Capacitors and Capacitance

The basic operation and use of capacitors.

Michael J. Cockcroft

The sheer number of different electronic components can make our subject daunting to the beginner. If we consider the complexity of some of these components while trying to understand the basic circuit principles, we are going to get bogged down in confusing detail. This can be avoided by learning here and now that any electronic circuit or component only has one or more of three properties: they have resistance, inductance, capacitance, or a combination of these properties and bearing them in mind when analyzing circuit actions will help to keep electronics simple.

Electrostatics

Electrostatics is the science of electric charges at rest (static electricity) and is fundamental to the study of capacitors and capacitance. The first law of electrostatics is: **Like charges repel; unlike charges attract.**

A force of attraction exists between two bodies of unequal charges and a force of repulsion exists between two bodies of equal charges. This principle can be demonstrated by a simple experiment which produces static electricity: if a balloon is rubbed on woollen clothing (or your hair — especially after it has recently been washed) and touched to a wall, the balloon will attach itself to the wall. This is an example of creating electricity by applying friction energy.

Electrons are dislodged from one material and attached to the other, giving one body (the balloon or the wool) a positive charge and the other a negative charge. The wall is neutral (like all matter under naturally conditions i.e. not under the influence of an external energy) so there is a force of attraction between the two unlike bodies.

This *force* is called an **electric field**; the balloon for example, acquired a field of force around it (the lines of force will, of course, be concentrated around the area of the balloon that was rubbed) after it had been charged by friction. The greater this charge on the balloon, the greater the electric field around it; also, the electric field will disappear when the dogy losses its charge (when it is in its normal neutral state).

An electric field exists between any two different voltages. The direction of the force in an electric field depends on the polarity of the charged body. The direction is away from negative charges and towards positive charges, as shown in Fig. 1a. When two unlike charges are acting upon each other (when they are close enough together, as in Fig. 1b) the negative charge moves towards the positive charge.

With this in mind, consider the simple circuit of Fig. 2 (the "load" resistor represents any component or components as an equivalent resistance). When the switch is open there is no current flow but the battery is charged (the chemicals inside the battery force an accumulation of electrons at one terminal with respect to the other terminal — we call the force acting to convert chemical energy into electrical energy [voltage] an **electromotive force** or EMF).

When the switch is closed the electric field causes electrons in the wire to move away from the negative terminal (where they are repelled by the excess of electrons) of the battery, through the component(s), and back to the positive terminal (where they are forced by a chemical action [electromotive force] back to the negative terminal inside the battery). This movement is repeated again and again around the circuit the whole time that there is enough charge in the battery.

So *current flows from negative to positive*; but be aware that early scientists, from the results of experiments and before a true theory could be formulated, thought that current moved in the opposite direction. We call the early theory, that current flows from positive to negative, *conventional current* and many authors of electronic texts still use it today.

Capacitors and Capacitance

Capacitance exists between any two conductors in close proximity and it is the property of a circuit that causes an electric charge to be stored. Components

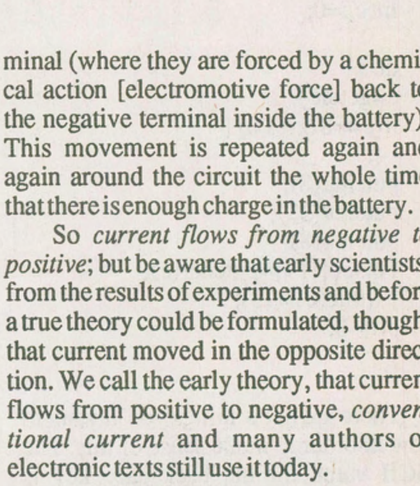


Fig. 1. The electric field.

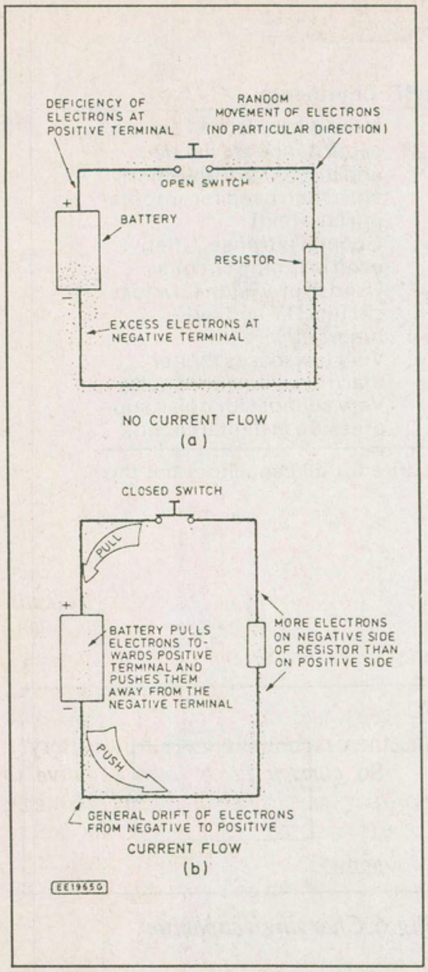


Fig. 2. Electrons in a simple circuit.

manufactured to specific values of capacitance are called *capacitors.*

Capacitors

Capacitors fall into two main groups, the *polarized* capacitor and the *non-polarized* capacitor. Electrolytic and tantalum capacitors are polarized and the correct polarity must be applied to their terminals. If a voltage is applied to the capacitor in the reverse direction the internal insulating layer, which we will talk about in a moment, will break down and short circuit the capacitor. The result will be damage to the capacitor and possibly other components in the circuit.

