ECE 3250
Electromagnetic Energy Conversion
Lecture 17: Three-Phase Transformers

Instructor: Adam Barnes

Office: Thornton E206

Email: ab6uy@virginia.edu

Today’s Agenda

- Lab notes
- Three phase systems
- Open delta configuration
- Three phase harmonics
- Power transmission infrastructure

Reverse Engineering a Transformer

- For this week's lab, you must come up with a procedure to reverse engineer the lab transformer, given a plastic ruler, a length of wire, and a multimeter.
  - You can also use spec sheets on Canvas (e.g. specifications for the E-I laminations)
- You must determine:
  - Number of laminations and the specific E-I lamination size used
  - Number of turns on both the primary and secondary
  - The wire gauge and length on the primary and secondary
  - Transformer model parameters R_{fe}, X_m,R_{cu}, and X_L

Measurement notes

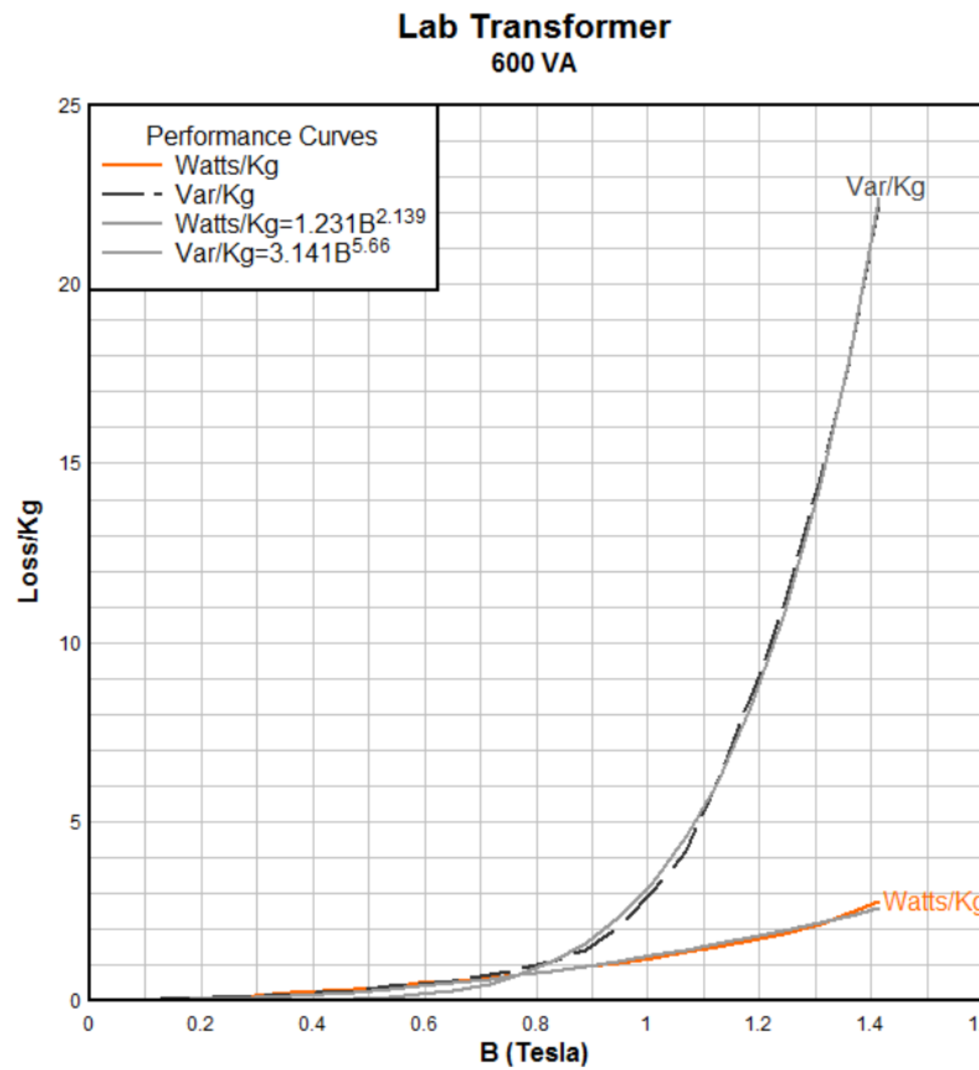
- The size of different E-I laminations varies considerably, but the ratio of the dimensions is fixed to allow them to be stamped out without wasting any steel
- We normally ignore resistance in the wires of our multimeter probes, but if you are measuring a very low resistance, you may need to take it into account.
- When making measurement with the multimeter in general, what are best practices to minimize contact resistance?

Finding the flux density in the lab

- To determine core loss and magnetization, you can refer to this curve
- It requires that you know the magnetic flux density
- We can find that using the transformer equation

