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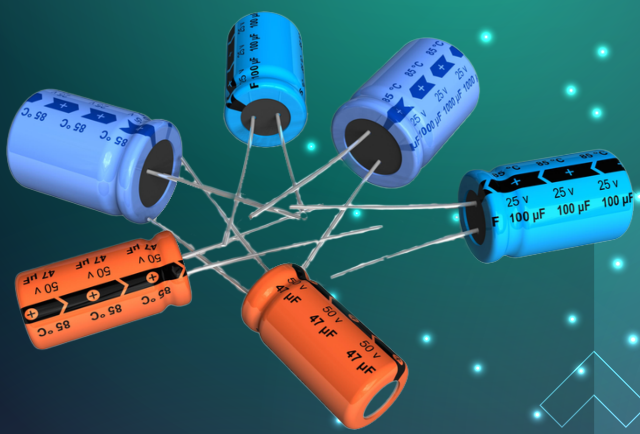
DET10013

ELECTRICAL TECHNOLOGY



CAPACITOR & CAPACITANCE

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CAPACITOR AND CAPACITANCE

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eNotes - Capacitor and Capacitance is a general references and readings especially to lecturers and students of polytechnics and colleges Malaysian community to apply best practices in method implementation online teaching and learning.

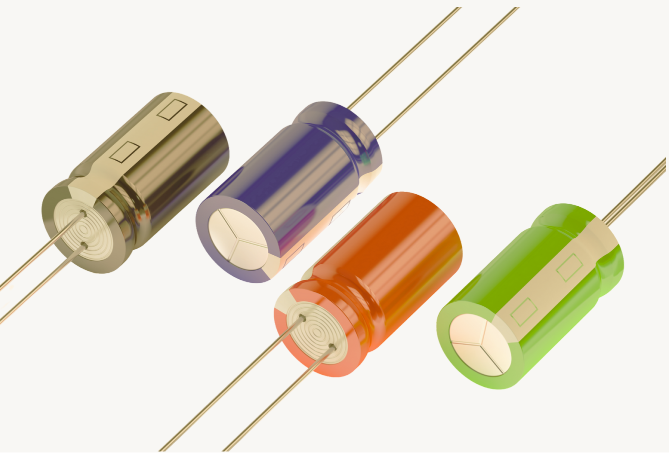
eNotes - Capacitor and Capacitance adalah sebagai rujukan dan bacaan umum terutama kepada pensyarah dan pelajar politeknik dan kolej komuniti Malaysia bagi mengaplikasikan amalan terbaik dalam perlaksanaan kaedah pengajaran dan pembelajaran atas talian.

PREFACE

In the name of Allah, the Most Beneficent and the Most Merciful. All praises and thanks to God the Almighty for His showers of blessings that this e-book is successfully published.

The authors would like to express deepest appreciation to all those who provided the possibility in publishing this E-book especially friends and colleagues. Many thanks also go to the Electrical Engineering Department team for the support and guidance throughout the process of completing this e-book.

Thank You



REVIEWER & COMENTATOR

To the Esteemed Authors of the Electrical Technology Module,

I am writing to express my sincere appreciation for the exceptional work put forth in crafting the Electrical Technology module. Your dedication and expertise in presenting complex concepts in a simplified manner deserve commendation. The module's simplicity in approach is truly commendable. It takes a subject as intricate as Electrical Technology and elucidates it in a manner that is easily digestible for learners of varying backgrounds. This approach fosters an environment conducive to learning, allowing students to grasp fundamental concepts without feeling overwhelmed.

One of the module's notable strengths lies in its ability to provide clear examples and step-by-step calculations. However, while the module excels in simplifying complex topics, it might benefit from expanding its range of examples to cover a broader spectrum of scenarios. Diversifying the examples could further enhance the module's comprehensiveness and applicability across various practical situations.

In conclusion, I extend my heartfelt gratitude for your outstanding efforts in creating an Electrical Technology module that excels in simplicity and clarity. Your dedication to fostering an accessible learning environment in such a complex field is truly commendable.

Warm regards,

Dr Intan Azmira Binti Wan Abdul Razak
Senior Lecturer
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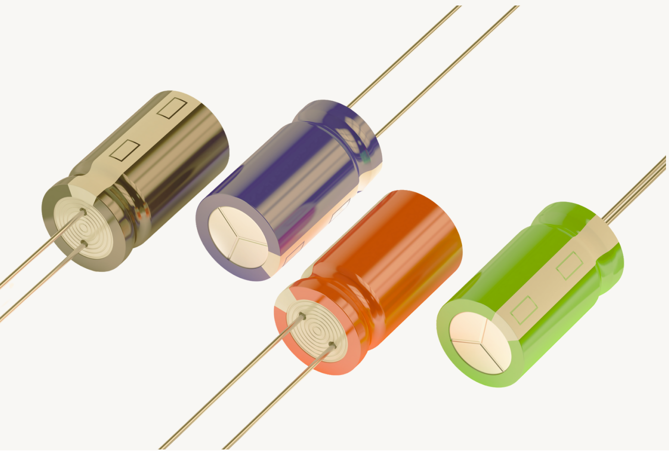
CAPACITOR AND CAPACITANCE

Suitable for Diploma students, this book concise for students to understand the characteristics of capacitor in Electrical Engineering. It contains basic theory and practical foundations for capacitance in electronics circuit.



ABSTRACT

E-book Capacitor and Capacitance provides an overview of Capacitor and Capacitance. This E-book will help students to know about Capacitor and Capacitance , understand the basic principles of capacitor and the process of charging and discharging in a capacitor based on the voltage and current curves. This E-book also as general references and readings especially to students and lecturers of polytechnics , colleagues and others educational institutions.

Table of Contents

1.0

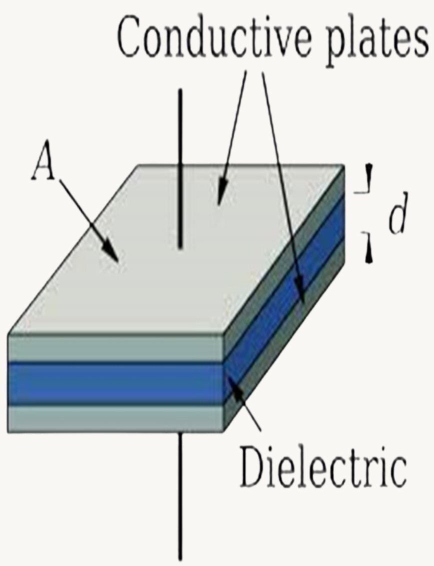
Introduction

In this introduction to capacitors , we will see that capacitors are passive electronic components consisting of two or more pieces of conducting material separated by an insulating material. The capacitor is a component which has the ability or “capacity” to store energy in the form of an electrical charge producing a potential difference (Static Voltage) across its plates, much like a small rechargeable battery.

