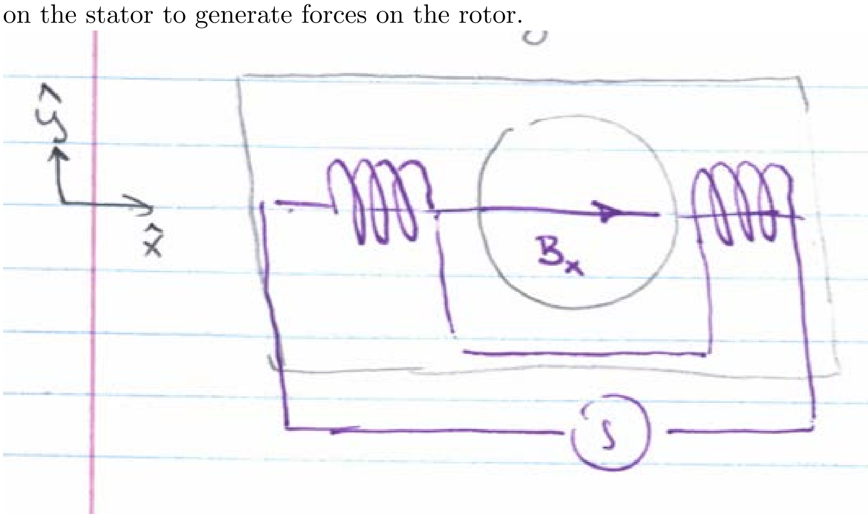
6.622 Power Electronics *Prof. David Perreault*

Lecture 21 - 3-Phase Systems 1

1 The Origins of Polyphase

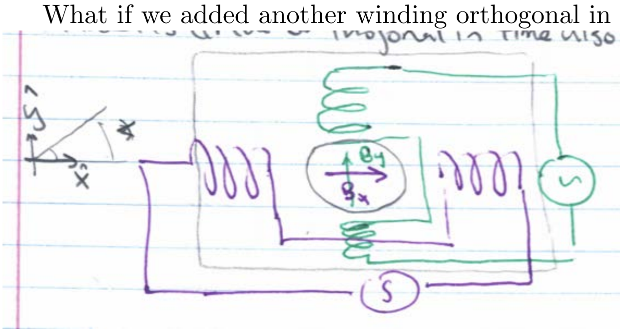
Suppose we wanted to build an AC machine where we wanted to use magnetic fields (or flux) from a winding on the stator to generate forces on the rotor.



with an appropriate sinusoidal drive we'd get

$$\vec{B} = B_0 \cos(\omega t)\hat{x}$$

This could generate a force on a rotor (e.g., to align with $\vec{B}$ e.g., by magnetic poles attracting) Unfortunately, if the rotor were already aligned with the $\hat{x}$ direction, we'd get no force or turning. What if we added another winding orthogonal in space and made its drive orthogonal in time also?



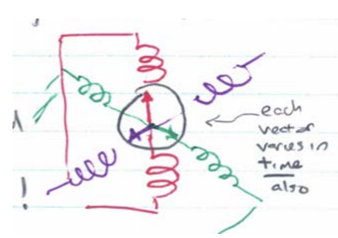
$$\hat{B} = \underline{B_0 cos(\omega t)}\hat{x} + \underline{B_0 sin(\omega t)}\hat{y}$$

$$|B| = B_0$$

$$\angle B = arctan(\frac{sin(\omega t)}{cos(\omega t)}) = \omega t$$

* we get a magnetic field (or flux) of constant magnitude that rotates in space. The rotor will be pulled rotationally at all conditions!

This type of characteristic is one that motivated early polyphase work (Tesla and others). Instead of 2 orthogonal phases, we <u>also</u> get this with 3 phases spaced in <u>time and phase</u> by 120°!



A three-phase voltage set is three sources separated by 120° in phase ($\frac{2\pi}{3}$ radians). The voltages sum to zero at all times.

e.g.

