Module- V

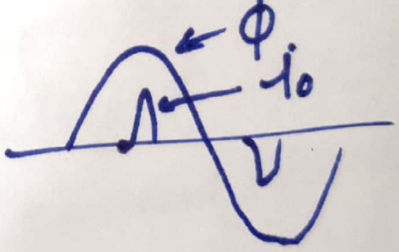
- Harmonics & Harmonic Filters
- HVDC Light / Plus
- Multi-Terminal HVDC Systems (MTDCs)

Harmonic Analysis: Sources of Harmonics:

i) **Generators:** Due to non-uniform field winding → Harmonics in generated voltage → Smaller in amplitude & hence negligible

ii) **Converter Transformers:** For sinusoidal flux, the excitation current is non-sinusoidal.

$i_0 \downarrow\downarrow$ → negligible



iii) **Converters:** α

I_s → distorted

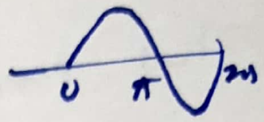
Characteristic harmonics, $h = np \pm 1$
$n = 1, 2, 3, \ldots$
$p = 6, 12$

Uncharacteristic harmonics

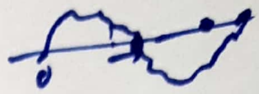
Causes: - Valves are not fixed at equal 60° intervals due to unbalanced 3-ϕ source.

61 → 12 → 23 → 34 → 45 → 56

- Due to Jitter in electronic circuitry (Shif in ZC instants);



- Saturation of converter Xmers;



- Interaction of charact. harmonics with ~~com~~ fundamental component in ~~ee~~ non-linear elements of Power system,
- Some control actions like CEA control

- Don't need separate filters for uncharacteristic harmonics

Effect of Harmonics:

i) Ineffective operation of converter & sometimes instability of CC control

ii) Maloperation ~~on~~ of critical/sensitive equipments

iii) Additional losses in AC motors

iv) False tripping of relays

v) EM Interference with nearby telephone lines

vi) Shifting of ZCs;

vii) OVs due to harmonic resonances

viii) Blowing of fuses

③

$$\% \, THD = \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} \times 100$$

Variation of Harmonic current with α and u:

i) For $u = 0°$, as $\alpha \uparrow$, Harmonics $\uparrow$

ii) Magnitude of harmonics $\downarrow$ as $u \uparrow$.

iii) Each harmonic decreases upto a certain limit at an angle of $u = \frac{2\pi}{n}$ beyond which harmonics $\uparrow$ slowly.

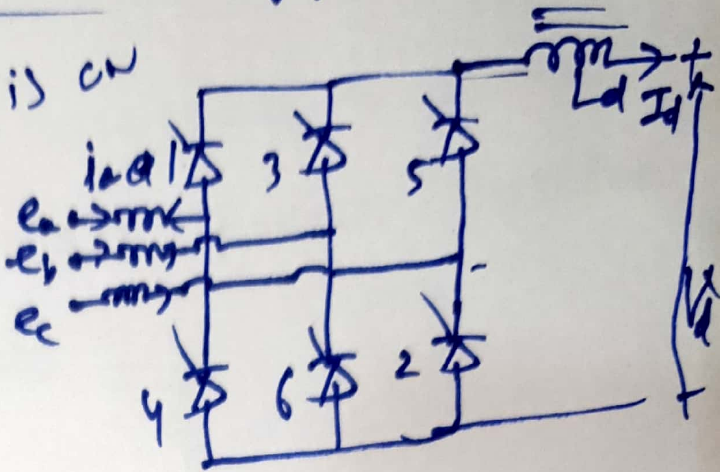
For $u > \frac{2\pi}{n}$, harmonics $\uparrow$ with $u \uparrow$

