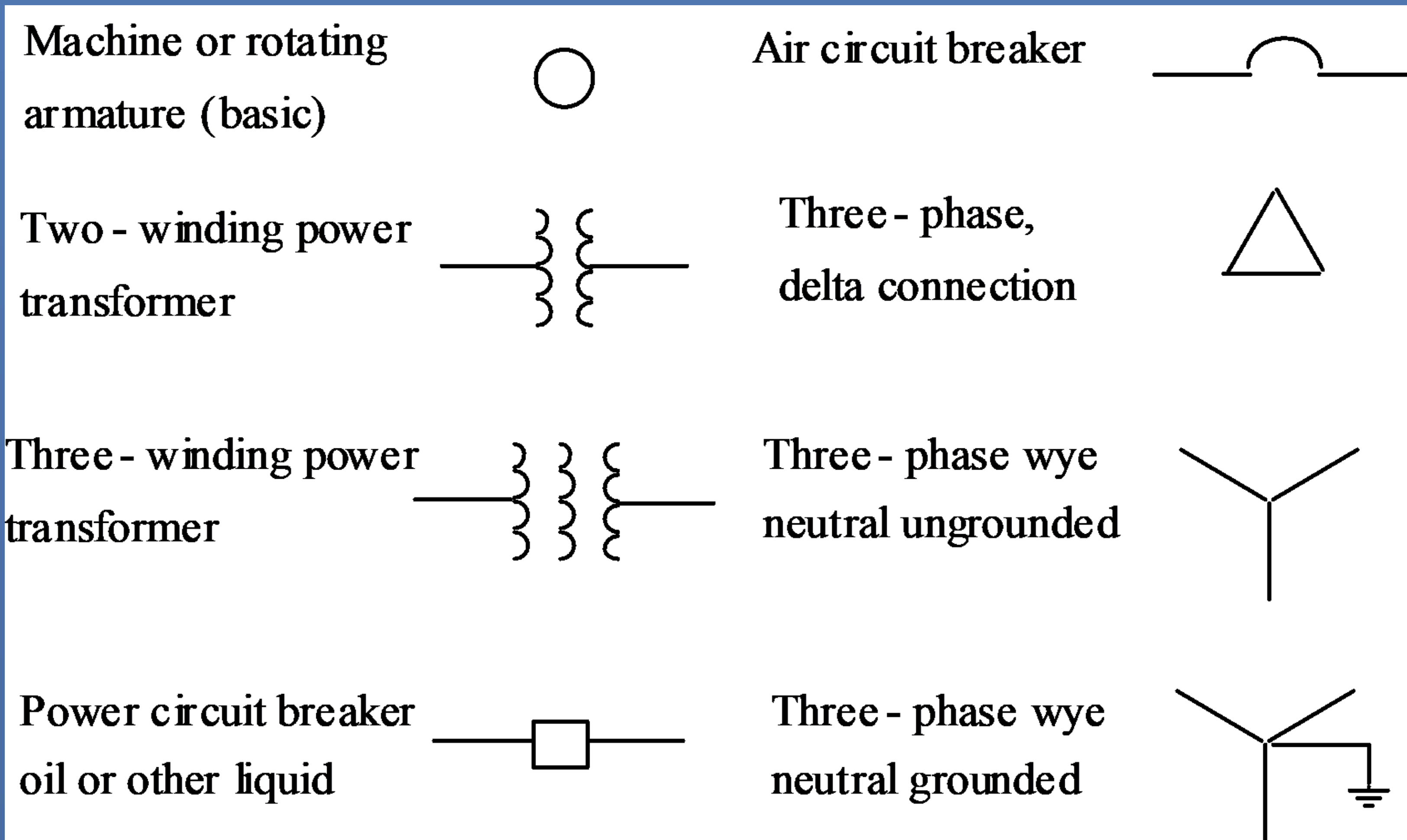
B4.2 Power System One-Line Diagrams

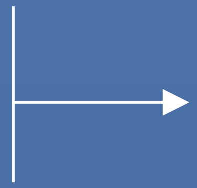
A convenient way to represent power systems uses “one-line” diagrams. The one-line diagram can be obtained from a per-unitized circuit by:

1. Omitting the neutral.
2. Representing each component by simple, standardized symbols.

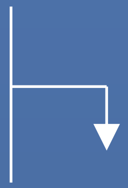
Standard symbols for one-line diagrams.

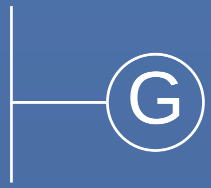


Another important symbol is the “bus” or node, which typically represents a substation or a generation plant switchyard. Loads are always represented at a bus with an arrow. Generators and motors are also always represented at a bus.



