Basic Electronics — NPTEL

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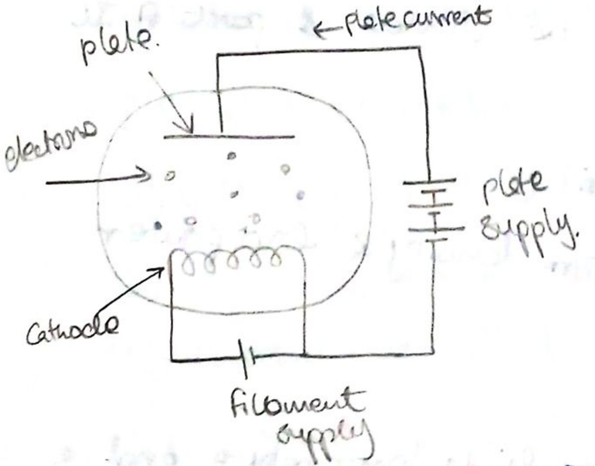
IIT BOMBAY

WEEK 1

Lecture 1 : A brief history of electronics.

→ Vaccum tubes — the diode

↳ was invented by John Fleming



→ Deforest invented the triode by inserting a third electrode betwen cathode and anode called 'Grid' which is negatively charged.

– reduces the plate current.

→ dimension of vaccum tube ~ 5x5 cm.

→ glow like "light bulb" when they conduct

→ consume very high power. (nearly 100's of volts)

→ ENIAC computer

↳ one of the first computers. Constructed using an entire room, using vaccum tubes.

- heralded as the ~~"Great~~ "Giant Brain" by the press.
- Several tubes burned out everyday, leaving it non-functional about half the time and soldering joints gave problems.
- could be programmed to perform complex sequences of operations.

→ **The first transistor**

- vacuum tube was a bulky and fragile device which consumed significant power.

- The first transistor was a "point contact transistor". The modern transistor is a junction transistor.

- invented first by Shockley, Bardeen & Brattain at Bell Labs

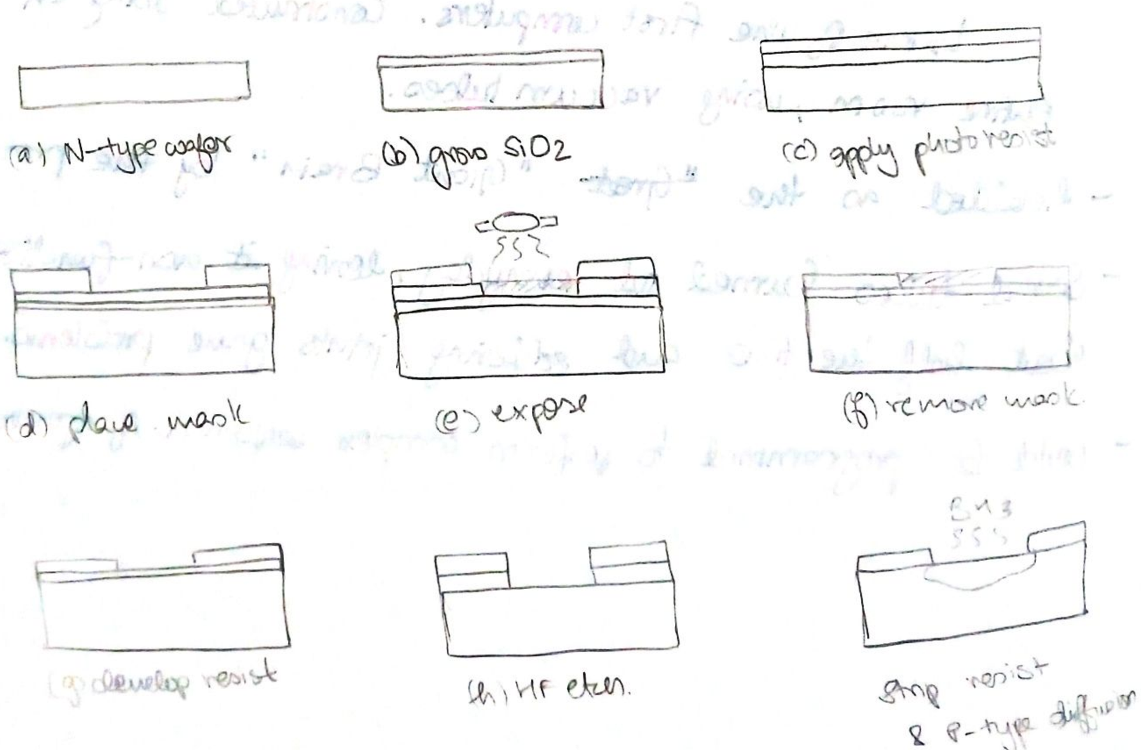
→ **Semiconductor Technology**.