All polarized capacitors are clearly marked "+" and "-" on the body of the device and care must be taken that these polarities are observed when constructing circuits. Electrolytics, in particular, may explode if connected in reverse polarity to a sufficiently high voltage.

Non-polarized capacitors can be freely placed either way round into a circuit. All capacitors, however, have a maximum voltage rating; they are usually marked with their working voltages and this voltage should never be exceeded, as stated in Part 2.

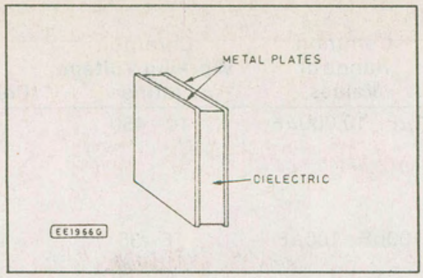


Fig. 3. Basic capacitor.

A capacitor consists of a thin strip of insulating material, known as the *dielectric*, sandwiched between two metal plates, as shown in Fig. 3. The dielectric describes the capacitor type and is often paper, air, mica, polyester or ceramic.

All capacitors have (at least) two plates and a dielectric layer. The use of a variety of dielectrics and the employment of different construction processes yield an assortment of capacitor shapes and sizes (se Table 2.5 — Part 2).

High values of capacitance, in a compact form, can be achieved by rolling or stacking strips of metal foil and dielectric material, as shown in Fig. 4. Sometimes the dielectric is a paste or liquid instead of a solid; electrolyte, in the electrolytic capacitor for example, is a paste. Table 1 gives a small selection of typical capacitors with relevant comments about each (refer to Part 2 for more information including value colour coding).

Variable capacitors are also available. The dielectric in these capacitors is usually air because it is convenient to vary capacitance in variable capacitors by mechanically adjusting the distance between their plates (or the amount of overlap of the plates). The distance between the plates (which is the thickness of the dielectric) is only one of three factors that determine the capacitance of capacitors.

Capacitance of Capacitors

The capacitance value of a capacitor determines the amount of charge it is capable of storing; this depends on the following characteristics of the device: A) the area of the plates; B) the thickness of the dielectric; and C) the material used for the dielectric.

Plate Area

The value of a capacitor determines the amount of charge it is capable of holding. The amount of charge it will hold is directly proportional to the area of its plates; this stands to reason since a larger plate area holds more electrons. Fig. 5a shows that, for two capacitors with the same dielectric material and distance between the plates, the one with the larger plates has the greater capacitance.

Dielectric Thickness

The strength of the electric field between the plates depends on the distance between them; the closer the plates are together the greater the intensity of the field. The distance between the plates is, of course, a function of the thickness of the dielectric. Fig. 5b shows that, for two capacitors with the same dielectric material and plate area,

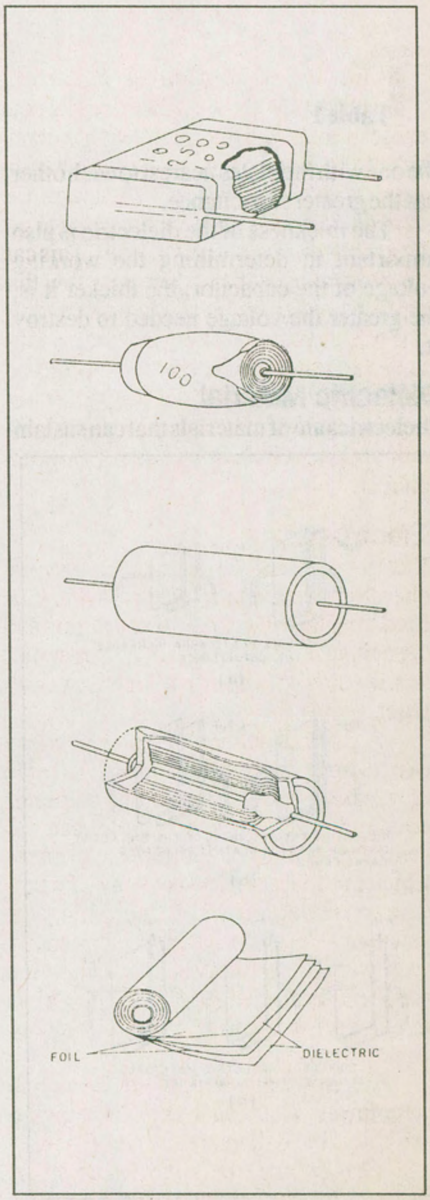
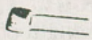
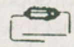


Fig. 4. Construction of capacitors.

Type	Identification	Common Range of Values	Common Working Voltage ratings	Polarised?	Comments
Electrolytic		1μF−10,000μF	10−450	Yes	Used where large values of capacitance are needed and losses *are unimportant. Often used for smoothing (see text)
Tantalum		100nF−100μF	6−35	Yes	General purpose. Often used in timing circuits
Mica (silvered)		2pF−10nF	350	No	Used in precision (low loss) circuits (TV and radio tuners etc)
Polystyrene		10pF−10nF	Up to 500	No	Very low losses (better than mica) but more bulky
Ceramic		10pF−100nF	1000V d.c. 300V a.c.	No	Very suitable for noise suppression in digital circuits

*A proportion of the energy supplied to a capacitor is lost in the dielectric. This is true for all capacitors but the amount of loss varies with the dielectric material.

Table 1

the one with the plates nearest to each other has the greater capacitance.