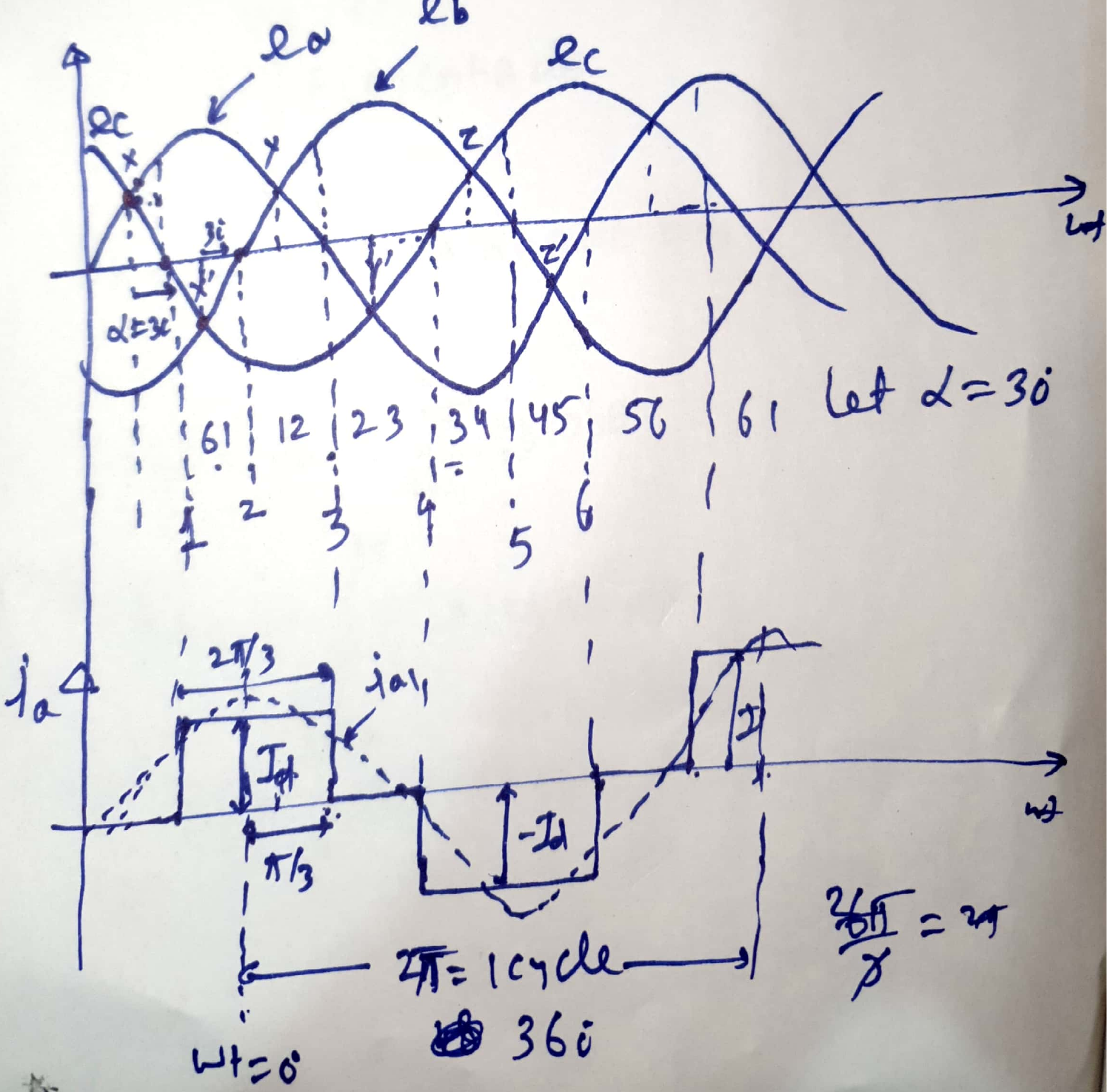
—o—

Mathematic Expression for source or line current drawn by a converter:

$i_a = +I_d$ when 1 is ON

$i_a = -I_d$ if 4 is ON





By Fourier Analysis,

$$F(\theta) = \frac{A_0}{2} + \sum_{n=1}^{\infty} (A_n \cos n\theta + B_n \sin n\theta)$$

where A_0 is DC component of current and A_n and B_n are Fourier coefficients.