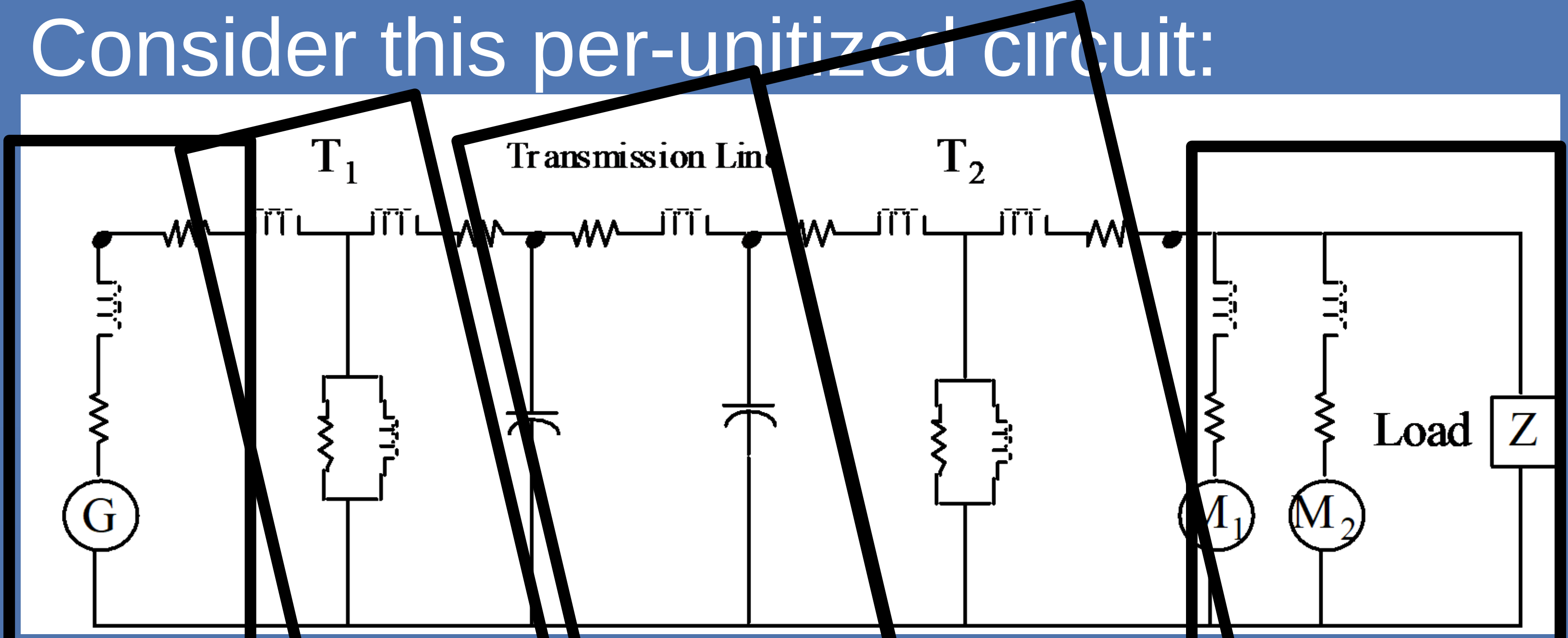
or



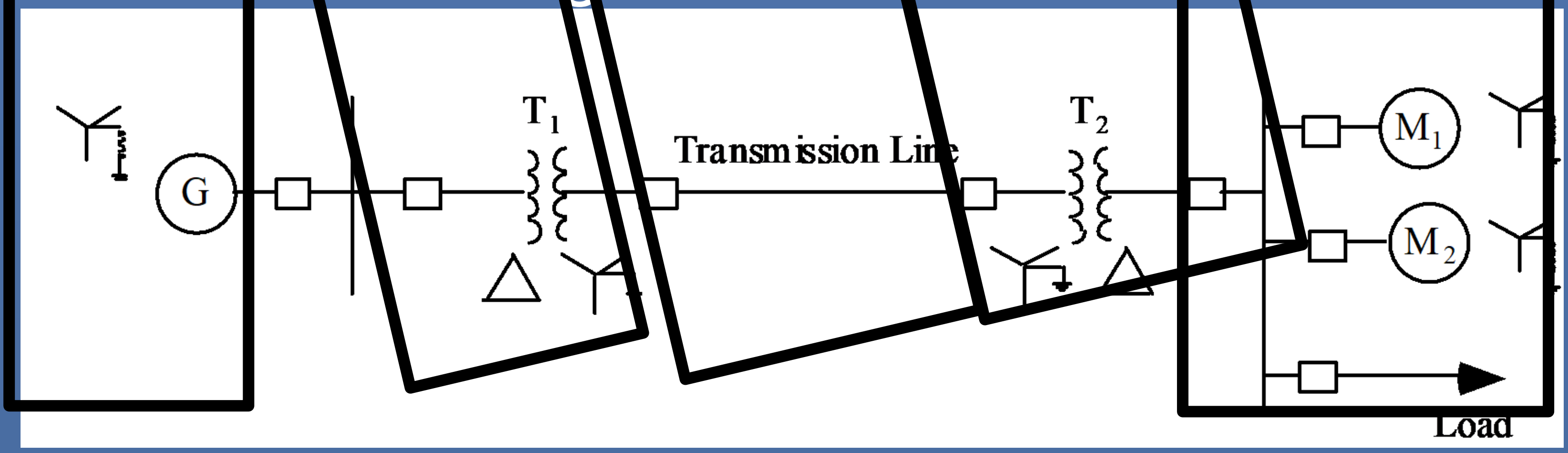


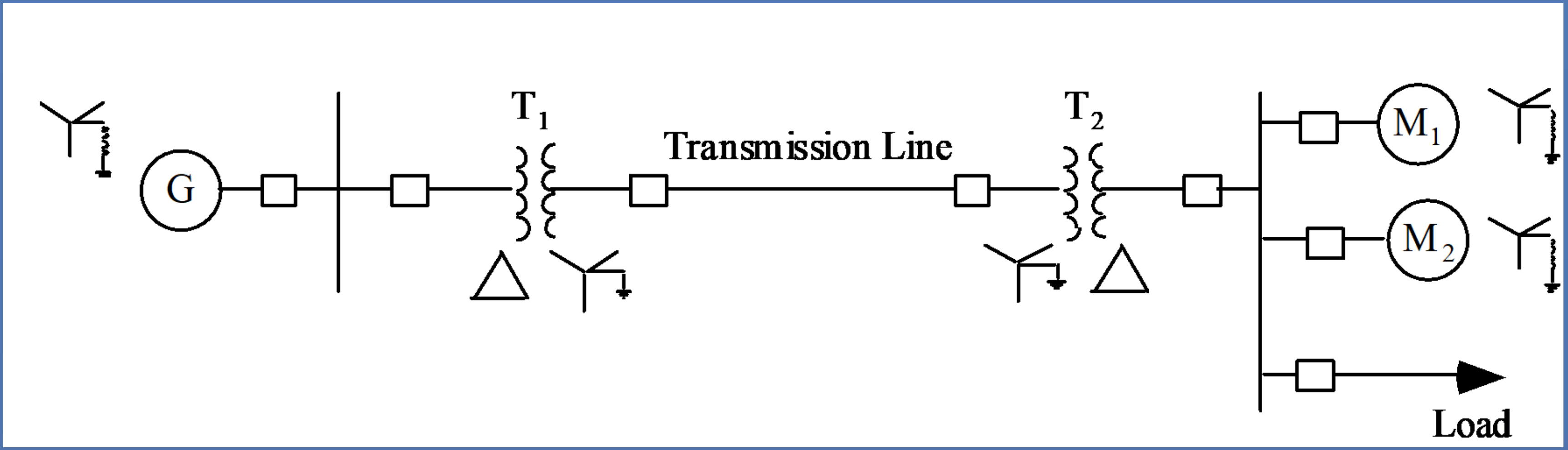
If a circle does not have a “G” or “M” inside, assume it is a generator.

Consider this per-unitized circuit:



The one-line diagram is:





Often, for an even simpler representation, we omit breakers and connection types, and we use a single "squiggle" for transformers.

The "simpler" representation becomes:

Brief comments on transformers (xfmrs):

Xfmrs convert voltages from one level to another.

Power systems use 3 phase xfmrs, which can be thought of as 3 single phase xfmrs with primary and secondary windings connected either in Wye or Delta.

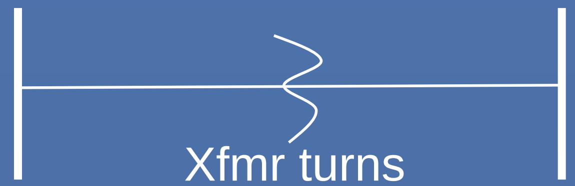
Per-phase equivalent circuits represent xfmrs as single phase.

Brief comments on transformers (xfmrs):

The simplest xfmr model is the ideal xfmr.
The next simplest is the ideal xfmr with a reactance.
We called this “approximate equivalent circuit #3” in our previous treatment of transformers.

The transformation ratio of ideal xfmrs in per-unitized circuits is 1:1. Why is this?

Nominal voltage = 69 kV



Choose V_{base1}=69 kV for this side.

Xfmr turns ratio=V_1/V_2= 69/161

Compute V_{base2}=69 kV*161/69=161 kV for this side.

$$\frac{V_{pu1}}{V_{pu2}} = \frac{V_1 / V_{base1}}{V_2 / V_{base2}} = \frac{V_1}{V_2}\frac{V_{base2}}{V_{base1}} = \frac{69}{161}\frac{161}{69} = 1.0$$

Therefore, in per-unit, we only need to represent the reactance (when using the “approximate model #3”).

