A capacitor is defined as a device that stores energy in an electrostatic field. The energy is stored in such a way as to oppose any change in voltage.

From this it can be stated, that where a difference of potential exists, an electrostatic field will be produced and energy will be stored. This condition produces capacitance.

Capacitance can be defined in terms of this stored energy or charge and the difference of potential (volts) that exists. This may be expressed mathematically;

$$C(\text{FARADS}) = \frac{Q(\text{Coulombs})}{E(\text{volts})}.$$

Capacitance is measured in units called FARADS. A one-farad capacitor stores one coulomb (unit of charge (Q) equals to 6.28×10^{10} electrons) of charge when an potential difference if one (1.0) volt exists across the terminals of the capacitor.

A simple capacitor is shown in FIGURE 3, consisting of three basic parts; two plates and a dielectric.

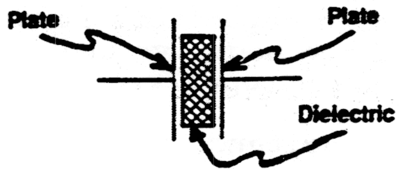


FIGURE 3

The two plates must be conductive material. The dielectric is made of a non conducting material. Listed below, are some types of dielectric materials or non conductors.

Air	Porcelain
Mica	Glass
Castor oil	Fiber
Wax paper	Resin
Quartz	Vacuum

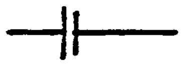
FIGURE 4

Above, the capacitance in farads was defined and showm mathematically, however, the farad or Coulombs per volts is such a large value that a one FARAD capacitor would be very large and impractical to use. Thus the microfarad (one millionth of a farad) is used and is written in numerical notation as 1×10^{-6} farads. In many cases values as small as one billionth of a farad are used and is written
$1 \times 1 \times 10^{-12}$ farads.

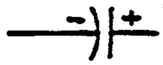
This is expressed as picofarad.

The letter symbol is C.

The schematic symbol is:

Fixed 

Variable 

The Electrolytic 

The unit value of the capacitor may be shown in microfarads (uf) or picofarads (pf).

The curved plate in the schematic diagram indicates an electrolytic capacitor. These capacitors have the polarity indicators by + and - or a band around the negative end. Electrolytic capacitors can be exploded if connected improperly.

The amount is capacitance of a capacitor depends upon the area of the plates (A).

The distance between the plates and the type of dielectric material that is used also determines the amount of capacitance. The capacitance is directly related to the plate area but inversely related to the distance between the plates and dielectric material.

The larger the area of the plates (A) of a capacitor, the greater the capacitance.

The greater the distance between the plates (d), the less the capacitance. When the distance between two charges particles increases, the reaction between the two is less. Capacitance may be expressed mathematically in terms of its physical characteristics as follows:

$$C(Pfd) = 0.2249 \frac{KA}{d}$$

Where:

C = Capacitance in picofarads

Area of one plate, in square inches

d = Distance between the plates, in inches

K = Dielectric constant of the insulating material

0.2249 = Constant resulting from the conversion from Metric to British units.

Dielectric constants for some common materials are listed in FIGURE 5.

MATERIAL	CONSTANT (K) in the formula)
Vacuum	1.0000
	1.0006
Paraffin Paper	3.5
Glass	5 to 10
Mica	3 to 6
Rubber	2.5 to 3.5
Wood	2.5 to 8
Glycerine (15°C)	56
Petrolrum	2.0
Pure water	81

FIGURE 5

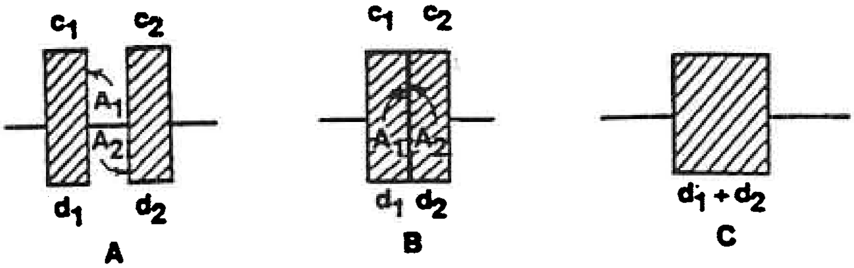
NOTE: Since vacuum is the standard of reference, it is assigned a constant of one. For all practical purposes, air is also considered one.

