17-Three Phase Transformers Part 2

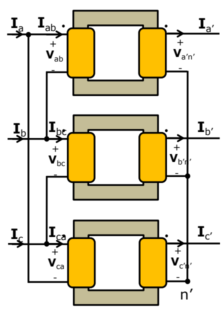
ECEGR 450
Electromechanical Energy Conversion

Overview

- Delta-Y Transformer Connection
- Delta-Y Transformer Analysis
- Transformer Phase Shifts
- Y-Delta Transformer Connection
- Y-Delta Transformer Analysis
- Practical Considerations

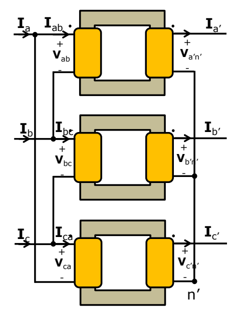
Δ-Y Transformer

- Secondary has a neutral connection
- Primary connected "top-to-bottom"
- Line-line voltages appear on the coils on primary
- Phase voltages appear on the coils on the secondary
- Less insulation needed on HV winding



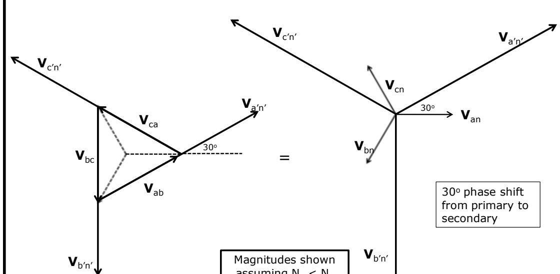
Δ-Y Transformer Analysis

- By Faraday's Law:
  - $\mathbf{V}_{ab}$ will be in-phase with $\mathbf{V}_{a'n'}$
  - Phase shift introduced
- By KCL:
  - $\mathbf{I}_a = \mathbf{I}_{ab} - \mathbf{I}_{ca}$
- By Ampere's Law:
  - $\mathbf{I}_{ab}$ will be in-phase with $\mathbf{I}_{a'}$
  - Phase shift introduced
- Similar results for b, c phases



Δ-Y Transformer Analysis

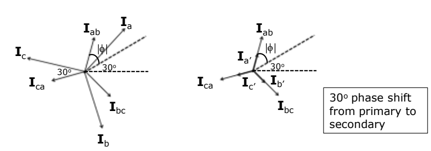
Phasor Diagram for Ideal Delta-Y Connected Transformer



Delta-Y Transformer Analysis

Phasor Diagram for Ideal Delta-Y Connected Transformer

$\mathbf{I}_a = \mathbf{I}_{ab} - \mathbf{I}_{ca}$
$\mathbf{I}_b = \mathbf{I}_{bc} - \mathbf{I}_{ab}$
$\mathbf{I}_c = \mathbf{I}_{ca} - \mathbf{I}_{bc}$



Three-Phase Transformer Analysis: Delta-Y

- Let k be the transformer voltage gain
- For Δ-Y transformers:

$$\mathbf{V}_{a'n'} = n\mathbf{V}_{ab} = n\mathbf{V}_{an}\sqrt{3}e^{\frac{j\pi}{6}} = k\mathbf{V}_{an}$$

therefore $k = n\sqrt{3}e^{\frac{j\pi}{6}}$ Important result!

$$\mathbf{I}_{a'} = \frac{\mathbf{I}_{ab}}{n} = \frac{\mathbf{I}_a e^{\frac{j\pi}{6}}}{\sqrt{3}n} = \frac{\mathbf{I}_a}{k^*}$$

same phase shift as voltage

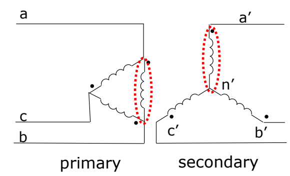
Delta-Y Transformer Analysis

- Voltage relationships

$$\mathbf{V}_{a'n'} = k\mathbf{V}_{an},\quad \mathbf{V}_{a'b'} = k\mathbf{V}_{ab}$$
$$\mathbf{V}_{b'n'} = k\mathbf{V}_{bn},\quad \mathbf{V}_{b'c'} = k\mathbf{V}_{bc}$$
$$\mathbf{V}_{c'n'} = k\mathbf{V}_{cn},\quad \mathbf{V}_{c'a'} = k\mathbf{V}_{ca}$$

- Current relationships

$$\mathbf{I}_{a'} = \frac{\mathbf{I}_a}{k^*}$$
$$\mathbf{I}_{b'} = \frac{\mathbf{I}_b}{k^*}$$
$$\mathbf{I}_{c'} = \frac{\mathbf{I}_c}{k^*}$$



