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1

BASIC ELECTRICAL PRINCIPLE AND COMPONENTS

Prerequisite knowledge

✓ Current electricity of +2 standard
✓ Static electricity of +2 standard

1.1 Introduction

The recorded observations related to various electrical events and facts are found dating back to the fifth century BC. The lighting in a stormy night, or the attraction between a rubbed amber and cat's fur have always provoked human curiosity. But, it was merely a subject of the philosopher's mind, rather than the business of technology. It was only in the mid-sixteenth century that scientists developed techniques to store electrical charge. Suddenly, like a flash of thunder, everything was changed. We were able to convert a spontaneous event into a continuous operation. The technology had shifted from the era of the mechanical intentions to the era of electrical progression. We can call it a paradigm shift of technology.

Like any other paradigm shift, this change did not occur overnight. We have achieved the great electrical inventions through gradual efforts by scientists. Different theories and formulae had made it possible. In this chapter, we are going to discuss these preliminary concepts and related theories to begin with, starting with static electrical charges to laws of current electricity. We shall also observe that the application of these theories requires a great deal of measurement and quantification of various electrical parameters, such as electrical potential, current flow and resistance. Let us explore this world of electricity from the perspective of an electrical engineer.

1.2 Charge

Electrical charge is the fundamental concept of electricity. In a mechanical system 'the matter' matters, for an electrical system the charge takes all the charges. We conceptualize our materialistic world as an accumulation of particles. In the electrical domain, it is the charge of a particle; we are more concerned about it.

Every atom is constituted of a number of charges. There are two types of charges which play major roles in electricity. To distinguish these 'two types', let us call one as 'positive charge' the other one as 'negative charge'. The major distinguishable feature of the negative charge is that they are mobile. These can be easily transmitted from one atom to another while the positive counter part is heavy, stable and tightly bound to a small region of the atom called the nucleus. These negatively charged particles inside an atom are known as electrons and the positive ones are known as protons. In the most stable state, an atom possesses equal numbers of proton and electron. This equality of positive and negative amounts of charges null each other's effect and make an atom electrically neutral. Electrons can jump from one atom to another. This restlessness of charges creates electron inequality and hence unstability results in an atom. This leads to presence of an excess electron in one atom and a lack of electron in another. The atom with excess electrons has more negative charges than positive charges. We call it a positive ion or positively charged atom. Likewise, the atom with less negative charges is called negative ion or negatively charged atom.

We quantify the electric charge by the unit Coulomb. The charge may be either positive or negative. We must mention the positive Coulomb or negative Coulomb accordingly.

The charge of $6.241509324 \times 10^{18}$ number of electrons is considered to be one negative Coulomb. The amount of negative charge of an electron is equal to the amount of positive charge of a proton. Thus, the same numbers (i.e., $6.241509324 \times 10^{18}$) of protons are needed to get one positive Coulomb.

Applying unitary method we get the charge of one electron as $1.60217657 \times 10^{-19}$C (negative).

1.3 Electric Potential or Voltage

A negative charge attracts positive charge. Two negative charges or two positive charges repulse each other. This is the fundamental law of electricity. This attractive and repulsive force between two charges was qualified and quantified by Coulomb in his laws of electric field. Coulomb's law is to be discussed in later chapter of the book.

Now, whenever there is a charge, there will be an electrical field surrounding it also. If the charge is positive we need to overcome the repulsive force to bring any other positive unit charge to any point of the said electric field. In other words, we need to do some amount of work for that, where as if the charge is negative then a positive unit charge will be attracted by the field and itself will do some work.

We define the electric potential at any point as the amount potential at any point as the amount of work done needed to bring a positive unit charge from infinity to that point. According to our previous discussion, the potential has to be positive for positive charge and negative for negative charge.

The unit of potential is Volt. If we need 1 Joule of work done to bring 1 Coulomb charge from infinity to a particular point, then the electric potential of that point is 1 Volt.

1.4 Electric Current

Suppose we have two points A and B having electric potential V_A and V_B. Let there be a media in which point A and B are situated. If $V_A > V_B$, it is obvious that the electrons of the media will be attracted towards A and repelled by the negative potential at B.

Some media have loosely attached electrons known as free electron. These free electrons can be made free by electric field between A and B. So there will be a net drift velocity of electron from B to A. This is equivalent to positive charge flow from A to B. The rate of change of positive charge in a particular direction is called the current flow. The current flow continues till the potential of both the points become equal. The accumulation of electron at A and loss of electron at B makes $V_A = V_B$. This phenomenon is known as current medium electricity and this type of medium is called conductor.