The thickness of the dielectric is also important in determining the working voltage of the capacitor; the thicker it is, the greater the voltage needed to destroy it.

Dielectric Material

Dielectrics are of materials that can sustain strong electric fields without breaking down. A measure of this strength is termed the *dielectric constant*. The greater the dielectric constant, the better the dielectric.

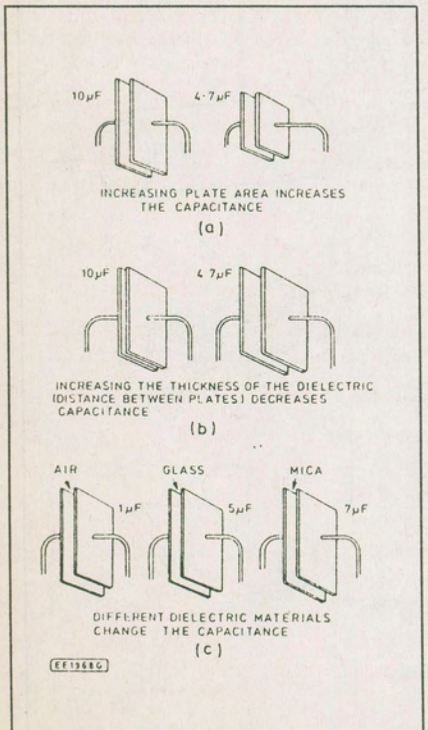


Fig. 5. Variation of capacitance with dimensions of a capacitor.

Dry air has a dielectric constant of 1, glass about 5, and mica about 7. The higher the dielectric constant for the same plate area, the greater the capacitance; for example, a 1uF air capacitor would become 7uF if a mica dielectric were placed between its plates, and 5uF for a glass dielectric. Fig. 5c shows that, for three capacitors with the same dielectric thickness and plate area, the values vary according to the dielectric constants of the different dielectric materials.

Unit of Capacitance

A capacitor holds (stores) electric charge, rather like a bucket holds water. The amount of charge it stores depends on the capacitance value (in farads) of the capacitor and the size of the voltage used to charge it. Charge (symbol Q) is a quantity of electricity, the elementary particles of which are protons and electrons. Since the charge on an electron (or proton) is very small, charge is measured in *coulombs* (symbol C); one coulomb is equal to 6.29×10^{18} electrons.

A capacitor is "charged" by connecting it to a voltage source, as shown in Fig. 6. The amount of charge acquired by the capacitor can be defined as follows:

A capacitor has a capacitance of one farad if a charge of one coulomb raises the potential difference by one volt.

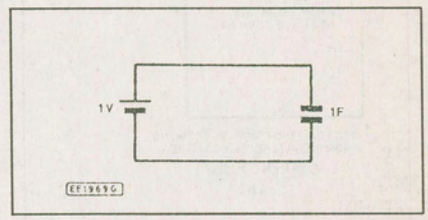


Fig. 6. Charging a capacitor.

This means that for a one farad capacitor connected to a one volt DC source, as shown in Fig. 6, the capacitor will acquire a charge of one coulomb (i.e. 6,290,000,000,000,000,000 more electrons on one plate than on the other plate). So, for any given capacitor:

Capacitance = Charge/Voltage, ie, C=Q/V

Illustrative Example

What is the charge on a 100u capacitor connected across a supply of 10V DC?

$C=Q/V \quad CV=QV/V$

$Q=CV=10 \times 100 \times 10^{-6}$

$=1000 \times 10^{-6}=1 \times 10^{-3}$

Therefore Charge (Q)=1mC (one milli-coulomb)

Capacitors in Parallel

Total capacitance in a circuit containing capacitors in parallel is the sum of all the individual capacitors:

$$C_t=C_1+C_3...+C_n$$

This is easy to understand because

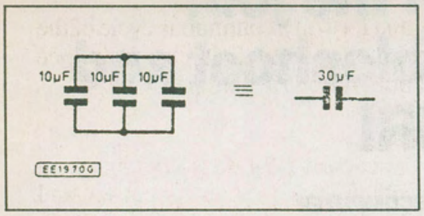


Fig. 7. Capacitors in parallel.

adding capacitors is the same as increasing the plate area and, as we have just seen, an increase in plate area increases the value of the capacitor. Fig. 7 demonstrates that adding three 10u capacitors connected in parallel produces an equivalent 30u capacitance.

Care should be taken, when increasing a particular value of capacitance by connecting capacitors in parallel, not to reduce the working voltage of the combination below the required value. The working voltage of the combination will be the rating of the capacitor having the lowest working voltage; for example, a 47u capacitor with a working voltage of 6.3 volts and a 10u capacitor with a working voltage of 100 volts connected in parallel have a maximum working voltage of 6.3 volts for the combination.

Capacitors in Series

Connecting capacitors in *series* reduces the total capacitance in the same way that connecting resistors in *parallel* reduces

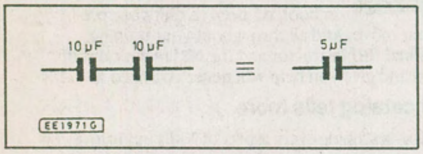


Fig. 8. Capacitors in series.

the total resistance (Fig. 8). So the formula for calculating the equivalent capacitance of series capacitors is similar to the formula for finding the equivalent resistance of parallel resistors:

$$C_t = 1/(1/C_1 + 1/C_2...etc)$$

The expression can be simplified by using the "product over the sum" process when there are only two capacitors:

$$C_t = (C_1 \times C_2)/(C_1 + C_2)$$

The maximum working voltage for a combination of series connected capacitors will be greater than any one of the voltage ratings of the individual capacitors; for example, for a couple of 10u capacitors each with a 10 volt working voltage rating (connected in series to make an equivalent 5u capacitor), the equivalent safe working voltage for the combination will be 20 volts.

