PMSM Problems Notes

Q1: L_d is direct inductance aligned with the magnetic of the PM, $L_q \perp$ with it, what is L_d when a motor have >1 PM?

→ It will be combined to a vector, we can determine it

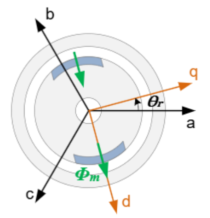
Q2: What is the meaning of L_d and L_q?

$$\begin{cases} v_{ds} = R_s \cdot i_d + L_d \cdot \frac{di_d}{dt} + E_d \\ v_{qs} = R_s \cdot i_q + L_q \cdot \frac{di_q}{dt} + E_q \end{cases}$$

→ • l_d tell you how the motor respond to the current flowing in the same direct as PM field.

• L_q ———————— perpendicular to the PM field.

Q3: PMSM fundamental equation



PMSM reference frame convention

$$V_{abcs} = r_s \cdot i_{abcs} + \frac{d\lambda_{abcs}}{dt}$$

$$\underbrace{\lambda_{abcs}}_{\text{flux linkage of the motor}} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{ls} + L_{ms} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{ls} + L_{ms} \end{bmatrix} + \begin{bmatrix} \sin\theta_r \\ \sin(\theta_r - \frac{2\pi}{3}) \\ \sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix} \Phi_m$$

stator phase winding mutual inductance

Stator phase winding leakage inductance

flux linkage due to the PMs

- Simplifies by using dq axis:

$$\begin{cases} v_{qs} = R_s \cdot i_{qs} + L_q \cdot \frac{d i_{qs}}{dt} + \omega_r \cdot \lambda_{ds} \\ v_{ds} = R_s \cdot i_{ds} + L_d \cdot \frac{d i_{ds}}{dt} + \omega_r \cdot \lambda_{ds} . \end{cases}$$

$$\begin{cases} \lambda_{qs} = L_{qs} \cdot i_{qs} \\ \lambda_{ds} = L_{ds} \cdot i_{ds} + \phi_m \end{cases}$$

- with PM-PMSM: $L_s = L_{ds} = L_{qs} = \frac{3}{2} L_{ms}$:
- with IPMSM :

* SM - PMSM FOC

- Electromagnetic of PM-PMSM:

$$T_e = \frac{3}{2} \bar{p} (\lambda_{ds} \cdot i_{qs} - \lambda_{qs} \cdot i_{ds}) \quad (1)$$

$$= \frac{3}{2} \bar{p} (L_s \cdot i_{ds} \cdot i_{qs} - L_s i_{qs} i_{ds} + \phi_m \cdot i_{qs})$$

$$\boxed{= \frac{3}{2} \bar{p} \cdot (\phi_m \cdot i_{qs})} \quad (2)$$

→ i_{ds} has no effect

→ $I_s = \sqrt{i_{qs}^2 + i_{ds}^2}$

= motor rated current

=> should $\begin{cases} i_{ds} = 0 \\ i_{qs} = I_s \end{cases}$

- IPMSM: (1) → $\boxed{T_e = \underbrace{\frac{3}{2} \bar{p} \cdot \phi_m \cdot i_{qs}}_{\text{PM excitation torque}} + \underbrace{\frac{3}{2} \bar{p} \cdot (L_{ds} - L_{qs}) \cdot i_{qs} \, i_{ds}}_{\text{reluctance torque}}}$

→ Because $L_{ds} < L_{qs}$ → T_e have the same direction if $i_{ds} < 0$

→ $\boxed{\text{MTPA}}$ (Maximum-torque-per-ampere) is calculate. the references (i_{qs}, i_{ds}) which maximize the ratio between produced torque vs copper losses

$$I_s = \sqrt{i_{qs}^2 + i_{ds}^2} \le I_s$$

Q3: Why and when we want over modulation ?

1. Run in higher speed : $V \propto \omega . \psi$ flux linkage

ω electrical speed.