As we have discussed earlier the current can be expressed as below:

$$I = \frac{dq}{dt} \qquad \text{.......... 1.1}$$

where q is the positive charge.

From the discussion so far, we can conclude that if two points A and B are connected via a conductor, the current will flow. But this flow of current is merely a transient phenomenon. Very quickly both A and B will be at same voltage level and current will stop flowing. To get a continuous current flow we must have a continuous potential difference between points A and B.

In 1800, physicist Alessandro Volta invented electric cell by which we were able to maintain a continuous voltage difference between two leads of the cell. Thus, we get current flow for a considerable time.

1.5 Alternating Current: Amplitude, Frequency and Phase

In the third decade of nineteenth century electro magnetic generators had taken over the electric cells. Generators can create the potential difference for a long period of time. But the potential difference in the case varies periodically with time.

In the closest assumption the voltage varies periodically with a sine function with respect to time. i.e.

$$V = V_0 \text{ Sin } \omega t \qquad \text{.......... 1.2}$$

If we represent that graphically we shall get where ω is the angular frequency, (rad/sec).

Thus, the frequency of the voltage $f = 2\pi\omega$.

The peak value or maximum value of voltage is V_0.

Such voltage was as depicted is Fig. 1.1 may have same frequency but a difference in phase. Say we have two simosoidal waves A and B. These are having same frequency but A is reaching to its peak value before B attains its peak value by

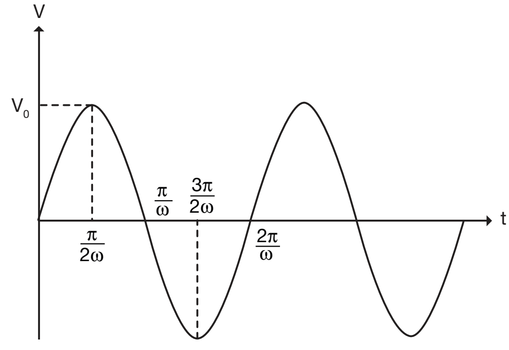

Fig. 1.1: Sinusoidal voltage wave

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a time $\frac{\phi}{\omega}$ or by a phase angle ϕ, here Fig 1.2 explains this case

We can write the both waves mathematically as;

$$V_A = V_{AO} \text{ Sin } \omega t \qquad \text{.......... 1.3}$$

and $$V_B = V_{BO} \text{ Sin } (\omega t - \phi) \qquad \text{.......... 1.4}$$

in this case V_B is lagging behind V_B by phase angle ϕ.

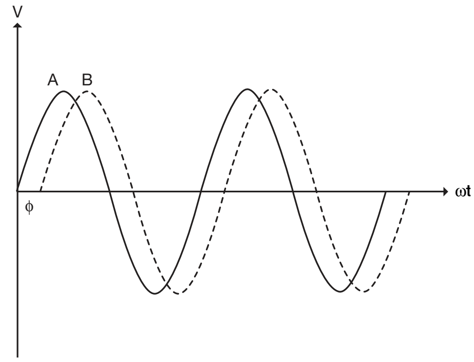

Fig. 1.2: Phase shifted wave

1.6 Ohm's Law: Resistance

In 1826, German Physicist George Ohm observed that the current flow through a wire is directly proportional to the potential difference at the two ends of it. Hence, he proposed a famous law named after his name as Ohm's law of electricity. The law is stated as:

> *The current flowing through a conductor is directly proportional to the potential difference across the conductor provided all the physical conditions of conductor remains unchanged.*

Now, it may be noted that these physical conditions mean temperature, pressure and chemical state (its composition) of the conductor. But, according to Joule's law whenever a current will flow and heat will be generated. This heat will increase the temperature of the conductor. So it is not practically possible to keep the temperature unchanged. So Ohm's law is only an approximation of reality.

Now, let us explain this law. Suppose we have a variable voltage source V connected to a PQ conductor. A current I is measured by an ammeter A connected in series with the conductor.