→ bipolar transistor – still important as device & part of IC

→ However, for digital circuits, MOSFET has gained popularity
  ∟ cause of high integration density & low power consumption it offers.

Diffusion furnace: wafer heated to very high temperature and a gas is passed over the surface of the wafer to dope it, either p-type or n-type.

Fabrication steps of p-n junction diode:



Scaling: shrinking of the smallest definable dimension on the chip has enabled a huge no. of transistors to be integrated on one chip.

Moore's law: a prediction by Gordon Moore: number of transistors will double every 2 years

Lecture 2: SuperPosition

Consider circuits made up of elements of the following types:

1) Resistor ($V = RI$)
2) Voltage controlled Voltage Source ($V = \alpha V_c$)
3) voltage controlled current source ($I = G V_c$)
4) current controlled voltage source ($V = R I_c$).
5) current controlled current source ($I = \beta I_c$)

What is common in all equations?

* They are all linear. That means quantity on left such as V or I depends on the quantity on the righ V_c or I_c.

and independent sources of the following types.

- Independent DC voltage source ($V = V_0$ (constant))
- Independent DC current source ($I = I_0$ (constant)).

How do we use Superposition?

* Superposition enables us to consider the independent sources one at a time (with the others deactivated), compute the desired quantity of interest in each case, and get the net result by adding the individual contributions.

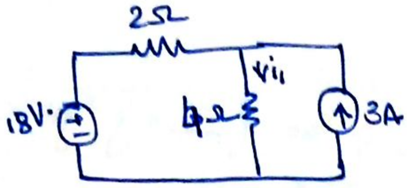
The procedure is generally simpler than considering all independent sources simultaneously.

* "Deactivating" an independent source?

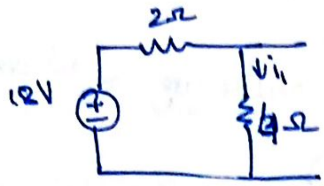
($I_0 = 0$) current source $\rightarrow$ replace with an open circuit

($V_0 = 0$) voltage source $\rightarrow$ replace with short circuit

Example 1



Case 1: Keep Vs, deactivate Is.



