Chapter 6 - Transformers

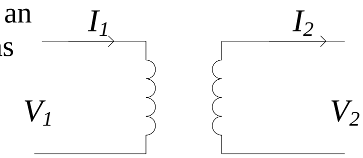
6.1 Introduction

Transformers are rated based on the apparent power. The apparent power in is equal to the apparent power out. Therefore, the device can raise voltage while lowering the current. They are also used to match the impedance between high and low Z circuits. The ideal transformer, like other machines can be modeled as a Thevenin equivalent voltage and impedance with a magnetizing circuit consisting of an inductor with its resistance.

Transformers can be connected in numerous configurations from single-phase to three-phase, step-up to step-down, and autotransformer. Although most electrical devices have a direct fluid analog, transformers are unique.

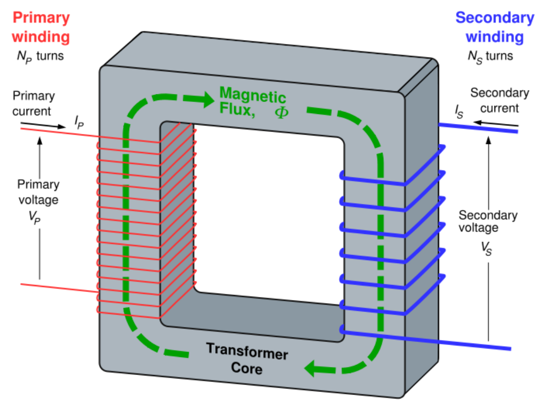
6.2 Model

A transformer is a machine that does not rotate. Otherwise, it is very similar to an induction AC machine. In application, the ideal transformer is represented simply as two coils.



Considering the representation of a magnetic circuit, the simplest transformer is a loop of steel laminations with a winding on each leg. A changing voltage across the primary winding causes a current to flow which results in a magnetic flux. The core carries the flux to the secondary winding. There, the changing flux induces a current with a voltage on the terminals.

The model of a transformer fits the Thevenin equivalent output with a magnetizing circuit input that induces the Thevenin voltage, all within a two port network.



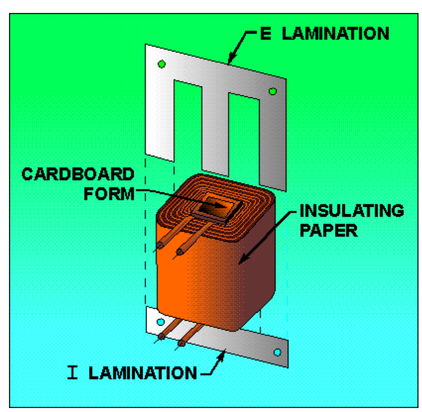
The relationship between input and output sides is dependent on the turns ratio, a.

$$a = \frac{V_{in}}{V_{out}} = \frac{I_{out}}{I_{in}} = \frac{N_{in}}{N_{out}}$$

The equivalent elements can be referred to the primary or input by the square of the turns ratio.

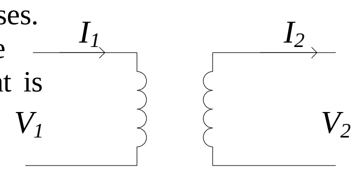
$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{aV_{out}}{I_{out}/a}$$
$$= a^2 Z_{out}$$

Typically the primary is wound first on an insulating form. Then an insulation material such as cardboard or Kraft paper is placed over the winding. Next, the secondary is wound on top of the primary. Another layer of insulation is attached. A steel core is constructed of stacks of thin steel. Then the wound form consisting of the primary and secondary is inserted over one leg of the steel core. The core loop is completed by bonding a straight stack of steel across the open side of the core.



6.4 Turns manipulation

Transformers consist of two inductors that are closely coupled. Usually an iron core provides an improved magnetic path. Laminations are used in the iron to reduce the hysteresis and eddy current losses. There are no moving parts to a transformer. It simply converts the voltage on one side to a different voltage dependent on the number of turns on each side. The current is converted inversely to the turns.



