SECTION 4

ELECTROSTATICS AND CAPACITANCE

SECTION 4

CHAPTER 1

ELECTROSTATICS

Paragraph

PART 1, SECTION 4, CHAPTER 1

ELECTROSTATICS

Introduction

1. It was stated in Sect. 1, Chap. 1 that an electron is the elementary particle of negative electricity or charge. An atom which is deficient of an electron (or electrons) assumes a positive charge and is termed a positive ion. Similarly, *any* body which has a deficiency of electrons is positively-charged; a body with an excess of electrons over its normal complement is negatively-charged. Electrostatics, as the name implies, is primarily the science of electric charges at rest. It is a subject which has many applications in radio (e.g., capacitors, thermionic valves, and cathode-ray tubes); an elementary knowledge of the subject is, therefore, required before its applications can be considered.

The First Law of Electrostatics

2. Much has been known about electrification by friction since early times. For instance, a comb after passing through dry hair attracts the individual hairs, which then themselves tend to stand on end repelling one another. If a glass rod is rubbed with a piece of silk, the silk is then attracted towards the glass. In this case, the silk *removes* electrons from the glass which is thus left with a *positive* charge; the electrons acquired by the silk give it an *equal negative* charge; between the glass and the silk there is a force of attraction. If two glass rods are treated in this manner both become positively-charged, and between the two there is a force of repulsion. From these facts the first law of electrostatics can be stated:—

"*Like charges repel each other; unlike charges attract.*"

Coulomb's Law

3. The size of the mechanical force of attraction (or repulsion) is greater between large charges than between small ones, and is greater when the charges are close together than when they are more distant. **Coulomb's Law** states that the force between two quantities of electricity Q_1 and Q_2, situated at two points a distance r apart is proportional to the product Q_1Q_2, and inversely proportional to r^2. It also depends on the nature of the *medium* between the charges. Thus, the equation for the force F between charges Q_1 and Q_2 coulombs at points separated by a distance r metres in free space is:—

$$F = \frac{1}{\kappa_0} \cdot \frac{Q_1Q_2}{4\pi r^2} \quad \text{(newtons)} \quad \ldots \quad (1)$$

where κ_0 is a factor known as the *permittivity of free space* (see Para. 21).

Potential

4. If an insulated metal sphere A is charged positively and another positively-charged body B is brought up towards it, there is a force of repulsion between them, and the nearer the two approach the greater is this force. *Work* has to be done to overcome the repulsion and bring B nearer to A, and if the repulsion is allowed to take effect it will return this work and move B back again. The nearer B is brought to A, the greater is the *potential energy of the system.* The single word, **potential,** is used in describing this fact; the potential increases as A is approached, there being a *difference* of potential between two points such as X and Y at different distances from A (Fig. 1).

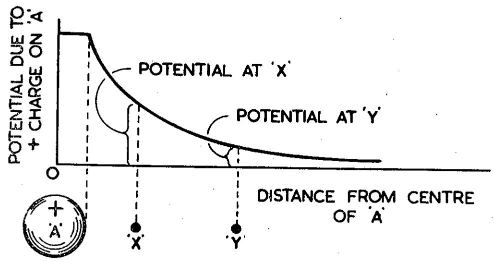

Fig. 1—THE POTENTIAL DUE TO A POSITIVELY-CHARGED BODY

5. Positive charges tend to move in the direction X—Y, from the *higher* to the *lower* potential. The change of potential per unit distance—known as the **potential gradient**—increases as A is approached as Fig. 1 indicates by the change in steepness.

The Electric Field

6. A charged body produces a distribution of electric potential in its neighbourhood, which was not there before it was charged and will disappear when the charge is removed. Thus, around a charged body, there is said to be an **electric field**—the volume of space in which electric effects are experienced.

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electric field strength E will be $\frac{V}{d}$ or $\frac{200}{0.01}$ which equals 20,000 V/m. The graph (Fig. 8) shows how the potential of the electric field varies with distance from N, assuming the field to be uniformly distributed. If the plates are brought closer together, or if the p.d. V is increased, the slope of the graph will rise to indicate an increase in the potential gradient.

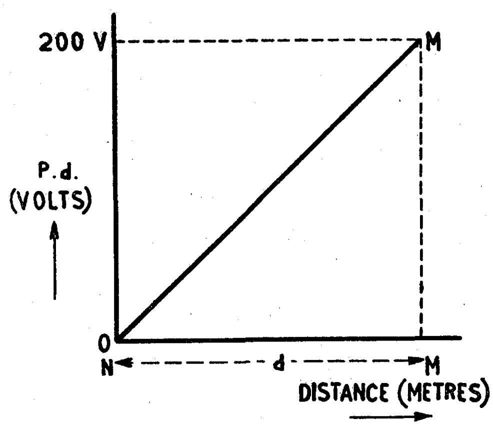

Fig. 8—VARIATION OF POTENTIAL IN A UNIFORM ELECTRIC FIELD.

18. Consider four plates A, B, C, and D as shown in Fig. 9. Plate A is 10V positive with respect to plate C; plate B is 100V positive; and plate D 200V positive. The electric fields existing between the plates are as shown, and their directions should be

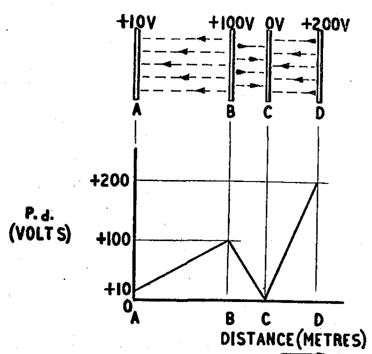

Fig. 9—POTENTIAL GRADIENT BETWEEN PLATES AT DIFFERENT POTENTIALS.

noted. The graph shows how the potential of the uniform electric field varies in the region between the plates. This type of graph is one which is often encountered in the study of thermionic valves where it is necessary to understand how an electron behaves in an electric field.

Electric Flux and Flux Density

19. The system of electric lines of force from a charge or through an electric field is termed the **electric flux.** The unit of flux is the flux associated with a charge of one coulomb; so the flux originating from a charge of + Q coulombs is directed *outwards* from it and *equal to Q coulombs.*

20. **Electric flux density** is defined as the amount of flux per unit area falling on a surface taken at right angles to the direction of the flux. If a tube of flux issuing from a charge of Q coulombs has a cross-section *a* square metres, the electric flux density (symbol D) will be:—

$$D = \frac{Q}{a} \text{ (coulombs/square metre)} \quad .. \quad (4)$$

Permittivity of Free Space

21. The ratio of the *electric flux density D* to the *electric strength E* in *free space* is termed the *permittivity of free space* (symbol κ_o). Thus:—

$$\kappa_o = \frac{D}{E} = \frac{Q}{a} \div \frac{V}{d} = \frac{Qd}{Va}$$

But $\frac{Q}{V} = C$

$$\therefore \kappa_o = C\frac{d}{a}$$

$$\text{And } C = \kappa_o \frac{a}{d} \text{ (farads) (in free space)} \quad (5)$$

The value for the constant κ_o is:—

$8{\cdot}85 \times 10^{-12}$ m.k.s. units.

Dielectric Constant

22. If a slab of insulating material is inserted to fill the space between the plates of the capacitor in Para. 15, the capacitance will increase. The ratio of the *capacitance of a capacitor having a certain material as dielectric* to the *capacitance of the same capacitor having free space (vacuum) as dielectric* is termed the **dielectric constant** or the relative permittivity of the material inserted. The symbol is κ_r.

23. It follows from equation (5) that when the plates of a capacitor are separated by an insulator of dielectric constant κ_r, the capacitance will be:—

$$C = \kappa_o \kappa_r \frac{a}{d} \text{ (farads)} \quad .. \quad .. \quad .. \quad (6)$$

24. From equation (2), $C = \frac{Q}{V}$. Thus, the

increase in capacitance obtained by inserting a material as dielectric indicates that the p.d. V volts for an original charge Q coulombs applied to the capacitor has decreased; this is because the *dielectric* has become polarized by induction from the plates and partially cancels the charge on the plates. Values of the dielectric constant for some of the more important insulating materials are given in Table 1.

Material	Dielectric Constant κ_r
Air	1·0006
Mica	5·5
Dry Paper	3·7
Porcelain	7
Bakelite	5
Glass	6
Rubber	3
Polythene	2
Ceramics (Barium titanate type)	3,000

TABLE 1. DIELECTRIC CONSTANT

Note. For practical purposes, air can be considered to have a dielectric constant of unity (as for free space).