Capacitors, due to construction, will have limited voltage capability. This simply means that the plates are separated by very thin dielectric and this limits the voltage that can be applied across the plates. If this voltage is exceeded, arcing will occur between the plates and short, thus destroying the capacitor.

Capacitors may be connected in many ways, series, parallel, and series-parallel. First we will see how to determine total capacitance when capacitors are connected in series.

In FIGURE 6, we have two capacitors connected in series, thus

$$C_T = \frac{kA}{(d_1+d_2)}$$



$$C = \frac{KA}{d_1 + d_2}$$

FIGURE 6

Under A in FIGURE 6, are two capacitors in series. It will be noted $C_1 = C_2$ and $d_1 = d_2$. In B, if the conductor between A_1 and A_2 is removed and the plates A_1 and A_2 become one, the electrical circuit is still the same. If the plate A_1 A_2 is removed, the circuit is electrically the same. The area (A) of the plates have not changed, but the distance (d) between them has doubled or $d_1 + d_2$.

The indication in FIGURE 6, is that the dielectrics of C_1 and C_2 will be added to become one, which will be inversely proportional to the capacitance. From the formula

$$C - \frac{KA}{d}, \text{ or } \frac{C}{2} = \frac{KA}{d_1+d_2}, \text{ or}$$

to express this in terms of total capacitance

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{then}$$

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

Capacitors in series are like resistors in parallel.

EXAMPLE:

If $C_1 = C_2$ then $C_T = \frac{C_1}{2}$

If $C_1 \neq C_2$ then use $C_T = \frac{C_1 C_2}{C_1+C_2}$

If C_1, C_2 and C_3 are in series and are all of different values then use

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

For capacitors connects in parallel as shown in FIGURE 7, then area add but the dielectrics remain the same.

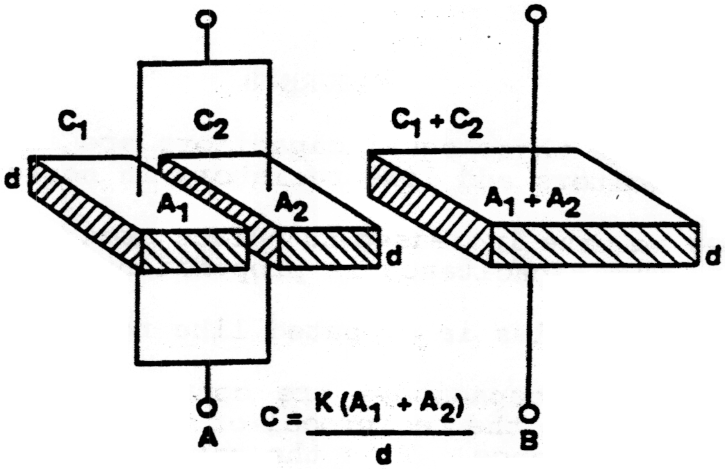


FIGURE 7

From the same formulas are used for series circuits;

$$C = \frac{KA}{d}.$$

As can be seen, the distance (d) between the plates did not change, however, the area (A) became $A_1 + A_2$. Applying this to the formula, we see that the area of the plates are directly proportional to the capacitance, this if

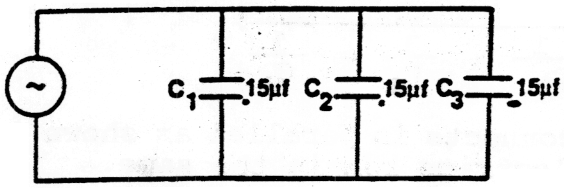
$$C = \frac{KA}{d}, \text{ then } 2C = \frac{K(A^1 + A_2)}{d}$$

the areas and add the capacitors. Thus

$$C_T = C_1 + C_2 + C_3$$

Capacitors in parallel add like resistors in series

Capacitors connects in a series-parallel circuit combination would be treated like a series-parallel resistor circuit combination. All circuits must be reduced to a series containing one capacitor and a power supply.



CT = C1 + C2 + C3

CT = .15 + .15 + .15

CT = .45µf

FIGURE 8

In FIGURE 8, the three equal capacitors are added. In this case, the parallel capacitors add like resistors in series.

Effectively we have increased the plate area by the number and size of the plates. The capacitance is proportional to the plate area.

Capacitance in series is computed like resistors in parallel.

