The Wye-Delta Center Tapped Transformer Bank

W. H. Kersting
Wayne Carr
Milsoft Utility Solutions

Introduction

- Loads to be served
  - Three-phase induction motor
  - 120/240 volt single-phase loads
- Transformer connection
  - Grounded wye-delta
  - Ungrounded wye-delta
- The question is should the neutral be grounded, grounded through an impedance or ungrounded?

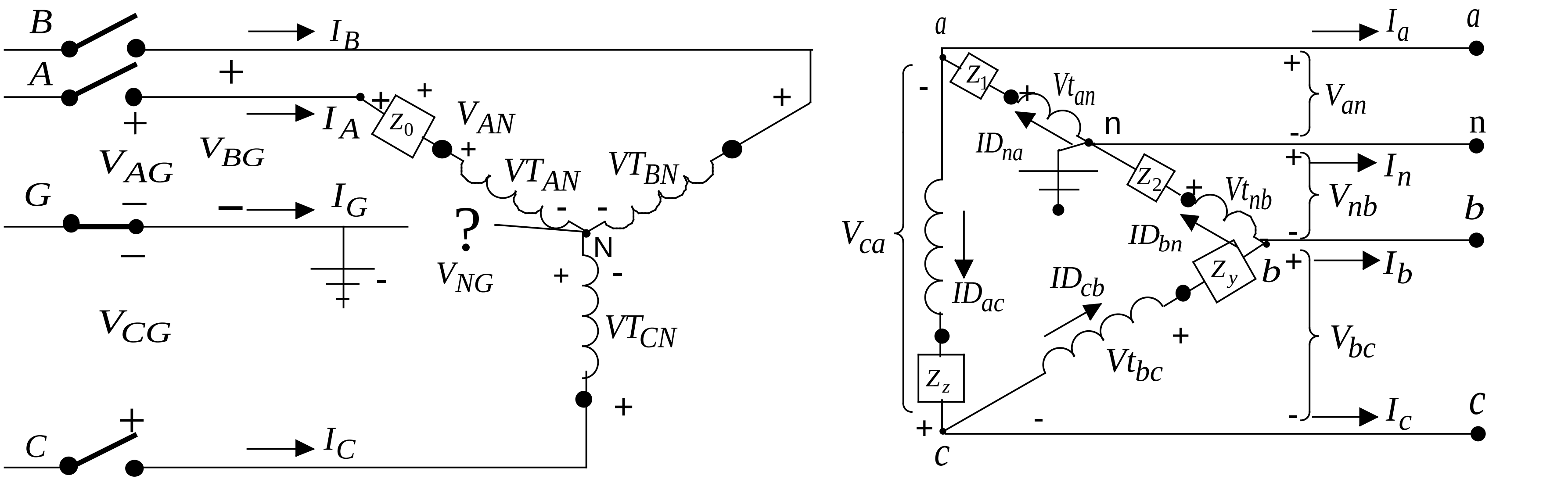
General Thoughts on Grounding

- Always taught that the grounded wye-delta is preferred because when a primary phase is open the secondary will still provide three-phase voltages.
- Always taught that if the neutral is ungrounded upon the loss of a primary phase the secondary will become single-phase.

Concerns about Grounding

- Paper at the 2016 REPC demonstrated large “feedback” current for upstream ground faults when transformer is connected grounded wye-delta.
- Do both the grounded and ungrounded cases provide a dangerous backfeed voltage?
- Purpose of this paper is to investigate the magnitude of the “feedback” voltages for both connections.

The Thirty Degree Transformer Connection



Note in the figure that there is a question mark between the neutral and ground. A primary purpose of this presentation is to answer the question on whether or not to ground the neutral.

Note also that there are switches on the three primary phases. This is done so that various open switch positions can be studied in order to help answer the question about grounding.

Very Basic Transformer Theory

$$n_t = \frac{kVLN_{\text{Rated Primary}}}{kVLL_{\text{Rated Secondary}}}$$

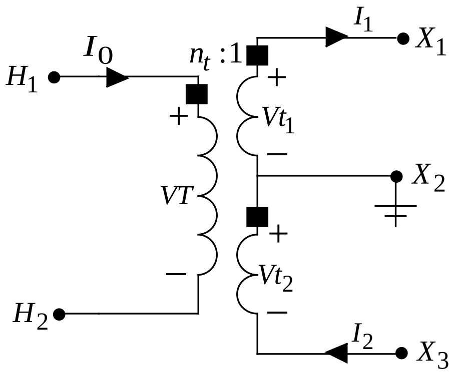
$$\text{Example: } n_t = \frac{7200}{240} = 30$$

Center Tap Transformer

$$Vt_1 = Vt_2 = \frac{1}{2 \cdot n_t} \cdot VT$$

$$VT = 2 \cdot n_t \cdot Vt_1$$

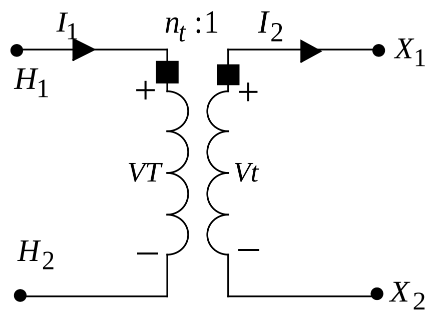
$$I_0 = \frac{1}{2 \cdot n_t} \cdot (I_1 + I_2)$$



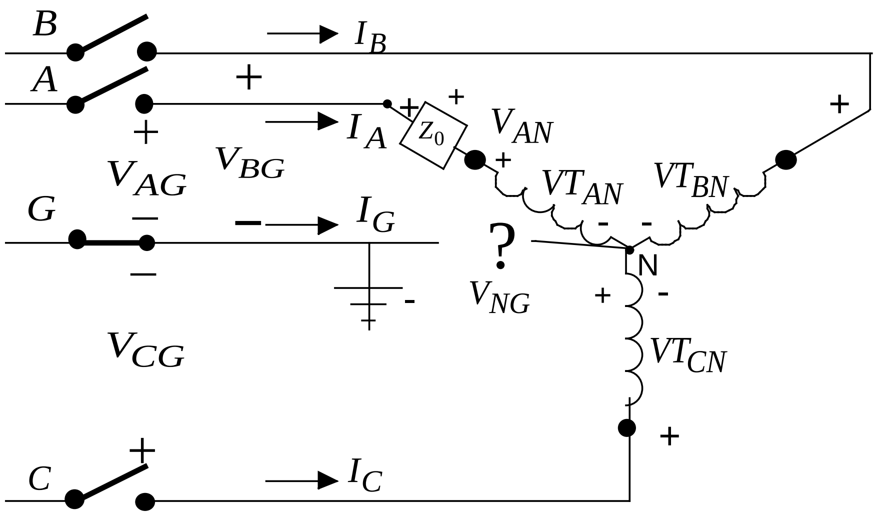
Two Winding Transformer

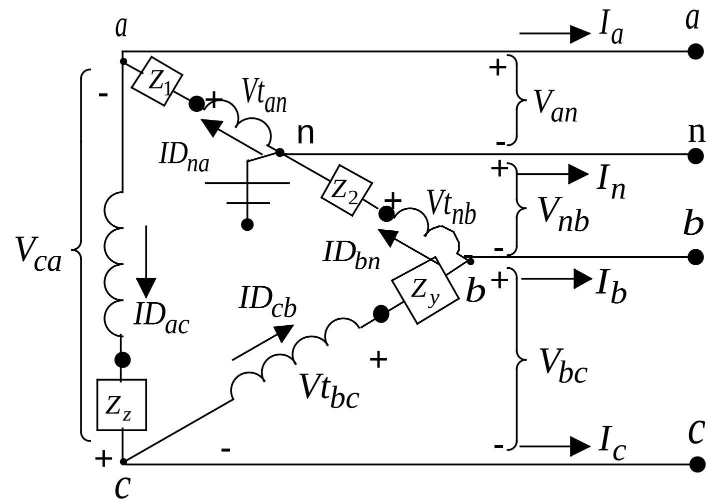
$$Vt = \frac{1}{n_t} \cdot VT$$

$$I_1 = \frac{1}{n_t} \cdot I_2$$



Two Laws Must Always be Satisfied





Kirchhoff's Voltage Law:

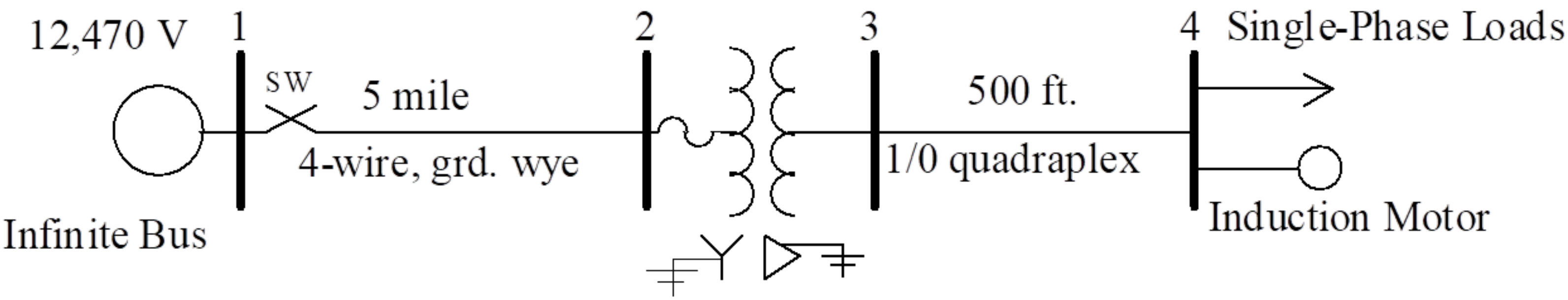
$$V_{an} + V_{nb} + V_{bc} + V_{ca} = 0$$

Kirchhoff's Current Law

$$I_a + I_b + I_c + I_n = 0$$

Every Node: $\sum I_{in} = \sum I_{out}$

Grounded Wye-Delta Test System



Forward Sweep:

$$[V2LG_{ABC}] = [ELG_{ABC}] - [Z_{ABC}] \cdot [I_{ABC}]$$

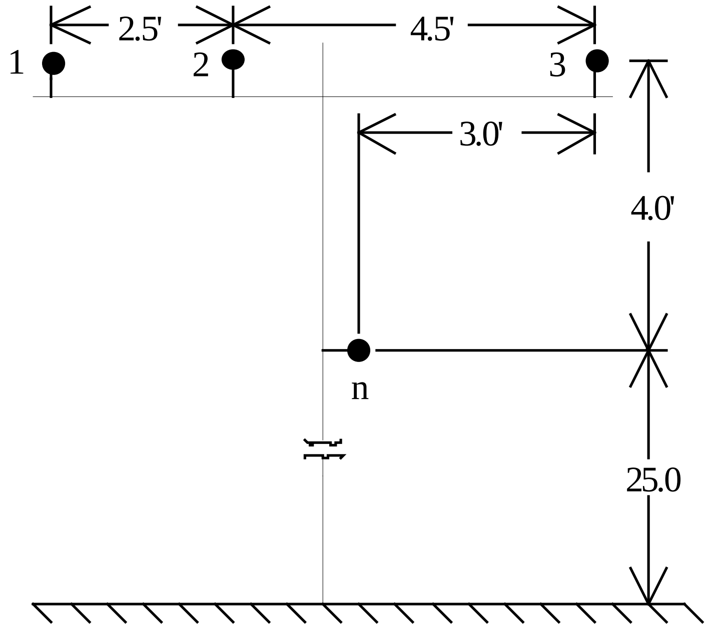
$$[V3_{anbc}] = [At]_n \cdot [V2LG_{ABC}] - [Bt]_n \cdot [I_{abc}]$$

$$[V4_{anbc}] = [V3_{anbc}] - [Zs_{anbc}] \cdot [I_{anbc}]$$

Backward Sweep:

$$[I_{ABC}] = [d_t] \cdot [I_{abc}]$$

Subtransmission Line

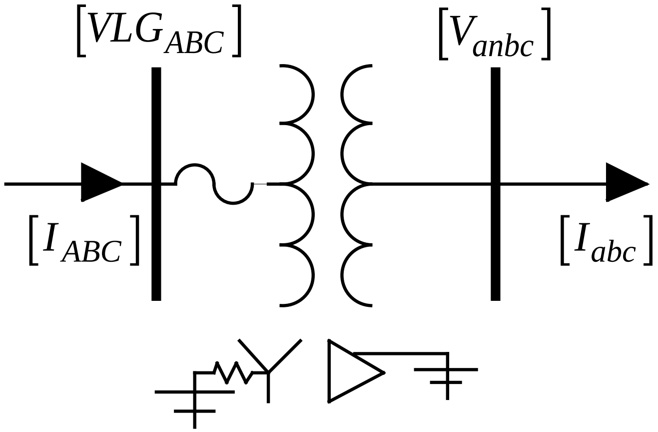


Phase Conductors: "Linnett" 336/400/ 26/7 ACSR

Neutral Conductor: 4/0 ACSR

$$Z_{.ABC} = \begin{pmatrix} 2.2878 + 5.3902i & 0.7797 + 2.5084i & 0.7674 + 1.9247i \\ 0.7797 + 2.5084i & 2.3331 + 5.2408i & 0.79 + 2.1182i \\ 0.7674 + 1.9247i & 0.79 + 2.1182i & 2.3074 + 5.3253i \end{pmatrix}$$

Grounded Wye-Delta Transformer Bank



The transformer bank data are:

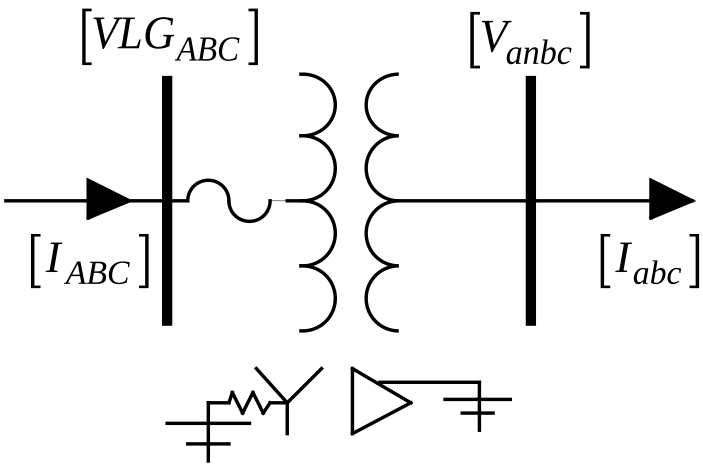
Lighting transformer (Phase A):

$kVA = 25$, 7200-240 volts, $Zt_{pu} = 0.012 + j0.017$

Power transformers (Phases B and C)

$kVA = 10$, 7200-240 volts, $Zt_{pu} = 0.016 + j0.014$

Final Grounded Wye-Delta Model



$$[V_{anbc}] = [A_t]_n \cdot [VLG_{ABC}] - [B_t]_n \cdot [I_{abc}]$$

$$[I_{ABC}] = [d_t]_n \cdot [I_{abc}]$$

where:

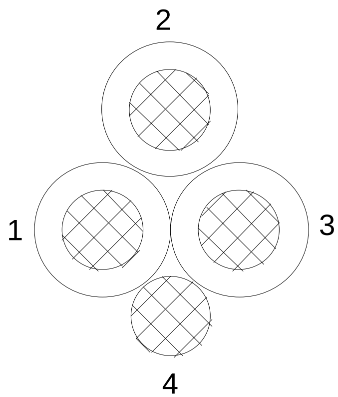
$$[A_t]_n = [KVL]_n \cdot [BV]$$

$$[B_t]_n = \left([KVL]_n \cdot \left([BV] \cdot [Z0G] \cdot [AI] + [Zt_{anbc}]\right) + [Z12]_n\right) \cdot [CI]_n$$

$$[d_t]_n = [AI] \cdot [CI]_n$$

Quadraplex Secondary

Quadraplex



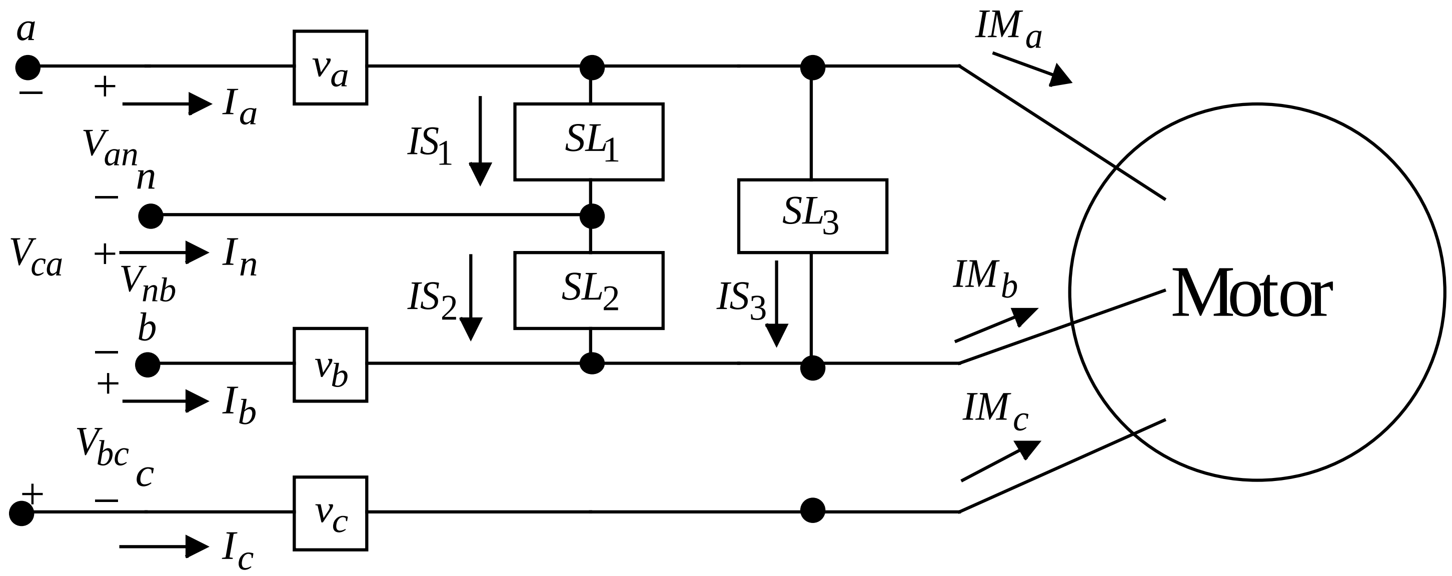
$$Zs_{anbc} = \begin{pmatrix} 0.1012 + 0.1429j & 0.009 + 0.1102j & 0.009 + 0.1102j & 0.009 + 0.1163j \\ 0.009 + 0.1102j & 0.1012 + 0.1429j & 0.009 + 0.1102j & 0.009 + 0.1084j \\ 0.009 + 0.1102j & 0.009 + 0.1102j & 0.1012 + 0.1429j & 0.009 + 0.1163j \\ 0.009 + 0.1163j & 0.009 + 0.1084j & 0.009 + 0.1163j & 0.1151 + 0.1534j \end{pmatrix}$$

3 - Insulated 1/0 All Aluminum

1 - Bare 1/0 ACSR

Insulation Thickness = 80 mil

The Secondary System



The single-phase lighting loads are:

$$S_{an} = 2.85 + j0.9367 \text{ kW+jkvar}$$

$$S_{nb} = 4.5 + j2.1794 \text{ kW+jkvar}$$

$$S_{ab} = 6.8 + j4.2143 \text{ kW+jkvar}$$

The three phase induction motor is:

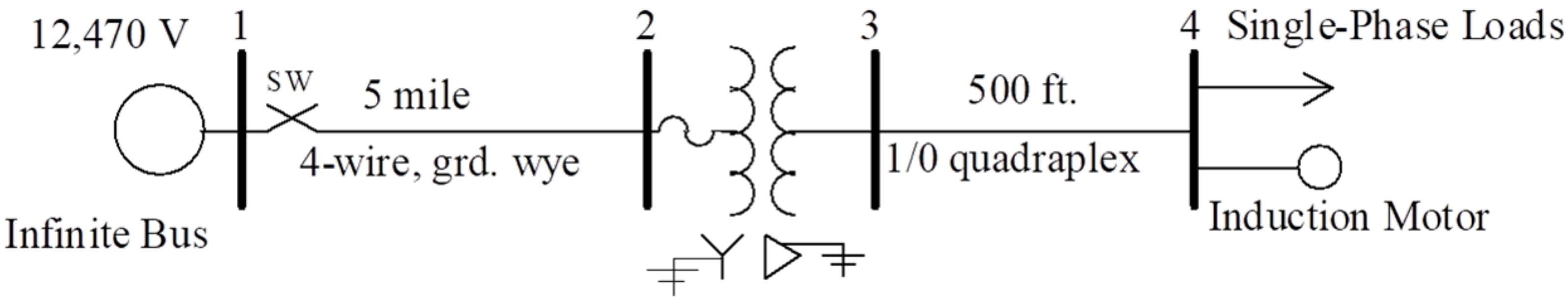
25 HP, 240 volts, slip = 0.3

Stator Z: $Zs_{pu} = 0.0366 + j0.08$

Rotor Z: $Zr_{pu} = 0.0394 + j0.08$

Magnitizing Z: $Zm_{pu} = 0 + j2.1$

Phase A Open, Motor Connected



Connected Motor Voltages and Currents

$$[VM_{abc}] = \begin{bmatrix} 201.5\underline{/-0.6} \\ 219.0\underline{/-115.2} \\ 226.6\underline{/118.5} \end{bmatrix} \qquad [IM_{abc}] = \begin{bmatrix} 38.8\underline{/-86.4} \\ 52.4\underline{/-158.1} \\ 73.3\underline{/51.2} \end{bmatrix}$$