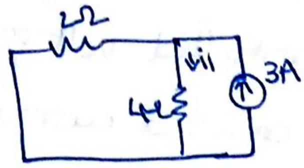
$18V = 6i_1$

$i_1' = \frac{18}{6} = 3A$

$i_1 = i_1' + i_1'' = 3A + 1A$

$\boxed{i_1 = 4A}$

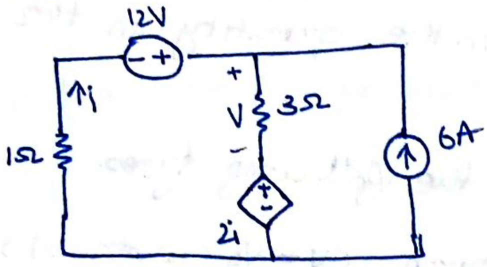
Case 2: Keep Is, deactivate Vs



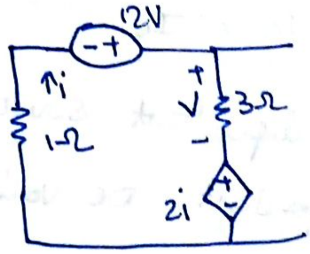
$i_1 = 3 \times \frac{2}{2+4}$

$i_1'' = 1A$

Example 2



Case 1: Keep Vs, deactivate Is



$12V - 2i(V) = (3+1)i$

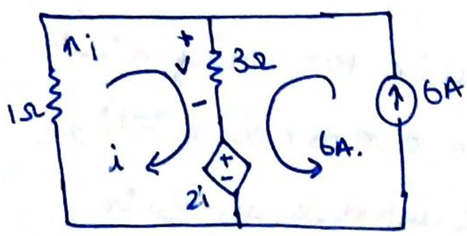
$12 - 6i = 0$

$12 = 6i$

$i' = \frac{12}{6} = 2A$

$V' = 2 \times 3 = 6V$

Case 2: Keep Is, deactivate Vs



KVL : $i + (i+6)3 + 2i = 0$

$6i + 18 = 0$

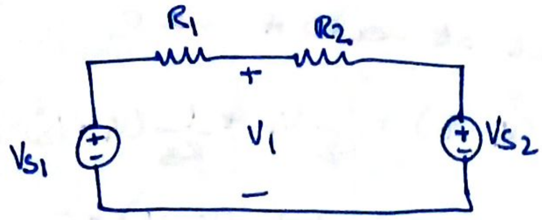
$i'' = -3A$

$V'' = 3(6-3) = 9V$

$V = v' + v'' = 6 + 9$

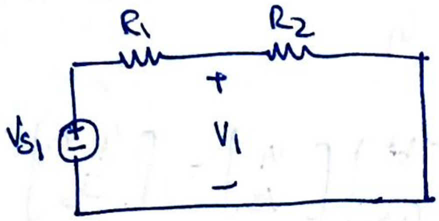
$\underline{\underline{= 15V}}$

Example 3



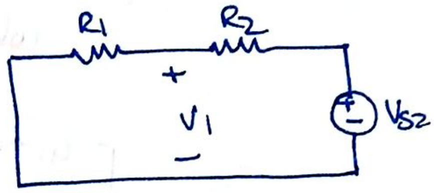
Find V_1 using superposition.

V_{s1} alone:



$$V_1' = \frac{R_2}{R_1+R_2} V_{s1}$$

V_{s2} alone:

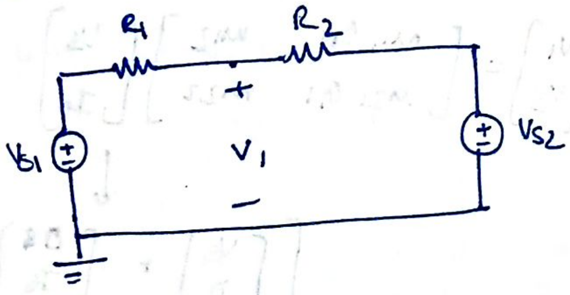


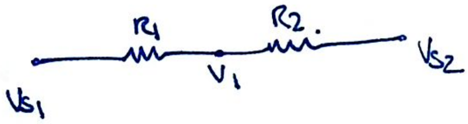
$$V_1'' = \frac{R_1}{R_1+R_2} V_{s2}$$

(voltage division rule).

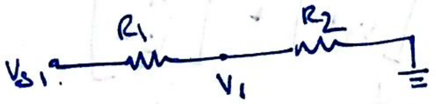
$$V_1 = V_1' + V_1'' = \frac{R_2}{R_1+R_2} V_{s1} + \frac{R_1}{R_1+R_2} V_{s2}$$

Alternate method (reference node / ground node).



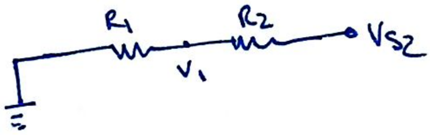


V_{s1} alone:



$$V_1' = \frac{R_2}{R_1+R_2} V_{S1}.$$

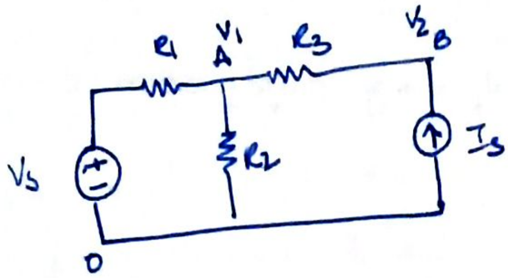
V_{s2} alone.



$$V_1'' = \frac{R_1}{R_1+R_2} V_{S2}.$$

$$V_1 = V_1' + V_1'' = \frac{R_2}{R_1+R_2} V_{S1} + \frac{R_1}{R_1+R_2} V_{S2}$$

* Superposition: why does it work?