Question

- Consider an ideal Delta-Y transformer, with 20 turns on each primary coil, and 80 turns on each secondary coil. If the primary side values are:

$\mathbf{V}_{ab} = 208\angle 0^\circ$ V

$\mathbf{I}_a = 10\angle 5^\circ$ A

- Compute: $\mathbf{V}_{a'b'}$, $\mathbf{V}_{a'n'}$ and $\mathbf{I}_a'$

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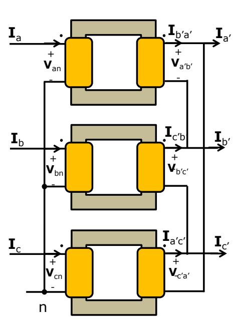
$$k = n\sqrt{3}e^{\frac{j\pi}{6}} = 4\sqrt{3}e^{\frac{j\pi}{6}} = 6.92\angle 30^\circ$$
$$\mathbf{V}_{a'b'} = \mathbf{V}_{ab}k = 1436\angle 30^\circ \text{ V}$$
$$\mathbf{V}_{a'n'} = \mathbf{V}_{an}k = (120\angle -30^\circ)(6.92\angle 30^\circ) = 830.4\angle 0^\circ \text{ V}$$
$$\mathbf{I}_{a'} = \frac{\mathbf{I}_a}{k^*} = \frac{10\angle 5^\circ}{6.92\angle -30^\circ} = 1.45\angle 35^\circ \text{ A}$$

Y-Δ Transformer

- No neutral point on secondary
- $\mathbf{V}_{an}$, $\mathbf{V}_{a'b'}$ in phase
- $\mathbf{I}_{an}$, $\mathbf{I}_{b'a'}$ in phase
  - Similar results for b, c phase
- Phase voltage across primary coils
- Line voltage across secondary coils



Three-Phase Transformer Analysis: Y-Δ

- Let k be the transformer voltage gain
- For Y-Δ transformers:

$$\mathbf{V}_{a'b'} = n\mathbf{V}_{an} = \frac{n\mathbf{V}_{ab}e^{\frac{-j\pi}{6}}}{\sqrt{3}} = k\mathbf{V}_{ab}$$

therefore $k = \frac{ne^{\frac{-j\pi}{6}}}{\sqrt{3}}$ Important result

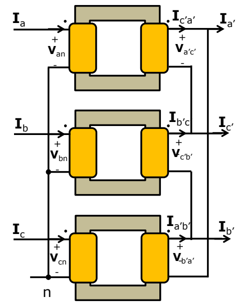
Note: phase shift is -30⁰, whereas for Delta-Y transformer connection in previous slides it is +30⁰

Question

Is there any concern in connecting a three phase Y-Delta transformer in parallel with a three phase Delta-Y transformer? Assume the transformers are appropriately rated.

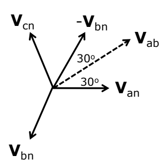
Y-Delta Transformer

- To achieve at +30º phase shift connect as shown
- Note the phasing on the secondary
- $\mathbf{V}_{an}$, $\mathbf{V}_{a'c'}$ in phase
- $\mathbf{I}_{an}$, $\mathbf{I}_{c'a'}$ in phase



Y-Delta Transformer

- A side note: $-\mathbf{V}_{bn} = \frac{1}{\sqrt{3}}\mathbf{V}_{ab}e^{\frac{j\pi}{6}}$



Three-Phase Transformer Analysis: Y-Δ

- Voltage relationship

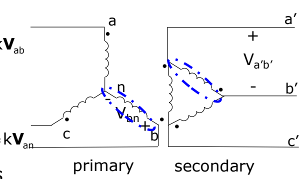
$$\mathbf{V}_{a'b'} = -n\mathbf{V}_{bn} = \frac{n}{\sqrt{3}}\mathbf{V}_{ab}e^{\frac{j\pi}{6}} = k\mathbf{V}_{ab}$$

therefore $k = \frac{n}{\sqrt{3}}e^{\frac{j\pi}{6}}$

$$\mathbf{V}_{a'n'} = \frac{\mathbf{V}_{a'b'}}{\sqrt{3}}e^{\frac{-j\pi}{6}} = \frac{n\mathbf{V}_{an}}{\sqrt{3}}e^{\frac{j\pi}{6}} = k\mathbf{V}_{an}$$

- For the other phases

$$\mathbf{V}_{a'n'} = k\mathbf{V}_{an}$$
$$\mathbf{V}_{b'n'} = k\mathbf{V}_{bn}$$
$$\mathbf{V}_{c'n'} = k\mathbf{V}_{cn}$$