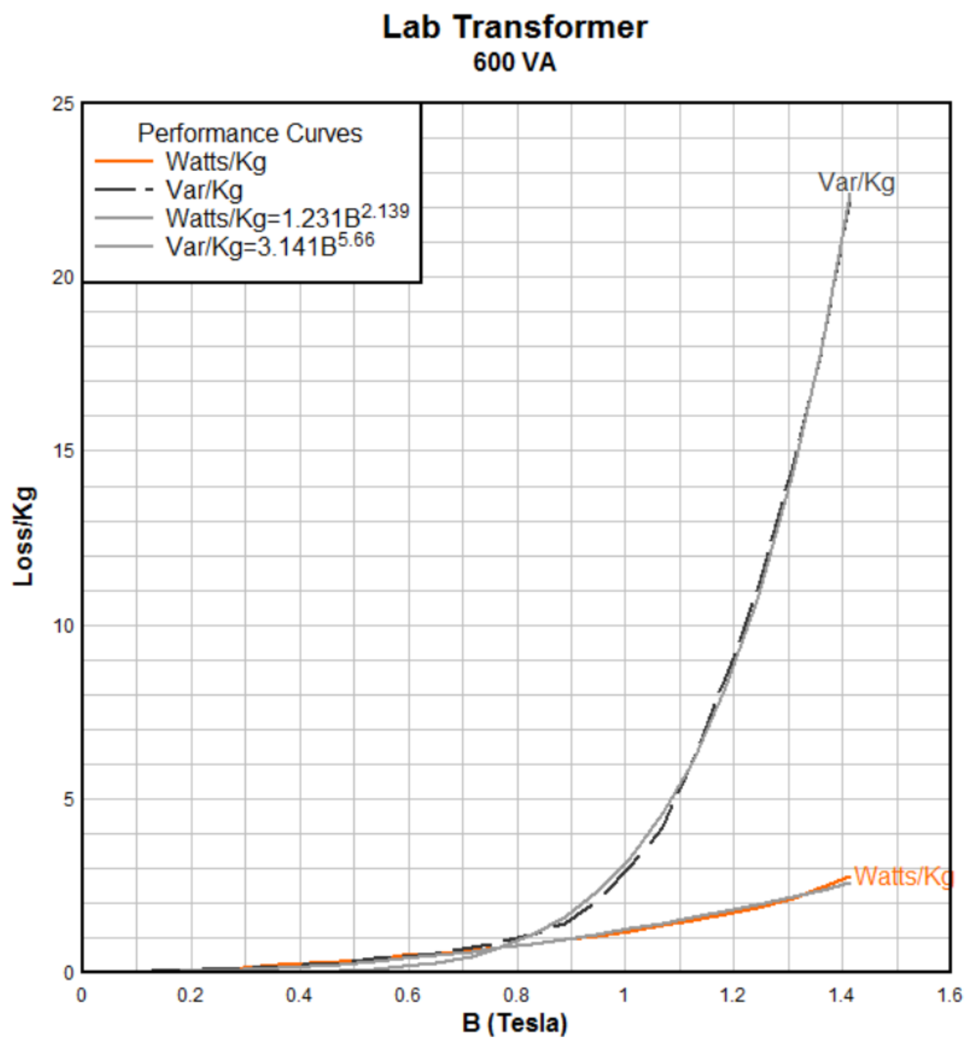
$$\varphi = \frac{V_{rms}}{4.44fN}$$

$$\varphi = BA_{core}$$



Finding the flux density in the lab

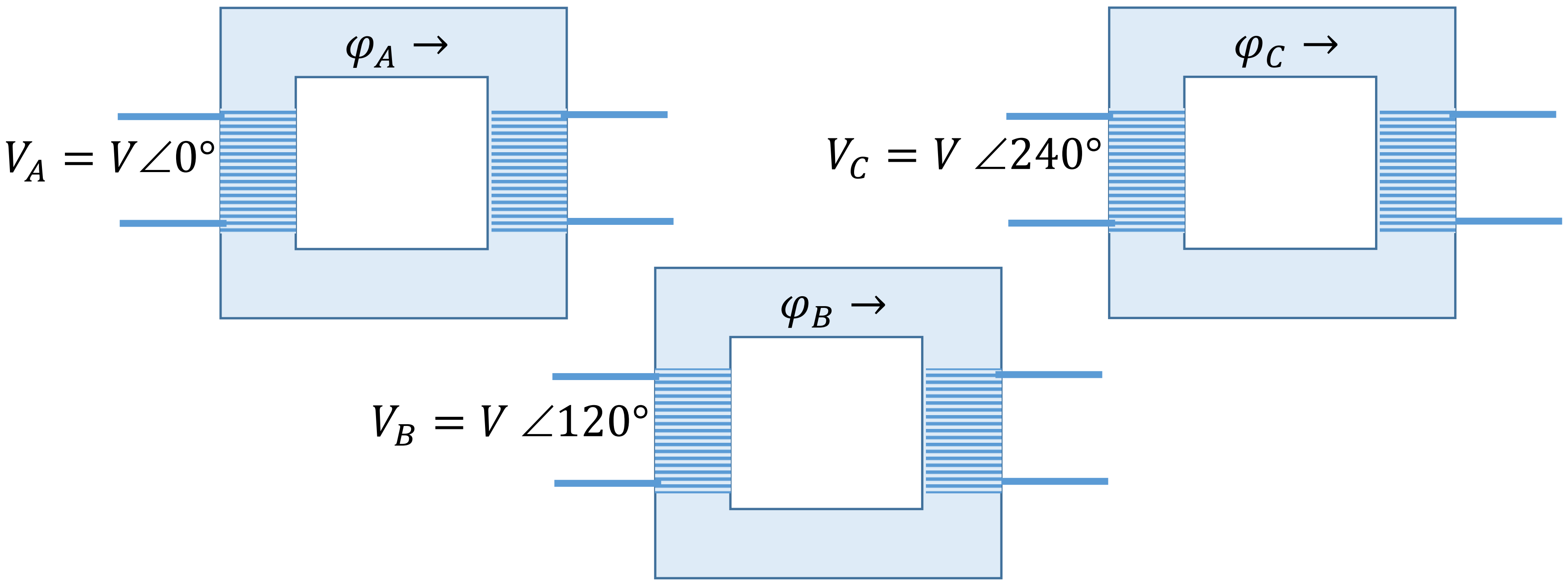
- To compare with results from the open circuit test of Lab 5, you should calculate B for both 60V and 120V
- From the curve, we see why the value of X_m was so different in each case
- What is the physical cause of the steep curve?



Three-Phase System

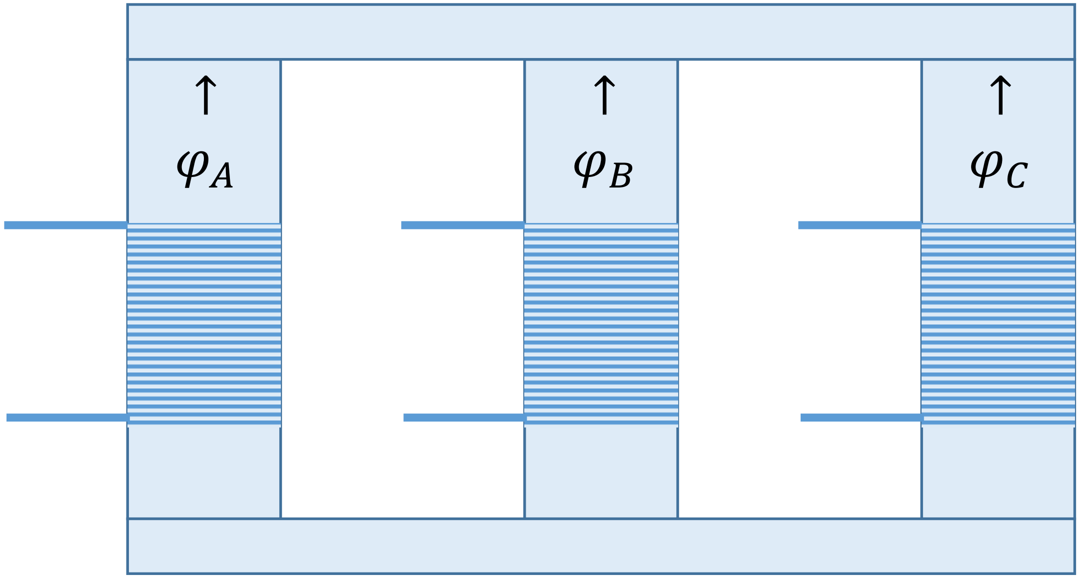
- Suppose we have 3 transformers: A, B, & C. In our system, they are each 120° out of phase with each other.
- What is the sum of the fluxes?

$$\sum \varphi_A + \varphi_B + \varphi_C = 0$$



Three-Phase System

- Since the sum of the flux is zero, we don't really need three separate transformers, we can share a common core
- This is more compact and cheaper than three separate transformers
- This also means lower core loss since we now only have flux in the vertical legs of our transformer and not in the horizontal sections

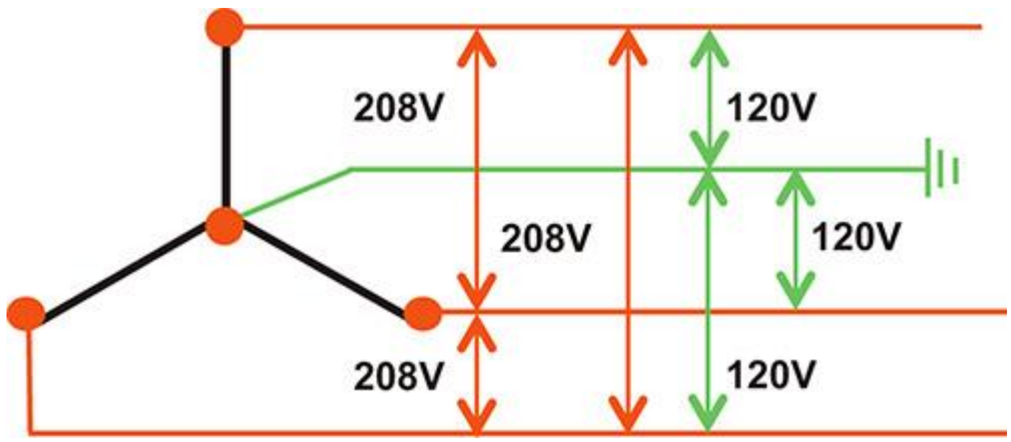


$$\sum \varphi_A + \varphi_B + \varphi_C = 0$$


Three-phase transformer on a common core
100 KVA
4160Y/2400
H3
H2
H1
HO
X3
X2
X1

Three-Phase Transformers

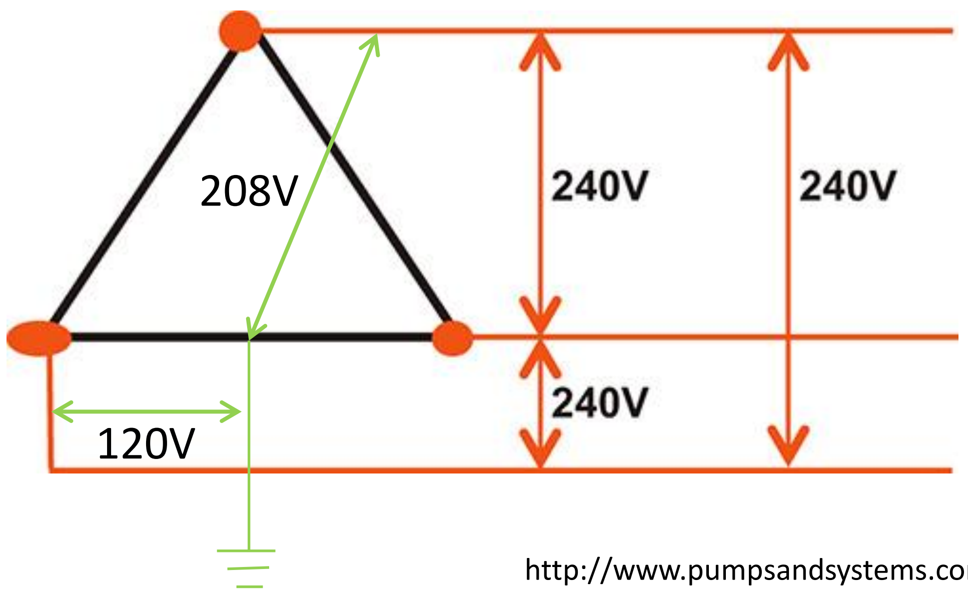
- Wye configured transformers are used in most commercial buildings, where most of the loads are single phase (lighting, computers, etc.). Thornton Hall for example.
- We still have access to 208V for loads needing that higher 3-phase voltage