KCL at nodes A and B.

$$\frac{1}{R_1}(V_1 - V_s) + \frac{1}{R_2}V_1 + \frac{1}{R_3}(V_1 - V_2) = 0$$

$$-I_s + \frac{1}{R_3}(V_2 - V_1) = 0$$

Rewriting in matrix form:

where $\frac{1}{R} = G$

$$\begin{bmatrix} G_1 + G_2 + G_3 & -G_3 \\ -G_3 & G_3 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} G_1 V_s \\ I_s \end{bmatrix}$$

ie $$A \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} G_1 V_s \\ I_s \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = A^{-1} \begin{bmatrix} G_1 V_s \\ I_s \end{bmatrix}$$

$$= \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} G_1 V_s \\ I_s \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} M_{11} G_1 & M_{12} \\ M_{21} G_1 & M_{22} \end{bmatrix} \begin{bmatrix} V_s \\ I_s \end{bmatrix}$$

$$\downarrow$$

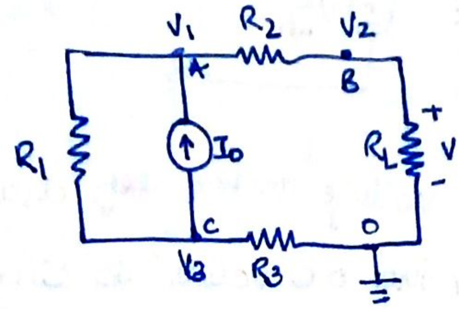
$$\left[\begin{bmatrix} V_s \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I_s \end{bmatrix} \right]$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \underbrace{\begin{bmatrix} V_1' \\ V_2' \end{bmatrix}}_{\substack{\text{due to } V_s \\ I_s = 0}} + \underbrace{\begin{bmatrix} V_1'' \\ V_2'' \end{bmatrix}}_{\substack{\text{due to } I_s \\ V_s = 0}}$$

All other currents and voltages are linearly related to V_1 and V_2.

Thevenin's Theorem

Consider



Assigning node voltages w.r.t to reference node.

Taking KCL

@A : $G_1(V_1 - V_3) + G_2(V_1 - V_2) - I_0 = 0$

@B = $G_2(V_2 - V_1) + G_L(V_2 - 0) = 0$

@C : $G_1(V_3 - V_1) + G_3 V_3 + I_0 = 0.$

Write in matrix form:

$$G \leftarrow \left\{ \begin{bmatrix} G_1+G_2 & -G_2 & -G_1 \\ -G_2 & G_2+G_L & 0 \\ -G_1 & 0 & G_1+G_3 \end{bmatrix} \right. \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} I_0 \\ 0 \\ -I_0 \end{bmatrix}$$

ie $GV = I_S$.

using Cramer's rule,

$$\cancel{V_2 = \det \left[G_1 + G_2 \ \ V_1 \right.} \quad V_2$$

$$V_2 = \frac{\Delta \begin{bmatrix} G_1+G_2 & I_0 & -G_1 \\ -G_2 & 0 & 0 \\ -G_1 & -I_0 & G_1+G_3 \end{bmatrix}}{\Delta G.} = \frac{\Delta_1}{\Delta G.} = \frac{\Delta_1}{\Delta + G_L \Delta_2}$$

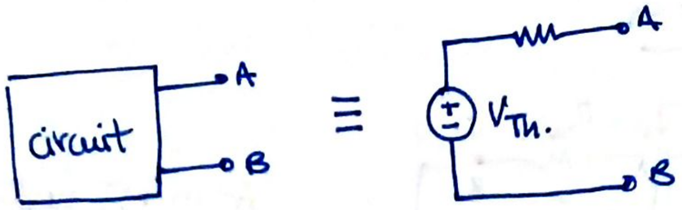
open circuit value of V_2 $\quad V_2^{oc} = \frac{\Delta_1}{\Delta}$

$$V_2 = \frac{\Delta_1 / \Delta}{1 + G_L \Delta_2 / \Delta} = \frac{V_2^{oc}}{1 + \frac{\Delta_2}{R_L}} = \frac{R_L}{R_L + \frac{\Delta_2}{\Delta}} V_2^{oc}$$

Defining $R_{Th} = \frac{\Delta_2}{\Delta}$ (Thevenin resistance)

$$V_2 = \frac{R_L}{R_L + R_{Th}} V_2^{oc}$$

$\frac{\Delta_2}{\Delta}$ has units of resistance



Let V_{oc} be the open circuit voltage for the left circuit. For the Thevenin equivalent ckt, the o c voltage is simply V_{Th} since there is no voltage drop across R_{Th} in this case.

$\rightarrow V_{Th} = V_{oc}$.

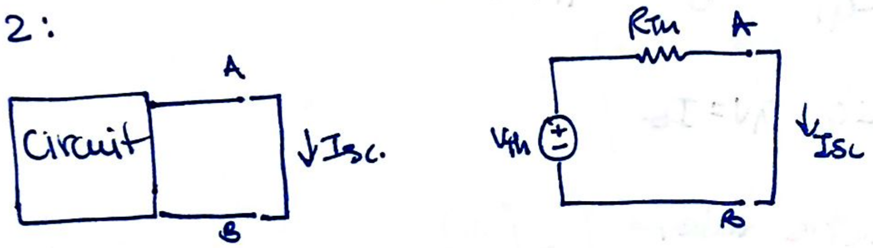
Method 1:

De activate all independent sources.