Definition:

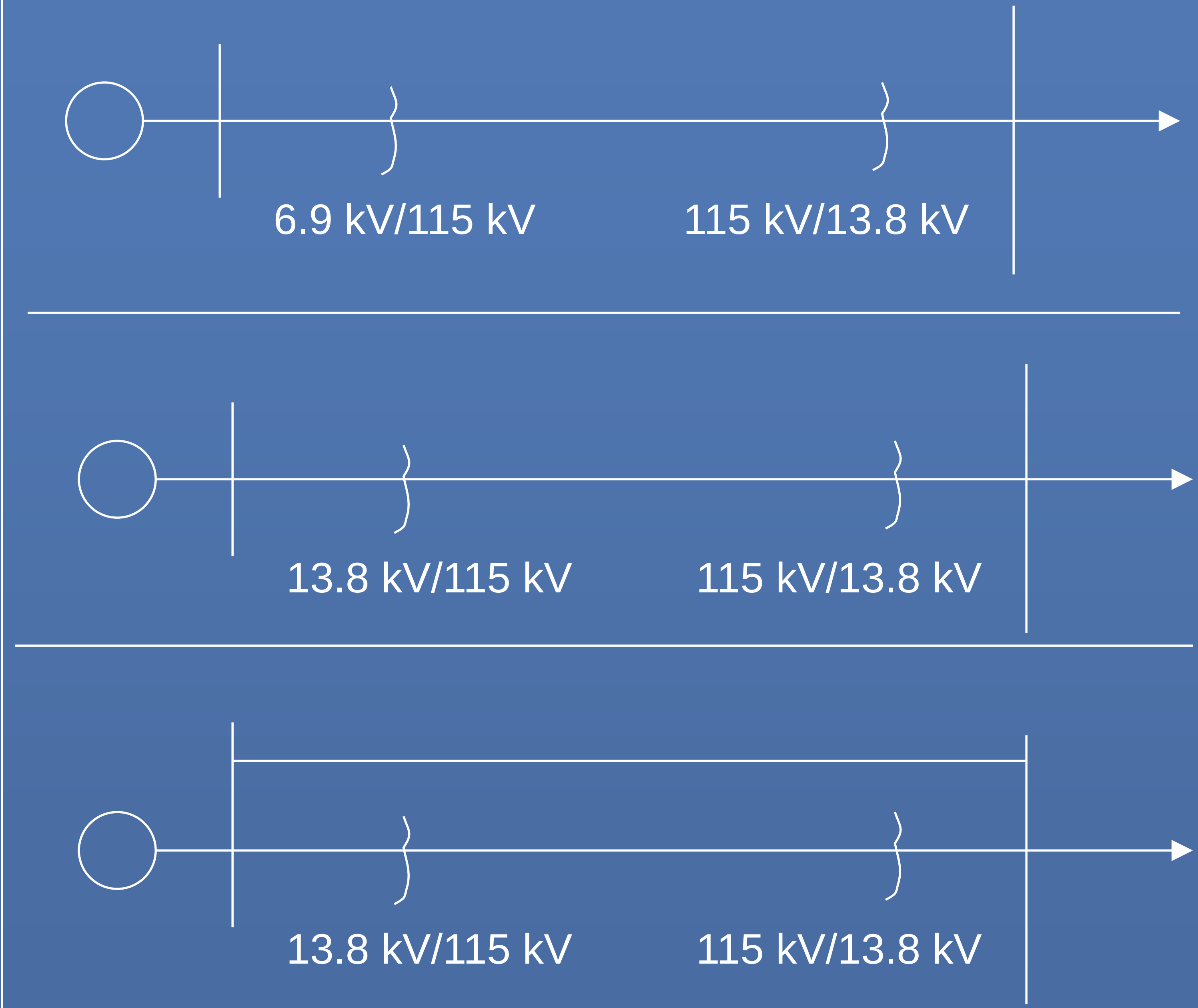
A “section” of a system is a set of interconnected components not separated by a transformer. If you can trace the one-line diagram from one component to another without crossing a transformer, these two components are in the same section.

Different sections are connected by transformers.

A single section may be connected to 1 or more other sections.

Voltages specified in xfmr ratios are assumed to be line-to-line unless otherwise indicated.

How many sections are in each of these systems?



Choosing bases for per unitizing systems with xfmrs

1. Select the system power base.
2. Select the voltage base for one section of the system.
3. Compute the voltage bases for all other sections. This computation is guided by the following rule:

   The ratio of voltage bases (line to line voltage bases and phase to neutral voltage bases) in two connected sections must be the same as the line-to-line voltage ratio across the transformer connecting the two sections.

   Therefore, we can use the transformer ratios indicated on the one-line to get the voltage bases.

4. Compute the current and impedance base for each section using the system power base and the appropriate voltage base.

Example: Select voltage base for one section & compute voltage bases for other sections. Then compute current & impedance bases for all sections of this system. Assume 3 phase power base is 100 MVA.