The voltage (V) ratio between the primary and secondary is equal to the corresponding turns (N) ratio.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = a$$

The inverse of the current (I) ratio between the primary and secondary is equal to the turns (N) ratio.

$$\frac{I_S}{I_P} = \frac{N_p}{N_s} = a$$

The impedance ratio is based on the square of the turns ratio.

$$V_P = aV_S$$

$$I_P = I_S / a$$

$$Z_P = \frac{V_P}{I_P} = \frac{aV_S}{I_S / a}$$

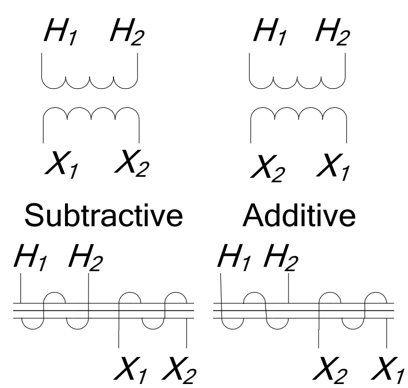
$$Z_P = a^2 \frac{V_S}{I_S} = a^2 Z_S$$

$$\frac{Z_P}{Z_S} = a^2 = \left(\frac{N_P}{N_S} \right)^2$$

Terminal markings

Transformer windings are identified either by location or by terminal markings. Primary windings are labeled with "H". Secondary windings are identified with "X". Subscripts identify the separate terminals.

The coupling between the turns is determined by the polarity. Normal polarity is subtractive. The same subscripts are aligned between the primary and secondary terminals. Additive polarity has the opposite subscripts aligned on the terminals. When connecting a bank of transformers with different polarities, connect according to the terminal numbers, rather than the position on the transformer. That is, connect X_1 on the first transformer to X_2 on the next transformer and H_1 to H_2 in all circumstances, regardless of polarity.



Step-up

The same transformer can be used as a step-up or step-down unit. A step-up transformer has a higher voltage and a lower current on the secondary. Conversely, a step-down transformer has a lower voltage and higher current on the secondary.

Autotransformer

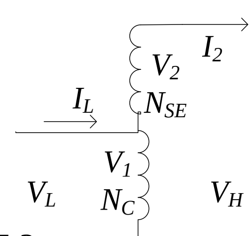
An autotransformer has the secondary and the primary connected together. The voltage is placed on the primary. One terminal becomes common with the output. The other primary terminal is connected to one of the secondary terminals. The remaining secondary terminal becomes the second output terminal.

If the secondary is connected with additive polarity, it is a boost connection. If the secondary is connected with subtractive polarity, it is a buck connection.

The input is the common coil, N_c, while winding 2 becomes the series coil, N_{se}, which is added or subtracted from the input.

$$V_1 = N_C$$

$$V_2 = N_{SE}$$



$$\frac{V_L}{V_H} = \frac{N_C}{N_C + N_{SE}}$$

$$\frac{I_L}{I_H} = \frac{N_C + N_{SE}}{N_C}$$

The apparent power into and out of the transformer must be equal.

$$S_{IN} = S_{OUT} = S_{IO}$$

The apparent power in the windings must be the same in the common and the series winding.

$$S_W = V_C I_C = V_{SE} I_{SE}$$

So the ratio of the apparent power gives a “gain” or apparent power advantage.

$$\frac{S_{IO}}{S_W} = \frac{N_{SE} + N_C}{N_C}$$

Example turns

Given: A transformer has a 120 volt primary and a 12 volt secondary. Primary current is 10 amps.

Find: Turns ratio

Secondary current

VA rating of each winding

Solution:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \Rightarrow \frac{120}{12} = \frac{N_p}{N_s}$$ Turns ratio = 10:1

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \Rightarrow \frac{I_s}{10} = \frac{10}{1}$$

$$I_s = \frac{10*10}{1} = 100$$

$$V_p I_p = V_s I_s \Rightarrow 120*10 = 1200VA$$

Example autotransformer

Given: Connect the transformer in the above example as a boost autotransformer with 120 volt primary.