Capacitors and DC

When a capacitor is first connected to a DC power supply, current flows in the circuit until the capacitor is fully charged (it is fully charged when the voltage across the plates is equal to the supply voltage) and then current stops. The fact that current flows at all may be a bit of a surprise; after all, the capacitor sits in the circuit rather like an open switch, particularly if the

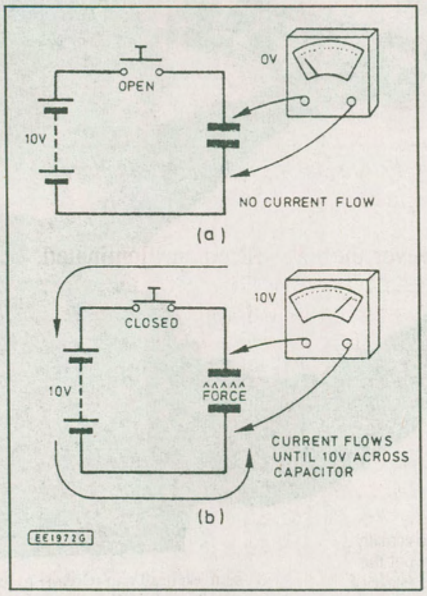


Fig. 9. Voltage across a capacitor.

dielectric of the capacitor is air.

Actually, open switch contacts do act like a capacitor but the distance between the contacts is so great (remember — the closer the capacitor plates are to each other, the greater the capacitance) the capacitance is negligible.

Consider the diagram of Fig. 9a. While the switch is open there is no voltage across the plates of the capacitor. When the switch is closed current flows, rapidly at first, in the direction of the arrows shown in Fig. 9b; current continues to flow, but diminishing all the time, until the capacitor is charged to the same level as the battery when current stops. How long it takes for the capacitor to charge is a period of time which is determined by the value of the capacitor and the resistance in the circuit (in this case, the resistance of the battery, connecting wires and component leads); we will come to this a little later.

Current flows because electrons from the top capacitor plate are attracted to the positive terminal of the battery (unlike charges attract), pushed towards the negative terminal inside the battery (by electromotive force), and repelled from the negative terminal to the bottom plate of the capacitor (like charges repel). An excess of electrons then exists on the bottom plate, giving a potential difference equal to the supply voltage across the two plates as the current ceases to flow.

The electrons belonging to the top capacitor plate are now on the bottom plate and they cannot return whence they came because of the insulating properties of the dielectric. An electrostatic field with a force equal to the supply voltage is now acting inside the capacitor; Fig. 10 shows how the unlike charges of the protons and electrons from the two plates line up in the electrostatic field, attempting to move together to equalize the charges. This force field remains even when the switch is opened or the capacitor is removed from the circuit; hence the capacitor is referred to as a storage device.

The capacitor can be discharged by

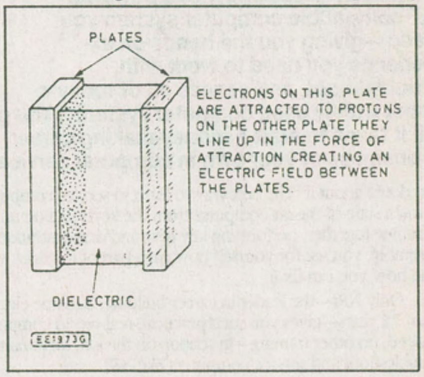


Fig. 10. Electrons in a charged capacitor.

providing a conductive path between the two plates, as shown in Fig. 11, allowing the excess electrons to bypass the dielectric and return to the plate from which they originally came. Fig. 12 shows a s.p.d.t. switch configured to charge the capacitor, through a resistor, in one position and discharge it, again through the resistor, in the other position.

In this circuit the capacitor charges or discharges, depending on the switch position, through the same resistance — the value of R — (the resistance in the battery and the wires is so small it can be ignored) so the time taken for both charge and discharge is the same.

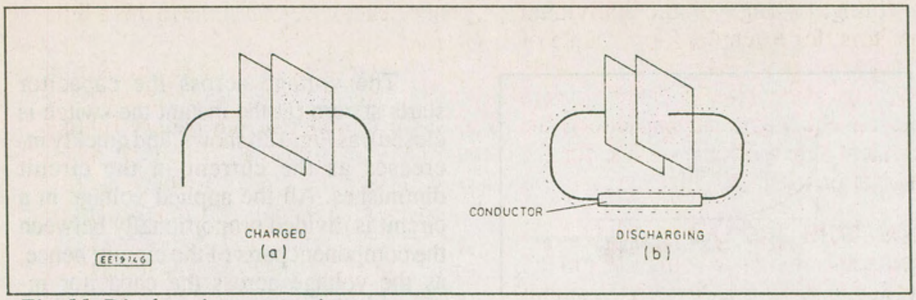


Fig. 11. Discharging a capacitor.

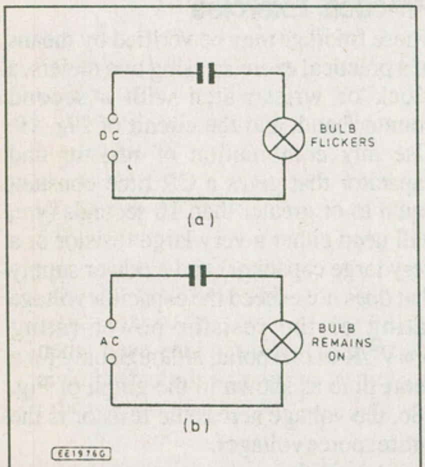


Fig. 12. Capacitors in AC and DC circuits.