When two or more capacitors are connected in series, the total capacitance is equal to the reciprocal of the sum of the reciprocals of the individual capacitance. This the same as the formula for finding resistors in parallel.

This is expressed by the formula.

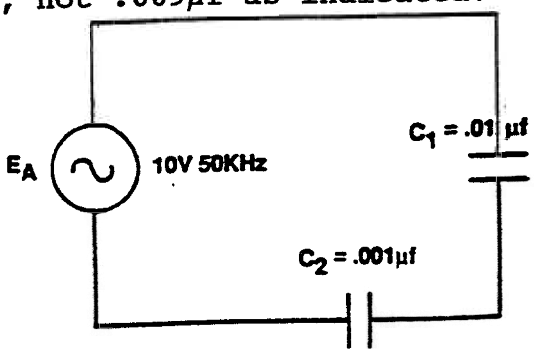
$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

C_T is the total capacitance, and C_1, C_2, and C_3 are the individual capacitances.

Calculate the total capacitance of a circuit when .001 ufd and .01 ufd are connected in series.

Note: CT= .0009µf, not .009µf as indicated.



$$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

$$C_T = \frac{.001 \times .01}{.001 + .01}$$

C_T = .009µf .0009µf

FIGURE 9

Capacitors in series have the effect of increasing dielectric thickness and decreasing the capacitance.

Resistance losses - Resistance losses are due to the resistance or the wires that are connected to the plates and the resistance of the plates themselves. The resistance losses equal the square of the current times the resistance (I^2R). These losses represent only a small amount of the total loss of the energy in a capacitor.

The thickness of the dielectric between A and B is twice as great as the thickness of the dielectric in only one of the capacitors. This increased dielectric decreases the capacitance by the sum of the dielectrics.

QUESTION: What happens to total capacitance when one capacitor is in series with another?

ANSWER: Capacitance decreases.

Leakage losses - Leakage losses are due to a small amount of current that flows through the dielectric material from one plate to the other. Air dielectric and mica dielectric capacitors have very small leakage losses, while other types have considerable leakage losses. These losses result in heat being developed in the dielectric material. Excessive leakage losses may cause enough heat to be generated in one capacitor to destroy the insulation qualities of the dielectric and thereby minimize or even eliminate the capacitance of the capacitor.

Dielectric absorption losses - Some dielectric materials, such as paraffin-impregnated paper, seem to absorb charges as the capacitor is being charged. These absorbed charges are not given up as the capacitor is discharged, and consequently constitute an energy loss. These losses are minimized in high quality capacitors by making the paraffined paper of uniform thickness and free from foreign substances and particles.

Voltage ratings - Another important characteristic of a capacitor is its voltage rating. This may be expressed as either a DC working voltage, peak voltage, or surge voltage rating. Working voltage is the maximum DC voltage that the capacitor can withstand under continuous operation.

Peak voltage is the maximum peak value of AC voltage the capacitor can withstand under continuous operation.

Surge voltage is the maximum voltage a capacitor can withstand under certain conditions for five minutes. This last rating is valuable information when you are analyzing circuits that are subject to periodic voltage surges.

Capacitors connected in series parallel must be reduce to one equivalent capacitor. FIGURE 10, gives an example of how this is done.

Calculate C2, C3 as a parallel circuit.

$C_{eq} = C_2 + C_3$

$C_{eq} = .05 + .05$

$C_{eq} = .1\mu f$

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_{eq}}}$$

$C_T = .05\mu f$

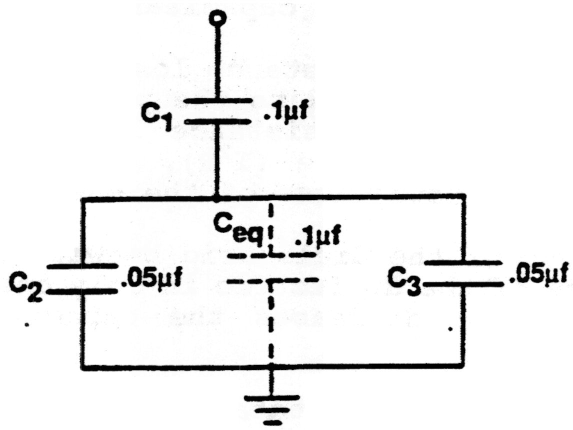


FIGURE 10

C_T can now be place in series with C1 as C equivalent (C_{eq}).