Find: Output voltage

Output current

Output power

Solution:

$$V_{OUT} = V_C + V_{SE} = 120 + 12 = 132\text{V}$$

$$I_{OUT} = I_{SE} = 100A$$

$$S_{IO} = V_H I_H = 132*100 = 13,200VA$$

6.5 System voltage levels

There are many different system voltage levels. Some of the common ones are listed. Others are in use at various locations. Obviously transformers are required to convert between the different voltage systems. Single-phase systems are identified with a single voltage. Three-phase systems show the line-to-neutral (LN) value separated by a diagonal slash (/) from the line-to-line (LL) rating. The line-to-line voltage is the number used for nominal system voltage rating on three-phase systems.

Controls

Controls are often less than 50 volts for safety considerations. Voltages less than this usually can be contacted without fatal consequences. The most common systems employ 48, 24, 12, 6, and 5 volts. Nevertheless, some systems safely retain 120 volts for convenience.

< 48	120

Secondary (utilization)

Most power equipment operates at these levels. The motors or other loads can be connected directly to the system or may be operated through another transformer at a lower voltage.

2400/4160	277/480	240	120/208

Typical applications fit in the matrix. System requirements may dictate other selections of voltage size.

Volts	Phase	Application	Size
4160	3	extra large	>1000 Hp
2400	3	very large	>250 Hp
480	3	large	>3 Hp
277	1	lighting	commercial
240	1	general	>1 Hp
208	3	motors	>1 Hp
120	1	general	<1 Hp

Primary (distribution)

Distribution level voltages are provided by the utility up to the final power transformer. As an aid in determining the nominal voltage rating of a power line, consider the number of insulators. For distribution voltages, typically one suspension insulator bell on the power line corresponds to approximately 10,000 volts.

2400/4160	7200/12470	7620/13200
7970/13800	14400/24940	19920/34500

Transmission

Transmission level is used for shipping electric power over large distances. For transmission voltages, typically one suspension insulator bell corresponds to approximately 20,000 volts.

34500	69 KV	138 KV	240 KV

Extra high voltage

There are only a limited number of these systems. Cost and concerns about hazards have limited their acceptance.

345 KV	700 KV	1 MV	>500 KV DC

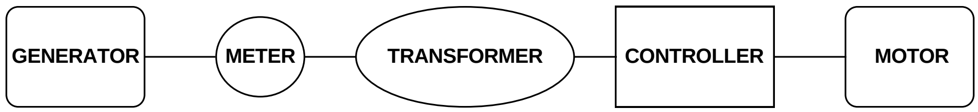
6.6 Voltage drop

Just as a pipeline experiences pressure drop due to friction, an electrical system experiences voltage drop due to impedance (resistance). Because of wire size and quantity of current flow, the voltage at a transformer will not be the same as the voltage that reaches the motor.

Voltage drop actually shows up on the utility bill as power. The power is simply used as waste heat in the wire. The power loss is the product of the voltage drop in each line, the current through the lines, and the phase factor. For single-phase the factor is 1, for three-phase the factor is √3, assuming the lines are balanced.

$$Power = V_{DROP} I_{WIRE} \times 1.732$$

Prudent design dictates the maximum voltage drop will be less than 5% from the source (transformer) to the load (motor). For a 480 volt transformer, the maximum voltage drop is .05 * 480 = 24 volt. The motor voltage must then be derated from the transformers voltage.



$$480 - 24 = 456 \text{ rounded to } 460$$

Since the controller is associated with a single motor, it is rated at the same voltage as the motor. Typical system voltages and motor voltages can be calculated in a similar manner. Before the standardization of system voltages, typical values were based on 110 volts, rather than 120.

System Voltage (Transformer)	Motor Voltage (Controller)	Good Old Days
120	115	110
240	230	220
480	460	440
2400	2300	2200

6.7 Class 2 transformers

Power limited transformers are commonly used for small power consumer devices. These are euphemistically referred to as “wall warts”. These are small units that plug directly into a 120 Vac receptacle. The output is less than 30 V. Some units have a rectifier in the case that provides a dc output.

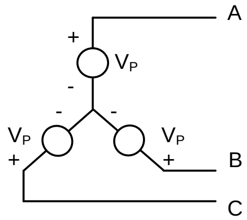
Class 2 uses a special design with an important characteristic. The device is impedance limited. The windings are very fine wire. Even with the secondary shorted, the high impedance limits the current so that the unit will not fail, a shock will not occur, and fire hazards are limited.

