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CAPACITORS (CONDENSERS) IN ELECTRONICS CIRCUITS

ASSIGNMENT 18

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If you look at the chassis of **any kind** of electronics equipment, there is a 1000 to 1 chance that you will find capacitors. This is true, whether the equipment you are examining is a transistorized computer, a television receiver, a missile control system, an automation control panel, or an "antique" radio 40 years old. Obviously, then, as an electronics technician, you will need a thorough understanding of capacitors, what they are, how they work, and what they do in a circuit.

Capacitors vary widely in physical appearance, but they all operate on the same principle. Figure 1 shows a number of typical capacitors which will be found in electronics equipment. The capacitors illustrated in Figure 1(A) through 1(H) are all fixed capacitors. Those illustrated in Figure 1(I) and (J) are variable capacitors, and in Figure 1(K) is a semi-variable capacitor. The construction and use of each of these capacitors will be discussed later in this assignment.

There are two names which are applied to the same components; **capacitors,** and **condensers.** You will find these two used interchangeably in the electronics field. The name **condenser** is an older term, and the term **capacitor** is perhaps more technically correct, since a condenser does not actually condense anything. You will find both of these terms used in this training program.

What A Capacitor Does

Although the capacitors shown in Figure 1 vary greatly in size and shape, they all have one thing in common. Each consists of two or more conducting "plates" separated by an insulating material. Let us study the action of the most simple capacitor we could make, and then apply the principles learned from it to the various types of capacitors.

A very simple capacitor could be made by using two metal plates slightly separated from each other, as shown in Figure 2. The material between the two plates in this case is air. Air is an insulator and is therefore, for all practical purposes, a non-conductor of electricity. The nature of the material used between the two plates has a large effect on the action of the capacitor. The material between the plates of the capacitor is called the **dielectric.** Dielectric materials such as air, mica, paper, mylar, and oil are often used in capacitors in electronics work.

In Figure 3(A), we have connected this capacitor in a simple series circuit, consisting of the capacitor, a battery, a milliammeter and a switch. The schematic diagram for the circuit is shown in Figure 3(B).

With the switch open as shown in Figure 3, no current will flow because there is air (an insulator) between the two open switch contacts. What will happen when we close the switch? It might still seem that nothing would happen, since the capacitor plates also have air (an insulator) between them. We know that the electrons cannot flow through the air between the capacitor plates any more than they can flow through the air between the switch contacts.

If this were the entire story, the effect produced by capacitors could not be produced. There is one vital point that we have overlooked, and that is the electrostatic field. We learned in an earlier assignment that an **electrostatic field** surrounds any charged body. Remember how a charged comb will pick up small bits of paper. Recall also, that the comb does not have to be placed against the bits of paper, but that it will exert force on the paper while it is still some distance from them. The electrostatic field exerts force **through the air**. It would also exert a force through any insulating material such as mica or glass.

If the switch in the circuit shown in Figure 3 is closed, there will be a momentary movement of electrons. The milliammeter will "kick" up-scale, and will then return to zero. Let's repeat this statement. **When the switch is closed, current will flow for an instant and then will cease to flow.**

How did current flow through the insulating material (air) between the capacitor plates? The answer is that it **did not** flow through the insulator. What actually happens is this: When the switch is closed, electrons travel from the negative terminal of the battery through the closed switch, to the top plate of the capacitor shown in Figure 3(A). These electrons spread out on the surface of this plate. In so doing, they are forming a negative charge on the plate. The **electrostatic** field of force produced by this charged plate exerts a force through the surrounding air to the other plate. Since like charges repel, this field of force repels the electrons on the other plate of the capacitor [the bottom plate in Figure 3(A)]. This causes electrons to move from the bottom plate of the capacitor to the positive terminal of the battery. The number of electrons which leave the bottom plate are just equal to the number that stack up on the top plate.

The movement of electrons constitutes a current flow. When the switch in Figure 3 is closed, **current flows** from the negative terminal of the battery, through the conductor to the top plate of the capacitor. **Current** also **flows** from the bottom plate of the capacitor, through the conductor to the positive terminal of the battery. This is shown in Figure 4(A). For a brief instant, current has passed through the entire circuit, except the **dielectric** of the capacitor. The **effect** of the electrons (the electrostatic field) operated across this space.

It was stated that the current flow continued for only an instant, and then stopped. Why did it not continue? Because, as electrons begin to stack up on the top plate of the capacitor, they begin to repel **each other**. In a short while, this repelling force is as strong as the force of the battery, and no more electrons are able to move from the negative terminal of the battery to the top plate of the capacitor. When no more electrons are piling up on the top plate, no more are leaving the bottom plate, so there is no current flowing in any part of the circuit. There are three ways to cause a greater current to flow in a circuit containing a capacitor. One of these ways is to increase the surface area of the plates. Then more electrons can "pile up" on the "negative" plate before the repelling action between them is great enough to equal the force produced by the battery. Another way to make more current flow is to increase the battery voltage. In this case, more electrons will be required to produce a force equal to the force of the battery. The third way is to move the plates closer together, so that the electrostatic field is stronger.

When a capacitor has more electrons on one plate than on the other, the capacitor is said to be **charged**. Notice one thing though; there are no more electrons in a charged capacitor than in an uncharged one; because as the electrons begin to pile up on the negative plate, an equal number leave the other plate, making it a positive plate. **One plate has an excess of electrons, and the other has a deficiency of electrons.**

Capacity

The measure of the ability of a capacitor to store electrical energy is called its capacity.

The unit of measure of the electrical size of a capacitor is the **farad**. A capacitor has one farad of capacity when 6.28×10^{18} excess electrons will pile-up on the negative plate when the applied voltage is one volt.

The farad was named after the early experimenter, Michael Faraday. This unit, one farad, is a **very** large unit, and a capacitor of this size is never found in electronics circuits. Capacitors found in practical circuits range in size from about 10,000 microfarads (10,000 millionths of a farad) to about 1 micromicrofarad (1 millionth part of one millionth part of a farad).

The correct abbreviation for farad is F. The abbreviation for microfarad is μF, and the abbreviation for micromicrofarad is $\mu\mu F$. It will be found that in a great number of cases these two units are abbreviated mfd (for microfarad), and mmfd (for micromicrofarad). This often confuses trainees who are just learning electronics, since the small m is supposed to stand for one thousandth part of a whole unit, and in this case stands for one millionth part of a whole unit. To prevent confusion in this matter, remember this point. When speaking of capacitors the units will **always** be in millionths, or millionths parts of a millionth part, **never** in thousandths. From this you will never be in doubt if you see a capacitor rated as 250 mmf. This means 250 micromicrofarads.

As we have already learned, the powers of ten are quite handy when dealing with small decimal quantities. It will be recalled that **one millionth** part, ($\frac{1}{1{,}000{,}000}$ or .000001) can be represented as 10^{-6}. Thus, 1 µfarad is 1 x 10^{-6} farad. Similarly, 1 micromicrofarad is 1 x 10^{-12} farad. Another term which is used to represent this same quantity is **pico**farad. Thus a 1µµF capacitor is sometimes called a 1 pF capacitor, and each term means 1 x 10^{-12} F.

When formulas which involve capacity are written, the letter C is used to represent capacity, just as R stands for resistance.

The Voltage Associated with a Capacitor

We have seen how the current acts in a circuit containing a capacitor. Let us examine how the voltage acts. Voltage, or difference of potential, is due to an excess of electrons at one point and a deficiency of electrons at another point. In the circuit of Figure 3, when the switch is open, there is no difference of potential across the capacitor, since there is a balanced condition in the number of electrons on the two plates. At the instant the switch is closed, there is no voltage, or difference of potential, across the plates of the capacitor because the electrons have not yet entered the top plate. **As the electrons begin to pile-up on the top plate, a fraction of a second after the switch is closed, an equal number leave the positive plate, and a difference of potential, or voltage, begins to build up across the capacitor.**

As the electrons continue to enter the top (negative) plate and leave the bottom (positive) plate, this voltage will increase until the point is reached when no more electrons are entering the negative plate. At this time, the voltage across the capacitor (measured from one plate to the other) will be equal to the applied voltage. The polarity of this voltage is such that the top plate of the capacitor in Figure 4(A) is negative (it has the excess electrons) and the bottom plate is positive. When the capacitor is fully charged, this voltage is equal to the battery voltage and is bucking the battery voltage.

Figure 4(B) shows what results when the switch is opened after the capacitor has been charged. Remember that the charged capacitor has an excess of electrons on one plate, and a deficiency of electrons on the other. When the switch is opened, there is no path present for this charge to be neutralized. Therefore, the capacitor will remain charged. There is a voltage across this capacitor (6 volts in Figure 4) and it now is a voltage source, rather than a load as it was when charging.

