Apparatus Models: Transformers

- Normally model as series impedance from winding resistance and leakage reactance
- Positive and negative impedances equal
- In a Y-Δ transformer that phase shift is in the opposite direction for negative sequence

Transformers (continued)

- Zero sequence impedance of the transformer depends on core construction
- X_0=X_1 for single phase cores
- X_0=X_1 for 5 leg or shell type core
  - Both have similar path for zero sequence current

Three Leg Cores

- Three leg core *3Ø* transformers have $X_0 < X_1$
- Zero sequence flux forced out of core
- Excitation branch becomes significant
- This leakage flux travels trough the oil and transformer tank.
- Oil and tank steel have a high reluctance and low inductance producing the low exciting branch inductance

Transformer Connections

- Zero sequence circuit impacted Y or Δ
- Also impacted by grounding
- Tertiary also complicates connection

Transformer Connections

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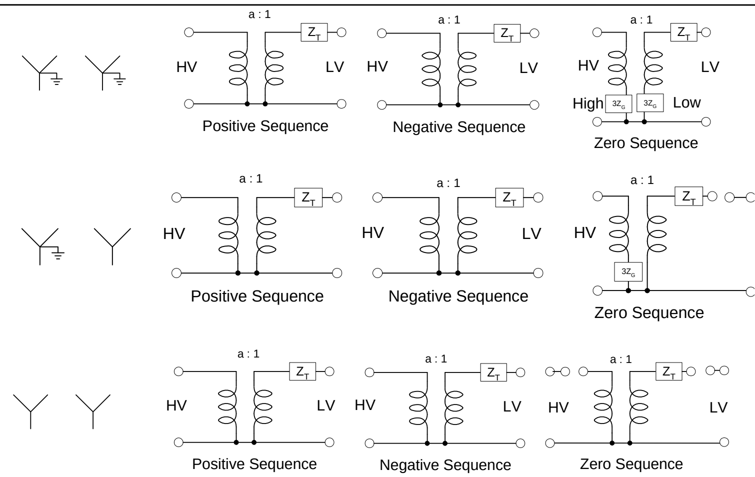

Sequence Models of Apparatus

Fall 2018

More Transformer Connections

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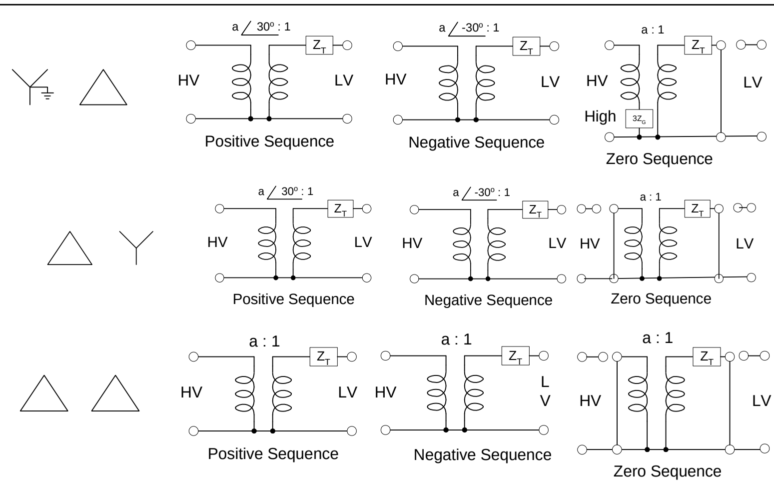
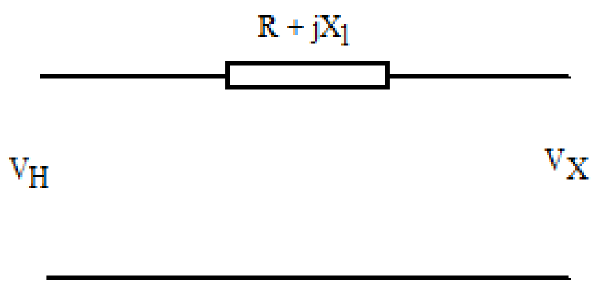