$$A_0 = \frac{1}{\pi}\int_0^{2\pi} F(\theta) d\theta = 0$$

$$A_n = \frac{1}{\pi}\int_0^{2\pi} F(\theta) \cos n\theta \, d\theta$$

$$B_n = \frac{1}{\pi}\int_0^{2\pi} F(\theta) \sin n\theta \, d\theta = 0$$

$$\therefore F(\theta) = i_a = \sum_{n=1}^{\infty} \underline{\underline{A_n}} \cos n\theta \quad \text{——} \; (1)$$

Now, $$A_n = \frac{1}{\pi}\int_0^{2\pi} F(\theta) \cos n\theta \, d\theta$$

$$A_n = \frac{1}{\pi}\left\{ \int_0^{\pi/3} I_d \cos n\theta \, d\theta + \int_{\pi/3}^{2\pi/3} 0 \, d\theta + \int_{2\pi/3}^{4\pi/3} -I_d \cos n\theta \, d\theta + \int_{4\pi/3}^{5\pi/3} 0 \, d\theta + \int_{5\pi/3}^{2\pi} I_d \cos n\theta \, d\theta \right\}$$

$$A_h = \frac{I_d}{\pi h}\left\{ \left|\sin h\theta\right|_0^{\pi/3} + \left|-\sin h\theta\right|_{2\pi/3}^{4\pi/3} \right.$$
$$\left. \left|\sin h\theta\right|_{5\pi/3}^{2\pi} \right\}$$

$$A_h = \frac{I_d}{\pi h}\left[\sin h\pi/3 - \sin h\frac{4\pi}{3} + \sin h\frac{2\pi}{3} \right.$$
$$\left. + \sin h 2\pi - \sin h\frac{5\pi}{3} \right]$$

For $h = 1$ (fundamental),

$$A_1 = \frac{I_d}{\pi}\left(\sin\frac{\pi}{3} - \sin\frac{4\pi}{3} + \sin\frac{2\pi}{3} \right.$$
$$\left. + \underbrace{\sin 2\pi}_{0} - \sin\frac{5\pi}{3} \right)$$

$$= \frac{I_d}{\pi}\left[\frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} \right]$$

$$= \frac{\cancel{4}^{2}\sqrt{3}}{\cancel{2}\pi} I_d$$

$$\Rightarrow A_1 = \frac{2\sqrt{3}}{\pi} I_d = I_{1m} \quad \text{— (2)}$$

~~For h=2,~~ For $h = 3$,

Scanned with CamScanner

$$A_3 = \frac{I_d}{3\pi}\left[\sin 3\frac{\pi}{3} - \sin 3\frac{4\pi}{3} + \sin 3\frac{2\pi}{3} + \sin 3\times 2\pi - \sin 3\times 5\frac{\pi}{3}\right]$$

$$A_3 = \frac{I_d}{3\pi}\left[\underset{0}{\sin \pi} - \underset{0}{\sin 4\pi} + \underset{0}{\sin 2\pi} + \underset{0}{\sin 6\pi} - \underset{0}{\sin 5\pi}\right]$$

$$\therefore A_3 = 0 \quad — (3)$$

For $h = 5$. (5th harmonic component),

$$A_5 = \frac{I_d}{5\pi}\left[\sin\frac{5\pi}{3} - \sin\frac{20\pi}{3} + \sin\frac{10\pi}{3} + \underset{0}{\sin 10\pi} - \sin\frac{25\pi}{3}\right]$$

$$A_5 = \frac{I_d}{5\pi}\left[-\frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2}\right]$$

$$A_5 = -\frac{2\sqrt{3}}{5\pi} I_d = -\frac{I_{1m}}{5} \quad — (4)$$

$$A_7 = \frac{2\sqrt{3}}{7\pi} I_d = \frac{I_{1m}}{7} \quad — (5)$$

$\therefore$ From eqn. ①, $i_a = \sum_{n=1}^{\infty} A_n \cos n\theta$

$$\boxed{i_a = \frac{2\sqrt{3} I_d}{\pi}\left[\cos\theta - \frac{1}{5}\cos 5\theta + \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta \cdots\right]}$$

$$i_a = A_1 \cos\theta + A_3 \cos 3\theta + A_5 \cos 5\theta + A_7 \cos 7\theta + A_9 \cos 9\theta + A_{11} \cos 11\theta + A_{13} \cos 13\theta - -$$

