielectric strength of a material is typically rated in volts per mil (V/mil). One mil is 0.001 inch or one thousandth of an inch. The V/mil rating of a dielectric material indicates how many volts a one-mil thickness of the material can withstand without breaking down. **Figure 6.14** lists some V/mil ratings of several dielectric materials commonly used in the construction of capacitors.

MATERIAL	DIELECTRIC STRENGTH (VOLTS/MIL)
AIR	20
CERAMICS	600-1250 VARIES WITH TYPE
PYREX GLASS	330
MICA	600-1500 VARIES WITH TYPE
TEFLON	1525
OIL	375
PAPER	400-1250 VARIES WITH TYPE

FIGURE 6.14 Dielectric Strength of Various Materials

It is also important to remember that the working voltage of any capacitor decreases as temperature increases. Therefore, if the circuit in which a capacitor of a particular WVDC rating is to be used will be subjected to high temperatures, the capacitor should be chosen so that its working voltage will exceed expected circuit voltages at those temperatures.

TYPES OF CAPACITORS

As stated previously, the dielectric material used in the construction of a capacitor primarily determines the type of capacitor. Some of the common types are ceramic, paper, air, and electrolytic capacitors.

Ceramic Disc Capacitors

Ceramic disc capacitors usually consist of two conductive discs on each side of a piece of ceramic insulator, one lead attached to each plate, and coated with some type of inert, waterproof coating, often made of some type of ceramic composition. Ceramic capacitors typically are manufactured in values from 1 picofarad up to thousands of microfarads and dc working volts from 10 volts up to 5,000 volts. Several ceramic disc capacitors are shown in [Figure 6.2](#).

Paper Capacitors

A paper capacitor typically consists of a sheet of paper insulator (dielectric) sandwiched between two sheets of foil, rolled in cylindrical form as shown in [Figure 6.15](#). Paper capacitors are typically manufactured in capacitive values from about 1,000 picofarads to one microfarad.

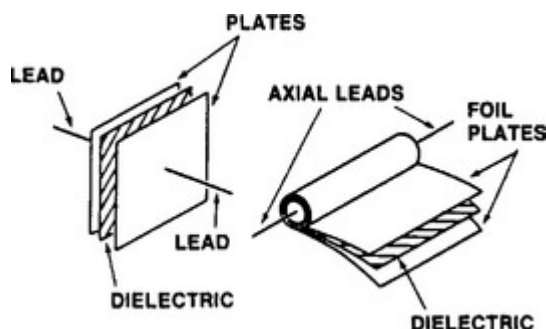


FIGURE 6.15 Typical Paper Capacitor

Paper, mylar, and other tubular film-type capacitors typically have a band at one end of the capacitor as shown in [Figure 6.16](#). The band identifies the outside foil of the capacitor. The lead closest to the band should be connected to the ground or lowest potential point in the circuit. This provides rf shielding in high frequency circuits. It also provides a safety factor for the technician if the insulating material would happen to wear away and expose the capacitor's outside plate.

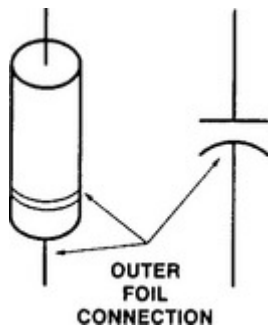


FIGURE 6.16 Capacitor with Outer Foil Connection Indicated with Band
Electrolytic Capacitors

A typical electrolytic capacitor consists of an outer aluminum shell and an inner aluminum electrode. As shown in [Figure 6.17](#), the electrode is wrapped in gauze permeated with a solution of phosphate, borax, or carbonate. This solution is called the *electrolyte*. When a dc voltage is placed across the plates of the capacitor, an oxide coating forms between the electrode and the electrolyte. A capacitor is then formed with the oxide as the dielectric, the inner electrode as the positive plate (anode), and the outer shell and electrolyte as the negative plate (cathode). Several capacitors of different values can be formed within one outer shell by using several electrodes and applying different potentials to the electrodes. [Figure 6.18](#) shows two views of a typical multisection electrolytic capacitor. The side view shows a typical way the capacitance and WVDC ratings of each section of the capacitor are marked on its side. Note that a small geometric symbol is marked beside each of the section ratings. These symbols are used to identify each of the capacitor's sections. The bottom view shows several lugs extending outward from the bottom of the capacitor.

Each of the inner lugs is connected to an inner (usually positive) electrode of each individual capacitor section.

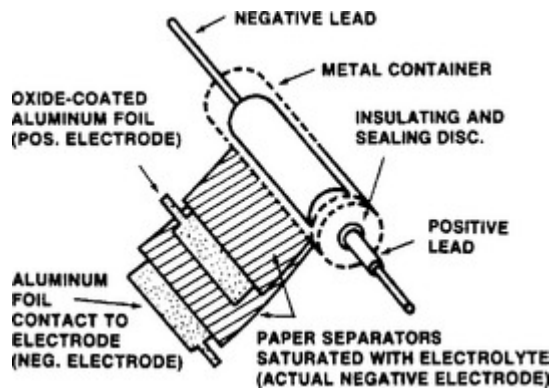


FIGURE 6.17 Construction of an Electrolytic Capacitor

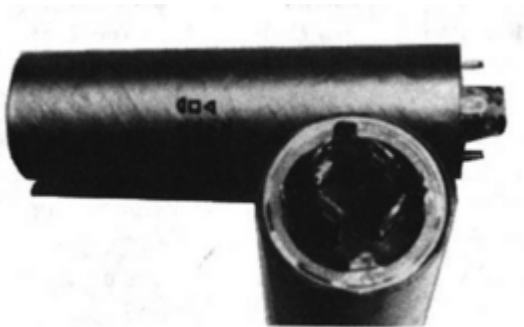


FIGURE 6.18 A Multisection Electrolytic Capacitor

Note that the small geometric symbol marked beside each of these lugs match the symbols marked on the side. Therefore, the capacitance value and WVDC rating of each section (lug) can be determined easily. Note also that there are several lugs around the outer edge of the capacitor. These lugs are part of the outer shell of the capacitor that is usually the negative (ground) side of the capacitor, common to each section. These lugs are used to mount the capacitor and provide a common negative connection in the circuit.

Some electrolytic capacitors use special metals called *tantalum* or *niobium* as the anode and are called *tantalum* or *niobium* capacitors. These capacitors have a larger capacitance in a much smaller size than other types of standard electrolytics. Because of their small physical size, they are ideal

for use in miniaturized electronic circuits where space considerations are important.

Since an electrolytic capacitor utilizes a *chemical* process for its capacitive ability, it has a designated *shelf life*. That is, an electrolytic capacitor can be stored only for a specified length of time without use before it changes value. The schematic symbol for an electrolytic capacitor has the added notation of the plus and minus signs. Electrolytic capacitors must be used in circuits with the end marked positive always at a more positive potential than its negative end. Thus, they are normally used only where dc or pulsating dc voltages are present. Special types of non-polarized electrolytic capacitors are available for use in ac circuits. Specified symbols for electrolytic capacitors are shown in **Figure 6.19**.

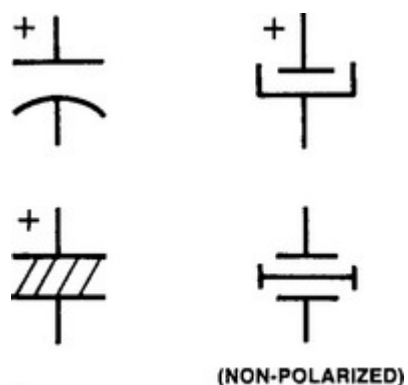


FIGURE 6.19 Electrolytic Capacitor Symbols

Electrolytic capacitors are available from about one microfarad to several thousand microfarads, with working voltage ranging from several volts to several hundred volts. The applied voltage to an electrolytic capacitor should be approximately equal to the voltage rating of the electrolytic. This will help insure that the proper value of capacitance will be present in the circuit.

Air Capacitors

With air capacitors, capacitance is varied by meshing and unmeshing the capacitor plate, with the air between the plates serving as the dielectric.

As shown in [Figure 6.20](#), air capacitors are commonly used as a variable tuning capacitor in receiver circuits.

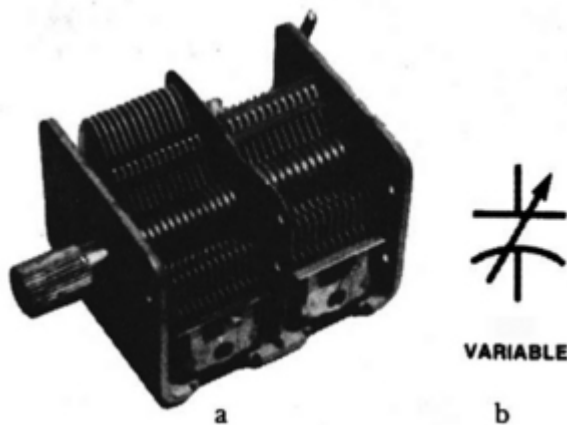


FIGURE 6.20 Variable Tuning Air Capacitor and Its Schematic Symbol

The variable capacitor is designated schematically by adding an arrow to the standard schematic symbol also shown in [Figure 6.20](#). Air capacitors are available usually in variable values from a few picofarads to several hundred picofarads.

Leakage Current

A theoretical capacitor will hold a charge indefinitely. Practically, however, if a capacitor is charged and set down for a time, it actually loses a small amount of its charge. This is because all insulators are conductors to some degree. The dielectric, even though a poor conductor, allows some electrons to “leak” back across to the other plate. This small electron flow discharge is what is called *leakage current*. Leakage current is greatest in electrolytic capacitors due to their method of construction and impurities in the foil and electrolyte. A table showing leakage current for common types of capacitors for typical ranges of values and WVDC ratings is shown in [Figure 6.21](#).

Capacitor Type	Range of Capacitance	Range of WVDC (in volts)	Range of Temperature (°C)	R_i = Insulation Resistance I_L = Leakage Current (at 25°C)	Comments
Ceramic	1 pF – 2.5 μ F	20 – 200	–55 + 125	R_i = 100 G Ω / μ F	Small size Low cost
Paper	0.001 – 2 μ F	50 – 2000	–55 + 105	R_i = 3 – 20 G Ω / μ F	Low cost
Electrolytic	0.5 – 1,000,000 μ F	2.5 – 700	–80 + 125	I_L = 0.1 μ A or more	Very small size Very low cost
Mylar	0.001 – 20 μ F	50 – 1000	–55 + 150	R_i = 50 G Ω / μ F	Small size Relatively high cost
Air	10 – 400 pF	200/0.01 in air gap	—	—	Variable
Mica	1 pF – 1 μ F	50 – 100,000	–55 + 150	R_i = 10 – 100 G Ω / μ F	Cap. change with age very small
Oil Filled	0.001 – 15 μ F	100 – 12,500	–55 + 85	R_i = 2 – 100 G Ω / μ F	Low cost

FIGURE 6.21 Typical Capacitor Parameters

COMPARISON OF RESISTANCE AND CAPACITANCE

A comparison of resistive and capacitive properties should help you understand better the effects of capacitors in circuits. A resistor limits, and therefore, controls the flow of current in a circuit. A capacitor stores a charge and as a result, opposes a change in voltage in the circuit.

Resistors In DC And AC Circuits

Recall previously that in dc and ac circuits, as shown in [Figure 6.22](#), a resistor places a fixed amount of resistance in the circuit. Governed by Ohm's law the resistance value determines the amount of current flow. A capacitor, however, stores a charge and as a result, it opposes any change in voltage across it in a circuit.

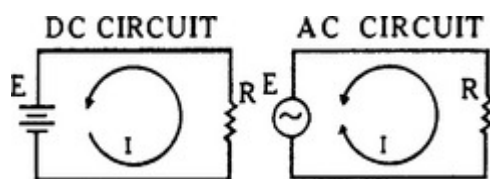


FIGURE 6.22 Resistors in DC and AC Circuits

Capacitors In DC Circuits

In dc circuits, when a dc voltage is first applied to a capacitor with no charge, it initially acts almost as a short circuit by allowing a maximum value of current to flow, as shown in [Figure 6.23a](#). As the capacitor charges, the voltage across the capacitor increases in a polarity which opposes the battery or voltage source and the amount of current flowing decreases. Once the capacitor is fully charged, current no longer flows in the circuit, and the capacitor then acts as an open circuit, as shown in [Figure 6.23b](#). The time required for a capacitor to become fully charged is determined by the RC time constant of the circuit which will be discussed in more detail in [Chapter 10](#).