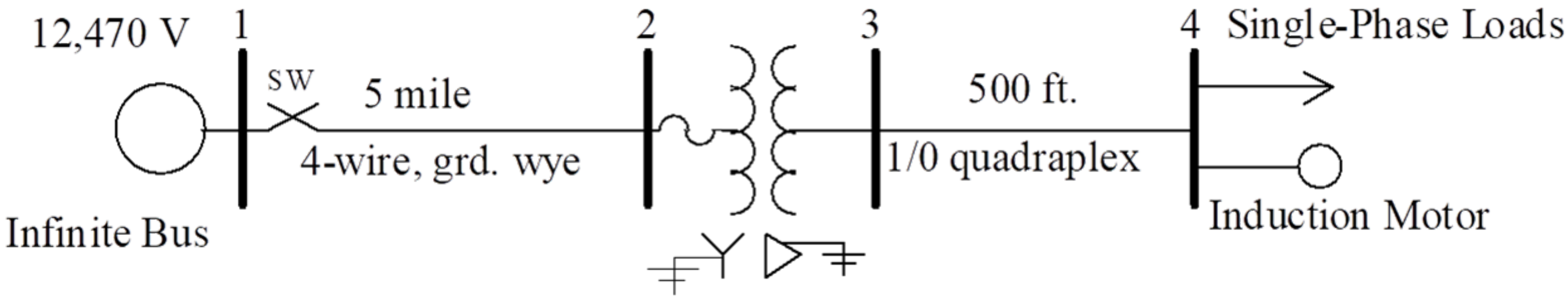
$$V_{unbalance} = 6.6\% \qquad I_{unbalance} = 33.7\%$$

Backfeed Voltages:

$$V1_{AG} = 6302.8\underline{/-1.9} \text{ volts}$$

$$V2_{AG} = 6313.7\underline{/-1.8 \text{ volts}}$$

Phase A Open, Motor Off



Backfeed Voltages

$$V1_{AG} = 6557.0\underline{/-1.1} \text{ volts}$$

$$V2_{AG} = 6565.5\underline{/-1.0 \text{ volts}}$$

Secondary Currents

$$[I_{anbc}] = \begin{bmatrix} I_a \\ I_n \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 66.4\underline{/-26.6} \\ 18.0\underline{/-39.2} \\ 84.0\underline{/150.7} \\ 0 \end{bmatrix}$$

Single-Phase Load Voltages

$$\begin{bmatrix} VL_{an} \\ VL_{nb} \\ VL_{bc} \end{bmatrix} = \begin{bmatrix} 103.4\underline{/-0.7} \\ 108.1\underline{/-0.8} \\ 211.5\underline{/-0.8} \end{bmatrix}$$

Phase B and Phase C Open

Phase B Open

$V1_{BG} = 6794.5\underline{/-120.4}$

$V2_{BG} = 6806.1\underline{/-120.3}$

$V_{unbalance} = 1.7$

$I_{unbalance} = 11.7\%$

Phase C Open

$V1_{CG} = 6874.0\underline{/119.1}$

$V2_{CG} = 6878.6\underline{/119.2}$

$V_{unbalance} = 1.2\%$

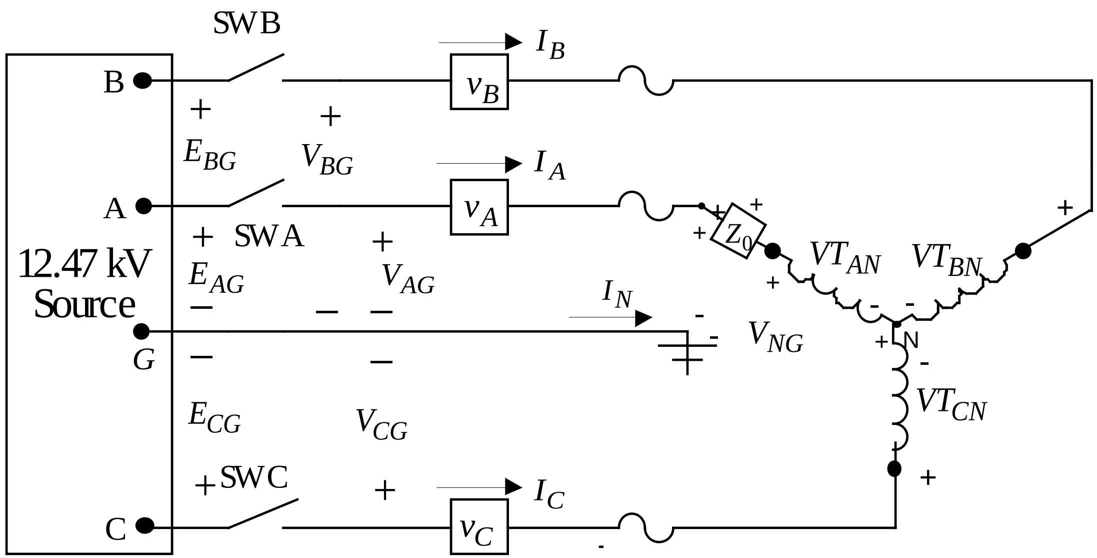
$I_{unbalance} = 6.9\%$

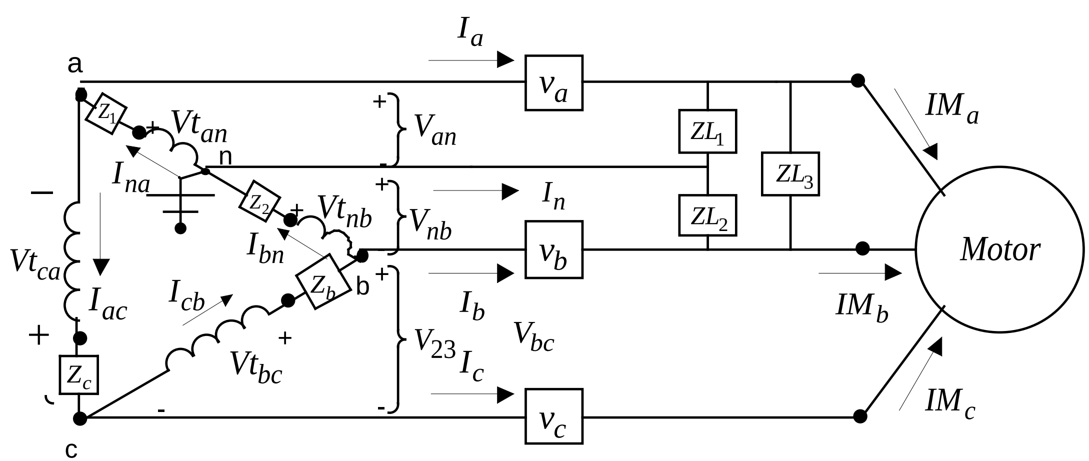
Because the voltage unbalance is below the 3% level, the motor will not be tripped

Summary for Grounded Wye-Delta

- No matter which phase is open, there will be a significant backfeed voltage at the open switch
- When phase A is open the voltage unbalance at the motor will be high and therefore the protective device will trip the motor off.
- When phase B or phase C is open the voltage unbalance is low so motor will continue to operate.
- In all cases the single-phase loads are served

Ungrounded Wye-Delta Circuit





Phase A Open No-Load Operating Condition

- Motor and Single-Phase Loads are Off

$$[VM] = \begin{bmatrix} 0 \\ 207.8\underline{/-90} \\ 207.8\underline{/90} \end{bmatrix}$$

- Single-Phase voltages so motor will not start
- Without three-phase voltages the rotational magnetic field needed to start the motor is not there.