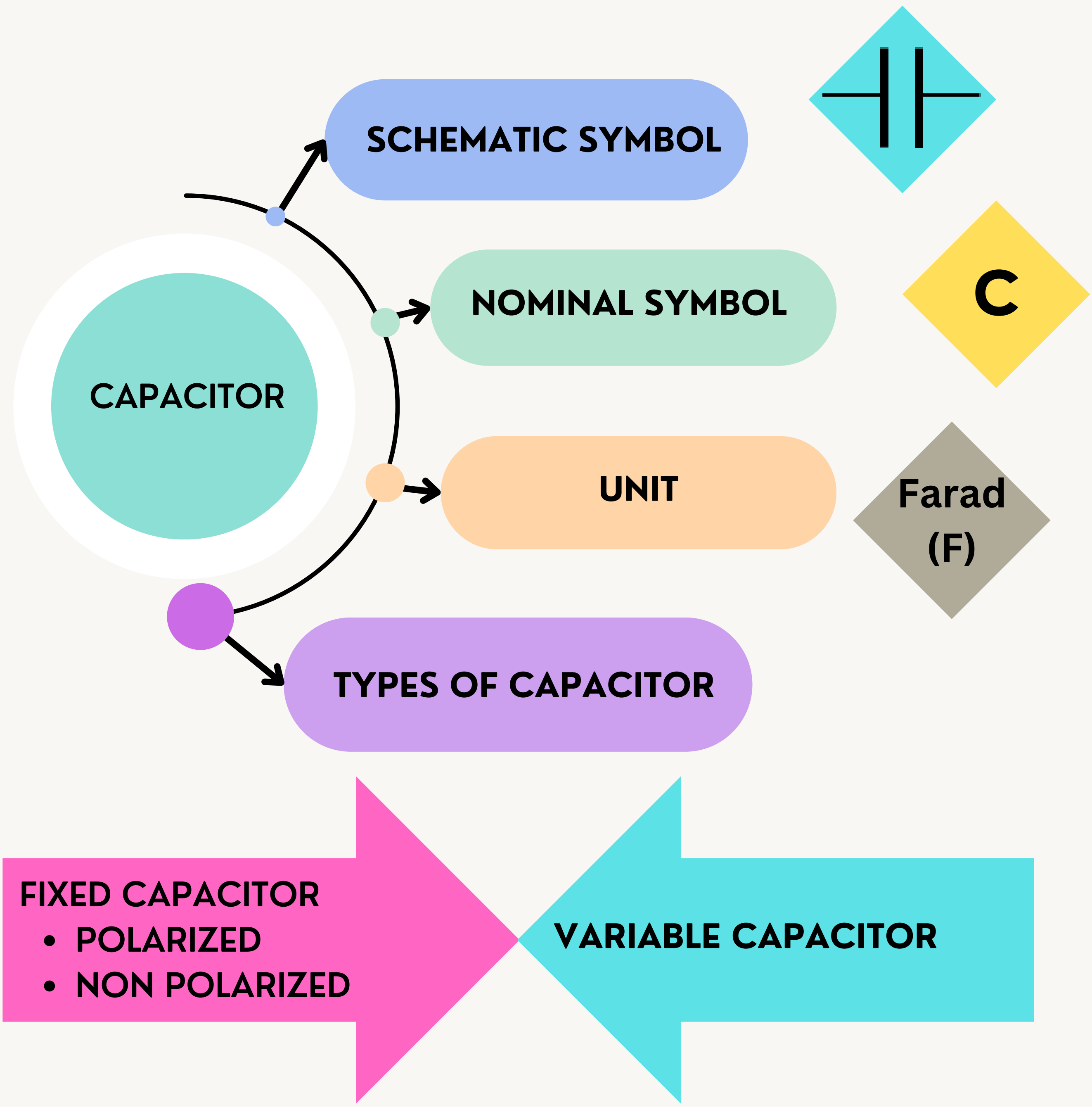
1.1 CAPACITOR

- Capacitor is an electrical component that stores electrical charge/energy.
- It is constructed with 2 conductive plates facing each other separately by a dielectric such as air, paper, mica ceramic and others.

A capacitor essentially consists of two conducting surfaces separated by a layer of an insulating medium called dielectric. The conducting surfaces
may be in the form of either circular (or rectangular) plates or be of spherical or cylindrical shape. The purpose of a capacitor is to store electrical energy
by electrostatic stress in the dielectric.



1.2 Quantities Associated with capacitance



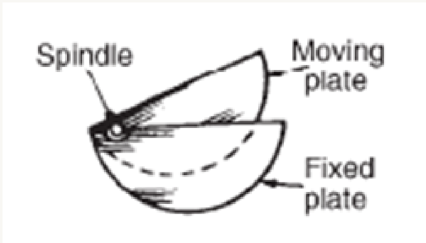
2.0
TYPES OF CAPACITOR

There are many different kinds of capacitors available from very small capacitor beads used in resonance circuits to large power factor correction capacitors, but they all do the same thing, they store charge.

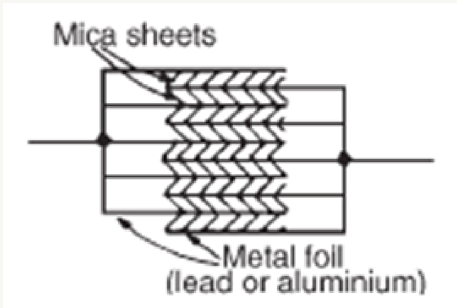
- Practical types of capacitor are characterized by the material used for their dielectric.
- The main types include: variable air, mica, paper ceramic, plastic, titanium oxide and electrolytic.

