Understanding Mixed Delta-Wye Transformers

I. Four Cases
   Δ - Y Step Down
   Y - Δ Step Up

II. Review of 1Φ Transformer Ckt. Model
   Y - Δ or Δ - Y Transformer

III. Amplitude and Phase Effects
   A. Phase
      \[ L_{sec} = L_{prim} - 30 \] Step-down
      \[ L_{sec} = L_{prim} + 30 \] Step-up

   B. Amplitude
      \[ V_{sec} = \frac{V_{prim} N}{\sqrt{3}} \] for Y-Δ
      \[ V_{sec} = V_{prim} NT_3 \] for Δ-Y

IV. Primary (Y) - Secondary (Δ)

A. Load (Δ):
   8 Cases
IV  B  Δ - Y: Series of two step-down transformers & a load

Δ Y — line — Δ Y — load

Δ Y  Δ Y

V  Generation - Transm - Distrib Systems

A. Example #1

B. Example #2

VI  Transformers: Add'l. Info.
Understanding Mixed Δ-Y and Y-Δ Transformers

The ideal three-phase transformer is a bank of three ideal single-phase transformers. The primary and secondary of the ideal three-phase transformer is connected either delta or wye. The purpose of this section is to present the per-phase equivalent circuit models for various ideal three-phase transformer connections. There are six possible ideal transformer connections of interest in Table 5.1. By definition, the primary winding is the one connected to the electrical source and the secondary winding is the output winding. A step-up or unit transformer has a higher secondary voltage than the primary, and a step-down or power transformer has a lower secondary voltage than the primary.

Table 5.1 - Ideal Three-Phase Transformer Connections

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
<th>Comment</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. wye</td>
<td>wye</td>
<td>step-up or step-down</td>
<td>Fig. 5.2</td>
</tr>
<tr>
<td>2. delta</td>
<td>delta</td>
<td>step-up or step-down</td>
<td>Fig. 5.3</td>
</tr>
<tr>
<td>3. delta (low-voltage)</td>
<td>wye (high-voltage)</td>
<td>step-up</td>
<td>Fig. 5.4</td>
</tr>
<tr>
<td>4. delta (high-voltage)</td>
<td>wye (low-voltage)</td>
<td>step-down</td>
<td>Fig. 5.5</td>
</tr>
<tr>
<td>5. wye (high-voltage)</td>
<td>delta (low-voltage)</td>
<td>step-down</td>
<td>Fig. 5.3</td>
</tr>
<tr>
<td>6. wye (low-voltage)</td>
<td>delta (high-voltage)</td>
<td>step-up</td>
<td>Fig. 5.4</td>
</tr>
</tbody>
</table>

At this point, it is necessary to describe the notation that was used to derive the per-unit equivalent circuits of the ideal three-phase transformer connections in Figs. 5.2 through 5.5. \( V_{ab} \) denotes the terminal line (i.e., phase a - to - phase b) voltage phasor of the primary. The subscript, "ab", refers to the reference polarity of phase a with respect to phase b. \( V_{an} \) is the phase (i.e., phase a - to - neutral) voltage phasor of the primary. Note from Unit 4 that the line and phase voltage phasors are related by \( V_{ab} = \sqrt{3} V_{an} \angle 30^\circ \) for a balanced, three-phase system. Corresponding secondary line and phase voltage phasors are distinguished with primes on the subscripts, namely \( V_{a'b'} \) and \( V_{an'} \), respectively.

\( I_a \) and \( I_{an} \) both denote the primary side line current phasor of phase a, where the former notation is reserved for a delta-connected primary and the latter notation is reserved for a wye-connected primary. Note that the assumed current reference arrows for primary side line current phasors are directed into the transformer. \( I_{a'} \) and \( I_{an'} \) both denote the corresponding secondary side line current phasor of phase a, where the former notation is reserved for a delta-connected secondary and the latter notation is reserved for a wye-connected secondary. Note that the assumed current reference arrows for secondary side line current phasors are directed out of the transformer.

Next, the per-unit equivalent circuits of the ideal three-phase transformer connections are presented. Table 5.2 summarizes the results from Figs. 5.2 through 5.5 for the three-phase transformer connections of Table 5.1. In general, the per-unit equivalent circuit of an ideal three-phase transformer is depicted at the bottom of Figs. 5.2 through 5.5 as a box which contains an ideal single-phase transformer and a phase-shifting block. As a result, the box has an effective turns ratio, \( K \), which is generally a complex number with a magnitude and phase angle. The magnitude of the complex turns ratio, \( |K| \), is the turns ratio of the ideal single-phase transformer; and the phase angle of the complex turns ratio, \( \angle K \), is the angle in the phase-shifting block.
II Review of 1 φ Transformer Model

Figure 5.6 - Per Phase Equivalent Circuits for Single Phase Transformer

"Exact" Equivalent Circuit

\[ I_1 = \frac{N I_2}{n_1} \]

1: N where \( N = \frac{n_2}{n_1} \)

"Exact" Equivalent Circuit Referred to Primary

\[ R_{1q} = R_1 + \frac{R_2}{N^2} \]

\[ j X_{1q} = j (X_1 + X_2) \]

Final Approximate Equivalent Circuit Referred to Primary

- \( R_1 \) and \( R_2 \) are series resistances which account for conductor losses of the primary and secondary windings, respectively.

- \( X_1 \) and \( X_2 \) are series reactances which account for leakages fluxes at the primary and secondary sides.

- \( X_M \) is a shunt reactance which accounts for the small primary magnetization current which must flow to sustain the magnetic field.

- \( R_C \) is a shunt resistance to account for magnetic core losses due to the effects of hysteresis and eddy currents.

