SECTION 2

ADVANCED PRACTICAL RADIO ENGINEERING

TECHNICAL ASSIGNMENT

CAPACITY

215E

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CAPACITY

INTRODUCTION.—Capacity is the principal property of the electrical capacitor. A capacitor may be defined as any apparatus in which energy or power can be stored in the form of an ELECTRO-STATIC field. In turn an electro-static field may be defined as the stationary ELECTRIC FIELD existing between two unlike electric charges, positive and negative.

It is much easier to arrive at a thorough understanding of the operation of a capacitor than to understand the effects of inductance in a circuit. This is due to the fact that exact mechanical analogies may be used to explain most of the effects of capacity. That is not true of inductance.

MECHANICAL ANALOGY.—The term "capacity" immediately brings to mind the idea of volume or amount. For example, the capacity of a water tank is the amount of water the tank will hold, measured in gallons, cubic feet, or whatever unit it is desired to use. The capacity of an air tank is the number of cubic feet of air that can be forced into the tank *with any given applied pressure.* This example of the air tank compares almost exactly with the effects of a capacitor and for that reason will be used to explain the elementary capacitor operation. Air is compressible and so is an electric charge; their effects under pressure are almost identical. If too much air is forced into a tank, the pressure inside the tank will become so great as to burst the walls of the tank and release the pressure; if too large an electric charge is forced into a capacitor, the voltage or pressure between the plates of the capacitor will build up to such an extent as to break down the insulation between the plates and discharge the capacitor.

In Fig. 1 two containers are connected together by a pipe with a valve between. With the valve closed container B is exhausted of all air, assuming that this is possible.

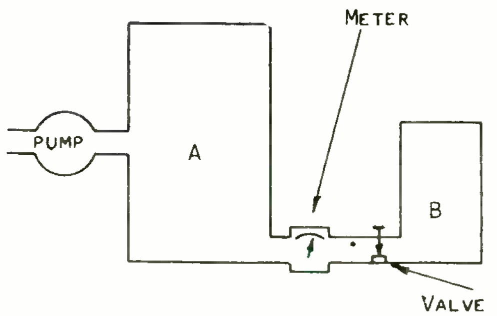


Fig. 1.—Mechanical analogy of capacitance.

Container A is pumped up to an air pressure of 100 pounds per square inch. A certain definite number of cubic feet of air, the amount depending directly upon the dimensions (capacity) of the container, must be pumped into the container to raise the pressure to 100 pounds per square inch. If the pump is capable of supplying a pressure exactly equal to 100 pounds per square inch, as soon as sufficient air has been forced into the tank to cause the internal pressure to exactly equal the maximum pressure of the pump, even though the pump is left running, no more air will be forced into the tank. There is now sufficient air stored in tank A to cause a pressure of 100 lbs/sq.in. on all walls of the tank. The air in B is zero, the pressure therefore being zero also.

If the valve is opened suddenly there will exist the condition of a container holding air at high pressure connected directly to a container at zero pressure. The air will flow through the valve into tank B UNTIL THE PRESSURE OF B EQUALS THE PRESSURE OF A. If the pump is still running it will supply the deficiency in A caused by the air leaving to go to B, and the pressure of A will be maintained at 100 lbs/sq.in.

Since container B is much smaller than A, a smaller actual volume of air will be required to raise its pressure to 100 lbs/sq.in. than must be contained in A to produce that pressure. The "capacity" of the small tank is less than that of the large tank.

When the valve is first opened the difference in pressure between A and B is 100 lbs/sq.in. The pressure in B being zero, there is at that instant no opposition to air flow into B, (assuming that the connecting pipe is sufficiently large that the friction of the air on the walls of the pipe may be neglected). Since there is no opposition, the instantaneous rush of air into B will be large and the meter, which indicates cubic feet per second, will register a large air-flow. However, as the air flows into B a pressure is built up, the pressure increasing as the number of cubic feet of air in B increases. As this back pressure builds up it offers more and more opposition to the flow of air from A to B, until when the pressures of A and B are equal no air will flow through the connecting pipe. Thus the air-flow meter will deflect to maximum the instant the valve is opened, and will then gradually drop to zero as the pressures become equal.

OPERATION OF A CAPACITOR.—Referring to Fig. 2, it will be seen that an exactly similar condition exists if an electrical capacitor is connected across a steady source of voltage.

In this case the battery acts as container A and the chemical action of the battery, which moves a

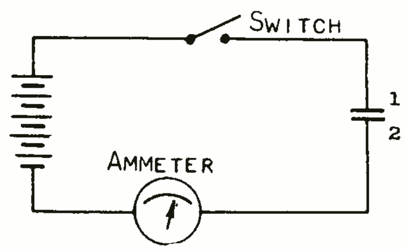


Fig. 2.—Electrical circuit showing operation of a capacitor.

sufficient number of electrons from the positive terminal to the negative terminal of the battery to cause a difference of potential, (pressure), of 100 volts, is analogous to the pump. When the deficiency of electrons on the positive terminal and the excess on the negative terminal are such as to cause a difference of potential of 100 volts, the chemical action causes no further movement of electrons. If, however, some of this pressure is neutralized the chemical action will again commence.

The capacitor takes the place of container B, and in its normal state no difference of potential exists between the plates.

The switch replaces the valve, and the ammeter, which measures ELECTRONS PER SECOND moving past a given point, is analogous to the air-flow meter which measures cubic feet of air per second flowing through it. The moving element has been changed from cubic feet of air to electrons. The air PRESSURE has been changed to the electrical pressure or difference of potential caused by the excess of electrons on the negative terminal trying to neutralize the deficiency of electrons on the positive terminal.

As the switch is closed the positive terminal of the battery will attract electrons to it from the capacitor plate and the negative terminal will repel electrons toward the other plate of the capacitor. As electrons move away from plate number 1, that plate assumes a positive charge. As an excess of electrons is forced to plate number 2 that plate assumes a negative charge. The movement of electrons will continue until the difference of potential between the plates equals the applied voltage of the battery, 100 volts.

