1. Module detail and its structure

Subject Name	Physics
Course Name	Physics 03 (Physics Part 1 ,Class XII)
Module Name/Title	Unit- 04, Module- 06: **LC Circuit and LC oscillations** Chapter- 07: Alternating Current
Module Id	Leph_10703_eContent
Pre-requisites	Alternating current, ac circuits, components in ac circuits, inductive reactance, capacitive reactance, phasor, current voltage phase difference in ac circuits
Objectives	**After going through this module learner will be able to:** • **Differentiate** different components in Alternating voltage circuits • **Analyze ac** electrical circuits with resistor- inductor and resistor - capacitor • **Appreciate** reactance and impedance offered by resistance and inductor in ac circuits • **Distinguish** the reactance and impedance offered by resistance and inductor with resistance and capacitor in ac circuits • **Represent** current and voltage using phasors for pure RL and RC circuits • **Understand** LC Circuit and LC oscillations
Keywords	Resonant frequency, quality factor, impedance, Reactance, Phasors, watt-less currents, choke coil, Sine function, Power factor

2. Development team

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1. UNIT SYLLABUS

Unit IV: Electromagnetic Induction and Alternating Currents

Chapter-6**: Electromagnetic Induction**

Electromagnetic induction; Faraday's laws, induced emf and current; Lenz's Law, Eddy currents; Self and mutual induction.

Chapter-7: **Alternating Current**

Alternating currents, peak and rms value of alternating current/voltage; reactance and impedance; LC oscillations (qualitative treatment only), LCR series circuit, resonance; power in AC circuits, wattless current; AC generator and transformer

2. MODULE WISE DISTRIBUTION 09 Modules

The above unit is divided into 9 modules for better understanding.

Module 1	• Electromagnetic induction • Faraday's laws, induced emf and current; • Change of flux • Rate of change of flux
Module 2	• Lenz's Law, • Conservation of energy • Motional emf
Module 3	• Eddy currents. • Self induction • Mutual induction. • Unit Numerical
Module 4	• AC generator • Alternating currents, • Representing ac ✓ *Formula* ✓ *Graph* ✓ *Phasor* • Frequency of ac and what does it depend upon • peak and rms value of alternating current/voltage;
Module 5	• AC circuits • Components in ac circuits • Comparison of circuit component in ac circuit with that if used in dc circuit • Reactance ✓ *pure R* ✓ *pure L* ✓ *Pure C* • Phasor, graphs for each

Module 6	• AC circuits with RL, RC and LC components • Impedance; LC oscillations (qualitative treatment only), • Resonance • Quality factor
Module 7	• Alternating voltage applied to series LCR circuit • Impedance in LCR circuit • Phasor diagram • Resonance • Power in ac circuit • Power factor • Wattles current
Module 8	• Transformer
Module 9	• Advantages of ac over dc • Distribution of electricity to your home

MODULE 6

3. WORDS YOU MUST KNOW

Let us remember the words we have been using in our study of this physics course:

- **Magnetic field**: The region around a magnet, within which its influence can be felt, denoted by B
- **Magnetic flux**: Intuitive way of describing the magnetic field in terms of field lines crossing a certain area in a magnetic field. Magnetic flux is defined in the same way as electric flux is defined . Magnetic flux through a plane of area A placed in a uniform magnetic field B , denoted by ϕ_B
- **Electric cell** a simple device to maintain a steady current in an electric circuit is the electrolytic cell
- **Electromotive Force e**: The amount of work done by a cell (the amount of energy provided by the cell) , to take a unit charge once round the circuit . e is, actually, a

potential difference and *not a force*. The name emf, however, is used because of historical reasons, and was given at a time when the phenomenon was not understood properly.

- **Area vector**: A vector perpendicular to a given area whose magnitude is equal to the given area.
- **Ampere**: It is the unit of current.
- **Volt:** It is the unit of emf and potential difference.
- **Induced emf and Induced current:** The emf developed in a loop when the magnetic flux linked with it changes with time is called induced emf when the conductor is in the form of a closed loop, the current induced in the loop is called an induced current.
- **Weber**: One weber is defined as the amount of magnetic flux, through an area of $1m^2$ held normal to a uniform magnetic field of one tesla. The SI unit of magnetic flux is weber (Wb) or tesla meter squared (Tm^2).
- **Faraday's laws of electromagnetic induction**:

First law: It states that whenever the amount of magnetic flux linked with the coil changes with time, an emf is induced in the coil. The induced emf lasts in the coil only as long as the change in the magnetic flux continues.

Second law: It states that the magnitude of the emf induced in the coil is directly proportional to the time rate of change of the magnetic flux linked with the coil.