The exact equivalent circuit models are shown at the top of Fig. 5.6. The second model has the secondary electrical quantities referred to the primary, based on Eqs. (5.2), (5.4) and (5.5). The third approximate equivalent circuit model neglects core losses and primary magnetization current and is adequate for the purpose of this
III. Four Cases of Mixed $A-Y$

We consider $3$

A. Phase Effects

$Y-D$

Prim sec for $abc$

$\text{Step-Down}$

$L_{sec} = L_{prim} - 30$

$\text{Step-Up}$

$L_{sec} = L_{prim} + 30$

B. Amplitude Effects

$\frac{V_{sec}}{V_{pp}} = \frac{N_{T3}}{N}$

$Y-D$

Step-up or step-down $V_{sec} = \frac{V_{pp}N}{N_{T3}}$

$\Delta-Y$

Step-up $V_{sec} = V_{pp}N_{T3}$

Step-down $V_{sec} = V_{pp}N_{T3}$
Step-down $Y - \Delta$ 41

Figure 5.4 - Per-Phase Circuit for Ideal Primary Wye (HV) - Secondary Delta (LV)

Primary Y (HV) - Δ (LV) Secondary

![Circuit Diagram]

$$V_{ab} = \sqrt{3} V_{an} \angle 30^\circ$$
$$= \sqrt{3} \left( \frac{V_{a'b'}}{N} \right) \angle 30^\circ$$

or

$$V_{a'b'} = K_5 V_{ab}$$

where

$$K_5 = \left( \frac{N}{\sqrt{3}} \right) \angle 30^\circ$$

![Turns Ratio]

$1 : N = \frac{n_2}{n_1}$
$(n_1 > n_2)$
Step-up Y-Δ

Figure 5.5 - Per-Phase Circuit for Ideal Primary Wye (LV) - Secondary Delta (HV)

Primary Y (LV) - Δ (HV) Secondary

\[ I_{a'} = \frac{1}{K_6} I_{an} \]

or \[ \sqrt{3} \left( I_{an} / N \right) \angle 30^\circ \]

or \[ \sqrt{3} (V_{a'b'} / N) \angle 30^\circ \]

where \[ K_6 = (N / \sqrt{3}) \angle 30^\circ \]
Figure 5.2 - Per-Phase Circuit for Ideal Primary Delta (LV) - Secondary Wye (HV)

**Step-up**

Primary \( \Delta \) (LV) - \( Y \) (HV) \hspace{1cm} \text{Secondary}

\[ V_{a'b'} = \sqrt{3} V_{a'n'} \angle 30^\circ \]
\[ = \sqrt{3} N V_{ab} \angle 30^\circ \]

or \[ V_{a'b'} = K_3 V_{ab} \]

or \[ V_{n'a'} = \frac{1}{K_3} V_a \]

where \[ K_3 = \sqrt{3} N \angle 30^\circ \]

\[ 1 : \sqrt{3} N \] or \[ 1 : \sqrt{3} \]

\text{where} \quad N = \frac{n_2}{n_1} \quad (n_1 < n_2)
Step-Down $\Delta - Y$ Transformer

Figure 5.3 - Per-Phase Circuit for Ideal Primary Delta (HV) - Secondary Wye (LV)

### Primary

- $\Delta$ (HV) - Y (LV)

### Secondary

- $N_1 / N_2$

**Turns Ratio**: $1 : N = \frac{n_2}{n_1}$

($n_1 > n_2$)

### Equations

\[
\begin{align*}
I_a &= I_{ab} - I_{ca} \\
    &= I_{ab} + I_{ac} \\
    &= \sqrt{3} \cdot I_{ac} \angle 30^\circ \\
    &= \sqrt{3} \cdot N \cdot I_{n'a'} \angle 30^\circ \\
\end{align*}
\]

or

\[I_{n'a'} = \frac{1}{K_4} I_a\]

where

\[K_4 = \sqrt{3} \cdot N \angle -30^\circ\]

### Circuit Diagram

- $I_a$ and $I_{n'a'}$

- $\sqrt{3} N$ and $\angle -30^\circ$

- $1 : \sqrt{3} N$

- $I_{an}$ and $I_{a'n'}$

- $e^{-j\pi/6}$ or $e^{j\pi/6}$

- $I_{n'a'} = K_4 I_{ab}$
Common 3-phase transformer connections; the transformer windings are indicated by the heavy lines.
Summary: 3 & for transf.

Δ-Δ  NO Phase issues

Δ-Y  Always an extra

30° phase shift

Y-Δ  Occurs

Both

Δ-Y < Step-up +30° V_s = \frac{V_P}{\sqrt{3}}

Δ-Y < Step-down -30° V_s = \frac{N V_P}{\sqrt{3}}

Table 5.2 - Complex Turns Ratio, K, and Relationships Between Primary and Secondary Electrical Quantities for Ideal Three-Phase Transformers [11]

<table>
<thead>
<tr>
<th>Connection</th>
<th>Line Voltages</th>
<th>Line Currents</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. wye-wye</td>
<td>\psi_{a'b'} = K_1 \psi_{ab}</td>
<td>\psi'<em>{n'a'} = \frac{1}{K_1} \psi</em>{n'a}</td>
<td>K_1 = N = \frac{n_2}{n_1}</td>
</tr>
<tr>
<td>2. delta-delta</td>
<td>\psi_{a'b'} = K_2 \psi_{ab}</td>
<td>\psi'<em>{a'} = \frac{1}{K_2} \psi</em>{a}</td>
<td>K_2 = N = \frac{n_2}{n_1}</td>
</tr>
<tr>
<td>3. delta (LV) - wye (HV)</td>
<td>\psi_{a'b'} = K_3 \psi_{ab}</td>
<td>\psi'<em>{n'a'} = \frac{1}{K_3} \psi</em>{n'a}</td>
<td>K_3 = \sqrt{3} N \angle +30°</td>
</tr>
<tr>
<td>4. delta (HV) - wye (LV)</td>
<td>\psi_{a'b'} = K_4 \psi_{ab}</td>
<td>\psi'<em>{n'a'} = \frac{1}{K_4} \psi</em>{n'a}</td>
<td>K_4 = \sqrt{3} N \angle -30°</td>
</tr>
<tr>
<td>5. wye (HV) - delta (LV)</td>
<td>\psi_{a'b'} = K_5 \psi_{ab}</td>
<td>\psi'<em>{a'} = \frac{1}{K_5} \psi</em>{a}</td>
<td>K_5 = \frac{N}{\sqrt{3}} \angle -30°</td>
</tr>
<tr>
<td>6. wye (LV) - delta (HV)</td>
<td>\psi_{a'b'} = K_6 \psi_{ab}</td>
<td>\psi'<em>{a'} = \frac{1}{K_6} \psi</em>{a}</td>
<td>K_6 = \frac{N}{\sqrt{3}} \angle +30°</td>
</tr>
</tbody>
</table>
Per Phase Circuit Diagram of Three Phase Trf.