Suppose we were to take this charged capacitor and connect it in a circuit as shown in Figure 5(A). When the switch is closed, as shown in Figure 5(B), there will be a momentary flow of electrons from the negative plate of the capacitor, through the resistor to the positive plate. In this manner, the charge on the capacitor becomes neutralized; that is, enough of the excess electrons on the negative plate flow around to the positive plate to make an equal number on each plate. This process is called **discharging** the capacitor. The important point is that, when a load was connected across the **charged** capacitor, a current was caused to flow through the load until the capacitor became discharged.

The entire charging and discharging cycle is shown in Figure 6. In (B) of this figure, switch No. 1 is closed and the capacitor becomes charged. In (C) of this figure, switch No. 1 is opened and the capacitor retains, or holds, its charge. In (D) of this figure, switch No. 2 is closed and the capacitor discharges through the resistor. In (A) of the figure, switch No. 2 is again opened and the entire cycle may be repeated. If we keep repeating this cycle of switch movements, we can completely wear out the battery. No energy has been lost in the capacitor. The capacitor has merely **stored** the electrical energy during a portion of the cycle.

Dielectric Materials

A capacitor consists of two or more conductors separated by an insulating material. In the capacitor we have been dealing with so far, the insulating material between the plates was air. Capacitors can be made with any insulator as the dielectric. For example, if we were to place a "slab" of mica between the plates of the simple capacitor shown in Figure 2, and maintain the same spacing between the plates as before, we would find that the capacitor would still function. In fact, we would be able to **store** a much greater quantity of electrical energy in this mica dielectric capacitor than in the air dielectric one. It would probably store about 8.7 times as much electrical energy. The reason why the mica dielectric enables the capacitor to store more energy is illustrated in Figure 7.

Figure 7(A) shows a cross-section of a part of the capacitor. The mica is an insulator and has almost no free electrons. In this figure, the capacitor is discharged, and there is no electrostatic field present. Two molecules of the dielectric are illustrated in this figure (actually, molecules of mica will have many more than one proton and one electron, but it is illustrated in that fashion for simplicity). When the capacitor is in an uncharged condition, the electrons follow their accustomed paths as shown. In Figure 7(B), the capacitor is charged. Notice that now the electrons follow distorted paths. This is because they are being repelled by the electrostatic field. These electrons are not forced completely away from the nucleus as they would be if they were free electrons, but their orbits are distorted. They move until the forces of distortion within the molecules are sufficient to balance the force of the electrostatic field. This isn't hard to picture, for a ship at anchor can be moved slightly by a hard wind, and a dog on a leash is free to move a short distance one way or another. When the wind blows against the ship at anchor, the ship will move until the tension in the anchor cable is sufficient to balance the wind pressure. The dog on the leash will keep moving away until you pull back with an equal force.

The reason why the mica dielectric increases the capacity of the capacitor is because the electrostatic field does not have to act all of the way across the space between the plates by itself, but is aided by the action which takes place in the dielectric. In Figure 7(B), the electrostatic field causes the distortion of the orbit of the electron in the molecule nearest the negative plate. This distortion of the orbit causes the orbit of the electron in the next molecule to be distorted and so on. This aiding of the electrostatic field by the dielectric is similar to the aiding of the magnetic field about a coil by an iron core.

Dielectric Constant

The ratio of the capacity of a capacitor with a dielectric, compared to the capacity of the same capacitor with air as the dielectric, is called the **dielectric constant** of the dielectric. For example, in the capacitor we have just discussed, the capacity with the mica dielectric is 8.7 times as large as with air, so the dielectric constant of mica is 8.7.

Dielectric Strength

In the charged capacitor shown in Figure 7(B), it is evident that the electrostatic field is exerting a **stress** on the electrons in the molecules of the dielectric. If the voltage applied to the capacitor is too great, this **stress** may be greater than the forces of the molecules restraining the electrons in their orbits. This might be compared with a hurricane blowing so hard against a ship that the anchor cable would be broken. When the **stress** becomes too great and the electrons are torn away from their orbits, an electric current, in the form of an arc, will pass from the negative plate of the capacitor to the positive plate. This will cause a carbonized path to develop across the dielectric and the capacitor will be ruined. The amount of voltage required to cause this break-down of the dielectric is called the break-down voltage of the capacitor. The amount of voltage which a given dielectric will withstand is called the **dielectric strength** of the material.

The greater the strength of the dielectric material in a capacitor, the higher is the safe operating voltage. The strength of the dielectric can be increased in either of two ways. One way to do this is to increase the thickness of the dielectric material. The other way is to replace the dielectric material with another dielectric having a greater unit strength.

In the following table, the dielectric constants of different commonly used dielectric materials are listed. The dielectric constants (K) are determined experimentally in laboratories. Dielectric strengths have also been determined experimentally and are given in kilovolts per centimeter. This is the pressure in kilovolts that a "slab" of the material 1 centimeter in thickness can safely withstand without rupturing. A "slab" of the material ½ centimeter in thickness will withstand only half the voltage of a 1 centimeter "slab", and so on.

Material	Dielectric Constant K	Dielectric Strength
Air	1.0	31 (KV/cm)
Rubber, hard	3.0	173
Paper, dry kraft	3.5	300-400
Cloth, varnished	4.5	169
Bakelite	4.5	100-200
Fiber	5.0	50
Porcelain	7.0	57
Glass	7.6	60-120
Mica	8.7	2250
Paraffin Oil	2.2	1500
Mylar	3.25	28,000

This list is by no means complete. Many other materials are used as dielectrics. The values given hold true for the particular samples tested. Variations in the quality of the dielectric material will affect both the dielectric constant and the dielectric strength.

Now that we know what dielectric constant means, let us summarize the things which affect the capacity of a capacitor.

The capacity (in farads) of a capacitor depends on three main points: (1) the area of the plates, (2) the distance between plates, and (3) the nature of the material used for the dielectric.

If we increase the area of the plates, the capacity will increase. If we move the plates closer together, the capacity will increase, and if the dielectric with a larger dielectric constant is inserted, the capacity will increase.

Capacitor Construction

The simple capacitor with which we have been dealing consists of but two plates. To make a capacitor in this fashion which has the amount of capacity required in most electronics circuits would require the use of very large plates. A much more compact capacitor can be made as shown in Figure 8. In this case, plates No. 1, 3, and 5 are connected together, and plates No. 2, 4, and 6 are connected together. Let us look closely at one of these plates, No. 2 for example. The electrostatic field will be built up on both sides of plate No. 2. There will be capacity between plate No. 2 and plate No. 1, and there will also be capacity between plate No. 2 and plate No. 3. This effectively doubles the area of plate No. 2, since both sides of the plate are now being used. This same effect is true for each of the other plates except plate No. 1 and plate No. 6, only one side of which is being used. This illustrates the fact that a much more compact capacitor can be made by sandwiching plates and insulators together and then connecting alternate plates together. The mica capacitor in Figure 1(B) is made in just this fashion. The insulator in this capacitor is, of course, mica.

Some capacitors use a different method for obtaining a greater surface area in a given space. This method is shown in Figure 9. Two long sheets of tin or aluminum foil (10 to 20 feet long) are separated by sheets of waxed paper or mylar as shown in Figure 9(A). Then the entire unit is rolled up as shown in Figure 9(B). Leads are then fastened to the protruding edges of the foil as shown in Figure 9(C). The final product is then enclosed in a tubular container of paper, plastic, or sometimes metal. A typical paper capacitor is shown in Figure 1(A) and a mylar capacitor is shown in Figure 1(C). Paper and mylar capacitors are relatively inexpensive, and are used very widely in electronics circuits. These capacitors can be purchased in voltage ratings of 200 volts, 400 volts, and 600 volts. For special applications, 1000 volt and 1500 volt paper capacitors can also be obtained. The voltage rating of a paper or mylar capacitor indicates the safe operating voltage which may be used with a capacitor without danger of a voltage break-down occurring.

Figure 1(H) shows a transmitting capacitor, called an oil filled capacitor. In this type of capacitor, the separating paper is impregnated with insulating oil. The entire unit is sealed in a metallic container which is filled with oil. These capacitors can be made to withstand very high voltages.

Variable capacitors operate on the principle that the effective area of capacitor plates is only that part which is overlapping. Figure 10 illustrates the action of a variable capacitor. A variable capacitor is made up of two sets of plates, one set, which does not move, is called the **stator** plates, and the other set of plates, which rotate by turning a shaft, is called the **rotor.** For simplicity, only one rotor and one stator plate are shown in Figure 10. Actually, most variable capacitors have many plates in both the stator and rotor, as may be seen in the capacitors in Figure 1(I) and 1(J).