2. Deliver full Torque in Field-Weakening Region.

 - In const power / field weakening region, we want reduce flux (using i_d) to go ↗ rated speed.

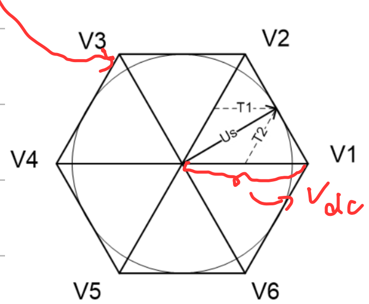
But • Back EMF still rise with speed.

→ To maintain the speed (hence torque), you need higher voltage to over come restance + inductance + back EMF.

3. Compensate with limited DC bus voltage

- Modulation index : $m = \frac{V_{ref}}{V_{max\ linear}}$

+ Linear modulation: $0 < m \le 1$
+ Over modulation: $1 < m \le m_{max}$
+ Six Step mode : $m = m_{max}$ (square wave)



📈 2. Linear vs Overmodulation

Mode	Modulation Index	Output Voltage	Harmonics
Linear	$m \le 1$	Sinusoidal	Low
Overmodulation	$m > 1$	Higher	More THD
Six-step	Max	Highest	Highest

+ Linear modulation in SVPWM : $V_{ref} \le \frac{\sqrt{3}}{2} V_{dc}$

Q4 : The relationship between phase current frequency and the motor speed?

$$\boxed{f_{elec} = p \cdot f_{mech}}$$ (1) p = num of pole pairs
f_{mech} = rev/s
n = RPM

or

$$\boxed{f_{elec} = \frac{p \cdot n}{60}}$$ (2) → one mechanical revolution causes multiple electrical cycles (if the motor have multiple poles)

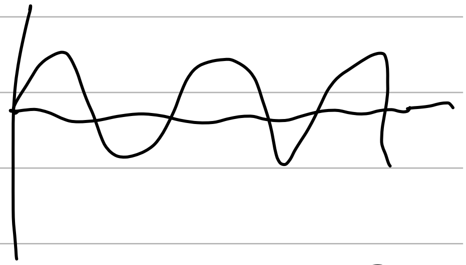
Ex: A motor: 8 poles → 4 pp
Running at 1500 RPM → $f_{elec} = \frac{4 \cdot 1500}{60} = 100$ Hz

Q5: Why we want low THD (Total Harmonic Distortion)?

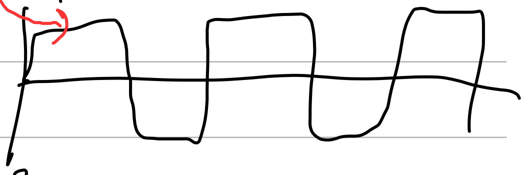
1. More Harmonics = More losses
   - Harmonics generate extra current at high freq
   - These currents cause:
     + I^2R loss
     + Iron losses (eddy current and hysteresis) in the stator and rotor core.
     + ↗ switching losses in the inverter.
2. Torque Ripple: Harmonics interact with rotor magnets or produce non-sinusoidal torque.
   → Torque ripple → + Vibration.
   + Noise.
   + Mechanical stress on bearing and shafts
3. EMI → interface with other electronics
4. Thermal stress → More harmonics → more heat → ↓ age.
5. Grid distortion → Poor power quality, regulation violation.

Q6: PMSM

BT mình đo dòng pha có dạng kiểu



mà dòng BLDC có dạng



thế thì có ≠ gì ĐK six step đâu?

→ Có phải SVPWM o ≠ gì six step mà o dùng cảm biến?

(vì dòng đo về để đưa đi estimate E_α, E_β → xđ đc θ_r, mà tại đó = phẳng → θ_r o đổi ⇒ o ≠ gì six step??)

Answer:

→ Basically, yes, but in my case, my phase currents from experiments are sinsoidal → My BLDC has sinusoidal Back-emf waveforms (It's depend on the stator winding

{ Distributed winding → sinusoidal waveform
{ Concentrated winding → trapezoidal waveform)

Q7: How SVPWM + Hall sensor control method work?