Figure 5.7: Per-Phase Equivalent Circuits for Three-Phase Transformers

Below $K = \frac{1}{a}$ of prior models

DELTA - CONNECTED PRIMARIES

\[
\begin{align*}
\frac{1}{3} R_1 & \quad j \frac{1}{3} X_1 \\
\frac{1}{3} R_1 & \quad j \frac{1}{3} X_M
\end{align*}
\]

\[
E_{an} = \frac{E_{a'n'}}{K}
\]

\[
K = |K| e^{j\theta}
\]

where $K_2 = N$

Primary Delta - Secondary Delta

$K_3 = \sqrt{3} N e^{j30^\circ}$

Primary Delta (LV) - Secondary Wye (HV)

$K_4 = \sqrt{3} N e^{-j30^\circ}$

Primary Delta (HV) - Secondary Wye (LV)

Note factor of $\frac{1}{3}$ in primary

and $N = \frac{n_2}{n_1}$

WYE - CONNECTED PRIMARIES

\[
\begin{align*}
R_1 & \quad j X_1 \\
\frac{R_2}{|K|^2} & \quad j X_2
\end{align*}
\]

\[
E_{an} = \frac{E_{a'n'}}{K}
\]

where $K = |K| e^{j\theta}$

$K_1 = N$

Primary Wye - Secondary Wye

$K_5 = \frac{N}{\sqrt{3}} e^{-j30^\circ}$

Primary Wye (HV) - Secondary Delta (LV)

$K_6 = \frac{N}{\sqrt{3}} e^{+j30^\circ}$

Primary Wye (LV) - Secondary Delta (HV)

and $N = \frac{n_2}{n_1}$
Fig. 5.8: Per-Phase Equivalent Circuits for Three-Winding, Three-Phase Transformers

**WYE-CONNECTED PRIMARY**

**DELTA-CONNECTED PRIMARY**
A. 8 Possible Windings

Three 5 MVA single-phase transformers, each rated 8:1.39 kV, have leakage impedance of 6%. These can be connected in a number of different ways to supply three identical 5 ohm resistive loads. Various transformer and load connections are outlined in the following table. Complete the table columns. Use a three-phase base of 15 MVA.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Transformer Connection</th>
<th>Load Connection</th>
<th>Line-to-Line base HV</th>
<th>Load R in per Unit</th>
<th>Total Z as viewed from the high side Per Unit</th>
<th>Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WYE</td>
<td>WYE</td>
<td>13.86</td>
<td>2.41</td>
<td>12.95</td>
<td>165.789+0.768</td>
</tr>
<tr>
<td>2</td>
<td>WYE</td>
<td>DELTA</td>
<td>13.86</td>
<td>2.41</td>
<td>4.32</td>
<td>55.267+0.768</td>
</tr>
<tr>
<td>3</td>
<td>WYE</td>
<td>WYE</td>
<td>13.86</td>
<td>1.39</td>
<td>38.82</td>
<td>496.807+0.768</td>
</tr>
<tr>
<td>4</td>
<td>WYE</td>
<td>DELTA</td>
<td>13.86</td>
<td>1.39</td>
<td>12.94</td>
<td>165.622+0.768</td>
</tr>
<tr>
<td>5</td>
<td>DELTA</td>
<td>WYE</td>
<td>8.00</td>
<td>2.41</td>
<td>12.95</td>
<td>165.622+0.768</td>
</tr>
<tr>
<td>6</td>
<td>DELTA</td>
<td>DELTA</td>
<td>8.00</td>
<td>2.41</td>
<td>4.32</td>
<td>18.423+0.768</td>
</tr>
<tr>
<td>7</td>
<td>DELTA</td>
<td>WYE</td>
<td>8.00</td>
<td>1.39</td>
<td>38.82</td>
<td>165.632+0.768</td>
</tr>
<tr>
<td>8</td>
<td>DELTA</td>
<td>DELTA</td>
<td>8.00</td>
<td>1.39</td>
<td>12.94</td>
<td>55.211+0.256</td>
</tr>
</tbody>
</table>

Transformer = Load

\[ S = \frac{15 \text{ MVA}}{0.06 Z_n (\text{pu})} \]

Transformer varies with wiring.
Voltage Levels: HV in / LV out

$HV_{1-1} = 8\sqrt{3} = 13.856 \text{ kV}$ for Cases 1-4

$HV_{1-1} = 8 \text{ kV}$ for Cases 5-8

$LV_{1-1} = 1.39\sqrt{3} = 2.408 \text{ kV}$ for Cases 1 & 2,5,6

$LV_{1-1} = 1.39 \text{ kV}$ for Cases 3,4,7 & 8

Case 1: $Y_{trf} = Y_{load}$

Load $R_{Base} = (2.408)^2/15 = 0.386$

Load $R_{pu} = R/R_{Base} = 5/0.386 = 12.953_{pu}$

$Z_{pu_{HV}} = 12.953 + j0.06 = Z_{(load)} + Z_{(trf)}$

$Z_{HV} = (13.856)^2(12.953 + j0.06)/15$

$= 165.789 + j0.768 \text{ ohms}$

Case 2: $Y_{trf} = \Delta (load)$

Load $R_{pu} = (5/3)/0.386 = 4.318$

$Z_{pu_{HV}} = 4.318 + j0.06 = Z_{(load)} + Z_{(trf)}$

$Z_{HV} = (13.856)^2(4.318 + j0.06)/15$

$= 55.267 + j0.768 \text{ ohms}$

Explain $5/3$ in $R_{load}$?
Case 3:

\[
Y - \Delta - Y(\text{load})
\]

\[
\begin{align*}
R_{lv\ Base} &= (1.39)^2/15 = 0.1288 \\
\text{Load } R_{p.u} &= 5/0.1288 = 38.820 \\
Z_{p.u\ HV} &= 38.820 + j0.06 = Z(\text{load}) + Z(\text{trf}) \\
Z_{HV} &= (13.856)^2(38.820 + j0.06)/15 \\
&= 496.867 + j0.768 \text{ ohms}
\end{align*}
\]