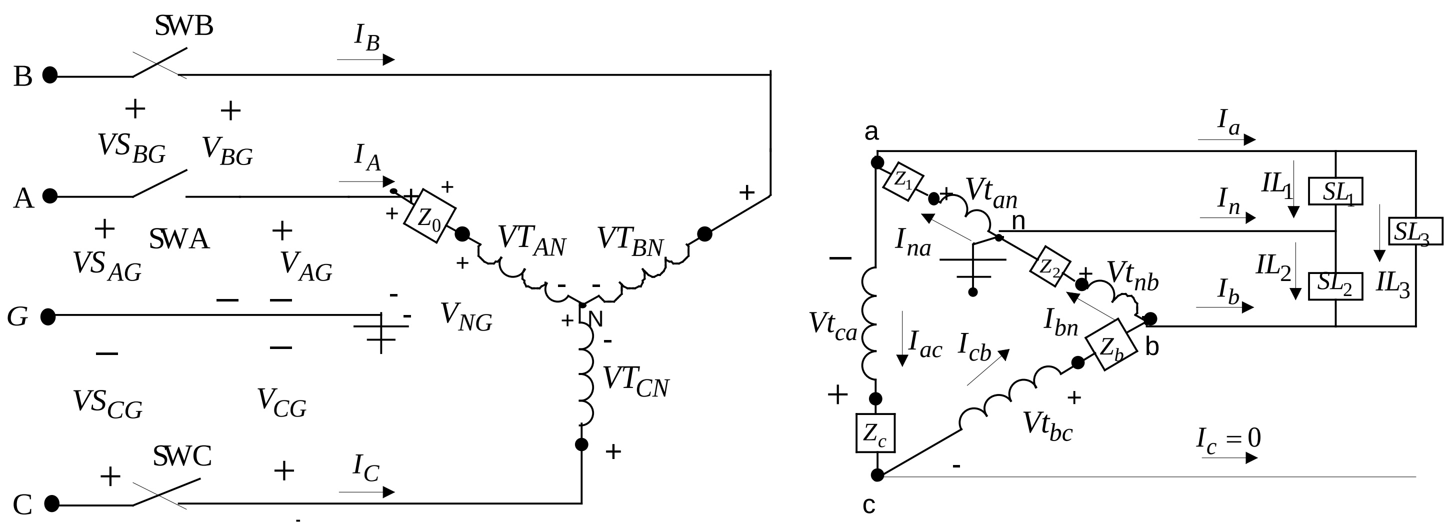
Phase A Open with Motor and Loads On

$$[VM_{abc}] = \begin{bmatrix} 117.3\underline{/-20.9} \\ 169.3\underline{/-106.0} \\ 214.0\underline{/107.1} \end{bmatrix} \qquad [IM_{abc}] = \begin{bmatrix} 71.7\underline{/-168.6} \\ 78.6\underline{/-101.8} \\ 125.6\underline{/46.5} \end{bmatrix}$$

$$V_{unbalance} = 29.7\ \% \qquad I_{unbalance} = 36.5\ \%$$

Because of the high voltage unbalance the protective device for the motor will open turning the motor off.

Open Phase A, Motor Off



$$V_{NG} = 3600\angle 180$$

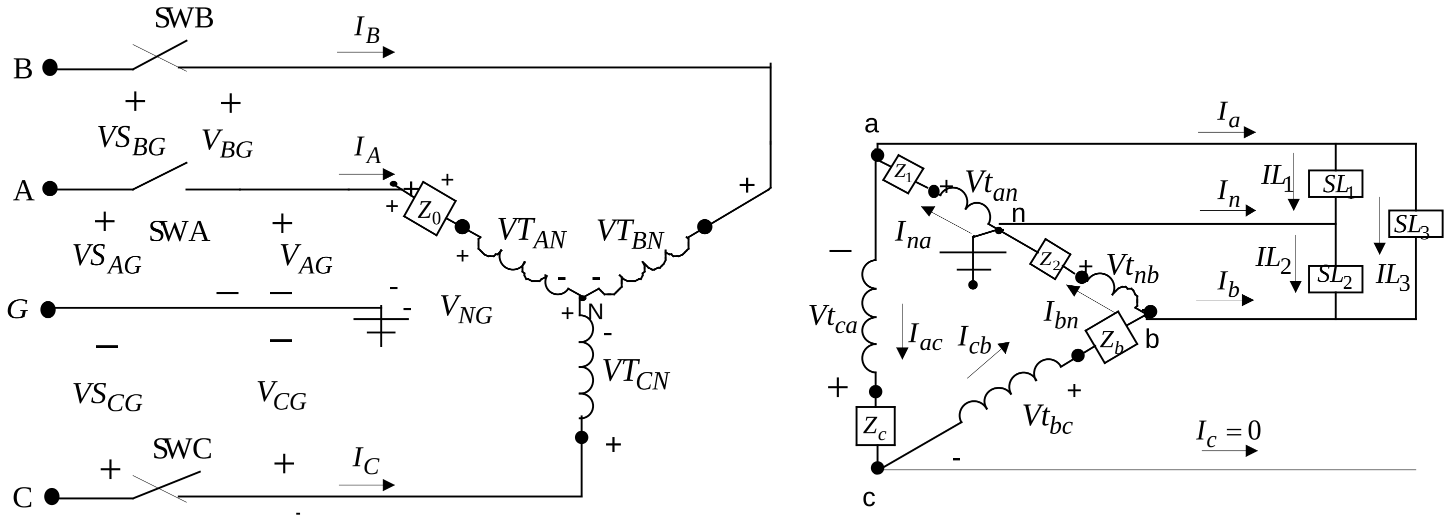
$$VT_{AN} = 0, \quad VT_{BN} = 6235.4\angle -90, \quad VT_{CN} = 6235.4\angle 90$$

$$Vt_{an} = Vt_{nb} = 0, \quad Vt_{bc} = 207.8\angle -90, \quad Vt_{ca} = 207.8\angle 90$$

$$V1_{AG} = 3600\angle 180, \quad V1_{BG} = 7200\angle -120, \quad V1_{CG} = 7200\angle 120$$

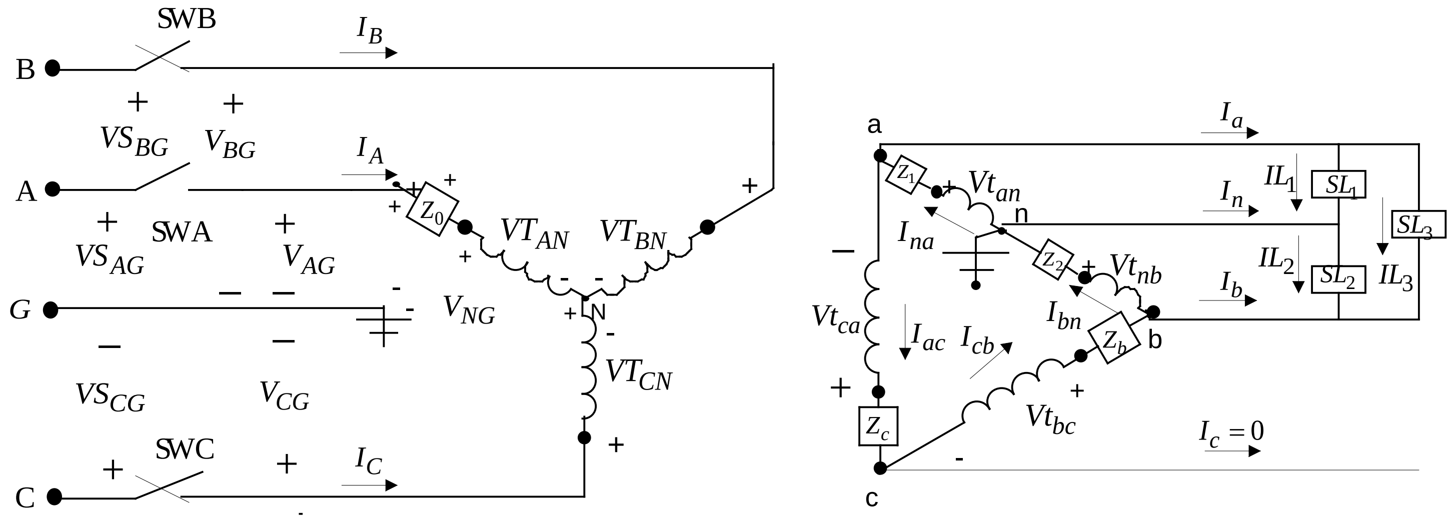
All currents primary, secondary and single-phase loads = 0