Capacitor C_1 and C_{eq} equivalent can be now used to calculate C_T, as in a series circuit.

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_{eq}}$$

$$\frac{1}{C_T} = \frac{1}{.1} + \frac{1}{.1}$$

$$\frac{1}{C_T} \quad 10 + 10$$

$$\frac{1}{C_T} = \frac{20}{1}$$

$$\frac{C_T}{1} = \frac{1}{20}$$

C_m = .05 uf

Now the capacitor must be studied in the transient state, that is, how does it charge and discharge? This will be briefly covered here, but will covered more thoroughly in an later lesson.

Studying FIGURES 11, 12, and 13, this action will be shown.

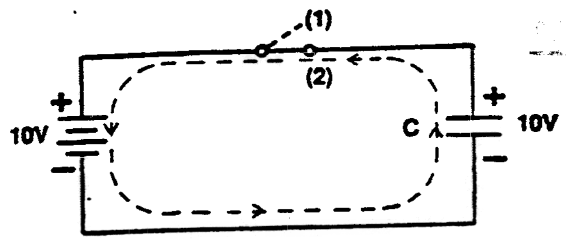


FIGURE 11

With the switch in position 1, the circuit is open and voltage is applied to the capacitor.

To charge the capacitor, the switch must be in position 2 which places the capacitor across the terminals of the battery.

As the capacitor charges, the voltage across the capacitor rises until it is equal in amount to the source voltage. Once the capacitor voltage equals the source voltage, the two voltages balance one another and current ceases to flow in the circuit.

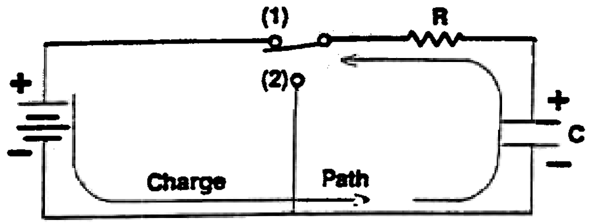


FIGURE 12

In FIGURE 12, with the switch in position 1, electron flow is conterclockwise around the circuit. The flow of electrons cease when the capacitor is charged to the battery voltage.

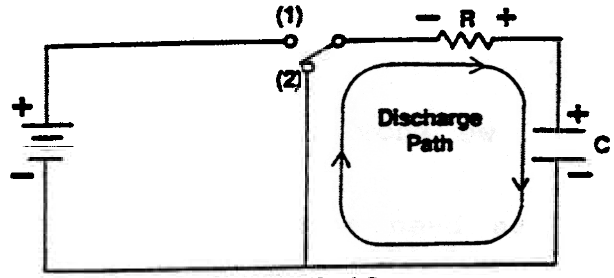


FIGURE 13

In FIGURE 13, with the switch in position 2, the capacitor will discharge. Electron flow in the circuit is clockwise from the negative plate of the capacitor through switch position 2, and through the resistor to the position plate of the capacitor.

The charge and discharge of the capacitor demonstrate its opposition to a change in voltage. This opposition is called CAPACITIVE REACTANCE.

This capacitive reactance has a letter symbol X_C. The unit of measurement is the ohm.

From $X_C = \frac{1}{2\pi FC}$ it may be shown that X_C can vary from an infinite value to very near zero, as shown in FIGURE 14.

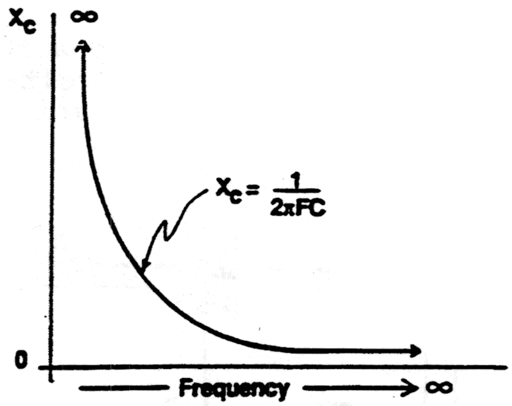


FIGURE 14

As frequency approaches infinity (∞), X_C approaches zero (0). As frequency approaches zero (0), X_C approaches infinity (∞). This simply indicates that X_C is inversely proportional to frequency and capacitance. The formula for X_C is:

From $X_C = \frac{1}{2\pi FC}$

From the formula we know that a capacitor is sensitive to the frequency.