- **Fleming's Right Hand rule**: Fleming's right hand rule gives us the direction of induced emf/current in a conductor moving in a magnetic field.

If we stretch the fore-finger, central finger and thumb of our right hand mutually perpendicular to each other such that **fore-finger** is in the direction of the field **, thumb** is in the direction of motion of the conductor, then the central finger would give the direction of the induced current.

- **Induced emf by changing the magnetic field**: The movement of magnet or pressing the key of coil results in changing the magnetic field associated with the coil, this induces the emf.

- **Induced emf by changing the orientation of coil and magnetic field**: When the coil rotates in a magnetic field the angle ϴ changes and magnetic flux linked with the coil changes and this induces the emf. This is the basis of ac generators.
- **Induced emf by changing the area A: MOTIONAL EMF:** Motional emf is a type of induced emf which occurs when a wire is pulled through the magnetic field. The magnitude of motional emf depends upon the velocity of the wire, strength of magnetic field and the length of the wire. Motional emf arises due to the motion of charges due to a magnetic field.

- Alternating currents and voltages have instantaneous value given by:

$$i = i_0 \sin(\omega t + \Phi)$$

$$V = V_0 \sin(\omega t + \Phi)$$

Φ is the initial phase of the sinusoidal current or voltage.

- Alternating currents and voltages have peak value I_0 and V_0
- Alternating currents and voltages have average value over half cycle:

$$V_{avg(T/2)} = \frac{2V_0}{\pi} \cong 0.636\ V_0$$

- Alternating currents and voltages have root mean square values:

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

- Self inductance of a coil: L An electric current can be induced in a coil by flux changes produced by the changing current in it self

$$L = \mu_0 n^2 A l$$

Where nl = N total number of turns of the coil, A area of the face of the coil , μ_0 is the permeability of free space.

SI unit henry

Self inductance is also called back emf. It depends upon the geometry of the coil and permeability of the medium inside the coil

- Energy required to build up current I: in a coil of inductance L = $\frac{1}{2}LI^2$
- Capacitor: a system of two conductors separated by an insulator .parallel plate capacitors, spherical capacitors are used in circuits. Capacity of parallel plate capacitor is given by

$c = \frac{\mu_0 A}{d}$ 'A' area of the plate,'d' separation between the plates. , 'μ_0' is the permeability of free space

Capacitors block dc but ac continues as charging and discharging of the capacitor maintains a continuous flow of current.

- Capacitance : $C = \frac{Q}{V}$ S I unit farad
- Dielectric constant of a material K: is the factor by which the capacitance increases from its vacuum value when the dielectric (material) is inserted fully between the plates of a capacitor.
- Combination of capacitors: capacitors may be combined in ways to obtain a value of effective capacitance.

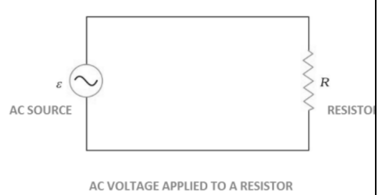
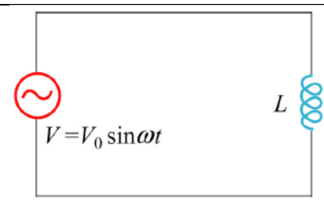
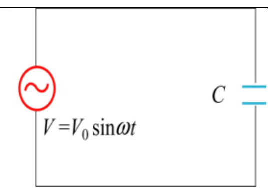
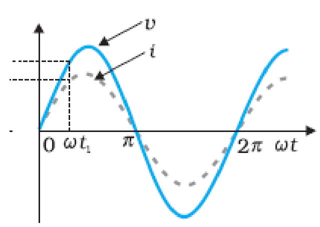
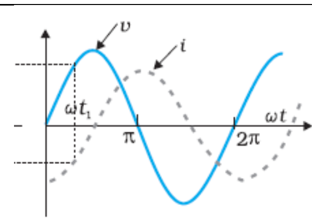
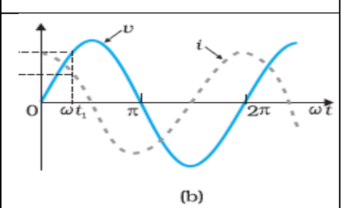
Series combination: capacitances are said to be in series if the effective combined capacitance C is given by