Case 4:

\[
Y - \Delta - \Delta(\text{load})
\]

\[
\begin{align*}
\text{Load } R_{p.u} &= (5/3)/0.1288 = 12.94 \quad \text{Why } \frac{5}{3} ? \\
Z_{p.u\ HV} &= 12.94 + j0.06 \\
Z_{HV} &= (13.856)^2(12.940 + j0.06)/15 \\
&= 165.622 + j0.768 \text{ ohms}
\end{align*}
\]

Case 5:

\[
\Delta - \gamma - \gamma(\text{load})
\]

\[
\begin{align*}
\text{Load } R_{p.u} &= 5/.386 = 12.953 \\
Z_{p.u\ HV} &= 12.953 + 0.06 \\
Z_{HV} &= (8.00)^2(12.953 + 0.06)/15 \\
&= 55.266 + j0.256 \text{ ohms}
\end{align*}
\]
Case 6:

\[
\Delta - \gamma - \Delta_{\text{load}}^\prime
\]

\[
\begin{align*}
8.0 & \quad 2.4 \\
\end{align*}
\]

Load \( R_{p.u} = (5/3) / .386 = 4.318 \text{ ohms} \)

\[ Z_{p.u \, HV} = 4.318 + j0.06 \]

\[ Z_{HV} = (8.00)^2(4.318 + j0.06)/15 \]

\[ = 18.423 + j0.256 \text{ ohms} \]

Why \( \frac{5}{3} \)?

Case 7:

\[
\Delta - \Delta - \gamma_{\text{load}}
\]

\[
\begin{align*}
8 & \quad 1.39 \\
\end{align*}
\]

Load \( R_{p.u} = 5 / .1288 = 38.820 \text{ ohms} \)

\[ Z_{p.u \, HV} = 38.820 + j0.06 \]

\[ Z_{HV} = (8.00)^2(38.820 + j0.06)/15 \]

\[ = 165.632 + j0.256 \text{ ohms} \]

Case 8:

\[
\Delta - \Delta - \Delta_{\text{load}}
\]

\[
\begin{align*}
8.0 & \quad 1.39 \\
\end{align*}
\]

Load \( R_{p.u} = (5/3) / .1288 = 12.940 \text{ ohms} \)

\[ Z_{p.u \, HV} = 12.940 + j0.06 \]

\[ Z_{HV} = (8.00)^2(12.940 + j0.06)/15 \]

\[ = 55.211 + j0.256 \text{ ohms} \]
### IVB. Δ-Y Transformers

- Example of Transformer Modeling & Per Phase Analysis

#### HV: LV

- **Utility**
  - 10 MVA
  - 69 kV - 13.8 kV
  - \(|Z| = 7\%

- **T1**
  - 1500 ft of 1 - 3/4"/c cable with 250 kcmil (Cu) conductors in non-magnetic duct.
  - 13.8 kV - 4.16 kV
  - \(|Z| = 5.5\%

- **T2**
  - 5 MVA
  - 2000 HP INDUCTION
  - Drawing 1.1 MW, 0.9 PF @
  - Rated Voltage = 4.0 kV.

#### PER-PHASE EQUIVALENT CIRCUIT

#### TRANSFORMER REACTANCES

- \(X_{T1} = |Z_{T1}| = 7\%\) of base series \(|Z|\) from primary ratings

\[
X_{T1} = \frac{0.07 \cdot \text{rated primary kV}_{L-N}}{\text{rated primary kA}_L} \cdot \frac{\text{rated primary kV}_{L-N}}{\text{rated primary kA}_L} = 0.07 \left(\frac{69 / \sqrt{3}}{10 / 3}\right)^2 = 33.327 \Omega
\]

- \(X_{T2} = 0.055 \left(\frac{13.8 / \sqrt{3}}{5 / 3}\right)^2 = 2.0948 \Omega\)

- \(X_C = \left(\frac{0.0348 \Omega / \text{conductor}}{1000 \text{ feet}}\right) (1500 \text{ feet}) = 0.0522 \Omega\)

#### LOAD CALCULATION

See Example 2, Page 33-35

Load Not yet considered
System

\[ S = 100 \text{ MVA} \]

Given Ratings and Impedance Data

**Gen.**

\[ G: \ 30 \text{ MW}, \ 0.9 \text{ p.f.}, \ 3\phi \ 60 \text{ Hz}, \ 13.8 \text{ kV}-\text{L} \]

\[ x_{d'} = 30\% \text{ @ rated MVA} \]

**Trf.**

\[ T1: \ 38.3 \text{ MVA}, \ 115-13.2 \text{ kV}-\text{L} \]

\[ Z = j10\% \text{ @ rated MVA} \]

**Line**

\[ L: \ 115 \text{ kV}, \ Z = 5 + j20 \text{ ohms} \]

**Trf.**

\[ T2: \ 30 \text{ MVA}, \ 115-13.8 \text{ kV}-\text{L} \]

\[ Z = j10\% \text{ @ rated MVA} \]

**Motor**

\[ M: \ 32,000 \text{ hp}, \ 0.95 \text{ p.f.}, \ 3\phi \ 60 \text{ Hz}, \ \eta = 92\% \]

\[ 13.8 \text{ kV}-\text{L} \]

\[ x_{d'} = 30\% \text{ @ rated MVA} \]

Determine all power system component impedance values in per unit on a 100 MVA base. Select 115 kV as the kV-L base value for the high voltage transmission system.
Old MVA Base (3φ):

Generator 30 (MW) / 0.9 (p.f.) = 33.33 MVA = S\(_{\text{gen.}}\)

T1 = 38.3 MVA (given)

T2 = 30 MVA (given)

Motor \((32800 \text{hp}) \times 746) / (0.95\text{ (p.f.)} \times 0.92\text{ (efficiency)})\) = 28.0 MVA

Remember that \(S(\text{base}) = 100 \text{ MVA}\)

Recall:

Old Z Base:

\[(\text{Old } kV_{L-L})^2 / \text{Old MVA Base (3φ)}\]

Old Per Unit Z: \((\text{given})\) for ratings not @ operation

New MVA Base (3φ): \((\text{given as } 100)\)

New \(kV_{L-L}\) Base:

Generator is changed to 13.2 kV to match with transformer rating. All others stay the same.