http://www.pumpsandsystems.com/topics/pumps/why-wye-why-delta

Three-Phase Transformers

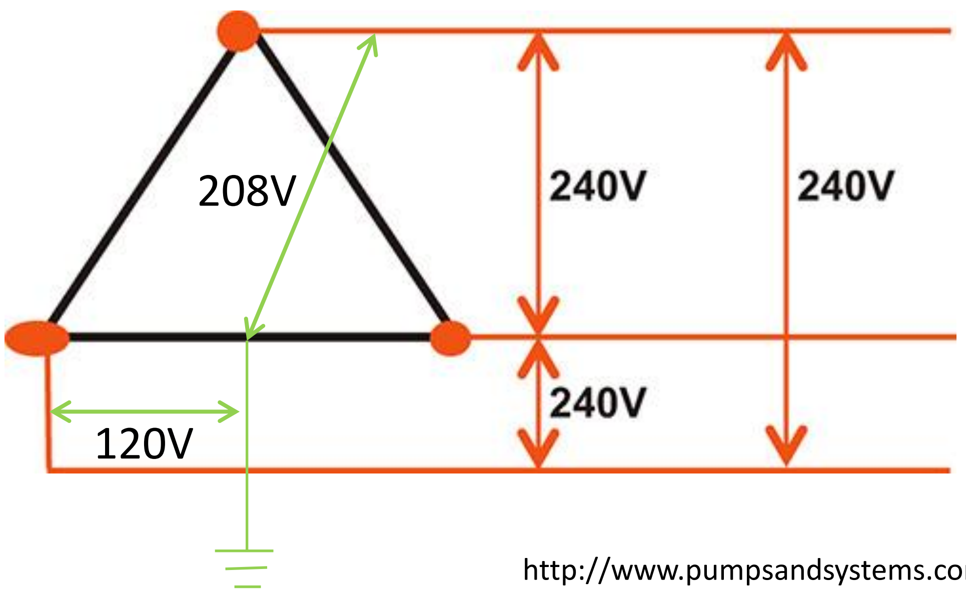
- Delta configured transformers are used in industrial settings where equipment needs 240V supply.
- But industry still needs lights and such that run on 120V.
- We could use a buck transformer to do that. Or we could take a center tap from one phase to get 120V



http://www.pumpsandsystems.com/topics/pumps/why-wye-why-delta

Three-Phase Transformers

- The center tap on one phase of the delta transformer allows us access to 120V supply
- As long as the 120V demand is small relative to the overall load (and in industry this is typically the case), this is a reasonable compromise



http://www.pumpsandsystems.com/topics/pumps/why-wye-why-delta

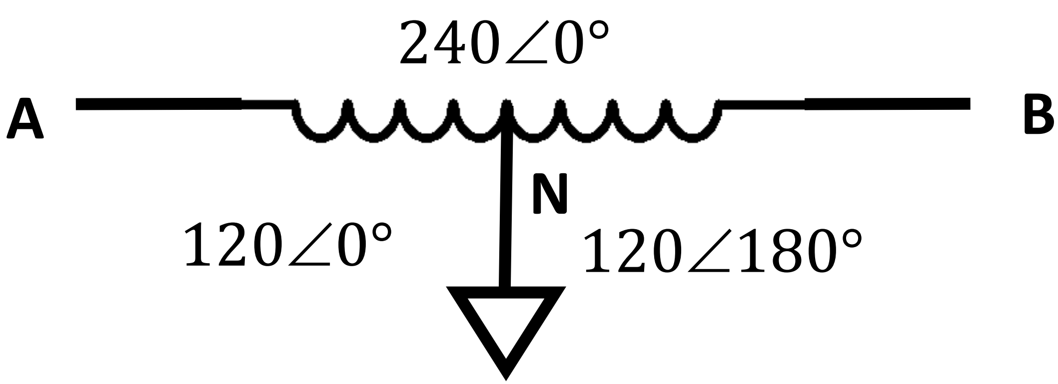
Three-Phase Transformers

- Now let's consider another way to wire our delta transformer, paying careful attention to the phasors

$$V_{AN} = 120\angle 0° \qquad V_{BN} = 120\angle 180°$$

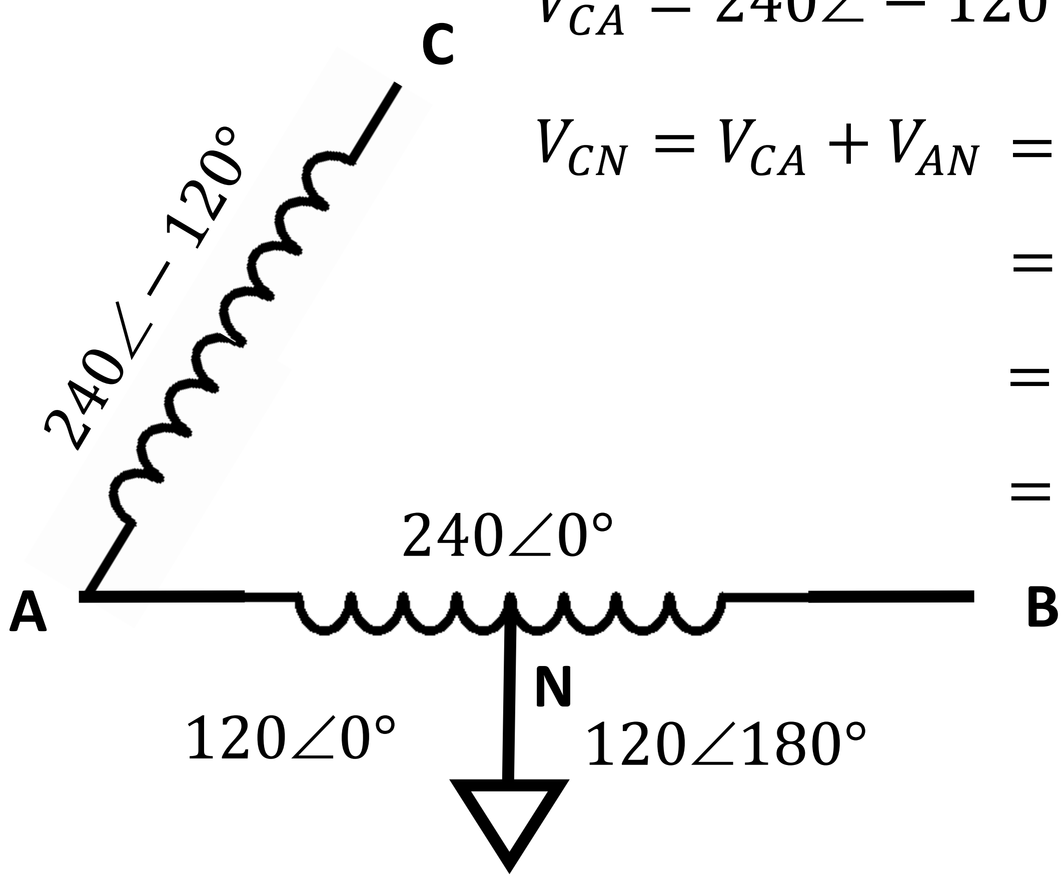
$$V_{AB} = V_{AN} - V_{BN} = 120\angle 0° - 120\angle 180°$$