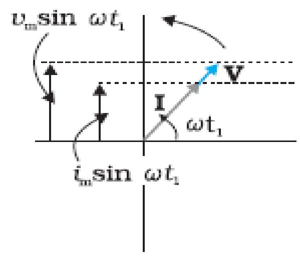
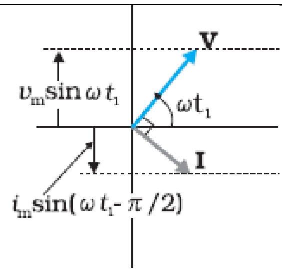
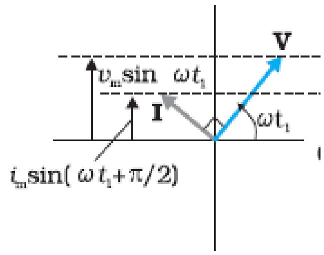
$$\frac{1}{\mathrm{C}} = \frac{1}{\mathrm{C}_1} + \frac{1}{\mathrm{C}_2} + \cdots \ldots . . + \frac{1}{\mathrm{C}_n}$$

Parallel combination of capacitors: capacitances are said to be in series if the effective combined capacitance C is given by

$$C = C_1 + C_2 + \cdots \ldots . + C_n$$

- Choke Coil: In electronics, a choke is an inductor used to block higher-frequency alternating current (AC) in an electrical circuit, while passing lower-frequency currents or direct current (DC).
- Watt-less current: Watt-less current is that AC component of AC current, whereby the power consumed by the circuit, is zero.

	Pure resistance circuit	Pure inductive circuit	Pure capacitive circuit
Circuit diagram			
Input voltage	**V=V$_0$sinωt**	**V=V$_0$sinωt**	**V=V$_0$sinωt**
Current	$\mathbf{I = \frac{V_0}{R} \sin\omega t}$ $\mathbf{I = I_0 \sin\omega t}$	$\boldsymbol{I = I_0 \sin(\omega t - \frac{\pi}{2})}$	$\boldsymbol{I = I_0 \sin(\omega t + \frac{\pi}{2})}$
reactance	**R**	**X_L=2πfL**	**X_C=1/2πfC**
Current voltage graph	**Current and voltage are in the same phase**	**Voltage leads the current by π/2**	**Voltage leads the current leads voltage by π/2**

Current voltage phasor			

4. INTRODUCTION

The fundamental circuit elements are the resistances (R), capacitors (C) and coils (L). These circuit elements can be combined to form an alternating current circuit in four distinct ways:

- **The R C series circuit**
- **The R L series circuit,**
- **The L C circuit**
- **The L C and R circuit**

These circuits exhibit important types of behavior

Why would such circuits be important to us? the answer lies in the fact that inductor or capacitor in an alternating current circuit set up a phase difference between voltage and current which means if the voltage across them is increasing the current need not , this phase lead or lag causes the **reactance** meaning an **obstruction like resistance in dc circuits** .

Then why do we not call it resistance , the reason is that if a resistance wire is connected in dc or ac circuit , it decides the value of current but does not vary the phase of current wrt voltage .

We have learnt that **an inductor** offers no resistance to current in dc circuit but in ac circuit offers a resistance called inductive reactance $X_L = \omega L$ depending upon

-inductance L

-frequency of ac source f or angular frequency $\omega = 2\pi f$

The value X_L is **called inductive reactance** and has a unit of ohm

Similarly a capacitor in dc circuit would block the current after the capacitor is charged , but in ac circuit continuous charging and discharging will cause a resistance which we call **capacitive reactance** $X_C = \frac{1}{\omega C}$

X_C depends upon

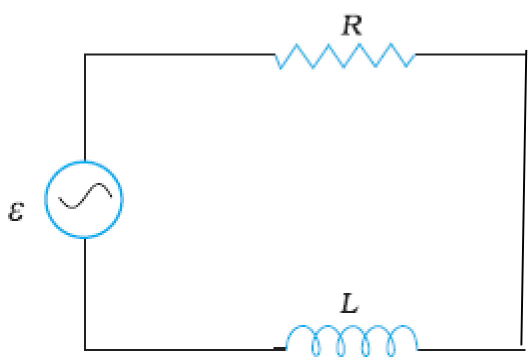
- Capacitance C

- Frequency of ac source f or angular frequency $\omega = 2\pi f$

In this module we will study the RL, RC, LC circuits

5. CIRCUIT CONTAINING INDUCTANCE AND RESISTANCE IN SERIES

A RL circuit is composed of one resistor and one inductor and is the simplest type of RL circuit.