Parallel Plate Capacitor

25. The capacitor shown in Fig. 10 is termed a parallel plate capacitor. The capacitance C in farads of such a capacitor with plates of known area *a* square metres and distance *d* metres apart is given by equation (6) :—

$$C = \kappa_o \kappa_r \frac{a}{d} \text{ (farads)},$$

where $\kappa_o = 8{\cdot}85 \times 10^{-12}$.

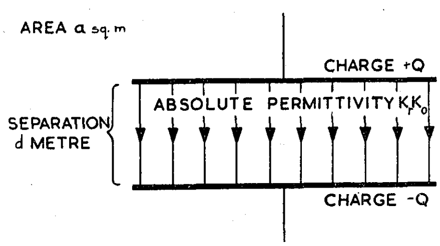

Fig. 10—A PARALLEL PLATE CAPACITOR.

26. In practice, units larger than micro-farads are never used and very frequently, particularly in electronic equipment, the micro-micro-farad (or pico-farad) is sufficiently large. In terms of micro-farads the above formula becomes:—

$$C = \frac{8{\cdot}85 \times 10^{-6} \times \kappa_r \times a}{d} (\mu F)$$

In pico-farads:—

$$C = \frac{8{\cdot}85 \times \kappa_r \times a}{d} \quad (pF)$$

Capacitance of a Multi-plate Capacitor

27. Fig. 11 shows a capacitor made up of seven parallel plates, four being connected to A and three to B. Each side of the three plates connected to B is in contact with the dielectric. Of the plates connected to A, only *one* side of the outer plates is in contact

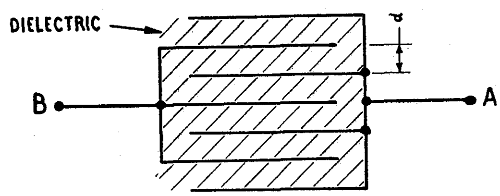

Fig. 11—A MULTI-PLATE CAPACITOR.

with the dielectric. Consequently, the opposing surface area of each set of plates is the same, namely *6a* square metres. Hence for *n* plates, the effective surface area is (*n* — *1*) *a* square metres, and from equation (6) the capacitance of a multi-plate capacitor is:—

$$C = \frac{8{\cdot}85 \times 10^{-6} \times \kappa_r \times (n - 1)a}{d} (\mu F) \quad (7)$$

where κ_r = the dielectric constant
n = total number of plates
a = surface area of one plate in square metres
d = thickness of dielectric in metres.

Capacitors in Parallel

28. Consider three capacitors of capacitance C_1, C_2, and C_3 respectively connected in parallel across a p.d. of V volts as shown in Fig. 12. For circuits in parallel the current through each component may be different and is given by I_1, I_2 and I_3 respectively. Further, since Q = It, the charge Q_1, Q_2 and Q_3 on each capacitor may be different.

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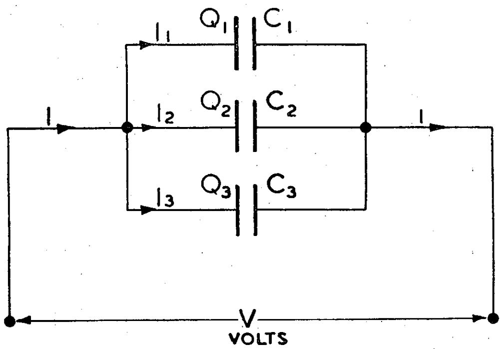

Fig. 12—CAPACITORS IN PARALLEL.

29. From Kirchhoff's first law:—

$$I = I_1 + I_2 + I_3$$

$$\therefore It = I_1t + I_2t + I_6t$$

$$\therefore Q = Q_1 + Q_2 + Q_3$$

Divide throughout by V.

$$\therefore \frac{Q}{V} = \frac{Q_1}{V} + \frac{Q_2}{V} + \frac{Q_3}{V}$$

$$\therefore C = C_1 + C_2 + C_3 \text{ (farads)} \quad .. \quad (8)$$

Thus, the equivalent capacitance of capacitors connected in *parallel* is the *sum* of the individual capacitances. It is easy to see that this must be so, for if three identical sets of plates are connected in parallel the result is to make a larger capacitor of which the total area is the sum of the individual areas

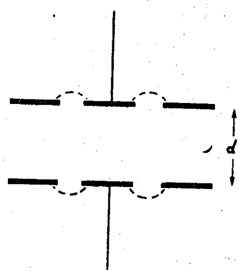

Fig. 13.—CAPACITORS IN PARALLEL REGARDED AS A SINGLE CAPACITOR

(Fig. 13). Thus, capacitors of 1μF, 2μF, and 3μF respectively in parallel are equivalent to a single capacitor of $1 + 2 + 3 = 6\mu$F.

Capacitors in Series

30. Consider three capacitors of capacitance C_1, C_2, and C_3 respectively connected in series across a p.d. of V volts as shown in Fig. 14. For a series circuit, the current is the same at all points and equals the total current I. Further, since Q = It *the charge on each capacitor will be the same and equal to the total charge Q in the circuit,* i.e.,

$$Q = Q_1 = Q_2 = Q_3.$$

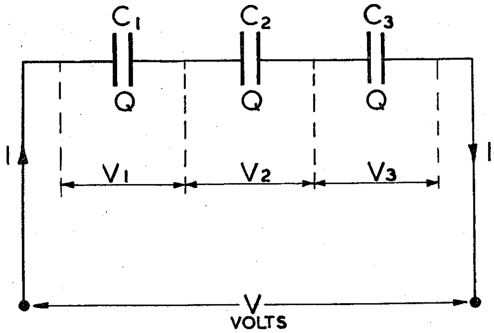

Fig. 14—CAPACITORS IN SERIES.

31. The p.d. across each component in a series circuit may be different, the sum of all the p.d.s (from Kirchoff's second law) being equal to the applied voltage.

i.e., $V = V_1 + V_2 + V_3$

$$\therefore \frac{Q}{C} = \frac{Q_1}{C_1} + \frac{Q_2}{C_2} + \frac{Q_3}{C_3}$$

$$\therefore \frac{Q}{C} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

Divide throughout by Q.

$$\therefore \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad .. \quad (9)$$

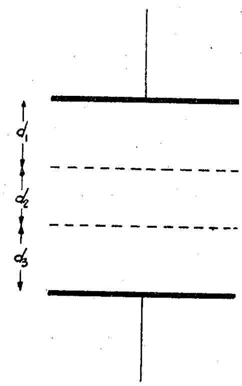

Fig. 15—CAPACITORS IN SERIES REGARDED AS A SINGLE CAPACITOR.

Thus, for capacitors in *series*, the reciprocal of the total capacitance equals the sum of the reciprocals of the individual capacitances. Capacitors in series may be regarded, as a single capacitor of greater plate separation, as shown in Fig. 15.

Energy Stored in a Charged Capacitor

32. If a capacitor having a capacitance C farads is charged at a *constant* rate of I amps for t seconds, the charge Q = It coulombs. During charge, the p.d. across the capacitor will have risen from zero to V volts at a constant rate, so that the average p.d. during charge is $\frac{V - O}{2} = \frac{V}{2}$ volts.

33. The average power is the product of the average p.d. and the current.

i.e. $P = \frac{V}{2} \times I$ (watts)

The energy expended in charging the capacitor is stored in the charged capacitor and is given by:—

$$\text{Energy, } W = P \times t = \frac{V}{2} \times I \times t = \frac{VQ}{2}$$

$$\therefore \quad W = \tfrac{1}{2}VQ = \tfrac{1}{2}\frac{Q^2}{C} = \tfrac{1}{2}CV^2 \text{ (joules)} \quad (10)$$

Electrostatic Screening

34. In many cases in radio it is not desirable that an electric field be established between two components in a circuit since mutual interference may result. An *earthed* copper can is placed round the component whose electric field has to be confined; a field will then be established between the component and the can, and no electric flux from the component will exist outside the can. Similarly, no external lines of flux will reach the component which is screened, all such lines terminating on the earthed can.