In Figure 10(A), the rotor is in such a position that it is not overlapping the stator plate. In this position, there is very little capacity in the capacitor because, to have capacity, the plates must be overlapping. In Figure 10(B), the rotor has been turned so that part of the plates of the capacitor are overlapping. The capacity of the capacitor in this case is approximately the same as it would be if the plate were only the size of the shaded area.

In Figure 10(C), the rotor has been turned so that the plates are completely enmeshed and are completely overlapping each other. In this position, the capacitor has maximum capacity. To vary the capacity of a variable capacitor, then, it is only necessary to rotate the rotor plates. When the plates are enmeshed, the capacity is maximum. When they are out of mesh, the capacity is minimum.

The variable capacitor shown in Figure 1(I) is a three gang capacitor such as is used in radio receivers. In this type of capacitor, there are actually three separate variable capacitors. The rotors are all varied at the same time by the common shaft.

The variable capacitor shown in Figure 1(J) is a transmitting capacitor. The spacing between the plates is greater than the receiving capacitor, so that the **breakdown** voltage will be higher.

The semi-variable capacitor shown in Figure 1(K) operates on the principle that when the capacitor plates are brought closer together, the capacity will increase. In this capacitor, one plate is fastened rigidly to the ceramic base, and the other plate, usually made of spring brass, can be moved closer to or farther away from the fixed plate by turning the adjusting screw with a screw driver. The dielectric is usually a combination of mica and air. When semi-variable capacitors with large capacity are desired, several pairs of plates are used, with alternate plates connected together. These semi-variable capacitors are sometimes called "trimmers", or "padders".

In all of the previously mentioned capacitors, it makes no difference which plate is connected to the positive terminal of the supply voltage, and which plate is connected to the negative terminal. The capacity is the same with either connection.

The capacitors illustrated in Figures 1(D), (E), (F) and (G) are called **electrolytic** capacitors. These capacitors differ from the other capacitors in one respect. They have one terminal marked (+) and the other terminal marked (—). They must always be connected in a circuit with the polarity as indicated.

A sheet of metal is used as one plate of the electrolytic capacitor. The dielectric is a **very** thin layer of oxide coating on this metal plate. The other "plate" is a chemical solution or paste that is a conductor of electricity. The chemical is called the **electrolyte**. This is where these capacitors get their name.

In an electrolytic capacitor, current will **not** flow from the electrolyte to the metal plate. When the capacitor is connected in a circuit so that the electrolyte is negative and the metal plate is positive, the unit acts as a capacitor.

Oddly enough, current flows quite easily from the metal plate to the electrolyte. If the unit is connected in a circuit with the wrong polarity, it will act as an almost "dead" short. This may damage the capacitor.

In early types of electrolytic capacitors—called the "wet" type—the electrolyte was in the form of a solution, and the unit was mounted in a cylindrical metal can. All modern electrolytic capacitors are the "dry" type and the electrolyte is in the form of a paste. These units may be mounted in a metal can as shown in Figure 1(E) or they may be mounted in a paper or plastic container as shown in Figures 1(D), (F) and (G). Very often more than one electrolytic capacitor will be held in the same container. For example, the unit shown in Figure 1(F) contains two separate electrolytic capacitors and the unit shown in Figure 1(E) contains 3 separate electrolytic capacitors. In some cases, the negative lead of the two electrolytic capacitors in a container is made a common lead. Such a unit has only three leads—the common negative lead, and the two positive leads, one for each capacitor. In Figure 1(E) the metal can and the twist-prong terminals are the common negative and the three positive terminals are the ones shown toward the middle of the base with soldering eyelets. The great advantage of electrolytic capacitors is that a large amount of capacitance can be obtained in a small space. This is due mainly to the fact that the dielectric (the coating of oxide) is very thin. For example, the electrolytic capacitor of Figure 1(G) has a rating of 100 microfarads. This type of capacitor is used widely in transistorized equipment.

Capacitor Losses

In the assignment on inductance, it was stated that we could never obtain a perfect inductance (one with no resistance), since a coil is made of wire which has some resistance.

It is also impossible to obtain a perfect capacitor; however, we can approach a perfect capacitor very closely. For a capacitor to be perfect, **no** electrons would pass from the negative plate to the positive plate. This would require a perfect insulator, and there is no such material. Even the best insulators contain a few free electrons. Therefore, there will be a minute amount of current flow through the dielectric of a capacitor. This is called **leakage current.** Also, a certain amount of electrons will flow around the outside of a capacitor from the negative terminal to the positive terminal. Both of these currents represent a loss in the circuit, and are undesirable. The effect is the same as connecting a high value of resistance in parallel with the capacitor as shown in Figure 11.

The **leakage current,** and therefore the loss, in a mica capacitor is very low. It is a little higher in a mylar capacitor, still higher in a paper capacitor, and quite high in an electrolytic capacitor. In fact, it is so high in an electrolytic capacitor, that these capacitors cannot be used in applications where a large leakage current cannot be tolerated. Also, the leakage current in electrolytic capacitors increases as they become old. For this reason, electrolytic capacitors cause more trouble than any other type of capacitor.

Capacitors Connected in Parallel and in Series

Now that we have found out what capacitors are and how they are made, let us find out what happens when we connect capacitors in parallel or in series.

In quite a few applications, you will find capacitors connected together in electronics circuits. Let us see how they behave when connected together.

Parallel Capacitors

In Figure 12, we see two equal capacitors, capacitor No. 1, and capacitor No. 2. These have been connected in parallel, by connecting the No. 1 plate of each together, and by connecting the No. 2 plate of each together. The result of this is that we have made these two capacitors into **one** equivalent capacitor. The spacing between the plates of this effective capacitor is equal to the spacing of each of the original capacitors, but we have effectively doubled the **area** of the plates. We know that increasing the area of the plates will increase the capacity of a capacitor. In this case, the effective capacity of the combination is equal to the sum of the individual capacitors, or to state this as a formula:

$$C_T = C_1 + C_2.$$

If two or more capacitors are connected in parallel, even if their sizes are different, the equivalent capacity of the combination can be found by adding the individual capacitors together.

The formula for capacitors connected **in parallel** is:

$$C_T = C_1 + C_2 + C_3 + \text{etc.}$$

For example, suppose these three capacitors are connected in parallel; 1μF, 4μF, and 10μF. (Remember the term 1μF means .000001 F, or 1×10^{-6} F, 4μF means 4×10^{-6} F, etc.) The total capacity of the combination would be:

$$C_T = C_1 + C_2 + C_3$$
$$C_T = 1 \times 10^{-6} + 4 \times 10^{-6} + 10 \times 10^{-6}$$
$$C_T = 15 \times 10^{-6} = 15\mu F.$$

Series Connection

In Figure 13, we have used the same two capacitors as in Figure 12, but have them connected in series in this case. With this connection, we have effectively doubled the thickness of the dielectric, but the plate area has not increased. We have the same effect as if the two plates, which are connected together, were removed and the two dielectrics moved together, leaving the resultant capacitor made up of the No. 1 plate of the No. 1 capacitor, and the No. 2 plate of the No. 2 capacitor with a dielectric thickness equal to the sum of the two dielectric thicknesses. This causes the capacity to decrease. The capacity of capacitors in series can be found by the formula:

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

For example, suppose a 1μF and a 10μF capacitor are connected in series:

$$C_T = \frac{(1 \times 10^{-6})\ (10 \times 10^{-6})}{(1 \times 10^{-6}) + (10 \times 10^{-6})}$$

$$C_T = \frac{10 \times 10^{-12}}{11 \times 10^{-6}}$$

$$C_T = \frac{10 \times 10^{-6}}{11} = .91 \times 10^{-6} \text{ or } .91\mu F.$$

Capacitors will not be found connected in series in many applications.

Remember these points: 1. The equivalent capacity of **parallel** capacitors is equal to the **sum** of the individual capacitors. 2. The equivalent capacity of **series** capacitors is **less** than the smallest one and may be found by using the formula $C_T = \frac{C_1 \times C_2}{C_1 + C_2}$.

Voltage and Current Relationship in a Capacitor

In Figure 14, we have again shown a capacitor and a battery. We also show a resistor in series in the circuit. This is the "lumped" resistance of the connecting wires and the internal resistance of the battery. For simplicity, we have let this resistance be 5 ohms, and battery voltage be 10 volts.

When we close the switch we know that there will be a short pulse of charging current. Picture this action in **slow** motion. The action which takes place during the time the capacitor is charging is very important, even though the entire operation will take place in a fraction of a second.

In (A) of Figure 14, the capacitor is uncharged. In (B), we close the switch. Since the capacitor is uncharged, it offers no opposition to the flow of electrons into its negative plate. The resistor is the only element in the circuit that will oppose the current flow.