2.1 TYPES OF CAPACITOR

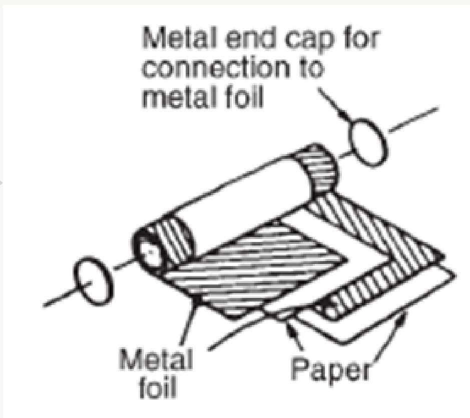
Variable Air Capacitor

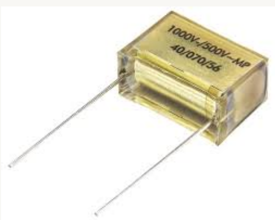


Mica Capacitor

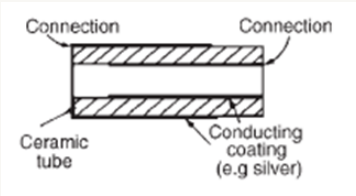


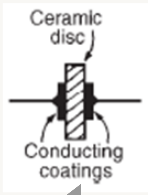
Paper Capacitor

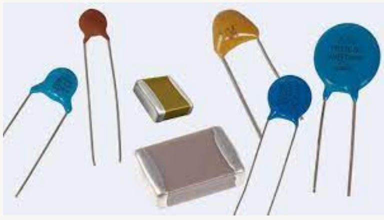


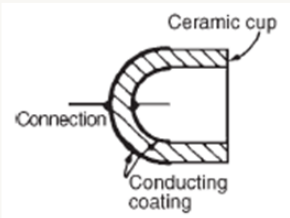


TYPES OF CAPACITOR



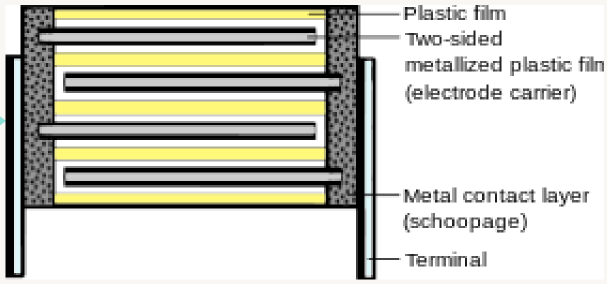






Ceramic Capacitor

Plastic Capacitor



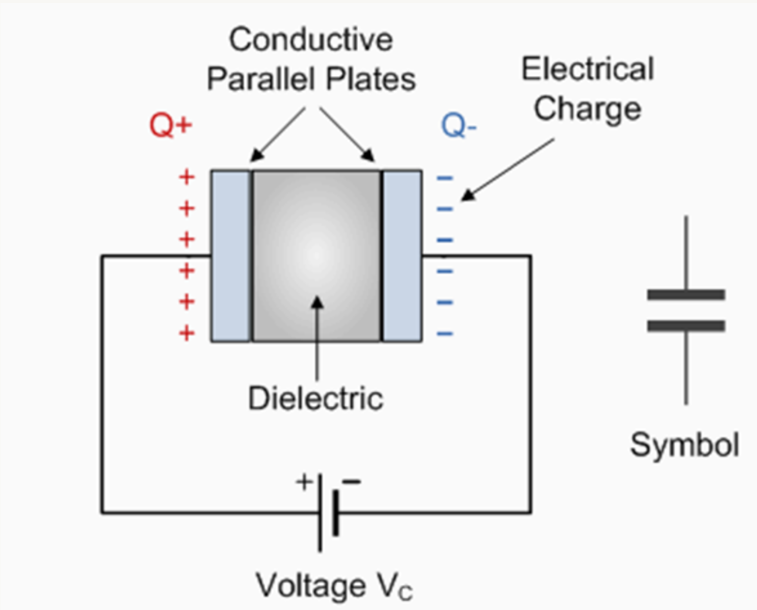
Electrolytic Capacitor

Titanium Oxide Capacitor

2.2 Construction of the capacitor

In its basic form, a capacitor consists of two or more parallel conductive (metal) plates which are not connected or touching each other, but are electrically separated either by air or by some form of a good insulating material. This insulating material could be waxed paper, mica, ceramic, plastic or some form of a liquid gel as used in electrolytic capacitors.

As a good introduction to capacitors, it is worth noting that the insulating layer between a capacitors plates is commonly called the Dielectric.



3.0

CAPACITANCE

Capacitance is the electrical property of a capacitor and is the measure of a capacitors ability to store an electrical charge onto its two plates with the unit of capacitance being the Farad (abbreviated to F) named after the British physicist Michael Faraday.

Capacitance is defined to be the amount of charge Q stored in between the two plates for a potential difference or voltage V existing across the plates. In other word;

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

where C = capacitance (Farad)

Q = Charge (coulomb)

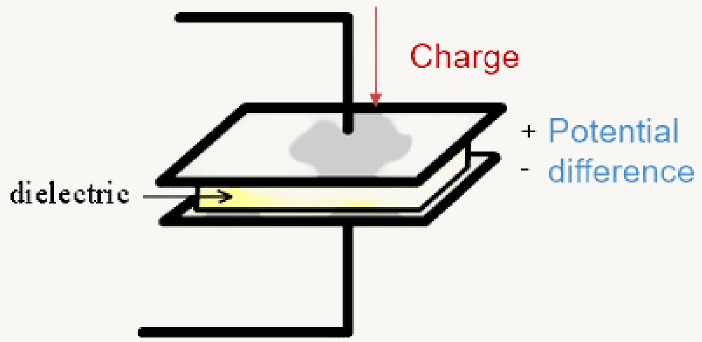
V = voltage (volt)

3.0 CAPACITANCE

The property of a CAPACITOR to store electricity is called CAPACITANCE

The quantities associated with CAPACITANCE:

- amount of electric charge, Q
- Potential Difference between capacitor plates, V



Standard Units of Capacitance
Microfarad (μF) 1μF = 1/1,000,000 = 0.000001 = 10-6 F
Nanofarad (nF) 1nF = 1/1,000,000,000 = 0.000000001 = 10-9 F
Picofarad (pF) 1pF = 1/1,000,000,000,000 = 0.000000000001 = 10-12 F

Example

3.1 Determine potential difference across a 4 μF capacitor when charged with 5 mC.

$$V = \frac{Q}{C} = \frac{5m}{4\mu} = 1.25\ \text{kV}$$

3.2 A capacitor with a capacitance of 5 farads is connected to a 10-volt battery. How much charge will be stored on each of its conducting plates?