New Z Base \(\text{will be for operation conditions}\)

Same calculation as in Old Z Base except use New MVA Base and New \(kV_{L-L}\) Base.
New Per Unit Z:

\[
\text{Generator} = \frac{(\text{Old Per Unit Z}) \times (\text{Old Z Base})}{\text{New Z Base}}
\]

\[
= \frac{(j0.30) \times (5.713)}{1.742} = j0.9836
\]

All the other components follow the same process except the transmission line.

\[
\text{Line} = \frac{\text{(given impedance)}}{\text{New Z Base}}
\]

\[
= \frac{(5 + j20)}{132.25} = (0.0378 + j0.1512)
\]

New I Base (A):

\[
\text{Generator} = \frac{(\text{New MVA Base} \times 3\phi) \times 10^{3}}{\text{(New kV}_{L-L} \text{ Base} \times \sqrt{3})}
\]

\[
= \frac{(100 \times 10^{3})}{(13.2 \times 1.732)} = 4374
\]

\textbf{On the next page we summarize } Z(\text{pu}) \text{ for each component }

\[
Z(\text{ratings}_{\text{pu}}) \text{ vs } Z(\text{operation}_{\text{pu}})
\]
<table>
<thead>
<tr>
<th>New Per Unit ((N))</th>
<th>New (Z) Base</th>
<th>(1.904)</th>
<th>(1.322)</th>
<th>(1.322)</th>
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<th>(1.322)</th>
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<tr>
<td>(4374)</td>
<td>(0.04)</td>
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<td>(0.333)</td>
<td>(1.07)</td>
<td>(345.3)</td>
<td>(38.3)</td>
<td>(30)</td>
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<td>(1.742)</td>
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<td>(132.2)</td>
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<td>(13.2)</td>
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<td>(13.2)</td>
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<tr>
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<td>(100)</td>
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<td>(100)</td>
<td>(100)</td>
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</tr>
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<td>(j.0.10)</td>
<td>(j.1.0)</td>
<td>(j.10)</td>
<td>(j.30)</td>
<td>(441)</td>
<td>(8.0)</td>
<td>(28.0)</td>
</tr>
<tr>
<td>(j.0.30)</td>
<td>(j.0.10)</td>
<td>(j.1.0)</td>
<td>(j.10)</td>
<td>(j.30)</td>
<td>(441)</td>
<td>(8.0)</td>
<td>(28.0)</td>
</tr>
</tbody>
</table>

Operating Condition Based

Rating of Each Component Base Per Unit Ratio

New Per Unit \(Z\) = Old Per Unit \(Z\) * \(\frac{\text{New MVA Base}}{\text{Old MVA Base}}\)
Example 41 Eq. Circuit

Given: \( V_m = 115 = 1 + j 0 \text{ pu} \), \( \phi_m = 18.2^\circ \) V

\[ V_m = 7.67/10 \text{ V}_m \] (12,300 V)

\[ I_m = \frac{\mathbf{E}}{Z_m} = \frac{767/(10 \text{ V}_m)}{0.28/(60 \text{ mH})} = 0.28/(0.35 - j 0.312) = 0.28 - j 0.0874 \text{ pu} \]

\[ I_m = 0.28 - j 0.0874 \text{ pu} \]

\[ I_g = I_m \] (pu) = \( 0.28 - j 0.0874 \) pu.

\[ I_1 = V_m - 110.74 \frac{E}{Z_m} = 1 - 110.74 \frac{0.28 - j 0.0874}{0.35 - j 0.312} = 0.9234 - j 0.1123 \]

\[ I_1 = 0.9234 - j 0.1123 \text{ pu} \]

\[ I_2 = V_m + (0.0778 + j 0.135)(0.28 - j 0.0874) = 10 + 0.07724 + j 0.1185 \]

\[ I_2 = 10.07724 + j 0.1185 \text{ pu} \]

\[ I_3 = \frac{10.425}{10.25} = 1.01 \text{ pu} \]

\[ I_4 = 0.28 - j 0.0874 \text{ pu} \]

\[ I_5 = 12.25 - j 0.25 \text{ pu} \]

\[ I_6 = I_2 + j 0.0627 \text{ pu} \]

\[ I_7 = 1.01724 + j 0.1185 + 0.0627 = 1.0875 + j 0.1247 \text{ pu} \]

\[ I_8 = \frac{9.509}{12.14} \text{ V}\]

\[ I_9 = 12.25 - j 0.25 \text{ pu} \]

\[ I_{10} = 112.8 \text{ pu} \]
\[ S_x = V_x I_x^* = (1.0329 R / 42^\circ)(0.28 / 182^\circ) = 0.28922 / 125^\circ \]
\[ P_x = 26.6 \text{ MW} \quad \text{Q}_x = 11.3 \text{ MVARs} \]

\[ S_y = V_y + (0.0378 + 0.1512)(0.28 / 182^\circ) \]
\[ = 1.0293 + 0.0886 + (0.1535 / 182^\circ)(0.28 / 182^\circ) \]
\[ = 1.0524 + 0.12557 = 1.05796 / 62^\circ \mu \text{u.} \Rightarrow 121.9 \text{ kV} \]

\[ S_z = V_z I_z^* = (1.05796 / 62^\circ)(0.28 / 182^\circ) = 0.29676 / 250^\circ \mu \text{u.} \]
\[ P_z = 26.9 \text{ MW} \quad \text{Q}_z = 12.5 \text{ MVARs} \]

\[ P_m = 26.6 \text{ MW} \quad \text{Q}_m = 8.74 \text{ MVARs} \]

\[ \Rightarrow \text{Voltage} \]

2. For a balanced operating condition in which the motor is being operated at rated voltage, horsepower, and power factor, and assuming motor terminal voltage, \( V_m \), to be the reference voltage (assume phase a to neutral voltage), determine the following values (as indicated on D-magnet):

- Generator internal voltage, \( E_g \), in per unit and in \( kV_{L-N} \)
- Generator terminal voltage, \( V_g \), in per unit and in \( kV_{L-N} \)
- Generator phase a current, \( I_g \), in per unit and in amperes
- Motor internal voltage, \( E_m \), in per unit and in \( kV_{L-N} \)
- Motor terminal voltage, \( V_m \), in per unit and in \( kV_{L-N} \)
- Motor phase a current, \( I_m \), in per unit and in amperes
Fig. 6.5 summarizes the steps to perform per-unit analysis on the example.