Assuming that the connecting leads, etc., are such that the circuit resistance is negligible, then the only opposition to the electron flow is the pressure built up across the capacitor. When the switch is first closed there is no difference of potential across the capacitor, therefore no opposition, and the electron movement will be large. As the electrons leave one plate and become in excess on the other, a pressure is built up across the capacitor which opposes the electron movement, and the greater this pressure, the greater the opposition. At the instant the capacitor voltage is equal to the applied voltage the electron movement ceases.

This effect will be indicated by the ammeter in the following manner: the ammeter which measures the electrons per second moving through the circuit will indicate the greatest movement at the instant of least opposition. That instant is at the closing of the switch, therefore when the switch is closed the indicator of the ammeter will instantly jump to a maximum reading and gradually fall off, reaching zero as the capacitor voltage equals the applied voltage.

From then on, so long as the voltage of the battery remains constant, no more current will flow through the circuit. If, however, the battery voltage is INCREASED, current will again flow IN THE SAME DIRECTION AS BEFORE, in order that the capacitor voltage may be maintained equal to the battery voltage.

If the battery voltage is DECREASED current will flow in the circuit but in THE OPPOSITE DIRECTION discharging the capacitor, that is, neutralizing the difference of potential across the capacitor in order that the capacitor voltage may still equal the applied voltage.

Assuming that the resistance of the circuit is negligible, and remembering that the electron flow is always of such amplitude and in such a direction as to tend to keep the capacitor voltage at every instant equal to the applied voltage, it will be seen that if the applied voltage is increased very rapidly the electron flow, tending to build up the capacitor voltage just as rapidly, must be large. If the applied voltage is increased slowly the electrons will not be required to move through the circuit so rapidly to keep the counter EMF, (capacitor voltage), equal to the applied EMF, therefore the ammeter will not indicate as large a current flow on the slow voltage increase as on the rapid voltage increase.

If in both cases voltage is increased the same amount, the same actual number of electrons must be transferred from one plate of the capacitor to the other. On the slow increase, however, the same number of electrons requires a longer time to pass a given point, the RATE OF FLOW is therefore less and the ammeter will indicate a smaller flow of current for a longer period of time.

The same principles apply to the capacitor discharging on a decrease of the applied voltage. The more rapidly the applied voltage drops off, the more rapidly the electrons must flow through the circuit in such a direction as to decrease the capacitor charge. The rate of flow is always such as to keep the CEMF exactly equal to the applied voltage. (This statement is true only in the case where the capacitor has a circuit through which it can discharge rapidly as in the type of circuit being discussed. Later it will be seen that there are circuits in which this free discharge action cannot take place and different conditions will be extablished. For ease of explanation in this assignment, all charging and discharging circuits will be considered such that the charge and discharge is governed only by the actual applied EMF and counter EMF as shown.)

The important fact to remember in the study of capacitor action is that for a given capacitor the current flow, either on charge or discharge, WILL BE GREATEST AT THE INSTANT THE VOLTAGE IS VARYING THE MOST RAPIDLY.

THE ANGLE OF LEAD.—Applying this fact to an alternating-current circuit: The voltage supplied by the alternator is continuously varying except at the instants of maximum voltage which occur twice each cycle, at 90 degrees and 270 degrees. At those instants there will be no current flow in a pure capacity circuit. As with inductance it is not possible to totally eliminate resistance, but the condition may be assumed for the study of the effects of capacity alone.

The voltage variations, when in the form of a sine curve, are the most rapid when the voltage is passing through zero. From the preceding statements on capacitor action it is evident that the current flow must be greatest at that instant. In a pure capacity circuit when the voltage variation is in the form of a sine curve, the current flow will be maximum when the voltage is passing through zero and will be zero when the voltage is at a maximum value.

The curves of Fig. 3(C) clearly demonstrate the current-voltage relation. Since the effects of capacity are manifest when voltage variations are taking place, the study of the curves will be based on the curve of the applied voltage E. Curve E is divided into 4 changes and the voltages and currents in the circuit will be studied for each of the four changes of applied voltage. Assume that the switch is closed exactly at the instant the voltage is leaving zero at its zero phase angle as shown in Fig. 3(C).

At that instant, as the voltage is just leaving zero, it is changing the most rapidly. At that instant the capacitor is totally discharged and the capacitor voltage, shown on curve CEMF, is zero. The current will then rise instantly to its maximum value. As the applied voltage continues to rise the current continues to flow in such a direction as to charge the capacitor, that is, to build up a counter EMF equal and opposite to the applied voltage. The direction of current flow is shown by the arrows, 1, on Fig. 3 (A).

Again referring to 3 (C), as the applied voltages rises, the CEMF rises in exact opposition and exactly equal both in amplitude and in the shape of the curve; also, as the applied voltage rises the current gradually drops off, until at 90 degrees the current becomes zero. This agrees with the theory as previously explained because as the voltage increases its RATE OF INCREASE *DECREASES*. (Due to the shape of the sine curve.) In a capacity circuit the current flow depends, not upon the amplitude of the voltage, but upon the amount of the VOLTAGE VARIATION. At the 90 degree instant the capacitor is fully charged, the applied voltage and