From all that has been said we may conclude that the voltage developed across the capacitor lags the current through the capacitor by 90°, as shown in FIGURE 15.

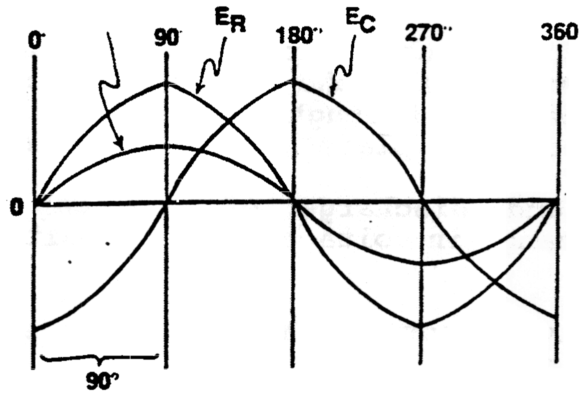


FIGURE 15

It can be seen that when the current I is maximum, the voltage is zero. These voltages are shown vectorially in FIGURE 16.

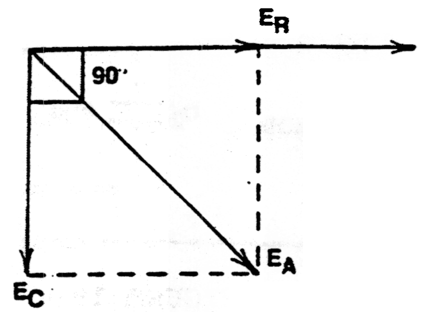


FIGURE 16

It must be remembered that only voltages in phase (zero phase shift) can be added directly. If the circuit consist of capacitors only, the voltages, will be added, as shown in FIGURE 17.

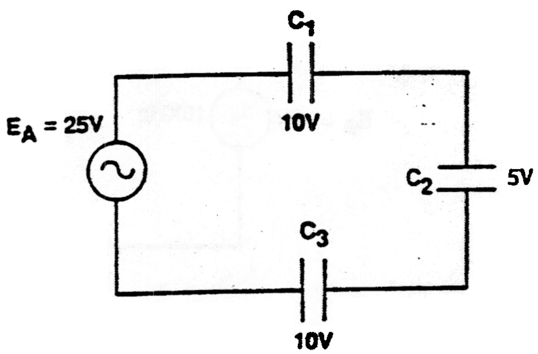


FIGURE 17

The capacitors C_1, and C_2 and C_3 have the voltages shown. These voltages add up to the applied voltage. These voltages are in phase.

The total capacitance can only be calculated by the use of the reciprocal formula, since this is a series circuit.

The reactance X_{C1}, X_{C2}, and X_{C3} will be treated like a resistor circuit.

$$X_{CT} = X_{C1} + X_{C2} + X_{C3}$$

In order for you to fully understand how to handle the combination of resistance and reactance; a new term, IMPEDANCE, must be introduced. The unit for impedance is the OHM. The letter symbol is Z.

IMPEDANCE describes the total impeding force or resistance to the AC current in the circuit. Impedance will include resistance and capacitive reactance.

From the circuit shown in FIGURE 18, we have a series-parallel complex circuit.

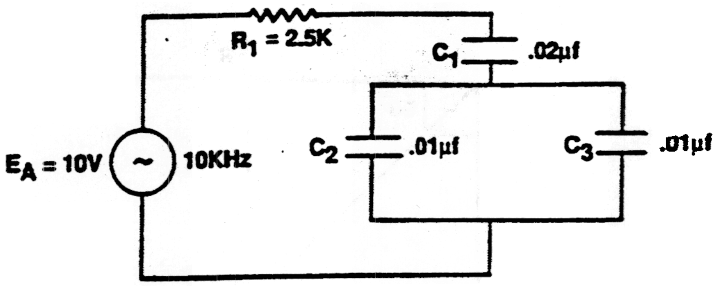


FIGURE 18

The objective is to first reduce the two parallel capacitors to one equivalent. Having done this, we have the circuit shown in FIGURE 19.