Answer: • Because Hall sensors only give us 6 sector over a electrical period → 60° resolution.

→ To run SVPWM, we must have continuous θ over time.

→ We must interpole the θ using.

$$\theta(t) = \theta_{start} + \omega_e . t$$

$\omega_e = p.\omega_m$ → must calculate

t → using timer to count from the last Hall transition.

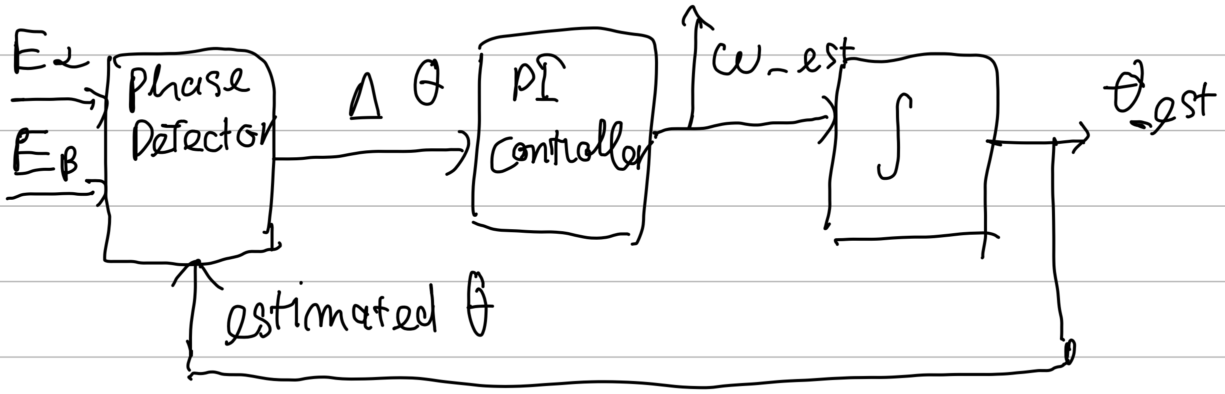
→ Not work well in High frequency.

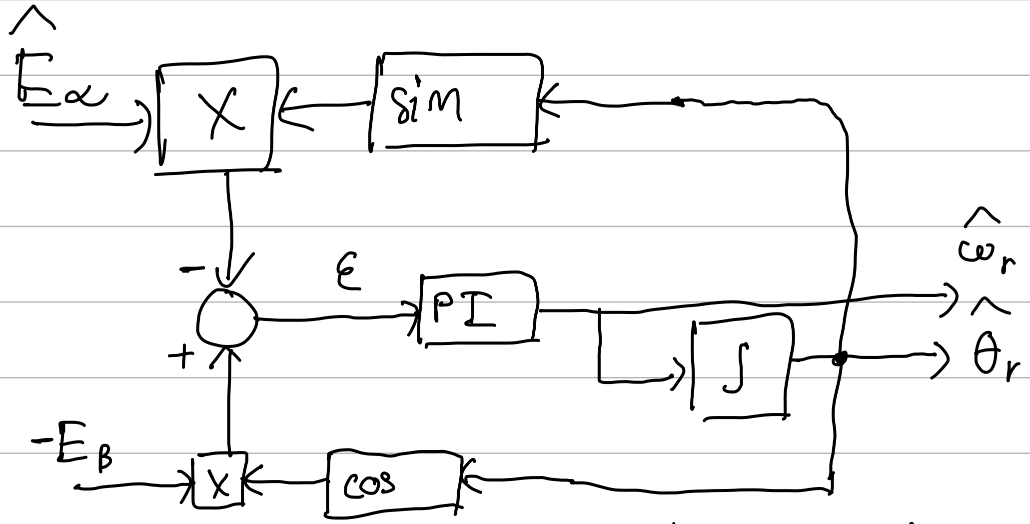
Q8: How PLL work?

Answer:

- What is a PLL?: A Phase-Locked Loop (PLL) is a control system that tracks the phase (angle) of a periodic signal.