Q = CV

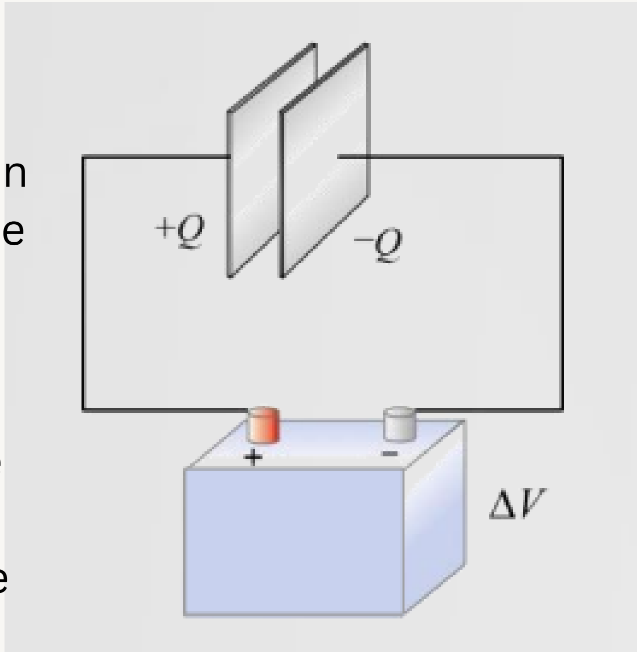
= (5) (10)

=50 Coulombs

3.1 CAPACITANCE EQUIVALENT CIRCUITS FOR SERIES AND PARALLEL CONNECTIONS

A capacitor can be charged by connecting the plates to the terminals of a battery, which are maintained at a potential difference ΔV called the terminal voltage.

The connection results in sharing the charges between the terminals and the plates. For example, the plate that is connected to the (positive) negative terminal will acquire some (positive) negative charge. The sharing causes a momentary reduction of charges on the terminals, and a decrease in the terminal voltage.



Chemical reactions are then triggered to transfer more charge from one terminal to the other to compensate for the loss of charge to the capacitor plates, and maintain the terminal voltage at its initial level. The battery could thus be thought of as a charge pump that brings a charge Q from one plate to the other.

3.1.1 CAPACITOR IN SERIES CONNECTIONS

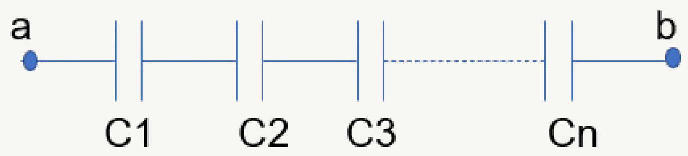
Capacitors are connected together in series when they are daisy chained together in a single line

With capacitors in series, the charging current (iC) flowing through the capacitors is THE SAME for all capacitors as it only has one path to follow.

Then, Capacitors in Series all have the same current flowing through them as iT = i1 = i2 = i3 etc. Therefore each capacitor will store the same amount of electrical charge, Q on its plates regardless of its capacitance. This is because the charge stored by a plate of any one capacitor must have come from the plate of its adjacent capacitor. Therefore, capacitors connected together in series must have the same charge.

$$Q_T = Q_1 = Q_2 = Q_3 \ldots etc$$

Consider the following circuit in which the three capacitors, C1, C2 and C3 are all connected together in a series branch across a supply voltage between points A and B.



$$C_{ab} = C_{total} = \frac{1}{\frac{1}{C1}+\frac{1}{C2}+\frac{1}{C3}+\cdots+\frac{1}{Cn}}$$

Series Capacitors Equation

When adding together Capacitors in Series, the reciprocal (1/C) of the individual capacitors are all added together (just like resistors in parallel) instead of the capacitance's themselves. Then the total value for capacitors in series equals the reciprocal of the sum of the reciprocals of the individual capacitances.

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\text{.etc}$$

Example

3.3 Calculate the equivalent capacitance of two capacitors of 6 μF and 4 μF connected in series.

In series, equivalent capacitance C is given by:

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

$$C = \frac{6 \times 4}{6 + 4} = \frac{24}{10} = \mathbf{2.4\ \mu F}$$

3.1.2 CAPACITOR IN PARALLEL CONNECTIONS

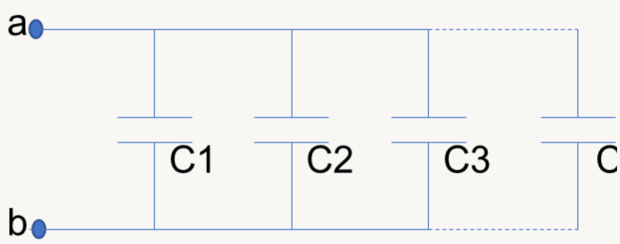
Capacitors are connected together in parallel when both of its terminals are connected to each terminal of another capacitor

The voltage (Vc) connected across all the capacitors that are connected in parallel is THE SAME. Then, Capacitors in Parallel have a "common voltage" supply across them giving:

VC1 = VC2 = VC3 = VAB

In the following circuit the capacitors, C1, C2 and C3 are all connected together in a parallel branch between points A and B as shown.

When capacitors are connected together in parallel the total or equivalent capacitance, CT in the circuit is equal to the sum of all the individual capacitors added together. This is because the top plate of capacitor, C1 is connected to the top plate of C2 which is connected to the top plate of C3 and so on.



$$C_{ab} = C_{total} = C1 + C2 + C3 + \ldots\ldots + Cn$$

Parallel Capacitors Equation

When adding together capacitors in parallel, they must all be converted to the same capacitance units, whether it is μF, nF or pF. Also, we can see that the current flowing through the total capacitance value, CT is the same as the total circuit current, iT

We can also define the total capacitance of the parallel circuit from the total stored coulomb charge using the Q = CV equation for charge on a capacitors plates. The total charge QT stored on all the plates equals the sum of the individual stored charges on each capacitor therefore,

$$Q_T = Q_1 + Q_2 + Q_3 \quad \text{but, } Q = CV$$

$$\therefore Q_T = CV_T = CV_1 + CV_2 + CV_3$$

$$\text{or } C_T = C_1 + C_2 + C_3$$

Example

3.4 Calculate the equivalent capacitance of two capacitors of 6 μF and 10 μF connected in parallel.

C = C1 + C2

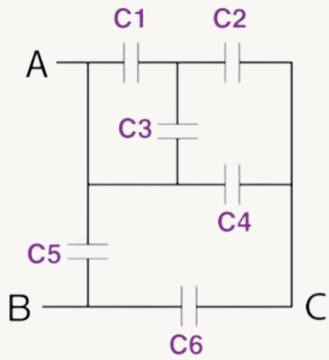
C = 6 μF + 10 μF

C = 16 μF

Series Parallel Capacitors Circuit

Example

3.5 Find the equivalent capacitance between points A and B. The capacitance of each capacitor is 2 μF.



Solutions:

In the system given, C1 and C3 are in parallel. C5 is connected between A and B. So, they can also be represented as follows:

- As C1 and C3 are in parallel, their effective capacitance is 4μF
- 4μF and 2μF are in series, so their effective capacitance is 4/3μF
- 4/3μF and 2 μF are in parallel, so their effective capacitance is 10/3μF
- 10/3μF and 2μF are in series, so their effective capacitance is 5/4μF
- 5/4μF and 2μF are in parallel, so their effective capacitance is 13/4μF

Therefore, the equivalent capacitance of the given system is 13/4μF.

4.0

CIRCUITS WITH CAPACITIVE LOAD

Electric charges generate electric fields. The electric fields influence other electric charges with electric force and this force is also influenced by other charges with the same force in the opposite direction. There are two types of electric charge, positive charge and negative charge. The electric charge is measured with the unit of coulomb (C). One coulomb has the charge of 6.25×10^{18} electrons.

4.1 CURRENT IS THE RATE OF CHANGE OF CHARGE

Remember that the current is the rate of flow of charge (electrons). Therefore, the instantaneous current, *I*, can be expressed as the instantaneous rate of change of charge, *q*, with respect to time, *t*.

$$I = \frac{dq}{dt}$$

where: dq = changing of charge

dt = changing of time

I = current (ampere)

For a steady state condition:

$$I = \frac{Q(charge)}{t(time)}\text{, thus } Q = It$$

Q = charge (coulomb)

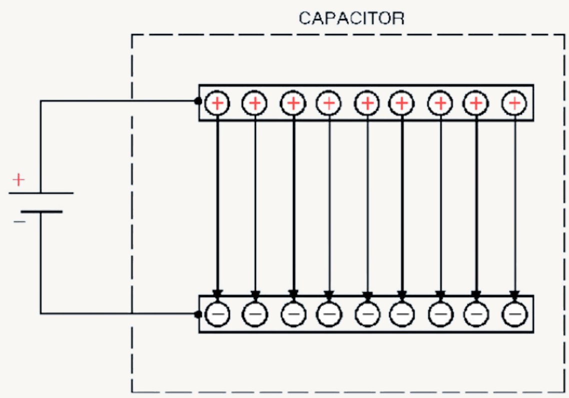
t = time (second)

4.2 TERMS RELATED TO CAPACITANCE

Electric Flux

In terms of electromagnetism, electric flux is the measure of the electric field lines crossing the surface. Although an electric field cannot flow by itself, it is a way of describing the electric field strength at any distance from the charge creating the field. The electric field E can generate a force on an electric charge at any point in space.

The electric lines of force tat move out from the positive charges in an electric field is called electric fluc. The symbol of electric flux is ψ and is measured in coulomb (C),



$$\therefore Electric\ Flux, \psi = \text{Charge, } Q$$

Electric Flux Density

Electric flux density is a measure of the strength of an electric field generated by a free electric charge, corresponding to the number of electric lines of force passing through a given area.

Electric flux density is the ratio between the charge of the capacitor and the surface area of the capacitor plates and can be expressed as;

$$D = \frac{Q\ (unit{:}Coulomb)}{A\ (unit{:}metre^2)}$$

where;

D= Electric flux density (C/m 2)
Q= Charge (C)
A= Cross-sectional area (m 2)

Electric Field Strength

When 2 metal plates is charged and separated by a distance, a potential difference exist between the plates. A force is also generated between the plates known as electric force or electric field strength, E.

This electric force depends on the potential difference and the distance between the plates.

$$E = \frac{V\ (unit{:}Volt)}{d\ (unit{:}metre)}$$

where;

E= Electric field strength in V/m
V= voltage in V
d= thickness of dielectric in m

Absolute Permittivity

Absolute permittivity is defined as the measure of permittivity in a vacuum and it is how much resistance is encountered when forming an electric field in a vacuum. The absolute permittivity is normally symbolised by ε0. The permittivity of free space - a vacuum - is equal to approximately 8.85 x 10-12 Farads / metre (F/m).

The ratio of flux density to the electric field strength is known as the absolute permittivity of dielectric and can be expressed as

$$\varepsilon = \frac{D}{E} \text{ (Unit : } \frac{Farad}{metre} \text{)}$$

where;

ε = absolute permittivity in F/m

D = electric flux density in C/m 2

E = electric field strength in V/m

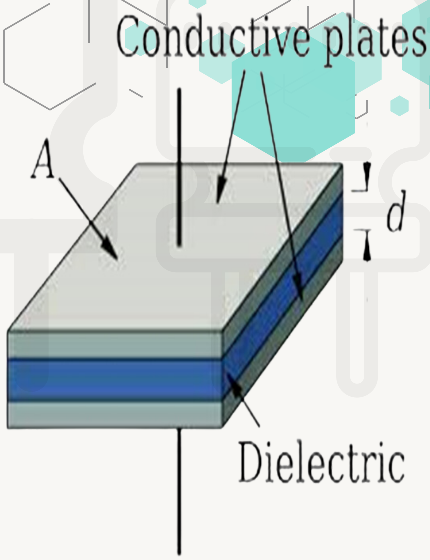
Relative permittivity is defined as the permittivity of a given material relative to that of the permittivity of a vacuum. It is normally symbolised by: εr.

$$\varepsilon = \varepsilon_r * \varepsilon_0 \text{ (Unit : } \frac{Farad}{metre} \text{)}$$

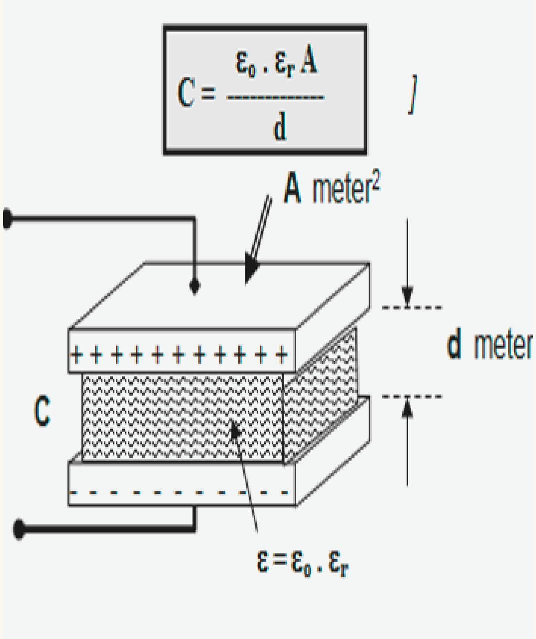
The relative permittivity, εr, of a dielectric is different between materials. The relative permittivity of free space or vacuum is 1, εr = 1.