A RL circuit is one of the simplest. It consists of a resistor and L an inductor, in series driven by an alternating voltage source e

Figure below shows pure inductor of inductance L (which means a coil of negligible resistance) connected in series with a resistor of resistance R through sinusoidal voltage:

$$V = V_0 \sin(\omega t)$$

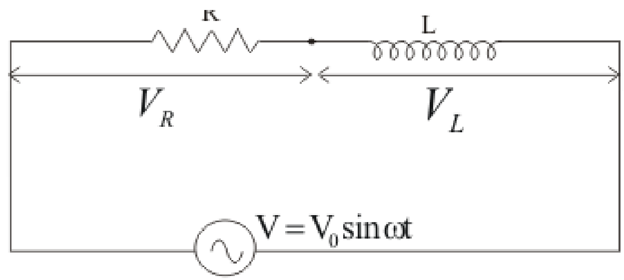
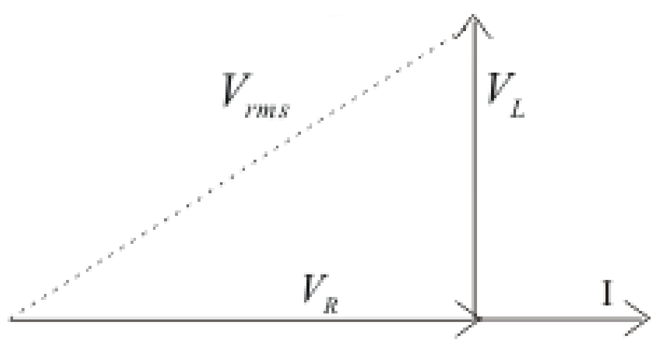


Figure shows AC circuit with R and L

An alternating current I flowing in the circuit give rise to voltage drop V_R across the resistor and voltage drop V_L across the coil. The Voltage drop V_R across R would be in phase with current but voltage drop across the inductor will lead the current by a phase angle π/2.
Now voltage drop across the resistor R is:

V_R=IR, and across inductor V_L=I (ωL)

Where I is the value of current in the circuit at a given instant of time. Hence, the voltage phasor diagram for LR circuit is as shown:



In the figure we have taken current as a reference quantity because same amount of current flows through both the components.

Thus from phasors diagram we have:

$$V = \sqrt{V_R^2 + V_L^2}$$
$$= I\sqrt{R^2 + \omega^2 L^2}$$

$= IZ$

Here notice $Z = \sqrt{R^2 + \omega^2 L^2}$

Z gives the **impedance** of the circuit and therefore the **Current** in steady state will be:

$$I = \frac{V_0 \sin(\omega t - \Phi)}{Z}$$

The current it lags behind the applied voltage by an angle φ such that tan=ωL/R

WHAT IS Φ?

When a alternating voltage source is connected to a circuit containing L and R from our previous study the voltage and current for resistor can be given by

$$\boldsymbol{V = V_0 sin\omega t}$$

And current I will be

$$\boldsymbol{I = I_0 sin\omega t}$$

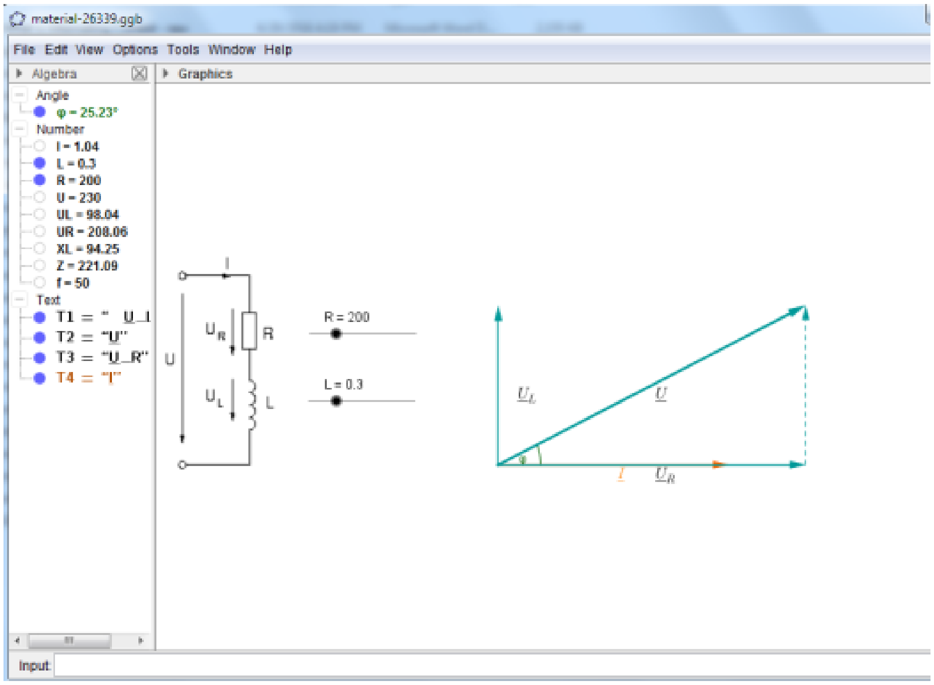
For inductor

$$\boldsymbol{V = V_0 sin\left(\omega t + \frac{\pi}{2}\right)}$$

$$\boldsymbol{I = I_0 sin\omega t}$$

The current in inductor and resistor remains same because they are connected in series but the voltage across inductor and resistor differ in phase by π/2.