We know what happens (slow motion). A current starts flowing. How much current is there **right at the start?**

$$I = \frac{E}{R} = \frac{10}{5} = 2 \text{ amperes.}$$

(Remember, that at this instant the capacitor is not opposing the flow of current.)

This current flow is shown in Figure 14(B). The current flow is 2 amperes, and the voltage across the capacitor is **zero.**

Free electrons begin to pile up on the negative plate of the capacitor. Voltage begins to build up across the plates of the capacitor. Part of the battery voltage is now needed to overcome this bucking voltage across the capacitor. This leaves less than full battery voltage available for the resistor, and therefore the current will be smaller. This is shown in (C) of Figure 14.

The capacitor voltage will build up more and more slowly. Finally, the capacitor will be charged to full battery voltage and current flow will cease [Figure 14(D)].

The important point to recognize in the previous example is this: **Just after we close the switch, we had maximum current flow and no voltage across the capacitor.** Finally, **when the current flow had stopped, the voltage across the capacitor was maximum.**

Considering the capacitor itself, we can definitely state that the **current** was at its **maximum before** the **voltage** across the capacitor reached its maximum. A graph of the current and voltage associated with the capacitor are shown in Figure 15(A) and (B)

Action of a Capacitor with A-C Applied

Figure 16(A) shows a capacitor connected to the output of an a-c generator. Let us follow the action of the current and voltage during one cycle of the applied voltage. A graph of the voltage across the capacitor, and the current through the capacitor is shown in Figure 16(B). At 0 on the time axis, the capacitor is discharged. As the voltage begins to build up, the current flow into the negative plate of the capacitor is maximum, as indicated in the graph. As the voltage builds up to a maximum, the capacitor is becoming charged, so the current in the circuit decreases, until at 90°, the voltage is at a maximum, and the current is zero. Consider the next statement carefully, since it is important. The capacitor has been charged, and as the applied voltage begins to decrease (from 90° to 180°) the capacitor begins to discharge, sending current through the generator in the **opposite direction.** This action is comparable to the capacitor discharging through the resistor in Figure 5(B) and Figure 6(D).

When the applied voltage reaches 180° in its cycle, the capacitor is completely discharged, and as the voltage begins to build up on its negative alternation, maximum current will again flow into the capacitor plate. (Note that since the polarity of the generator has reversed, the opposite plate of the capacitor is now the negative plate.)

As the voltage builds up to maximum at 270°, the current decreases to zero. As the voltage decreases to zero at 360°, the capacitor has been charged to a higher value than the generator voltage, so it will discharge through the generator in the opposite direction.

Notice these points:

(1) Current flows from the generator into the capacitor half of the time, and during the other half of the time, current flows from the capacitor through the generator. This is often stated that the capacitor draws energy from the

generator during one half cycle, and returns the same amount of energy on the next half cycle.

(2) Although a current does **not** flow through the capacitor, there is an alternating current flowing through the rest of the circuit. The effect is just the same as if an alternating current were flowing through the capacitor. This is shown in Figure 17. A 10µF capacitor and a light bulb are connected in series across a 110 Volt a-c line. The bulb will light brightly. For this reason, you may see the statement that a capacitor will pass an alternating current. This statement is not strictly true, but a capacitor does have the **effect** of passing a-c.

(3) The current into a capacitor leads the voltage across the capacitor by 90°. This can be seen in the sine wave in Figure 16(B). The vector diagram for this condition is shown in Figure 16(C).

If the capacitor action is not perfectly clear to you, think of this example. Imagine a long spring connected between two opposite walls of your room. There is a handle at the center.

Grasp the handle and move it several feet towards one wall. For example, let us say that you have moved the handle to your left. In order to keep the handle off center to your left, you will have to keep applying pressure to the left. You will not have to pull the handle to the right to start it moving to the right. All you have to do is ease up a little with the force to the left and the spring will overcome your weaker force and move the handle back to the right.

Picture the time relation between force (voltage) and movement of the handle (current) as you move the handle back and forth several feet each side of center.

Capacitive Reactance

We know that a resistor opposes the flow of current. We call this property resistance and measure it in ohms. We have learned that a coil also opposes the flow of an a-c current. We call this property **inductive reactance** and measure it in ohms. A capacitor also opposes the flow of an alternating current in a circuit. This opposition is called the **capacitive reactance**, and it is measured in ohms.

The larger the capacity of a capacitor is, the **lower** the **capacitive reactance** will be. This is easy to understand, since more electrons can pile up on the negative plate of a larger capacitor than on a small capacitor, and therefore less opposition is offered to the flow of an alternating current in the circuit.

The higher the frequency of the alternating current, the **lower** the **capacitive reactance** will be. This is easy to understand also, since, with an increase in frequency, the current is changing more rapidly, the electrons are causing the capacitor to charge and discharge at a more rapid rate.

The formula for finding the capacitive reactance of a capacitor is:

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

Where:

X_c = capacitive reactance in ohms

π = 3.14 (approx.)

f = frequency in hertz (cycles per second)

C = capacity in **farads**

To illustrate the use of this formula, let us find the capacitive reactance of several capacitors.

Example 1. What is the opposition offered by a 1 microfarad capacitor to an a-c current at the frequency of 60 hertz?

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

$$X_c = \frac{1}{6.28 \times 60 \times 1 \times 10^{-6}}$$

$$X_c = \frac{10^6}{6.28 \times 60}$$

$$X_c = \frac{10^6}{376.8}$$

$$X_c = 2653 \text{ ohms.}$$

Example 2. What is the capacitive reactance of a 1 microfarad capacitor at a frequency of 1000 hertz?

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

$$X_c = \frac{1}{6.28 \times 1 \times 10^3 \times 1 \times 10^{-6}}$$

$$X_c = \frac{1}{6.28 \times 1 \times 10^{-3}}$$

$$X_c = \frac{10^3}{6.28}$$

$$X_c = 159 \text{ ohms.}$$

Notice that the capacitive reactance (opposition to the flow of alternating current) of this 1 microfarad capacitor **decreased** as the **frequency** of the alternating current **increased.**

Example 3. What is the capacitive reactance of a 10 μF capacitor at a frequency of 1000 hertz?

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

$$X_c = \frac{1}{6.28 \times 10^3 \times 10 \times 10^{-6}}$$

$$X_c = \frac{1}{6.28 \times 10^{-2}}$$

$$X_c = \frac{10^2}{6.28} = 15.9 \text{ ohms.}$$

Compare Example 2 and Example 3 to prove that increasing the capacity of a capacitor will decrease the capacitive reactance.

There is a short-cut which may be used with the formula: $X_c = \frac{1}{2\pi fC}$

The short-cut is:

$$X_c = \frac{.159}{fC}$$

The .159 was obtained by dividing 1 by 2π (1 ÷ 6.28 = .159). In this formula, f is still in hertz, and C is in farads.

Let us work Example 3 using the short-cut.

$$X_c = \frac{.159}{fC}$$

$$X_c = \frac{.159}{1 \times 10^3 \times 10 \times 10^{-6}}$$

$$X_c = \frac{.159}{10^{-2}}$$

$$X_c = .159 \times 10^2 = 15.9 \text{ ohms.}$$

Let us also solve Example 1 using this short-cut.

$$X_c = \frac{.159}{fC}$$

$$X_c = \frac{.159}{60 \times 1 \times 10^{-6}}$$

$$X_c = \frac{.159 \times 10^6}{60}$$

$$X_c = \frac{159 \times 10^3}{60}$$

$X_c = 2.65 \times 10^3$

$X_c = 2650$ ohms. This answer is accurate to three places which is sufficient for electronics work.

Example 4. How much current will the a-c milliammeter register in the circuit of Figure 18?

f = 1,000 hertz.

C = 2μF = 2 micro farads = 2×10^{-6} farads.

$$X_c = \frac{.159}{fC} = \frac{.159}{10^3 \times 2 \times 10^{-6}} = \frac{.159 \times 10^3}{2} = \frac{159}{2} = 79.5 \text{ ohms.}$$

The current flowing can be found by the formula:

$I = \frac{E}{X_c}$; the answer will be in amperes, since we are dividing volts by ohms.