Fund. comp. of current,

$$i_{a1} = \frac{2\sqrt{3} I_d}{\pi} \cos\theta = I_{a1max.} \cos\theta$$

Peak value of fund. comp. of current,

$$I_{a1max.} = \frac{2\sqrt{3} I_d}{\pi}$$

RMS value of fund. comp. of source current,

$$I_{a1} = \frac{I_{a1max.}}{\sqrt{2}} = \frac{2\sqrt{3} I_d}{\pi \times \sqrt{2}} \times \frac{\sqrt{2}}{\sqrt{2}}$$

$$= \frac{\cancel{2}\sqrt{6} I_d}{\cancel{2}\pi} = \boxed{\frac{\sqrt{6}}{\pi} I_d}$$

Scanned with CamScanner

$\therefore$ For $\underline{\underline{Y-Y}}$ system,

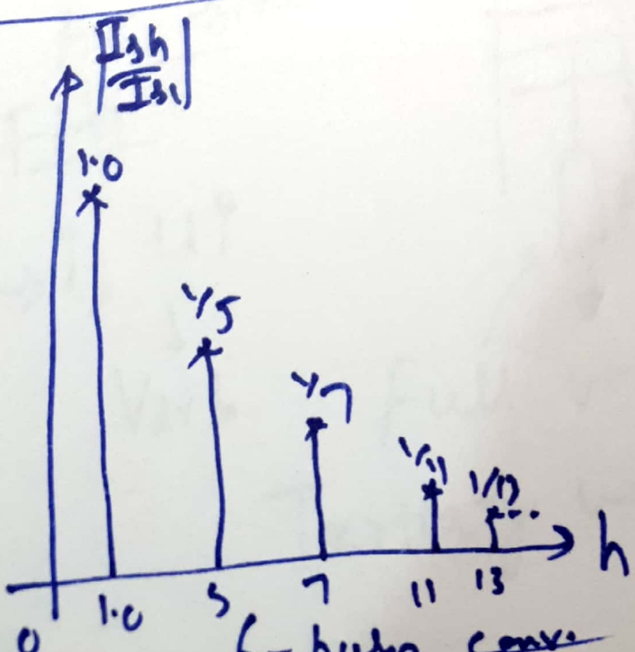
$$i_a = \frac{2\sqrt{3}I_d}{\pi}\left[\cos\theta - \frac{1}{5}\cos 5\theta + \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta \cdots\right]$$

For $\underline{\underline{Y-\Delta}}$ connected system,

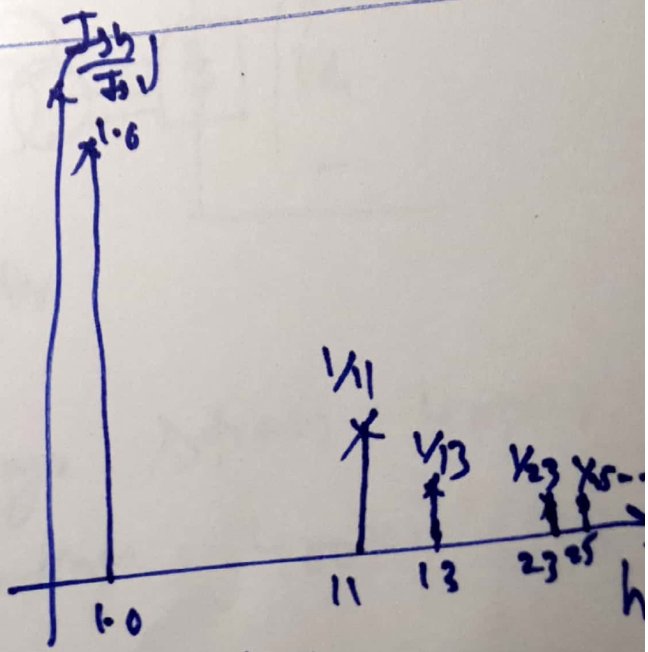
$$i_a = \frac{2\sqrt{3}I_d}{\pi}\left[\cos\theta + \frac{1}{5}\cos 5\theta - \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta \cdots\right]$$

$\therefore$ For a 12-pulse converter,

$$\boxed{i_a = \frac{2\sqrt{3}I_d}{\pi}\left[\cos\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta \cdots\right]}$$



6-pulse conv.