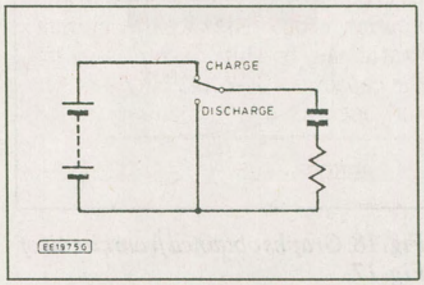


Fig. 12. Circuit to charge and discharge a capacitor.

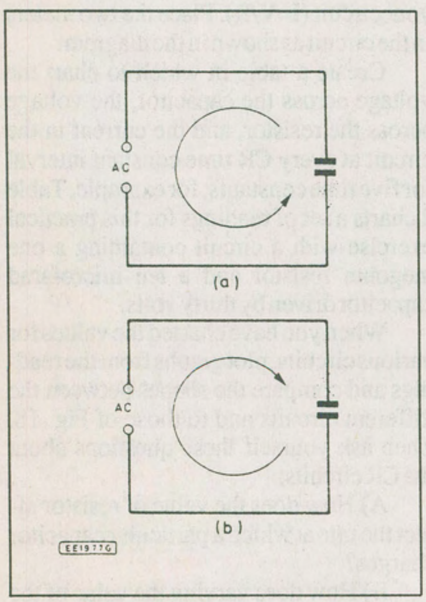


Fig. 14. Electrons in an AC circuit.

Capacitors and AC

When a DC voltage is applied to the circuit of Fig. 13a, the bulb just flickers as a result of the transient current. When an AC voltage is applied to the same circuit (Fig. 13b), however, the bulb will remain illuminated. Alternating current flows continuously in an AC circuit. It is important to realize, though, that current does *not* flow *through* the capacitor — it cannot because of the dielectric between the plates.

In fact, as illustrated in Fig. 14, current flows into the capacitor (to charge it — electrons accumulate on one plate) during one half cycle and out of the capacitor (to discharge it in the opposite direction, (electrons accumulate on the other plate) during the other half cycle. It does this repeatedly for as long as the AC supply is present.

The capacitor is first charged positively and then discharged to zero volts, then it is charged negatively followed by being discharged back to zero again. So, as Fig. 14 shows, electrons repeatedly flow back and forth in a continuous cycle of the capacitor trying to first charge in one direction and then in the other.

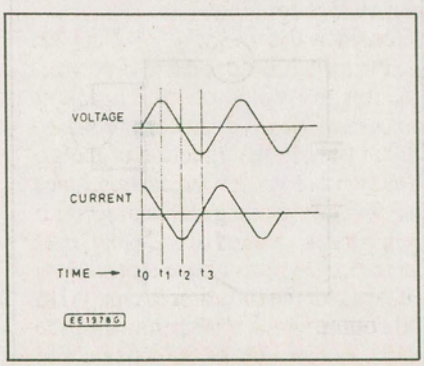


Fig. 15. Voltage and current in Fig. 14 circuit.

Phase

But the current flow does not change in step with the voltage (we say current and voltage are out of phase in a capacitor circuit), as illustrated in the graph of Fig. 15. At the instant AC is applied, the voltage starts to rise in the positive direction. As the supply voltage increases, the capacitor charges, the voltage across it gets closer to the supply voltage and current decreases accordingly. At time t_1 the capacitor is charged to the maximum value and current is zero.

As the supply voltage decrease the capacitor discharges and, at time t_2, the power supply voltage is zero and current has taken a maximum negative value. The current continues to flow but diminishes as the voltage builds up in the negative direction. When the supply voltage has reached its maximum in the negative direction (at t_3) the capacitor has again become fully charged and current has dropped to zero. It can be seen from the graph that current is a quarter of a cycle (90°) ahead of the supply voltage.

CR Time Constant

The time taken for capacitors to either charge or discharge through a resistance is measured in terms of *capacitance-resistance time constants* (usually abbreviated to CR time constants). The CR time constant is the time taken to charge any value capacitor to a voltage equal to 63.2 percent of the final fully charged voltage or discharge a capacitor to 36.8 percent of the original fully charged voltage. The time constant (T) of a CR circuit is: $T = C \times R$.

A capacitor charges to 63.2 percent of its final value in one CR time constant so, for example, a 10u capacitor charged through a 10k resistor from a 10 volt source would have 6.32 volts ((63.2 x 10)/100=6.32) across its plates 100 milliseconds $(10^{-3} \times 10^{4}=10^{-1}=0.1$ sec=100ms) after power was applied to the circuit. For the same CR circuit, the same time constant (100ms) applies for discharging the capacitor of 3.68 volts. Capacitor charge and discharge times are shown graphically, in terms of CR time constants and voltage, in Fig. 16.