Use the GeoGebra App to see the change in ϕ if the values of resistance R and inductance L are changed.



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The net voltage is

$$V_{net} = \sqrt{V_R^2 + V_L^2}$$

The above description is geometrical and does not convince us completely. We can draw the corresponding phasor diagram in terms of resistances. The resultant will depend upon the values of R and X_L.

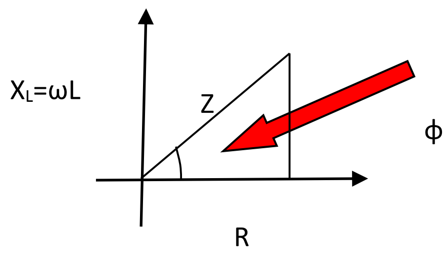
The resultant is called impedance .It is represented by Z . The SI unit is Ohm

So we have in an AC circuit

- Resistance due to a resistor

- Inductive reactance or capacitive reactance due to an inductor or a capacitor
- Impedance which is a combination of resistance and reactance

Now let us draw a triangle using R and X_L



$$Z = \sqrt{R^2 + X_L^2}$$

The current in the circuit will be given by

$$I = \frac{V_{net} = \sqrt{V_R{}^2 + V_L^2}}{z = \sqrt{R^2 + X_L^2}}$$

The phase difference between net voltage and current will be

$$\phi = \tan^{-1}\left(\frac{V_L}{V_R}\right)$$

$$\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$

THINK ABOUT THESE

- **What if we have a very large resistance with an inductor of small reactance value?**
- **What if we choose X_L on the x axis and R on the y axis?**
- **What if the R and X_L axis are not at right angles?**

- **Will the current always lag the voltage even if the inductive reactance is small?**
- **How would the phase angle change if the frequency of the AC changes with time?**
- **What does phase angle predict?**
- **What would be the shape of Z vs. f graph?**

6. CIRCUIT CONTAINING CAPACITANCE AND RESISTANCE IN SERIES

A resistor–capacitor circuit (RC circuit), composed of resistors and capacitors driven by a ac source

A simple RC circuit is composed of one resistor and one capacitor in **series.**

Figure below shows capacitor connected in series with a resistor of resistance R through sinusoidal voltage:

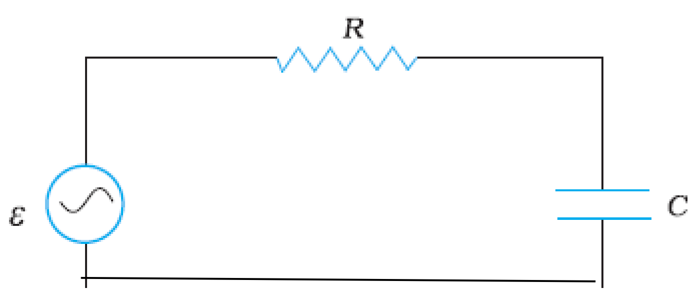
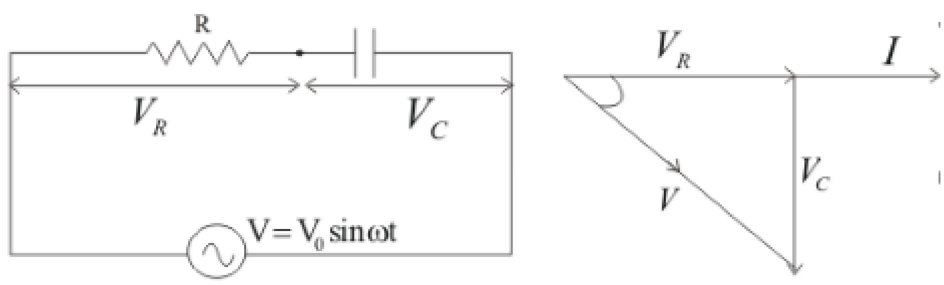


Figure below shows a circuit containing capacitor and resistor connected in series through a sinusoidal voltage source of voltage

V= V_0sin (ωt)



AC Circuit with R and C Phasor Diagram

In this case instantaneous potential difference across R is

$V_R = IR$, and

Across the capacitor C is

$V_C = 1/\omega C$

In this case V_R is in phase with current I and V_C lags behind I by a phase angle 90^0