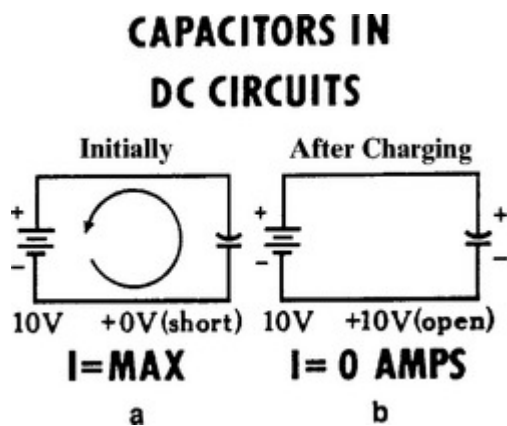


FIGURE 6.23 Capacitors in DC Circuits

Capacitors In AC Circuits

In ac circuits, the capacitive property of capacitors is observed in two related ways. First, the voltage across the capacitor lags the current through the capacitor by 90 degrees, as shown in [Figure 6.24](#). Second, also shown in [Figure 6.24](#), a capacitor acts as a variable opposition to current flow that is inversely related to the frequency of the ac source causing the current flow. The average opposition of a capacitor to current flow is called its *capacitive reactance*.

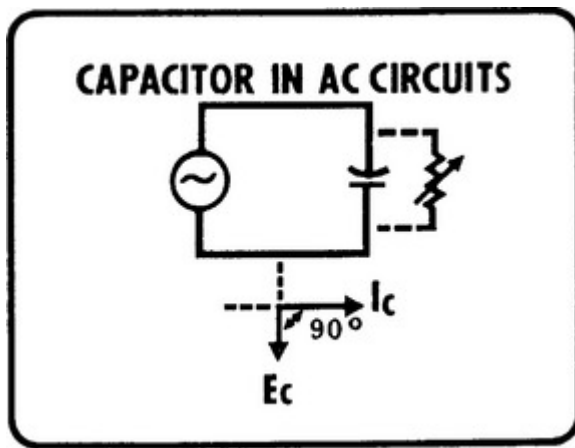


FIGURE 6.24 Capacitor in AC Circuits

PHASE RELATIONSHIPS IN CAPACITIVE CIRCUITS

In every capacitive electrical circuit there are predictable and precise relationships between current, voltage, and capacitance. These relationships can be precisely described in terms of *phase relationships*. A good way to begin a discussion and understanding of capacitive circuits is by analyzing phase relationships in such circuits.

E_c and I_c Relationships

As mentioned earlier, an equation that mathematically describes the relationship between the voltage and current in a capacitive circuit is

$$I_c = C \frac{\Delta E_c}{\Delta t} \quad (6-3)$$

Where I_c = capacitive current (amperes)

C = capacitance (farads)

Δ = a change in quantity

E_c = volts across the capacitor

t = time (seconds)

Since Δ designates a change in quantity, then the value

$$\frac{\Delta E_C}{\Delta t}$$

is the change in voltage (in volts) across the capacitor divided by the change in time (in seconds) in which that

change occurred. This

$$\frac{\Delta E_C}{\Delta t}$$

is called the *rate of change* of the voltage. Because

$$\frac{\Delta E_C}{\Delta t}$$

is the rate of change (ROC) of voltage, [equation 6-3](#) can be rewritten:

$$I_C = C \times [\text{ROC } E_C] \quad (6-4)$$

Rate Of Change Of E_C

Since there are rates of change of voltage in a capacitive ac circuit, it is important that you know where the maximum and minimum rates of change occur. Using [equation 6-4](#), certain characteristics of the current can be determined. A good example is to examine the rate of change of voltage at various points in a sine wave. A fixed amount of time, Δt , will be moved along a time axis and examined to see how much change in voltage occurs at various intervals of the sine wave. As shown in [Figure 6.25](#), the maximum change in voltage occurs as the sine wave crosses the axis at the zero voltage level. Thus, the rate of change of voltage is a *maximum* as the sine wave crosses the zero voltage level.

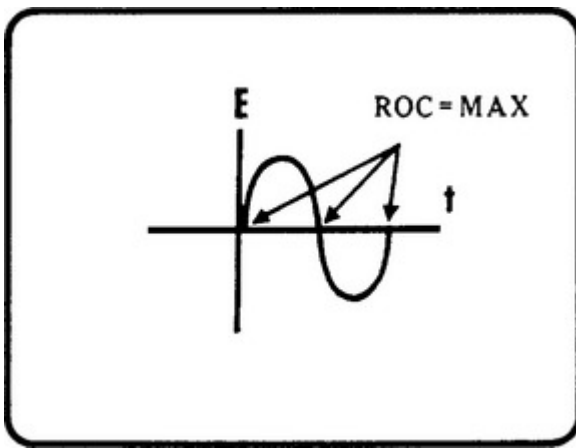


FIGURE 6.25 Maximum Rate of Change of Voltage

On the other hand, the change in voltage is minimum or zero as the voltage peaks. Thus, the rate of change of voltage is zero as the sine wave peaks as shown in [Figure 6.26](#). This should be obvious because when the sine wave peaks, the voltage *stops* increasing and begins decreasing.

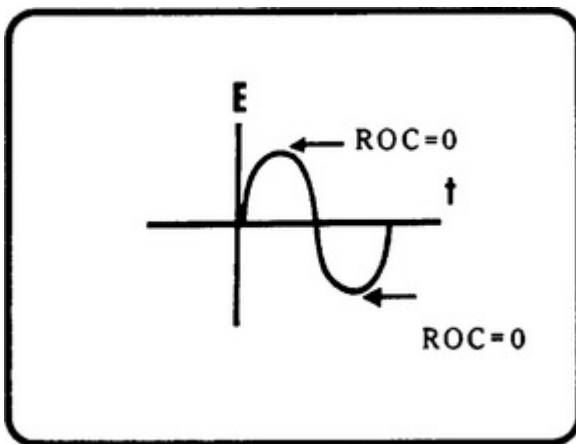


FIGURE 6.26 Minimum Rate of Change of Voltage

E_C versus I_C

Remember that the current is equal to the value of the capacitor times the rate of change of the voltage. When the rate of change of voltage is zero (E_C is at either peak), the value of the current is zero. When the rate of change of voltage is a maximum (as E_C crosses the zero voltage level), the value of the current is a maximum. The zero and maximum points of I_C are indicated by the X's in [Figure 6.27](#). Since the voltage changes sinusoidally, the rate of change of voltage changes in a sinusoidal shape and

therefore, so does the current. Connecting these points with a sinusoidal waveform, as shown in **Figure 6.28**, the current waveform can be plotted. Note in **Figure 6.28** that the current leads the voltage by 90 degrees as was described earlier.

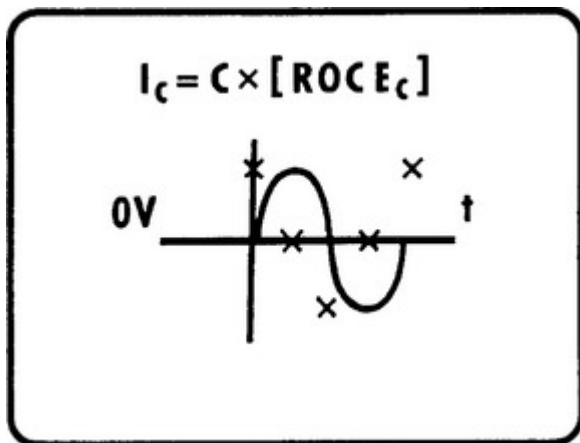


FIGURE 6.27 Zero and Maximum Points of I_c

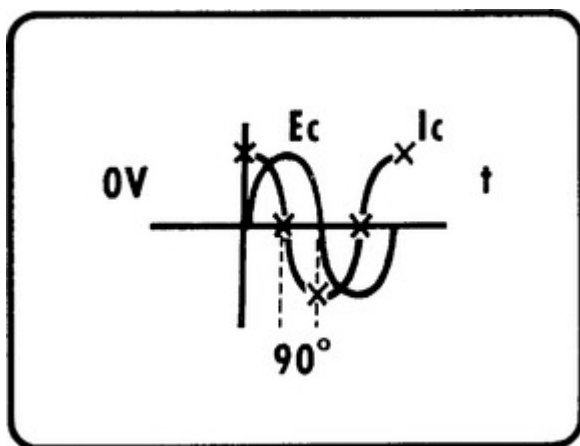


FIGURE 6.28 Relationship of I_c to E_c

FREQUENCY RELATED TO CAPACITIVE IMPEDANCE

In a circuit, a capacitor impedes, opposes, reacts to the flow of a varying current. The average opposition is called capacitive reactance. The capacitive reactance depends on the frequency of the source. The rate-of-change equation can be used to relate the capacitive opposition to the frequency of the voltage in a capacitive circuit.

Rate Of Change Versus Frequency

As frequency increases, the rate of change of the voltage is much higher. For example, as shown in **Figure 6.29a**, a 10 volt peak-to-peak one kilohertz waveform makes a 10 volt transition in 0.5 (½) millisecond. But, as shown in **Figure 6.29b**, with the same amplitude, and an increase in frequency to 4 kilohertz, the same 10-volt transition is made in one-fourth of this time, or in 0.125 millisecond. Calculating the rate of change of voltage in each case, it is found that at 1 kilohertz:

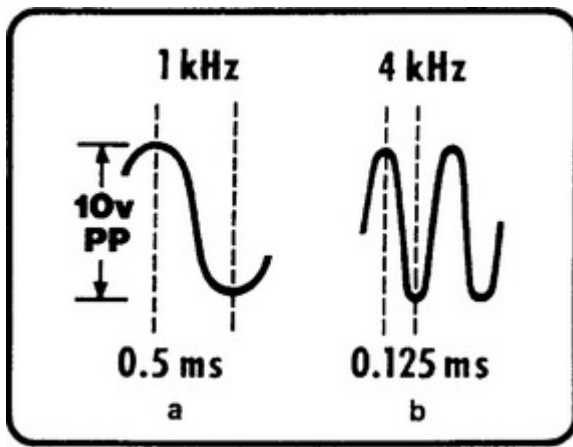


FIGURE 6.29 Rate of Change of voltage versus Frequency

$$\begin{aligned}\text{Rate of change} &= \frac{\Delta E}{\Delta t} \\ &= \frac{10 \text{ V}}{0.5 \text{ ms}} \\ &= \frac{20 \text{ V}}{\text{ms}}\end{aligned}$$

and at 4 kilohertz:

$$\begin{aligned}\text{Rate of change} &= \frac{\Delta E}{\Delta t} \\ &= \frac{10 \text{ V}}{0.125 \text{ ms}} \\ &= \frac{80 \text{ V}}{\text{ms}}\end{aligned}$$

The approximate rate of change of the 1-kilohertz waveform is 20 volts per millisecond. The approximate rate of change of the 4-kilohertz waveform is 80 volts per millisecond. Obviously, the rate of change of the higher frequency voltage is greater. According to **equation 6-4**, the voltage with the higher frequency with its greater rate of change would produce a higher current when applied to a capacitor.

$$f \uparrow \frac{\Delta E_c}{\Delta t} \uparrow I_c \uparrow$$

According to Ohm's law, if voltage is constant and current increases then the opposition to current flow must have decreased.

$$I \uparrow = \frac{E}{X_c \downarrow}$$

On the other hand, if source frequency is decreased, the current will also decrease, which means an increase in opposition must have occurred.

These relationships can be expressed as:

$$f \downarrow \frac{\Delta E_c}{\Delta t} \downarrow I_c \downarrow \text{ and } X_c \uparrow$$

CAPACITIVE REACTANCE

As stated earlier, this changing opposition of a capacitor is called *capacitive reactance* and is inversely related to the source frequency.

Equation For X_c

Capacitive reactance is measured in *ohms* of reactance like resistance, and depends on the frequency of the *applied voltage* and the *value* of the *capacitor*.

$$X_c(\Omega) = \frac{1}{2 \pi f(\text{Hz})C(\text{F})} \quad (6-5a)$$

where $2\pi = 6.28$.

The symbol for reactance is X. To specify a specific type of reactance, a subscript is used. In this case, since it's capacitive reactance, the subscript C is used. The constant 2π comes from the number of radians in one cycle of a sinusoidal ac waveform. **equation 6-5a** is valid only for calculating the capacitive reactance of a capacitor to sinusoidal alternating current.

Analysis Of An AC Capacitive Circuit

The circuit in **Figure 6.30** will be used to determine the capacitive reactance using the capacitive reactance equation. That circuit contains a 10 microfarad capacitor with an applied voltage with a frequency of 4 kilohertz. The capacitive reactance is calculated:

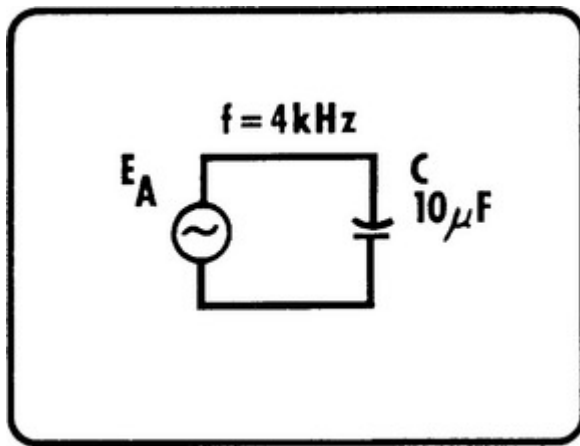


FIGURE 6.30 Example Circuit to Calculate X_C

$$\begin{aligned}
 X_C &= \frac{1}{2\pi fC} \\
 &= \frac{1}{2\pi(4 \times 10^3 \text{ Hz})(10 \times 10^{-6} \text{ F})} \\
 &= \frac{1}{251.2 \times 10^{-3}} \\
 X_C &= 3.98 \Omega
 \end{aligned}$$

If the applied voltage is 10 volts, as shown in **Figure 6.31**, the current in the circuit will be the value of the applied voltage divided by the value of the capacitive reactance.