It can be seen from these graphs that it takes about five CR time constants to completely charge or discharge a capacitor; we have to decide on a voltage very close to the supply because theoretically, as

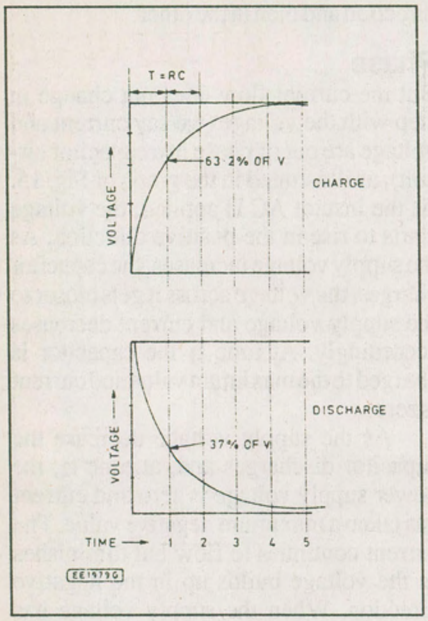


Fig. 16. RC charge and discharge graphs.

shown by the graphs, the capacitor never quite completes the charging or discharging process. We say, as a rule of thumb, that it takes five CR time constants to complete the process.

The subject of the time constant equation can be changed to determine the value of either the resistor or capacitor for the required time constant:

R=T/C and C=T/R

Illustrative Example

What capacitor must be used with a 500 ohm resistor for a 50ms time constant?

$C=T/R=0.1 \times 10^{-3}$ or 100u.

What resistor must be used with a 10n capacitor for 100us time constant?

$R=T/C=10 \times 10^{3}$ or 10k.

We have looked, above, at how the capacitor works with respect to current flow in the process of storing a charge, and at the charge and discharge of capacitors in time constants. Now let us look a little closer at what happens with respect to current and voltage in a CR circuit. Fig. 17 shows a capacitor and resistor connected in series across a battery supply via an SPST. switch. The capacitor is initially uncharged with zero volts across its plates.

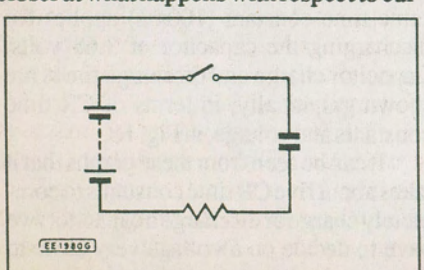


Fig. 17. Simple test circuit.

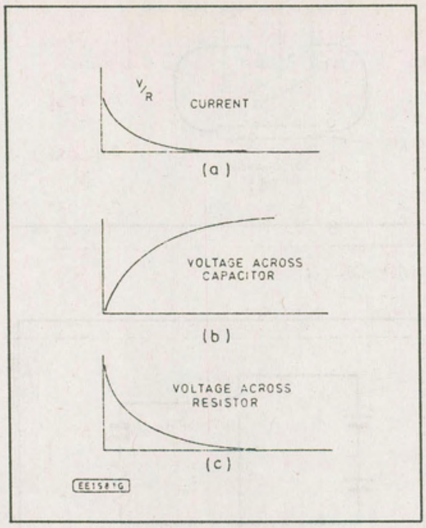


Fig. 18. Graphs obtained from circuit of Fig. 17.

If we measured the voltage across the resistor and the current through it, and the voltage across the capacitor at regular intervals throughout the time that the transient current flows (i.e. the time it takes for the capacitor to charge up), the whole picture may be represented by the three graphs of Fig. 18. Current would vary throughout the transient period as shown in Fig. 18a: at the instant the switch is closed the current will be at its maximum value (V/R) and then fall quickly over the period to zero as the capacitor becomes charged.

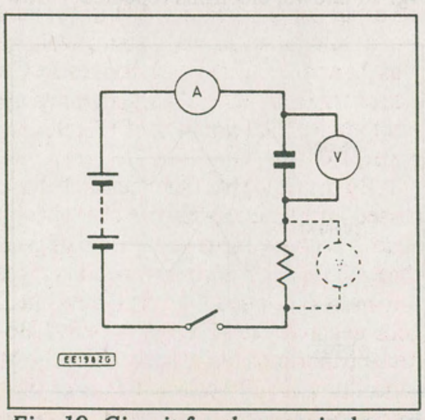


Fig. 19. Circuit for the practical exercise.

The voltage across the capacitor starts at zero (at the instant the switch is closed), as Fig. 18b shows, and quickly increases as the current in the circuit diminishes. All the applied voltage in a circuit is divided proportionally between the component parts of the circuit; hence, as the voltage across the capacitor increases, the voltage across the resistor falls, as shown in Fig. 18c.

Practical Exercise

These findings may be verified by means of a practical exercise using two meters, a clock or wrist-watch with a second counter/hand, and the circuit of Fig. 19. Use any combination of resistor and capacitor that gives a CR time constant equal to or greater than 10 seconds (you will need either a very large resistor or a very large capacitor) and a power supply that does not exceed the capacitor voltage rating or the resistor power rating ($P=V^2/R$-at one point, although only for a short time as shown in the graph of Fig. 18c, the voltage across the resistor is the entire source voltage).

Adjust the voltmeter range to a setting greater than the supply voltage and the ammeter to a setting greater than the supply voltage divided by the resistor in your circuit (I=V/R). Place the two meters in the circuit as shown in the diagram.

Create a table in which to chart the voltage across the capacitor, the voltage across the resistor, and the current in the circuit at every CR time constant interval for five time constants; for example, Table 2 charts a set of readings for this practical exercise with a circuit containing a one megohm resistor and a ten microfarad capacitor driven by thirty volts.

When you have charted the values for various circuits, plot graphs from the readings and compare the shapes between the different circuits and to those of Fig. 18. Then ask yourself these questions about the CR circuits:

A) How does the value of resistor affect the rate at which a particular capacitor charges?