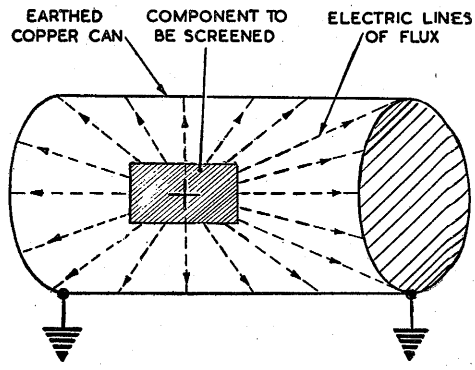

Fig. 16—ELECTROSTATIC SCREENING CAN.

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SECTION 4

CHAPTER 2

CAPACITORS

PART 1, SECTION 4, CHAPTER 2

CAPACITORS

Introduction

1. Capacitors are used for a wide variety of purposes in radio. In their construction, consideration must be given to the dielectric to be used, and in the choice of dielectric three factors are important:—

(*a*) The *dielectric constant* (see Chap. 1, Para. 22).

(*b*) The *dielectric strength*.

(*c*) The *losses* associated with the dielectric.

Dielectric Strength

2. This is a measure of the p.d. required to break down the dielectric. It is quoted as the voltage required to break down a one millimetre thickness of the dielectric and is given in *kilovolts per millimetre* (kV/mm). In any given dielectric the breakdown voltage will depend on:—

(*a*) The *material* from which the dielectric is made.

(*b*) The *thickness* of the dielectric; the thicker this is, the greater is the voltage required to break it down (although not proportionally).

(*c*) The *temperature* of the dielectric; an increase in temperature gives a reduction in the breakdown voltage.

(*d*) The *frequency* of an applied alternating voltage. A higher frequency causes the electrons in the dielectric to alternate more rapidly and the resultant increase in temperature gives a reduction in the breakdown voltage. For example, a certain capacitor withstood a p.d. of 10,000V when the frequency was 100c/s; at a frequency of 10Mc/s, the capacitor broke down at 200V.

3. Because of the factors given in Para. 2, the voltage which a capacitor is capable of withstanding is sometimes given as a d.c. voltage at a certain temperature—e.g., "350V d.c. Working, 71°C".

Displacement Current

4. This occurs in dielectrics where, under certain conditions (such as that shown in Fig. 1) the orbital electrons will be attracted towards a point which is positive and the electron orbit becomes distorted. During

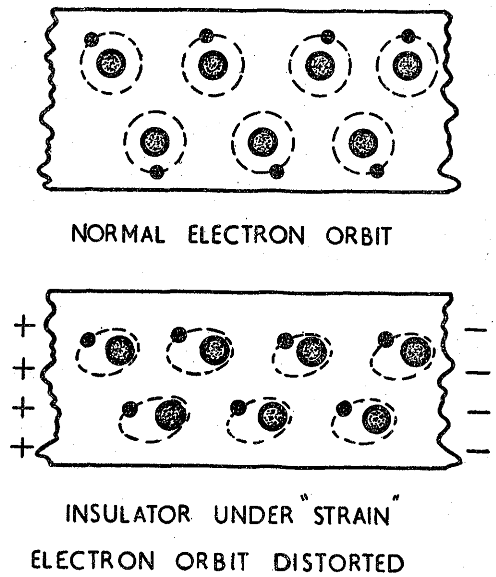

Fig. 1—DISPLACEMENT CURRENT.

the time that the electron orbit is changing there is a general movement of electrons in the dielectric. This constitutes a *displacement current*. If the applied external force is excessive, the electrons will be "pulled away" from their parent nuclei, resulting in breakdown of the dielectric.

Losses in the Dielectric

5. Of the energy supplied to a capacitor, a certain proportion is expended in the dielectric. The factors determining this energy loss are given below.

(*a*) No dielectric is a perfect insulator. Thus, when a p.d. is applied across a dielectric, a leakage current results.

(*b*) If the voltage applied to a capacitor is alternating, the continual alternate displacement of the electrons in the dielectric develops heat. Thus, some of the original energy supplied to the capacitor has been "lost" in heat energy.

(*c*) Some dielectrics exhibit a form of hysteresis similar to magnetic hysteresis. In *dielectric hysteresis* the electric flux density D ($=\frac{Q}{a}$ coulombs/square metre)

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lags behind the electric field strength E ($= \frac{V}{d}$ volts/metre). In other words, the charge Q lags on the applied voltage V, and if the voltage is alternating rapidly, the capacitor will never receive the full charge. Further, since $C = \frac{Q}{V}$, the effective capacitance will have decreased. Dielectric hysteresis (or dielectric absorption) gives rise to a loss of energy in a manner similar to that for magnetic hysteresis.

Capacitator Efficiency

6. The efficiency of a capacitor is given as:—

$$\text{Efficiency} = \frac{\text{Energy supplied on charging}}{\text{Energy obtained on discharging}} \times 100 \text{ (per cent.)}$$

The efficiency is always less than 100% because of:—

(*a*) The *dielectric losses* (Para. 5).

(*b*) *Skin effect* in the connecting leads and plates (see Sect. 2, Chap. 4, Para. 13).

(*c*) *Brush discharge;* this is an intermittent discharge (similar to a lightning discharge) from sharp corners of a capacitor plate into the surrounding air when the capacitor is charged to a high potential. For this reason, many high voltage capacitors have the corners of their plates rounded off.

Comparison of Capacitor Dielectrics

7. Table 1 gives a comparison of some of the more important dielectrics used in capacitors.

Dielectric	Losses	Dielectric Constant	Dielectric Strength	Remarks	Use
Air	Almost loss-free	Nearly 1	3kV/mm.	—	Variable tuning capacitors and trimmers.
Mica	Low losses	5·5	100kV/mm.	Can withstand high temperatures but expensive	Small fixed capacitors of good quality
Paper	Very high losses	3·7	15kV/mm.	The paper is absorbent. Very cheap and relatively compact	Large fixed capacitors where losses are of little importance
Polystyrene	Very low losses	2·5	75kV/mm.	Temperature limited to 60°C. Bulkier than paper equivvalents.	A wide range of fixed capacitors. Suitable for rapid discharge circuits.
Ceramics	Very low losses	100	60kV/mm.	Can have positive or negative temperature coefficients	Small fixed capacitors. Used considerably in temperature compensating circuits.
High Dielectric Constant Ceramics	Low losses	3,000	5kV/mm.	Wide variation of capacitance with temperature	Miniature and sub-miniature capacitors

TABLE 1—COMPARISON OF DIELECTRICS

Paper Type Capacitor

8. Two long, thin strips of aluminium foil (about 0 002 inches thick), with similar strips of dry paper are assembled as shown in Fig 2(*a*). The whole is then rolled up very tightly as in Fig. 2(*b*) to form a capacitor of small volume. The metal foil electrodes are extended at several points along their

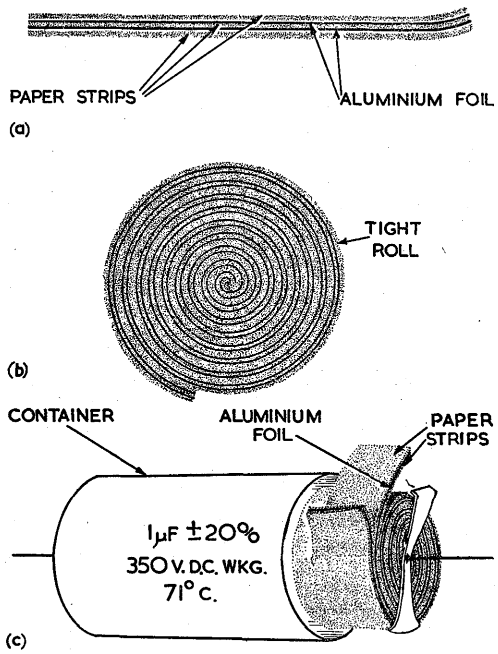

Fig. 2—CONSTRUCTION OF PAPER TYPE CAPACITOR.

length to form connecting tabs, the tabs common to each electrode being soldered together and taken out to the two terminals. The capacitor so assembled is placed inside a sealed container of waxed cardboard, metal, ceramic, or plastic; the shape is either tubular or rectangular. Such capacitors have capacitance values ranging from 0·0002 μF to 12μF at working voltages of up to 150kV d.c. and temperatures up to 100°C. One end of the capacitor is sometimes marked with a black band to indicate the outer electrode connection. Since the paper type capacitor is constructed in the form of a coil, its self-inductance gives rise to certain difficulties at high frequencies; this will be discussed in later Sections.