Select section 3 voltage base as 13.8 kV. Then

$$\text{voltage base } V_2 = \frac{V_{2,xfmr}}{V_{3,xfmr}} \text{ voltage base } V_3 = \frac{115}{13.8} \times 13.8\,\text{kV} = 115\,\text{kV}$$

$$\text{voltage base } V_1 = \frac{V_{1,xfmr}}{V_{2,xfmr}} \text{ voltage base } V_2 = \frac{6.9}{115} \times 115\,\text{kV} = 6.9\,\text{kV}$$

Now we can compute current and impedance bases.

<u>**Note**</u>: All voltage bases are line to line, so we will use relations with line to line voltages (we could also compute line-to-neutral voltage bases, then use the relations with line-to-neutral voltages).

$$\text{base current } I = \frac{\text{base power } S_{3\phi}}{\sqrt{3}(\text{base voltage } V_{LL})}, \quad \text{base imped. } Z = \frac{(\text{base voltage } V_{LL})^2}{\text{base power } S_{3\phi}}$$

$$\text{current base } I_1 = \frac{100\times10^6}{\sqrt{3}(6.9\times10^3)} = 8367.4 \text{ amps}$$

$$\text{base imped. } Z_1 = \frac{(6.9\times10^3)^2}{100\times10^6} = 0.4761\,\Omega$$

$$\text{current base } I_2 = \frac{100\times10^6}{\sqrt{3}(115\times10^3)} = 502.04 \text{ amps}$$

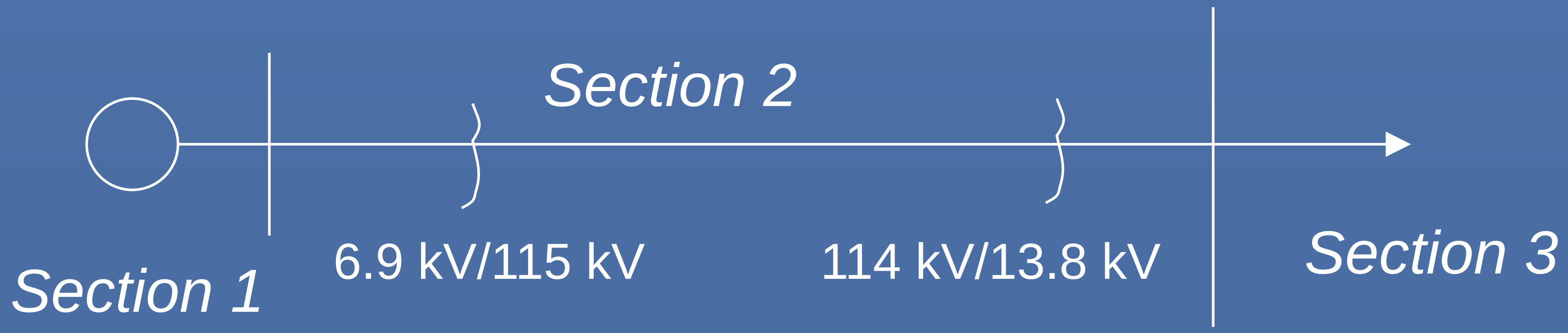
$$\text{base imped. } Z_2 = \frac{(115\times10^3)^2}{100\times10^6} = 132.25\,\Omega$$

$$\text{current base } I_3 = \frac{100\times10^6}{\sqrt{3}(13.8\times10^3)} = 4183.7 \text{ amps}$$

$$\text{base imped. } Z_3 = \frac{(13.8\times10^3)^2}{100\times10^6} = 1.9044\,\Omega$$

Watch out! Xfmr voltage ratios characterize the base voltage ratios but not necessarily the base voltages themselves. You must be careful if a section is connected by multiple xfmrs.

Example: Repeat the calculations from the previous example. 3 phase power base is 100 MVA



Select section 3 voltage base as 13.8 kV. Then

$$\text{voltage base } V_2 = \frac{V_{2,xfmr}}{V_{3,xfmr}} \text{voltage base } V_3 = \frac{114}{13.8} \times 13.8 \text{ kV} = 114 \text{ kV}$$

$$\text{voltage base } V_1 = \frac{V_{1,xfmr}}{V_{2,xfmr}} \text{voltage base } V_2 = \frac{6.9}{115} \times 114 \text{ kV} = 6.84 \text{ kV}$$

Now we can compute current and impedance bases. Note that all voltage bases are line to line, so we will again use the relations with line to line voltages (we could also compute line-to-neutral voltage bases, then use the relations with line-to-neutral voltages).