STEP 1: The first step of the procedure is to assign base values of line-to-line voltage and three-phase apparent power on each side of every three-phase power transformer in accordance with the selection rules of Fig. 6.4. In particular, base $MVA_{3φ} = 10$ was selected and is common throughout the system; and base $kV_{L-L}$ on any side of a three-phase power transformer is simply the nominal line-to-line nameplate kV rating for that side of the transformer. The other two per-phase base quantities of current and impedance are derived from the assigned base values of line-to-line voltage and three-phase apparent power, according to the formulas of Fig. 6.4.

STEP 2: The next step is to draw the per-phase equivalent circuit for per-unit analysis. For this example, the per-phase equivalent circuit model of a three-phase transformer is simply a per-unit series leakage reactance (cf. Sec. 6.8). (For this example, resistances are neglected.)

STEP 3: The percentage impedances of the transformers are based on the nameplate ratings. Therefore, they must be adjusted with respect to the three-phase system base quantities, according to the formula of Fig. 6.3. Note that the unadjusted per-unit impedance of the transformer, $(X_T)^{old} = |Z_T|^{old}$, is found by dividing the percentage impedance by 100%. The per-unit reactance of the distribution feeder is calculated by dividing its ohmic value by the base impedance. (The ohmic value of the distribution feeder was calculated in Fig. 5.9a.)

STEP 4: The operating line-to-line voltage magnitude of the induction motor was specified on the one-line diagram as 4.0 kV. It is divided by $\sqrt{3}$ to yield the line-to-neutral voltage magnitude. The phase angle of the line-to-neutral motor voltage is chosen as the phase angle reference for the power system, and it is arbitrarily set to 0°. Finally, the line-to-neutral phasor voltage of the induction motor in kilovolts is divided by base $kV_{L-N}$ to yield the per-unit line-to-neutral phasor voltage. The per-unit phasor current of the induction motor is calculated by dividing the phasor current in kiloamperes by base current in kiloamperes. (The phasor current was calculated in Fig. 5.9a. from the load data of the induction motor.)

STEP 5: The utility voltage is found by applying Kirchhoff's Voltage Law to the per-phase equivalent circuit. Note that the per-unit utility phasor voltage was multiplied by base $kV_{L-N} = (69 / \sqrt{3})$ to yield the line-to-neutral utility voltage in kilovolts. Of course, the magnitude of the per-unit phasor voltage can be multiplied by base $kV_{L-L} = 69$ to yield the line-to-line voltage magnitude in kilovolts (cf. item 2 of Fig. 6.2); however, 30° must be added to the phase angle of the line-to-neutral utility voltage to yield the phase angle of the line-to-line voltage.
Figure 5.9a - Example of Transformer Modeling & Per Phase Analysis

**PER-PHASE EQUIVALENT CIRCUIT**

**TRANSFORMER REACTANCES**

\[ X_{T1} = |Z_{T1}| = 7\% \text{ of base series } |Z| \text{ from primary ratings} \]

\[ X_{T1} = \left[ \frac{0.07}{\text{rated primary } kV_{L-N}} \right] \frac{\text{rated primary } kA_L}{\text{rated primary } kV_{L-N}} = \frac{0.07}{\frac{69}{\sqrt{3}}} \left( \frac{1500 \text{ ft}}{1000 \text{ feet}} \right) = 0.07 \times \frac{(69/\sqrt{3})^2}{10} = 33.327 \Omega \]

\[ X_{T2} = 0.055 \left( \frac{13.8/\sqrt{3}}{5/3} \right)^2 = 2.0948 \Omega \]

\[ X_C = \left( \frac{0.0348 \Omega / \text{conductor}}{1000 \text{ feet}} \right) (1500 \text{ feet}) = 0.0522 \Omega \]

**LOAD CALCULATION**

\[ \frac{P_m(3\Phi)}{3} = 3 \text{ Re} \left\{ \frac{\gamma_{am}^{*}}{\gamma_{am}} \right\} \]

\[ = 3 \times \frac{\gamma_{am}^{*}}{\gamma_{am}^{*}} \times |I_{am}| \cos(\theta_m) \]

\[ = \sqrt{3} \times |\gamma_{am}^{*}| \times |I_{am}| \cos(\theta_m) \implies |I_{am}| = \frac{1.1 \text{ MW}}{\sqrt{3} \times (4.0 \text{ kV}) (0.9)} = 0.1764 \text{ kA} \]

\[ \theta_m = \cos^{-1}(pf_m) = \angle \gamma_{am}^{*} - \angle I_{am} = -\angle I_{am} \]

or \[ \angle I_{am} = -\cos^{-1}(0.9) = -25.84^\circ \]

\[ \angle I_{am} = -25.84^\circ \]

\[ \text{Power factor, } pf_m \]

\[ \angle I_{am} = -25.84^\circ \]
Fig. 6.5 - A Simple Example of Per-Unit Analysis
(cf. Fig. 5.9 for Reference.)

\[ \Delta \frac{\gamma_1}{\gamma_2} \]

**UTILITY**

10 MVA
69 kV - 13.8 kV
IZ = 7%

1500 ft of 1-3/0 cable with 250 kcmil (Cu) conductors in non-magnetic duct.
13.8 kV - 4.16 kV
IZ = 5.5%

**T1**

base kV₁₁ = 69
base MVA₃₀ = 10

\[ \text{base } Z_{i1} = \frac{(\text{base } kV_{11})^2}{\text{base } MVA_{30}} = 476.1 \text{ ohms} \]

\[ \text{base } kA_{i1} = \frac{\text{base } MVA_{30}}{\sqrt{3} \text{ base } kV_{11}} = 0.084 \]