E = 5 volts.

$$I = \frac{E}{X_c} = \frac{5}{79.5} = .0629 \text{ amperes, or } 62.9 \text{ milliamperes.}$$

Suppose in Figure 18 that the oscillator voltage is held at 5 volts but the frequency is decreased to 100 hertz.

$$X_c = \frac{.159}{fC} = \frac{.159}{10^2 \times 2 \times 10^{-6}} = \frac{.159}{2 \times 10^{-4}} = \frac{.159 \times 10^4}{2} = \frac{1590}{2} =$$

795 Ω

$$I = \frac{E}{X_c} = \frac{5}{795} = .00629 \text{ amperes or } 6.29 \text{ milliamperes.}$$

Suppose in Figure 18 that the oscillator voltage is held at 5 volts but the frequency is increased to 10,000 hertz.

$$X_c = \frac{.159}{fC} = \frac{.159}{10^4 \times 2 \times 10^{-6}} = \frac{.159}{2 \times 10^{-2}} = \frac{.159 \times 10^2}{2} = \frac{15.9}{2} =$$

7.95 Ω

$$I = \frac{E}{X_c} = \frac{5}{7.95} = .629 \text{ amperes or } 629 \text{ milliamperes.}$$

These examples illustrate that a given size capacitor will offer more opposition to the flow of the alternating current in a circuit if the frequency is low, than if it is high.

Example 5. What is the reactance of a .00025 microfarad capacitor at a frequency of 4 megahertz?

$$X_c = \frac{.159}{fC}$$

$$X_c = \frac{.159}{4 \times 10^6 \times .00025 \times 10^{-6}}$$

$$X_c = \frac{.159}{4 \times 10^6 \times 25 \times 10^{-11}}$$

$$X_c = \frac{.159}{4 \times 25 \times 10^{-5}}$$

$$X_c = \frac{.159}{100 \times 10^{-5}} = \frac{.159}{10^2 \times 10^{-5}}$$

$$X_c = \frac{.159}{10^{-3}} = .159 \times 10^3 = 159 \text{ ohms.}$$

Example 6. What is the opposition offered by a 25 μμF capacitor (This could, of course, be called a 25 pF capacitor.) to an a-c signal whose frequency is 20 MHz?

$$X_c = \frac{.159}{fC}$$

$$X_c = \frac{.159}{20 \times 10^6 \times 25 \times 10^{-12}} = \frac{.159}{20 \times 25 \times 10^{-6}}$$

$$X_c = \frac{.159}{500 \times 10^{-6}} = \frac{.159}{5 \times 10^2 \times 10^{-6}} = \frac{.159}{5 \times 10^{-4}}$$

$$X_c = \frac{.159 \times 10^4}{5} = \frac{1590}{5} = 318 \text{ ohms.}$$

Example 7. What size capacitor would you need to obtain 5,000 ohms reactance in a 465,000 Hz circuit?

$X_c = 5 \times 10^3$ ohms.

$f = 4.65 \times 10^5$ hertz.

$$X_c = \frac{.159}{fC} = \text{by Algebra: } C = \frac{.159}{fX_c}$$

$$C = \frac{.159}{4.65 \times 10^5 \times 5 \times 10^3} = \frac{.159 \times 10^{-8}}{23.25} = \frac{1590 \times 10^{-12}}{23.25}$$

$C = 68.4 \times 10^{-12}$ farads $= 68.4$ micromicrofarads (picofarads).

Phase Relationship

To review the phase relationships of the voltage and current associated with various circuit components, look at Figure 19. Here we have an oscillator connected to a resistor, a coil, and a capacitor. The vectors for the voltage and current for each circuit are also shown.

In the resistor, the current will faithfully follow the variations of oscillator voltage. The resistor current will be **in phase** with the oscillator voltage.

In the coil, the current will lag behind the oscillator voltage by 90 degrees, or one-quarter cycle. This, as you know, is due to the inertia effect of the magnetic field. The inertia effect of the magnetic field tends to keep the current moving in one direction even after the voltage has decreased to zero and is building up in the opposite polarity. In a coil, the larger the current, the bigger the inertia force tending to keep the current moving.

In the capacitor circuit, the current will **lead** the oscillator voltage by 90 degrees. In other words, the current will start moving in one direction a quarter cycle **before** the oscillator voltage tries to force current in that direction. In our capacitor circuit, as current flows in one direction, the capacitor voltage builds up to oppose the oscillator voltage.

Figure 20 illustrates two very important points concerning capacitors. In Figure 20(A), we see a series circuit consisting of a light bulb and a capacitor connected to a 115 volt **d-c** source. Voltmeters are connected across both components. At the instant the circuit is connected, we know that a pulse of current will flow, charging the capacitor. After this instant, **no current** will flow in the circuit. The bulb will not light. The voltmeters will indicate the full line voltage or 115 volts across the capacitor and 0 volts across the lamp. This illustrates the important point, that a capacitor will not allow a direct current to flow.

Now look at Figure 20(B). Here we have the same light bulb and capacitor connected to a 115 volt **a-c** source. Here we see that the light bulb is lighted. The capacitor is permitting the alternating current to flow through the circuit. If we notice the voltmeter readings, we may be surprised at first. The line voltage is 115 volts, the voltage across the light bulb is 90 volts and the voltage across the capacitor is 70 volts. How is it possible for the sum of the two voltage drops ($90 + 70 = 160$) to be greater than the source voltage? A little thought will give us the answer. The two voltage drops are **out of phase.** We have already learned that out of phase voltages cannot be added directly, but must be added vectorially. Figure 20(C) gives the vectors for the circuit of Figure 20(B). The current vector, I, is used as the reference vector, since it is a series circuit, and the same current flows through both components. The voltage drop across the light bulb (E_R) is in phase with the current, and the vector is drawn accordingly. The vector E_R is 9 units long (each unit equals 10 volts). The current into a capacitor leads the voltage by 90°, or to state the same thing in another way, the voltage **lags** the current by 90°. The vector for the capacitor voltage drop (E_C) is drawn lagging the current vector by 90°. The vector E_C is 7 units long. When the parallelogram is drawn and the resultant vector scaled off, it is found to be 11.5 units long. This represents 115 volts. Thus, we see why it is possible for the sum of the two voltage drops to total more than the line voltage. When they are added properly, by vectors, the total is the line voltage.

In Figure 20(B), if the capacitor is made larger, so that its reactance is less, the voltage drop across the capacitor will become smaller and the voltage across the lamp will be larger. This is shown in Figure 21(A).

If the capacitor is made smaller, so that its reactance increases, the voltage drop across the capacitor will increase, and the voltage drop across the lamp will decrease. This is shown in Figure 21(B).

Summary

1. Any two conductors, separated by an insulator, will form a capacitor.

2. The capacity (or capacitance) of a capacitor is determined by the area of plates, spacing between plates and the kind of insulating material used as a dielectric.

(a) The greater the plate area, the larger the capacity.

(b) The smaller the plate separation, the larger the capacity.

(c) The Dielectric Constant of an insulating material is a measure of its effectiveness in producing capacitance.

3. The unit of capacity is the farad. This is a large unit. Usual units in electronics circuits are μF, and μμF or pF.

4. The opposition offered by a capacitor to the flow of current in a circuit is called the reactance. The reactance of a capacitor is determined by the formula:

$$X_c = \frac{1}{2\pi fC} \text{ or } X_c = \frac{.159}{fC}$$

(a) As the frequency increases, reactance decreases.

(b) Capacitors will not pass d-c and tend to block lower frequency alternating currents.

5. For capacitors, current and voltage are 90 degrees (one quarter cycle) out of phase.

(a) Current leads (is ahead of) voltage by 90 degrees.

(b) Another way of stating the same thing, voltage lags (is behind) current by 90 degrees.

6. Capacitors connected in parallel add together just as resistors in series.

(a) $C_T = C_1 + C_2 + C_3$

(b) A 3μF and a 5μF capacitor connected in parallel have a total equivalent capacitance of 8μF.

7. Capacitors in series add up just as resistors in parallel.

(a) $C_T = \frac{C_1 \times C_2}{C_1 + C_2}$

(b) A 3μF and a 5μF capacitor connected in series have a total equivalent capacity of $\frac{3 \times 5}{3 + 5} = \frac{15}{8} = 1.875\mu F$.

(c) Three 10μF capacitors connected in series have a total equivalent capacity of $\frac{10}{3} = 3.33\mu F$.

Study this assignment very thoroughly. The information in this assignment is very important. In a future assignment, we will combine our knowledge of coils and capacitors, and find how they operate when connected together.

"HOW TO PRONOUNCE . . ."

(Note: the accent falls on the part shown in CAPITAL letters.)

capacitive	(kuh-PASS-uh-tiv)
capacitor	(kuh-PASS-uh-tor)
dielectric	(DIE-eh-LEKK-trick)
electrolytic	(ee-LEKK-troe-lit-ic)

ASSIGNMENT 18

TEST QUESTIONS

Use a multiple choice answer sheet for your answers to this assignment.

The questions on this test are of the multiple-choice type. In each case four answers will be given, one of which is the correct answer, except in cases where two answers are required, as indicated. To indicate your choice of the correct answer, **mark out** the letter opposite the question number on the answer sheet which corresponds to the correct answer. For example, if you feel that answer (A) is correct for Question No. 1, indicate your preference on the answer sheet as follows:

1. (X) (B) (C) (D)

Submit your answers to this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.