One caution should be noted. The heat generated during a short circuit is about the same as a 60 W lamp, so surface temperature can ignited some items that touch the case. Units for a dry environment are not sealed. Moisture from a hot, damp area can migrate into the unit and create a fault.

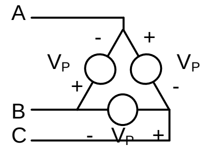
Article 725 of the NEC addresses power-limited circuits. Class 1 is conventional controls.
Class 2 is the most power limited. Class 3 is less restrictive power limited. The power limited circuits are differentiated from conventional electric light and power systems, therefore, alternative requirements are applied. Extensive details about the power limiting specification are in Chapter 9 of the NEC.

6.8 Three-phase limitations

Power transformer connections are critical to the operation of the system, for safety, and handling transients and harmonics in addition to voltage selection. For a three-phase system, the primary can be connected as a delta or wye. The secondary can be similarly connected. This gives four possible combinations. Typical single-phase and three-phase voltage values are shown for each combination.



WYE



DELTA

Because of the difference in orientation between the phase values on the wye and line values on the delta, there is a 30^o phase shift between the transformer phase voltages and the resulting currents. The phase shift is critical if a delta connection and a wye connection are connected in parallel on a system. The phase voltage across the respective transformer windings will be different .

Wye-delta

Utilities tend to operate and use single-phase devices connected in a three-phase arrangement. This leads to a wye connection on the primary, and a delta connection on the secondary. There are two serious problems with this arrangement. First, if the primary neutral is grounded, and a single-phase condition arises, then the unbalance circulating currents in the secondary will overload and damage the bank. Second, there is no ground on the secondary. To provide a ground, some utilities connect one corner of the delta to earth. This arrangement is particularly hazardous. It causes unbalanced voltage stress, and, more importantly, if the ground connection has any leakage, the current can be adequate to shock anyone touching the ground wire. Because of magnetizing currents, it may be necessary to ground the wye while switching, then remove the ground during normal operation.

1-φ	7200	240-480	3-φ	12470	480

Delta-delta

Industrial users at one time preferred this connection. It is inexpensive because only three conductors are required. Additionally, if one of the phases happens to fault to ground, equipment served from the secondary continues to run. This is acceptable if there is a procedure to alarm on the condition and a procedure to clear the fault. The arrangement still has the problem of inadequate secondary ground.

1-φ	12470	240-480	3-φ	12470	480

Wye-wye

The connection presents a difficulty because of high third-harmonic voltages. These create disturbances on telecommunications and other sensitive electronics. The problem can be somewhat mitigated if both the primary and secondary neutrals are effectively grounded. Although a ground is provided on the secondary, it is necessarily bonded to the primary. This creates problems with leakage currents which can impact living species at a significant distance from the power system. Moreover, any harmonics are readily coupled from the secondary to the primary.

1-φ	7200	277	3-φ	12470	480

Delta-wye

The preferred connection has many benefits in operation and safety. The secondary neutral can be grounded to create an independent source for safety and controls. The primary neutral is isolated. The phase shift between the delta primary and wye secondary mitigates harmonics from transfer to the primary. One down-side is that, if the secondary wye is not properly grounded, these harmonics will circulate in the delta and may cause overheating.

1-φ	12470	277	3-φ	12470	480

6.11 Exemplars

An exemplar is typical or representative of a system. These examples are representative of real world situations.

Exemplar 6.1

SITUATION:

A 1000/1250 kVA, OA/FA, 13.2kV:4160V single phase transformer is part of a 3000/3750 kVA Y-Δ bank. Factory tests are made on this transformer at 25°C and the following data recorded.

- DC Resistance: r1 = 0.40 Ω   r2 = 0.035 Ω
- With secondary open and 13.2kV applied to the primary: I_1 = 10A, P_{in} = 5500W
- With secondary shorted and 800V applied to the primary: I_1 = 75.76A , P_{in} = 5800W

Assume the three single phase transformers are equal.