$$= 120 - (-120) = 240\angle 0°$$



Three-Phase Transformers

- Now add a second leg to our delta system



$$V_{CA} = 240\angle-120°$$

$$V_{CN} = V_{CA} + V_{AN} = 240\angle-120° + 120\angle0°$$

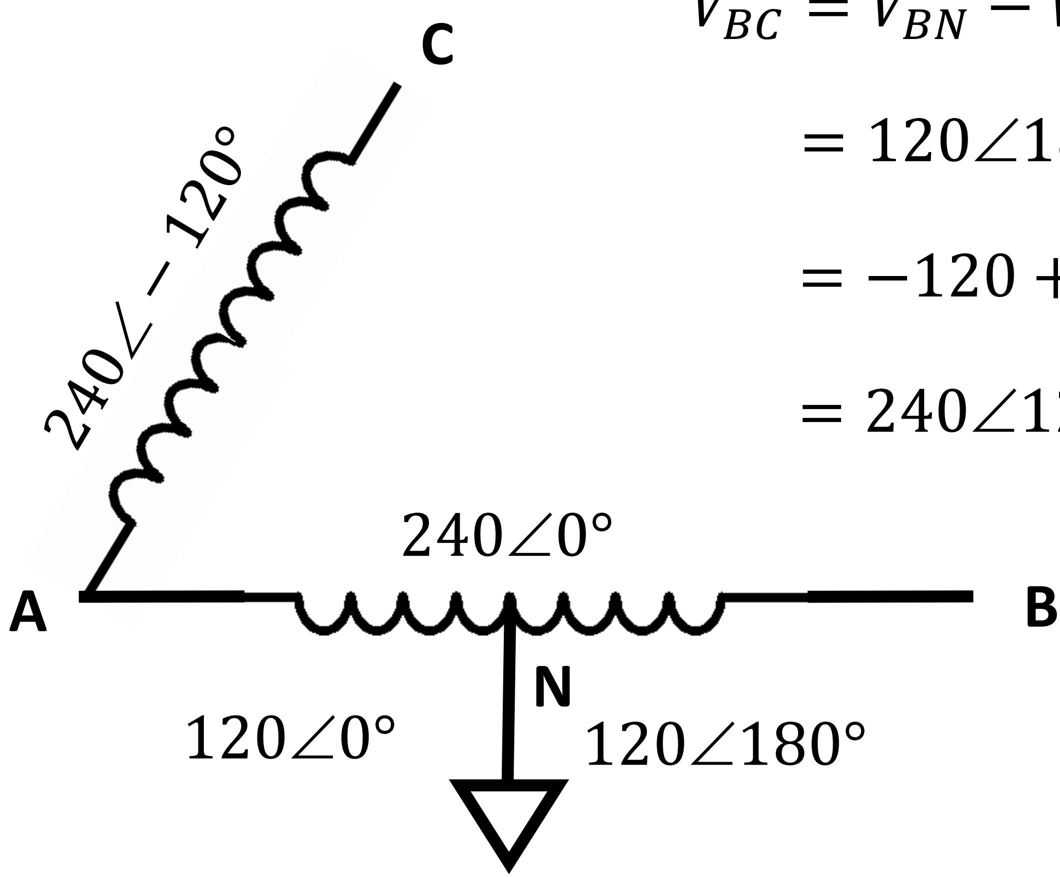
$$= -120 - j208 + 120$$

$$= -j208$$

$$= 208\angle-90°$$

Three-Phase Transformers

- Now find the resulting voltage across the missing leg



$$V_{BC} = V_{BN} - V_{CN}$$

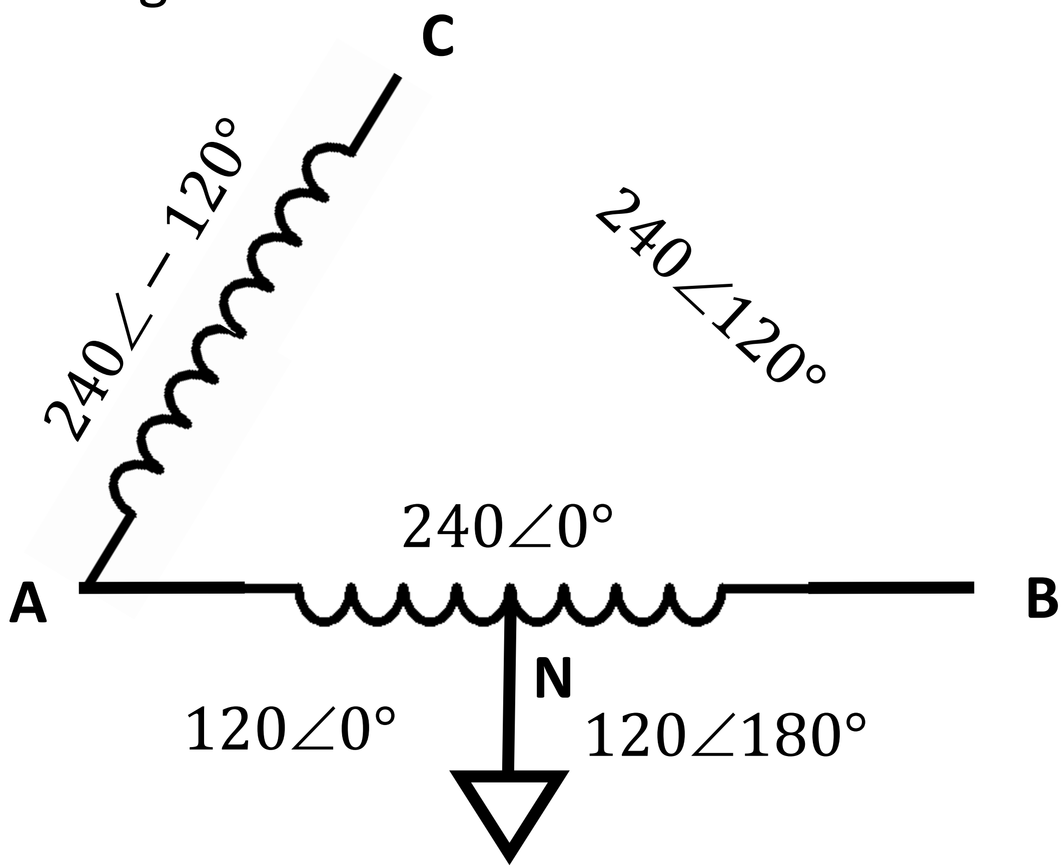
$$= 120\angle 180° - 208\angle -90°$$

$$= -120 + j208$$

$$= 240\angle 120°$$

Open Delta Configuration

- We find that we have a true 3-phase system, but only using two legs of the transformer. This is called an ***open delta*** configuration