The Figure shows, phasors diagram where vector OA represent the resultant of V_R and V_C this is the applied Voltage. Thus,

$$V = \sqrt{V_R^2 + V_C^2}$$

$$V = I\sqrt{R^2 + \frac{1}{(\omega C)^2}}$$

$$V = IZ$$

Where Z is the **impedance of the circuit**, given by

$$Z = \sqrt{R^2 + X_C^2}$$

X_c is the capacitive reactance $= \frac{1}{\omega C}$

In this case the applied voltage lags behind the current by a phase angle ϕ

Foe resistance only:

$$I = I_0 sin\omega t$$

$$V = V_0 \sin\omega t$$

For capacitor only:

$$I = I_0 sin\omega t$$

$$V = V_0 sin\left(\omega t - \frac{\pi}{2}\right)$$

Because C and r are in series, the current in both should be the same

But the voltage across the resistance is $\frac{\pi}{2}$ ahead of the voltage across the capacitor

The net voltage of the circuit will be given by

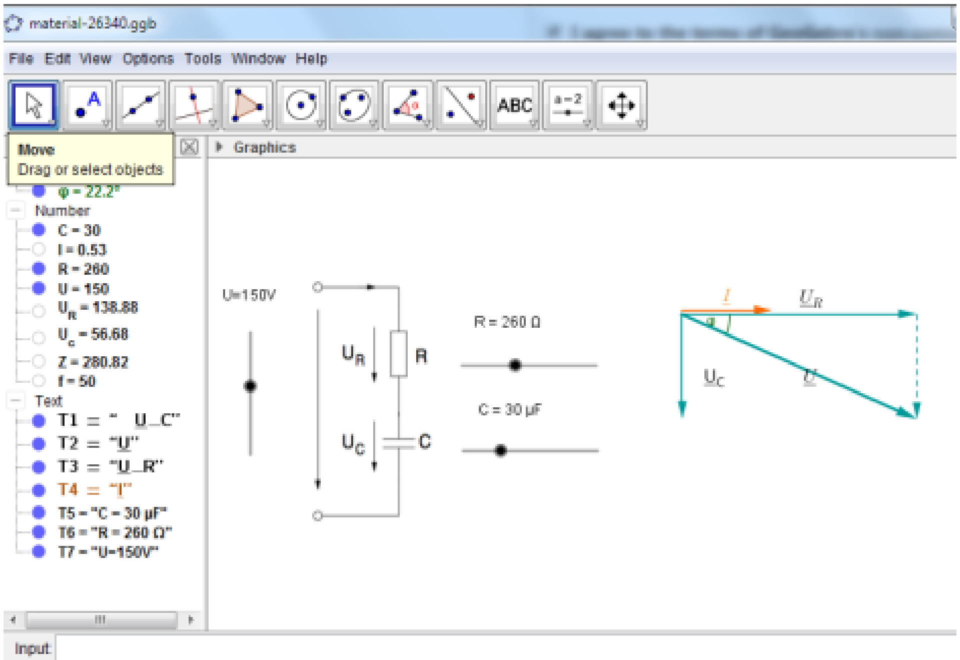
$$V = \sqrt{V_R^2 + V_C^2}$$

We can use GeoGebra App to visualize this

Check on the link given below, you may change the magnitude of

- R
- C and
- V

See the change in phase difference between net voltage and current



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The net obstruction to the current in the circuit is the impedance given by

$$Z = \sqrt{R^2 + X_C^2}$$

$$\text{thus, current in the circuit } I = \frac{\sqrt{V_R^2+V_C^2}}{\sqrt{R^2+X_C^2}}$$

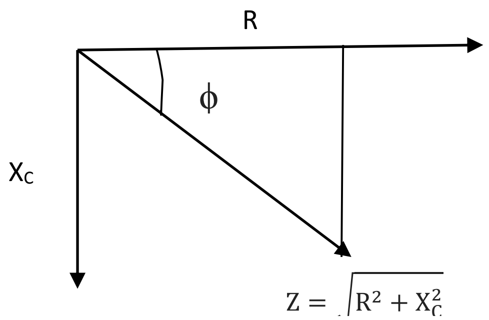
The phase difference between net voltage and current is

$$\phi = \tan^{-1}\left(\frac{V_C}{V_R}\right)$$

or

$$\phi = \tan^{-1}\left(\frac{X_C}{R}\right)$$

On an impedance triangle the phase difference ϕ may be seen as following

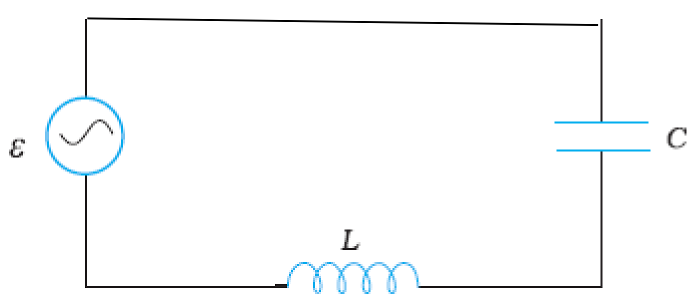


7. LC CIRCUIT

An LC circuit, also called a resonant circuit, tank circuit, or tuned circuit, is an electric circuit consisting of an inductor, represented by the letter L, and a capacitor, represented by the letter C, connected together..