Sequence Models of Apparatus

Fall 2018

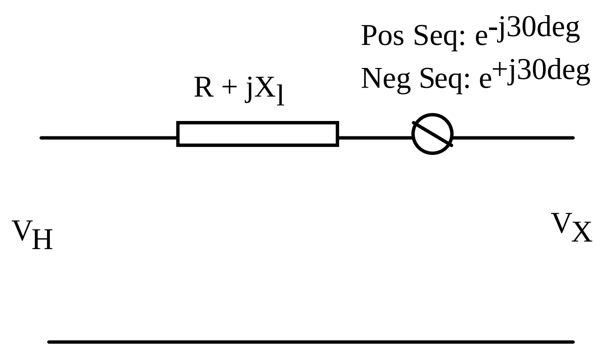
Per Unit Equivalents

- Positive and negative sequence equivalent for Y-Y, Δ–Δ, (and Y-Δ, Δ-Y when phase shift isn't a concern):

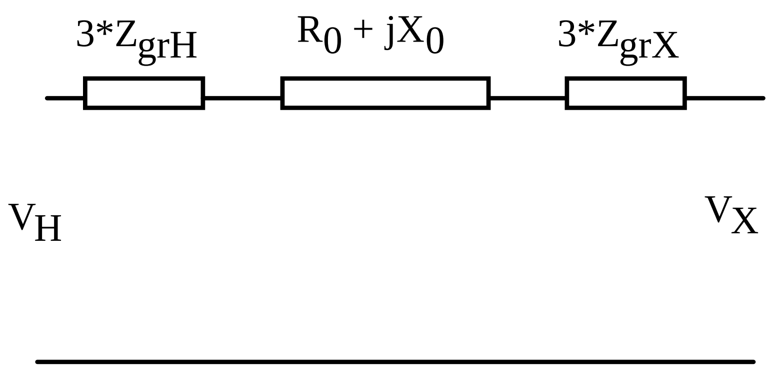


Per Unit Equivalents

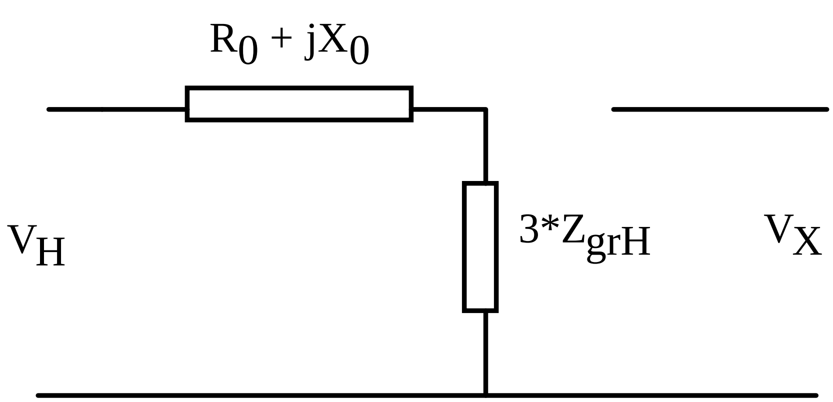
- Positive and Negative Sequence for Y-Δ, Δ-Y, ANSI phase shift