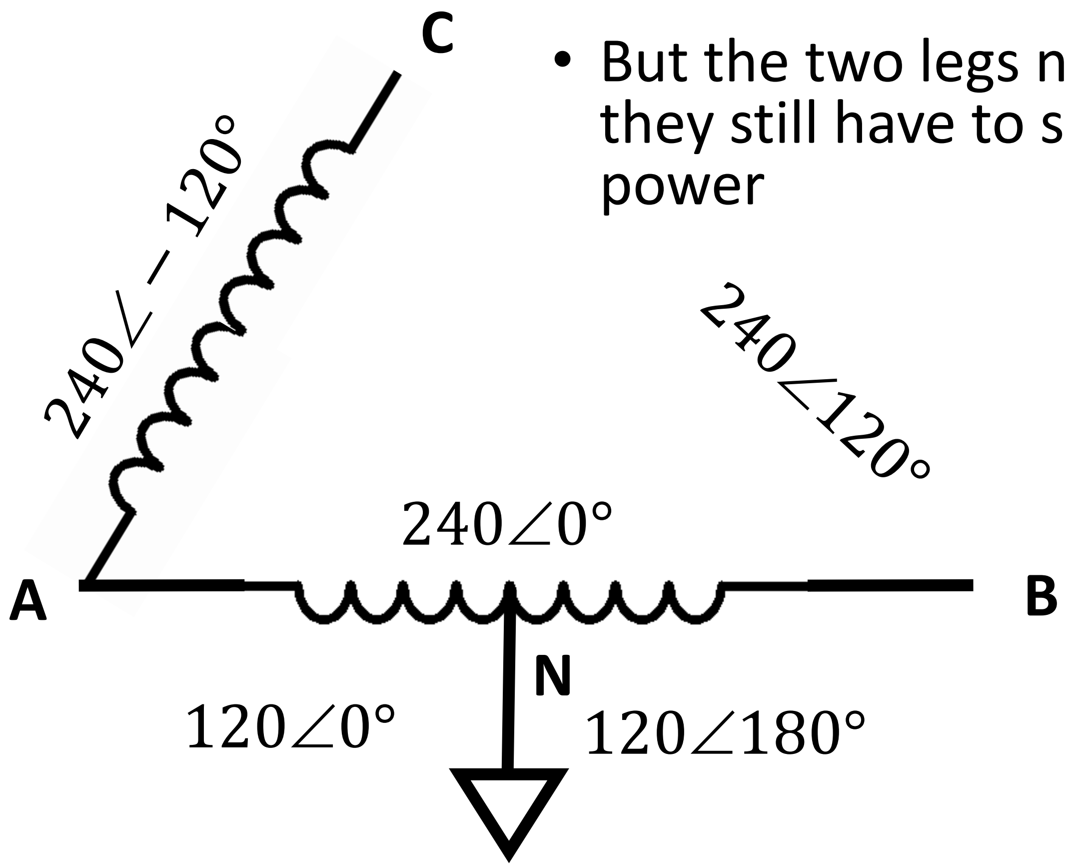
$$V_{AB} = 240\angle 0°$$

$$V_{BC} = 240\angle 120°$$

$$V_{CA} = 240\angle -120°$$

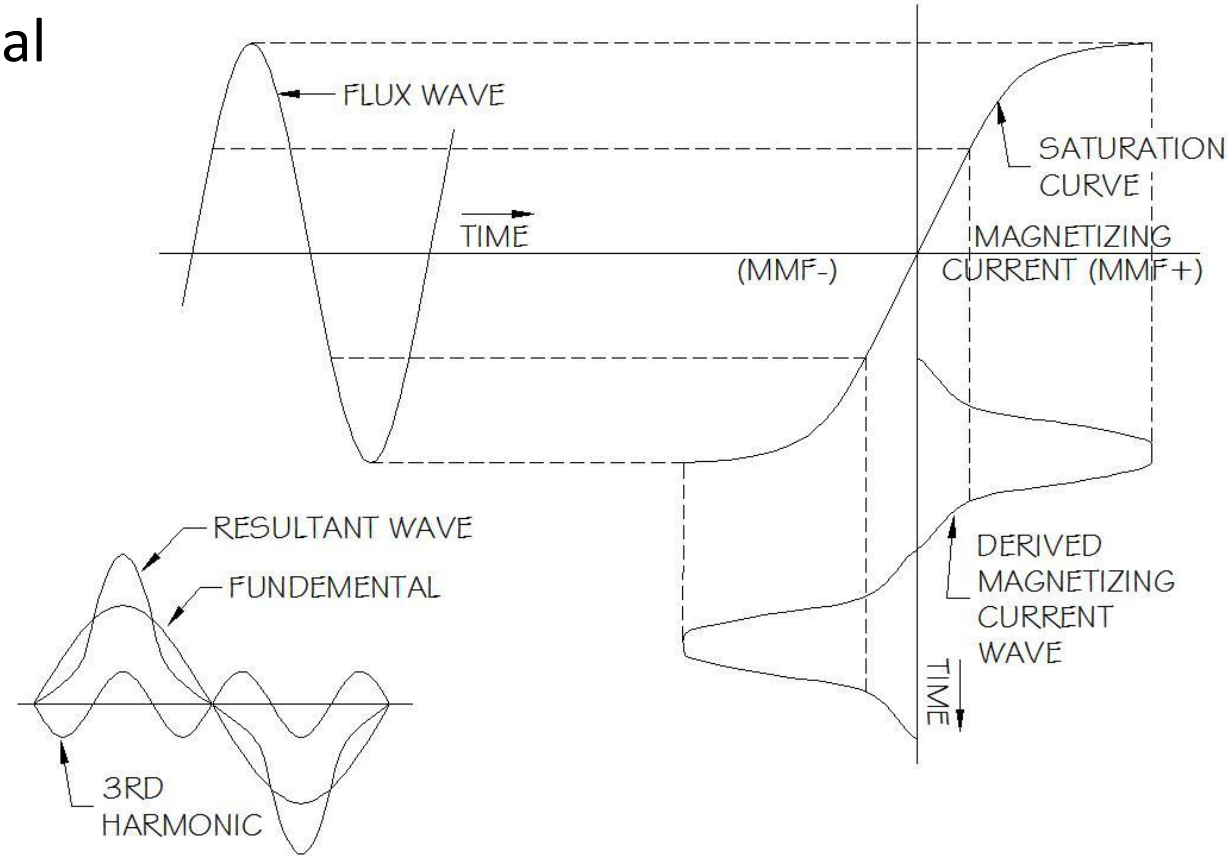
Open Delta Configuration

- The open delta is cheaper to implement because we only need two legs instead of three
- But the two legs need to be bigger since they still have to supply the full 3-phase power



Harmonic Distortion

- Recall that when the core saturates, it causes the input sine wave to be distorted
- This distortion can be modelled as harmonics added to the signal

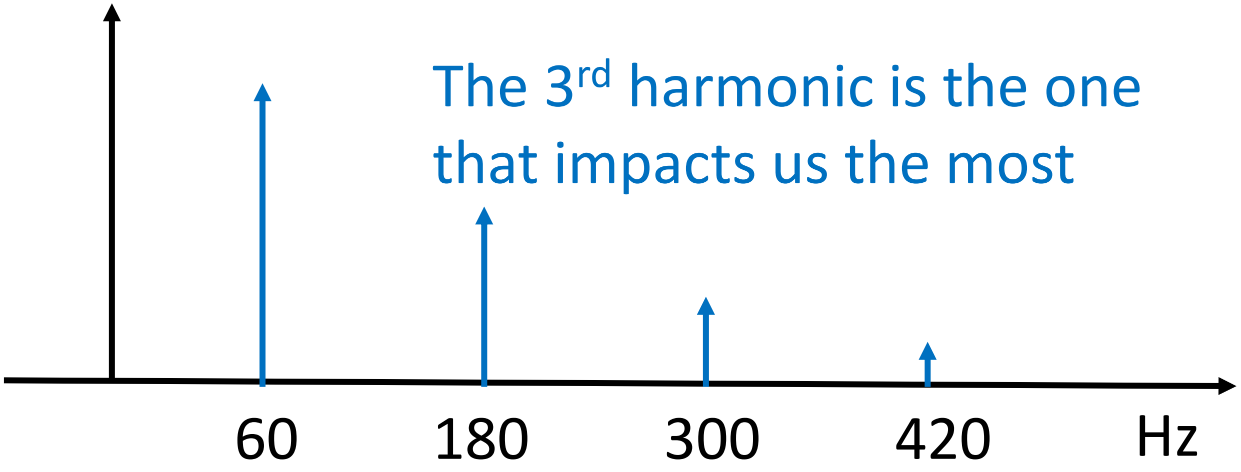


Higher Order Harmonics

- How do higher order harmonics affect 3-phase systems?
- Because inductances are proportional to frequency

$$jX = j\omega L$$

- This can mean a significant voltage drop due to line inductance



Harmonics

- If we include the 3rd harmonic in the current, our line current takes the form:

$$i_{line}(t) = A_1 \cos(\omega t) + A_3 \cos(3\omega t)$$

- Voltage in inductance is proportional to the derivative of the current, so we see the line voltage is distorted:

$$v_{line}(t) = -\omega A_1 \sin(\omega t) - 3\omega A_3 \sin(3\omega t)$$

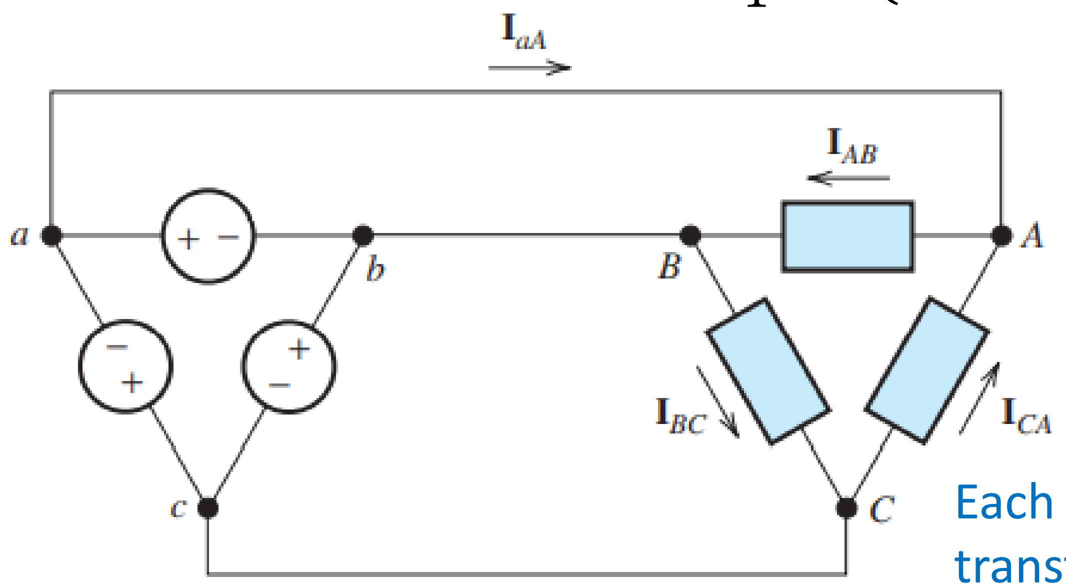
- The creates inefficiencies in the load, so we have losses that are not a result of the line loss directly, but the performance of the devices running on the distorted voltage
- The 3ω term also creates magnetic core loss