Phase A Open Currents



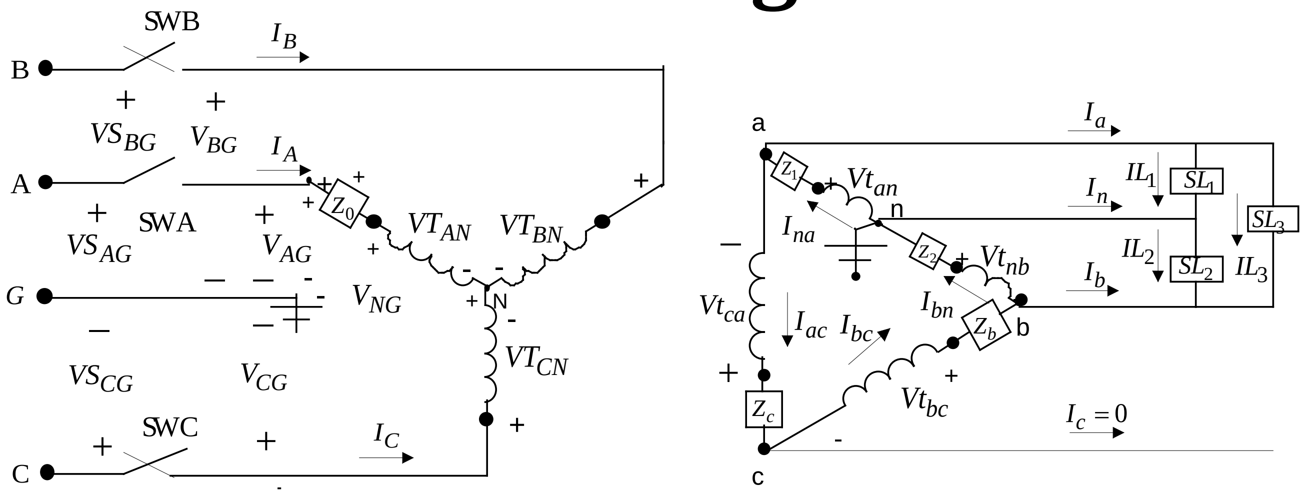
- $I_A = 0$ therefore $I_{an} + I_{bn} = 0$
- Path for I_B and I_C so $I_C = -I_B$
- Because of above $I_{ac} = -I_{cb}$
- With motor open $I_c = 0$ for all conditions
- At node c $I_c = I_{ac} - I_{cb} = 0$ this is impossible since $I_{ac} = -I_{cb}$
- Because of the above $I_{ac} = I_{cb} = 0$
- Therefore $I_B = I_C = 0$

Kirchhoff's Current Law (KCL)



- In previous slide $I_{ac} = I_{cb} = I_{na} + I_{nb} = I_c = 0$
- Since $I_{na} + I_{bn} = 0$ then $I_{bn} = -I_{na}$
- KCL at node a: $I_a = I_{na} - I_{ac} = I_{na} - 0 = I_{na}$
- KCL at node b: $I_b = I_{cb} - I_{bn} = 0 - I_{bn} = I_{na}$
- KCL at node n: $I_n = I_{bn} - I_{na} = -I_{na} - I_{na} = -2 \cdot I_{na}$
- KCL on secondary: $I_a + I_b + I_c + I_n = 0 = I_{na} - I_{bn} + 0 - 2 \cdot I_{na}$
  $I_{na} + I_{na} - 2 \cdot I_{na} = 0$

Phase A Open Voltages



- Voltage applied to primary windings: $VT_{BC} = VT_{BN} - VT_{CN} = 12,470\underline{/-90}$
- Phase B winding voltage: $VT_{BN} = 0.5 \cdot VT_{BC} = 6235\underline{/-90}$
- Phase C winding voltage: $VT_{CN} = -0.5 \cdot VT_{BC} = 6235\underline{/90}$
- The secondary ideal voltages are: $Vt_{bc} = 207.8\underline{/-90}$ and $Vt_{ca} = 207.8\underline{/90}$
- KVL: $Vt_{an} + Vt_{nb} + Vt_{bc} + Vt_{ca} = 2 \cdot Vt_{an} + 0 = 0$
- Since: $Vt_{an} = 0$ then $VT_{AN} = 0$
- Primary neutral voltage: $V_{NG} = V_{BG} - VT_{AN} = 3600\underline{/180}$
- Phase A backfeed voltage: $V_{AG} = VT_{AN} + V_{NG} = 0 + V_{NG} = 3600\underline{/180}$

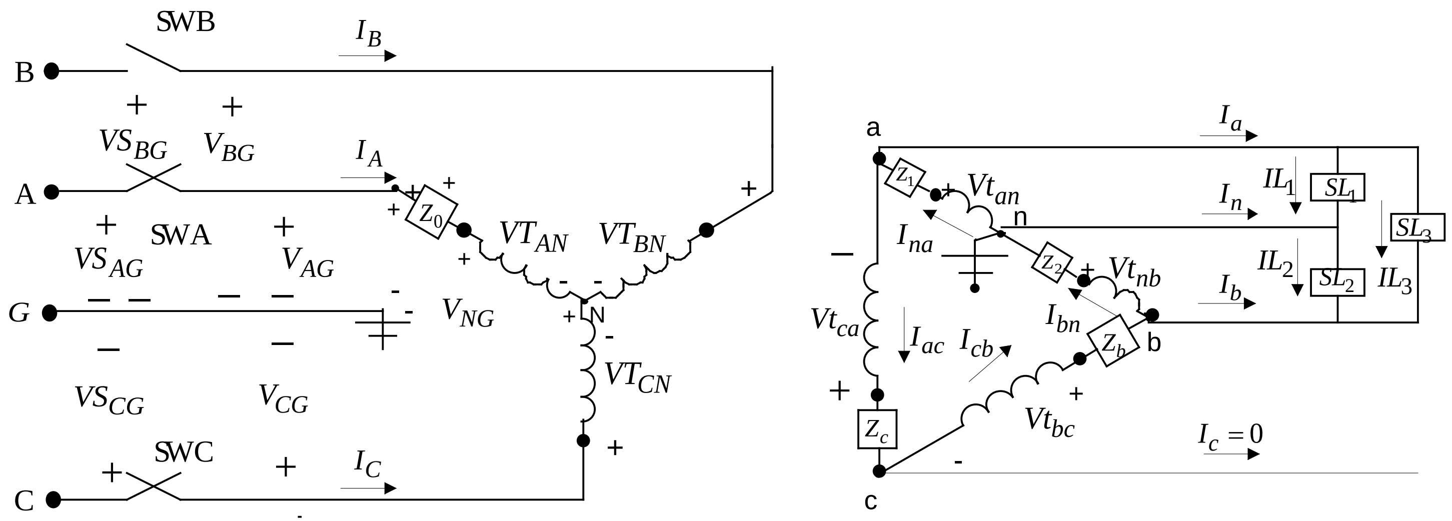
Phase B Open with Motor and Loads On

$$[VM_{abc}] = \begin{bmatrix} 192.1\underline{/-10.3} \\ 119.3\underline{/-121.4} \\ 186.0\underline{/133.0} \end{bmatrix} \qquad [IM_{abc}] = \begin{bmatrix} 102.3\underline{/-84.0} \\ 36.8\underline{/54.2} \\ 78.8\underline{/114.2} \end{bmatrix}$$

$$V_{unbalance} = 28.0\ \% \qquad I_{unbalance} = 49.3\ \%$$

Because of the high voltage unbalance the protective device for the motor will open turning the motor off.