This amts to making $V_{Th} \to 0$ in thevenin equivalent ckt.

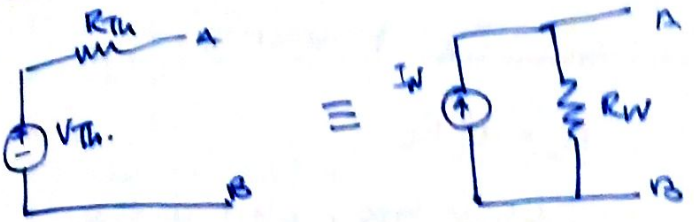
You can also use a test source. by connecting to the original circuit.

Method 2:



$V_{oc} = V_{Th}$, $I_{sc} = \dfrac{V_{Th}}{R_{Th}} = \dfrac{V_{oc}}{R_{Th}} \rightarrow \boxed{R_{Th} = \dfrac{V_{oc}}{I_{sc}}}$

Norton Equivalent circuit

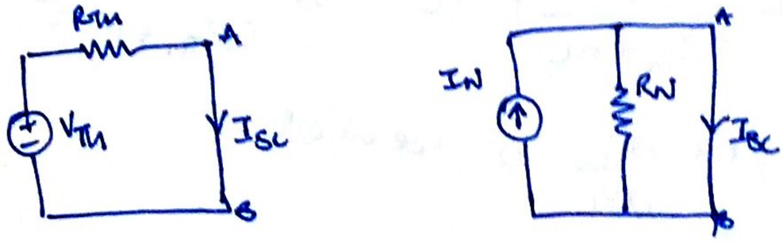


consider open ckt case.

Thevenin ckt $V_{AB}=V_{Th}$

Norton ckt $V_{AB}=I_N R_N$

$$V_{Th}=I_N R_N$$



Consider the short circuit case.

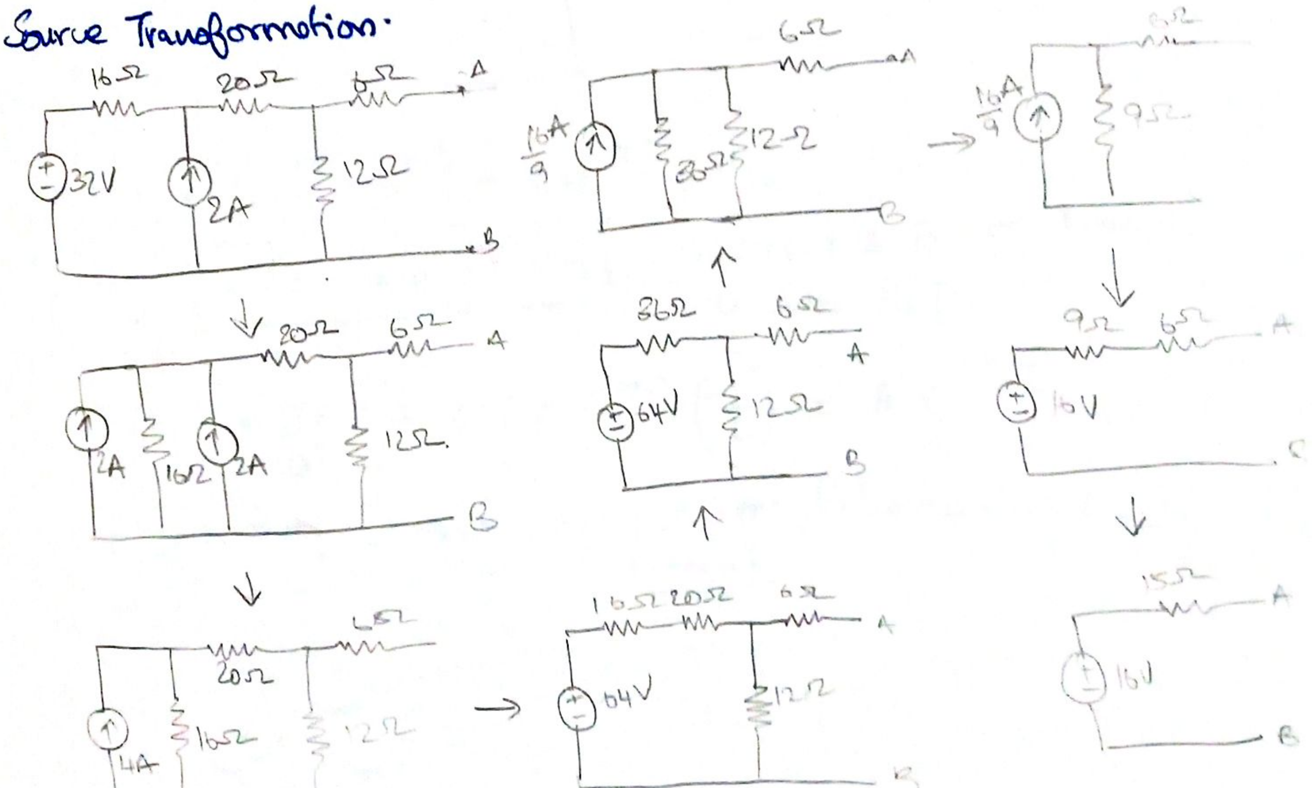
Thevenin ckt $I_{sc}=V_{Th}/R_{Th}$.