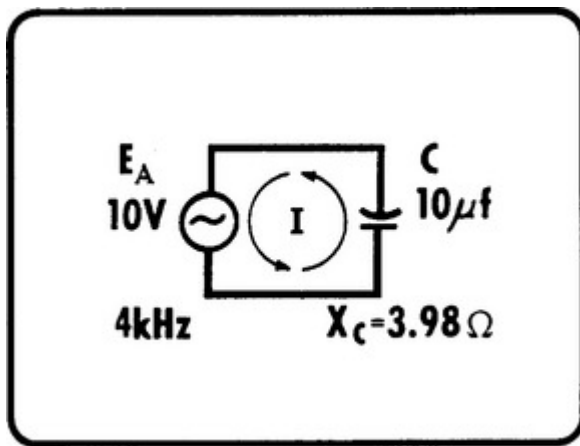


FIGURE 6.31 Example Circuit to Calculate I_C

$$\begin{aligned}
 I_C &= \frac{E_{AC}}{X_C} \\
 &= \frac{10 \text{ V}}{3.98 \Omega} \\
 &= 2.51 \text{ A}
 \end{aligned}$$

The current in the circuit is 2.51 amperes. Remember, the voltage and current values are rms values since they have not been otherwise specified.

A sine wave may be evaluated for its average rate of change of voltage as shown in [Figure 6.32](#). If the peak value of a sine wave is E_{pk} , then the average rate of change of the entire sine wave may be determined by evaluating its change in voltage divided by its change in time ($\frac{1}{4}$ the period) during only the first 90 degrees. In [equation 6-5b](#), the average rate of change of a sine wave is given as the change in voltage divided by the change in time. The change in voltage from 0 to 90 degrees is the value of E_{pk} . The change in time from 0 to 90 degrees is $\frac{1}{4}$ of the period.

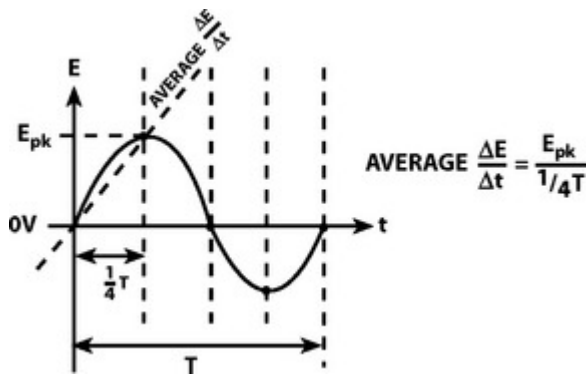


FIGURE 6.32 Evaluation of Average Rate of Change of a Sine Wave

$$\text{Average} \frac{\Delta E}{\Delta t} = \frac{E_{pk}}{1/4 T} \quad (6-5b)$$

Since the reciprocal of the frequency is equal to the period, the equation may be rewritten as

$$\text{Average} \frac{\Delta E}{\Delta t} = \frac{E_{pk}}{1/4 \times 1/f} \quad (6-5c)$$

The right side of [equation 6-5c](#) may be rearranged to obtain

$$\text{Average} \frac{\Delta E}{\Delta t} = 4 \times f \times E_{pk} \quad (6-5d)$$

As shown in the beginning of [Chapter 2](#), the average value of a sinusoidal voltage or current during its first half or quarter cycle may be written as 0.637 of its peak value.

$$\text{Average Current} = 0.637 \times I_{pk} = \frac{2}{\pi} \times I_{pk} \quad (6-5e)$$

Recall that [equation 6-3](#) describes the behavior of a capacitor.

$$I_c = C \times \frac{\Delta E_c}{\Delta t} \quad (6-3)$$

[equation 6-3](#) could also be written in terms of average current and average rate of change of voltage as

$$\text{Average } I_C = C \times \text{Average } \frac{\Delta E_C}{\Delta t} \quad (6-5f)$$

Substituting the average current ([equation 6-5e](#)) and average rate of change of voltage ([equation 6-5d](#)) expressions into [equation 6-5f](#) yields

$$\frac{2}{\pi} \times I_{pk} = C \times 4 \times f \times E_{pk} \quad (6-5g)$$

Rearranging [equation 6-5g](#) to solve for I_{pk} results in

$$I_{pk} = C \times 4 \times f \times E_{pk} \times \frac{\pi}{2} \quad (6-5h)$$

$$I_{pk} = 2 \times \pi \times f \times C \times E_{pk}$$

Capacitive reactance is the opposition by a capacitor to the flow of alternating current. Stated in Ohm's Law format

$$X_C = \frac{E_C}{I_C} \quad (6-5i)$$

The values of capacitive voltage and current may be specified in peak terms so that

$$X_C = \frac{E_{pk}}{I_{pk}}$$

Substituting the expression for I_{pk} from [equation 6-5h](#) into [equation 6-5i](#) produces the following result.

$$X_C = \frac{E_{pk}}{2 \times \pi \times f \times C \times E_{pk}}$$

When E_{pk} is factored out, the familiar result is [equation 6-5](#).

$$X_C = \frac{1}{2 \times \pi \times f \times C} \quad (6-5)$$

Analysis Of An AC Capacitive Circuit With An Increased Source Frequency

If the current in the previous example is 2.51 amperes, what is going to happen to the current if the frequency of the source voltage is increased?

Figure 6.33 shows the same circuit used in the previous example with one difference — the frequency has been increased from 4 kilohertz to 10 kilohertz. Capacitive reactance of the circuit is calculated as in the previous example.

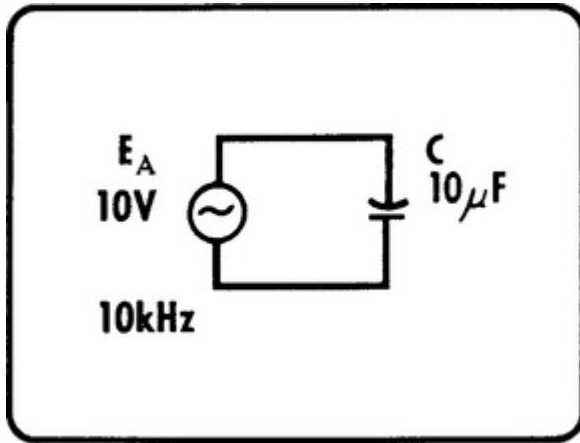


FIGURE 6.33 Example Circuit to Calculate X_C

$$\begin{aligned}
 X_C &= \frac{1}{2 \pi f C} & (6-6) \\
 &= \frac{1}{6.28(10 \times 10^3 \text{ Hz})(10 \times 10^{-6} \text{ F})} \\
 &= \frac{1}{6.28 \times 10^{-1}} \\
 &= 1.59 \, \Omega
 \end{aligned}$$

The current in the circuit, repeated in **Figure 6.34**, is calculated by dividing the applied voltage by the capacitive reactance of the circuit:

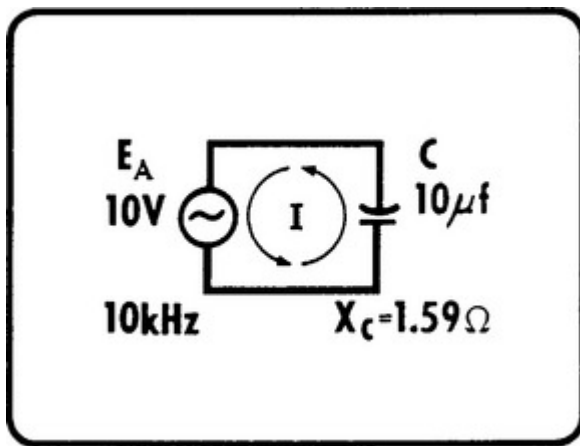


FIGURE 6.34 Example Circuit to Calculate I_C

$$\begin{aligned}
 I_C &= \frac{E_A}{X_C} \\
 &= \frac{10V}{1.59\Omega} \\
 &= 6.28A
 \end{aligned}$$

Obviously, this *current* is *greater* than the current in the same circuit when the applied frequency was lower.

Figure 6.35 summarizes the relationships between capacitive reactance, X_C , circuit current, I_C , and frequency, f , of the source voltage for the two example circuits just discussed. From this summary, it is apparent that as frequency of source voltage increases, capacitive reactance decreases and current increases.

$E_A = 10V$		
	$f = 4kHz$	$f = 10kHz$
X_C	3.98 Ω	1.59 Ω
I_C	2.51A	6.28A

FIGURE 6.35 X_C versus I_C at Two Different Frequencies of Source Voltage

The Capacitor As A Variable Resistance

A capacitor can be thought of as a variable resistor whose value is controlled by the applied frequency. As frequency increases, its *opposition to current* or its capacitive *reactance* decreases, as shown in [Figure 6.36](#).

[Figure 6.37](#) shows the same concept graphically.

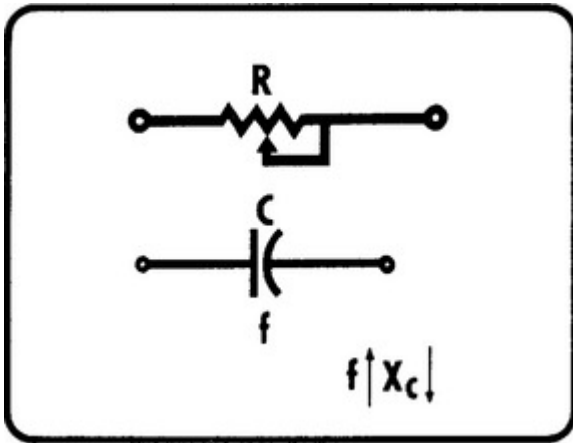


FIGURE 6.36 A Capacitor as a Variable Resistor

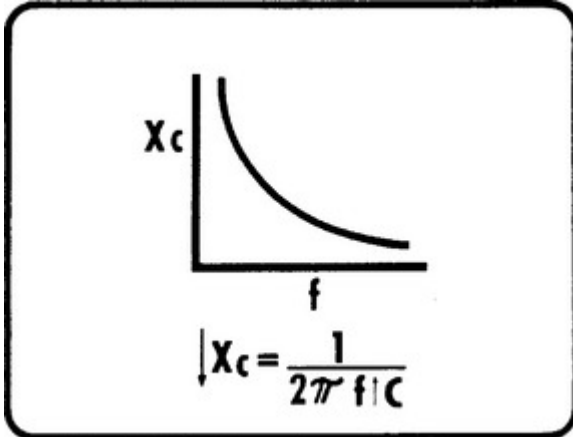


FIGURE 6.37 Capacitive Reactance versus Frequency

CAPACITIVE REACTANCE IN SERIES AND PARALLEL

As observed in the preceding section, capacitors in ac circuits present opposition to current flow based on the capacitive reactance equation, [equation 6-5a](#). As mentioned, it is similar to the resistance of a resistor.

The X_c designation differentiates it from a resistor R . In a purely capaci-

tive circuit where no resistance is present, totals of capacitive reactance can be calculated the same way that totals of resistance are calculated in purely resistive circuits.