12-pulse conv.

Harmonic Filters: Purpose:

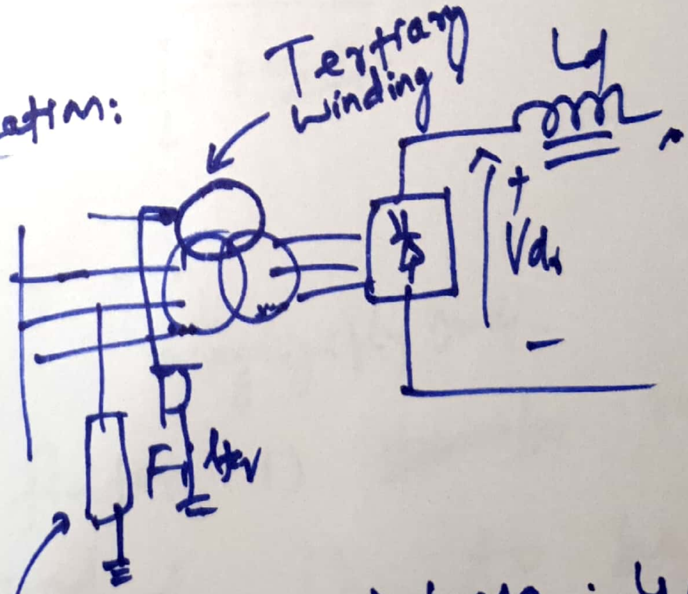
i) To suppress harmonic currents
ii) To provide some reactive power support

Harmonic Filters

- Based on Location
  - DC side Filter
  - AC side Filter
- Based on type of connection
  - Series Filter
  - Shunt Filter
- Based on Sharpness of Tuning
  - Tuned Filters
  - Damped Filter

a) Based on Location:

AC side Filter



$Z_s \uparrow$, $U \uparrow$

↓

Var ↓

Full voltage stress : 400KV

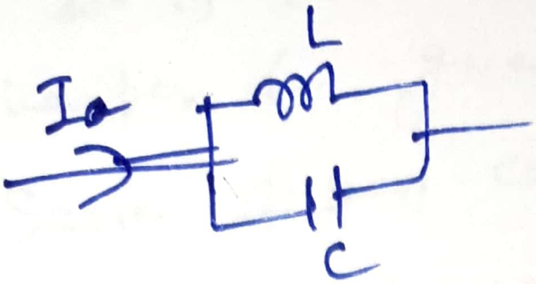
Tertiary winding : 400KV/66KV

↓

Filter

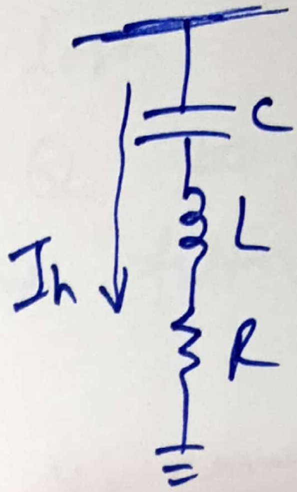
b) Based on type of connection:

i) Series Filter:



O.C. (High Z) to harmonics & S.C. (Low Z) to fund. comp. of line current

Shunt Filter



O.C. (High Z) to fund. comp. of current & S.C. (Low Z) to harmonics

$$I_{filter} = \sqrt{I_1^2 + \Sigma I_h^2}$$

$$I_{F1} = I_h$$

Negligibly small.

Comparison:

- Series filter is resting on ground & is to be insulated properly
- Series filter carries full line current → higher cost → bulky & more losses

(12)

On the other hand, shunt filter has to carry smaller harmonic currents & ~~as~~ is hence smaller in size, cheaper & gives low losses.