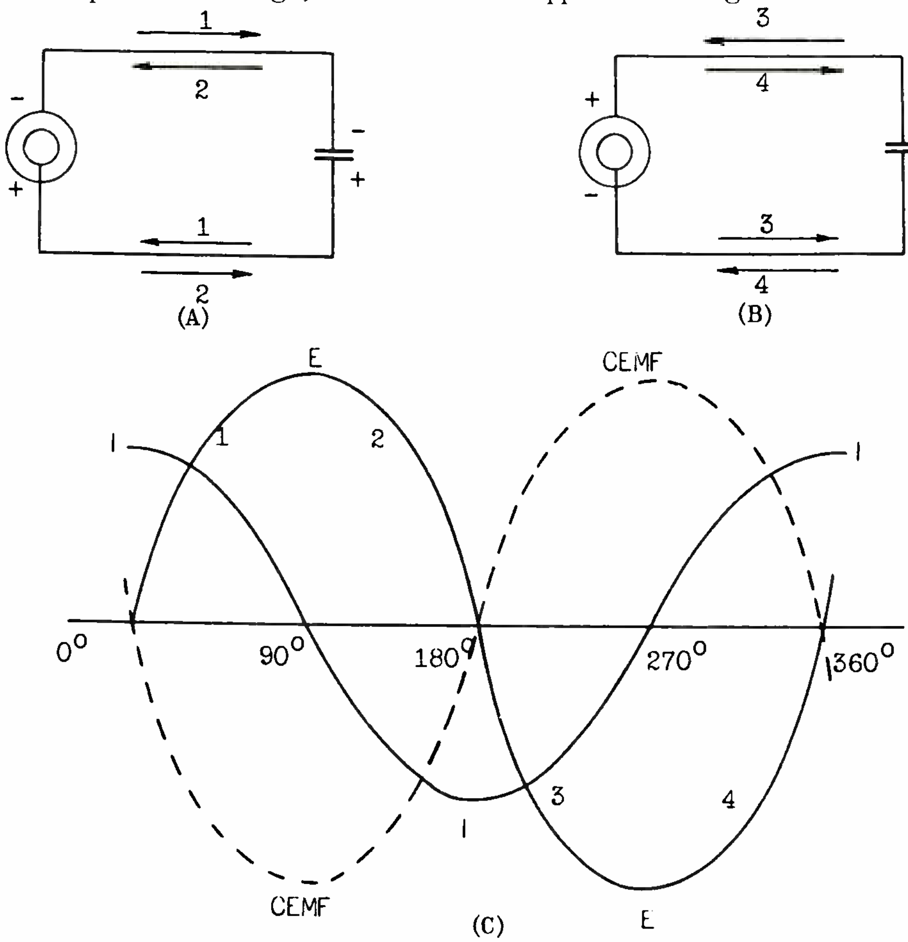


Fig. 3.—Charge and discharge of a capacitor.

CEMF are at maximum values AND THE CURRENT FLOW IS ZERO.

Consider change number two. The applied voltage is still of the same polarity but is now DECREASING IN AMPLITUDE. As the applied voltage falls off the current will flow in such a direction as to keep the CEMF equal to the applied voltage. Therefore the capacitor must now be discharging, that is, the electron must be moving in such a direction as to tend to neutralize the capacitor voltage. This is shown by arrows 2 in Fig. 3(A); also by the current curve from 90° to 180° on 3(C). When the voltage first begins to decrease, the decrease is very slow, therefore the current flow in the direction of discharge is small. However as the voltage approaches zero its decrease becomes more and more rapid, the current flow consequently increasing and the CEMF thereby falling off faster and faster, until at the instant the voltage reaches exactly zero, 180°, the CEMF will also be zero and the current flow will be at its maximum value. The capacitor at this instant is TOTALLY DISCHARGED. If the applied voltage remained at zero the current would instantly fall to zero. That however is not the case. As the voltage reaches zero it instantly reverses and begins to rise in the opposite direction.

Change three. The voltage is now rising in the direction opposite to its rise in change one. As the applied voltage has reversed the CEMF must also reverse. In order for the CEMF to reverse the capacitor must charge in a direction opposite to its first charge. This means that the electrons must move from one plate to the other in the opposite direction to their movement in change one. This causes a continuation of the electron movement in the same direction as the flow in change two, (discharge). Reference to Figs. 3(A) and 3(B) and the current curve of 3(C) will demonstrate this fact. Arrows 2 and 3 are in the same direction. The current flow as shown in change three is in the same direction as in charge two, the difference being that in change two the current is rising in amplitude as the capacitor discharges while in change three it is decreasing in amplitude as the capacitor charges.

At the 270° instant the capacitor is again fully charged, the applied E and the CEMF are at maximum values, and the current is zero.

In change four the capacitor again discharges, the current reversing when the applied voltage falls off causing the CEMF to fall off also. At 360° the condition of the circuit is the same as at 0°, one complete cycle having been completed.

It will be seen that the current in this purely capacitive circuit reaches its maximum value at the instant the voltage begins to rise above zero. The current is therefore 90° AHEAD OF THE VOLTAGE and is said to LEAD THE VOLTAGE by 90°. The effect of capacity in the circuit is exactly opposite to the effect of inductance.

CAPACITY OF A CAPACITOR.—Referring again to the air container: the number of cubic feet of air required to raise the pressure in the tank any given amount depends directly upon the dimensions of the tank, a large tank requiring more air input for a given pressure increase than a small tank. If the pressures of both are increased by the same amount in the same time, the air flow into the large tank must be at a greater rate than into the small tank.

The same principle applies in the case of a capacitor. A certain number of electrons must be moved from one plate of a capacitor to the other in order to raise the voltage across the capacitor any given amount, the number of electrons depending directly upon the CAPACITY of the capacitor. In a capacitor of large capacity more electrons must be moved to secure any given voltage difference between plates than in a capacitor of smaller capacity. Therefore if the voltage across two capacitors is raised the same amount in the same time, a greater number of electrons must be moved from plate to plate in the larger capacitor than in the smaller capacitor. The time element being the same in both cases, it is evident that the *rate of flow* must be greater into the larger capacitor. Since an ammeter measures RATE OF FLOW of electrons, the current in the circuit of the larger capacitor will be greater than in the circuit of the smaller capacitor.

As the only opposition to current flow is offered by the capacity of the circuit, (the resistance is assumed to be negligible), it will be seen that the smaller the capacitor, at a given frequency and voltage, the smaller the current flow and therefore the greater the opposition. The opposition that capacity offers to current flow is called the CAPACITIVE REACTANCE, (X_c), and is measured in ohms. The capacitive reactance is equal to E/I.

The capacity of a capacitor is not a function of the break-down voltage of the capacitor. A capacitor, mechanically large, does not necessarily have a large capacity. The capacity is determined by the number of electrons which must be moved from one plate to the other plate, (or between sets of plates), to raise the voltage a given amount.