Capacitive Reactance In Series

When capacitors are connected in series, the total reactance of the capacitors (X_{CT}) is simply a sum of the capacitive reactance of the capacitors present. This procedure is identical to the way total resistance (R_T) is determined in a series resistive circuit. [equation 6-6](#) is used to calculate total capacitive reactance (X_{CT}) in series:

$$X_{CT} = X_{C1} + X_{C2} + X_{C3} \dots + X_{CN} \quad (6-6)$$

[Figure 6.38](#) is a circuit containing four capacitors in series with the capacitive reactance shown for each. Using [equation 6-6](#), the total capacitive reactance for the circuit can be calculated:

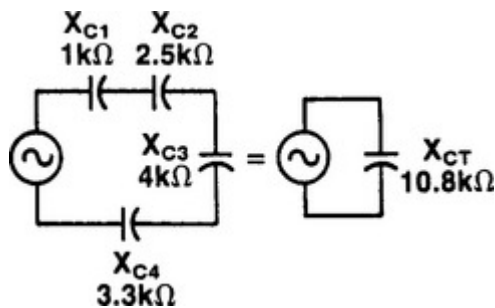


FIGURE 6.38 Example Circuit for Calculating X_{CT} in Series

$$\begin{aligned} X_{CT} &= X_{C1} + X_{C2} + X_{C3} + X_{C4} \\ X_{CT} &= 1\text{ k}\Omega + 2.5\text{ k}\Omega + 4\text{ k}\Omega + 3.3\text{ k}\Omega \\ X_{CT} &= 10.8\text{ k}\Omega \end{aligned}$$

Capacitive Reactance In Parallel

When capacitors are connected in parallel, the total reactance of the capacitors, X_{CT} , is found in the same manner that total resistance, R_T , is determined in a parallel resistive circuit. These two equations are used to calculate total capacitive reactance, X_{CT} , in parallel:

For two capacitors in parallel —

$$X_{CT} = \frac{X_{CA} \times X_{CB}}{X_{CA} + X_{CB}} \quad (6-7)$$

For any number of capacitors in parallel —

$$\frac{1}{X_{CT}} = \frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \dots + \frac{1}{X_{CN}} \quad (6-8)$$

Figure 6.39 is a circuit containing four capacitors in parallel with the capacitive reactance shown for each. Using **equation 6-8**, the total capacitive reactance for the circuit can be calculated:

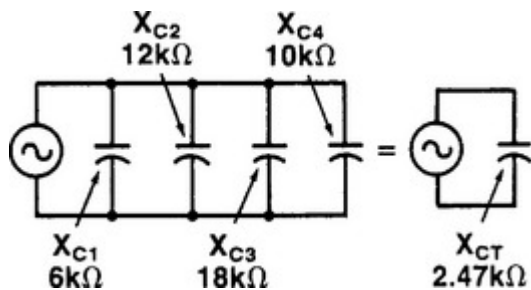


FIGURE 6.39 Example Circuit for Calculating X_{CT} in Parallel

$$\begin{aligned} \frac{1}{X_{CT}} &= \frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \frac{1}{X_{C4}} \\ \frac{1}{X_{CT}} &= \frac{1}{6\text{ k}\Omega} + \frac{1}{12\text{ k}\Omega} + \frac{1}{18\text{ k}\Omega} + \frac{1}{10\text{ k}\Omega} \\ \frac{1}{X_{CT}} &= \frac{3 + 1.5 + 1 + 1.8}{18\text{ k}\Omega} \\ \frac{1}{X_{CT}} &= \frac{7.3}{18\text{ k}\Omega} \\ \frac{X_{CT}}{1} &= \frac{18\text{ k}\Omega}{7.3} \\ X_{CT} &= 2.47\text{ k}\Omega \end{aligned}$$

In summary, in series circuits with only capacitive reactance, X_{CT} can be calculated the same as R_T in series. X_{CT} in circuits with parallel capacitive reactance can be calculated the same as R_T in parallel.

CAPACITANCE IN SERIES AND PARALLEL

Thus far, discussion has concerned capacitive reactance connected in series or in parallel in circuits. What about capacitance? What happens to total capacitance when several capacitors are combined in series or parallel? To best understand this concept, the variables that determine the value of a capacitor should first be examined.

Equation 6-2 explains the value of a capacitor, and it is repeated here:

$$C = K_E \left(\frac{A}{d} \right) \quad (6-9)$$

Notice that the value of a capacitor is determined by dividing the area of the plates by the distance between the plates and multiplying by a constant which is characteristic of the insulating materials. In this case the constant K_E is formed by multiplying the dielectric constant and ϵ_o , the permittivity of air. It is a simplified **equation 6-2** which was

$$C = K_E \left(\frac{A}{d} \right) \epsilon_o \quad (6-2)$$

equation 6-9 indicates that the value of a capacitor increases if the plate area of the capacitor increases:

$$C \uparrow = K_E \left(\frac{A \uparrow}{d} \right)$$

It also indicates that the value of a capacitor decreases if the distance separating the two plates increases.

$$C \downarrow = K_E \left(\frac{A}{d \uparrow} \right)$$

Capacitance in Series

With **equation 6-9** in mind, look at **Figure 6.40** in which two capacitors of equal value are connected in series. Note that the total effective dis-

tance between the plates connected directly to the battery is doubled. Since an increase in distance between the plates decreases capacitance, it can be concluded that the total capacitance of the two equal capacitors connected in series will be only one-half of the capacitance of one capacitor. This reciprocal relationship between total capacitance and capacitors in series is described by these two equations.

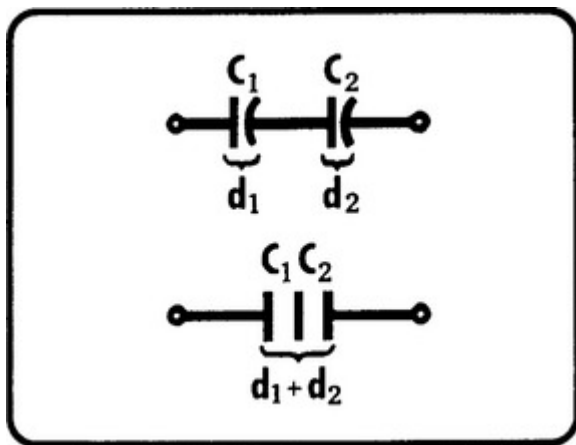


FIGURE 6.40 Capacitances Connected in Series Decrease Total Capacitance

For two capacitors in series —

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} \quad (6-10)$$

For any number of capacitors in series —

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots + \frac{1}{C_N} \quad (6-11)$$

These equations probably look familiar to because they are similar to the equations for total resistance when resistors are connected in *parallel*.

Figure 6.41 is a circuit containing four capacitors in series with the capacitance value for each shown. Using **equation 6-11**, the total capacitance for the circuit can be calculated:

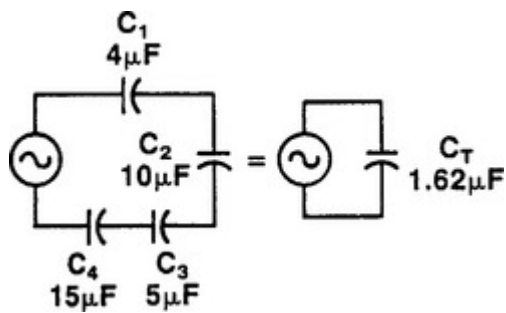


FIGURE 6.41 Example Circuit for Calculating C_T

$$\begin{aligned}\frac{1}{C_T} &= \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} \\ \frac{1}{C_T} &= \frac{1}{4\mu\text{F}} + \frac{1}{10\mu\text{F}} + \frac{1}{5\mu\text{F}} + \frac{1}{15\mu\text{F}} \\ \frac{1}{C_T} &= \frac{3.75 + 1.5 + 3 + 1}{15\mu\text{F}} \\ \frac{1}{C_T} &= \frac{9.25}{15\mu\text{F}} \\ \frac{C_T}{1} &= \frac{15\mu\text{F}}{9.25} \\ C_T &= 1.62\mu\text{F}\end{aligned}$$

Capacitance in Parallel

When two equal capacitors are connected in parallel, the plates of the individual capacitors, in effect, combine to form one capacitor representing total capacitance. Notice in [Figure 6.42](#) that the effective plate area of the equivalent capacitor has doubled. Since an increase in plate area increases capacitance, it can be concluded that the total capacitance of the two capacitors in parallel is equal to the sum of the two capacitors. This direct relationship between total capacitance and capacitors in parallel is described by this equation:

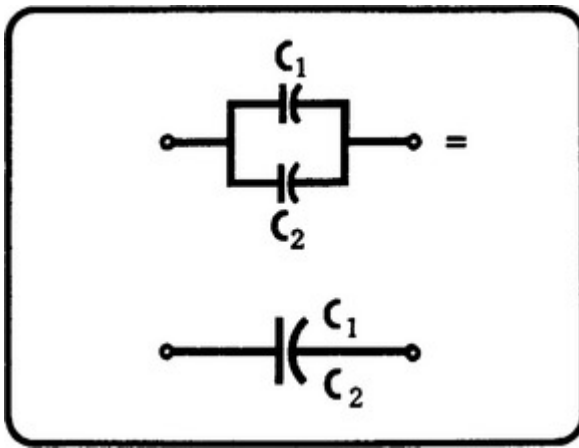


FIGURE 6.42 Capacitances Connected in Parallel Increase Total Capacitance

$$C_T = C_1 + C_2 + C_3 + \dots C_N \quad (6-12)$$

This equation should look familiar to you. It is similar to the equation used for calculating the total resistance of resistors connected in *series*.

Figure 6.43 is a circuit containing four capacitors connected in parallel with the capacitance value for each shown. Using **equation 6-12**, the total capacitance for the circuit can be calculated:

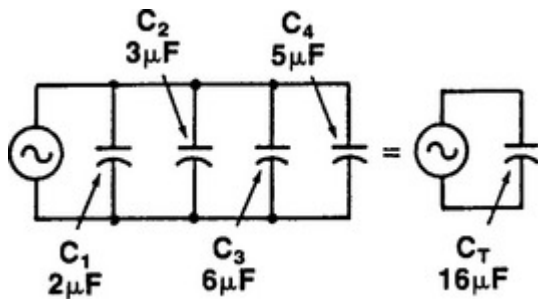


FIGURE 6.43 Example Circuit for Calculating C_T

$$\begin{aligned} C_T &= C_1 + C_2 + C_3 + C_4 \\ C_T &= 2\mu\text{F} + 3\mu\text{F} + 6\mu\text{F} + 5\mu\text{F} \\ C_T &= 16\mu\text{F} \end{aligned}$$

In summary, the total capacitance of capacitors in series can be described mathematically with an **equation (6-11)** similar to that for calculating the total resistance of resistors connected in parallel. Similarly, total ca-

capitance of capacitors connected in parallel can be calculated ([equation 6-12](#)) like the total resistance of resistors connected in series.

ANALYSIS OF SERIES AND PARALLEL CAPACITIVE CIRCUITS

Thus far in this chapter, capacitive circuits have been analyzed that contain only a known voltage source and a single capacitor. In this next discussion, circuits with a known voltage source and multiple capacitors connected in series or parallel will be analyzed.

Series Capacitive Circuit Analysis

In the circuit of [Figure 6.44](#) are two capacitors, 4 microfarads and 12 microfarads, connected in series. Applied voltage is 10 volts, 3 kilohertz. Capacitive reactance is calculated first using [equation 6-5a](#). The capacitive reactance of $C_1 = 4$ microfarads is:

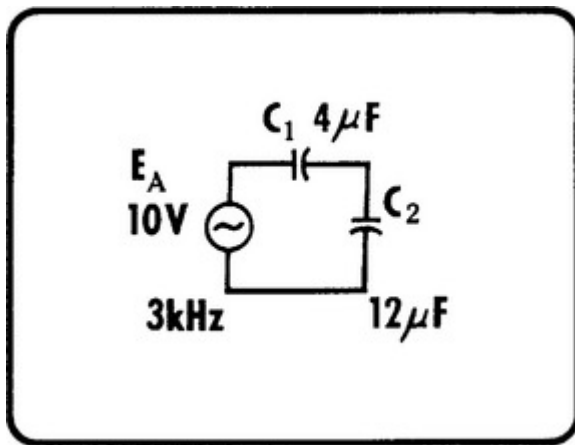


FIGURE 6.44 Example Series Capacitive Circuit

$$\begin{aligned} X_{C1} &= \frac{1}{2\pi f C_1} \\ &= 13.2 \Omega \end{aligned}$$

As shown, inserting values and calculating, it is found that $X_{C1} = 13.2$ ohms. Similar calculations are performed for the 12 microfarad capacitor, C_2 .

$$\begin{aligned} X_{C1} &= \frac{1}{2 \pi f C_2} \\ &= 4.4 \, \Omega \end{aligned}$$

And we find that $X_{C2} = 4.4$ ohms. Notice that as capacitance increases, the capacitive reactance decreases:

$$\downarrow X_c = \frac{1}{2 \pi f C \uparrow}$$

There is a definite mathematical relationship between increase and decrease of the values. In the circuit of [Figure 6.44](#) the capacitance of C_2 is three times the capacitance of C_1 :

$$\frac{12 \, \mu F}{4 \, \mu F} = \frac{3}{1}$$

The capacitive reactance of C_2 is one-third of the capacitive reactance of C_1 .

$$\frac{4.4 \, \Omega}{13.2 \, \Omega} = \frac{1}{3}$$

Now that the individual reactances in the circuit have been determined, the reactance ohms are treated as resistive ohms. That is, all series reactances are added.

$$\begin{aligned} X_{CT} &= X_{C1} + X_{C2} \\ &= 13.2 + 4.4 \\ &= 17.6 \, \Omega \end{aligned}$$

The total capacitive reactance is 17.6ohms. This *total capacitive reactance* is the total opposition that the circuit presents to current flow at the applied frequency.

An alternate method of finding this total reactance is to first determine the total capacitance. The total capacitance is 4 microfarads in series with 12 microfarads. An alternate product-over-sum method is then used to calculate total capacitance of two capacitors in series.

$$\begin{aligned}
 C_T &= \frac{C_1 \times C_2}{C_1 + C_2} \\
 &= \frac{(4)(12)}{4 + 12} \\
 &= 3 \mu\text{F}
 \end{aligned}$$

Total capacitance for the circuit is 3 microfarads. Using this, the total capacitive reactance of the circuit can be calculated using [equation 6-5a](#) as a total capacitive reactance equation.

$$X_{CT} = \frac{1}{2 \pi f C_T}$$

Substituting circuit values,

$$\begin{aligned}
 X_{CT} &= \frac{1}{6.28(3 \text{ kHz})(3 \mu\text{F})} \\
 &= 17.6 \Omega
 \end{aligned}$$

Total capacitive reactance is 17.6ohms, the same total capacitive reactance calculated earlier by adding individual reactances.