Nortion ckt $I_{sc}=I_N$

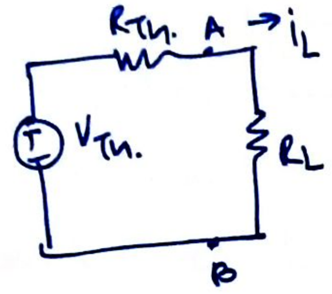
$$V_{Th}=\frac{V_{Th}}{R_{Th}}R_N \rightarrow R_{Th}=R_N.$$

$\boxed{R_{Th}=R_N}$ $\boxed{I_N=\frac{V_{Th}}{R_{Th}}}$

Source Transformation.



Maximum Power Transfer.



Power transferred to load is

$$P_L = i_L^2 R_L$$

For a given black box, what is the value of R_L for which P_L is maximum?

~~Replace the bla~~

$$i_L = \frac{V_{Th}}{R_{Th}+R_L}, \quad P_L = V_{Th}^2 \times \frac{R_L}{(R_{Th}+R_L)^2}$$

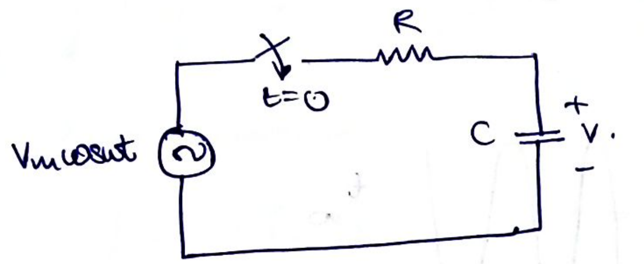
For $\frac{dP_L}{dR_L} = 0$ we need

$$\Rightarrow \boxed{R_{Th} = R_L}$$

Lecture 5 - Phasors.

- What is sinusoidal steady state?

Let us understand with an example.



Here $I = C\frac{dV_c}{dt} = CV'$

$R(CV_c') + V_c = V_m \cos\omega t, \quad t>0$ —— ①

The solution $V_c(t)$ is made up of two components

$$V_c(t) = V_c^{(h)}(t) + V_c^{(p)}(t).$$

$V_c^{(h)}(t)$ — satisfies the homogeneous differential equation.

$$RCV_c' + V_c = 0.$$

from which $V_c^{(h)}(t) = Ae^{-t/\tau}$ with $\tau = RC$.

$V_c^{(p)}(t) \rightarrow$ particular solution

Since the forcing function is $V_m \cos\omega t$ we try

$$V_c^{(p)}(t) = C_1 \cos\omega t + C_2 \sin\omega t.$$

Substituting in 1, we get

$$\omega RC(-C_1 \sin\omega t + C_2 \cos\omega t) + C_1 \cos\omega t + C_2 \sin\omega t = V_m \cos\omega t.$$

C_1 & C_2 can be found by equating eqns on LHS & RHS.