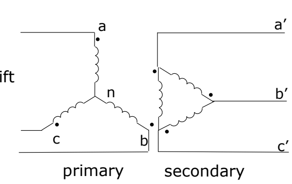
Phase shift is now +30º

Three-Phase Transformer Analysis

- It can be shown:

$$\mathbf{I}_{a'} = \frac{\mathbf{I}_a}{k^*}, \quad \mathbf{I}_{b'} = \frac{\mathbf{I}_b}{k^*}, \quad \mathbf{I}_{c'} = \frac{\mathbf{I}_c}{k^*}$$

same phase-shift as voltages



Three-Phase Transformer Analysis

- What about power?

$$\mathbf{S} = \mathbf{V}_{a'n'}\mathbf{I}_{a'}^* = k\mathbf{V}_{an}\left(\frac{\mathbf{I}_a}{k^*}\right)^* = \mathbf{V}_{an}\mathbf{I}_a^*$$ for all configurations

- For ideal three-phase xfmrs, power is conserved, as in the single phase case

Three-Phase Transformer Analysis

- What about impedances?
- For all transformer connections:

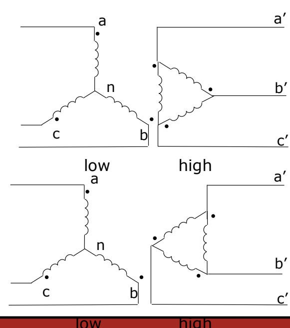
$$\text{secondary impedance referred to the primary} = \frac{1}{|k|^2}\mathbf{Z}_L$$

Transformer Phase Shifts

- Various winding connections of Δ-Y, and Y-Δ xfmrs lead to different phase shifts
- Standard is to have phase-neutral voltages advance by 30 degrees when going from low voltage to high voltage
- Previous slides have followed this convention
- Note: convention is most critical in interconnected power systems. Some homework problems do not follow this convention

Transformer Phase Shifts

- Which Y-Δ is correct?
- Check $V_{a'n'}$ for each



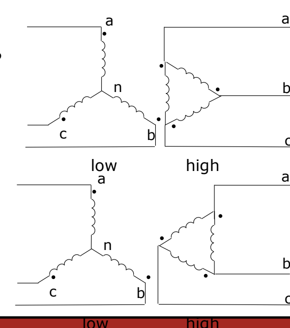
Transformer Phase Shifts

- Which Y-Δ is correct?
- Check $V_{a'n'}$ for each case:
  - top

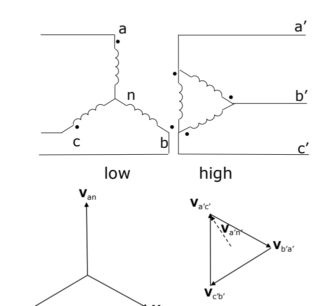
$$\mathbf{V}_{a'n'} = n\frac{\mathbf{V}_{an}}{\sqrt{3}}\angle 30^\circ$$

  - bottom

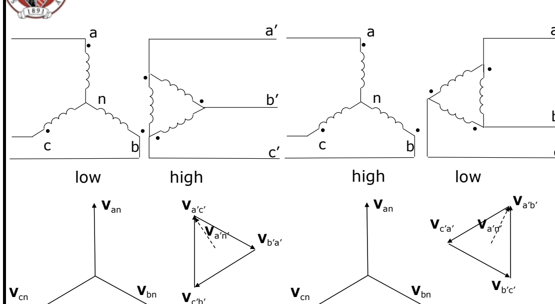
$$\mathbf{V}_{a'n'} = n\frac{\mathbf{V}_{an}}{\sqrt{3}}\angle -30^\circ$$



Transformer Phase Shifts

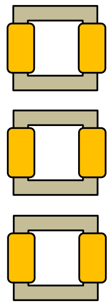


Transformer Phase Shifts



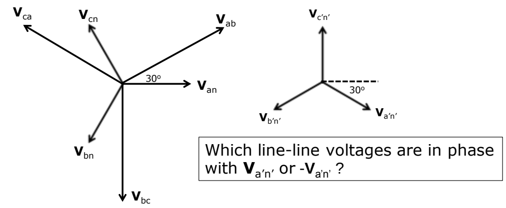
Example

Draw the connections, polarity markers and label the primary and secondary phases for a Delta-Wye step down transformer (assume left side is the high side)



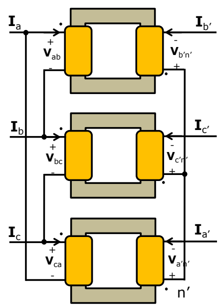
Example

- Need secondary (right) side to be regressed in phase by 30 degrees (per convention)