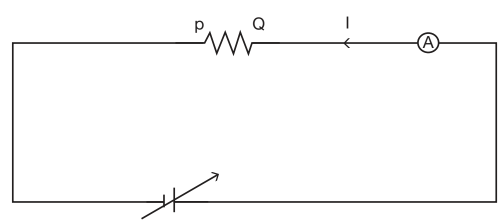

Fig. 1.3: Verification of Ohm's Law

Let us consider all physical parameters remain unchanged and V is varied. Each time we record I for different V. If we plot I as a function of V in graph we shall get a straight line passing through origin. As I is directly proportional to V the possible equation of the curve in Fig. 1.4 is V & I. V = IR.

where R is the proportionality constant or the slope of the curve,

$$R = \frac{V}{I} \qquad \text{.......... 1.5}$$

$$\left(\frac{\text{Volt}}{\text{Amp}} = \text{Ohm.}\right)$$

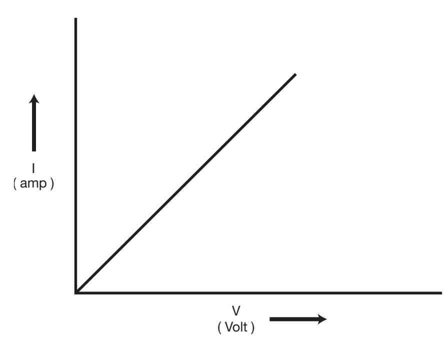

Fig. 1.4: Linear relationship between V & I.

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Now, look at the above equation, we can conclude R is a factor by which the conductor resists the flow of current through itself. R is a property of the conductor called resistance. The unit of resistance is Ohm (Ω). We can define 1 Ohm as if a current through a conduction is 1 Amp due to a potential difference of 1 Volt across it, the resistance of the conductor is 1 Ohm.

The law states that the slope of the V-I characteristic is always constant. This constant is known as the resistance of the conductor. This signifies a property of a conductor which opposes the current flowing through it.

But in real conductors it is almost impossible to implement Ohm's law accurately. It is not feasible to maintain all other physical parameters like temperature constant in a conductor when the current is flowing through it. We know from Joule's law of electric heating that whenever there is a current flow in a conductor, heat will be generated. The heat is directly proportional to the square of the current. More the current more will be the generated heat. This heat will increase the temperature of the conductor. The resistance will no longer be constant. The conductor will loose its linear property.

The relation between the temperature rise and the resistance is given by:

$$R = R_0(1+\alpha_1\theta+\alpha_2\theta^2+\alpha_3\theta^3+\ldots\ldots\ldots+\alpha_n\theta^n) \qquad \ldots\ldots\ldots\ 1.6$$

where α_n is the n^{th} order temperature coefficient of heat of the resistance, θ is the temperature change and R_0 is the resistance at the absolute 0°K temperature.

The resistance of a conductor is a function of it's cross sectional area A and length *l*. It has been observed that—

i. Resistance (R) is inversely proportional to area (A).
ii. Resistance (R) is directly proportional to length (*l*).

$$R \propto \frac{\ell}{A}$$

or, $$R = \rho\frac{\ell}{A} \qquad \ldots\ldots\ldots\ 1.7$$

The proportionality constant ρ is known as the resistivity. This is the property which determines how resistive the material is. For a non-conductive material ρ is infinite. The resiprocal of ρ is σ, which is conductivity of a material. It measures how electrically conductive the material is.

$$\sigma = \frac{1}{\rho} \qquad \ldots\ldots\ldots\ 1.8$$

The unit of ρ is Ohm-m. The unit of σ is mho-m^{-1}.

1.7 Combination of Resistances: Equivalent Resistance

1.7.1 Resistance in series

Let us suppose two resistances of R_1 and R_2 are connected in series. There is a voltage source V which is also connected to the series combination in series. A current I is following through the circuit.

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Now let us imagine another resistance Req, such that if we replace both R_1 and R_2 by a single resistance Req there will be no change in voltage and current in the circuit. Req is known as the equivalent resistance of the circuit.

We need to evaluate the Req from R_1 and R_2 in Fig. 1.5, I current is flowing through both R_1 and R_2. Let the voltage drop across R_1 and R_2 be V_1 and V_2, respectively.