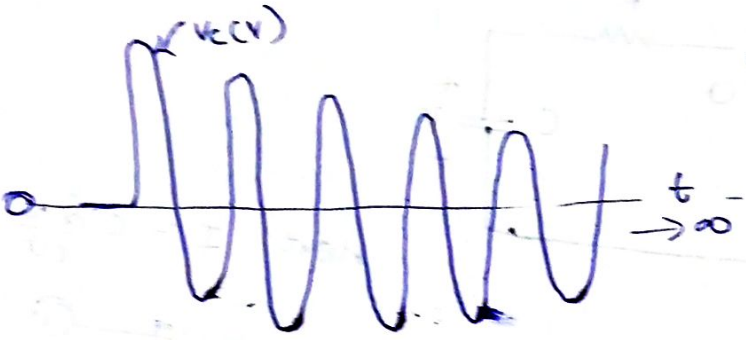
The complete solution.

$$V_c(t) = Ae^{(-t/\tau)} + C_1 \cos\omega t + C_2 \sin\omega t.$$

As $t \to \infty$, the exponential term becomes zero

$$V_C(t) = C_1 \cos \omega t + C_2 \sin \omega t$$

This is known as the "<u>sinusoidal steady state</u>" response since all quantities (currents and voltages) in the circuit are sinusoidal in nature. [@ $t \to \infty$].



<u>PHASORS</u>

In sinusoidal steady state, "phasors" can be used to represent currents and voltages.

A phasor is a complex number.

$$\vec{X} = X_m \angle\theta = X_m e^{(j\theta)}$$

In time domain.

$$x(t) = Re[X e^{j\omega t}] = Re[X_m e^{j\theta} e^{j\omega t}] = Re[X_m e^{j(\omega t + \theta)}]$$

$$x(t) = X_m \cos(\omega t + \theta).$$

- Substantially simplifies analysis of circuits in <u>S.S.S.</u>

$$\vec{X} = X_m \angle\theta = X_m e^{j\theta} = X_m \cos\theta + j X_m \sin\theta$$

The term <u>ωt</u> is <u>always implicit.</u>

Addition of phasors:

$$v(t) = v_1(t) + v_2(t)$$
$$= V_{m1}\cos(\omega t + \theta_1) + V_{m2}\cos(\omega t + \theta_2)$$

↳ 2 sinusoidal quantities.

Now phasors corresponding to $v_1(t)$ & $v_2(t)$

$$\vec{V} = \vec{V_1} + \vec{V_2} = V_{m1}e^{j\theta_1} + V_{m2}e^{j\theta_2}.$$

In time domain, $\vec{V} \Leftrightarrow \tilde{v}(t)$

$$\tilde{v}(t) = Re[\vec{V}e^{j\omega t}]$$
$$= V_{m1}\cos(\omega t + \theta_1) + V_{m2}\cos(\omega t + \theta_2).$$

$$\tilde{v}(t) \doteq v(t).$$

Addition of sinusoidal quantities in time domain can be replaced by addition of the corresponding phasors in sinusoidal steady state.

Impedance of a resistor

$$\boxed{Z = R + j0}$$

Impedance of capacitor.

$$\vec{I} = j\omega C\vec{V}$$

$$\vec{Z} = \frac{\vec{V}}{\vec{I}} = \frac{1}{j\omega C}$$

admittance: $\vec{Y} = \frac{\vec{I}}{\vec{V}} = j\omega C.$

Impedance of Inductor.

$$\vec{V} = j\omega L \vec{I}$$

$$Z = \frac{\vec{V}}{\vec{I}} = j\omega L$$

Sources

Independent sinusoidal current source.

$i_s(t) = I_m \cos(\omega t + \theta)$ can be represented by the phasor $I_m \angle \theta$.

(i.e a constant complex number).

Independent sinusoidal voltage source

$v_s(t) = V_m \cos(\omega t + \theta)$ can be represented by the phasor $V_m \angle \theta$.

(i.e constant complex number)

→ Dependent linear sources can be treated in the sinusoidal steady state in the same manner as a resistor. i.e by the corresponding phasor relationship

Lecture 6 :

In time domain KCL & KVL Eqns

$\sum i_k(t) = 0$ and $\sum V_k(t) = 0$.

In frequency domain KCL & KVL eqns

$\sum \vec{I_k} = 0$ and $\sum \vec{V_k} = 0$.

also $\vec{V} = Z \cdot \vec{I}$ [similar to $V = RI$ but instead deal with complex numbers.]

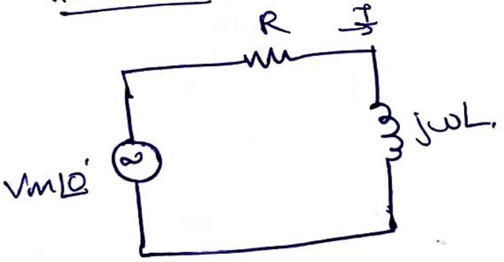
for dependent sources,

time domain, $i(t) = \beta \, i_c(t)$.