$$= C_2 + C_3$$

$$= .01 \times 10^{-6} + .01 \times 10^{-6}$$

$$.02 \times 10^{-6}$$

$$C_{eq} \quad .02\ \mu fd$$

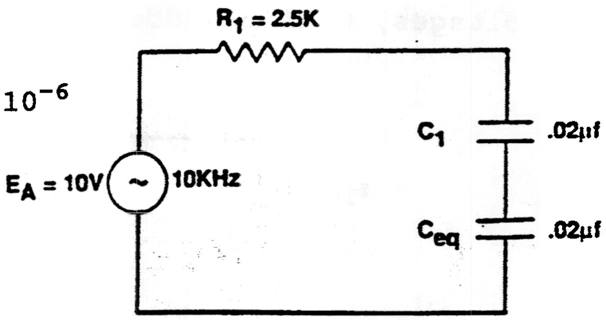


FIGURE 19

The second step is to combine the two series capacitor C_1 and C_{eq}, as shown in FIGURE 20.

$$C_T = \frac{C_1 \times C_{eq}.}{C_1 + C_{eq}.}$$

$$C_T = \frac{(.02 \times 10^{-6})(.02 \times 10^{-6})}{(.02 \times 10^{-6})+(.02 \times 10^{-6})}$$

$$C_T = \frac{.0004 \times 10_{-6}}{.04 \times 10^{-6}} = .01 \times 10^{-6}$$

$$C_T = .01\ \mu fd.$$

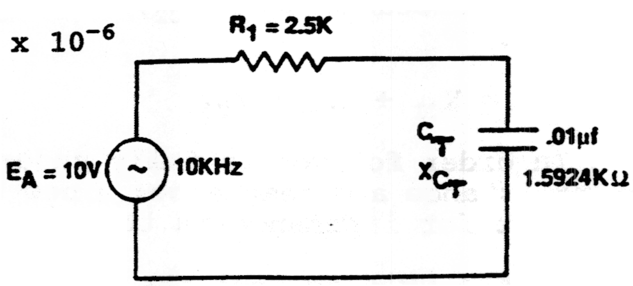


FIGURE 20

third step is to find the capacitive reactance of C_T or X_{CT}.

$$= \frac{1}{2\pi\ FC_{eq2}}$$

$$\frac{1}{6.28 \times 10 \times 10^3 \times .01 \times 10^{-6}}$$

$$X_{CT} = \frac{1}{6.28 \times 10^{-4}}$$

$$= 1.5924 \text{ K ohms}$$

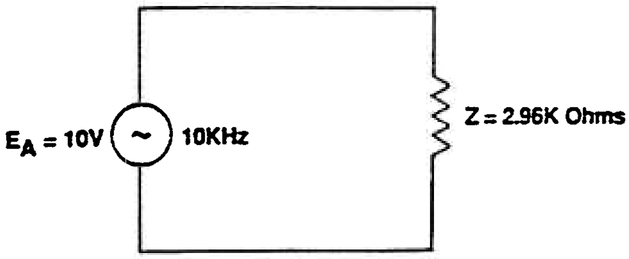


FIGURE 21

The fourth step is to calculate the Impedance (Z) of the circuit. This will result in the equivalent circuit shown in FIGURE 21. You must remember that the two impedance are 90° out of phase as shown in FIGURE 22.

$$Z = \sqrt{R_1{}^2 + X^2\ C_T}$$

$$Z = \sqrt{(2.5 \times 10^{3})^2 + 1.5924 \times 10^3)^2}$$

$$Z = \sqrt{6.25 \times 10^6 + 2.5357 \times 10^6}$$

$$Z = \sqrt{8.78 \times 10^6}$$

$$Z = 2.96K$$

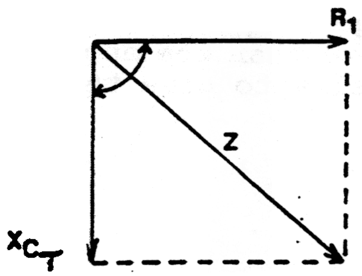


FIGURE 22

Now that Z has been calculated, the current may be calculated by using Ohm's Law.

$$I_T \quad \frac{EA}{Z} = \frac{10}{2.96 \times 10^3} = 3.38 \times 10^{-3} = 3.38 \text{ mA}$$