REQUIREMENTS:

For the operating temperature of 75°C, determine:

a) The percent effective resistance on the self-cooled rating base
b) The percent reactance on the self-cooled rating base.
c) The percent impedance on the self-cooled rating base
d) The no-load loss of the three-phase bank (kW)
e) The total loss of the three-phase bank (kW) with the transformer operating at its force cooled rating.
f) The efficiency of the bank carrying 3750 kVA at 85% pf

Background

1000/1250 kVA OA/FA

13.2kV/4.16 kV

DC Resistance: r_1=0.40Ω r_2=0.035Ω

Open Circuit Test: V_1=13.2kV I_1=10A P_{in}=5500W

Short Circuit Test: I_1=75.76A P_{in}=5800W

Fan Load = 750W

S_{base}=1,000 kVA V_{base}=13.2kV Z_{base} $= = \frac{V_{base}^{\ 2}}{S_{base}} = \frac{(13,200)^2}{1,0000,000} = 174.24\Omega$

Turns Ratio: $a = \frac{V_p}{V_s} = \frac{13.2}{4.16} = 3.173$

Solution:

(a)Percent effective (ac) resistance on the self-cooled rating base

$r_{ac} = r_{dc} + r_{core} + r_{mech}$ (r_{mech} is 0 for transformer)

Equivalent dc resistance referred to primary:

$$r_{dc}(25^\circ C) = r_1 + a^2 r_2 = 1.4\Omega + 3.173^2 * 0.035\Omega = 0.7524\Omega$$

Effective resistance from short circuit test

$$r_{ac} = r_e(25^\circ C) = \frac{P_{in}}{I_1^{\ 2}} = \frac{5800}{(75.76)^2} = 1.0105\Omega$$

The components of the ac resistance at test temperature

$$\begin{aligned} r_{ac}(25^\circ C) &= r_{dc}(25^\circ C) + r_{core}(25^\circ C) = 1.0105\Omega \\ 1.0105\Omega &= 0.7524\Omega + r_{core}(25^\circ C) \\ r_{core}(25^\circ C) &= 1.0105\Omega - 0.7524\Omega \\ &= 0.2581\Omega \end{aligned}$$

Resistance changes with temperature.

r_{dc} increases with temp (positive temp coeff)

r_{core} resistance decreases with temp (negative temp coeff)

$\Delta R/\Delta T = \alpha\ T_0$

or

$R = R_0\ [\ 1 - \alpha\ (T - T_0)]$

For copper, the inferred absolute zero coefficient is -234.4.

So the equation reverts to

$R\ /\ R_0 = (234.4 + T\ )/\ (234.4 + T_0)$

Apply to both the copper and the core resistance.

$$\begin{aligned} r_{ac}(75^\circ C) &= 0.7524\Omega\left(\frac{234.5^\circ + 75^\circ}{234.5^\circ + 25^\circ}\right) + 0.2581\Omega\left(\frac{234.5^\circ + 25^\circ}{234.5^\circ + 75^\circ}\right) \\ &= 1.1138\Omega \end{aligned}$$

Convert to per unit.

$$r_{ac}(pu 75^\circ C) = \frac{1.1138\Omega}{174.24\Omega} = 0.006392 = 0.6392\%$$

(b) Percent reactance on the self-cooled rating base

Impedance

Z = <u>V</u> = $\sqrt{}R^2 + X^2$

$$\begin{aligned} Z_{ac} &= \frac{V_{sc}}{I_{sc}} = \frac{800}{75.76} = 10.56\Omega \\ X_{ac} &= \sqrt{Z_{ac}^{\ 2} - r_{ac}^{\ 2}} \\ X_{ac} &= \sqrt{10.56\Omega^2 - 1.1138\Omega^2} \\ &= 10.501\Omega \end{aligned}$$

$$X_{ac}(pu) = \frac{10.501\Omega}{174.24\Omega} = 0.060267 = 6.0267\%$$

(c) Percent impedance on the self-cooled rating base

$$Z_{ac}(pu) = \frac{10.56\Omega}{174.24\Omega} = 0.0606 = 6.06\%$$

(d) No-load loss of 3 phase bank (from open circuit test)