Once the total capacitive reactance has been determined, the total current in the circuit can be calculated. The total current is equal to:

$$\begin{aligned}
 I_T &= \frac{E_A}{X_{CT}} \\
 &= \frac{10 \text{ V}}{17.6 \Omega} \\
 &= 568 \text{ mA}
 \end{aligned}$$

The applied voltage divided by the total capacitive reactance equals 0.568 amperes —568 milliamperes. Therefore, as shown in [Figure 6.45](#), most information about the circuit has been calculated.

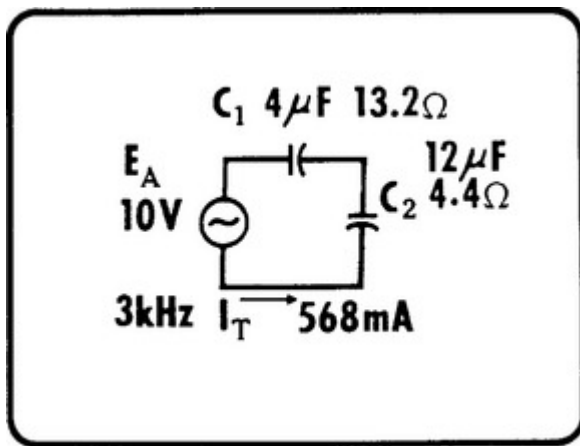


FIGURE 6.45 Summation of Calculated Circuit Values

Now the rules of series circuits are applied to find the voltage drops across C_1 and C_2 . Since it is a series circuit, the current is the total current and it is the same throughout the circuit. The voltage drop across C_1 is equal to the value of its capacitive current times its opposition to that current:

$$\begin{aligned} E_{C1} &= I_{C1} X_{C1} \\ &= I_T X_{C1} \\ &= (568 \text{ mA})(13.2 \Omega) \\ &= 7.5 \text{ V} \end{aligned}$$

The voltage drop across C_2 is calculated similarly.

$$\begin{aligned} E_{C2} &= I_{C2} X_{C2} \\ &= I_T X_{C2} \\ &= (568 \text{ mA})(4.4 \Omega) \\ &= 2.5 \text{ V} \end{aligned}$$

In a purely capacitive circuit, the voltage drops add to the total applied voltage as in a series resistive circuit:

$$\begin{aligned} E_A &= E_{C1} + E_{C2} \\ &= 7.5 \text{ V} + 2.5 \text{ V} \\ &= 10 \text{ V} \end{aligned}$$

The circuit with these calculated voltages indicated is shown in **Figure 6.46**.

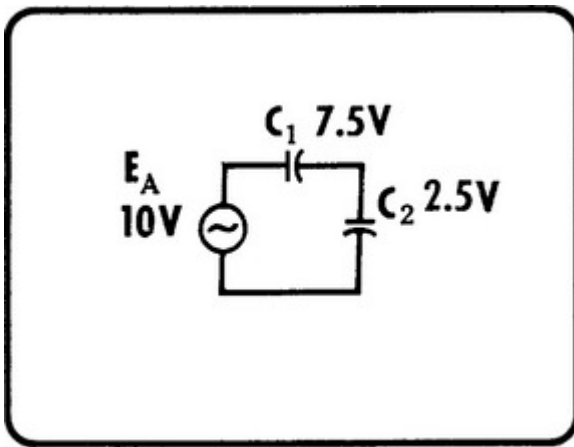


FIGURE 6.46 Example Circuit Calculated Voltages

Thus, you can see that knowing just a few factors about a circuit can allow you to calculate most all other factors.

Parallel Capacitive Circuit Analysis

Now, a parallel combination of two capacitors, as shown in **Figure 6.47**, will be analyzed. The same voltage, frequency and two capacitors used in the circuit of **Figure 6.44** will be used in this analysis. The capacitive reactance of the respective capacitors will be the same —13.2ohms for X_{C1} and 4.4ohms for X_{C2} — since the values of the capacitors and the applied frequency are the same. The branch current for the C_1 branch may be determined by dividing the voltage across the branch by the opposition in the branch.

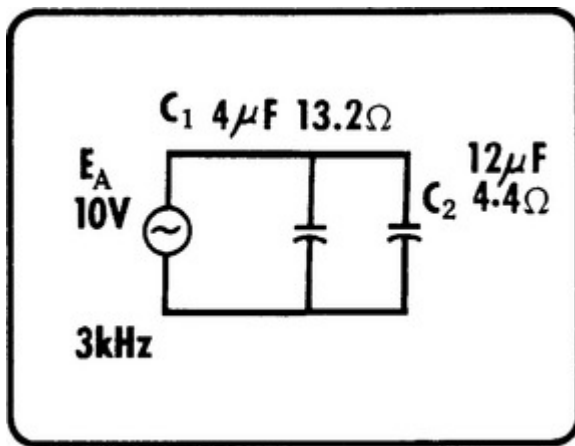


FIGURE 6.47 Example Parallel Circuit

$$\begin{aligned}
 I_{C1} &= \frac{E_{C1}}{X_{C1}} \\
 &= \frac{E_A}{X_{C1}} \\
 &= \frac{10V}{13.21 \Omega} \\
 &= 757 \text{ mA}
 \end{aligned}$$

The current for the C_2 branch is calculated similarly.

$$\begin{aligned}
 I_{C2} &= \frac{E_{C2}}{X_{C2}} \\
 &= \frac{E_A}{X_{C2}} \\
 &= \frac{10 \text{ V}}{4.4 \Omega} \\
 &= 2.273 \text{ A}
 \end{aligned}$$

The total current in the circuit is the sum of the branch currents:

$$\begin{aligned}
 I_T &= I_{C1} + I_{C2} \\
 &= 0.757 \text{ A} + 2.273 \text{ A} \\
 &= 3.03 \text{ A}
 \end{aligned}$$

This information can then be placed on the circuit as shown in **Figure 6.48**.

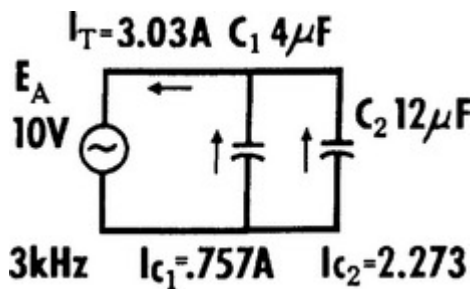


FIGURE 6.48 Example Parallel Circuit with Calculated Values

Another way to determine the total current is to first find the total capacitive reactance and then divide the applied voltage by the total capacitive reactance. One way to determine the total capacitive reactance, would be to use the product-over-sum equation to calculate the reactances of C_1 and C_2 . However, there's an easier method. First, the total capacitance is determined using [equation 6-12](#).

$$\begin{aligned} C_T &= C_1 + C_2 \\ &= 4\mu\text{F} + 12\mu\text{F} \\ &= 16\mu\text{F} \end{aligned}$$

Next, the total capacitive reactance is calculated using the value of total capacitance, 16 μ F.

$$\begin{aligned} X_{CT} &= \frac{1}{2 \pi f C_T} \\ &= \frac{1}{6.28(3 \text{ kHz})(16 \mu\text{F})} \\ &= 3.3 \Omega \end{aligned}$$

Last, total current in the circuit can be calculated:

$$\begin{aligned} I_{CT} &= \frac{E_A}{X_{CT}} \\ &= \frac{10 \text{ V}}{3.3 \Omega} \\ &= 3.03 \text{ A} \end{aligned}$$

The total current calculated is 3.03 amperes, which is the identical answer calculated previously using a different equation. Therefore, per-

forming this last calculation proved that the earlier calculation was correct.

Calculations Of Reactive Power

Power in capacitive circuits can be calculated similar to the way power is calculated in resistive circuits.

Recall that power in resistive circuits is converted to heat and dissipated. That is, the electrical energy is converted into heat energy. This is not true with capacitors. The electrical energy in capacitive circuits is stored temporarily on the plates of the capacitors in what is called an electrostatic field. The energy is then returned to the circuit.

Recall that the basic power equation is

$$P = EI \quad (6-13)$$

This same equation is used to calculate power in capacitive circuits. However, the power in capacitive circuits is measured in units called VAR, not watts as in resistive circuit. VAR stands for Volts-Amperes-Reactive. The power in a capacitive circuit is called reactive power since the opposition to current in the circuit is totally reactive. Therefore, the basic equation to calculate power in a capacitive circuit (with appropriate units) is:

$$\begin{array}{ccccccc} P & = & E & \times & I & & \\ \text{(VAR)} & & \text{(volts)} & & \text{(amperes)} & & \end{array} \quad (6-14)$$

Power In Series Capacitive Circuit

The series capacitive circuit of [**Figure 6.49**](#) (which is the circuit that was discussed earlier) will be used for the example of calculating power in such a circuit. In that circuit, E_{C1} is 7.5 volts and the current through C1 is 568 milliamperes (0.568 A).

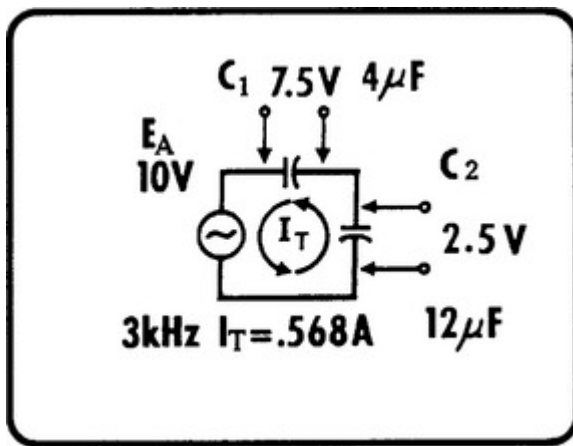


FIGURE 6.49 Example Series Circuit

The power equation can be used to calculate the reactive power of C_1 . P_{C1} equals E_{C1} times I_{C1} .

$$\begin{aligned} P_{C1} &= E_{C1} I_{C1} \\ &= (7.5 \text{ V})(0.568 \text{ A}) \\ &= 4.26 \text{ VAR} \end{aligned}$$

As shown this equals 7.5 volts times 0.568 amperes which equals 4.26VAR.

Similarly, the reactive power of C_2 can be calculated.

$$\begin{aligned} P_{C2} &= E_{C2} I_{C2} \\ &= (2.5 \text{ V})(0.568 \text{ A}) \\ &= 1.42 \text{ VAR} \end{aligned}$$

By adding these two values of reactive power the total reactive power of the circuit obtained:

$$\begin{aligned} P_{XT} &= P_{C1} - P_{C2} \\ &= 4.26 \text{ VAR} + 1.42 \text{ VAR} \\ &= 5.68 \text{ VAR} \end{aligned}$$

The total reactive power of the circuit could also have been determined by multiplying the total applied voltage times the total current.

$$\begin{aligned}
 P_{XT} &= E_A I_T \\
 &= (10V)(0.568A) \\
 &= 5.68VAR
 \end{aligned}$$

10 volts times 0.568 amperes equals 5.68VAR which is the same power calculated previously, and proves that calculation was correct. Thus, using the basic power equation as the reactive power equation, the individual and total reactive powers have been calculated.

Power In Parallel Capacitive Circuit

The same type of calculations can be performed to obtain the reactive power quantities for a parallel capacitive circuit. The parallel capacitive circuit of [Figure 6.47](#) used earlier will be used again, and is repeated in [Figure 6.50](#).

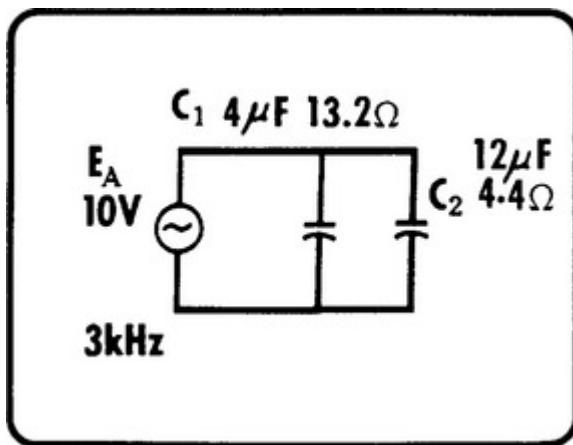


FIGURE 6.50 Example Parallel Circuit

First the power of capacitor C_1 is calculated.

$$\begin{aligned}
 P_{C1} &= E_{C1} I_{C1} \\
 &= (10V)(0.757A) \\
 &= 7.57VAR
 \end{aligned}$$

P_{C1} equals 10 volts across C_1 times 0.757 amperes I_{C1} equals 7.57VAR.