LC circuits are used either for generating signals at a particular frequency, or picking out a signal of a particular frequency from a more complex signal. They are key components in many electronic devices, particularly radio equipment; they are used in circuits such as tuners.

An LC circuit is an idealized model since it assumes there is no dissipation of energy due to resistance. Any practical implementation of an LC circuit will always include loss resulting from small but non-zero resistance within the components and connecting wires.



This circuit behaves in a peculiar manner. The reason being one component inductor offers reactance in a way that the current lags the applied voltage, while the capacitive reactance makes the current lead in the circuit. The magnitude of X_L and X_C depend upon angular frequency ω or frequency of ac (ω =2π f).

Resonance occurs when an LC circuit is driven from an external source at an angular frequency ω_0 at which the **inductive and capacitive reactance are equal in magnitude**.

The frequency at which this equality holds for the particular circuit is called the resonant frequency.

The resonant frequency of the LC circuit is:

$$\boldsymbol{\omega_0 = \frac{1}{\sqrt{LC}}}$$

Where *L* is the inductance in henries, and *C* is the capacitance in farads.

To arrive at the above result we are only saying that the condition for resonance is $X_L = X_C$

Or

$$\omega_0 L = \frac{1}{\omega_0 C}$$

$$\omega_0{}^2 = \frac{1}{LC}$$

Or

Resonant frequency

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

The angular frequency ω_0 has units of **radians per second.**

The frequency in units **of hertz** is:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

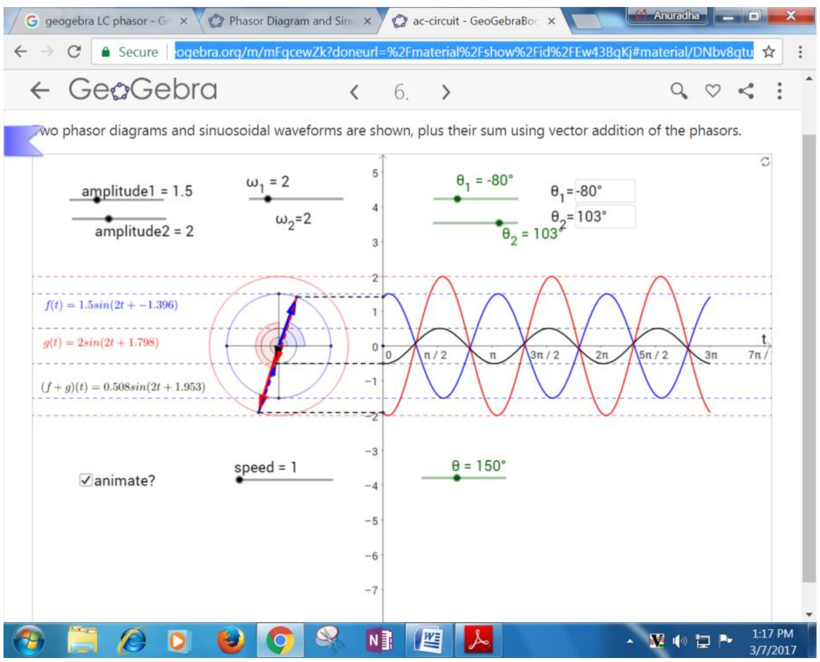
What kind of phasor diagram can be drawn for LC alternating current circuit?

Current in inductor will lag behind the current in capacitor by 180^0 or by $\frac{\pi}{2}+\frac{\pi}{2}=\pi$

So

At resonant frequency when the two would be equal and completely out of phase making the circuit impedance zero.

This condition is very useful in alternating current circuits and we will elaborate this in the next module.



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The two-element LC circuit described above is the simplest type of inductor-capacitor network (or LC network).

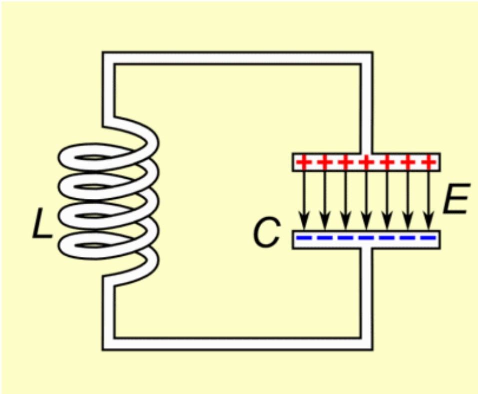
It is also referred to as a *second order LC circuit* to distinguish it from more complicated (higher order) LC networks with more inductors and capacitors. Such LC networks with more than two reactance may have more than one resonant frequency.