Stacked Mica Type Capacitor

9. This type consists of several layers of metal foil interleaved with layers of mica, with alternate foils joined together and taken out to the two terminals as shown in Fig. 3. The assembly is placed inside a moulded plastic or metal case. Such capacitors have capacitance values ranging from 50pF to 0·25μF at working voltages of up to 2kV d.c.

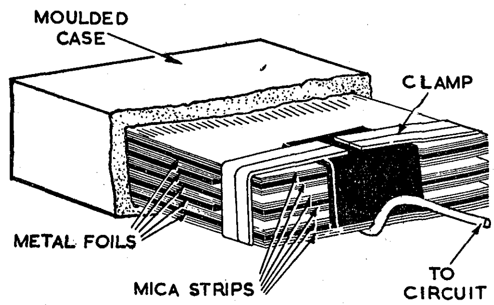

Fig. 3—CONSTRUCTION OF STACKED MICA CAPACITOR

Silvered Mica Type Capacitor

10. This type is similar in construction to the stacked mica type except that in place of the metal foils, silver is deposited directly on one side of each mica strip. A more compact and more stable capacitor results. After assembly, the whole is given a coating of wax or placed inside a plastic case. Capacitance values range from 10pF to 0·01μF at working voltages of up to 750V d.c.

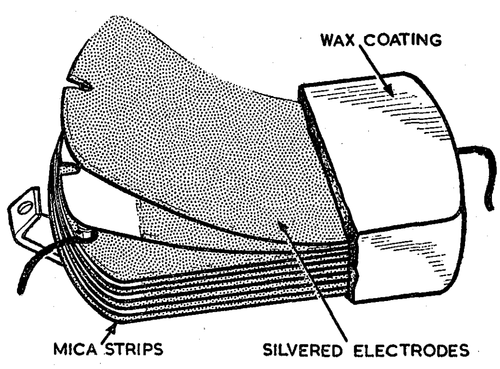

Fig. 4—CONSTRUCTION OF SILVERED MICA CAPACITOR.

Ceramic Type Capacitor

11. This type of capacitor comprises a low-loss ceramic rod or tube with silvered

electrodes to which are soldered metal end caps. The ceramic rod type is as shown in Fig. 5. Where a ceramic tube is used, the silver electrodes can be deposited on the outer and inner surfaces of the tube. The capacitor is finished with an enamel or wax coating, or placed inside another ceramic tube. Capacitance values range from 0·5 pF to 0·005μF at working voltages of up to 500V d.c.

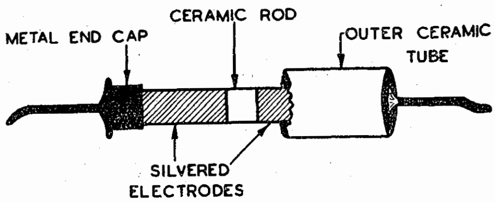

Fig. 5—CONSTRUCTION OF CERAMIC CAPACITOR.

Polystyrene Type Capacitor

12. This type is very similar in construction to the stacked mica capacitor described in Para. 9, with polystyrene strips in place of mica. Capacitance values range from 10pF to 4μF at working voltages of up to 500V d.c.

Electrolytic Capacitor

13. If a p.d. is applied across two aluminium plates immersed in a solution of ammonium borate, a current flows through the electrolyte. This current rapidly diminishes to a small value because of the formation of a thin insulating film of aluminium oxide on the positive electrode. Because of the extreme thinness of this dielectric film (e.g. 0·01 × 10^{-3} cm.) a high capacitance will exist between the position electrode and the electrolyte (since $C \propto \frac{1}{d}$). The solution is in direct contact with the *negative* electrode, so that between the two electrodes a very large value of capacitance can be obtained in a small volume.

14. The "wet" electrolytic type so described has been almost entirely replaced by the "dry" electrolytic type, where the electrodes take the form of two long strips of aluminium foil, the dielectric film having been previously formed on the positive electrode. The two electrodes are separated by strips of cotton gauze impregnated with the electrolyte, the whole then being rolled up very tightly in a manner similar to that for a paper type capacitor. The roll is mounted in an aluminium or a bakelite case and connections from each metal foil are taken out to the two terminals.

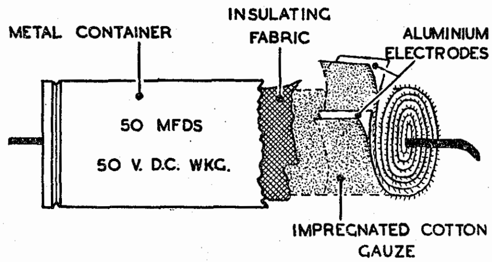

Fig. 6—CONSTRUCTION OF DRY ELECTROLYTIC CAPACITOR.

15. With an electrolytic capacitor, the dielectric film on the positive electrode must be formed and *maintained* before a capacitance is obtained. Because of this, electrolytic capacitors can be used only in those circuits where a polarizing d.c. voltage exists. The terminals are marked "positive" (red) and "negative" (black) to ensure the correct polarity. The capacitance depends on the "forming" voltage, the values ranging from 2μF to 32μF at working voltages of up to 600V d.c., and from 50μF to 3,000μF at working voltages of 50V to 6V d.c. The leakage current required to maintain the dielectric film is of the order of 0·2 milliamp.

Variable Capacitor

16. In many circuits in radio equipment it is necessary to be able to vary the capacitance. Variable capacitors used for this are normally of the air-dielectric, parallel-plate type. One set of plates, the *stators*, is fixed; the other set, the *rotors*, is controlled by a metal shaft such that the rotors can be moved into and out of mesh with the stators, as shown Fig. 7.

17. The stators are insulated from the chassis by ceramic posts, all the stator vanes being connected in parallel and a lead taken from them to the external circuit. The rotors are normally connected in parallel via the metal shaft which, in turn, is earthed to the chassis by a spring contact.

18. As the rotors are moved relative to the stators the area of overlap of each set of plates is varied. When the rotors are fully "out of mesh" with the stators the effective

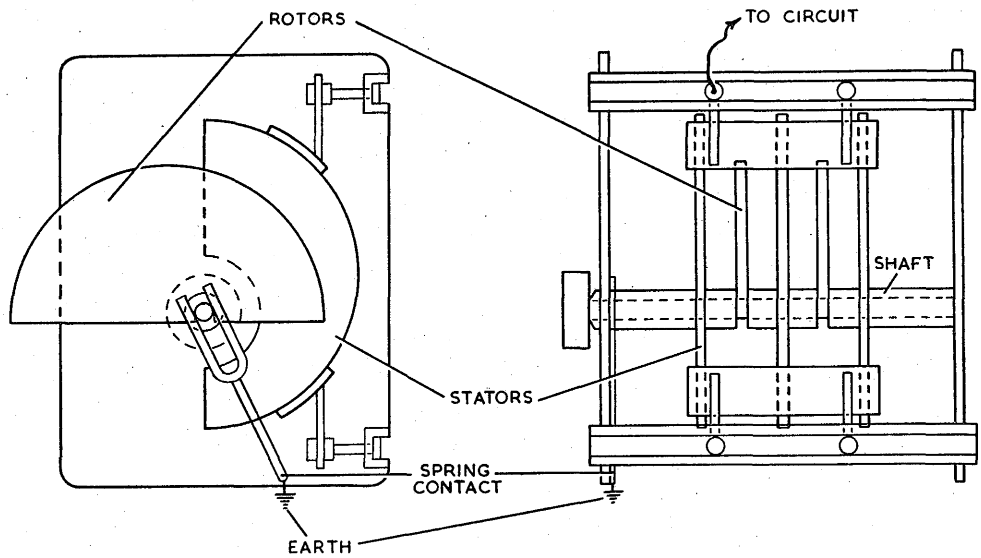

Fig. 7—CONSTRUCTION OF VARIABLE CAPACITOR.

area is nil; when fully "in mesh" the effective area is a maximum. In this way, the capacitance is varied. Although the effective area can be reduced to zero, the capacitance cannot. Even when the plates are fully out of mesh, "fringing" of the electric field between the edges of the plates gives a finite value of capacitance. A typical variation of capacitance is from 50pF to 500pF. In many cases, some of the vanes of the capacitor are *slotted* so that the final variation of capacitance can be adjusted by bending portions of the vanes in one direction or the other.