$$\text{base current } I = \frac{\text{base power } S_{3\phi}}{\sqrt{3}(\text{base voltage } V_{LL})}, \quad \text{base imped. } Z = \frac{(\text{base voltage } V_{LL})^2}{\text{base power } S_{3\phi}}$$

$$\text{current base } I_1 = \frac{100\times10^6}{\sqrt{3}(6.84\times10^3)} = 8440.2 \text{ amps}$$

$$\text{base imped. Z}_1 = \frac{(6.84\times10^3)^2}{100\times10^6} = 0.4679\,\Omega$$

$$\text{current base } I_2 = \frac{100\times10^6}{\sqrt{3}(114\times10^3)} = 506.45 \text{ amps}$$

$$\text{base imped. Z}_2 = \frac{(114\times10^3)^2}{100\times10^6} = 129.96\,\Omega$$

$$\text{current base } I_3 = \frac{100\times10^6}{\sqrt{3}(13.8\times10^3)} = 4183.7 \text{ amps}$$

$$\text{base imped. Z}_3 = \frac{(13.8\times10^3)^2}{100\times10^6} = 1.9044\,\Omega$$

Converting pu impedances from one base to another

Often impedances given in pu on one base must be converted to a pu value given on another base. The most common application of this is when

- component impedances are given on the component base
- and you want to represent them within a system on another base.

You can have

- a change of power base or
- a change of voltage base or
- a change of both.

In any of these three situations, the impedance base will change, and so the pu value of the impedance will change.

The module B4 text develops the following relation.

$$Z_{pu,new} = Z_{pu,old}\left(\frac{\text{base } V_{old}}{\text{base } V_{new}}\right)^2\left(\frac{\text{power base } S_{new}}{\text{power base } S_{old}}\right)$$

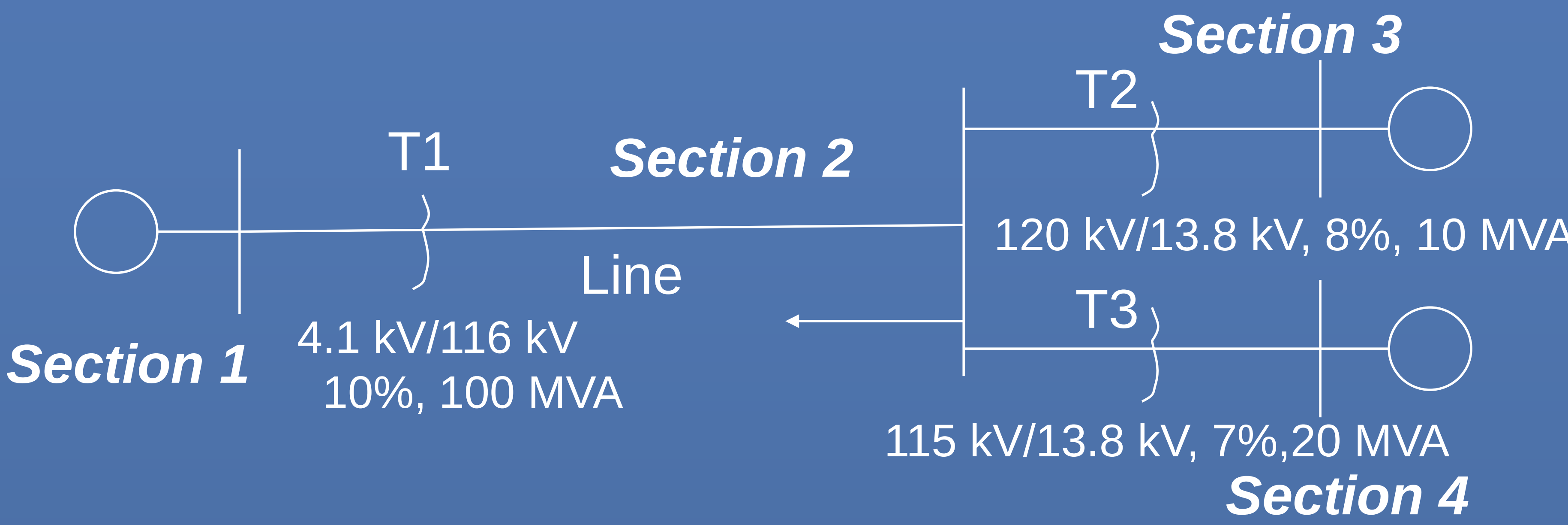
- base voltages can either be line to line or phase to neutral, but not both.
- Base powers can either be 3 phase or per phase, but not both.

The above relation is obtained by expressing

$$Z_{pu,new} = \frac{Z_{\Omega}}{Z_{base,new}}, \qquad Z_{pu,old} = \frac{Z_{\Omega}}{Z_{base,old}}$$

and then substituting appropriate expressions for $Z_{base,new}$ and $Z_{base,old}$, solving for Z_{Ω} in both cases, and equating the two results.