→ In motor control, we track the rotor angle $\theta(t)$ (and electrical speed $\omega_e(t)$)





$$\begin{cases} \hat{E}_\alpha = K_e \cdot \tilde{\omega}_r \cdot \cos\tilde{\theta}_r & (1) \\ \hat{E}_\beta = -K_e \cdot \tilde{\omega}_r \cdot \cos\tilde{\theta}_r \end{cases}$$

speed and phase angle of estimated Back Emf

$$\varepsilon = -\hat{E}_\alpha \cdot \sin\hat{\theta}_r - \hat{E}_\beta \cdot \cos\hat{\theta}_r \quad (2)$$

$$(1)(2) \rightarrow \varepsilon = -K_e \cdot \tilde{\omega}_r \cdot \cos\tilde{\theta}_r \cdot \sin\hat{\theta}_r + K_e \cdot \tilde{\omega}_r \cdot \sin\tilde{\theta}_r \cdot \cos\hat{\theta}_r$$

using $\sin(a-b) = \sin(a)\cdot\cos(b) - \cos(a)\cdot\sin(b)$

$$\rightarrow \varepsilon = K_e \cdot \tilde{\omega}_r \cdot \sin(\tilde{\theta}_r - \hat{\theta}_r)$$

$$\Rightarrow \varepsilon \approx K_e . \tilde{\omega}_r . (\tilde{\theta}_r - \hat{\theta}_r)$$

Q9: why we have E_α, E_β like $\boxed{Q8\ (1)}$?

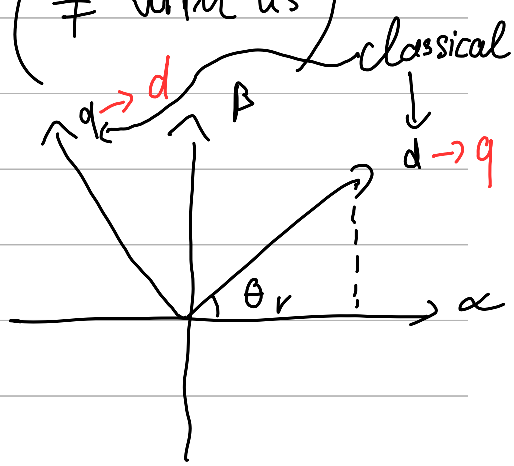
$$\vec{E}_{dq} = [\vec{E}_d = 0, \vec{E}_q = K_e . \hat{\omega}_r]$$

→ Transform to $\alpha\beta$ using inverse park:

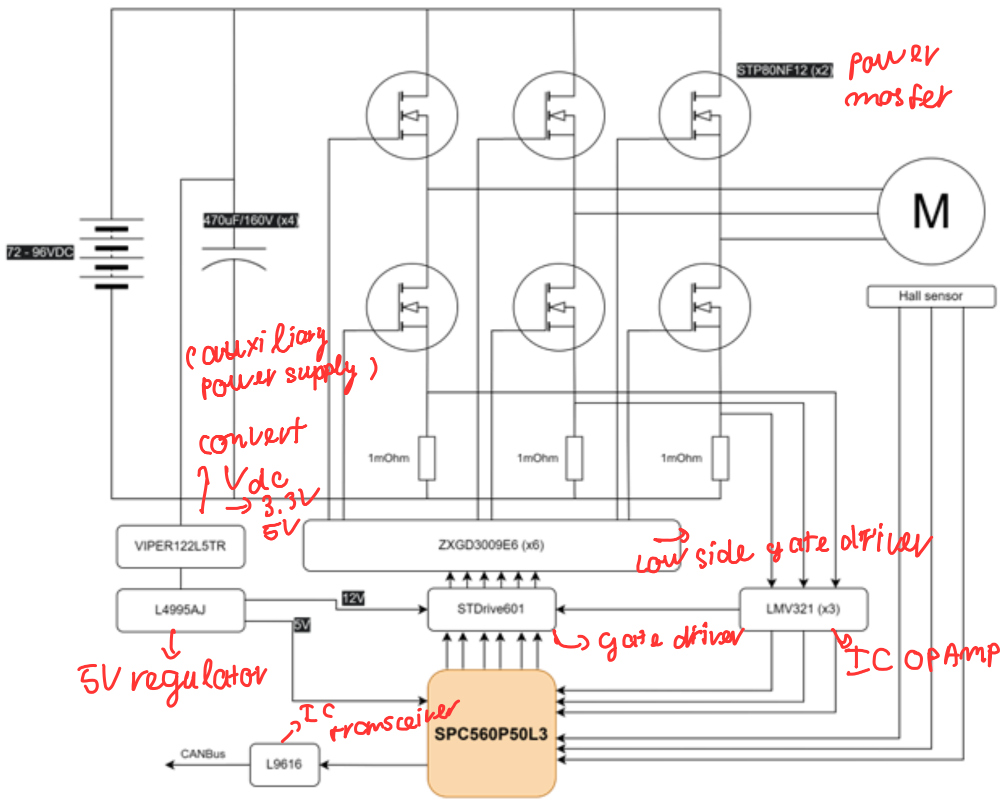
$$\begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta_r) & -\sin\theta_r \\ \sin(\theta_r) & \cos\theta_r \end{bmatrix} \begin{bmatrix} 0 \\ K_e . \hat{\omega}_r \end{bmatrix}$$

$$= \begin{bmatrix} -\sin\theta_r . K_e . \hat{\omega}_r \\ \cos\theta_r K_e . \hat{\omega}_r \end{bmatrix}$$

($\neq$ with us)

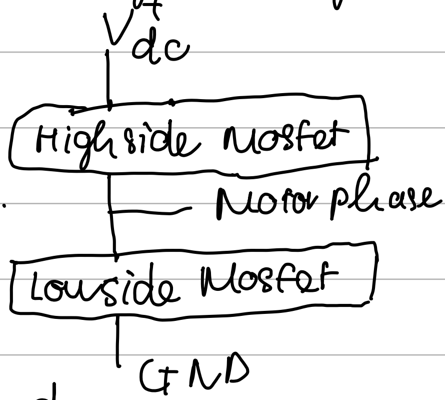


Q10:

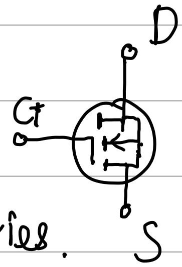


Q10: What is bootstrap circuit, why it need?

- Boostrap circuit is used to power the high side gate drivers of the mosfet.



- The low-side MOSFET gate can be driven directly with respect to ground.
- But the high-side Mosfet need its gate voltage to be higer than its source - and its source is not ground, it's the motor phase.



→ To turn on the high-side switch, its gate must be ~10V higer than the phase volage, which varies.

* What boostrap circuit does?

A bootstrap circuit generate the needed voltage using:

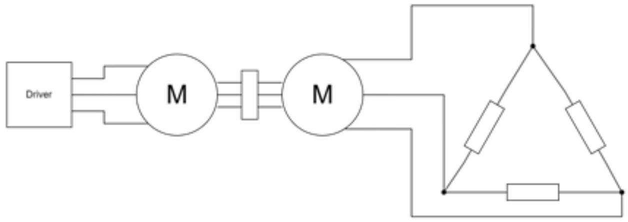
- A diode.
- A bootstrap capeitor.

- When lowsid MosFet is on, the bootstrap cap. charges via the diode from VCC.
- When high side MOSFET is to be turned on, the charged capacitor provides the gate voltage ($V_{boot} = V_{phase} + \sim 10V$)

- To turn on the high-side MosFet, we need:

$$V_{gs} = V_{gate} - V_{source} \approx 10-15V$$

Q11: Why use Δ load but not Y load.