Open Phase B, Motor Off



$$V_{NG} = 7200\underline{/0}$$

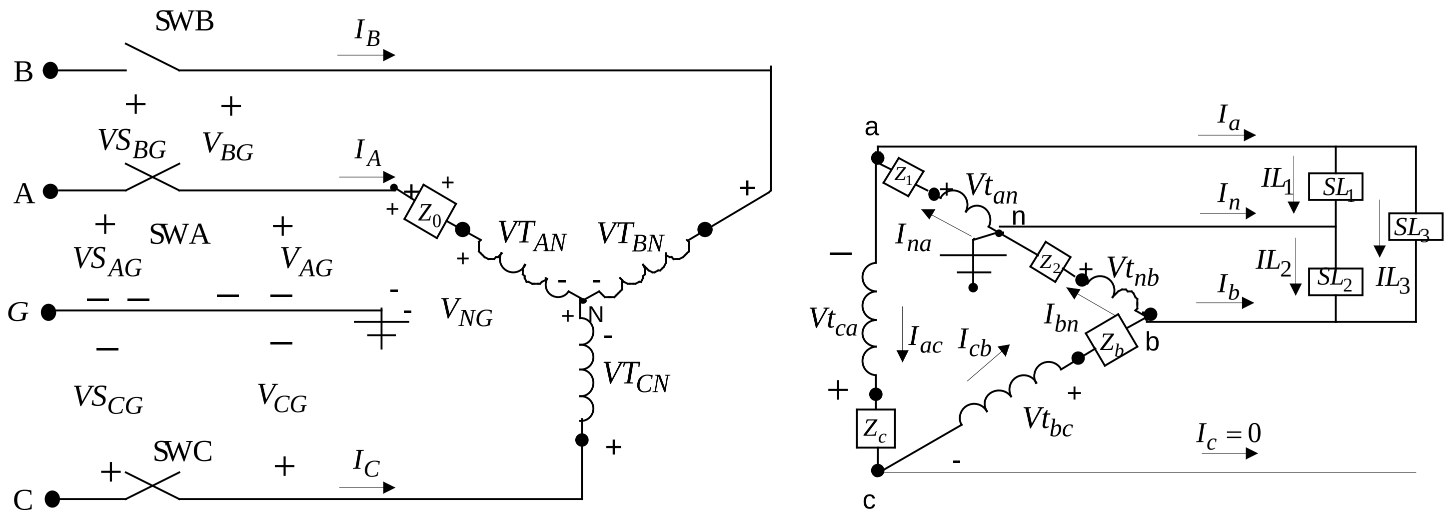
$$VT_{AN} = 0, \quad VT_{BN} = 12470.8\underline{/-30}, \quad VT_{CN} = 12470.8\underline{/150}$$

$$Vt_{an} = Vt_{nb} = 0, \quad Vt_{bc} = 415.7\underline{/-30}, \quad Vt_{ca} = 415/7\underline{/150}$$

$$V1_{AG} = 7200\underline{/0}, \quad V1_{BG} = 19049.4\underline{/-19.1}, \quad V1_{CG} = 7200\underline{/120}$$

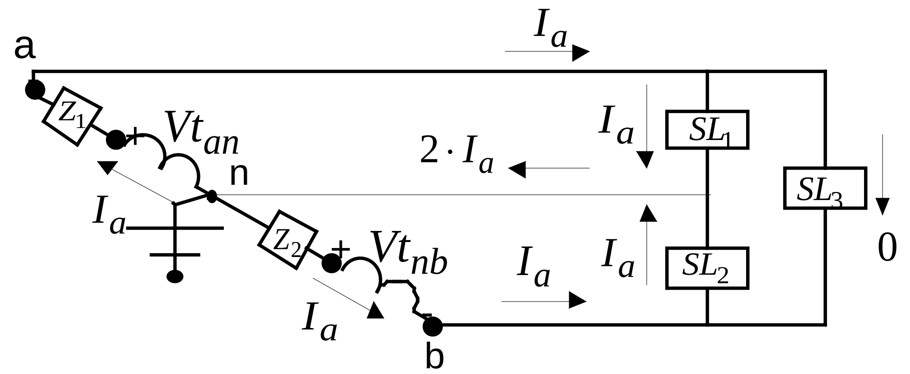
All currents primary, secondary and single-phase loads = 0

Phase B Open Currents



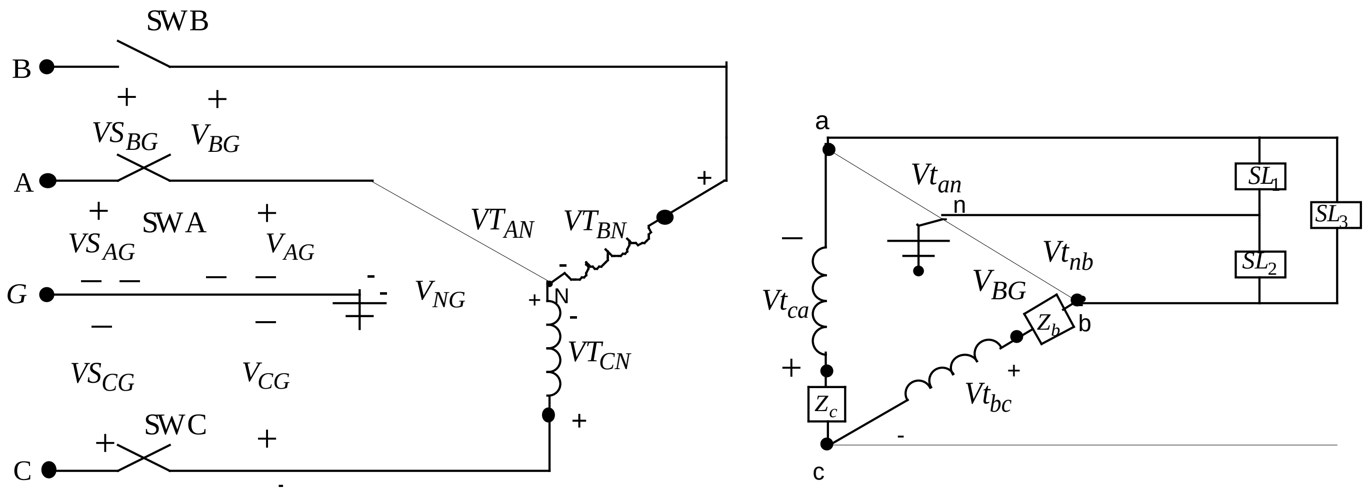
- $I_B = 0$ therefore $I_{cb} = 0$
- There is a path for I_C and I_A so $I_A = -I_C$
- With $I_{cb} = 0$ and $I_c = 0$ then KCL says $I_{ac} = 0$
- With $I_{ac} = 0$ then $I_C = 0$ and $I_A = 0$
- In short $I_A = I_B = I_C = 0$
- However: $I_{na} + I_{bn} = 0$ or $I_{bn} = -I_{na}$
- What about $Vt_{an} = Vt_{nb} = ?$