1. (CHECK TWO)
   (A) As a capacitor is being charged, energy is being supplied to it.
   (B) As a capacitor is being charged, energy is being removed from it.
   (C) As a capacitor is discharged, energy is supplied to it.
   (D) As a capacitor is discharged, energy is being removed from it.

2. The name used to designate insulating material between the plates of the capacitor is:
   (A) Plates.
   (B) Dielectric.
   (C) Electrostatic.
   (D) Electrons.

3. If the area of the plates of a capacitor is increased, the capacity of the capacitor will:
   (A) Remain unchanged.
   (B) Increase.
   (C) Decrease.
   (D) Change into an inductance.

4. What part of a farad is 1 micro-farad?
   (A) 1/1000
   (B) 1/1,000,000
   (C) 1/1,000,000 part of 1/1,000,000
   (D) 1/100

5. What is the correct formula for finding the capacitive reactance of a capacitor?
   (A) $X_c = \frac{1}{2\pi fC}$
   (B) $x_c = 2\pi fC$
   (C) $X_c = .159fC$
   (D) $X_c = \frac{2\pi}{fC}$

6. If the plates of a capacitor are moved farther apart, the capacity will:

(A) Remain the same.
(B) Increase.
(C) Decrease.
(D) Change into inductive reactance.

7. In an a-c circuit containing a capacitor:

(A) The current leads the voltage.
(B) The current lags the voltage.
(C) The current and voltage are in phase.
(D) There is no current.

8. If the frequency of the applied signal is increased, the capacitive reactance of a capacitor will:

(A) Increase.
(B) Decrease.
(C) Remain the same.
(D) Change to inductive reactance.

9. What is the capacity reactance of a 20μF capacitor at a frequency of 120 hertz?

(A) Approximately 2400 ohms.
(B) Approximately 6625 ohms.
(C) Approximately .00007 ohms.
(D) Approximately 66 ohms.

10. What is the capacitive reactance of a .0001μF capacitor at a frequency of 1 kHz?

(A) Approximately 1,590,000 ohms.
(B) Approximately 1.6 ohms.
(C) Approximately 628,000 ohms.
(D) Approximately 3975 ohms.

$X_C = \frac{.159000}{20\times10^{-6}\times120}$ 240) 159000 1440 1500 1440 600

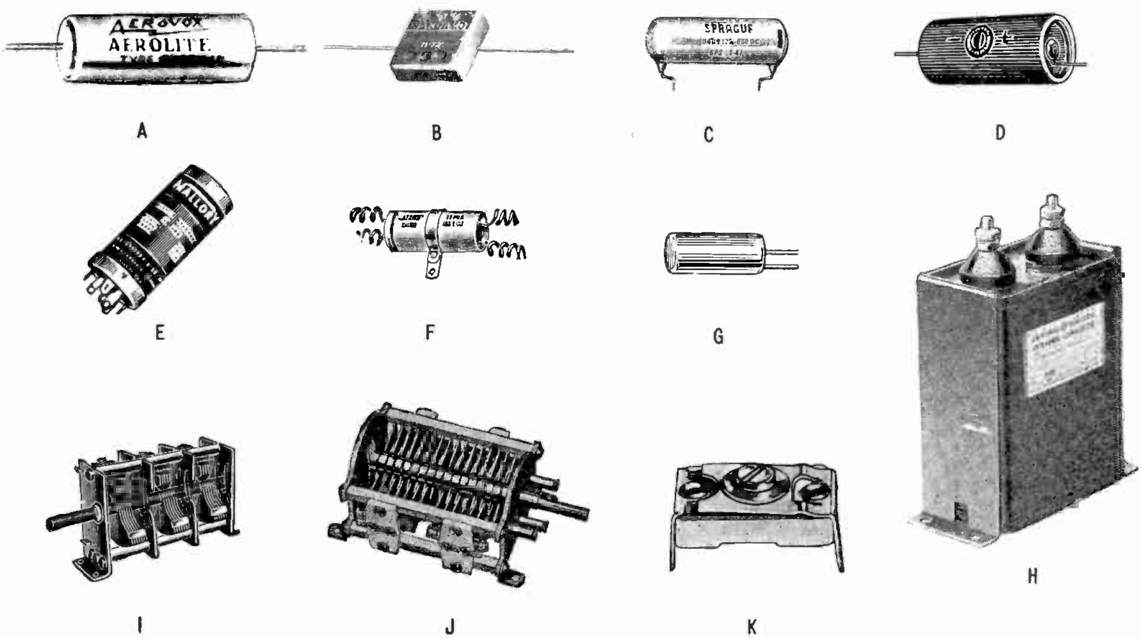


FIGURE 1

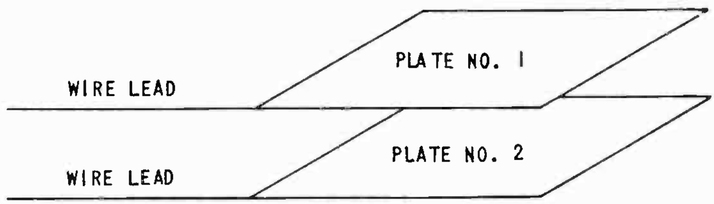


FIGURE 2

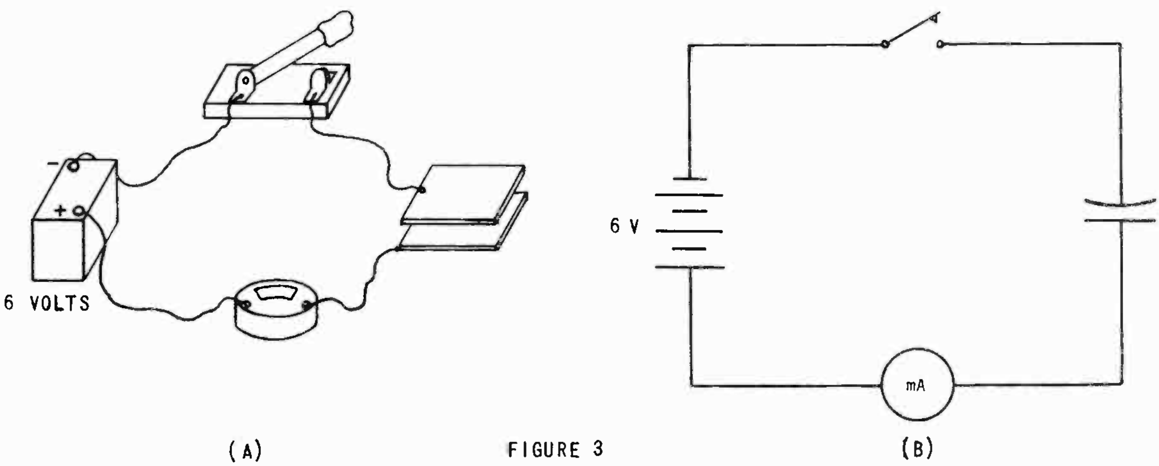
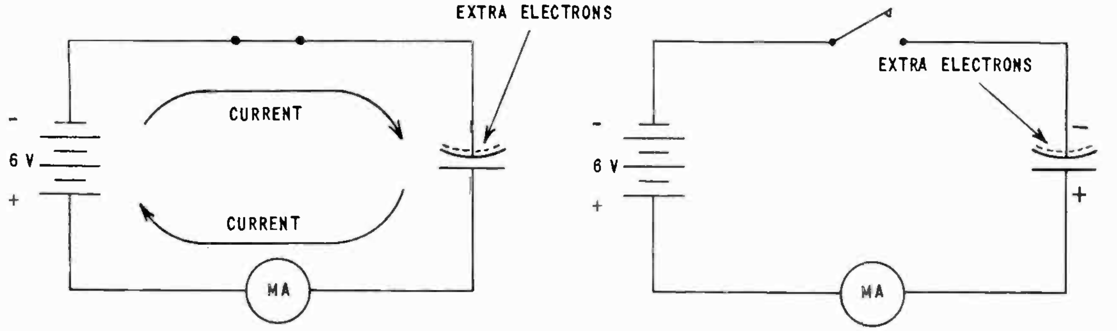
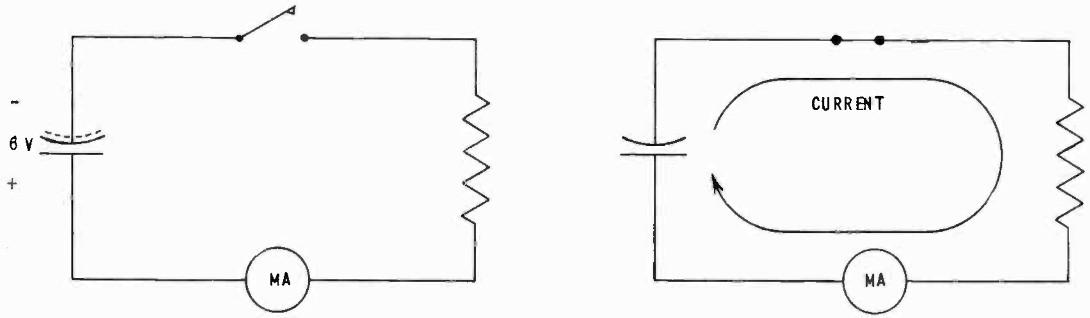