$$v_a = V_s sin(\omega t)$$

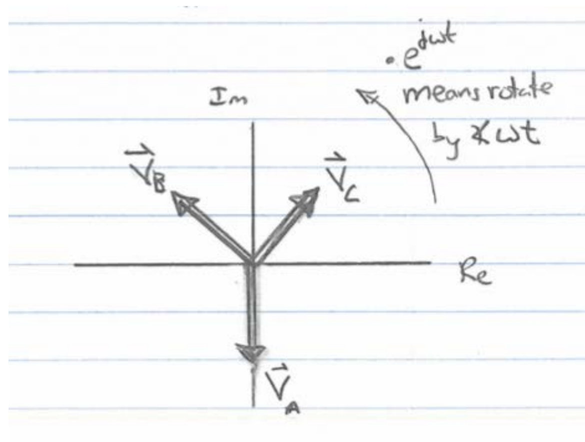
$$v_b = V_s sin(\omega t - \frac{2\pi}{3})$$

$$= Re\{V_s e^{-j\frac{\pi}{2}} \cdot e^{j\omega t}\}$$

$$v_c = V_s sin(\omega t + \frac{2\pi}{3})$$

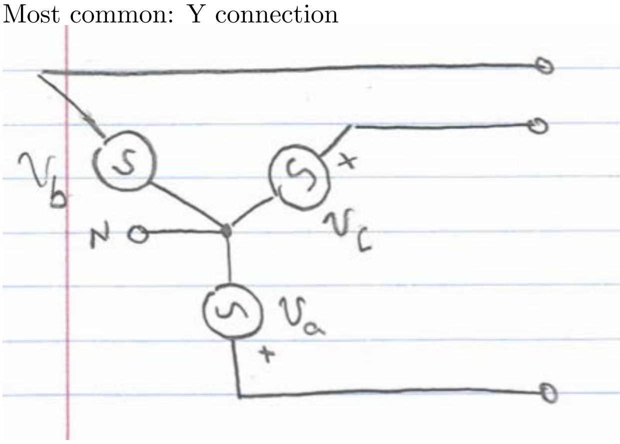
We can represent these as phasors

$$v_x(t) = Re\vec{V_x}e^{j\omega t}$$

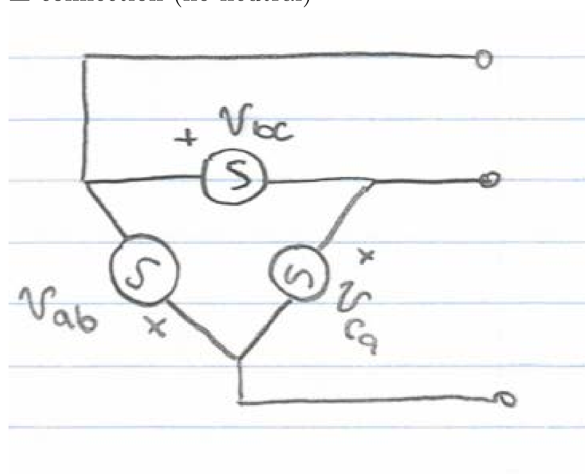


Connection of 3Φ sources

Most common: Y connection

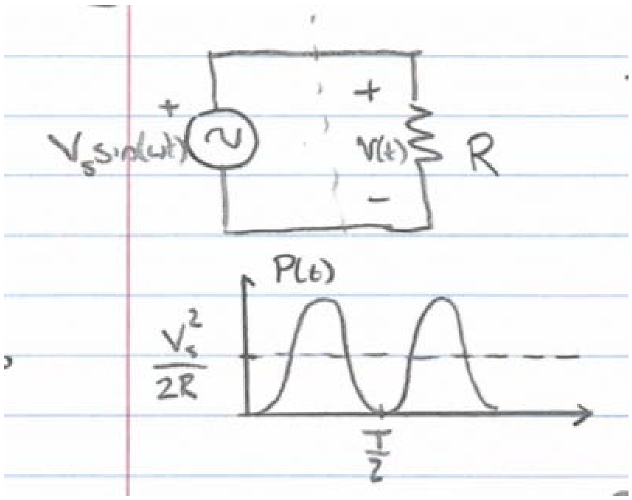


Δ connection (no neutral)



2 Why 3Φ

1. Consider power sourcing capability of 1Φ (best case @ unity P. F.)

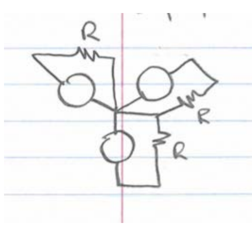


$$P(t) = \frac{v(t)^2}{R} = \frac{V_s^2}{R} sin^2(\omega t)$$
$$= \frac{V_s^2}{2R}[1 - cos(2\omega t)]$$

Even at unity power factor we get power pulsations between 0 and 2x average power at twice the line frequency. This makes sense as we cannot draw power when V $\rightarrow$ 0. This is bad for supplying power to machines, electronics, etc.