Next the power of capacitor C_2 is calculated.

$$\begin{aligned}
 P_{C2} &= E_{C2} I_{C2} \\
 &= (10 \text{ V})(2.273 \text{ A}) \\
 &= 22.73 \text{ VAR}
 \end{aligned}$$

P_{C2} equals 10 volts across C_2 times 2.273 amperes, I_{C2} , equals 22.73 VAR.

Last, the total reactive power of the circuit is calculated.

$$\begin{aligned}
 P_{XT} &= P_{C1} - P_{C2} \\
 &= 7.57 \text{ VAR} + 22.73 \text{ VAR} \\
 &= 30.3 \text{ VAR}
 \end{aligned}$$

Total reactive power equals 30.3VAR. Also, the total reactive power equals the total applied voltage times the total current. In this case, that would be 10 volts times 3.03 amperes which equals 30.3VAR. This is the same answer calculated previously and proves the previous calculations are correct.

Using the equations discussed you should be able to calculate similar information about any other series or parallel capacitive circuit.

Summary

chapter has provided an introduction to capacitive circuits. The physical properties of different types of capacitors and the concept of capacitance and charge were discussed. How a capacitor functions when it is charged and discharged relating capacitive properties to a stored charge and an opposition to voltage changes, was described. The concepts of capacitive reactance as an opposition to current flow and as a function of frequency

were covered. Current/voltage relationships were explained using the rate of change equation. Series and parallel capacitive circuits were analyzed determining reactance voltage drops, currents, and power. All of these concepts will be used in following chapters to solve more complex circuits.

1. Describe the characteristics of a ceramic disc capacitor.

Solution: The ceramic disc capacitor is available in small values of capacitance from approximately 1 picofarad to 2.5 microfarads. Typical working voltages are 20 volts up to about 200 volts. It is a good insulator, and it has a permittivity of almost 1,000 times more than that of dry air.

2. Define capacitance

Solution: Capacitance is the ability of a nonconductor to store a charge. If a voltage of 50 volts is applied to a capacitor for a period of time, the capacitor will charge to the 50-volt value and retain that difference in potential for a period of time after that voltage is removed.

3. Describe one effect of the capacitive property in ac circuits.

Solution: In ac circuits, the current through the capacitive branch of the circuit leads the voltage across the capacitor by 90 degrees. This is explained by the equation $I_C = C \times ROC$.

4. A mylar capacitor with a dielectric 2 mils thick has a value of 0.01 microfarads. What would be the result of increasing the dielectric 2 mils thickness to 4 mils if all of the other variables remain the same?

Solution: The equation describing the physical parameters of a capacitor is:

$$C = K_F \left(\frac{A}{d} \right) \epsilon_o$$

The d variable represents the distance between the plates, and the equation shows that distance is indirectly related to capacitance. If the distance between the plates increases as proposed in the problem, capacitance will decrease. Because the distance has doubled, the capacitance value will be halved, and the value of capacitance will be 0.005 microfarads.

5. Calculate the area of either plate of a 1 farad paper capacitor with a dielectric 1 millimeter thick. Assume $K_e = 4$.

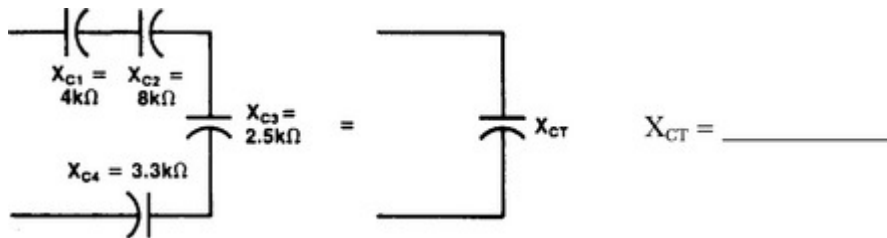
$$C = K_F \left(\frac{A}{d} \right) \epsilon_o$$

Solving for A:

$$A = \frac{C \times d}{K_E \epsilon_o} = \frac{1F \times 0.001m}{4 \times 8.85 \times 10^{-12}} = \frac{0.001}{3.54 \times 10^{-11}} = \mathbf{28.2 \times 10^6 \text{ square meters}}$$

or about 12 square miles

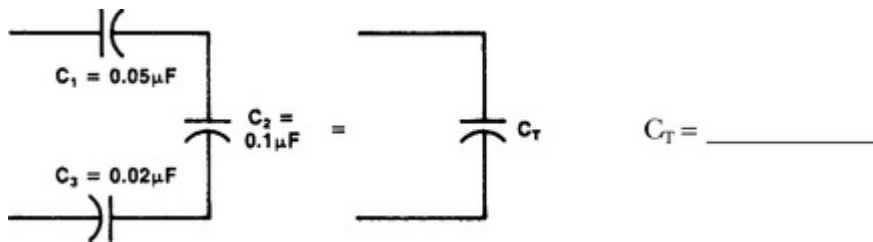
6. Solve for X_{CT} in this circuit:



Solution In a series capacitive circuit, total capacitive reactance is calculated the same as total resistance in series is calculated.

$$X_{CT} = X_{C1} + X_{C2} + X_{C3} + X_{C4} = 4k\Omega + 8k\Omega + 2.5k\Omega + 3.3k\Omega = \mathbf{17.8k\Omega}$$

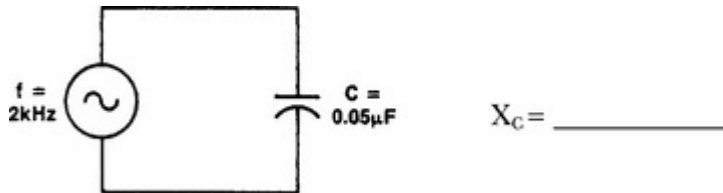
7. Solve for C_T in this circuit:



Solution In a series capacitive circuit, total capacitance is calculated similar to the way total resistance is calculated in a parallel resistive circuit.

$$\begin{aligned}\frac{1}{C_T} &= \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{1}{0.05 \mu\text{F}} + \frac{1}{0.1 \mu\text{F}} + \frac{1}{0.02 \mu\text{F}} \\ &= \frac{1}{0.05 \times 10^{-6}} + \frac{1}{0.1 \times 10^{-6}} + \frac{1}{0.02 \times 10^{-6}} = 20 \times 10^6 + 10 \times 10^6 + 50 \times 10^6 \text{ F} \\ &= 80 \times 10^6 \text{ F} \\ C_T &= \frac{1}{80 \times 10^6} \text{ F} = \mathbf{0.0125 \mu\text{F}}\end{aligned}$$

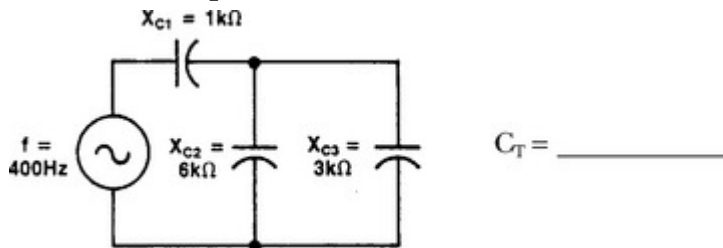
8. Solve for X_C in this circuit:



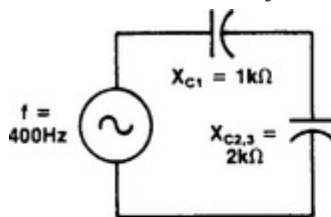
Solution

$$X_C = \frac{1}{2 \pi f C} = \frac{1}{628 \times 2 \times 10^3 \times 0.05 \times 10^{-6}} = \frac{1}{6.28 \times 10^{-6} \Omega} = 1.59 \times 10^3 = \mathbf{1.59 \text{ k}\Omega}$$

9. Solve for C_T in this circuit:



Solution: Solve for X_{CT} by circuit simplification.



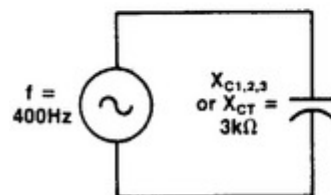
$$X_C = \frac{1}{2 \pi f C}$$

and

$$X_{CT} = \frac{1}{2 \pi f C_T}$$

Solving for C_T

$$\begin{aligned}C_T &= \frac{1}{2 \pi f X_{CT}} = \frac{1}{6.28 \times 400 \times 3,000} \\ &= \frac{1}{7.54 \times 10^6} = \mathbf{0.133 \mu\text{F}}\end{aligned}$$



$$X_C = \frac{1}{2 \pi f C}$$

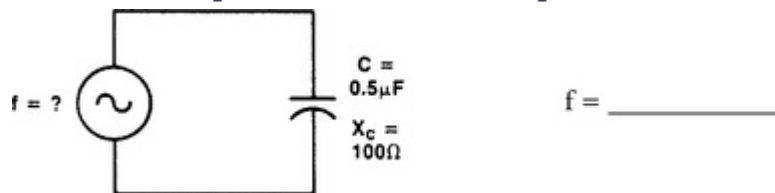
and

$$X_{CT} = \frac{1}{2 \pi f C_T}$$

Solving for C_T

$$C_T = \frac{1}{2 \pi f X_{CT}} = \frac{1}{6.28 \times 400 \times 3,000} \\ = \frac{1}{7.54 \times 10^6} = \mathbf{0.133 \mu F}$$

10. What source frequency must be applied to a 0.5 microfarad capacitor so that the capacitor will have a capacitive reactance of 100 ohms?



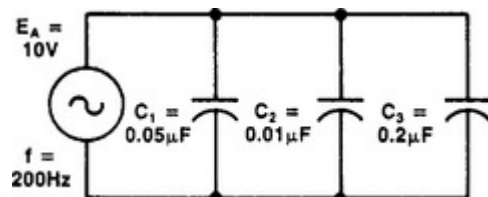
Solution

$$X_C = \frac{1}{2 \pi f C}$$

Solving for f

$$f = \frac{1}{2 \pi X_C C} = \frac{1}{6.28 \times 100 \times 0.5 \times 10^{-6}} = \frac{1}{314 \times 10^{-6}} = \mathbf{3.18 \text{ kHz}}$$

11. Solve for the circuit values specified for this circuit:



a. $C_T =$ _____

b. $X_{C1} =$ _____

c. $X_{C2} =$ _____

d. $X_{C3} =$ _____

e. $X_{CT} =$ _____

f. $E_{C1} =$ _____

g. $E_{C2} =$ _____

h. $E_{C3} =$ _____

i. $I_{C1} =$ _____

j. $I_{C2} =$ _____

k. $I_{C3} =$ _____

l. $I_{CT} =$ _____

m. $P_{C1} =$ _____

n. $P_{C2} =$ _____

o. $P_{C3} =$ _____

p. $P_{C3} =$ _____

q. $P_{CT} =$ _____

Solution

a.

$$C_T = C_1 + C_2 + C_3 = 0.05\mu\text{F} + 0.01\mu\text{F} + 0.2\mu\text{F} = \mathbf{0.26\mu\text{F}}$$

b.

$$X_{C1} = \frac{1}{2 \pi f C_1} = \frac{1}{6.28 \times 200 \times 0.05 \times 10^{-6}} = \frac{1}{6.28 \times 10^{-5}} = \mathbf{15.9 \text{ k}\Omega}$$

c.

$$X_{C2} = \frac{1}{6.28 \times 200 \times 0.01 \times 10^{-6}} = \frac{1}{12.58 \times 10^{-6}} = \mathbf{79.6 \text{ k}\Omega}$$

d.

$$X_{C3} = \frac{1}{6.28 \times 200 \times 0.2 \times 10^{-6}} = \frac{1}{251 \times 10^{-6}} = \mathbf{3.98 \text{ k}\Omega}$$

e.

$$\begin{aligned} \frac{1}{X_{CT}} &= \frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} = \frac{1}{15.9 \text{ k}} + \frac{1}{79.6 \text{ k}} + \frac{1}{3.98 \text{ k}} \\ &= 62.9 \times 10^{-3} + 12.6 \times 10^{-3} + 2.51 \times 10^{-3} = 327 \times 10^{-3} = \frac{1}{327 \times 10^{-3}} = \mathbf{3.06 \text{ k}\Omega} \end{aligned}$$

$$\begin{aligned} \text{or } X_{CT} &= \frac{1}{2 \pi f C_T} = \frac{1}{6.28 \times 200 \times 0.26 \times 10^{-6}} = \frac{1}{3.27 \times 10^{-4}} \\ &= 0.306 \times 10^4 = \mathbf{3.06 \text{ k}\Omega} \end{aligned}$$

f.,g.,h. In parallel E_A , 10VAC, is across all components.

i.

$$I_{C1} = \frac{E_{C1}}{X_{C1}} = \frac{10 \text{ V}}{15.9 \text{ k}\Omega} = \mathbf{630 \mu A_{rms}}$$

j.

$$I_{C2} = \frac{E_{C2}}{X_{C2}} = \frac{10 \text{ V}}{79.6 \text{ k}\Omega} = \mathbf{126 \mu A}$$

k.

$$I_{C3} = \frac{E_{C3}}{X_{C3}} = \frac{10 \text{ V}}{3.98 \text{ k}\Omega} = \mathbf{2.51 \text{ mA}}$$

l.