A capacitor has a capacity of one FARAD when one ampere flowing for one second raises the capacitor voltage one volt. This is much too large a unit for practical work so the microfarad, µF, (millionth of a farad), is commonly used. Even this unit is excessively large at high radio frequencies so at those frequencies the capacity of a capacitor is commonly expressed in micro-microfarads, µµf, (millionth of a microfarad).

The capacity of a capacitor is determined by three factors, the area of the plates, (a large area may be obtained either by two large plates or by two groups of plates in parallel, their areas adding), the distance between the plates, and the material, (Dielectric), between the plates.

The charge in a capacitor is in the form of an electrostatic field; that is, a stationary electric field, built up in the dielectric between the plates of the capacitor. An electric field is a strain in the medium between a positive charge, (deficiency of electrons), and a negative charge, (excess of electrons). As a difference of potential is applied across the capacitor the electrons are drawn away from one plate making that plate positive, and deposited in excess on the other plate making the second plate negative. With the plates relatively close together there will be an attraction between the two opposite charges creating a strain in the medium between the plates in which there is a TENDENCY for current flow to neutralize the difference of potential. If the plates, separated a given distance, are of small area, the medium in which the field will be built up, being confined practically within the limits of the plates, will be small, and a few electrons in excess on one plate and the same number deficient on the other will create a difference of potential equal to the applied voltage. Only those few electrons can be moved from one plate to the other with the given applied voltage, the capacity of the capacitor will therefore be small.

If the area of the two plates is increased, the same transposition of electrons will NOT create the same difference of potential between the plates and the same strain per cubic unit in the medium. The surface of the plates being larger the same small number of atoms which were deficient or in excess of electrons will be more widely separated and the electric field, which before was concentrated and therefore strong, will now be weak; the difference of potential between the plates will NOT equal the same applied voltage. Since the movement of electrons will continue until the CEMF equals the applied voltage, with the larger plates the electron transposition will continue until the strain in the medium, per cubic unit, is equal to the intensity of the electrostatic field in the capacitor of smaller plates and until the CEMF equals the applied voltage. This means that a larger charging current will be necessary to charge the capacitor having large plates in the same time that was required to charge the capacitor of smaller plate surface area to the same voltage. The capacity of a capacitor is therefore increased by an increase in the area of the plates.

The distance between the plates also has much to do with the capacity of a capacitor. If two plates of given area are placed a certain distance apart and a difference of potential applied across them, a charge will build up between the plates. The electrons on both plates are acted on by two forces. Consider the plate connected to the positive terminal of the source of EMF; the electrons are attracted away from this plate by the action of the generator; AT THE SAME TIME THEY ARE UNDER THE REPELLING FORCE OF THE NEGATIVE CHARGE THAT IS BUILDING UP ON THE OPPOSITE PLATE. The electrons on the opposite plate, (the negative plate), are also subjected to two forces, the repelling force of the negative terminal of the generator and the ATTRACTIVE FORCE OF THE OPPOSITE PLATE WHICH IS ASSUMING A POSITIVE CHARGE.

With the effects of both the alternator and the mutual attraction of the charges of the two plates, more electrons are caused to move from one plate to the other through the circuit than would be the case if the effect of the attraction between plates were no present.

The closer together the two plates are brought the greater the charging current flowing in the circuit and therefore the greater the capacity. In a capacitor composed of two plates of equal area the capacity varies inversely as the distance between the plates. If the distance between the plates is decreased to one-half, the capacity will be doubled, etc. In a multiplate capacitor the effect is that of a number of two plate capacitors in parallel. The capacity of a multi-plate capacitor can be calculated by the use of the following equation:

$$C = .0885\ \frac{K(N-1)S}{R}$$

where K = dielectric permeability (explained below)

S = area of one plate in square centimeters (all plates similar)

N = number of plates

R = separation between plates in centimeters

C = $\mu\mu F$

DIELECTRIC PERMEABILITY.—The factor K which enters into the determination of the capacity of a capacitor is the permeability of the dielectric, the medium between the plates in which the electric field is built up. In the ordinary variable capacitor the dielectric is mostly air, and the permeability of dry air is taken as the unit value of electric permeability. The electric permeability of a dielectric is defined as the ease with which an electric field may be set up in that dielectric. It has NOTHING TO DO WITH THE DIELECTRIC *STRENGTH* of the medium, that is, its breakdown voltage. An insulating material that will stand a higher applied voltage before breaking down than some other substance does not always have a higher electric permeability. Many insulating materials, glass, mica, bakelite, rubber, wax, etc., have a greater electric permeability than air. For a given applied voltage a greater displacement of electrons will take place in those dielectrics than in air, a greater attraction will therefore exist between the opposite charges on the capacitor plates, and it will be easier to set up an electric field than when the dielectric is air. The opposition to the charge will be less under these conditions and a given applied voltage will cause a greater transposition of electrons than is possible with the same plates separated by air only. This means that the capacity of the capacitor will be increased when the permeability of the dielectric is increased, all other conditions remaining unchanged.

The dielectric permeability of a substance, often called the dielectric "constant", is not a constant. It varies with frequency, moisture, temperature, voltage, etc. Therefore except in the case of an air capacitor employing *very little* insulating material the capacity may be considerably different at a high radio frequency from that measured at low frequency. The dielectric permeabilities of a few substances used as insulators in capacitors are shown below:

SUBSTANCE	FREQUENCY IN KILOCYCLES	DIELECTRIC PERMEABILITY
Fused Quartz	18,000	3.4
	100	4.2
Glass	30	5.1-7.9
Hard Rubber	210	3.0
	18,000	2.9
Mica, India	100-1,000	7.07-7.9
Mycalex	100	8.0
Beeswax	18,000	3.9
Maple Wood	500	4.4

CAPACITOR CONSTRUCTION.—All of the above methods of obtaining large capacity are made use of in the commercial design of fixed capacitors. In low voltage capacitors a large capacity is obtained by building up the capacitor with long strips of waxed paper alternated with strips of thin metal foil. Since the paper is thin the separation between the plates is small and the comparatively high dielectric permeability of the waxed paper combines to provide a large value of capacity. For compactness the combination of alternate strips of paper and metal foil is rolled up tightly, placed in a metal container, and melted wax then poured in to insure against change and to increase the insulating qualities.