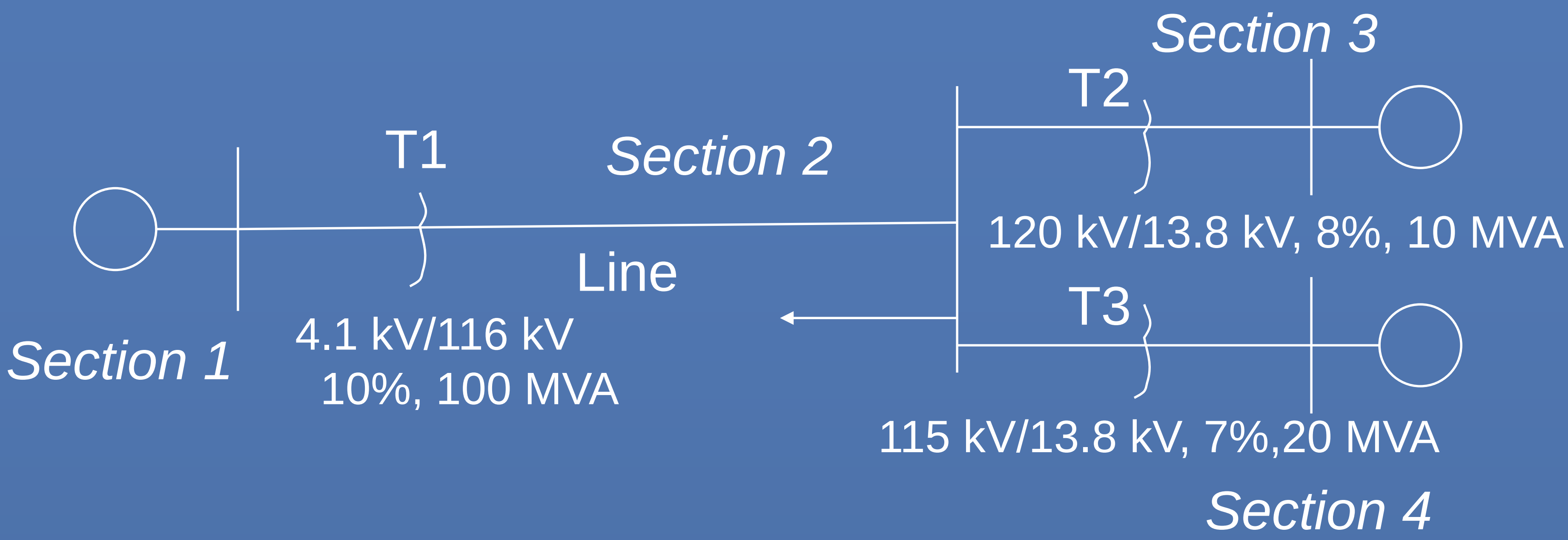
Example: system power base is 100 MVA



Transformer reactances are as shown.
Transmission line has impedance of 0.01+j0.1 pu
on base of 50 MVA, 115 kV.

These pu values are given on _component_ bases, not _system_ bases.

Convert 3 transformer reactances and line impedance to system base.



base voltage V1=4.1 kV

base voltage V2=116 kV

base voltage V3=116x13.8/120=13.34 kV

base voltage V4=116x13.8/115=13.92 kV

Assume xfmr impedances are given on rated voltage bases. Note that per cent is 100 times pu value.

Xfmr 1: No change of base is necessary.

Xfmr 2:

$$X_{T2,pu,new} = X_{T2,pu,old}\left(\frac{\text{base } V_{old}}{\text{base } V_{new}}\right)^2 \frac{\text{base } S_{new}}{\text{base } S_{old}} = 0.08\left(\frac{120}{116}\right)^2 \frac{100}{10} = 0.8561$$