Secondary and Load Currents



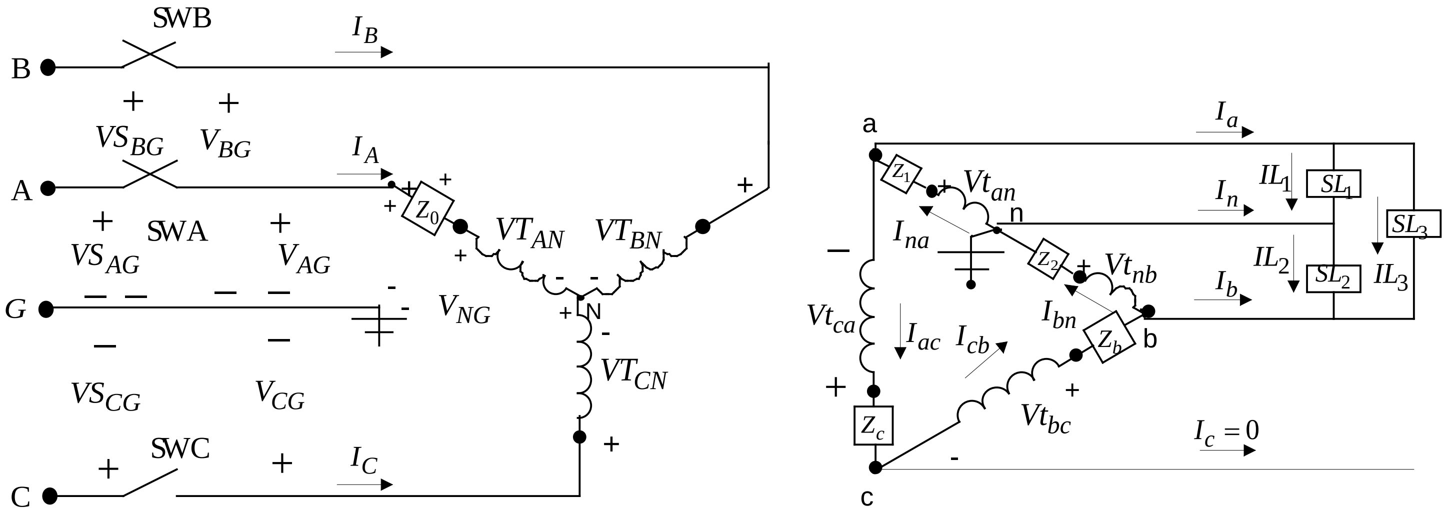
- Look at the circuit and note that $I_{bn} = -I_{na}$
- Shown in the circuit is only I_a since $I_{nb} = -I_{an} = I_a$
- This makes the same currents flow in phase a and phase b
- Now must have $2 \cdot I_a$ flowing in the neutral as shown
- Note the same current must flow thru the two 120 volt loads
- This requires the voltages $VL_{an} = VL_{bn}$
- This is impossible because of the polarities of Vt_{an} and Vt_{nb}
- Therefore the only thing that works is $Vt_{an} = Vt_{nb} = VT_{AN} = 0$

Computation of Open Switch B Line-to-ground Voltage



- With the shorted voltages the only primary voltage is $VT_{CN} = VT_{CA} = 12,470\underline{/150}$
- Now $Vt_{ca} = \frac{1}{n} \cdot VT_{CA} = 415.7\underline{/150}$
- To satisfy KVL: $Vt_{bc} = -Vt_{ca} = 415.7\underline{/-30}$
- Therefore: $VT_{BN} = n_t \cdot Vt_{bc} = 12,470\underline{/-30}$
- With the neutral and phase A shorted: $V_{NG} = V_{AG} = 7200\underline{/0}$
- Now: $V_{BG} = VT_{BN} + V_{NG} = 19049.4\underline{/-19.1}$

Phase C Open with Motor and Loads On

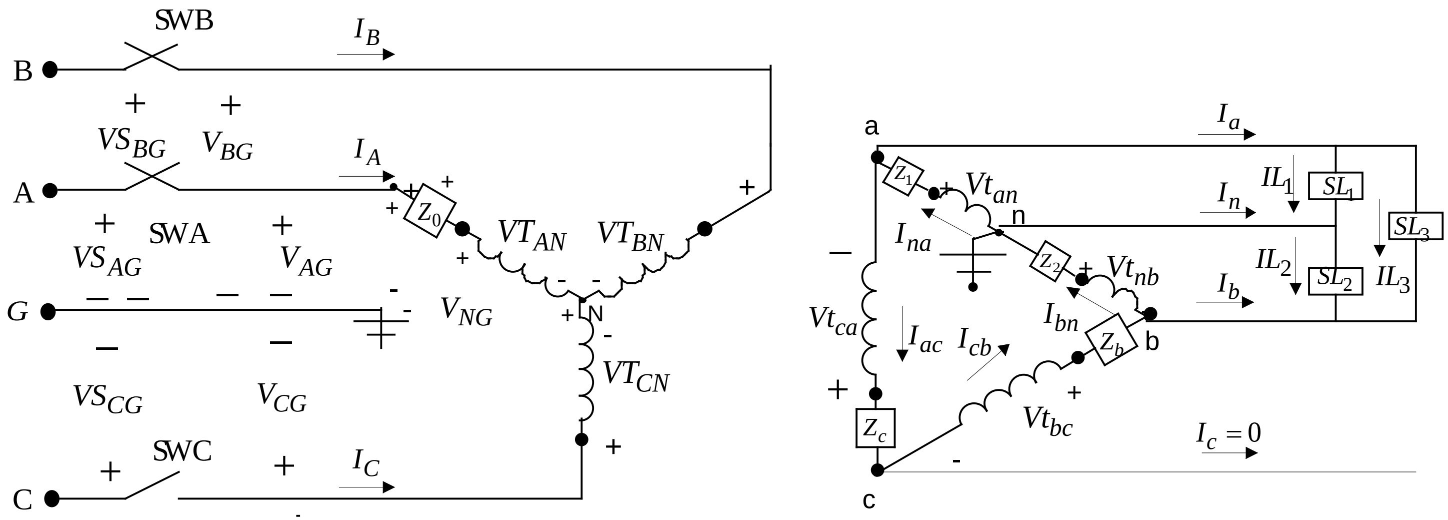


$$[VM_{abc}] = \begin{bmatrix} 165.5/\underline{2.1} \\ 229.0/\underline{-127.3} \\ 178.2/\underline{98.6} \end{bmatrix} \qquad [IM_{abc}] = \begin{bmatrix} 30.6/\underline{34.5} \\ 103.5/\underline{-174.7} \\ 78.2/\underline{-5.6} \end{bmatrix}$$

$$V_{unbalance} = 20.0\ \% \qquad I_{unbalance} = 56.7\ \%$$

Because of the high voltage unbalance the protective device for the motor will open turning the motor off.

Open Phase C, Motor Off



$V_{NG} = 7200\underline{/0}$

$VT_{AN} = 0,\quad VT_{BN} = 12470.8\underline{/-150},\quad VT_{CN} = 12470.8\underline{/30}$

$Vt_{an} = Vt_{nb} = 0,\quad Vt_{bc} = 415.7\underline{/-150},\quad Vt_{ca} = 415\,/\,7\underline{/30}$

$V1_{AG} = 7200\underline{/0},\quad V1_{BG} = 7200\underline{/-120},\quad V1_{CG} = 19049.4\underline{/19.1}$

All currents primary, secondary and single-phase loads = 0

Conclusions - 1

- The original question was whether the wye should be grounded. The answer is still ???
- Grounded Wye-Delta
  - Provides three-phase service with an open phase
  - High backfeed short circuit current for upstream ground faults
  - Provides a backfeed voltage below rated LG voltage but still dangerous

Conclusions - 2

- Ungrounded Wye-Delta
  - Does not provide three-phase service with an open phase
  - Does not provide a backfeed current for upstream ground faults
  - Provides a very high backfeed voltage (2.65 times rated LG voltage) when phase B or C is open
  - Lower backfeed voltage when the center tap phase is open

Conclusions-3

- So what is the answer?
  - Good question
  - Neither connection is perfect
  - What is known is that both connections will provide a very dangerous backfeed voltage on the downstream side of the open switch
  - **Linemen must be trained to understand that just because the switch is open, it is not save to touch the line on either side of the switch**