* Y Connection

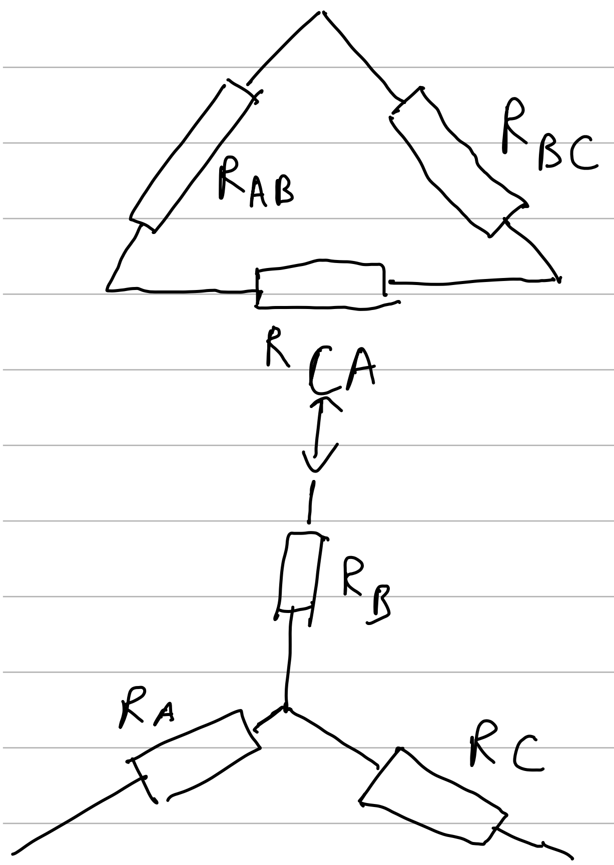
- Phase voltage: $V_{ph} = \frac{V_L}{\sqrt{3}}$
- Line current: $I_L = I_{ph}$

- Active power: $P = \sqrt{3} . V_L . I_L . \cos\varphi$ (W)
- Reactive power: $Q = \sqrt{3} . V_L . I_L . \sin\varphi$ (Var)
- Apparent power: $S = \sqrt{3} . V_L . I_L$. (VA)

* Δ Connection: same

- Phase voltage: $V_{ph} = V_L$.
- Line current: $I_L = \sqrt{3} . I_{ph}$.

* Convert R between Y and Δ connection:



- Δ → Y:

$$R_A = \frac{R_{AB} \cdot R_{CA}}{R_{AB} + R_{CA} + R_{BC}}$$

....

- Y → Δ:

$$R_{AB} = \frac{R_A R_B + R_B . R_C + R_C . R_A}{R_C} .$$

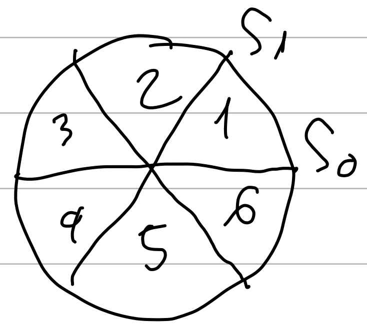
- Balance Loads:
  - $R_A = R_B = R_C = R_Y$
  - → $R_{AB} = R_{AC} = R_{BC} = R_\Delta = 3R_Y$
  - vice versa.

$$R_Y = \frac{R_\Delta}{3}$$

→ Because $R_\Delta = 3R_Y$

→ Need less restances

→ Reduce cost



Q11: Hall for FOC

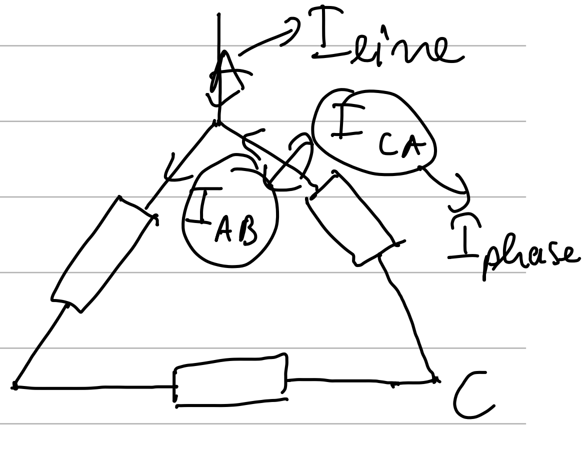
- FOC requires θ
- $\theta_{estimated} = \theta_0 + \omega_e . \Delta T$