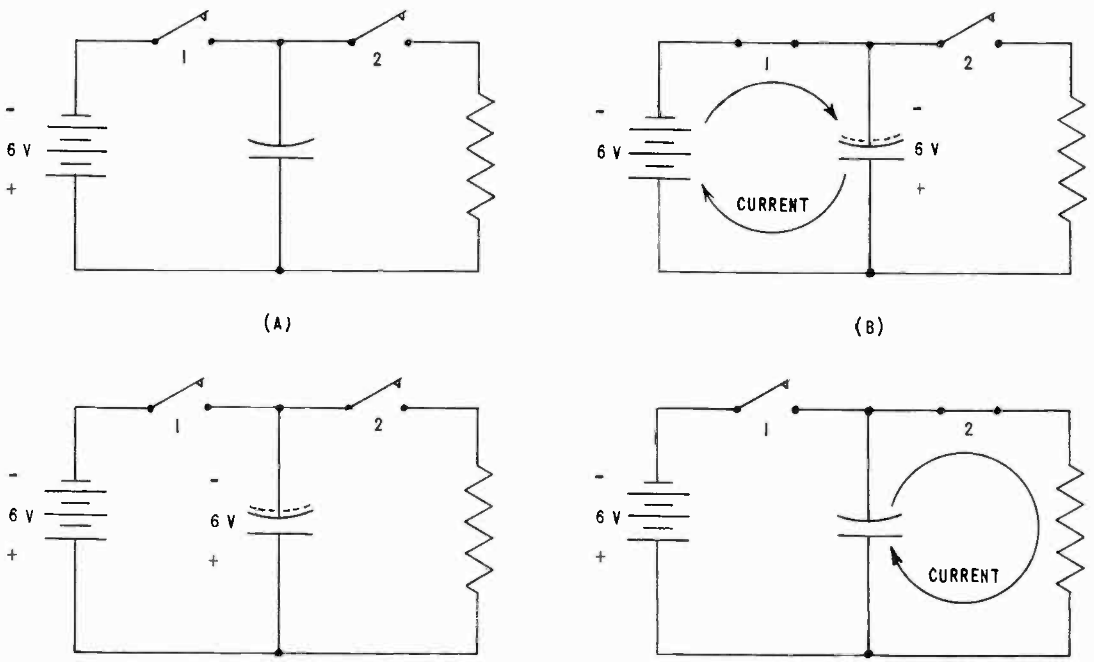
FIGURE 3



(A) FIGURE 4 (B)



(A) FIGURE 5 (B)



(C) FIGURE 6 (D)

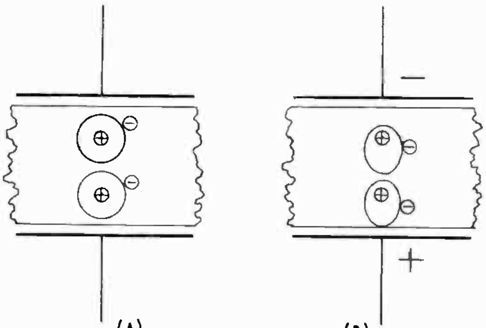


FIGURE 7

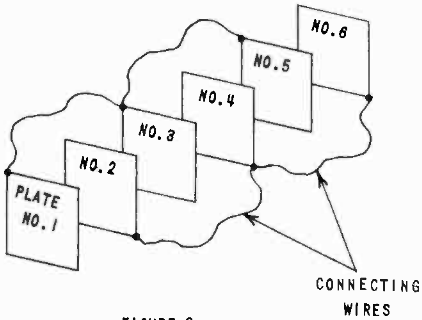


FIGURE 8

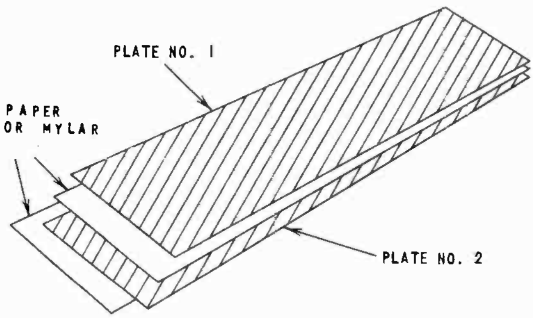


FIGURE 9 (A)

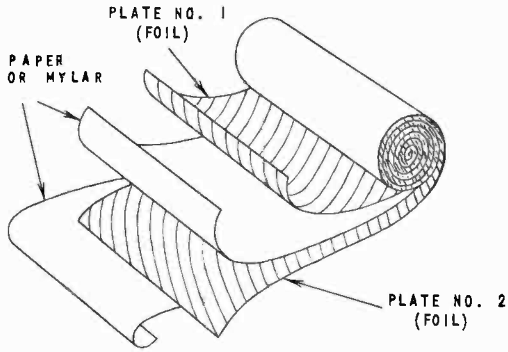


FIGURE 9 (B)

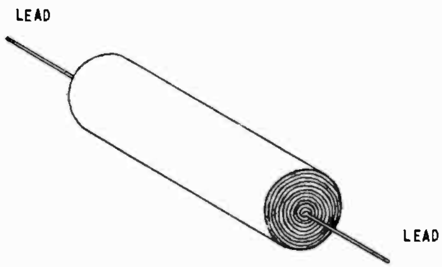


FIGURE 9 (C)