- torque pulsations in machine
- 2x f_{line} energy storage needed to maintain constant electronic load power

3Φ power solves this fluctuation problem:



$$P_{total} = \frac{V_s^2}{R}[\sin^2(\omega t) + \sin^2(\omega t - \frac{2\pi}{3}) + \sin^2(\omega t + \frac{4\pi}{3})]$$
$$= \frac{V_s^2}{2R}[3 - \cos(2\omega t) - \cos(2\omega t - \frac{4\pi}{3}) - \cos(2\omega t + \frac{4\pi}{3})]$$

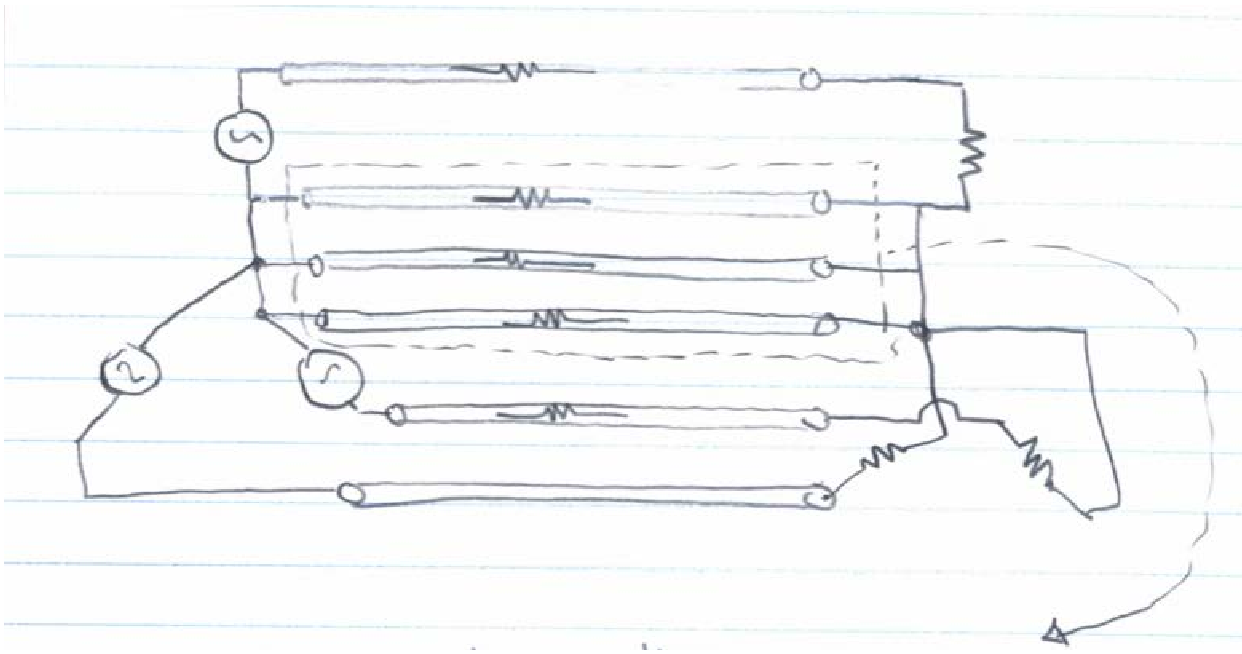
This 3Φ set always adds to zero.

$$\boxed{P_total = \frac{3V_s^2}{2R}}$$

We can source constant power into a balanced 3Φ load w/ no energy storage.

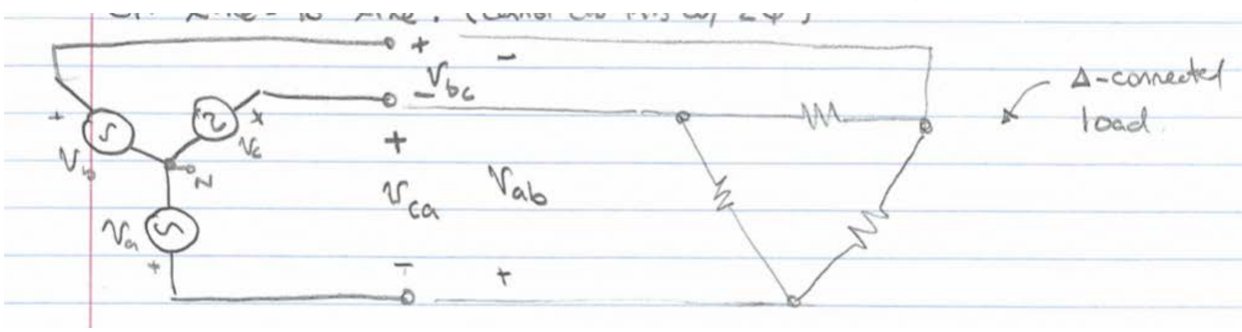
* Two-phase can also do this, as $sin^2(\psi) + cos^2(\psi) = 1$