In higher voltage capacitors the paper strips are replaced with strips of mica thus obtaining a slightly higher dielectric permeability and much better insulating qualities.

In variable capacitors, it is hardly practical to use insulation other than air between the plates. In variable receiving capacitors, for compactness and to obtain reasonably large values of capacity, the separation between plates is usually small. The use of variable capacitors having plates extremely close together however should be avoided; first, because of the probability of mechanical troubles due to the plates bending, getting out of line slightly and short-circuiting; and second, because, when the spacing is very small a small change in the separation between plates makes a large change in capacity, and when the plates are normally so close together any slight irregularity will cause a large percentage change in the capacity of the capacitor. It is usually better to sacrifice a certain amount of compactness in order to obtain sturdy construction and better constancy of calibration.

In variable transmitting capacitors, for high power work particularly, compactness is a secondary consideration. The primary consideration is a high breakdown voltage. The breakdown voltage of dry air is about twenty-eight thousand volts per inch depending on the character of the opposing surfaces. If very high voltages are to be handled it sometimes becomes necessary to separate the capacitor plates by several inches. This wide separation of the plates has the effect of decreasing the capacity, so that in order to obtain the desired capacity the wide spacing must be compensated for by increasing the area of the plates. Thus variable capacitors of very large physical dimensions as used in modern high power tube transmitters often have capacities less than those of the capacitors used in small receivers.

When the capacitor voltage approaches the point where ionization of the surrounding air begins, precautions must be taken against that condition because power is required for ionization, and the power expended is manifest in the form of losses in the capacitor. Ionization occurs most readily at points of high field concentration and in particular at conductor sharp points and edges. Therefore the edges of the plates of a high voltage variable capacitor should be rounded to minimize ionization losses. In a radio-frequency circuit quite high peak voltages may occur, even with comparatively low power, so this factor of design must not be neglected.

SELECTING A CAPACITOR.—In selecting a capacitor, particularly for a high-frequency circuit, great care should be taken to avoid unnecessary losses. The losses in a capacitor are mostly in the dielectric. As the capacitor is rapidly charged and discharged and the polarity of the plates reversed, the electrons in the dielectric are rapidly displaced from one side of their respective atoms to the other side. Most of the electrons do not actually leave the atoms but their orbits are changed or distorted with every change in the applied voltage. The rapid displacement of electrons, even though the actual current leakage through the dielectric is negligible, produces heat. The heat does no useful work and the power expended in causing the heat is therefore lost. This means a loss of power in the circuit in which the capacitor is used. The more rapid the displacement of electrons from one side to the other in the atoms, the greater the heat produced. Often when using fixed capacitors, the cases of which are filled with wax, if the capacitor is overloaded the capacitor will become so hot that the wax will melt out. A considerable amount of power or energy is required to raise the temperature of the wax to the melting point and that amount of power is taken from the circuit and wasted.

In receiving capacitors it is particularly important that the losses be kept to a minimum. If a receiver is expected to have sufficient gain to reproduce weak distant signals, every possible amount of the available energy must do useful work. If any appreciable amount of the received energy, which is small to begin with, is wasted, a marked decrease in signal strength will be noted. Also the gain per stage of the r-f and i-f amplifiers goes down rapidly with increased losses.

Most insulators which are good from the voltage breakdown viewpoint introduce comparatively large dielectric losses in the capacitor when placed directly in the electro-static field. A good variable capacitor, for that reason, should employ the minimum of insulating material consistent with good mechanical construction, and the insulating material should NEVER extend between the capacitor plates.

It has been shown that in charging a capacitor electrons must be moved from one plate of the capacitor to the other plate. Power is required to move those electrons and to overcome the CEMF that is built up in the capacitor. If, however, there were no resistance or dielectric losses during the charge, ALL of the energy used up in the charging process would be stored in the form of an electro-static field between the plates of the capacitor. Then, if the circuit were opened at the instant of full charge, the charge would remain in the capacitor; forever, if there were no leaks, or losses. The latter condition is of course impossible to attain; however in a good high voltage capacitor a large charge may be built up that may take several hours to leak off.

In the theoretically perfect capacitor ALL of the power required for building up the charge will be stored in the capacitor, a difference of potential will exist between the two plates, and the capacitor may then be considered a SOURCE of EMF. If the charged capacitor is short-circuited by a conductor it will discharge through the conductor expending its power in heat in the conductor. If this perfect capacitor is placed in an a-c circuit, the power taken from the alternator during the charge will be RETURNED TO THE ALTERNATOR CIRCUIT during the discharge, and no power will be expended IN THE CAPACITOR itself. Since no piece of electrical apparatus can be made perfectly NO-LOSS such a condition cannot be completely obtained. However, in a well designed radio-frequency circuit using a GOOD capacitor, the losses in the capacitor may be considered as a very small proportion of the total losses except at frequencies on the order of 15 megacycles and higher.

CAPACITIVE REACTANCE.—It has been shown that for a capacitor of a given capacity only enough electrons can flow through the circuit to keep the CEMF equal to the applied voltage; also that the smaller the capacity the smaller that number of electrons will be. A capacitor therefore introduces opposition, capacitive reactance, X_c, into the circuit. The reactance is equal to E/I and increases directly as the capacity decreases and vice versa; i.e., X_c varies inversely as the capacity.