General Zero Sequence Yg -Yg

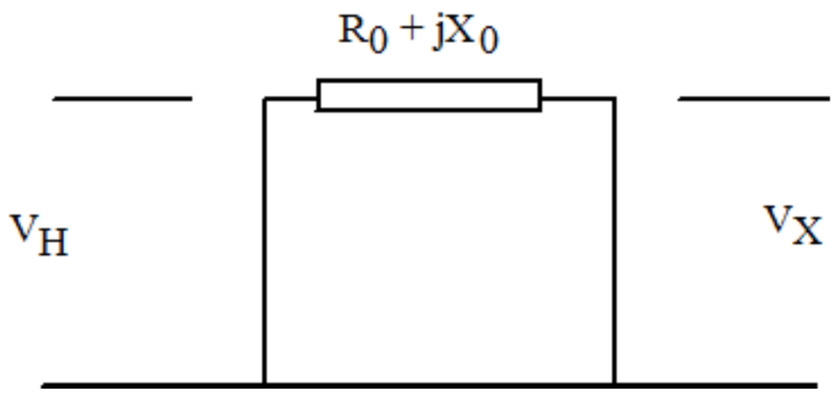


Zero sequence Yg-Δ



Zero sequence Δ-Δ

-



Transformers with Tertiaries

- Z_1=Z_2 -phase rotation doesn’t impact
- Low voltage winding often closed delta
- Zero sequence trap
- May float or ground corners through impedance

Transformers with Tertiaries

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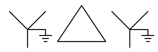
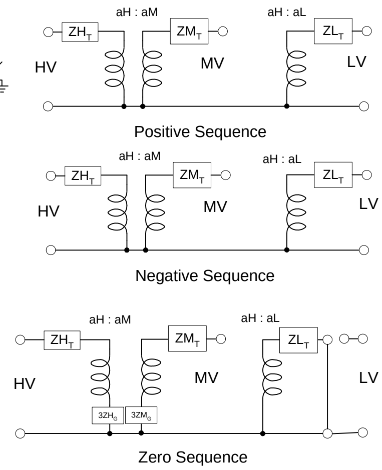
- See Fig A4.2.3 in Blackburn's relaying book for more configurations





Per Unit Equivalents (solid grounding)

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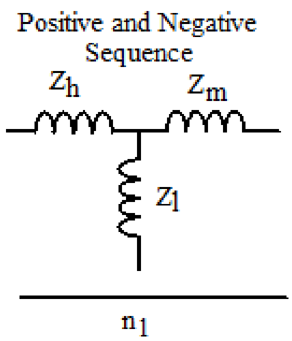

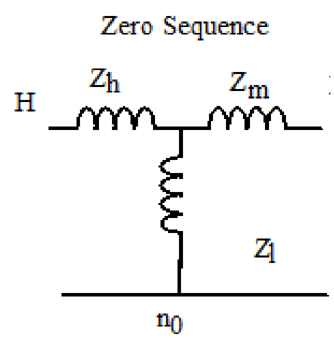

Calculating Z_h, Z_m and Z_l

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- Often given short circuit test data as Z_{hm}, Z_{hl} and Z_{ml}
- Not all on same per unit base, so first do change of base

$$X_h := \left(\frac{1}{2}\right)\cdot\left(X_{hl} + X_{hm} - X_{ml}\right)$$

$$X_m := \left(\frac{1}{2}\right)\cdot\left(X_{hm} + X_{ml} - X_{hl}\right)$$

$$X_l := \left(\frac{1}{2}\right)\cdot\left(X_{ml} + X_{hl} - X_{hm}\right)$$

Component Modeling: Lines

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- Z_1=Z_2 -phase rotation doesn't impact
- Often approximated with per phase equivalent self impedance
- Zero sequence current flows through earth and Z_0 often 2-6 times Z_1
- Usually neglect capacitances unless transient case
  - » Transient response matters for fast detection

Component Modeling: Lines

- Need to do detailed line constants calculation to get impedances accurately
- Form impedance matrix and then transform with Symmetrical Components Transformation matrix $Z_s=(A^{-1} * Z * A)$

Generators

- Positive sequence reactance broken into subtransient, transient and steady-state
- Direct vs Quadrature axis
  - » Fault currents typically near zero power factor
  - » D-axis only
- Subtransient or transient reactance based on time scale of interest

Generators: Negative Sequence

- MMF rotates backwards at twice the machines synchronous speed
- Double frequency currents in the rotor field and amortisseur windings
- Flux peak occurs along the d and q - axes
- $X_2 \approx 0.5*(X_d'' + X_q'')$