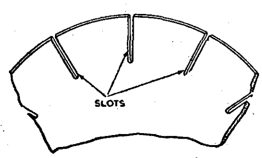

Fig. 8—SLOTTING OF CAPACITOR VANES.

19. The *shape* of the capacitor vanes will determine the manner in which the capacitance varies for angular rotation of the shaft and will depend on the particular requirement of the circuit considered. The symbol for a variable capacitor is as shown in Fig. 9.

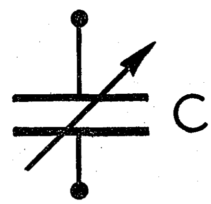

Fig. 9—SYMBOL FOR A VARIABLE CAPACITOR.

Split-stator Capacitor

20. This is a special type of variable, air-dielectric capacitor which is used in some radio equipments. The stators are split to form *two* sets of plates, the rotors being moved between the stators by a shaft as shown in Fig. 10.

21. There is no electrical connection to the rotors; these vanes are insulated from the chassis by the ceramic supports. The advantage thus obtained is that *no contact noise* is introduced into the circuit such as there is in a conventional variable capacitor where the rotors are earthed via a spring contact bearing on the metal shaft. The two stators are insulated from the chassis by ceramic supports, connection to the external circuit being made from each set of stators. Two equal capacitances exist between the top set of stators and the rotors, and between

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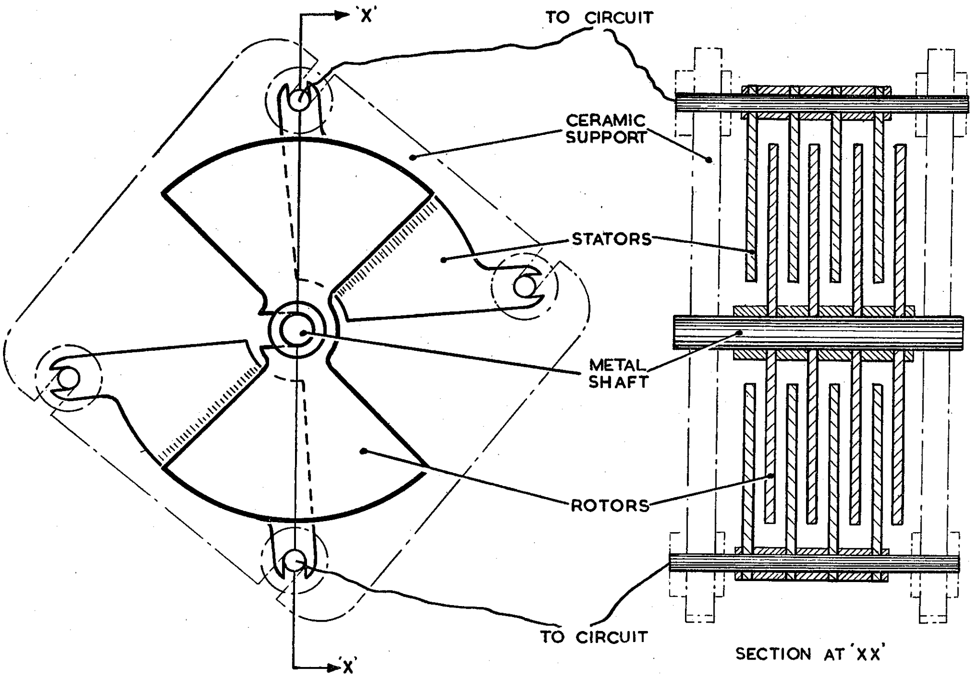


Fig. 10.—CONSTRUCTION OF A SPLIT-STATOR CAPACITOR.

the bottom set of stators and the rotors; the whole constitutes two variable capacitors in series, where $C = \frac{C_1 \times C_2}{C_1 + C_2}$ farads (Fig. 11). For capacitors in series, the total capacitance is less than the smallest individual capacitance, so that an extremely small value of capacitance can be obtained with this type of capacitor. This is an advantage in some circuits.

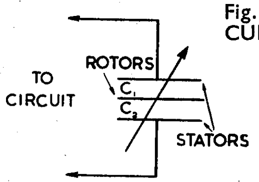


Fig. 11—EQUIVALENT CIRCUIT FOR A SPLIT-STATOR CAPACITOR.

Trimmer Capacitor

22. These are normally placed in parallel with the main variable capacitor, and they can be adjusted to give a slight variation to the final capacitance range. The arrangement is as shown in Fig. 12. Trimmer capacitors are constructed in various ways. In general, they are similar to a variable air-dielectric capacitor, but to a smaller scale. Some trimmers incorporate a solid dielectric, such as ceramic. Most are adjusted by a

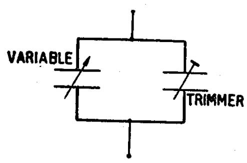
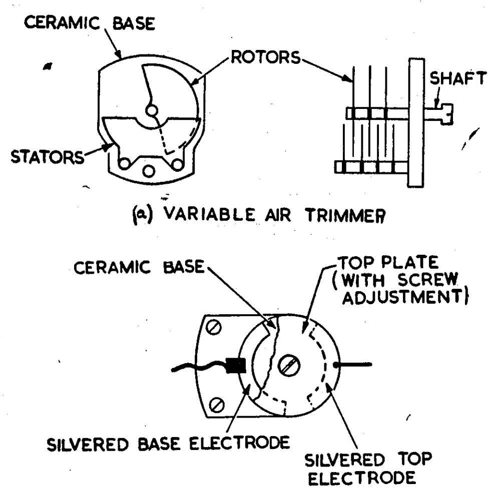


Fig. 12—USE OF A TRIMMER CAPACITOR.

screw. Capacitance values range from 2pF to 150pF at working voltages of up to 350V d.c.



(b) CERAMIC TRIMMER

Fig. 13—CONSTRUCTION OF TRIMMER CAPACITORS.

Summary of Capacitors

23. Table 2 gives the main points on the capacitors discussed in this Chapter. Fig. 14 shows a selection of typical capacitors used in radio.

Type	Capacitance Values	D.c. Working Voltage	Remarks
Paper	0·0002 μF to 12μF	up to 150kV	Used in circuits where losses are not important; cheap
Stacked Mica	50pF to 0·25μF	up to 2kV	Used in low-loss circuits: expensive
Silvered Mica	10pF to 0·01μF	up to 750V	Used in low-loss, precision circuits
Ceramic	0·5pF to 0·005μF	up to 500V	Used in low-loss, precision circuits where miniaturisation is important or where temperature compensation is required
Polystyrene	10pF to 4μF	up to 500V	Superior to mica type, but more expensive and bulky.
Electrolytics	2μF to 32μF 32μF to 3,000μF	up to 600V up to 50V	Used where losses are not important, e.g., Smoothing. A polarizing d.c. voltage must be operative in the circuit.
Variable	15pF to 500pF	up to 2kV	Used for circuit tuning
Trimmer	2μF to 150pF	up to 350V	Used for circuit alignment.