The capacitive reactance also varies with the applied frequency. With a given capacity and a given applied voltage, a certain definite number of electrons must be moved through the circuit. These electrons must move through the circuit at such a rate as to keep CEMF equal to E. This means that when a given applied voltage varies rapidly, (as at high frequencies), the electrons that move through the circuit to complete a given charge must, as the frequency is increased, move at a higher velocity than when the capacitor is charged and discharged slowly. Providing the peak voltage is the same for both conditions, the actual number of electrons moved *per* *charge* is the same, but at the higher frequency there are more charges per second. The rate of flow of the electrons is therefore greater, and since an ammeter registers RATE OF FLOW of electrons, it is apparent that the current flow has been increased by the increase of frequency. If the current flow is increased the opposition, capacitive reactance, has decreased. It may be stated that the capacitive reactance varies inversely as the frequency, increasing directly as the frequency decreases, and vice versa.

From the preceding paragraphs it is evident that the capacitive reactance varies inversely as both the capacity and the frequency, an increase of either capacity or frequency decreasing the capacitive reactance of the circuit. Since the reactance is a function of both capacity and frequency there will be an equation stating the capacitive reactance in terms of frequency and capacity. That equation is:

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

When calculating the capacitive reactance at radio frequencies where the frequency is stated in kilocycles, it is important to remember that the frequency in kilocycles must be converted to cycles. This is done by multiplying by one thousand or 10^3. Thus 200 kc/s will become 200,000 cycles, or 2×10^5 cycles.

In radio-frequency work the capacity values are usually given in either microfarads or micromicrofarads. These values must be converted to farads. In a previous assignment there is a table for such terms. To change from microfarads to farads the value should be multiplied by 10^{-6}. To change from micromicrofarads to farads multiply by 10^{-12}. For example,

$$.005\ \mu f \text{ becomes } .005 \times 10^{-6} =$$

$$5 \times 10^{-3} \times 10^{-6} = 5 \times 10^{-9} \text{ farads}$$

$$400\ \mu\mu f \text{ becomes } 400 \times 10^{-12} =$$

$$4 \times 10^{2} \times 10^{-12} = 4 \times 10^{-10} \text{ farads}$$

A capacitor of 400 $\mu\mu$f capacity is placed in a circuit operating at a frequency of 600 kc/s. Calculate the opposition to current flow offered by this capacitor, that is, the capacitive reactance. This is done as follows:

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

Where C = capacity in FARADS
F = frequency in CYCLES
2π = 6.28, a constant
X_c = the capacitive reactance in OHMS

$$F = 600 \text{ kc/s} = 600{,}000 \text{ cycles} =$$

$$6 \times 10^5 \text{ cycles}$$

$$C = 400\ \mu\mu f = 400 \times 10^{-12}\ F =$$

$$4 \times 10^{-10} \text{ farads}$$

$$2\pi = 6.28 = 628 \times 10^{-2}$$

Substituting given values for the symbols in the equation, it becomes,

$$X_c = \frac{1}{628 \times 10^{-2} \times 6 \times 10^{5} \times 4 \times 10^{-10}} = \frac{1}{628 \times 6 \times 4 \times 10^{-7}}$$

$$X_c = \frac{10^7}{628 \times 6 \times 4} = \frac{10^7}{15072} = 663 \text{ ohms}$$

By the use of whole numbers times ten to the required positive or negative power instead of large numbers and decimals, this type of problem is greatly simplified.

The derivation of the equation for X_c will be of interest. The two basic equations for the charge in a capacitor are:

$$Q = EC, \text{ where } Q = \text{amount of charge in coulombs}$$

$$E = \text{voltage of capacitor when charged}$$

$$C = \text{capacity in farads}$$

$$\text{And } Q = \text{Average } I \times \text{Time of Charge}$$

That is, the amount of the charge in coulombs is equal to the average current flow in amperes during the charge times the duration of the charge in seconds.

Since the right hand expression in each equation is equal to Q the equation may be written,

$$EC = \text{AVE } I \cdot T$$

During each complete cycle there are four complete changes, two charges and two discharges. The time of each cycle is 1/F second. The time of one change is then 1/4F second. Substituting the value of T, (1/4F), for T,

$$EC = \text{AVE } I \cdot 1/4F = \frac{\text{Ave } I}{4F}$$

Average I = .636 · I, therefore,

$$EC = \frac{.636 \cdot I}{4F} \left(\frac{.636}{4} = \frac{1}{6.28} \right)$$

$$\text{Cancelling, } EC = \frac{I}{6.28F} = \frac{I}{2\pi F}$$

Dividing through by C,

$$E = \frac{I}{2\pi FC}$$

But

$$E = IX_c$$

Therefore

$$IX_c = \frac{I}{2\pi FC}$$

Dividing through by I,

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

It has been shown that in a pure capacity circuit the current leads the voltage by exactly 90°. This will make the effects of capacity on the current 90° out of phase with the effects of resistance, and in a series circuit composed of both capacity and resistance the current will lead the voltage by some angle between zero and ninety degrees, the exact angle depending upon the ratio of X_c to R. The tangent of $\theta = X_c/R$. This condition is identical to that of the inductive circuit except that in the capacitive circuit θ represents an angle of lead while in the inductive circuit θ represents an angle of lag.

CAPACITORS IN SERIES AND IN PARALLEL.—If two or more capacitors are connected in parallel the effect is just as if the plate area of a capacitor had been increased. Thus the TOTAL CAPACITY OF CAPACITORS IN PARALLEL is equal to the SUM OF THE INDIVIDUAL CAPACITIES.

For example, if three capacitors are connected in parallel, one having a capacity of 300 μμf, one of 600 μμf, and one of 2000 μμf, the total capacity is equal to 300 + 600 + 2000 or 2900 μμf. (See Fig. 4.)

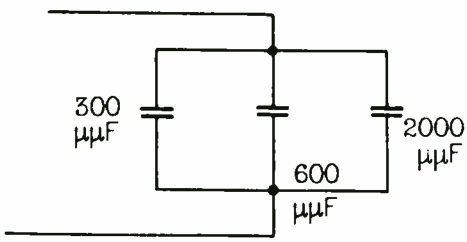


Fig. 4.—Capacitors in parallel.