**T2**

2000 HP INDUCTION
Drawing 1.1 MW, 0.9 PF
Rated Voltage = 4.0 kV.

base kV₁₁ = 13.8
base MVA₃₀ = 10

base Z₁ = 19.04 ohms
base kA₁ = 0.418

base kV₁₁ = 4.16
base MVA₃₀ = 10

base Z₁ = 1.73 ohms
base kA₁ = 1.39

**PER-PHASE EQUIVALENT CIRCUIT**
(Note: All Electrical Quantities in Per-Unit.)

\[ \Delta \frac{\gamma_1}{\gamma_2} \]

**DATA PREPARATION**

\[ X_{T1} = |I_{T1}| = 0.07 \left( \frac{10}{69} \right) \left( \frac{69}{69} \right) = 0.07 \text{ pu} \]

\[ X_{T2} = |I_{T2}| = 0.055 \left( \frac{10}{13.8} \right) \left( \frac{13.8}{13.8} \right) = 0.11 \text{ pu} \]

\[ X_C = \frac{0.0522 \Omega}{\text{base } Z_1 = 19.04 \Omega} = 0.0027 \text{ pu} \]

**LOAD CALCULATION**

\[ V_{am} = \frac{4.0}{\sqrt{3}} \angle 0^\circ \text{ kV} \]

\[ \text{base } kV_{L,N} = \frac{4.16}{\sqrt{3}} = 0.962 \angle 0^\circ \text{ pu} \]

\[ I_{am} = \frac{0.1764 \angle -25.84^\circ \text{ kA}}{\text{base } kA_L = 1.39} = 0.127 \angle -25.84^\circ \text{ pu} \]

**UTILITY VOLTAGE**

\[ V_{au} = j (X_{T1} + X_C + X_{T2}) I_{am} + V_{am} \]

\[ = (0.1827 \angle 90^\circ) (0.127 \angle -25.84^\circ) + 0.962 \text{ pu} \]

\[ = 0.9721 + j 0.0209 \text{ pu} \]

\[ = 0.9723 \angle 1.23^\circ \text{ pu} \]

\[ = 38.73 \angle 1.23^\circ \text{ kV} \text{ (line-to-neutral)} \]

**COMPLEX POWER REQUIREMENT OF UTILITY**

\[ S_u = -V_{au} I_{am}^* = -0.367 - j0.187 \text{ MVA (single-phase)} \]
Fig N1.1

X/R Ratio of Transformers (Based on ANSI/IEEE C37.010-1979 [2])

- TRANSFORMER DATA -

Fig. N1.1  X/R Ratio of Three-Phase Transformers  (ANSI / IEEE Std 141-1986)

Table 64a  Typical Per-Unit R and X for Indoor, Open Dry-Type, 150°C Rise  
Three-Phase Transformers from 15 - 2500 kVA; 2.5 - 15 kV Primaries; and  
208, 240, 480 and 600 volt Wye and Delta Secondaries  
(ANSI / IEEE Std 241 - 1990)

Table 64b  Typical Per-Unit R and X for Indoor, Open Dry-Type, 150°C Rise  
Single-Phase Transformers from 25 - 500 kVA; 5 and 15 kV Primaries; and  
120 / 240 volt Wye or Delta Secondaries  
(ANSI / IEEE Std 241 - 1990)

Table 64c  Typical Range of Per-Unit Values for Indoor, Open Dry-Type, 150°C Rise  
Three-Phase Transformers from 15 - 500 kVA; 480 volt Primary; and  
208 volt Wye Secondary  
(ANSI / IEEE Std 241 - 1990)

Table 64d  Typical Range of Per-Unit Values for Indoor, Open Dry-Type, 150°C Rise  
Single-Phase Transformers from 5 - 167 kVA; 240 x 480, 480 and 600 volt  
Primaries; and 120 / 240 volt Secondary  
(ANSI / IEEE Std 241 - 1990)

Table 2   Data for Three-Phase Transformers with Secondaries of 2400 volts  
or More for 750 - 60000 kVA  
(ANSI / IEEE Std 242 - 1986)

Table 14   Impedance Data for Single-Phase Transformers  
(ANSI / IEEE Std 242 - 1986)
### Table 64
**Transformers**

**(a)**

**Typical Per Unit R and X Values for Indoor, Open Dry-Type**

150 °C Rise Transformers Rated from 15 - 2500 kVA, Three-Phase, 2.5 - 15 kV Primaries, 208, 240, 480, 600 V Wye or Delta Secondaries

<table>
<thead>
<tr>
<th>kVA</th>
<th>HV (kV)</th>
<th>LV (V)</th>
<th>%Z</th>
<th>X/R</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>3.00</td>
<td>0.5</td>
<td>0.027</td>
<td>0.013</td>
</tr>
<tr>
<td>30</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.00</td>
<td>1.0</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>45</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.00</td>
<td>1.0</td>
<td>0.035</td>
<td>0.036</td>
</tr>
<tr>
<td>75</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.50</td>
<td>2.0</td>
<td>0.025</td>
<td>0.049</td>
</tr>
<tr>
<td>112.5</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>4.50</td>
<td>1.5</td>
<td>0.025</td>
<td>0.077</td>
</tr>
<tr>
<td>150</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.50</td>
<td>2.0</td>
<td>0.020</td>
<td>0.044</td>
</tr>
<tr>
<td>225</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.00</td>
<td>2.5</td>
<td>0.019</td>
<td>0.046</td>
</tr>
<tr>
<td>300</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.00</td>
<td>2.8</td>
<td>0.017</td>
<td>0.047</td>
</tr>
<tr>
<td>500</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.00</td>
<td>4.0</td>
<td>0.012</td>
<td>0.050</td>
</tr>
<tr>
<td>750</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.75</td>
<td>2.0</td>
<td>0.026</td>
<td>0.061</td>
</tr>
<tr>
<td>1000</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.75</td>
<td>2.5</td>
<td>0.021</td>
<td>0.063</td>
</tr>
<tr>
<td>1000</td>
<td>2.5-15</td>
<td>480Y</td>
<td>5.00</td>
<td>3.8</td>
<td>0.021</td>
<td>0.077</td>
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<tr>
<td>1500</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.75</td>
<td>3.3</td>
<td>0.017</td>
<td>0.065</td>
</tr>
<tr>
<td>2000</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.75</td>
<td>4.0</td>
<td>0.014</td>
<td>0.066</td>
</tr>
<tr>
<td>2500</td>
<td>2.5-15</td>
<td>208Y-600</td>
<td>5.75</td>
<td>4.3</td>
<td>0.013</td>
<td>0.066</td>
</tr>
</tbody>
</table>