B) How does varying the value of the capacitor affect the rate at which it charges when the resistor value is constant?

C) What percentage of the total supply voltage is dropped across the capacitor in the first CR time constant?

D) What percentage of the total supply voltage is dropped across the resistor in the first CR time constant?

E) What is the relationship between the voltage dropped across the capacitor

		CR TIME CONSTANTS				
		1st	2nd	3rd	4th	5th
Time (seconds)	0	10	20	30	40	50
Current (microamps)	30	11	6	2	1	Almost zero
Voltage across capacitor	0	19	26	28	29	Almost 30
Voltage across resistor	30	11	6	2	1	Almost zero

V=30V: C=10μF: R=1MΩ: CR=10 sec:

Table 2.

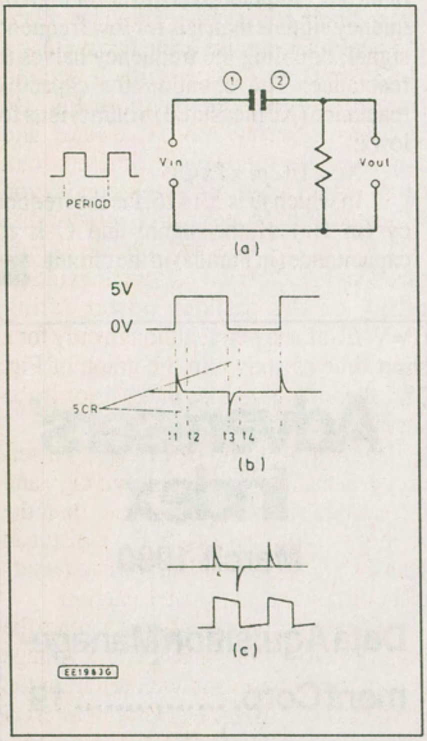


Fig. 20. Response of the circuit to a square wave.

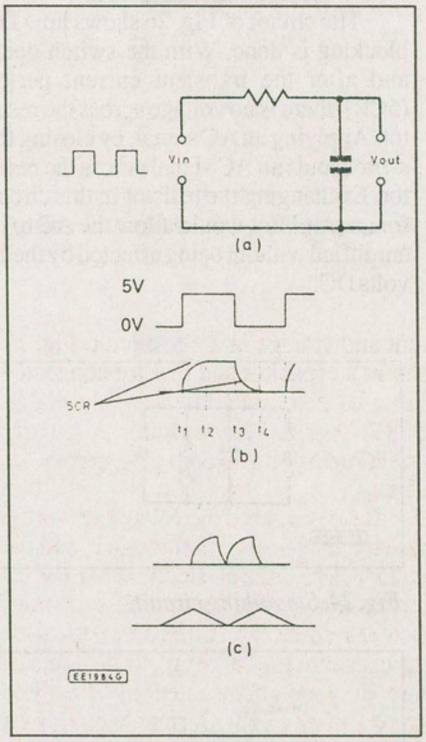


Fig. 21. Response of the circuit to ta square wave.

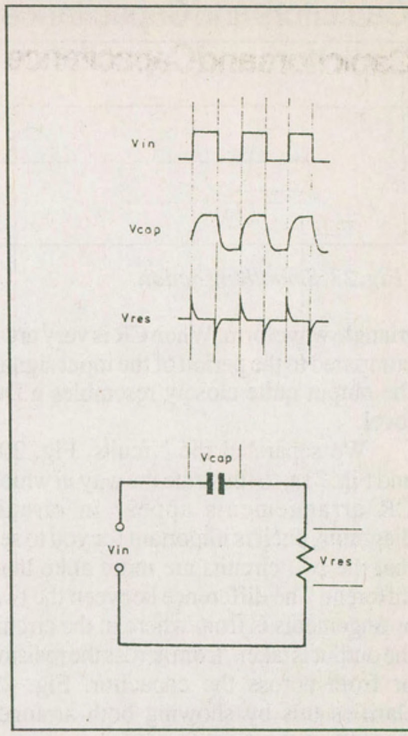


Fig. 22. Voltage graphs in a simple circuit.

and the voltage dropped across the resistor?

F) What happens to current in the circuit when the voltage across the capacitor is at a maximum?

G) What happens to current in the circuit when the voltage across the resistor is at a maximum?

CR Response to Digital Signals

Now that we have the concept of the CR time constant under our belts, we can look at the transient response of CR circuits to signals which are more likely to appear in digital circuits. We will analyze the response of the circuits in Fig. 20 and 21 to the input of a square wave.

Applying a square wave to the input of the circuit (a) in Fig. 20 produces an output looking like the graph in (b). When the input goes to +5 volts at time t_1, plate 2 of the capacitor also goes to +5 volts (current is at its maximum so all the source voltage must be across the resistor): it takes 5 x C x R to charge up — in the charged state plate 1 of the capacitor would be at +5 volts and plate 2 at 0 volts.

By the time five time constants have passed (at t_2) the capacitor is charged and plate 2 becomes zero volts; it remains at zero volts until the square wave changes to zero volts at t_3 when the voltage at plate 2 goes negative (to -5 volts — why? Because at the time immediately before t_3 the capacitor was fully charged, it takes time for it to discharge so 5 volts worth of negative charge piles onto plate 2 at the instant t_3). It discharges five time constants later (t_4). And so on at each transition from 0 volts to 5 volts and back again.

The waveforms in Fig. 20c show how the value of the CR time constant compared to the period of the input waveform change the shape of the output. The shorter the CR time is, compared to the period of the input, the more spiky will be the output. For CR times much greater than the period of the input, the shape of the output closely resembles the shape of the input.