If the capacitors are connected in series the effect is to increase the distance between the outside plates. If the distance between the plates is increased the capacity decreases in proportion. Therefore, if two capacitors of equal capacity are placed in series the effect is that of doubling the distance between the plates and the total capacity is equal to one-half of the capacity of one capacitor. If three equal capacities are connected in series the resulting capacity is one-third of the capacity of one, etc.

For example, if two 600 μμf capacitors are connected in series, C = 600/2 = 300 μμf. If three 600 μμf capacitors are connected in series, C = 600/3 = 200 μμf. If six .0006 μf capacitors are connected in series, C = .0006/6 = .0001 μf.

If the series capacities are not of equal value the equation becomes:

$$C = \cfrac{1}{\cfrac{1}{C_1} + \cfrac{1}{C_2} + \cfrac{1}{C_3}} \quad \text{Etc.}$$

This may be stated as follows: THE TOTAL CAPACITY OF CAPACITORS IN SERIES IS EQUAL TO THE RECIPROCAL OF THE SUM OF THE RECIPROCALS OF THE INDIVIDUAL CAPACITIES.

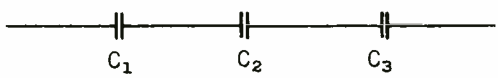


Fig. 5.—Series combination of capacitors.

The total capacity of several capacities in series is ALWAYS LESS than the capacity of the smallest. For example, if three capacitors, one of 200 µµf, one of 800 µµf, and one of 1000 µµf, are connected in series the total capacity of the combination will be something less than 200 µµf. This is clearly shown as follows:

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

$$C = \frac{}{\frac{1}{200} + \frac{1}{800} + \frac{1}{1000}}$$

$$C = \frac{1}{.005 + .00125 + .001} = 138 \ \mu\mu f$$

Consider the case of a small capacitor connected in series with a much larger capacitor, For example, C_1 = 20 µµf, C_2 = .002 µf = 2000 µµf.

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{1}{\frac{1}{20} + \frac{1}{2000}}$$

$$C = \frac{1}{.05 + .0005} = 19.8 \ \mu\mu f$$

This could also be handled by the product/sum method:

$$C = \frac{C_1 C_2}{C_1 + C_2} \qquad \frac{20 \times 2000}{20 + 2000}$$

$$+ \ C = \frac{40{,}000}{2020} = 19.8 \ \mu\mu f$$

The smallest capacitor of a group in series always has the greatest effect on the capacity of the combination. If a large capacity is placed in series with a comparatively small one, the effect of the larger capacitor on the total capacity usually may be considered negligible, as is clearly shown in the previous problem. This fact is often made use of in high power vacuum tube circuits where it is dersired to use a variable capacitor of small capacity, as in a balance or neutralizing circuit, and where the accidental short-circuiting of the variable capacitor might cause damage due to shorting to ground of the high voltage d-c power supply. To effectively prevent such an occurence, a fixed capacitor of fairly large capacity and high voltage breakdown factor is placed in series with the small variable capacitor. If the fixed capacitor has a capacity ten or more times greater than that of the variable capacitor, its effect on the total capacity may be practically neglected. Its high voltage breakdown point however protects the d-c supply in case the variable capacitor is accidently short-circuited during adjustment.

In high power radio transmitters it is often desired to use a certain standard type of capacitor in a circuit in which the current flow is very much greater than the maximum current rating of that type of capacitor.

For example: Assume a radio-frequency circuit in which, at maximum output, the current as indicated by the radio-frequency ammeter will be 40 amperes; it is desired to use a certain type of capacitor which, at the frequency at which the transmitter is to operate, is rated at 15 amperes. The circuit specifications call for a .002 µf capacity; the capacitors it is desired to use are rated at .002 µf.

In order to safely carry 40 amperes three capacitors rated at

15 amperes must be connected in parallel. (See Fig. 6.) Since the maximum permissible current is 40 amperes, the three capacitors should

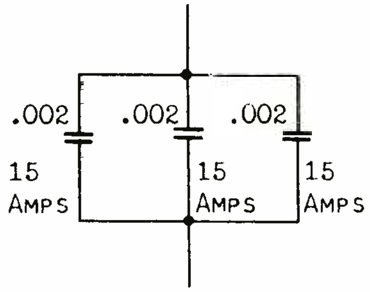


Fig. 6.—Current rating of capacitors.

not overheat. BUT—with three .002 µf capacitors in parallel the capacity is .002 × 3 or .006 µf, three times the specified capacity of the circuit.

In order to bring the circuit capacity back to the specified value, .002 µf, it will be necessary to place three of these combinations in series. (See Fig. 7.) By placing the three equal values of capacity

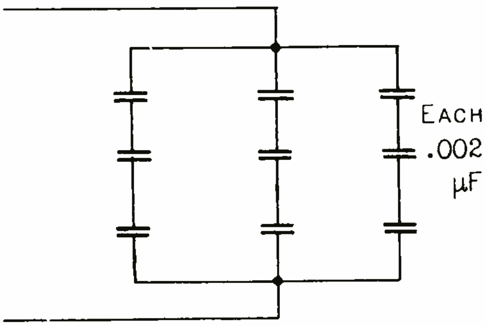


Fig. 7.—Voltage distribution in a bank of capacitors.

in parallel the capacity is increased to three times the original value. Then by placing three combinations of capacity in series the resulting combined capacity will be decreased to one-third that of a single parallel combination. The total capacity of the nine capacitors is thus equal to the capacity of a single capacitor but the current carrying capacity is three times as great.

Another advantage of such a combination is the fact that with three equal capacities in series the voltage drop across each capacitor is only one-third of the total voltage across the combination. Thus, if the capacitor combination as shown in Fig. 7 has a total effective voltage across it of 6,300 volts, the effective voltage across each capacitor is only 6300/3 or 2,100 volts. By building up such a combination of capacities a type of capacitor having a much lower breakdown voltage can be used than would be possible if a single capacitor of the same capacity as the combination had been used.

Assume the circuit conditions as those for which the combination shown in Fig.7 was designed. It is desired to use the capacity in a circuit through which 40 amperes will flow at a frequency of 200 kc/s. To compute the effective voltage across the combination it is first necessary to determine X_c.