Harmonics & 3 phase

- Now look at the currents in delta system
- For current $I_{AB}(t) = A_1\cos(\omega t) + A_3\cos(3\omega t)$
- Then: $I_{BC}(t) = A_1\cos(\omega t + 120°) + A_3\cos(3(\omega t + 120°))$

$$= A_1\cos(\omega t + 120°) + A_3\cos(3\omega t + 360°)$$

$$= A_1\cos(\omega t + 120°) + A_3\cos(3(\omega t))$$



We see that the harmonic value is identical for I_{AB} and I_{BC}

Each phase here represents a transformer and its load

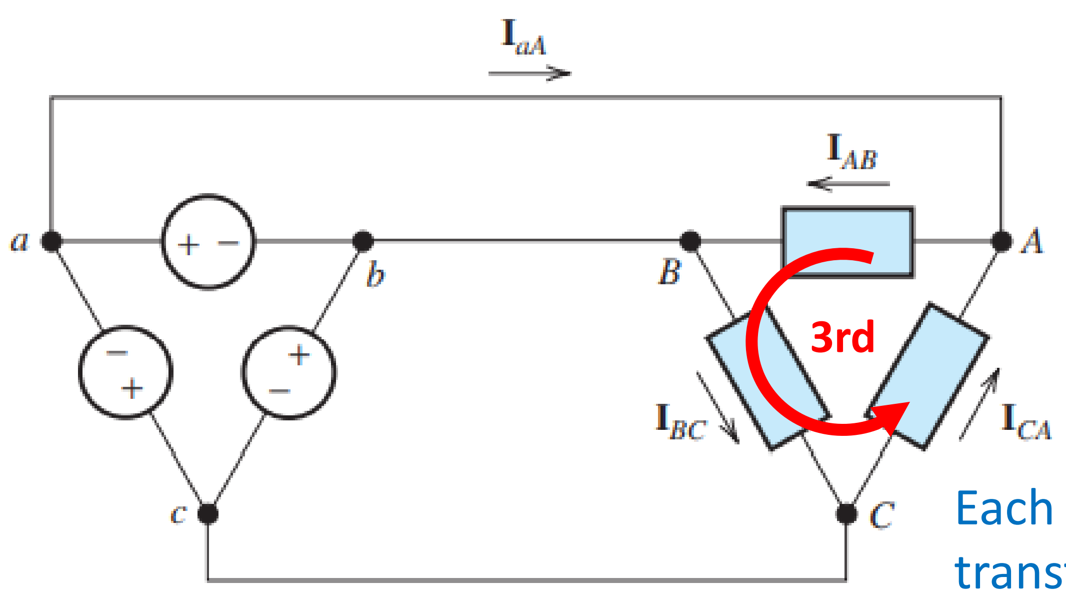
Harmonics & 3 phase

- We find a similar result for I_{CA}; all the 3rd harmonics are the same. This give us:

$$I_{AB}(t) = A_1 \cos(\omega t) + A_3 \cos(3\omega t)$$

$$I_{BC}(t) = A_1 \cos(\omega t + 120°) + A_3 \cos(3(\omega t))$$

$$I_{CA}(t) = A_1 \cos(\omega t - 120°) + A_3 \cos(3(\omega t))$$

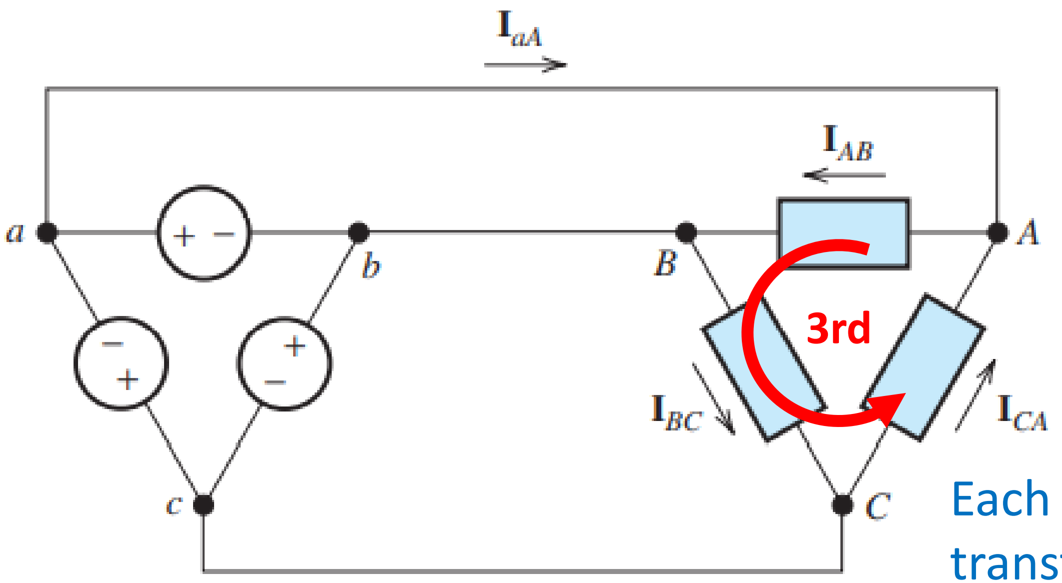


This means that the third harmonic just circulates through the load transformer and doesn't affect the line voltages

Each phase here represents a transformer and its load

Harmonics & 3 phase

- Keeping the 3rd harmonic off of the line is a definite benefit of the delta configuration
- But that current still flows in the transformers, so they still need to be built to carry the extra current
- Also, this only works for balanced loads



Each phase here represents a transformer and its load

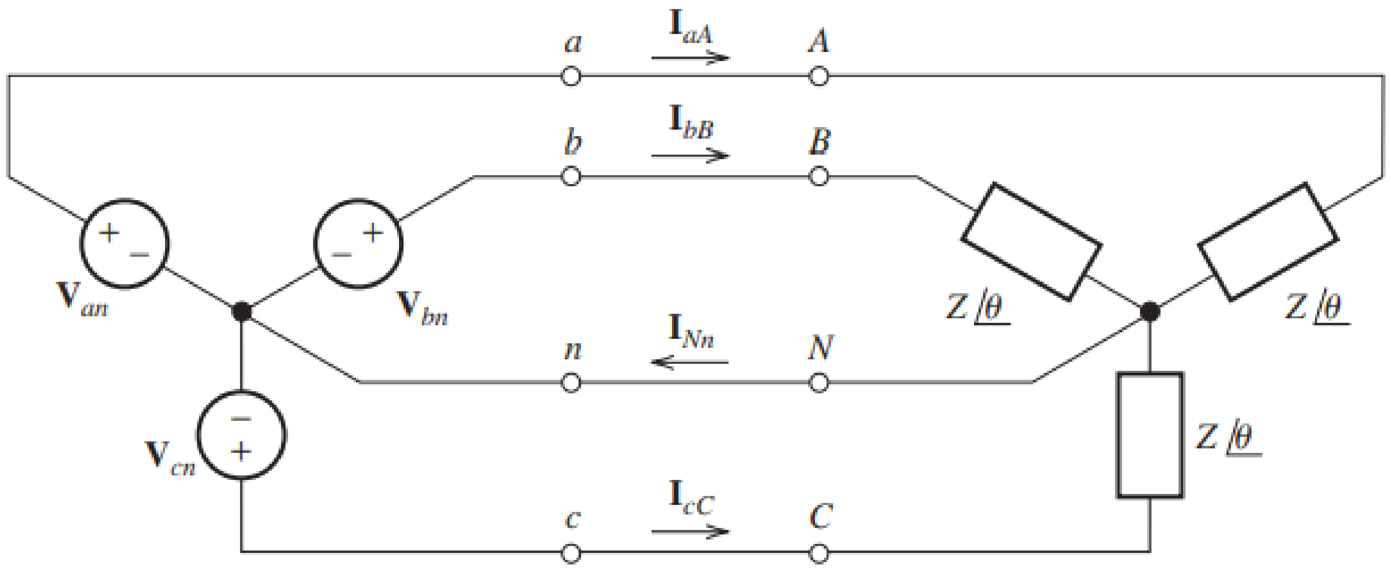
Harmonics & 3 phase

- What about a wye-configured transformer system?