$P_{no\text{-}load}$=3*P_{in} = 3*5500 = 16.5kW

(e) Total loss of 3 phase bank operating at FA rating

S = VI* → I = S / V

$$I_{FA} = \frac{1250kVA}{13.2kV} = 94.697A$$

$$P_{lossFA} = 3*(I_{FA}{}^2 r_{ac} + P_{no-load})$$

$$= 3*(94.697^2 * 1.1138 + 5500)$$

$$= 46.46kW$$

(f) Efficiency

$$P_{out} = 3750kVA * 0.85pf$$

$$= 3{,}187.5kW$$

$$eff = \frac{P_{out}}{P_{in}} = \frac{3{,}187.5kW}{(3{,}187.5kW + 46.46kW + 0.75kW)} = 98.54\%$$

Exemplar 6.2

SITUATION:

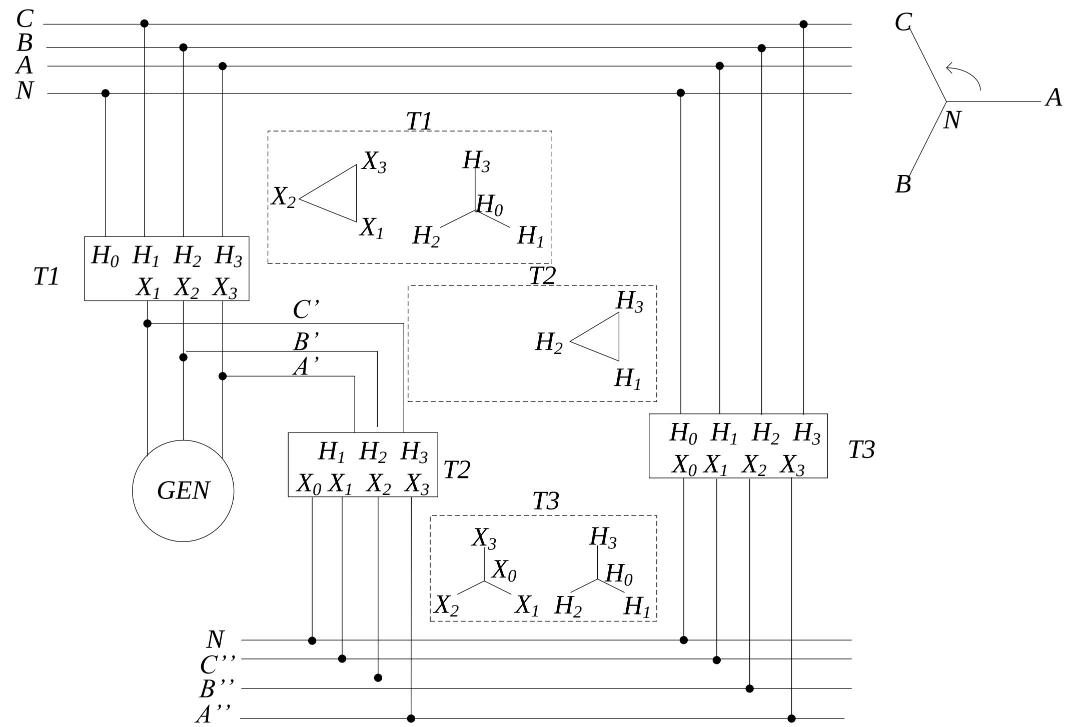
A generating station is connected as shown in Figure Problem 2-7 below. Transformer T_2 was destroyed and must be replaced; however, no records exist of the nameplate, and the proper phase relations must be determined so that a new transformer can be specified.

REQUIREMENTS:

Neatly sketch and label phasors A'B'C', and state sequence A'B'C' or C'B'A'.

Neatly sketch and label phasors A"B"C" and state sequence A"B"C" or C"B"A"

Complete the nameplate for T_2 – ratings not required.



SOLUTION:

This is a problem about phase sequences. It illustrates the phase shifting between (1) wye and delta, (2) between line-line and line-ground, and (3) between line and phase. Although these are obviously related, the actual connections can be quite different.