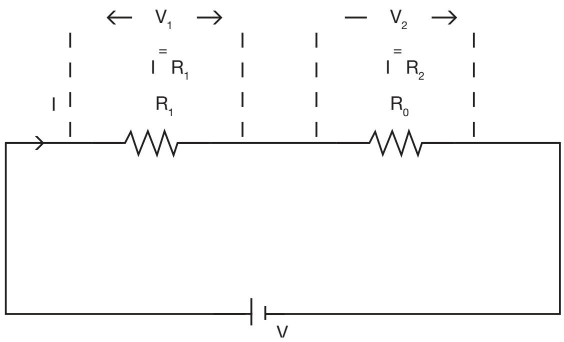

Fig. 1.5: Series combination of two resistances R1 and R2

Therefore, Applying Ohm's law

$$I = \frac{V_1}{R_1} = \frac{V_2}{R_2} \quad \text{.......... 1.9}$$

where we get

$V_1 = IR_1$ and $V_2 = IR_2$

The total voltage in the circuit is V

$$V = V_1 + V_2$$
$$= IR_1 + IR_2$$
$$= I\,(R_1 + R_2) \quad \text{.......... 1.10}$$

Now if we replace R_1 and R_2 by Req we shall get the following circuit.

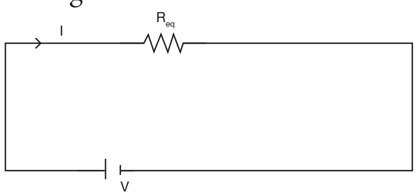

Fig. 1.6: Equivalent resistance, Req

Applying Ohm's law in the circuit we get,

$$V = R_{eq}\, I \quad \text{.......... 1.11}$$

Compairing equation 1.10 with equation 1.11

We get,

$$R_{eq} = R_1 + R_2 \quad \text{.......... 1.12}$$

Similarly, if n number of resistors are connected in series:

The equivalent resistance Req will be

$$R_{eq} = R_1 + R_2 + R_3 + \ldots + R_n \quad \text{.......... 1.13}$$

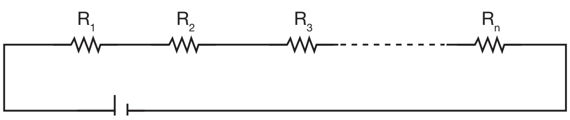

Fig. 1.7: n number of resistances in series connection

Voltage divider rule

As we have seen in the circuit of Fig. 1.7 when two resistors are in series the total voltage across them. Let us see in what proportion the voltage gets divided.

From equation 1.10.

$$V_1 = V - V_2$$
$$V_1 = V - IR_2$$
$$V_1 = V - \frac{V}{R_{eq}} . R_1$$
$$V_1 = V\left(1 - \frac{R_1}{R_1 + R_2}\right)$$

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$$V_1 = V.\frac{R_1}{R_1 + R_2} \qquad \text{.......... 1.14}$$

Similarly, $V_2 = V.\frac{R_2}{R_1 + R_2}$ 1.15

Thus, voltage will be divided in proportional to the resistance. More the resistance more the voltage required to get such current flow.

1.7.2 Resistance in parallel

Let us suppose that two registors R_1 and R_2 are connected in parallel to a voltage source V. In this case, the voltage drop across both the registers R_1 and R_2 will be same as V, but the current will be different. Let I_1 and I_2 be the current flowing through R_1 and R_2, respectively. The total current drawn by the combination of registors R_1 and R_2 is I. From Fig. 1.8.

We get $V = I_1 R_1 = I_2 R_2$ and $I = I_1 + I_2$. From equation 1.10, we can write

$I = V/R_1 + V/R_2.$

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad \text{.......... 1.16a}$$

Now, if Req be the equivalent resistance of the circuit, then we can write

$$I = V/R_{eq} \qquad \text{.......... 1.16b}$$

Now comparing equation 1.16, we can have

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

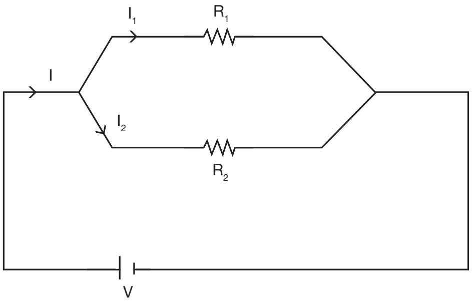

Fig. 1.8: Resistance R_1 and R_2 are in parallel

$$\text{or } R_{eq} = \frac{R_1 R_2}{R_1 + R_2} \qquad \text{.......... 1.17}$$

Similarly, if we have *n* number of resistors in parallel, so

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ \ldots\ldots \ \frac{1}{R_n} \qquad \text{.......... 1.18}$$

Current divider rule

As we have seen in the above case, the total current I gets divided into two branches through R_1 and R_2 as I_1 and I_2, respectively. Let us see in what (ratio) proportion the current (I) gets divided. Now let us imagine the flow of current as a large number of people walking through a street. Now they reach at a junction where the street gets divided into two lanes where, one lane is narrower than the other one, it is very obvious, that more number of people will follow the