Dielectric

A dielectric material is used to separate the conductive plates of a capacitor. This insulating material significantly determines the properties of a component. The dielectric constant of a material determines the amount of energy that a capacitor can store when voltage is applied.



4.3 FACTORS AFFECTING CAPACITANCE



Capacitance is directly proportional to the **cross sectional area of the plates.**

$C \propto A$

Capacitance is **inversely** proportional to the **distance between the two plates**

$C \propto 1/d$

Capacitance depends on the **type of dielectric material** used for the capacitor

OR

Capacitance is **directly** proportional to the **permittivity of the dielectric material**

$$C = \frac{\varepsilon A}{d}$$

5.0

CHARGING AND DISCHARGING OF CAPACITORS

The capacitor is fully charged when the voltage of the power supply is equal to that at the capacitor terminals. This is called capacitor charging; and the charging phase is over when current stops flowing through the electrical circuit. When the power supply is removed from the capacitor, the discharging phase begins.

The rate of charging and discharging of a capacitor depends upon the capacitance of the capacitor and the resistance of the circuit through which it is charged.

5.1 CHARGING PROCESS OF CAPACITOR

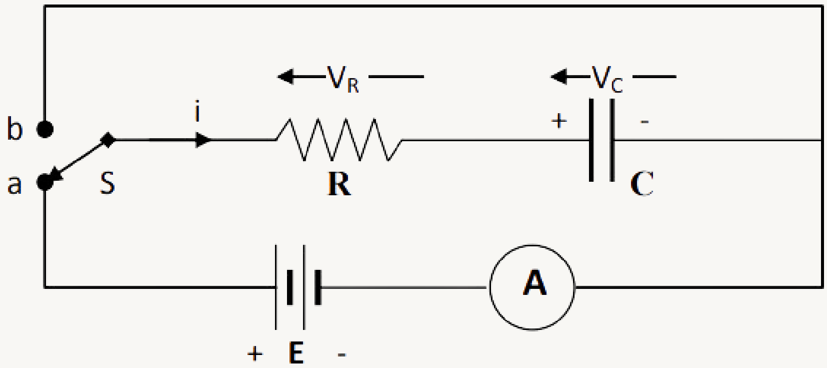


Figure 8: Capacitor circuit for charging process

Capacitor in charging mode whenever it is connected to a voltage supply. (switch, SW at point a)

When a battery is connected to a series resistor and capacitor, the initial current is high as the battery transports charge from one plate of the capacitor to the other.

Figure 9 show both curves current and voltage for capacitor during charging process, in x-axis (t, time). The current and voltage curve may be represented by exponent equations respectively.

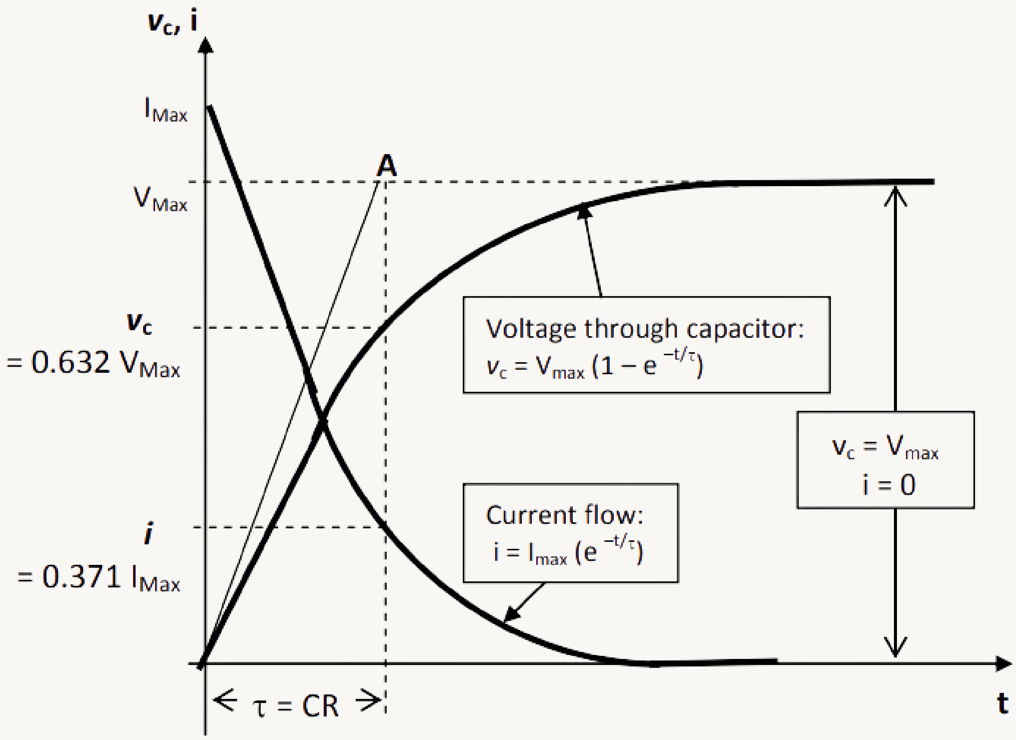


Figure 9: Current and voltage curve in capacitor during charging process

The charging current asymptotically approaches zero as the capacitor becomes charged up to the battery voltage. Charging the capacitor stores energy in the electric field between the capacitor plates. **The rate of charging is typically described in terms of a time constant RC.**

REMEMBER!