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

$$\frac{1}{6.28 \times 2 \times 10^5 \times .002 \times 10^{-6}} =$$

$$\frac{10^6}{2512} = 398 \text{ ohms}$$

The effective voltage across the capacity combination will be,

$$E = IX_c = 40 \times 398 = 15{,}920 \text{ volts.}$$

The peak voltage across this combination will be

$$E_{eff}/.707 = \frac{15{,}920}{.707} = 22{,}517 \text{ volts.}$$

If a single capacitor having a capacity of .002 µf were placed in this circuit it would be required to not heat excessively at an effective current of 40 amperes and not to break down at peak voltages of 22,500 volts. This would be an extremely expensive capacitor.

By using three capacities in series, capacitors having a breakdown factor of 10,000 volts would provide an excellent margin of safety. By placing three capacities in parallel, capacitors having a current rating of 15 amperes should not heat excessively in this circuit.

Such smaller sizes of capacitors are much less expensive and if a single capacitor proves defective and breaks down it is only necessary to replace the one defective unit. Capacity combinations of this sort are used in practically all high power transmitters, particularly in the intermediate-frequency range.

When operating large capacity capacitors in series at high voltage for d-c filtering, it becomes necessary to use a resistance voltage divider to equalize the voltage across the capacitors. The circuit arrangement is shown in Fig. 8. This is done to minimize the effect of leakage if one capacitor unit

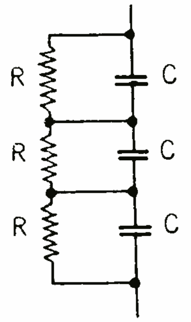


Fig. 8.—Use of capacitors in series at high voltages.

becomes defective. If the resistance network were not used, a leaky capacitor which would not take a full charge would act as a partial short-circuit and throw practically the full voltage across the two good capacitors, the voltage across each thus being increased by fifty percent. The equalizing network of three equal values of R minimized the effect of leakage and divided the total voltage equally across the three capacitors. Total R whould be sufficiently great to make the power loss negligible. A leakage current of 10 mils through R is ordinarily sufficient for quite high power filter circuits.

CAPACITY

Examination

1. (A) A capacitor requires two amperes flowing for two seconds to increase its voltage by 2 volts. Its rated capacity is (1 farad, 2 farads, 4 farads, 8 farads, 16 farads).

   (B) If two capacitors are connected in series across a 100 V battery, the rate of current flow will be (less than, the same as, greater than) if they are connected in parallel.

2. (A) Four 1 μf capacitors connected in series have a capacity (.25 μf, .50 μf, 1 μf, 4 μf).

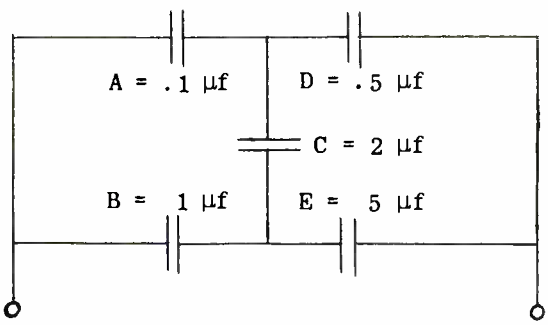
   (B) Four 1 μf capacitors connected in series have (1/4, 1/2, 2, 4, 8) times the reactance of four 2 μf capacitors connected in same manner at the same frequency.

3. (A) Variable capacitor A is rated at 100 μf. Capacitor B has twice the plate area and double the distance between the plates. Capacity of B equals (25 μf, 50 μf, 100 μf, 200 μf, 400 μf).

   (B) Two capacitors use the same material as a dielectric. Capacitor A is rated at .1 μf 300 volts, capacitor B at .05 μf 300 volts. A would require (twice the, one-half of the, the same) area of dielectric as B.

4. (A) Four capacitors are connected in series across a 1500 volt source. A = .5 μf at 100 volts; B = .25 μf at 200 volts; C = .05 μf at 1000 volts; D = .005 μf at 1000 volts. Capacitor (A, B, C, D) would be most likely to break down first.

   (B) Five capacitors are connected as shown below. Capacitor (A, B, C, D, E) has the lowest current flowing through it.



5. (A) Four capacitors, each having a capacitive reactance of 10 ohms at 1000 cycles, are connected in series across a 4000 cycle source. The capacitive reactance of the combination is (2.5 ohms, 5 ohms, 10 ohms, 20 ohms, 40 ohms).

5. (B) The current through a capacitor is *directly* proportional to the (applied voltage, frequency, capacity, area of plates, dielectric constant). (Check *all correct* answers to this problem).

6. (A) The losses in a capacitor are mostly in (the plates, the dielectric, the leads within the capacitor case).

7. (A) In the process of tuning a transmitter "tank" circuit it is found that there is arcing across the tank capacitor. This is an indication that (the plates are too far apart, the plates are too close together, the capacitor losses are excessive).

(B) Capacitor A has a value of .004 µf and capacitor B has a value of .1 µf; if these two capacitors are placed in series, capacitor (A, B) will have the greatest effect on the total effective series capacity value of the combination.

8. (A) What will be the capacitive reactance of a .00015 µf bypass capacitor used in a television receiving set at a frequency of 400 kc/s? At 1,500 kc/s? At 100 mc? At 1,000 cycles? *Show all work.*

9. Given a 25-plate capacitor, the plates being separated by mica dielectric; the mica having a thickness of 20 mils. Each plate has a length of 3 inches and a width of 2 inches. Assume the dielectric constant of mica to be 5.8. Calculate the capacity of the capacitor in μf. *Show all work.*

10. A capacitance of 640 μμf is required for a television i-f amplifier. Four capacitors are available, the capacities of which are respectively, C_1 = 600 μμf, C_2 = .0004 μf, C_2 = .001 μf, C_4 = 800 μμf.

(A) What is the capacity of the four capacitors connected in parallel? *Show your work.*

(B) What is the capacity of the four capacitors connected in series? *Show your work.*