$$I_{aA}(t) = A_1 \cos(\omega t) + A_3 \cos(3\omega t)$$

$$I_{bB}(t) = A_1 \cos(\omega t + 120°) + A_3 \cos(3(\omega t))$$

$$I_{cC}(t) = A_1 \cos(\omega t - 120°) + A_3 \cos(3(\omega t))$$

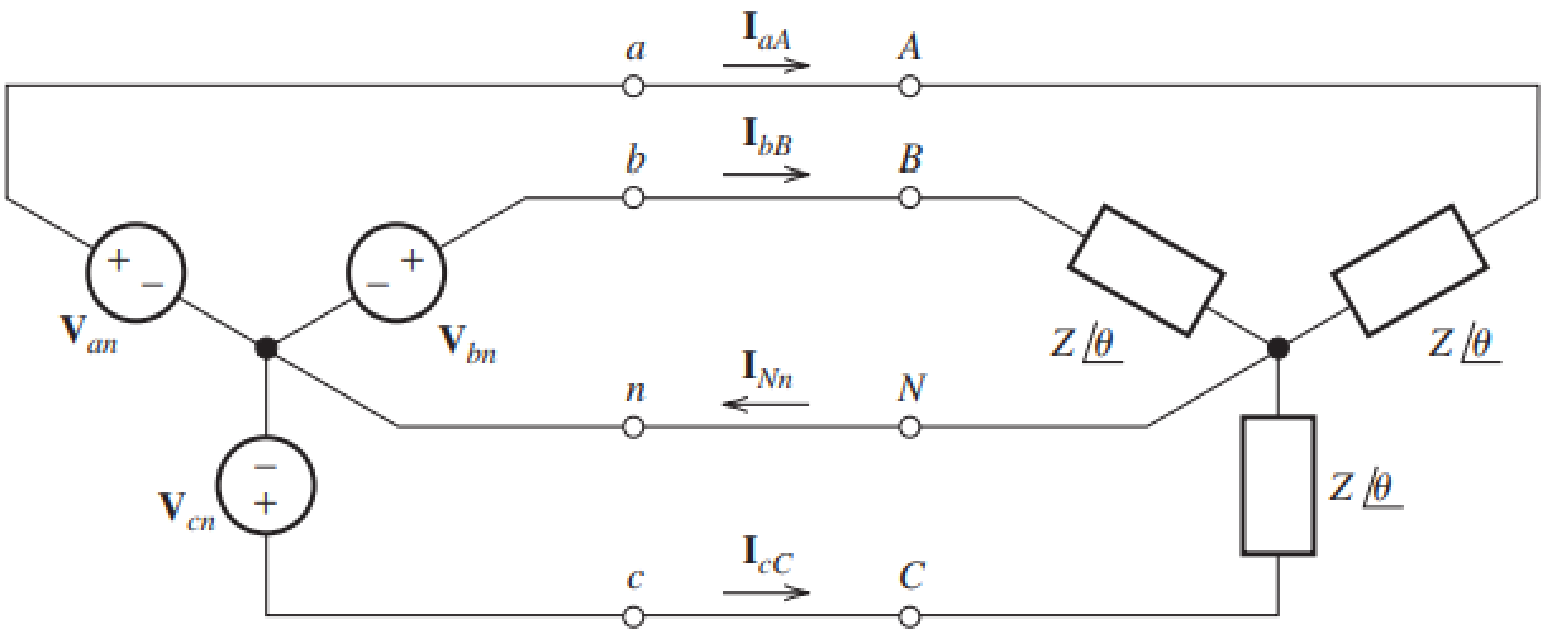


Each phase here represents a transformer and its load

Harmonics & 3 phase

- By KCL

$$I_{Nn} = I_{aA} + I_{bB} + I_{cC}$$



Harmonics & 3 phase

- By KCL $\quad I_{nN} = I_{aA} + I_{bB} + I_{cC}$

$$I_{aA}(t) = A_1 \cos(\omega t) + A_3 \cos(3\omega t)$$

$$I_{bB}(t) = A_1 \cos(\omega t + 120°) + A_3 \cos(3(\omega t))$$

$$I_{cC}(t) = A_1 \cos(\omega t - 120°) + A_3 \cos(3(\omega t))$$

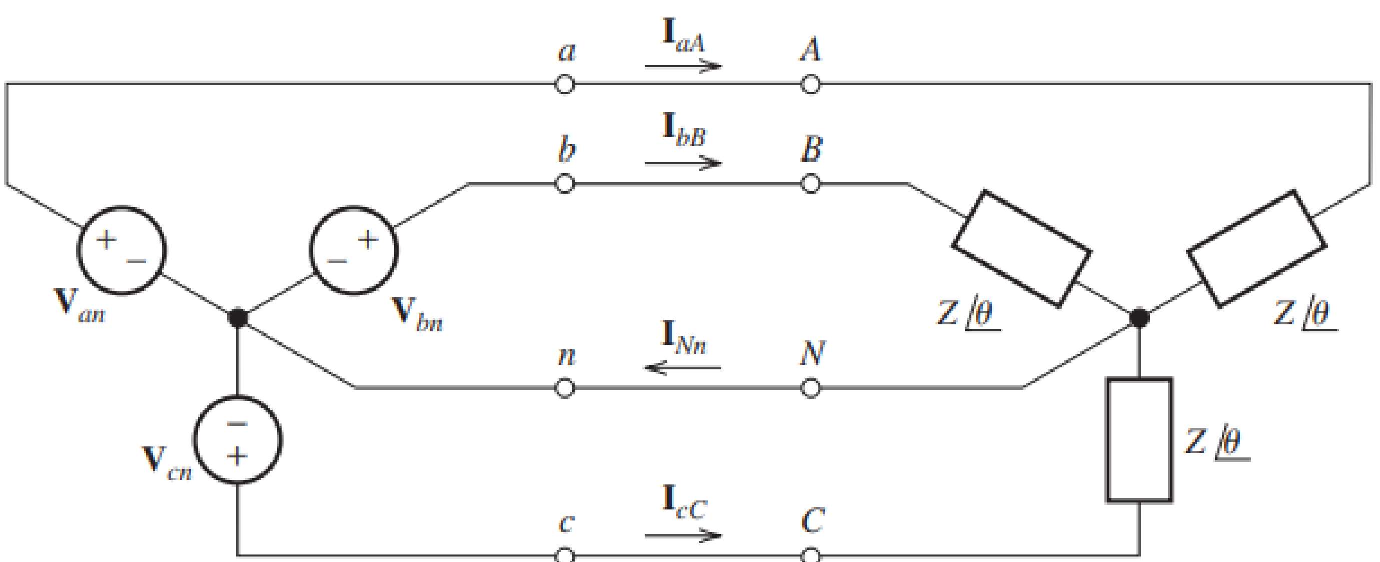
- We know three cosines each $120°$ out of phase will sum to zero, so we are just left with the 3rd harmonic

$$I_{Nn} = A_3 \cos(3\omega t) + A_3 \cos(3\omega t) + A_3 \cos(3\omega t)$$

$$I_{Nn} = 3A_3 \cos(3\omega t)$$

Harmonics & 3 phase

- Then in a wye configuration, not only do we still have the 3rd harmonic on the line, we now also have a significant current in our neutral line
- Our transformers still need to be rated to be able to carry the extra current from the 3rd harmonic