- Series filters consume Q ~~as~~ as I^2X whereas shunt filters generate Q.

- Shunt filters can be Y-connected or Δ-connected (Generally Y-connected) whereas series filters are phase filters.

---

c) Based on Sharpness of Tuning:

i) Tuned filters & ii) Damped filter

i) Tuned filters : a) Single-tuned filter

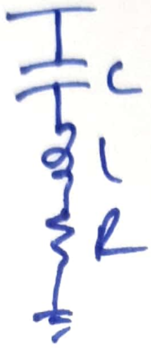
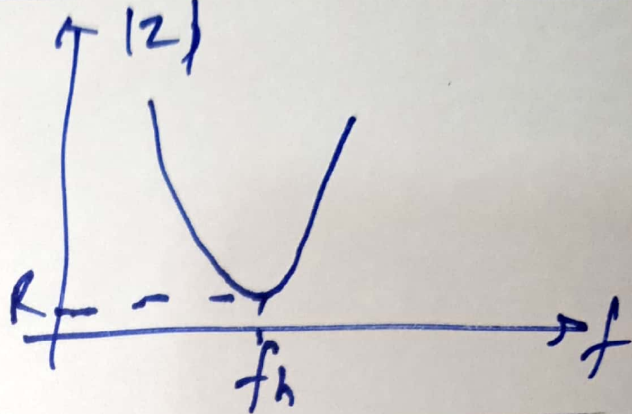
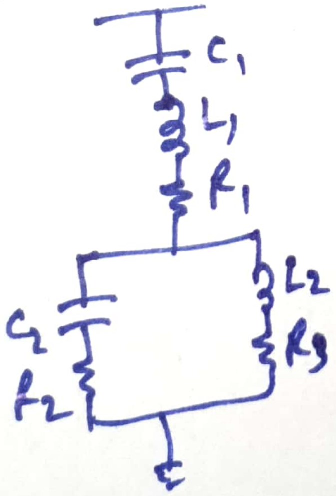
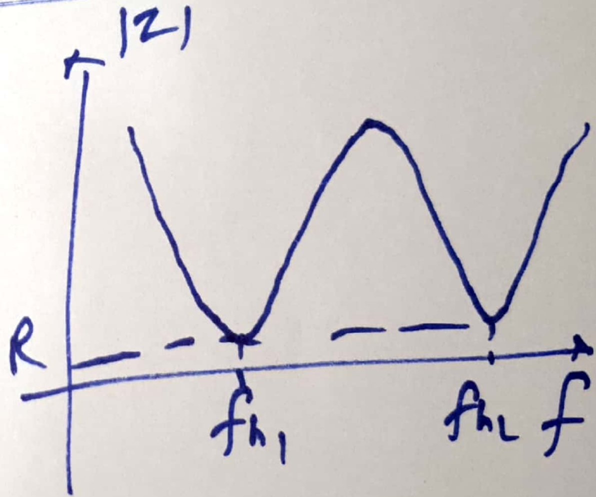
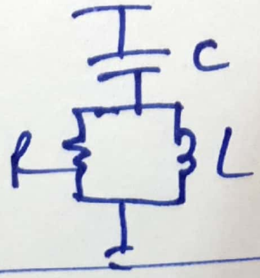
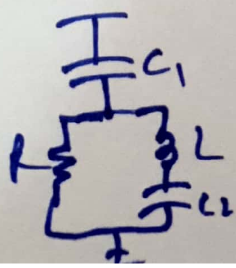
b) Double-tuned filter

ii) Damped filters: characts:

- Low Q - Sharp tuning is not required - can tolerate large steady-state variation in frequency

- Low transient voltages due to high R
- Low power loss due to C

(C-type H.P.F.)

<table>
<tr><th>Type of filter</th><th>Circuit</th><th>|Z| Vs frequency</th></tr>
<tr><td>Single-tuned Filter</td><td>
</td><td>
</td></tr>
<tr><td>Double-tuned filter</td><td>
</td><td>
</td></tr>
<tr><td>Second-order H.P.F.</td><td>
</td><td></td></tr>
<tr><td>C-type H.P.F.</td><td>
</td><td></td></tr>
</table>