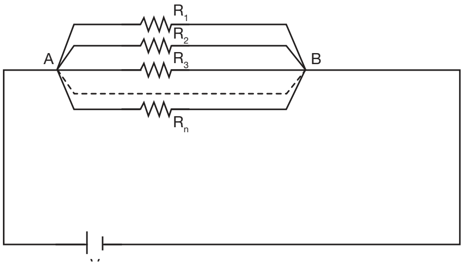

Fig. 1.9: n number of resistances are in parallel

broader lane. The same thing will happen to the current. When the current gets branched, the more amount of current will flow through the less resistive path and vice versa.

From equation

$$I = I_1 + I_2 \ldots. I_n \qquad \ldots\ldots\ldots. 1.19$$

$$\text{or } I_1 = I - I_2$$

$$I_1 = I - \frac{V}{R_2}$$

$$I_1 = I - I.\frac{R_{eq}}{R_2}$$

$$I_1 = I - \left(1 - \frac{R_{eq}}{R_2}\right)$$

$$I_1 = I - \left(1 - \frac{\frac{R_1R_2}{R_1 + R_2}}{R_2}\right)$$

$$I_1 = I\left(1 - \frac{R_1}{R_1 + R_2}\right) \qquad \ldots\ldots\ldots. 1.20$$

$$I_1 = I.\frac{R_2}{R_1 + R_2}$$

$$\text{Similary } I_2 = I\frac{R_1}{R_1 + R_2} \qquad \ldots\ldots\ldots. 1.21$$

Thus, the current flowing through a branch is proportional to the resistance of the other branch.

1.7.3 Equivalent resistance of circuit

Here we are going to discuss how we can evaluate the equivalent resistance of a circuit. Suppose we need to estimate the equivalent resistance of a circuit in between terminals A and B (Fig. 1.10) with the charges travelling from A to B. So our starting point is at A and destination point is B. If there is branching in the way the circuit is parallel and when two paths meeting at any junction it again becomes in series. Let us explain this with few examples.

Here we want to go from A to B, at P we will be offered two paths one through R_1 and R_2, and another through R_3 and R_4. Thus, the one diamensional representation of the above current

Case-I

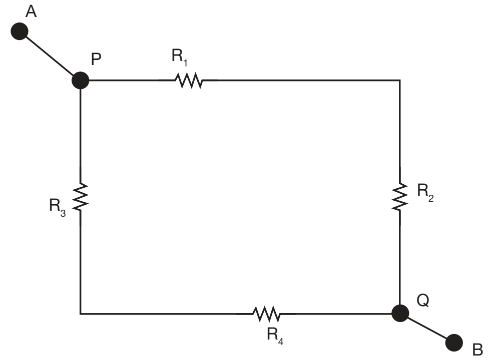

Fig. 1.10: Eqiuvalent resistance (case I)

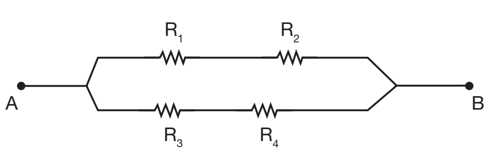

Fig. 1.11: Eqiuvalent resistance (case I) simplified

and the equivalent resistance would be simply

$$R_{eq} = (R_1 + R_2) // (R_3 + R_4) = \frac{(R_1 + R_2)\ (R_3 + R_4)}{R_1 + R_2 + R_3 + R_4} \qquad \text{.......... 1.22}$$

Case II

Now let us complicate the situation by adding another resistance R_5

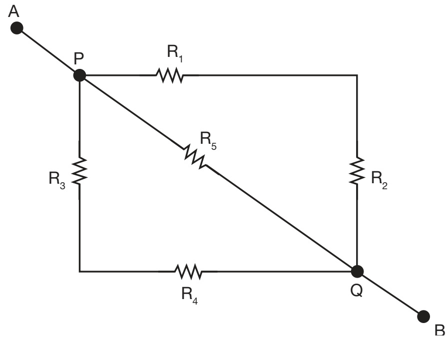

Fig. 1.12: Equivalent resistance (Case II)