Applying the same square wave to the input of the circuit in Fig. 21 (where, compared to Fig. 20 the positions of the resistor and capacitor have been reversed) produces an output looking like that in (b) of the same figure. At time t_1 the capacitor starts to charge through the resistor, taking five time constants to reach 5 volts (at t_2). The capacitor remains charged until t_3 when the input changes from 5 volts to 0 volts; from this time it takes five time constants to discharge back to zero at t_4. And so on at each transition from 0 volts to 5 volts and back again.

The wave shapes for time constants greater than and shorter than the period of the input waveform are shown in Fig. 21c. When CR is shorter than the period of the input waveform, the output is a rounded

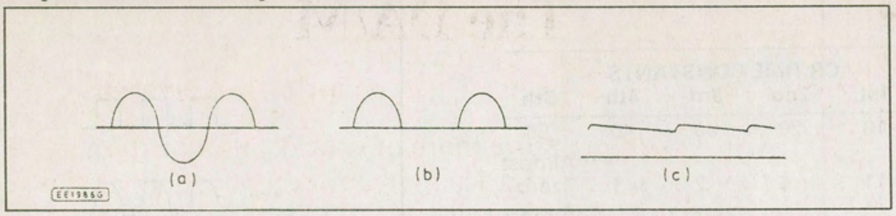


Fig. 23. Smoothing action.

triangle waveform. When CR is very great compared to the period of the input signal, the output quite closely resembles a DC level.

We separated the circuits, Fig. 20a and Fig. 21a, to illustrate the way in which CR arrangements appear in circuit diagrams, but it is important for you to see that the two circuits are more alike than different. The difference between the two arrangements is from where in the circuit the output is taken, from across the resistor or from across the capacitor. Fig. 22 clarifies this by showing both arrangements from the same circuits.

It can be seen from the foregoing examination that the ability of such circuits to change the shape of the signal can be used to great advantage in some applications. An application of particular interest to us, in this course, is that of "smoothing".

Smoothing

Smoothing is an application of the above ideas used in mains derived DC power supply circuits. The smoothing capacitor is used in the process of converting AC into DC. We do not go into detail here but the stages involved in a simple AC to DC conversion are outlined in Fig. 23.

First the negative half cycle of the AC signal (a) has to be removed to produce a signal like that in (b). This is a pulsating DC and not *smooth* enough for most applications. The easiest way of smoothing out the pulses is by feeding the signal into a capacitor (as shown in Fig. 24) to produce a DC output something like that in Fig. 23c. This DC voltage still fluctuates but it is acceptable for many applications.

The smoothing capacitor works by holding the charge (or only discharging a little) between one input pulse and the next, as illustrated in Fig. 25. The larger the capacitor, the longer it holds the charge and the smoother the DC signal becomes.

Blocking

Blocking is used in applications where AC and DC voltages are both present in the same circuit. An amplifier, for example, has both types of voltage and often requires just the AC signal to be amplified; the DC voltage must be *blocked*.

The circuit of Fig. 26 shows how DC blocking is done. With the switch open, and after the transient current period (5CR), there is no voltage across the resistor. Applying an AC signal, by closing the switch, puts an AC signal across the resistor. Exchanging the resistor in this circuit for an amplifier would allow the AC to be amplified without being affected by the 10 volts DC.

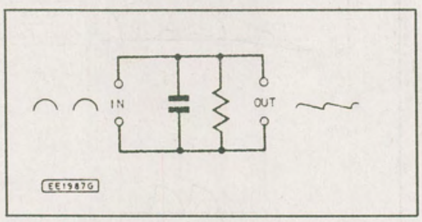


Fig. 24. Smoothing circuit.

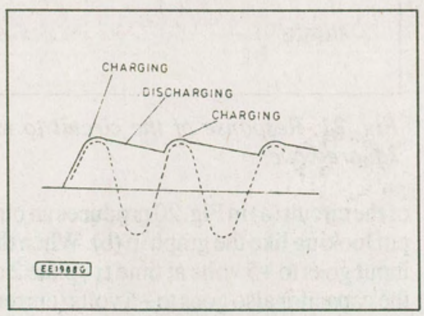


Fig. 25. Illustration of smoothing.

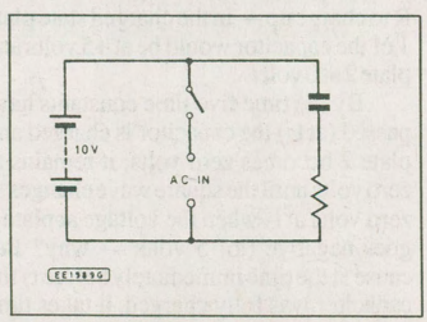


Fig. 26. Illustration for blocking.

Reactance

Before we leave the subject of capacitors and capacitance we should mention a property called *reactance*. Reactance is a sort of resistance that only affects capacitive (and inductive) AC circuits; for example, replacing the capacitor in the circuit of Fig. 13b by a wire link would cause the bulb to get brighter — this means that more current would flow so the capacitor must have a resistance to AC.

Reactance, unlike resistance, is not a constant — it changes with the frequency of the AC. Reactance is lower for high frequency signals than it is for low frequency signal; doubling the frequency halves the reactance. The equation for capacitive reactance (Xc measured in ohms) is as follows:

$X_c = 1/(2\pi \times f \times C)$

In which *pi* is 3.1416, f is the frequency (in Hz) of the signal and C is the capacitance (in Farads) in the circuit. ■

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