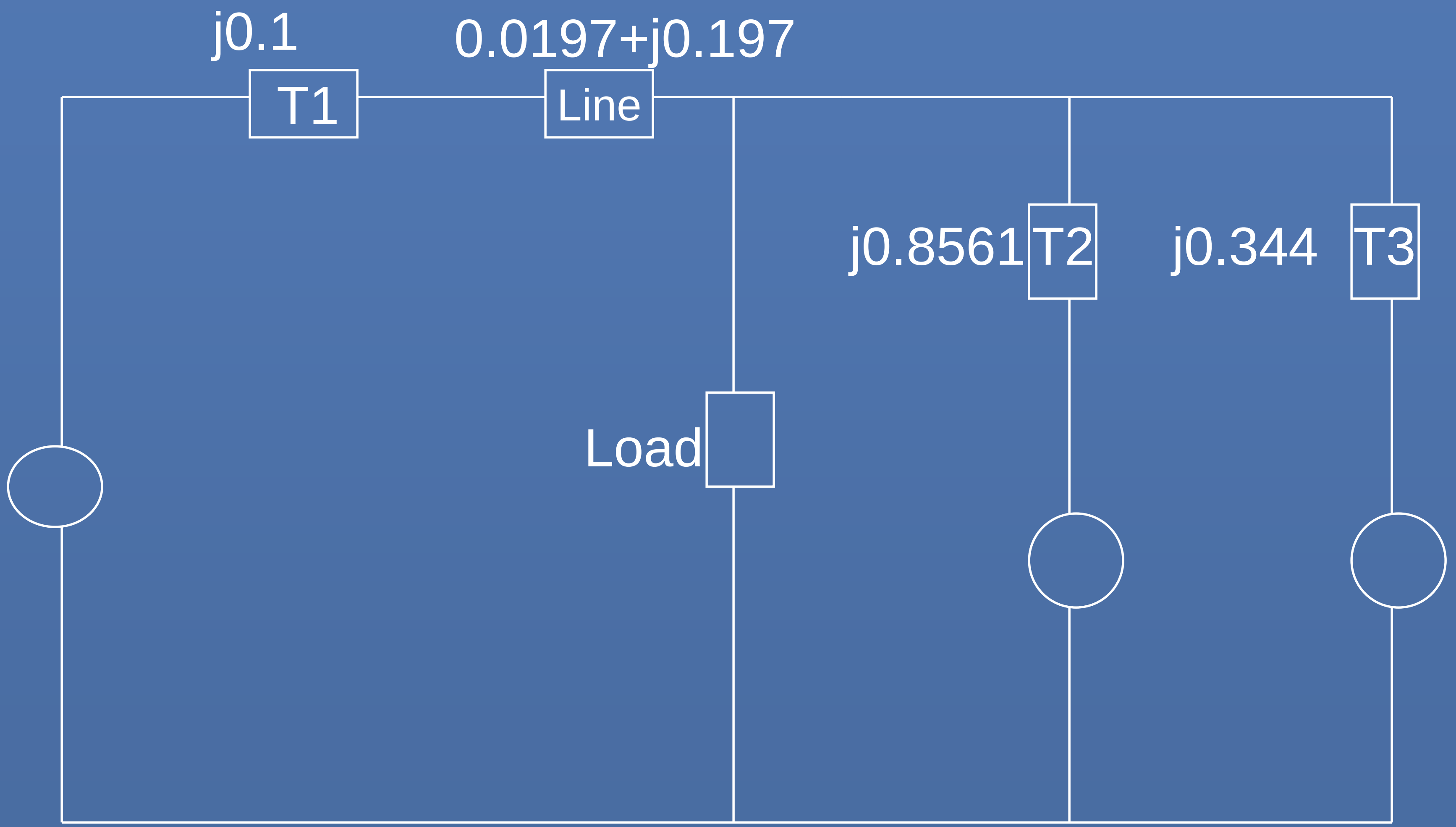
Xfmr 3:

$$X_{T3,pu,new} = X_{T3,pu,old}\left(\frac{\text{base } V_{old}}{\text{base } V_{new}}\right)^2 \frac{\text{base } S_{new}}{\text{base } S_{old}} = 0.07\left(\frac{115}{116}\right)^2 \frac{100}{20} = 0.344$$

Transmission line:

$$Z_{L,pu,new} = (0.01 + j0.1)(\frac{115}{116})^2 \frac{100}{50} = 0.0197 + j0.197$$

These impedances would be used in the following per unit circuit.

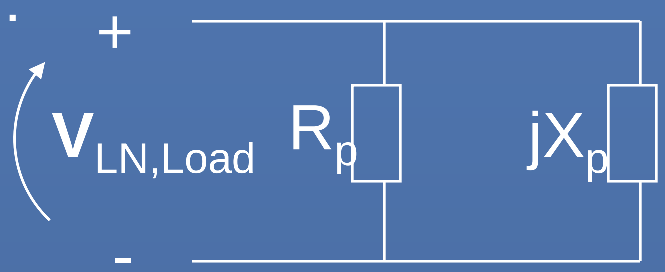


A comment on loads: See example B3.1, Module 3.
Also see problem 1a, Module 4.

Loads can be represented as constant impedance. Assume we are given line-to-line load voltage magnitude $V_{LL,load}$ and three phase power consumption $P_{3\phi}+jQ_{3\phi}$.

There are two different equivalent representations.

1. R and jX in parallel:



$$R_p = \frac{V_{LN,Load}^2}{P_{1\phi}} = \frac{V_{LL,Load}^2}{P_{3\phi}}$$

$$X_p = \frac{V_{LN,Load}^2}{Q_{1\phi}} = \frac{V_{LL,Load}^2}{Q_{3\phi}}$$

2. R and jX in series:

$$Z_s = \frac{V_{LN,Load}^2}{P_{1\phi}+jQ_{1\phi}} = \frac{V_{LL,Load}^2}{P_{3\phi}+jQ_{3\phi}}$$

$$R_s = \mathrm{Re}\{Z_s\}; \quad X_s = \mathrm{Im}\{Z_s\}$$

Then, in both cases, you can obtain the pu values as usual:

$R_{pu}=R/Z_{base}$

$X_{pu}=X/Z_{base}$