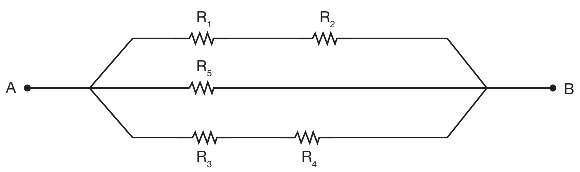

Fig. 1.13: Equivalent resistance (Case II) simplified

Here at node P we have three choices of path to reach B. Thus, there are three parallel branches. The one diamensional representation would be

$$R_{eq} = (R_1 + R_2) \| R_5 \| (R_3 + R_4)$$

$$R_{eq} = \frac{(R_1 + R_2).\ R_5.(R_3 + R_4)}{R_1 + R_2 + R_3 + R_4 + R_5} \qquad \text{.......... 1.23}$$

1.8 Colour Code of Resistor

It is very important to identify the value of the resistance of a resistor by looking at it. We use some standard colour codes to know the value of the resistance by identifying the colour of the bands painted on the resistor.

Every colour has a decimal number for it. These numbers are the power of 10.

The colour and the significant decimal numbers are showing in the chart.

Genarally there are four colour bands. We start counting from the left side. For example, a resistor with bands of yellow, violet, red and gold will have first digit 4 (yellow), second digit 7 (violet), followed by 2 (red). The value of the resistance will be 47 followed by two zeros i.e., 4700 Ohm. The golden band signifies ±5% tolerance level.

Colour		Number
black		0
brown		1
red		2
orange		3
yellow		4
green		5
blue		6
violet		7
gray		8
white		9
gold	Tolerence band	± 5%
silver		± 10%

1.9 Electric Power and Energy

Power is the rate of change of energy and energy is the work done. So in other words, power is the rate of change in work done with respect to time.

As per definition, potential (V) is the amount of work done for positive unit charge. Therefore, the total work done to bring ΔQ amount of charge will be:

$\Delta W = V.\Delta Q$ 1.24

The work done is by the time Δt. The rate of work done, i.e., power $P = \frac{\Delta W}{\Delta t} = V.\frac{\Delta Q}{\Delta t}$

by definition current $I = \frac{\Delta Q}{\Delta t}$

$P = V.\ I$ 1.25

thus, in electric circuit

Power (P) = Potential (V) × Current (I)

The energy would be $E = \Sigma\Delta w = \Sigma P.\Delta t$ 1.26

1.10 Basic Idea of Capacitor and Capacitance

A water vassel has a capacity to store the water. A spring can store the mechanical energy. Likewise an electric capacitor can store or hold the charges. This is called static electricity. A capacitor makes the electric charges static. Charge cannot flow through capacitor if we apply the DC voltage across it. A capacitor is basically two inonised (one is positive and another is negative) plates separated by a dielectric media. Dielectric can not conduct the current in ideal condition (for example, dry air, dry papaer, mica etc). The conductivity of an ideal capacitor is zero (σ = 0) while the resistivity is infinite (ρ = ∞). But like a water vessel, an electric capacitor also has a limit to hold the charges. If we apply more and more voltage across the plates of the capacitor, at a point the charge will overflow. This happens due to breaking of the dielectric property of the dielectric separating the plates. We can not have a perfect dielectric in reality. Every dielectric has strength to withstand the voltage. After that threshold limit of applied voltage the dielectric behaves like a conductor. The capacitor starts to discharge and the dielectric conducts the current from possitively ionised plate to the negatively ionised plate. In terms of modern physics, beyond this capacitive limit the applied voltage supplies the energy which is sufficient to overcome the barrier potential. AC can flow through capacitor by simultaneous charging and discharging.

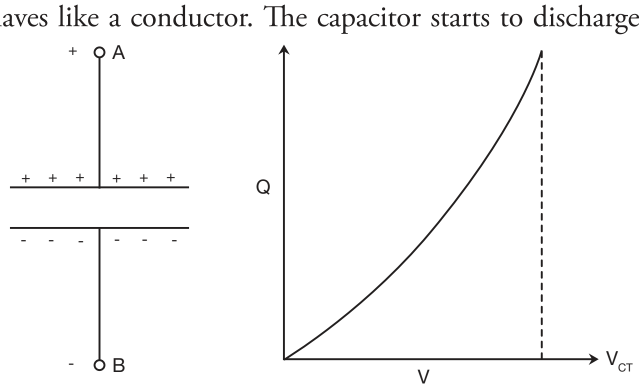

Fig 1.14a and b: Capacitor and charging of capacitor

When we increase the voltage the charge stored in plate rises and after reaching the threshold