Time constant, $\tau = CR$

- The times taken for voltage achieve value of $0.632V_{max}$ and current achieve value of $0.371I_{max}$

- Max. voltage of capacitance,
  $V_{max} = E$ (unit: V)

- Max. current of capacitance,
  $I_{max} = \frac{E}{R}$ (unit: A)

- Charging voltage of capacitor,
  $v_c = V_{max}(1 - e^{-t/\tau})$

- Charging current of capacitor,
  $i_c = I_{max}(e^{-t/\tau})$

- Time for charging to maximum,
  $t_{max} = 5\tau$ (unit: s)

ENERGY STORED IN CAPACITORS

The amount of energy stored is dependent on the charge stored and the voltage of the capacitor.

$$W = \frac{1}{2}CV^2 \text{ joules}$$

EXAMPLE

Problem:

5.1 A capacitor with the capacitance of 8μF is connected in series to a 0.6M resistor across the dc voltage supply of 240V.

Determine :

a) Time constant

b) Initial charge current

c) Time for capacitor voltage increases to 150V

d) The current and the potential difference across the capacitor after 4 seconds it is charged to the voltage supply.

e) Energy stored in the capacitor when it is fully charged.

f) Sketch the charging voltage curve.

Solution:

A capacitor with the capacitance of 8μF is connected in series to a 0.6MΩ resistor across the dc voltage supply of 240V. Determine :

a) Time constant

$$\tau = CR$$

$$= 8 \times 10^{-6} F \times 0.6 \times 1$$

$$= 4.8 \text{ seconds}$$

b) Initial charge current

$$I_{initial} = I_{max}$$

$$I_{initial} = \frac{V}{R}$$

$$= \frac{240}{0.6 \times 10^6}$$

$$= 4.00 \times 10^{-4}$$

$$= 400\mu A$$

c) Time for capacitor voltage increases to 150V

$$V_C = 150\ V, t = ?$$

$$V_C = E(1 - e^{-\frac{t}{\tau}})$$

$$150 = 240\left(1 - e^{-\frac{t}{4.8}}\right)$$

$$1 - e^{-\frac{t}{4.8}} = 0.625$$

$$e^{-\frac{t}{4.8}} = 0.375$$

$$\ln e^{-\frac{t}{4.8}} = \ln 0.375$$

$$-\frac{t}{4.8} = -0.981$$

$$t = 4.709\ seconds$$

d) The current and the potential difference across the capacitor after 4 seconds it is charged to the voltage supply.

$$V_C = E\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$= 240\left(1 - e^{-\frac{4}{4.8}}\right)$$

$$= 240(1 - 0.435)$$

$$= 135.6\ V$$

$$i_C = I_{max}\left(e^{-\frac{t}{\tau}}\right)$$

$$= 400\mu\left(e^{-\frac{4}{4.8}}\right)$$

$$= 400\mu(0.435)$$

$$= 1.74 \times 10^{-4}$$

$$= 174\mu A$$

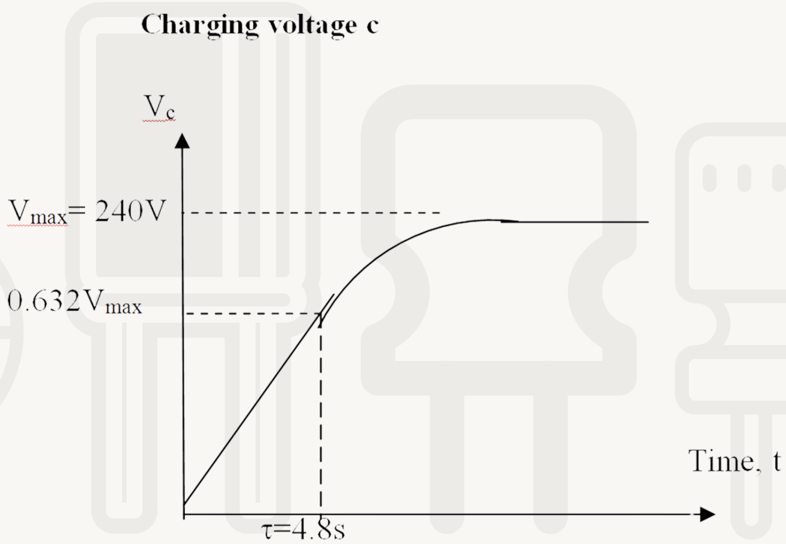
e) Energy stored in the capacitor when it is fully charged

$$W = \frac{1}{2}CE^2$$

$$= \frac{1}{2}(8\mu)(240)^2$$

$$= 0.2304\ Joules$$

f) Sketch the charging voltage curve.



5.2 DISCHARGING PROCESS OF CAPACITOR

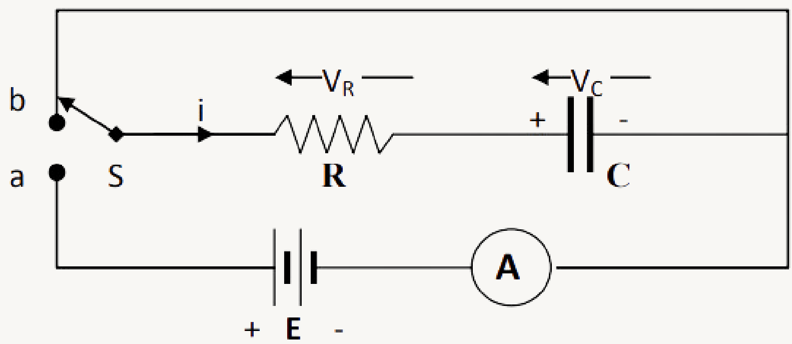


Figure 10: Capacitor circuit for discharging process

When capacitor fully charge and then switch being transformed to 'b', discharge process for capacitor will happen. The time taken to recharge and fully discharge is .

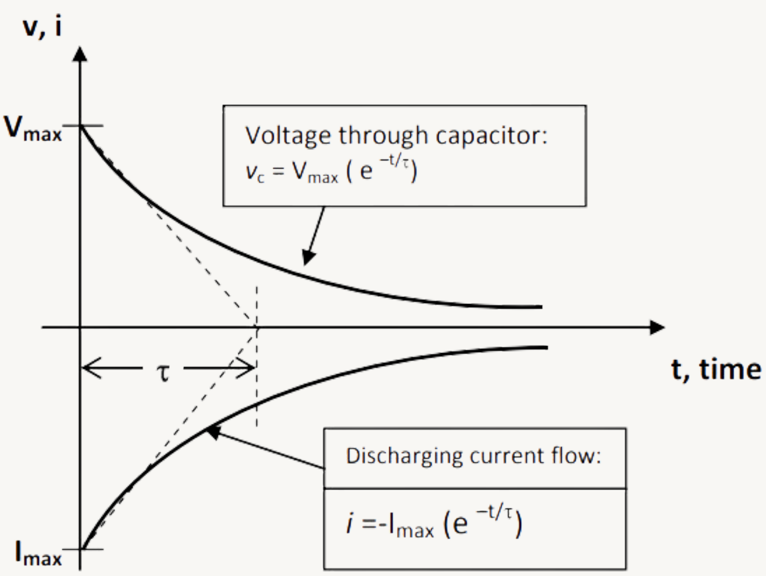


Figure 11: Current and voltage curve in capacitor during discharging process

REMEMBER

- Time constant, $\tau = CR$ (unit: s)
- Max. voltage of capacitance, $V_{max} = E$ (unit: V)
- Max. current of capacitance, $I_{max} = \frac{E}{R}$ (unit: A)

EXAMPLE

Problem:

5.2 A capacitor is charged to 100 V and then discharged through a 50 kΩ resistor. If the time constant of the circuit is 0.8 s.