Consider distribution loss benefits of 3Φ vs. 1Φ or 2Φ: If the load is far from the source

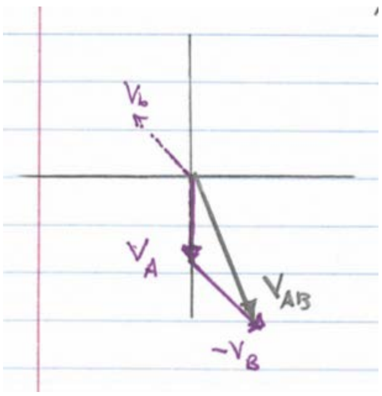


- Because the 3 phase voltages add to zero, if the loads are balanced (equal), the net currents in the return lines add to zero! Ideally, then we can <u>remove</u> the return lines (saving loss + \$). At minimum we use a single small return line to carry only the "imbalance" current (3-phase, 4-wire). This doesn't happen with 2-phase, since voltage vectors don't add to zero.
- Just as voltages (+currents) may add to zero in polyphase, Transformer fluxes add to zero with 3 phase legs, and we can build 3-phase transformers that are smaller and/or more efficient than 3 1-Φ transformers would be.
- Similar benefits can be applied to help improve electric machines =¿ 3Φ provides decided benefits compared to both 1Φ and 2Φ

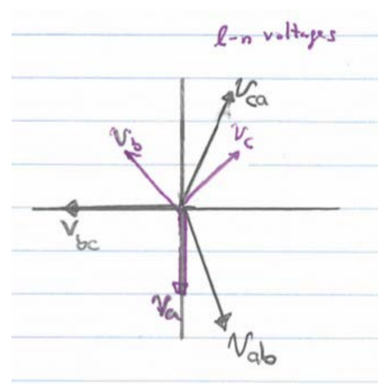
2. With a 3Φ set we can form a balanced 3Φ load on line-to-line (can't do this w/ 2Φ)



We can find line-to-line voltages from vector analysis



$$v_{ab} = v_a - v_b$$
$$= \sqrt{3}v_s sin(\omega t + \frac{\pi}{6})$$



- l-l voltages are $\sqrt(3)$ larger in magnitude than l-n (120V l-n -¿ 208V L-L)
- l-l voltages are shifted by $\frac{\pi}{6}$ (30°) from l-n voltages.

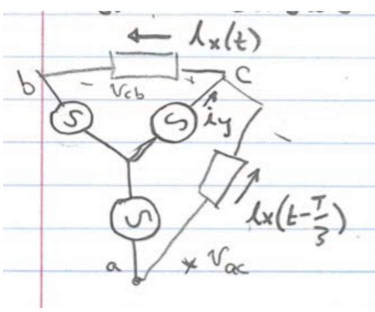
This can be handy depending on the desired load characteristic.

* Also, we can create balanced voltage sets with any phase shift + by appropriate summing of voltages (e.g., w/ transformers)

⇒ Very handy for some designs.

3. 3Φ systems allow cancellation of all triples harmonics (harmonics that are multiples of 3x fundamental frequency)

   How? Consider a "Δ" connected load on a "Y" source



If load is balanced, l-l currents are the same but shifted in time by $\frac{T}{3}$
$\therefore i_y = i_x(t) - i_x(t - \frac{T}{3})$, $\frac{T}{3}$ is 120° @ fundamental
$\therefore$ 3n harmonics of $i_x(t)$ disappear in i_y by harmonic canellation

That is, if $f(t) = \Sigma a_n sin(n\omega t + \Phi_n)$

$$f(t) - f(t - \frac{T}{3}) = \Sigma_n a_n[sin(n\omega t + \Phi_n) - sin(n\omega t + \frac{nT}{3} - \Phi_n)]$$

The sine terms cancel for any multiple of 3

Since the current waveforms have fundamentals that differ by 120° = $\frac{2\pi}{3}$ radians, they are time shifted by $\frac{T}{3}$, and the triple-n harmonic content gets cancelled.

⇒ No even harmonics, 3n's gone ⇒ 5th, 7th, 11th, 13th... left