TABLE 2—SUMMARY OF CAPACITORS

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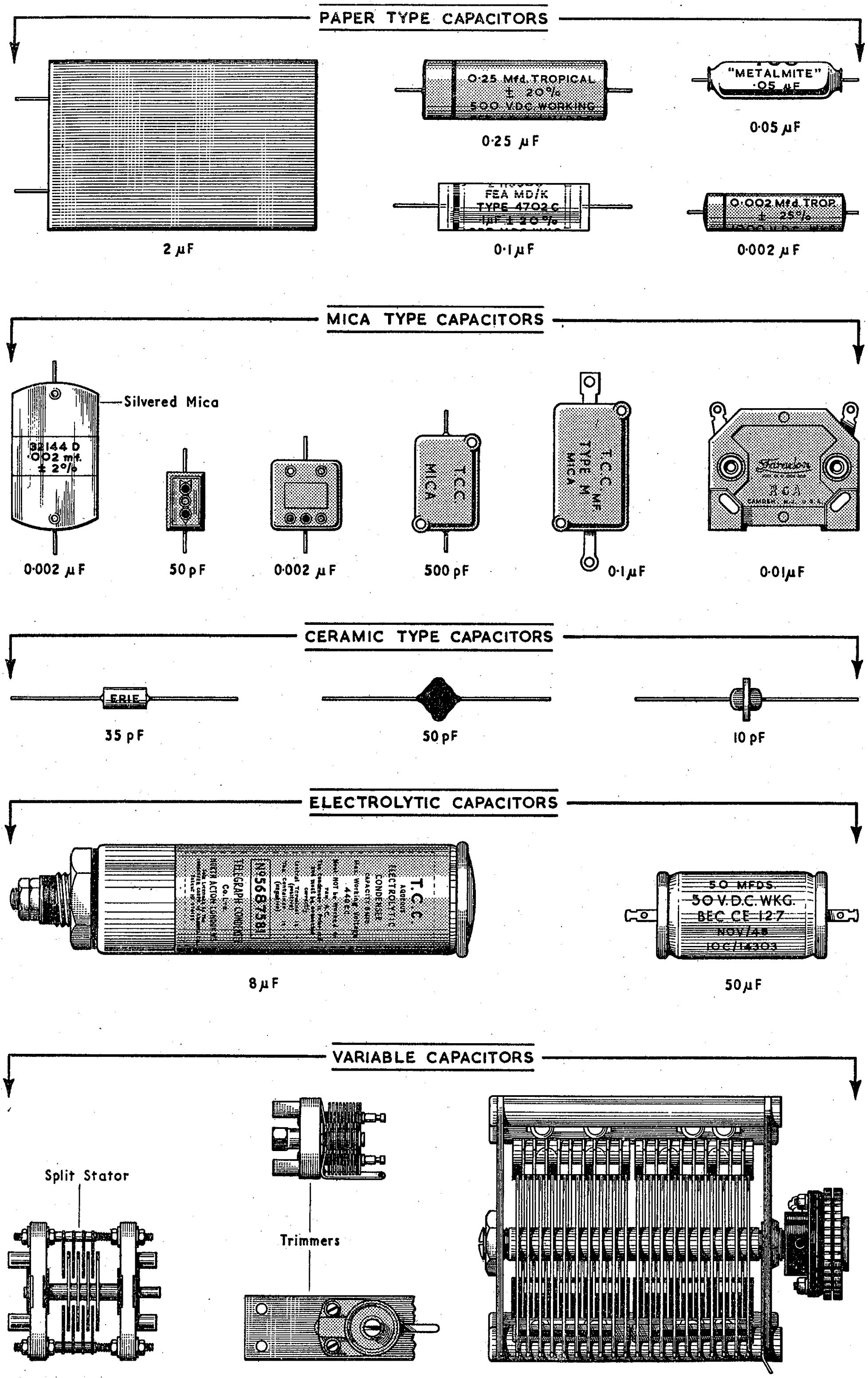

Fig. 14—TYPICAL CAPACITORS USED IN RADIO.

SECTION 4

CHAPTER 3

CAPACITIVE CIRCUITS

Paragraph

CAPACITIVE CIRCUITS

Introduction

1. Fig. 1 shows a capacitor of capacitance C farads connected in series with a resistor of resistance R ohms across a supply of e.m.f. E volts, via a switch.

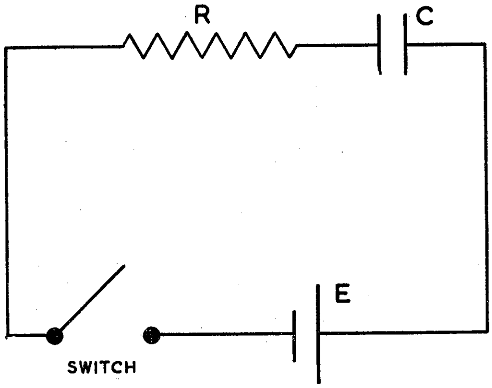

Fig. 1.—CIRCUIT TO SHOW THE CHARGE OF A CAPACITOR.

2. (a) The capacitor is initially uncharged and has zero p.d. across its terminals. From Kirchhoff's second law, on closing the switch, the p.d. across the resistor is E volts, and the current through the resistor $I = \frac{E}{R}$ amps. Thus, at the instant of closing the switch, the instantaneous current i is a maximum, the p.d. across the resistor V_R is a maximum, the p.d. across the capacitor V_C is zero — the sum of the p.d.s across R and across C being at all times equal to the applied voltage. Since the capacitor has no effect at this instant, it can be looked upon initially as a virtual short circuit.

(*b*) With a current established in the circuit, the capacitor is charging and V_C is rising. From Kirchoff's second law:—

$$E = V_R + V_C$$

$$\therefore \quad V_R = E = V_C$$

Thus, V_R is falling; and since $i = \frac{V_R}{R}$, the current in the circuit is falling too.

(*c*) V_C, V_R, and i vary in an *exponential* manner, the process continuing until the capacitor is fully charged; V_C will then equal the supply voltage, and V_R and i will be zero.

Experimental Study of the Charge of a Capacitor

3. The facts stated in Para. 2 can be verified by means of a simple experiment. In the circuit of Fig. 2, C = 2μF, R = 5MΩ, and E = 120V; M_1 is an instrument for measuring the current in micro-amps, and M_2 an instrument for measuring the p.d. across the capacitor in volts. A stop-watch is required to give accurate measurement of time in seconds.

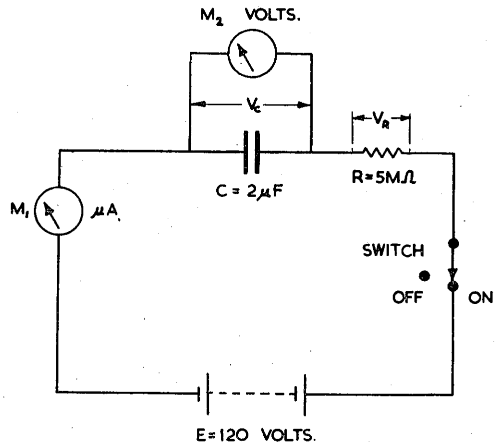

Fig. 2.—CIRCUIT FOR EXPERIMENT.

4. Readings of the current i passing through M_1, and the p.d. across the capacitor V_C (measured by M_2) are taken at intervals of 10 seconds after the closing of the switch. A typical set of readings is given in Table 1, and from these readings the graphs of Fig. 3 and Fig. 4 are plotted.

Time from start of charging (sec)	0	10	20	30	40	50	60
Current i (μ A) ..	24	8·5	3·2	1·2	0·6	0·2	Very small
P.d. V_c (volts) ..	0	76	104	114	117	119	nearly 120

TABLE 1

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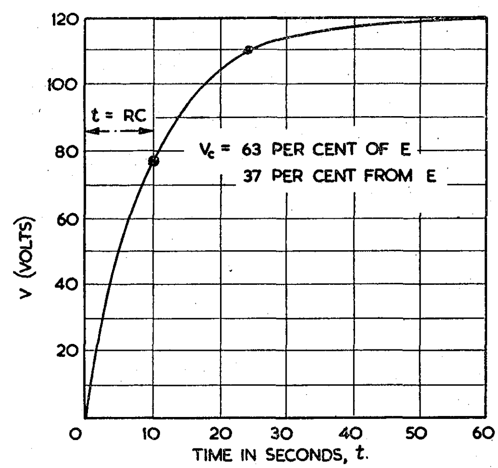

Fig. 3—VARIATION OF V_c DURING CHARGE.

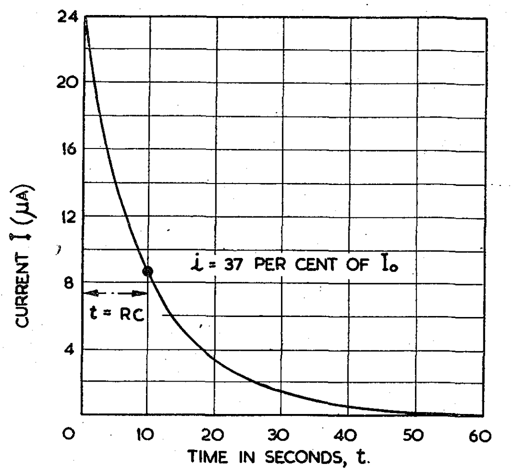

Fig. 4—VARIATION OF i DURING CHARGE.

5. The experiment could be repeated with different values of C and R. It would be found that with a *smaller* value of R, the 2μF capacitor would charge more rapidly. This is to be expected since the initial current $\frac{E}{R}$ would be larger. A similar result would be seen with a *smaller* value of C and the 5 MΩ resistor, for then the total charge required to produce a given voltage across C would be less (Q = CV). Reducing both C and R together would speed up the operation for both these reasons. It is seen that the product CR is what determines the rate of growth of the p.d. across the capacitor and so its rate of charging.