θ_0 = vị trí đc tính từ đó

$\omega_e = \frac{\pi/3}{T_{S1} - T_{S0}}$

ΔT = Kc giữa mỗi lần tính = lần cắt

Q12: Explain why we have these equations in Δ and Y connect in Q10?



* Δ - connection:

+ Voltage

- $V_{Line} = V_{AB} = V_A - V_B$
- Each phase is a component connected between two lines.

→ Phase AB across A and B

→ $V_{phase} = V_{AB} = V_{Line}$.

+ Current:

Kirchhoff's current law at node A:

$$I_A = I_{AB} - I_{CA}$$

$$\rightarrow |I_A| = |I_{AB} - I_{CA}|$$

$$= |I_m \angle 0 - I_{CA} \angle 120|$$

$$= \sqrt{I_m^2 + I_m^2 + I_m^2} = \sqrt{3}.I_m$$

$I_{AB} = I_m \angle 0°$

$I_{BC} = I_m \angle -120°$

$I_{CA} = I_m \angle 120°$

$|\vec{A} - \vec{B}| = \sqrt{A^2 + B^2 - 2AB.\cos(\alpha)}$

+ power

For the balanced 3 phase system, each phase delivers the same power:

$$S_{phase} = U_{phase} \cdot I_{phase} \cdot e^{j\varphi}$$

angle between voltage and current (power factor angle)

→ Σ 3 phase:

$$S = 3\, U_{phase} \cdot I_{phase} \cdot e^{j\varphi}$$

→ Express in line values

- Y connection: $\begin{cases} U_{line} = \sqrt{3} \cdot U_{phase} \\ I_{line} = I_{phase} \end{cases}$

$$\rightarrow S = 3 \cdot \frac{U_{line}}{\sqrt{3}} \cdot I_{line} \cdot e^{j\varphi}$$

$$= \sqrt{3} \cdot U_{line} \cdot I_{line} \cdot e^{j\varphi}$$

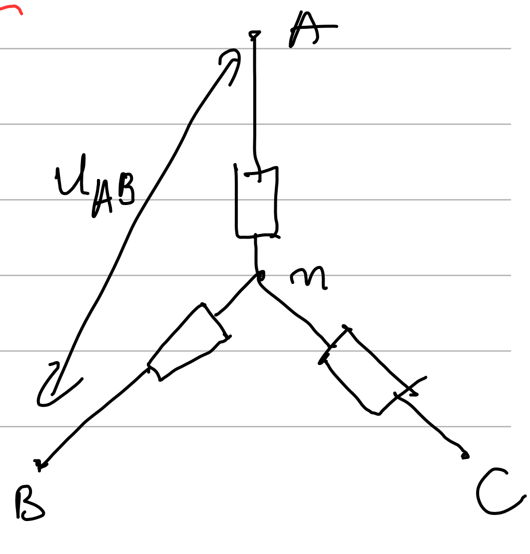
- Δ : $\begin{cases} U_{line} = U_{phase} \\ I_{line} = \sqrt{3} \cdot I_{phase} \end{cases}$

$$\rightarrow S = 3 \cdot U_{line} \cdot \frac{I_{line}}{\sqrt{3}} \cdot e^{j\varphi}$$

$$= \sqrt{3} \cdot \underbrace{U_{line} \cdot I_{line}}_{\text{rms values}} \cdot e^{j\varphi}$$

* Y Connection

- $U_{phase} = U_{AN}$
- $U_{line} = U_{AB}$



$$\rightarrow U_{AB} = U_{AN} - U_{BN}$$

$$= \sqrt{3} \cdot U_{m}$$

- $I_{line} = I_{phase}$