Example

- $-\mathbf{V}_{ca}$ must be connected to $\mathbf{V}_{a'n'}$ winding
- $-\mathbf{V}_{ab}$ must be connected to $\mathbf{V}_{b'n'}$ winding
- $-\mathbf{V}_{bc}$ must be connected to $\mathbf{V}_{c'n'}$ winding

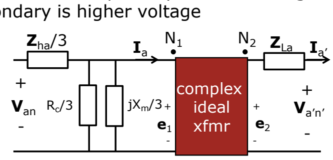


Per-Phase Analysis (Δ-Y)

- Per-phase equivalent of a non-ideal Δ-Y transformer
- Complex ideal transformer with gain k or k*

$k = \sqrt{3} n e^{j\pi/6}$

  - +30º shift when primary is lower voltage and secondary is higher voltage



Per-Phase Analysis (Y-Δ)

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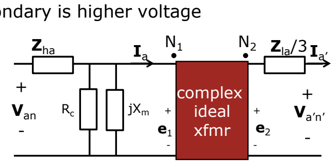
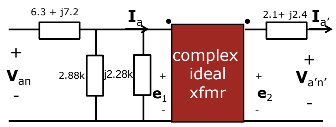


Example

- Consider three, single-phase transformers. The transformers have the following specifications:
  - 720VA, 360/120V, R_H = 18.9Ω, X_H = 21.6Ω, R_L = 2.1Ω, X_L = 2.4Ω, R_{cH} = 8.64kΩ, X_{mH} = 6.84kΩ
- Draw the per-phase equivalent circuit if the transformers are connected as Delta-Y
- What are the nominal line voltages on each side of the transformer?

Example

- Nominal per-phase voltage on primary is 360V and 208V on secondary
  - Nominal primary line voltage: 360V
  - Nominal secondary line voltage: 208V



$k = 1.732\angle -30°$

Example

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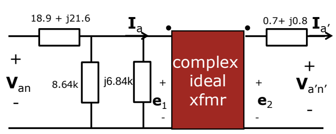
- Draw the per-phase equivalent circuit if the transformers are connected as Y-Delta
- What are the nominal line voltages on each side of the transformer?

Example

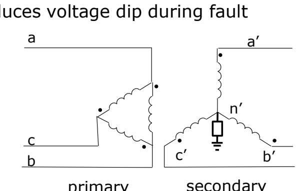
- Nominal per-phase voltage on primary is 360V and 69V on secondary
  - Nominal primary line voltage: 624V
  - Nominal secondary line voltage: 120V



$k = 5.196\angle -30°$

Practical Considerations

- Medium-voltage industrial facilities often use Δ-Y incoming transformers
- Y-side is grounded through a resistor
  - Reduces ground current during fault
  - Reduces voltage dip during fault



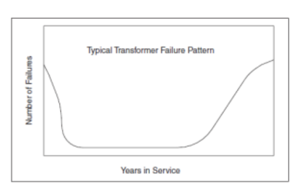
Practical Considerations

TABLE 1. CAUSE OF TRANSFORMER FAILURES [2].

Cause	Percent of Failures
Insulation failures	26%
Manufacturing problems	24%
Unknown	16%
Loose connections	7%
Through faults	5%
Improper maintenance	5%
Oil contamination	4%
Overloading	4%
Fire/Explosions	3%
Lighting	3%
Floods	2%
Moisture	1%

Source: Mozina, C.J.; , "Protection and Commissioning of Digital Transformer Relays: Improvements in Medium-Voltage Industrial Transformer Protection," *Industry Applications Magazine, IEEE* , vol.18, no.6, pp.63-73, Nov.-Dec. 2012

Practical Considerations



Source: Wang, M.; Vandermaar, A.J.; Srivastava, K.D.; , "Review of condition assessment of power transformers in service," *Electrical Insulation Magazine, IEEE* , vol.18, no.6, pp.12-25, Nov.-Dec. 2002

Practical Considerations

- Condition assessment of transformers: Wang, M.; Vandermaar, A.J.; Srivastava, K.D.; , "Review of condition assessment of power transformers in service," *Electrical Insulation Magazine, IEEE* , vol.18, no.6, pp.12-25, Nov.-Dec. 2002 [available online in IEEE Xplore through SU library]

Summary

- There is a complex gain associated with Y-Delta and Delta-Y transformers
- Connection of transformer coils allows for different phase shifts to be achieved
- Convention: phase-neutral voltages advance by 30 degrees from lower voltage to higher voltage side
- Power in ideal three phase transformers is conserved
- Impedances are transferred from secondary to primary by: $\frac{1}{|k|^2}\mathbf{Z}_L$