6. It is found that whatever the actual values of C and R in such an experiment, the product CR equals the time in seconds for the voltage across the capacitor to rise to 63·2% of the applied voltage. In the circuit of Fig. 2, $CR = 2 \times 10^{-6} \times 5 \times 10^{6} =$ 10 sec. Thus, in 10 seconds from the start the p.d. across the capacitor V_C rose to 76 volts; this is 63·2% of 120 volts. The figures for the charging current show that after time CR = 10 seconds the current has fallen by 63·2% from 24μA, to about 8·5μA which is 36·8% of the initial value. This quantity CR is termed the *time constant* of the circuit and is defined in full in Para. 16.

General Case of the Charge of a Capacitor

7. Paras. 3 to 6 have dealt with a particular circuit. In the general case, for purposes of accurate calculation, the p.d. across the capacitor at any instant t after closing the switch is given by;—

$$V_C = E\,(1 - \epsilon^{-\frac{t}{CR}}) \text{ (volts)} \quad .. \quad .. \quad (1)$$

where, V_C = the p.d. across the capacitor at any instant

E = the applied voltage

ϵ = Napierian log base = 2·718

t = time in seconds after closing the switch

C = capacitance in farads

R = resistance in ohms

8. (a) From Kirchhoff's second law:—

$$E = V_R + V_C$$

$$\therefore V_R = E - V_C \text{ (volts)} \quad .. \quad .. \quad .. \quad (2)$$

(*b*) From Ohm's law:—

$$i = \frac{V_R}{R} = \frac{E - V_C}{R} \text{ (amps)} \quad .. \quad .. \quad (3)$$

9. A graph can be plotted showing the variation in V_C, V_R or *i* with respect to the time t seconds after closing the switch. There are two ways of doing this:—

(*a*) Repeat the experiment of Paras. 3 to 6. Having obtained the values for V_C and *i*, the corresponding values for V_R follow from equation (2).

(*b*) Insert the values for E, C, and R in equation (1) and thence calculate for V_C at various instants of time t seconds. From equations (2) and (3) respectively, the corresponding values for V_R and *i* can be obtained.

10. In either case, three instants of time are sufficient for most purposes:—

(*a*) *At the instant of closing the switch* (*t = o*)

$V_C = 0 \;:\; V_R = E \;:\; i = \frac{E}{R}$

(*b*) *At t = CR seconds after closing the switch*

$V_C = 0{\cdot}632E \;:\; V_R = 0{\cdot}368E \;:\; i = 0{\cdot}368 \frac{E}{R}$

(*c*) *At t = 5 CR seconds after closing the switch*

$V_C \simeq E \;:\; V_R \simeq 0 \;:\; i \simeq 0$

11. These three instants of time are used to plot the graph showing the exponential rise in the p.d. across the capacitor V_C, and the fall in the p.d. across the resistor V_R against the time t in seconds after closing the switch (Fig. 5). The graph for the current *i* will fall in a manner similar to that for V_R.

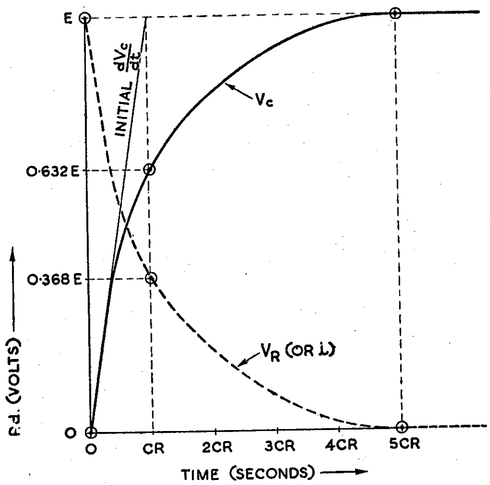

Fig. 5—VARIATION OF V_C AND V_R DURING CHARGE.

Discharge of a Capacitor

12. Consider the circuit shown in Fig. 6. With the circuit switched on, V_C will rise exponentially to its maximum value E volts in a time of approximately 5CR seconds; the p.d. across the resistor and the current in the circuit will both be zero after this time. Assume the capacitor to be now fully charged and the switch put to the off position. The capacitor is now connected across the resistor and will commence to discharge. As soon as the capacitor partly discharges, V_C falls and the current is reduced—i.e., the *rate* of discharge decreases. The curve of the discharge of the capacitor can again

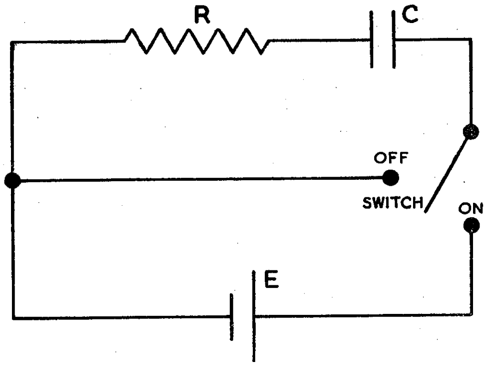

Fig. 6—CIRCUIT TO SHOW THE DISCHARGE OF A CAPACITOR.

be obtained from a simple experiment. A stop-watch is started at the instant of putting the switch to the OFF position and readings of V_C and *i* taken at regular intervals of time. The graphs resulting from such a set of readings will show that the discharge of the capacitor is exponential.

13. (*a*) For purposes of accurate calculation, the p.d. across the capacitor at any instant t after disconnecting the supply is given by:—

$$V_C = E.\epsilon^{-\frac{t}{CR}} \text{ (volts)} \quad \ldots \quad \ldots \quad (4)$$

where all the terms have the same significance as in equation (1).

(*b*) From Kirchhoff's second law, the sum of the p.d.s in the circuit must equal the applied voltage (which is now zero).

$$\therefore V_R + V_C = 0$$

$$\therefore V_R = -V_C \text{ (volts)} \quad \ldots \quad \ldots \quad (5)$$

(*c*) From Ohm's law:—

$$i = \frac{V_R}{R} = -\frac{V_C}{R} \text{(amps)} \ldots \quad \ldots \quad (6)$$

14. A graph van be plotted showing the variation in V_C, V_R, or *i* with respect to the time t seconds after disconnecting the supply. Either of the two methods described in Para. 9 can be used to obtain such a graph and again three instants of time are significant:—

(*a*) *At the instant of disconnecting the supply* (*t = o*)

$V_C = E \;:\; V_R = -E \;:\; i = -\frac{E}{R}$

(*b*) *At t = CR seconds after disconnecting the supply*

$V_C = 0{\cdot}368E \;:\; V_R = -0{\cdot}368E \;:\; i = -0{\cdot}368\frac{E}{R}$

(*c*) *At* t = *5CR seconds after disconnecting the supply*

$V_C \simeq 0$: $V_R \simeq 0$: $i \simeq 0$

15. These three instants of time are used to plot the graph showing the variations in the p.d.s across the capacitor and across the resistor with respect to the time t seconds (Fig. 7). The graph for the current *i* will vary in a manner similar to that for V_R.

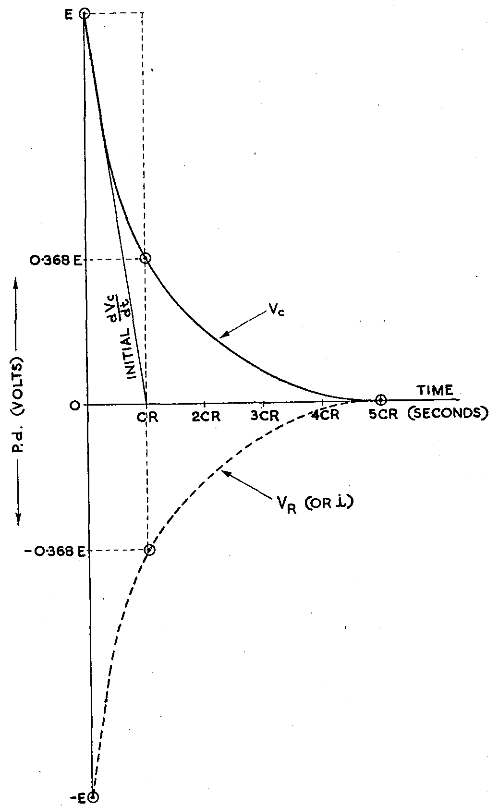

Fig. 7—VARIATION OF V_C AND V_R DURING DISCHARGE.