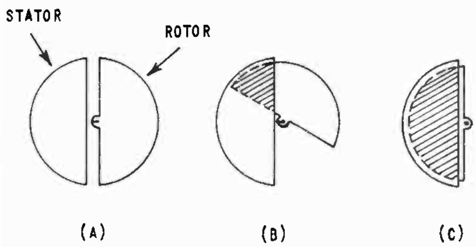


FIGURE 10

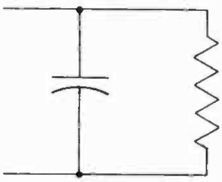


FIGURE 11

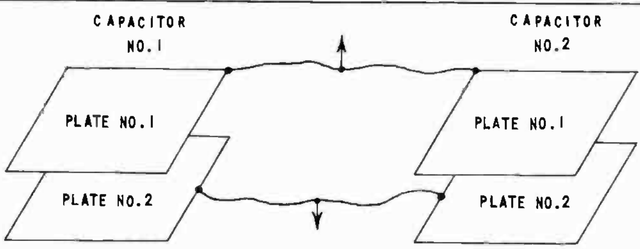


FIGURE 12

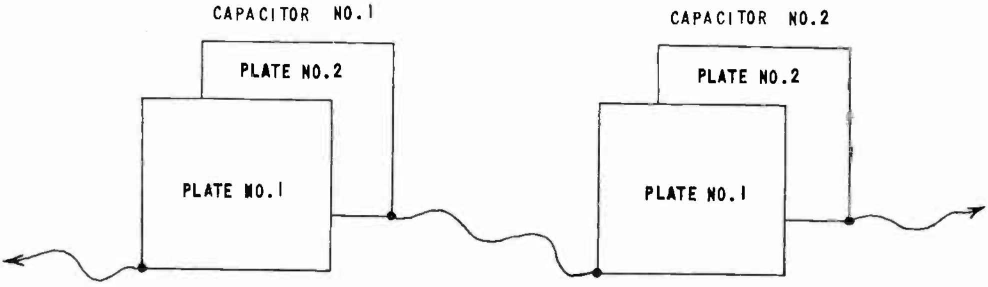


FIGURE 13

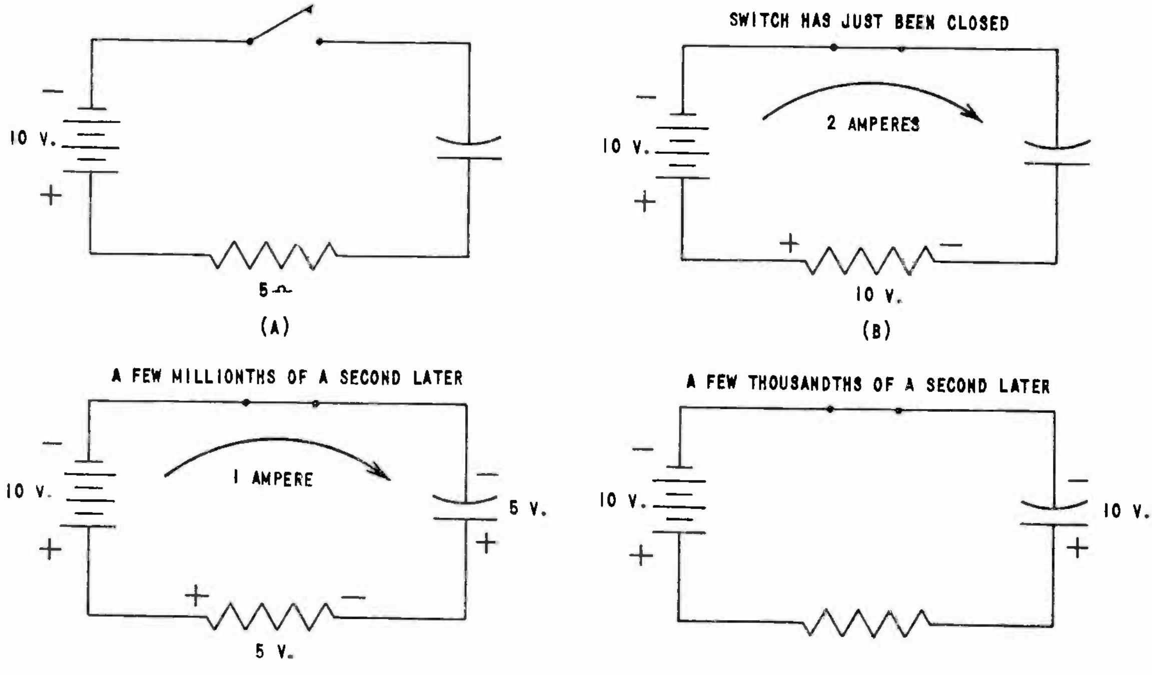


FIGURE 14

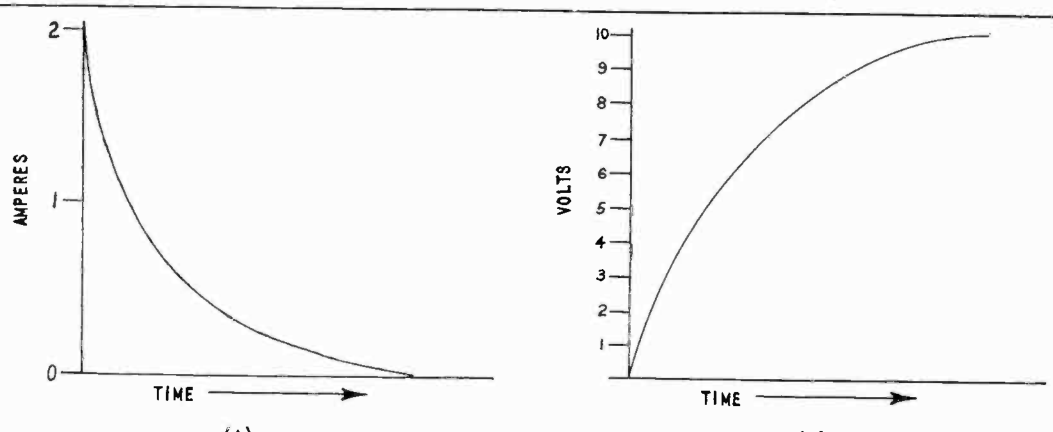


FIGURE 15

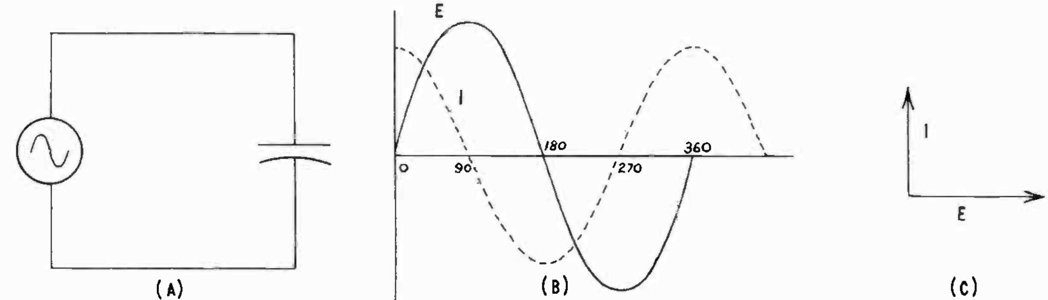


FIGURE 16

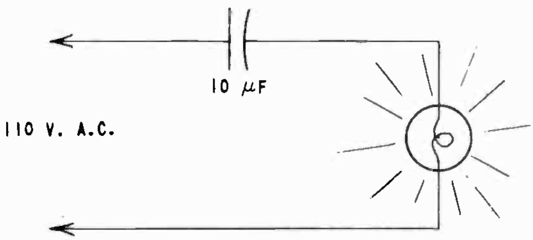


FIGURE 17

ASSUME THAT THERE IS A NEGLIGIBLE AMOUNT OF RESISTANCE IN THE CIRCUIT

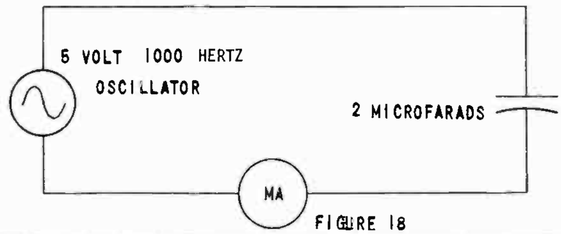


FIGURE 18

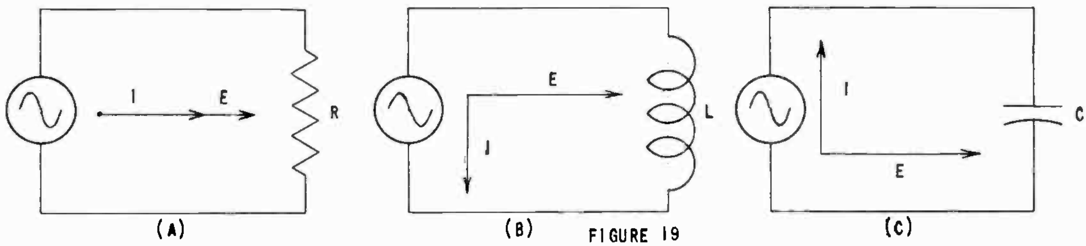


FIGURE 19

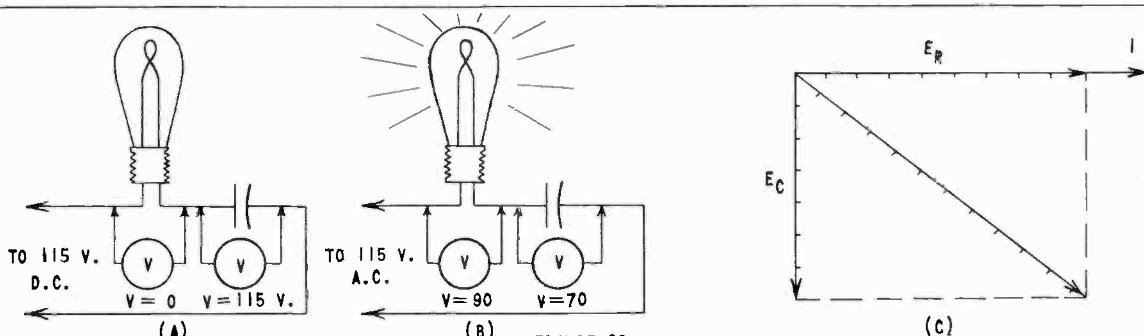


FIGURE 20

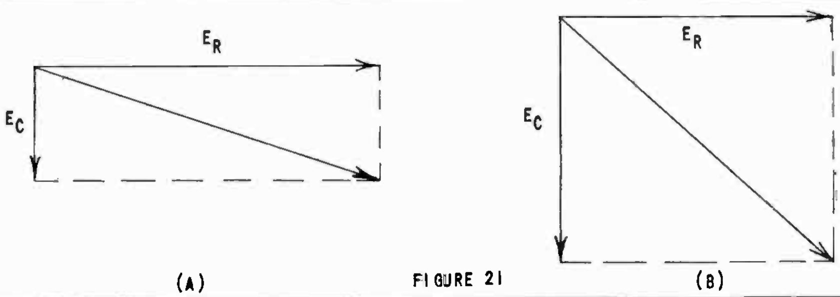


FIGURE 21