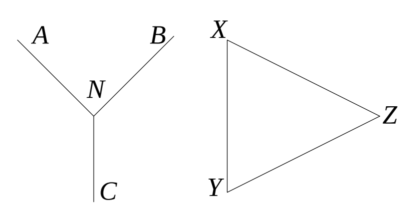
Delta	Delta	Wye	Wye
Phase	Line	Phase	Line
L-L	L-L	L-N	L-L

Phase sequence is drawn from the perspective of looking down the x-axis to the left. The phasors rotate CCW. Record the phase sequence AN, BN, CN or CN, BN, AN or record the line sequence AB, BC, CA or CA, BC, AB. Select every other letter. The sequence is positive ABC or negative CBA.

For a transformer the terminals are labeled on the primary and secondary.

				Neutral
Primary	H1	H2	H3	H0
Secondary Additive	X1	X2	X3	X0

Transformers in a wye-delta configuration are shown. Note the corresponding orientation that does not result in a phase shift. AN-XY, BN-YZ, CN-ZX



Steps for determining transformer connection. Make a table of the line connections and the transformer connections. Fill in the rows of unknowns. Note the order that data is filled.

Order	Action	Options			
	Reference phase	AN BN CN or AB BC CA	AN	BN	CN
	Transformer primary connection	H1 H2 H3 H0			
	Primary actual phase/line connection	AN BN CN or AB BC CA			
	Transformer secondary connection	X1 X2 X3 X0			
	Secondary actual phase/line connection	AN BN CN or AB BC CA			
	Orientation of primary & secondary draw sketch	0^o 120^o 240^o or 90^o 210^o 330^o			
7	Sequence	ABC or CBA			

Transformer T3 is a wye-wye. The primary and secondary are aligned in phase.

Order	Action	Connection			
1	Reference phase	AN BN CN or AB BC CA	AN	BN	CN
2	Transformer primary connection	H1 H2 H3 H0	H1H0	H2H0	H3H0
3	Primary actual phase/line connection	AN BN CN or AB BC CA	AN	BN	CN
4	Transformer secondary connection	X1 X2 X3 X0	X1X0	X2X0	X3X0
5	Secondary actual phase/line connection	AN BN CN or AB BC CA	C"N	B"N	A"N
6	Orientation of primary & secondary draw sketch	0^o 120^o 240^o or 90^o 210^o 330^o	0^o	120^o	240^o
7	Sequence	ABC or CBA	CBA		

Transformer T1 is a wye-delta. The primary and secondary are shifted in phase.

Order	Action	Connection			
1	Reference phase	AN BN CN or AB BC CA	AN	BN	CN
2	Transformer primary connection	H1 H2 H3 H0	H3H0	H2H0	H1H0
3	Primary actual phase/line connection	AN BN CN or AB BC CA	AN	BN	CN
4	Transformer secondary connection	X1 X2 X3 X0	X3X1	X2X3	X1X2
5	Secondary actual phase/line connection	AN BN CN or AB BC CA	A'C'	B'A'	C'B'
6	Orientation of primary & secondary draw sketch	0^o 120^o 240^o or 90^o 210^o 330^o	0^o	120^o	240^o
7	Sequence	ABC or CBA	ABC		

Transformer T2 is a delta-wye. The primary & secondary are shifted in phase. The secondary orientation is unknown

Order	Action	Options			
1	Reference phase	AN BN CN or AB BC CA	AN	BN	CN
4	Transformer primary connection	H1 H2 H3 H0	H1H3	H2H1	H3H2
2	Primary actual phase/line connection	AN BN CN or AB BC CA	A'C'	B'A'	C'B'
5	Transformer secondary connection	X1 X2 X3 X0	X1X0	X2X0	X3X0
3	Secondary actual phase/line connection	AN BN CN or AB BC CA	C"N	B"N	A"N
6	Orientation of primary & secondary draw sketch	0^o 120^o 240^o or 90^o 210^o 330^o	90^o	210^o	330^o
7	Sequence	ABC or CBA	CBA		

6.11 Applications

Applications are an opportunity to demonstrate familiarity, comfort, and comprehension of the topics.

⇐⇑⇒