Time Constant

16. The time t = CR seconds is termed the **time constant** of a capacitive circuit and has been referred to in Para. 6. It is defined as follows:—

The time constant t = CR seconds is the time taken for the p.d. across the capacitor to rise to 63·2% (approximately two-thirds) of its maximum value on charge, or to fall by 63·2% of its maximum value on discharge. Alternately, it is the time taken for the p.d. across the capacitor to rise to its **maximum** *value on charge, or to fall to* **zero** *on discharge, provided the* **initial** *rate of change of voltage is maintained.*

(The latter is shown in the graphs although it cannot apply in practice).

17. In theory, a capacitor would take an infinitely long time to completely charge or discharge. However, after a time of *5CR seconds* the charge or discharge is so nearly complete as to be considered so for practical purposes.

Practical Example

18. In the circuit shown in Fig. 8, C = 2μF, R = 50kΩ, and E = 100V. The circuit is switched on for one second and then switched off. It is required to sketch graphs to indicate how the p.d.s across the capacitor and across the resistor vary with time.

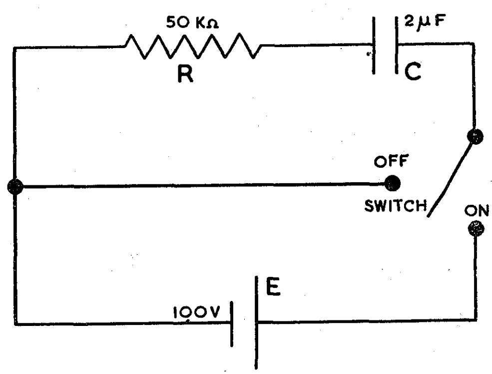

Fig. 8—EXAMPLE.

19. (*a*) The time constant $t = CR = 2 \times 10^{-6} \times 50 \times 10^3 = 0{\cdot}1$ seconds.

(*b*) The p.d.s at the relevant instants of time are given in the table.

	Time (seconds)	0	CR 0·1	5CR 0·5
During charge	V_C (volts) V_R (volts)	0 +100	+63·2 +36·8	+100 0
During discharge	V_C (volts) V_R (volts)	+100 —100	+36·8 —36·8	0 0

(*c*) The required graphs are given in Fig. 9.

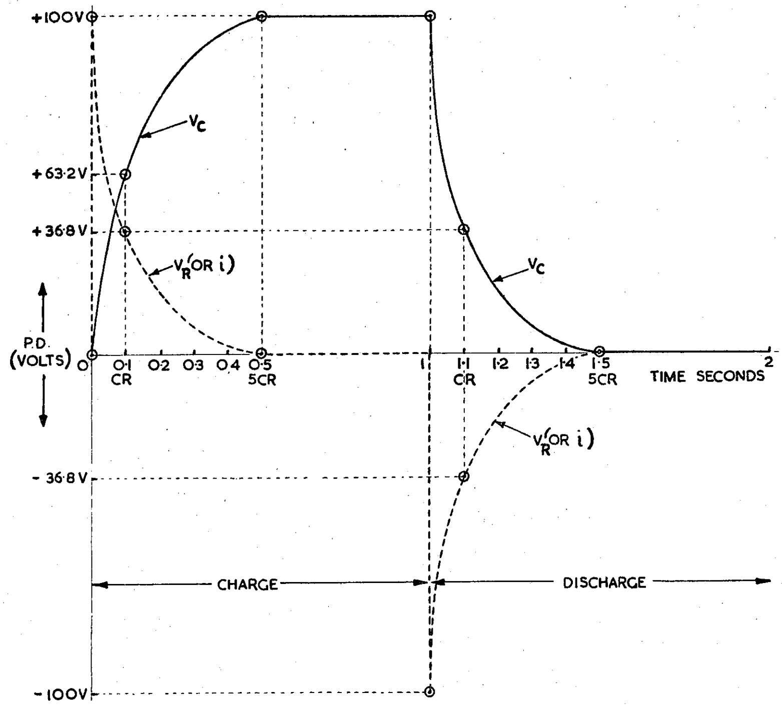

Fig. 9—VARIATION OF V_c AND V_R DURING CHARGE AND DISCHARGE, EXAMPLE.

Square Waves Applied to a Capacitive Circuit

20. The preceeding paragraphs have shown the effect of charging a capacitor from a d.c. supply and then allowing the capacitor to discharge. In some radio circuits it is more important to consider the effect of applying a *square wave* of voltage to a capacitive circuit.

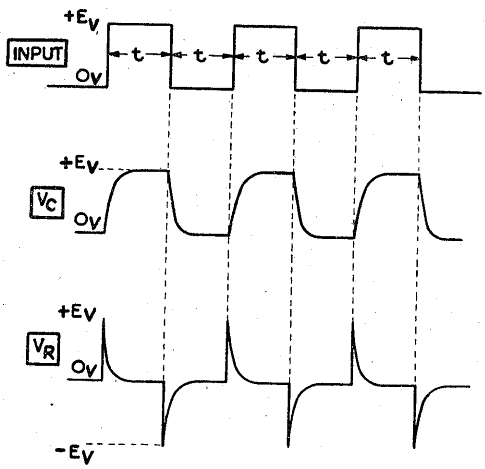

Fig. 10—SQUARE WAVE APPLIED TO A CAPACITIVE CIRCUIT.

21. Consider a capacitor connected in series with a resistor across a square wave input. Provided the time t seconds taken for one half cycle of the square wave input is much *longer* than the time constant of the circuit, the p.d.s across the capacitor and across the resistor will vary in the manner described in Para. 19 and as shown in Fig. 10.

Current Through a Capacitor

22. It has been assumed so far in this Publication that there must be a complete circuit in order that current may flow, yet the dielectric of a capacitor is necessarily an insulator. The process of charging is indicated in Fig. 11, where the charging of the positive plate A is represented by a flow of positive charges towards it. (Really, of course, electrons are led away in the opposite direction, but in terms of conventional current direction the flow of positive charges is considered). A few representative neutral atoms are shown on the other plate B. As positive charges reach A, equal negative charges are *induced* in B, and equal positive charges repelled away from B. That is, during charge, the current flowing away from B is exactly equal to the current flowing towards A, which is just what would happen

if there were a complete circuit. Actual charges do *not* traverse the dielectric; but the electric flux from the charges on A does so and establishes the field between the plates to induce equal and opposite charges on B. There is also a displacement current in the dielectric (see Chap. 2, Para. 4).

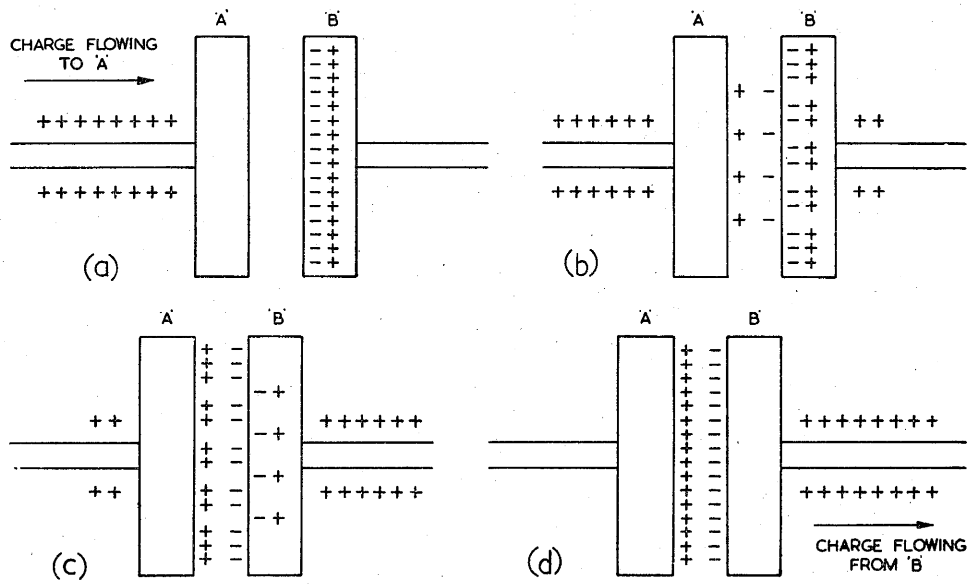

Fig. 11—CURRENT THROUGH A CAPACITOR.