**(b)**

**Typical Per Unit R and X Values for Indoor, Open Dry-Type**

150 °C Rise Transformers Rated from 25 - 500 kVA, Single-Phase, 5 and 15 kV Primaries, 120/240 V Wye or Delta Secondaries

<table>
<thead>
<tr>
<th>kVA</th>
<th>HV (kV)</th>
<th>LV (V)</th>
<th>%Z</th>
<th>X/R</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>5</td>
<td>120/240</td>
<td>4</td>
<td>2</td>
<td>0.018</td>
<td>0.036</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>120/240</td>
<td>6</td>
<td>4</td>
<td>0.015</td>
<td>0.068</td>
</tr>
</tbody>
</table>

**(c)**

**Typical Range of Per Unit Values for Indoor, Open Dry-Type**

150 °C Rise Transformers Rated from 15 - 500 kVA, Three-Phase, 480 V Primary, 208 V Wye Secondary

<table>
<thead>
<tr>
<th>kVA</th>
<th>%Z</th>
<th>X/R</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>4.5</td>
<td>0.41</td>
<td>0.042</td>
<td>0.017</td>
</tr>
<tr>
<td>to</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>5.9</td>
<td>2.09</td>
<td>0.025</td>
<td>0.063</td>
</tr>
</tbody>
</table>

**(d)**

**Typical Range of Per Unit R and X Values for Indoor, Open Dry-Type**

150 °C Rise Transformers Rated from 5 - 167 kVA, Single-Phase, 240 X 480 V, 480 V, 600 V Primaries, 120/240 V Secondaries

<table>
<thead>
<tr>
<th>kVA</th>
<th>HV (kV)</th>
<th>LV (V)</th>
<th>%Z</th>
<th>X/R</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>240 x 480</td>
<td></td>
<td>3</td>
<td>0.6</td>
<td>0.026</td>
<td>0.015</td>
</tr>
<tr>
<td>to</td>
<td>to</td>
<td>120/240</td>
<td>to</td>
<td>to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>167</td>
<td>600</td>
<td></td>
<td>6</td>
<td>2.0</td>
<td>0.027</td>
<td>0.061</td>
</tr>
</tbody>
</table>
### Table 2
**Data for Three-Phase Transformers With Secondaries of 2400 V or More (750–60 000 kVA)**

<table>
<thead>
<tr>
<th>Primary kV</th>
<th>Primary kV BIL</th>
<th>Standard Percent Impedance (see notes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4–22.9</td>
<td>60–150</td>
<td>5.5 or 6.5</td>
</tr>
<tr>
<td>- 34.4</td>
<td>-200</td>
<td>6.0 or 7.0</td>
</tr>
<tr>
<td>- 43.3</td>
<td>-250</td>
<td>6.5 or 7.5</td>
</tr>
<tr>
<td>- 67.0</td>
<td>-350</td>
<td>7.0 or 8.0</td>
</tr>
<tr>
<td>- 115.0</td>
<td>-450</td>
<td>7.5 or 8.5</td>
</tr>
<tr>
<td>- 138.0</td>
<td>-550</td>
<td>8.0 or 9.0</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Actual values are generally within ± 7.5% of the standard values [1].
2. Add 0.5% for load tap changing [8].
3. Lower values are usually for OA 55 °C or OA 55/65 °C rise transformers.
4. Higher values are usually for OA 65 °C rise transformers.
5. $X/R$ values are similar to those in Table 1. Consult manufacturer or use the values in [4] for transformers rated over 2500 kVA.

### Table 14
**Impedance Data for Single-Phase Transformers**

<table>
<thead>
<tr>
<th>kVA 10</th>
<th>Suggested $X/R$ Ratio for Calculation</th>
<th>Normal Range of Percent Impedance (%Z)*</th>
<th>Impedance Multipliers** for Line-to-Neutral Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>for $X$ for $R$</td>
</tr>
<tr>
<td>25.0</td>
<td>1.1</td>
<td>1.2–6.0</td>
<td>0.6</td>
</tr>
<tr>
<td>37.5</td>
<td>1.4</td>
<td>1.2–6.5</td>
<td>0.6</td>
</tr>
<tr>
<td>50.0</td>
<td>1.6</td>
<td>1.2–6.4</td>
<td>0.6</td>
</tr>
<tr>
<td>75.0</td>
<td>1.8</td>
<td>1.2–6.6</td>
<td>0.6</td>
</tr>
<tr>
<td>100.0</td>
<td>2.0</td>
<td>1.3–5.7</td>
<td>0.6</td>
</tr>
<tr>
<td>167.0</td>
<td>2.5</td>
<td>1.4–6.1</td>
<td>1.0</td>
</tr>
<tr>
<td>250.0</td>
<td>3.6</td>
<td>1.9–6.8</td>
<td>1.0</td>
</tr>
<tr>
<td>333.0</td>
<td>4.7</td>
<td>2.4–8.0</td>
<td>1.0</td>
</tr>
<tr>
<td>500.0</td>
<td>5.5</td>
<td>2.2–8.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* National standards do not specify %Z for single-phase transformers. Consult manufacturer for values to use in calculation.
** Based on rated current of the winding (one-half nameplate kVA divided by secondary line-to-neutral voltage).
TRANSFORMER PROTECTION

LARGE TRANSFORMER (10 MVA OR LARGER)

* Differential (87T)
* Phase Overcurrent (50/51)
* Ground Overcurrent (50/51G)
* Sudden Pressure (63)
* Thermal Overload (49)

SMALLER TRANSFORMER (LESS THAN 10 MVA)

* Phase Overcurrent (50/51)
* Ground Overcurrent (50/51N)
* High Side Fuse
* Thermal Overload (49)

MAGNETIZING INRUSH