Each phase here represents a transformer and its load

Three-Phase Transformers

Phases are often color-coded Red-Yellow-Blue

Oil tank to store cooling oil

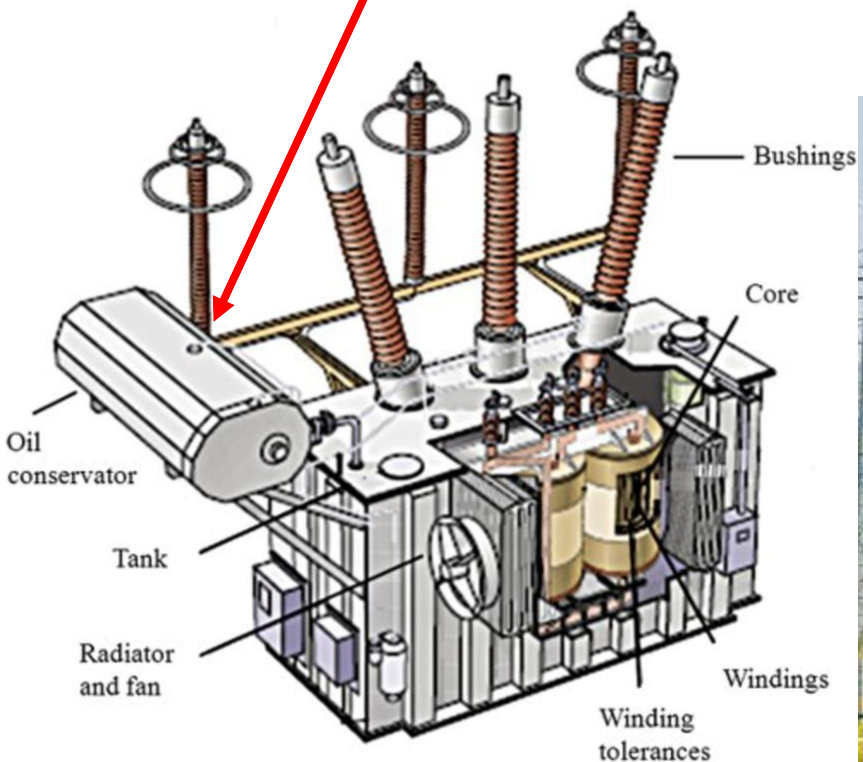


Image: http://www.dfliq.net/the-basics-of-electrical-transformers/

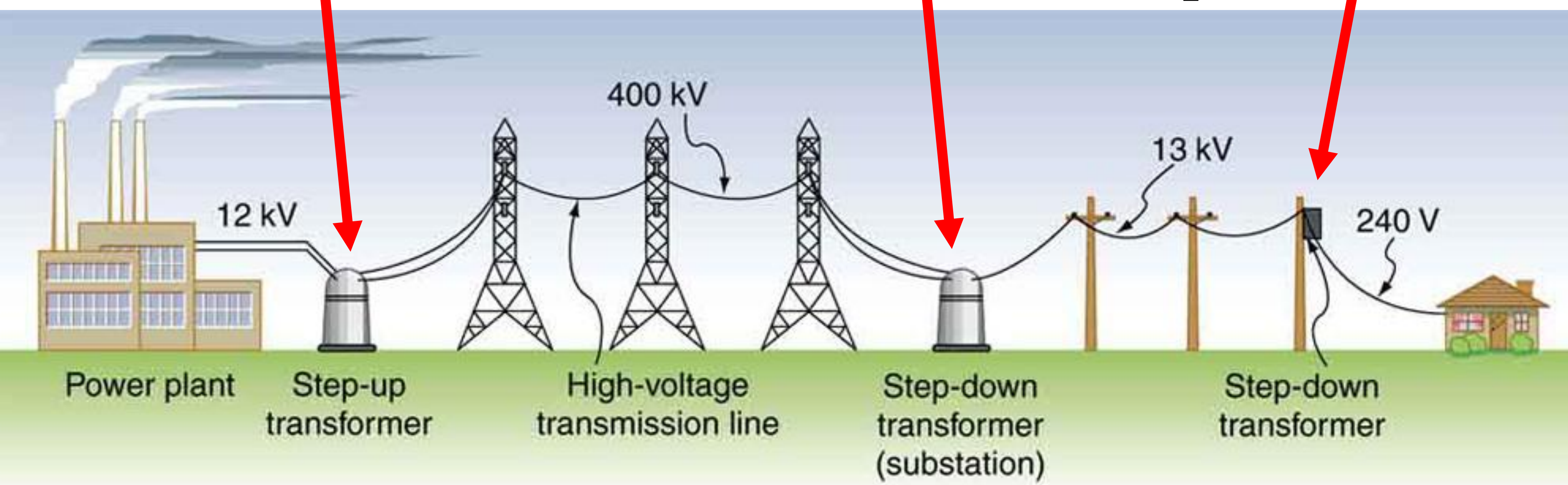
Image: https://www.dreamstime.com/royalty-free-stock-images-modern-power-plant-new-model-transformer-inside-electrical-yellow-blue-red-capacitors-details-image33195159

Power Transmission

http://www.meppi.com/TransformerFactory/Pages/default.aspx

http://relaypowersystems.com/products/substations/

https://en.wikipedia.org/wiki/Transformer



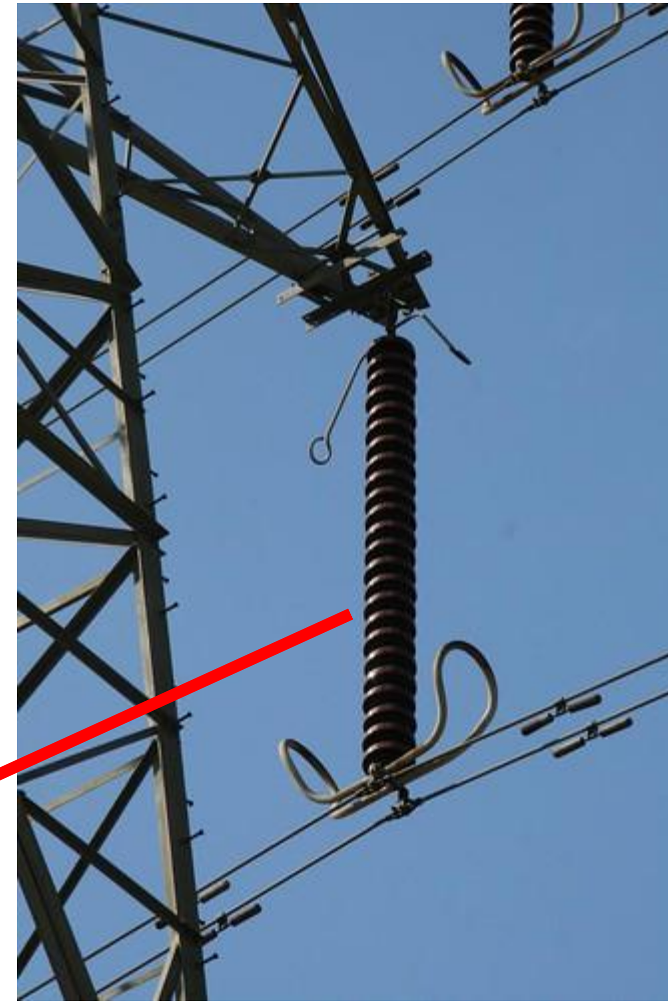
http://philschatz.com/physics-book/contents/m42414.html

Transmission Lines

- Typically uninsulated, stranded aluminum wire
  - Aluminum lighter & cheaper than copper
  - Air acts as insulation between cables
  - Stranded cable is more flexible and carries more current than solid cable

Transmission Line Paraphernalia

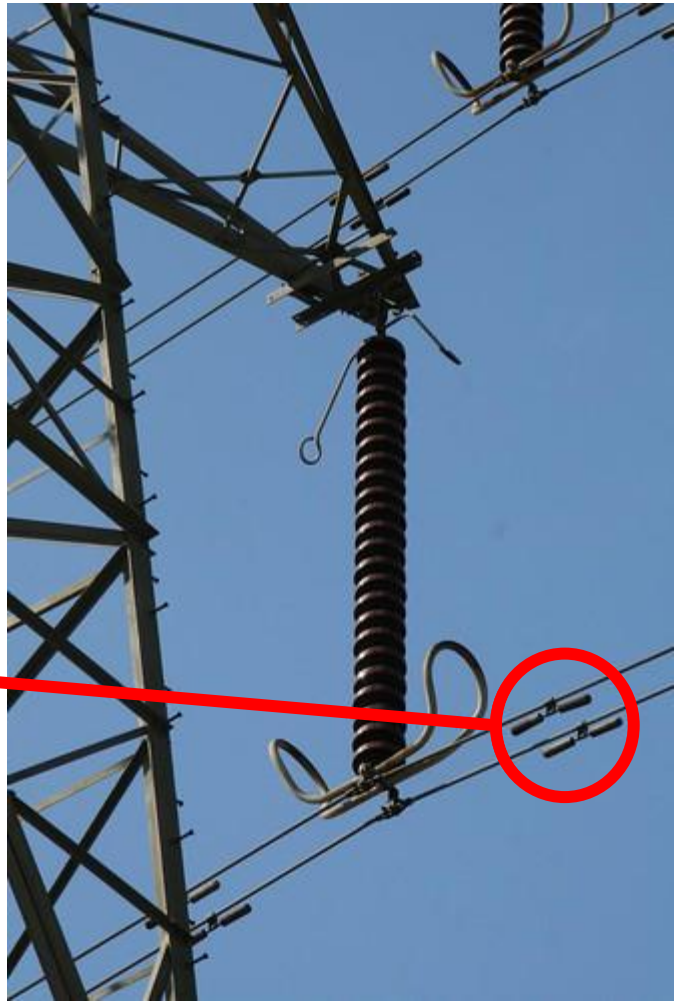
- Each suspension insulator can withstand 11kV
- You can determine the voltage of a line by counting the number of disks and multiplying by 11kV
- The current path on an insulator is over its surface. For this reason, the underside is designed so that it stays dry in the rain.



https://www.theengineerspost.com/types-of-insulators/

Transmission Line Paraphernalia

- Stockbridge damper reduces vibrations on the transmission line caused by wind



https://www.theengineerspost.com/types-of-insulators/