$$I_{CT} = I_{C1} + I_{C2} + I_{C3} = 630 \mu A + 126 \mu A + 2.51 \text{ mA}_{\text{rms}} = \mathbf{3.27 \text{ mA}}$$
 or

$$I_{CT} = \frac{E_A}{X_{CT}} + \frac{10 \text{ V}}{3.06} = \mathbf{3.27 \text{ mA}}$$

m. $P_{C1} = I_{C1} \times E_{C1} = 630 \mu A \times 10 V = 6.3 \text{ mAVAR}$

n. $P_{C2} = I_{C2} \times E_{C2} = 126 \mu A \times 10 V = 1.26 \text{ mAVAR}$

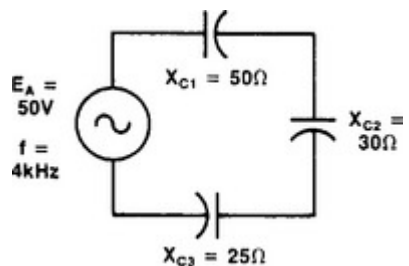
o. $P_{C3} = I_{C3} \times E_{C3} = 2.51 \text{ mA} \times 10 V = 25.1 \text{ mAVAR}$

p.

$$P_{CT} = P_{C1} + P_{C2} + P_{C3} = 6.3 \text{ mVAR} + 1.26 \text{ VAR} + 25.1 \text{ mVAR} = \mathbf{32.7 \text{ mVAR}}$$
 or

$$P_{CT} = I_{CT} E_A + (3.27 \text{ mA})(10 \text{ V}) = \mathbf{32.7 \text{ mVAR}}$$

12. Solve for the circuit values specified for this circuit:



a. $X_{CT} =$ _____

b. $C_1 =$ _____

c. $C_2 =$ _____

d. $C_3 =$ _____

e. $C_T =$ _____

f. $I_{C1} =$ _____

g. $I_{C2} =$ _____

h. $I_{C3} =$ _____

i. $I_{CT} =$ _____

j. $E_{C1} =$ _____

k. $E_{C2} =$ _____

l. $E_{C3} =$ _____

m. $E_{CT} =$ _____

n. $P_{C1} =$ _____

o. $P_{C2} =$ _____

p. $P_{C3} =$ _____

q. $P_{CT} =$ _____

Solution

a.

$$X_{CT} = X_{C1} + X_{C2} + X_{C3} = 50 \Omega + 30 \Omega + 25 \Omega = 105 \Omega$$

b.

$$C_1 = \frac{1}{2 \pi f X_{C1}} = \frac{1}{6.28 \times 4 \text{ k} \times 50} = \frac{1}{1.256 \times 10^6} = 0.796 \mu\text{F}$$

c.

$$C_2 = \frac{1}{2 \pi f X_{C2}} = \frac{1}{6.28 \times 4 \text{ k} \times 30} = \frac{1}{754 \times 10^3} = 1.33 \mu\text{F}$$

d.

$$C_3 = \frac{1}{2 \pi f X_{C3}} = \frac{1}{6.28 \times 4 \text{ k} \times 25} = \frac{1}{628 \times 10^3} = 1.59 \mu\text{F}$$

e.

$$C_T = \frac{1}{2 \pi f X_{CT}} = \frac{1}{6.28 \times 4 \text{ k} \times 10^5} = \frac{1}{2.64 \times 10^6} = \mathbf{0.379 \mu F}$$

f.,g.,h. In series, total current flows through all components, See I_{CT}

i.

$$I_{CT} = \frac{E_A}{X_{CT}} = \frac{50 \text{ V}}{105 \Omega} = \mathbf{0.476 \text{ A(rms)}}$$

$$j. E_{C1} = I_{C1} \times X_{C1} = 0.476 \text{ A} \times 50 \Omega = 23.8 \text{ V}$$

$$k. E_{C2} = I_{C2} \times X_{C2} = 0.476 \text{ A} \times 30 \Omega = 14.3 \text{ V}$$

$$l. E_{C3} = I_{C3} \times X_{C3} = 0.476 \text{ A} \times 25 \Omega = 11.9 \text{ V}$$

$$m. E_{CT} = E_A = E_{C1} + E_{C2} + E_{C3} = 23.8 \text{ V} + 14.3 \text{ V} + 11.9 \text{ V} = 50 \text{ V}$$

$$n. P_{C1} = I_{C1} \times E_{C1} = 0.476 \text{ A} \times 23.8 \text{ V} = 11.3 \text{ VAR}$$

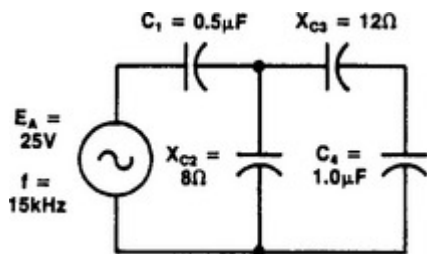
$$o. P_{C2} = I_{C2} \times E_{C2} = 0.476 \text{ A} \times 14.3 \text{ V} = 6.81 \text{ VAR}$$

$$p. P_{C3} = I_{C3} \times E_{C3} = 0.476 \text{ A} \times 11.9 \text{ V} = 5.66 \text{ VAR}$$

$$q. P_{CT} = P_{C1} + P_{C2} + P_{C3} = 11.3 + 6.81 + 5.66 = 23.8 \text{ VAR or}$$

$$P_{CT} = I_{CT} \times E_A = 0.476 \text{ A} \times 50 \text{ V} = 23.8 \text{ VAR}$$

13. Solve for the circuit values specified for this circuit:



a. $X_{C1} =$ _____

b. $X_{C4} =$ _____

c. $C_2 =$ _____

d. $C_3 =$ _____

e. $X_{CT} =$ _____

f. $C_T =$ _____

g. $I_T =$ _____

h. $I_{C1} =$ _____

i. $E_{C1} =$ _____

j. $E_{C2} =$ _____

k. $I_{C2} =$ _____

l. $I_{C3} =$ _____

m. $I_{C4} =$ _____

n. $E_{C3} =$ _____

o. $E_{C4} =$ _____

p. $P_{C1} =$ _____

q. $P_{C2} =$ _____

r. $P_{C3} =$ _____

s. $P_{C4} =$ _____

t. $P_T =$ _____

Solution

a.

$$X_{C1} = \frac{1}{2 \pi f C_1} = \frac{1}{6.28 \times 15 \text{ k} \times 0.5 \times 10^{-6}} = \mathbf{21.2\Omega}$$

b.

$$X_{C4} = \frac{1}{6.28 \times 15 \text{ k} \times 1 \times 10^{-6}} = \mathbf{10.6\Omega}$$

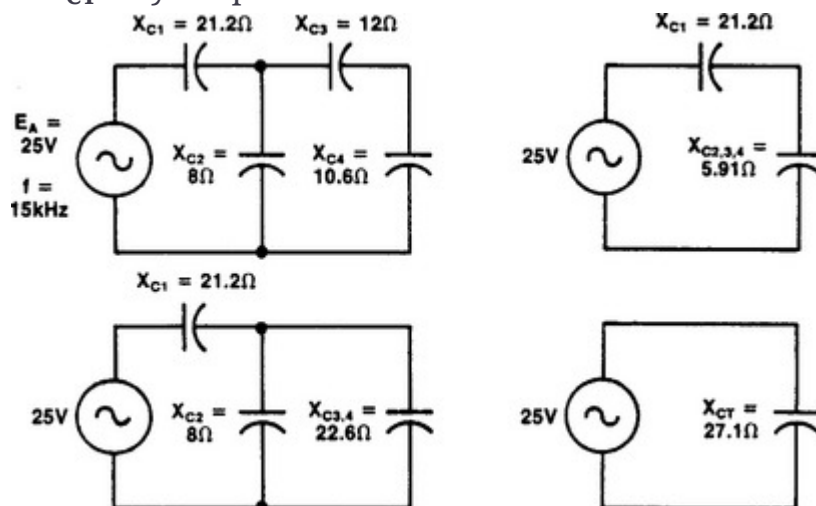
c.

$$C_2 = \frac{1}{2 \pi f X} = \frac{1}{6.28 \times 15 \text{ k} \times 8} = \mathbf{1.33\mu F}$$

d.

$$C_3 = \frac{1}{6.28 \times 15 \text{ k} \times 12} = \mathbf{0.885mF}$$

e. X_{CT} = by simplification



f.

$$C_T = \frac{1}{2 \pi f X_{CT}} = \frac{1}{6.28 \times 15 \text{ k} \times 27.1} = \frac{1}{6.28 \times 15 \times 10^3 \times 27.1} = \frac{1}{2.55 \times 10^6} = \mathbf{0.39\mu F}$$

g.

$$I_T = \frac{E_A}{X_{CT}} = \frac{25V}{27.1 \Omega} = \mathbf{0.923 A_{rms}}$$

h. $I_{C1} = I_T = 0.923A$

i. $E_{C1} = I_{C1} \times X_{C1} = 0.923 A \times 21.2W = 19.6V$

j.

$$E_{C2} = E_{C2,3,4} = I_T \times X_{C2,3,4} = I_T \left(\frac{8 \Omega (12 \Omega + 10.6 \Omega)}{8 \Omega + 12 \Omega + 10.6 \Omega} \right) = 0.923 A \times 5.91 \Omega = \mathbf{5.45 V}$$

k.

$$I_{C2} = \frac{E_{C2}}{X_{C2}} = \frac{5.45 V}{8 \Omega} = \mathbf{0.681 A}$$

l,m.

$$I_{C3} = I_{C4} = \frac{E_{C3,4}}{X_{C3,4}} = \frac{E_{C2,3,4}}{X_{C3,4}} = \frac{5.45 V}{12 \Omega + 10.6 \Omega} = \frac{5.45 V}{22.6 \Omega} = \mathbf{0.241 A}$$

n. $E_{C3} = I_{C3} \times X_{C3} = 0.24 A \times 12\Omega = 2.88V$

o. $E_{C4} = I_{C4} \times X_{C4} = 0.24 A \times 10.6W = 2.54V$

p. $P_{C1} = I_{C1} \times E_{C1} = 0.923 A \times 19.6 V = 18.1VAR$

q. $P_{C2} = I_{C2} \times E_{C2} = 0.681 A \times 5.45 V = 3.71VAR$

r. $P_{C3} = I_{C3} \times E_{C3} = 1.241 A \times 2.88 V = 0.695VAR$

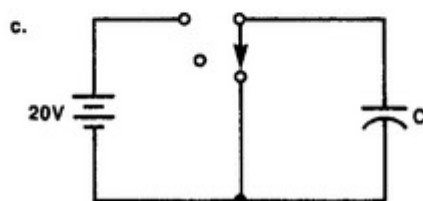
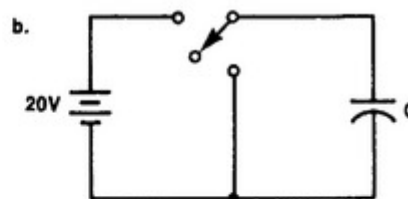
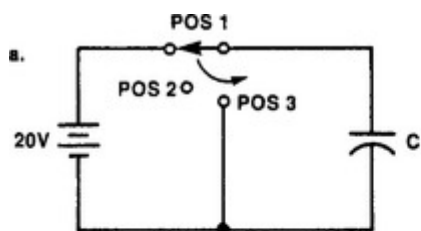
s. $P_{C4} = I_{C4} \times E_{C4} = 0.241 A \times 2.54 V = 0.612VAR$

t.

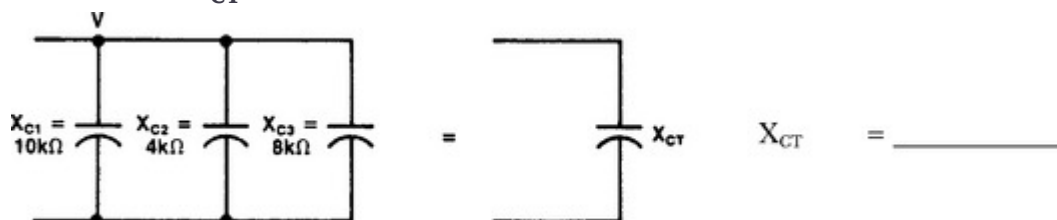
$$P_T = P_{C1} + P_{C2} + P_{C3} + P_{C4} = \mathbf{23.1 \text{ VAR}} \text{ or}$$

$$P_T = I_{CT} \times E_A = 0.923 \text{ A} \times 25 \text{ V} = \mathbf{23.1 \text{ VAR}}$$

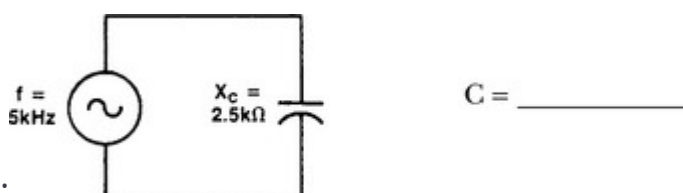
- Describe the characteristics of a paper capacitor. Use the tables provided in the text.
- Predict what will happen in the circuits below: a. with the switch in position 1; b. with the switch moved from position 1 to position 2; c. with the switch moved from position 2 to position 3.