Once the current has been calculated, then the voltage drops can be found by:

$$= I_T R_1 = 3.38 \times 10^{-3} \times 2.5 \times 10^3 = 8.45 \text{ V}$$

$$= 8.45 \text{ V}$$

The next step is to calculate the voltage drop across the total capacitive reactance (E_{CT}), Thus:

$$E_{CT} = I_T \, X_{CT}$$

$$3.38 \times 10^{-3} \times 1.5924 \times 10^3$$

$$= 5.38 \text{ V}$$

From FIGURE 19, the voltage drop across C_1 and the equivalent parallel combination C_{eq}, can be easily determined because C_1 is equal to C_{eq}. Thus half the voltage of E_{CT} will be across C_1 and the other half across C_{eq}.

$$E_{CT} = E_C + E_{Ceq}$$

$$E_{CT} = 5.38\text{V}$$

$$= \frac{5.38}{2}$$

$$= 2.69\text{V}$$

$$2.69\text{V}$$

The voltage dropped across the resistor R_1 and X_{CT}, if added, would be equal to more than the applied voltage. These voltage drops must be added vectorially to give the correct E_A.

$$E_A = \sqrt{E_{R1}^2 + E_{CT}^2}$$

$$E_A = \sqrt{(8.45)^2 + (5.38)^2}$$

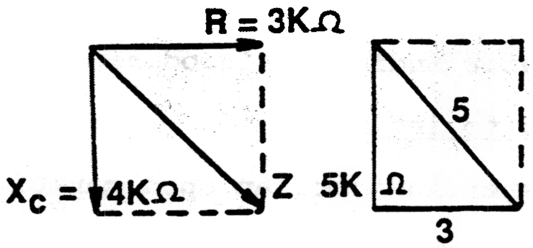
$$E_A = \sqrt{71.40 + 28.94}$$

$$= \sqrt{100.34}$$

$$= 10.02 \text{ VAC}$$

Since the values are rounded off, it will be noted that there are small fractional differences in the answers.

The student, with some math knowledge, will understand that the solution to the problem involving right triangles is by the use of the Pythagorean Theorem. Which is the square root of the sum of the squares. Some examples of these triangles will be given in FIGURE 23.



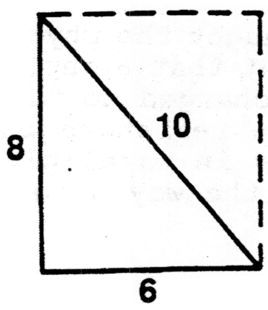
$$Z = \sqrt{R^2 + X_C 2}$$

$$Z = \sqrt{(3)^2 + (4)^2}$$

$$Z = \sqrt{9 + 16}$$

$$Z = \sqrt{25}$$

$$Z = 5\,\Omega$$



$$10 = \sqrt{(6)^2 + (8)^2}$$

$$10 = \sqrt{36 + 64}$$

$$10 = \sqrt{100}$$

$$10 = 10\,\Omega$$

FIGURE 23

The student will recognize as shown in FIGURE 23, some basic relationships for right triangles. These relationships are true for the 30, 60, 90 degree right triangle. They are true for the forces that may be composed of resistance, reactance or voltage values.

Capacitors may be checked with the digital multimeter, as follows:

By closely observing the meter, we can determine the state of most capacitors on the basis of open, resistive, short or good.

The open capacitor will read infinite on the ohm meter. Measure the capacitor on the highest ohm scale if the capacitor is small. Reverse the leads back and forth plus to minus while closely observing the meter. If the capacitor is open, the reading will be infinite.

The resistive capacitor, that is, if the reading stays at some point on the meter. The capacitor is resistive and should be replaced.

The shorted capacitor will read zero ohms.

The good capacitor will cause the meter to read and return to infinity. The smaller the capacitor the smaller the reading. The digital meter will react numerically to the amount of the charge and the size of the capacitor.

The good technician will want to practice this technique.

QUESTION: How does an ohmmeter indicate a good capacitor?

ANSWER: <u>Reads and returns to infinity</u>

QUESTION: How does an ohmmeter indicate an open capacitor?

ANSWER: <u>The ohm meter will read infinity when placed across a capacitor</u>.

SUMMARY:

During this lesson you were taught the physical factors controlling capacitance. You were also, taught that a capacitor passes the effects of AC and blocks DC after it has charged to the DC potential. Capacitors in parallel are treated like resistors in series; capacitors in series are treated like resistors in parallel. You also studied how the rate of change of AC affects the way a capacitor reacts to the change.