Notice the circuit given below has no power source, obviously the capacitor must have been first charged, the charging battery removed and the stored electrical energy in the capacitor being converted into magnetic energy around the coil due to changing current in it

To understand this further, if an inductor is connected across a charged capacitor; current will start to flow through the inductor, building up a magnetic field around it and reducing the voltage on the capacitor. Eventually all the charge on the capacitor will be gone and the voltage across it will reach zero.

However, the current will continue, because inductors resist changes in current. The current will begin to charge the capacitor with a voltage of opposite polarity to its original charge. Due to Faraday's law, the EMF which drives the current is caused by a decrease in the magnetic field, thus the energy required to charge the capacitor is extracted from the magnetic field. When the magnetic field is completely dissipated the current will stop and the charge will again be stored in the capacitor, with the opposite polarity as before.

Then the cycle will begin again, with the current flowing in the opposite direction through the inductor.



Source: Wikipedia

The charge flows back and forth between the plates of the capacitor, through the inductor. The energy oscillates back and forth between the capacitor and the inductor until (if not replenished from an external circuit) internal resistance makes the oscillations die out.

In most applications the tuned circuit is part of a larger circuit which applies alternating current to it, driving continuous oscillations.

If these are at the natural oscillatory frequency (Natural frequency), resonance will occur. The tuned circuit's action, known mathematically as a harmonic oscillator, is similar to a pendulum swinging back and forth, or water sloshing back and forth in a tank; for this reason the circuit is also called a *tank circuit*. The natural frequency (that is, the frequency at which it will oscillate when isolated from any other system, as described above) is determined by the capacitance and inductance values. In typical tuned circuits in electronic equipment the oscillations are very fast, thousands to billions of times per second.

APPLICATIONS OF LC CIRCUIT

The resonance effect of the LC circuit has many important applications in signal processing and communications systems.

Resonant circuits have a variety of applications, for example, in the tuning mechanism of a radio or a TV set. The antenna of a radio accepts signals from many broadcasting stations. The signals picked up in the antenna acts as a source in the tuning circuit of the radio, so the circuit can be driven at many frequencies.

But to hear one particular radio station, we tune the radio. In tuning, we vary the capacitance of a capacitor in the tuning circuit such that the resonant frequency of the circuit becomes nearly equal to the frequency of the radio signal received. When this happens, the amplitude of the Current with the frequency of the signal of the particular radio station in the circuit is maximum.

It is important to note that resonance phenomenon is exhibited by a circuit only if both L and C are present in the circuit. Only then do the voltages across L and C cancel each other (both being out of phase)

- The most common application of tank circuits is tuning radio transmitters and receivers. For example, when we tune a radio to a particular station, the LC circuits are set at resonance for that particular **carrier frequency.**
- Both parallel and series resonant circuits are used in induction heating.

8. SUMMARY

In this module we have learnt

- **In this module we learnt alternating current circuits with inductors and resistance, capacitors and resistance and inductor and capacitor.**
- **Behavior of RC RL and LC ac circuits with circuit elements in series.**
- **The Phase relation between current and voltage depends upon resistance and reactance. Reactance depends upon magnitude of L or C and frequency of alternating current used in the circuit.**
- **The meaning of terms:**

Resistance: in a circuit the obstruction offered by a conductor to the current following Ohm's law.

Reactance: In electrical and electronic systems, reactance is the opposition of a circuit element to a change in current or voltage, due to that element's inductance or capacitance.

Impedance: Electrical impedance is the measure of the opposition that a circuit presents to a current when a voltage is applied. In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit.

Phasors: In physics and engineering a phasor, is a complex number representing a sinusoidal function whose amplitude (A), angular frequency (ω), and initial phase (ϕ) are time-invariant. Basically, Phasors are rotating vectors.

Quality Factor: A parameter of an oscillatory system or device, such as a laser, expressing the relationship between stored energy and energy dissipation.

- **Power Factor**: In electrical engineering, the power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit, and is a dimensionless number in the closed interval of -1 to 1.
- **Choke Coil**: In electronics, a choke is an inductor used to block higher-frequency alternating current (AC) in an electrical circuit, while passing lower-frequency or direct current (DC).
- **Watt-less current**: Watt-less current is AC component, whereby the power consumed in the circuit is zero.

- **Sine Function: The sine of an angle is the ratio of the length of the opposite side to the length of the hypotenuse.**