- In Example 3 of the Worked-Out Examples, one effect of the capacitive property was discussed. Discuss briefly the other effect.
- Relate the plate area of a capacitor to capacitors connected in parallel.
- Solve for X_{CT} in this circuit:



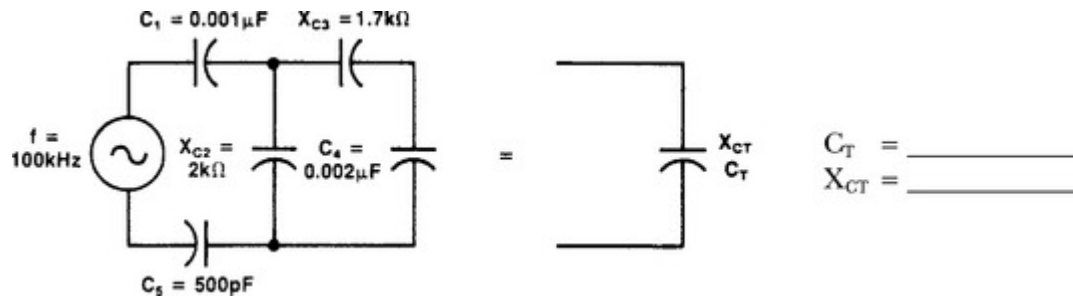
$$X_{CT} = \underline{\hspace{2cm}}$$



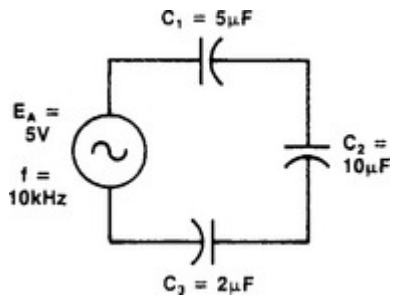
- Solve for C_T in this circuit:

$C_T = \underline{\hspace{2cm}}$

7. What value of capacitor will have a resistance of $2.5k\Omega$ in this circuit:



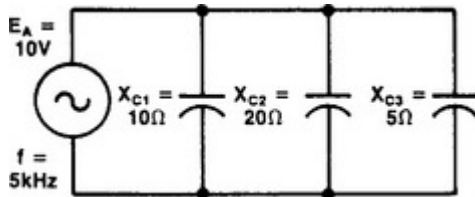
8. Solve for X_{CT} and C_T in this circuit:



C_T

X_{CT}

9. Solve for the circuit values specified in this circuit:



a. $C_T = \underline{\hspace{2cm}}$

b. $X_{C1} = \underline{\hspace{2cm}}$

c. $X_{C2} = \underline{\hspace{2cm}}$

d. $X_{C3} =$ _____

e. $X_{CT} =$ _____

f. $I_{C1} =$ _____

g. $I_{C2} =$ _____

h. $I_{C3} =$ _____

i. $E_{C1} =$ _____

j. $E_{C2} =$ _____

k. $E_{C3} =$ _____

l. $E_{CT} =$ _____

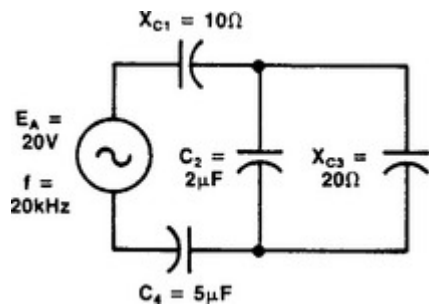
m. $P_{C1} =$ _____

n. $P_{C2} =$ _____

o. $P_{C3} =$ _____

q. $P_{CT} =$ _____

10. Solve for the circuit values specified in this circuit:



a. $X_{CT} =$ _____

b. $C_1 =$ _____

c. $C_2 =$ _____

d. $C_3 =$ _____

e. $C_T =$ _____

f. $E_{C1} =$ _____

h. $E_{C2} =$ _____

i. $E_{C3} =$ _____

j. $I_{C1} =$ _____

k. $I_{C2} =$ _____

l. $I_{C3} =$ _____

m. $I_{CT} =$ _____

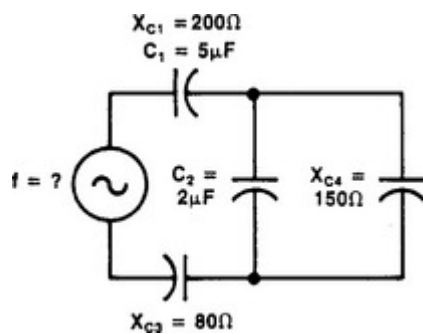
n. $P_{C1} =$ _____

o. $P_{C2} =$ _____

p. $P_{C3} =$ _____

r. $P_{CT} =$ _____

11. Solve for the circuit values specified in this circuit:



a. $C_1 =$ _____

b. $C_3 =$ _____

c. $X_{C2} =$ _____

d. $X_{C4} =$ _____

e. $X_{CT} =$ _____

f. $C_T =$ _____

g. $E_{C1} =$ _____

h. $E_{C2} =$ _____

i. $E_{C3} =$ _____

j. $E_{C4} =$ _____

k. $I_{C1} =$ _____

l. $I_{C2} =$ _____

m. $I_{C3} =$ _____

n. $I_{C4} =$ _____

o. $I_T =$ _____

p. $P_{C1} =$ _____

q. $P_{C2} =$ _____

r. $P_{C3} =$ _____

s. $P_{C4} =$ _____

t. $P_T =$ _____

1. Using the tables provided in the text, answer the following questions:

Which type of capacitor has:

- a. The greatest dielectric strength?
- b. The largest dielectric constant?
- c. The largest capacitance value?
- d. The largest value of working voltage?

2.

- a. If a neutrally-charged capacitor is connected to a 50-volt source, what will happen to the capacitor?
- b. If the source is then removed from the capacitor, what happens?
- c. If a charged capacitor is shorted with a piece of wire, what occurs in the resulting circuit?

3. Draw a phasor diagram showing the relationship of IC and EC in an ac capacitive circuit.

4. Draw a sine wave graph showing the relationship of IC and EC in an ac capacitive circuit.

5. A capacitor in an ac circuit may be best defined as:

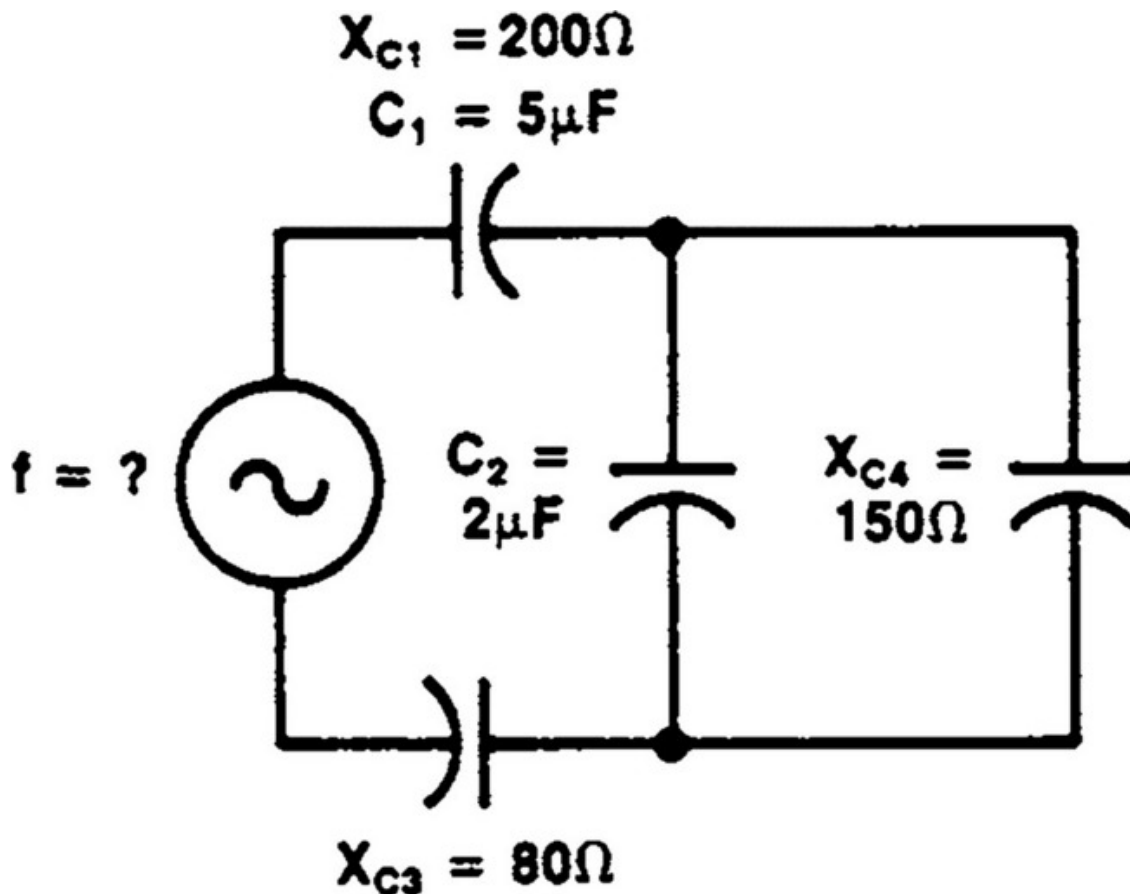
- a. An open circuit
- b. A short circuit
- c. A fixed resistance
- d. A variable resistance
- e. A short circuit instantly, an open circuit after the capacitor is charged.

6.

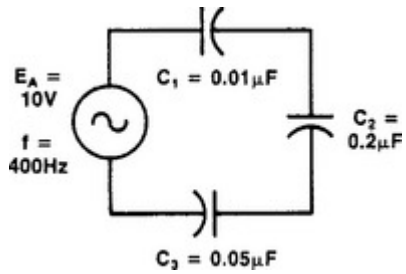
a. What is the source frequency? Note the given values of C_1 and X_{C1}

b. $X_{CT} = \underline{\hspace{2cm}}$

c. $C_T = \underline{\hspace{2cm}}$



7. Solve for the circuit values specified for this circuit:



a. $C_T =$ _____

b. $X_{C1} =$ _____

c. $X_{C2} =$ _____

d. $X_{C3} =$ _____

e. $X_{CT} =$ _____

f. $I_{C1} =$ _____

g. $I_{C2} =$ _____

h. $I_{C3} =$ _____

i. $I_T =$ _____

j. $E_{C1} =$ _____

k. $E_{C2} =$ _____

l. $E_{C3} =$ _____

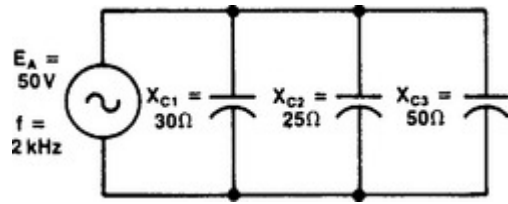
m. $P_{C1} =$ _____

n. $P_{C2} =$ _____

o. $P_{C3} =$ _____

p. $P_T =$ _____

8. Solve for the circuit values specified for this circuit:



a. $X_{CT} =$ _____

b. $C_1 =$ _____

c. $C_2 =$ _____

d. $C_3 =$ _____

e. $C_T =$ _____

f. $E_{C1} =$ _____

g. $E_{C2} =$ _____

h. $E_{C3} =$ _____

i. $I_{C1} =$ _____

j. $I_{C2} =$ _____

k. $I_{C3} =$ _____

l. $I_T =$ _____

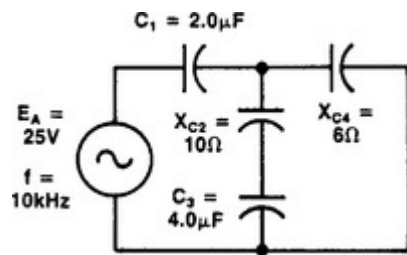
m. $P_{C1} =$ _____

n. $P_{C2} =$ _____

o. $P_{C3} =$ _____

p. $P_T =$ _____

9. Solve for the circuit values specified for this circuit:



a. $C_2 =$ _____

b. $C_4 =$ _____

c. $X_{C1} =$ _____

d. $X_{C3} =$ _____

e. $X_{CT} =$ _____

f. $C_T =$ _____

g. $I_{C1} =$ _____

h. $I_{C2} =$ _____

i. $I_{C3} =$ _____

j. $I_{C4} =$ _____

k. $I_T =$ _____

l. $E_{C1} =$ _____

m. $E_{C2} =$ _____

n. $E_{C3} =$ _____

o. $E_{C4} =$ _____

p. $P_{C1} =$ _____

q. $P_{C2} =$ _____

r. $P_{C3} =$ _____

s. $P_{C4} =$ _____

t. $P_{C5} =$ _____

10. Are the voltage, current, and power values calculated in Problems 7, 8, and 9 rms, peak, or peak-to-peak values?

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