Determine:

(a) The value of the capacitor,
(b) The time for the capacitor voltage to fall to 20 v,
(c) The current flowing when the capacitor has been discharging for 0.5 s
(d) The voltage drop across the resistor when the capacitor has been discharging for one second.

Solution:

Given :

V = 100V, τ= 0.8s, R = 50kΩ

(a)

$$\tau = RC$$

$$C = \tau / R$$

$$= 0.8 / (50 \times 10^3)$$

$$= \mathbf{16\mu F}$$

(b)

$$V_c = V e^{-t/\tau}$$

$$20 = 100 e^{-t/0.8}$$

$$1/5 = e^{-t/0.8}$$

$$e^{t/0.8} = 5$$

$$t/0.8 = \ln 5$$

$$t = 0.8 \ln 5$$

$$= \mathbf{1.29\ s}$$

(c) $I = V/R$

$= 100 / 50 \times 10^3$

$= 2\ mA$

$i = I\, e^{-t/\tau}$

$= 2m\, e^{-0.5/0.8}$

$= 2m\, e^{-0.625}$

$= 2m \times 0.535$

$= \mathbf{1.07mA}$

(d) $V_C = V_R = V\, e^{-t/\tau}$

$= 100\, e^{-1/0.8}$

$= 100\, e^{-1.25}$

$= 100 \times 0.287$

$= \mathbf{28.7\ V}$

6.0

TUTORIALS

This tutorials will help you quickly assess your understanding of capacitance, an object's ability to store electric energy. The tutorials including the function of dielectrics, capacitor's, common uses of capacitors, calculating capacitor charge, and the definition of capacitance.

TUTORIALS

Q1 Refer to Figure 2(c) ,a capacitor 100 uF is chargerd to a voltage of 20V and has a resistance of 470 ohm.

Calculate :

i.Instantaneous value of current ic when t= 47ms

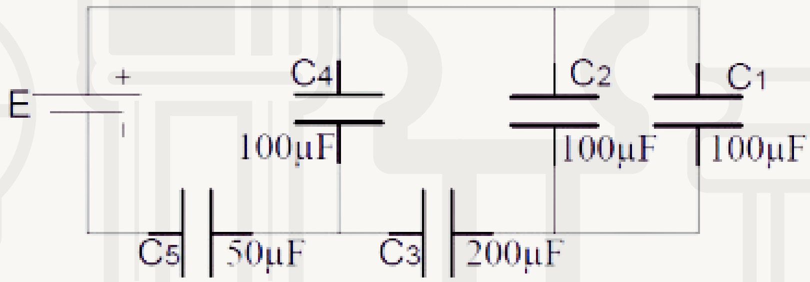
answer: ic(t)=15.653 mA

ii.Time taken to make the instantaneous value of charging voltage equals to 10V

answer: t=32.58ms

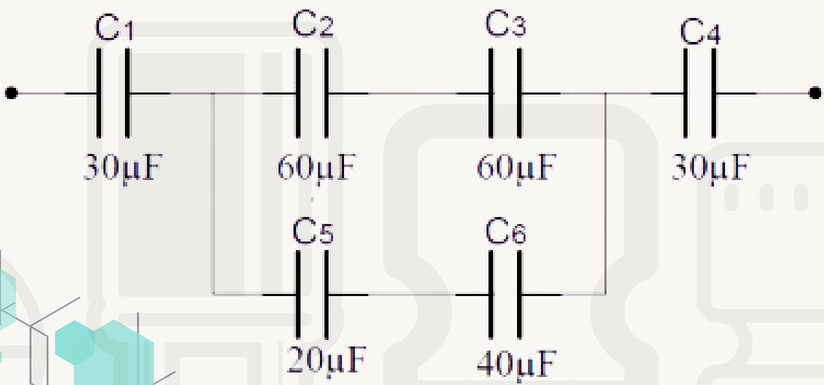
Q2 Find total capacitance for the circuit below:

a)



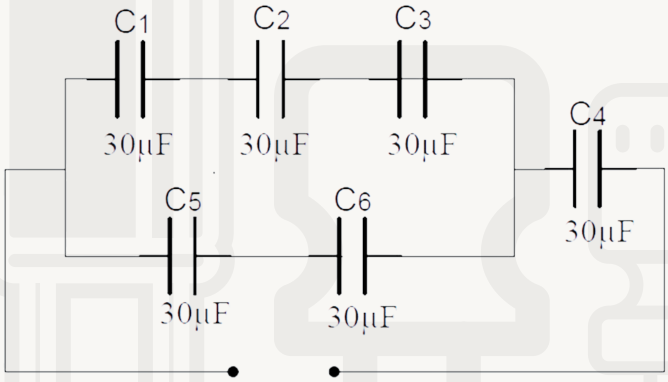
answer: 40uF

b)



answer: 11.14uF

c)



answer: **1.2u**F

Q3 A capacitor with an capacitance of 20μF which is connected in series to a 200KΩ resistor is being placed with a 250V DC voltage supply. Calculate the initial current ,initial potential difference across capacitor,the time constant during charging and the energy stored in the capacitor.

answer: Imax=1.25mA;Vc initial=0v; time constants=4s; Energy stored =0.625J

Q4 A capacitor 100μF is charged to a voltage of 20v and has a resistance of 470 ohm .Calculate :

i. instantaneous value of current ic when t= 47ms

answer: ic(t)=15.653 mA

ii. Time taken to make the instantaneous value of charging voltage equals to 10v

answer: t= 32.58ms

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