Freq domain, $I = \beta I_c$.

$\Rightarrow \therefore$ Circuit analysis in sinusoidal steady state using phasors is therefore very similar to DC circuits with independent and dependent sources and resistors.

RL circuit.



$I = \dfrac{V_m \angle 0}{R + j\omega L} = I_m \angle -\theta$.

where $I_m = \dfrac{V_m}{\sqrt{R^2 + (j\omega L)^2}}$

net angle $= 0° - \tan^{-1}\left(\dfrac{\omega L}{R}\right)$

$\downarrow$ num $\quad \downarrow$ denominator

θ has -ve sign.

In time domain.

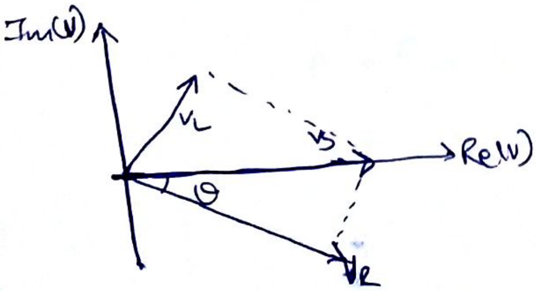
$i(t) = I_m \cos(\omega t - \theta)$

$\vec{V_s} = \vec{V_R} + \vec{V_L}$

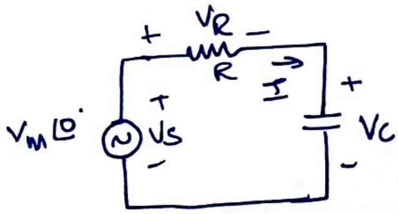
$\vec{V_s} \rightarrow V_m \angle 0$

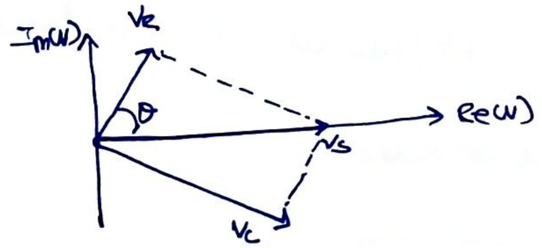
$\vec{V_R} \rightarrow IR = R I_m \angle -\theta$

$\vec{V_L} \rightarrow I \cdot j\omega L = \omega I_m L \angle(-\theta + \pi/2)$



RC Circuit





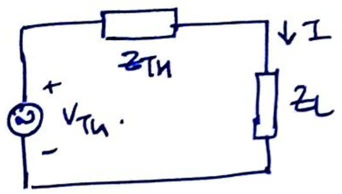
$$I = \frac{V_m \angle 0^\circ}{R + \frac{1}{j\omega C}} = I_m \angle \theta .$$

where $$I_m = \frac{\omega C V_m}{\sqrt{1+(\omega RC)^2}} \qquad \theta = \frac{\pi}{2} - \tan^{-1}(\omega RC)$$

$$V_R = I \times R = R I_m \angle \theta$$
$$V_c = I \times (1/j\omega C) = (I_m/\omega C) \angle \theta - \pi/2$$

KVL eqn, $V_s = V_R + V_c$. → represented using phasor diagram.

Maximum Power Transfer (sinusoidal steady state)



Let $Z_L = R_L + jX_L$, $Z_{Th} = R_{Th} + jX_{Th}$

$I = I_m \angle \phi$

The power absorbed by Z_L is

$$P = \frac{1}{2} I_m^2 R_L$$
$$= \frac{1}{2} \left| \frac{V_{Th}}{Z_{Th} + Z_L} \right|^2 R_L$$
$$= \frac{1}{2} \frac{|V_{Th}|^2}{(R_{Th}+R_L)^2 + (X_{Th}+X_L)^2} R_L$$

For P to be maximum.

$(X_{Th} + X_L)$ must be minimum or zero.

$\Rightarrow X_L = -X_{Th}$.

$$P = \frac{1}{2} \frac{|V_{Th}|^2}{(R_{Th}+R_L)^2} R_L$$

which is max. for $R_{Th} = R_L$.

∴ For max. Power Transfer to load Z_L

$R_L = R_{Th}$, $X_L = -X_{Th}$.

ie $Z_L = Z_{Th}^*$