Chapter 6 - Transformers

6.1 Introduction

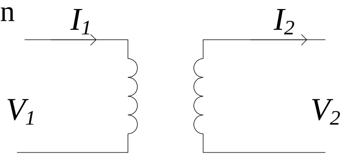
Transformers are rated based on the apparent power. The apparent power in is equal to the apparent power out. Therefore, the device can raise voltage while lowering the current. They are also used to match the impedance between high and low Z circuits. The ideal transformer, like other machines can be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

Transformers can be connected in numerous configurations from single-phase to three-phase, step-up to step-down, and autotransformer. The ratings of transformers depend on temperature, altitude, and basic impulse levels.

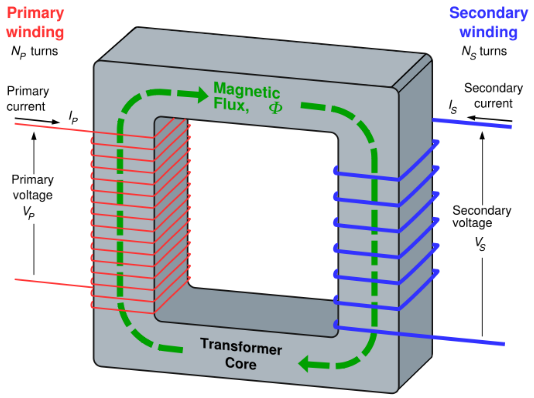
Although most electrical devices have a direct fluid analog, transformers are unique.

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 from Chapter 3, 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.

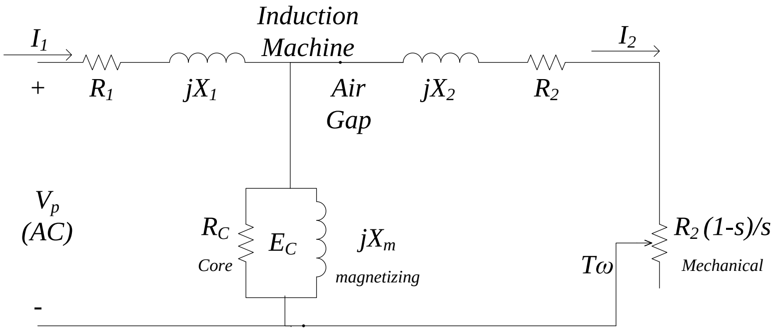
$$R_1 = R_p \qquad jX_1 = jX_p$$

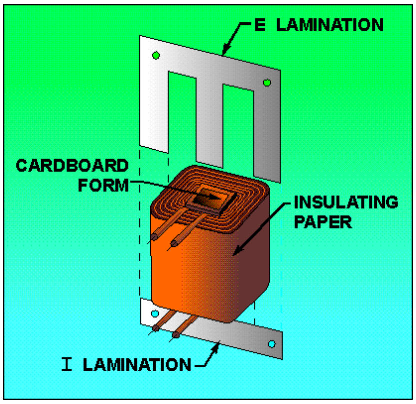
$$R_2 = a^2 R_s \qquad jX_2 = ja^2 X_s$$

Alternately, the circuit can be referred to the output or secondary again by the square of the turns ratio.

$$R_1 = \frac{R_p}{a^2} \qquad jX_1 = \frac{jX_p}{a^2}$$

$$R_2 = R_s \qquad jX_2 = jX_s$$



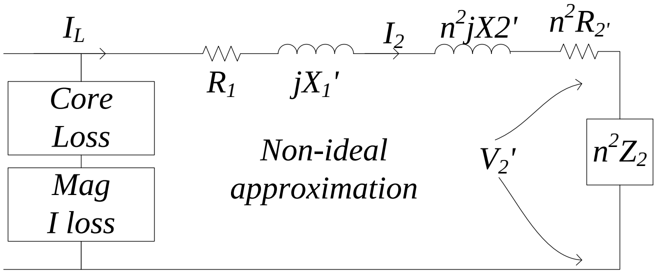


Typically the primary is wound first on an insulating form. Then an insulation material such as cardboard or Kraft paper is placed over the winding. Next, the secondary is wound on top of the primary. Another layer of insulation is attached. A steel core is constructed of stacks of thin steel. Then the 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.

6.3 Transformer tests

Transformer tests are conducted according to the standard test procedures. The series impedance in the primary and secondary cannot be easily separated. Therefore, these are left in combination. The non-ideal approximation model determined is a one-port circuit. The magnetic core is in shunt across the test terminals. The windings are in series with the winding across the core compensating for the turns ratio.

6.3.1 Open circuit test



Conduct the core tests with the secondary or output disconnected. Apply rated full voltage.

Since the output is open, the voltage drop is across the excitation coil. So the test yields values of the core impedance.

Measure $V_{oc.}$, I_{oc}, and a third parameter that represents the real, in-phase, dc component, P_{oc} or R_{oc}

The calculations can refer to the primary or secondary using the turns ratio..

$$\frac{1}{Z_E} = Y_E = \frac{1}{R_c} - \frac{j}{X_c}$$

$$|Y_E| = \frac{I_{oc}}{V_{oc}}$$

The angles are determined from measured magnitudes of voltage and current with the third, real parameter.

$$pf = \cos\theta = \frac{P_{oc}}{V_{oc} I_{oc}} = \frac{R_{oc}}{V_{oc}/I_{oc}}$$

$$\theta = \angle Z_E$$

$$-\theta = \angle Y_E$$

6.3.2 Short circuit test

Conduct the windings test with secondary winding shorted. Apply reduced voltage from a variac, and increase the voltage until rated current is measured.

Since the output is closed, most current is flowing in the low resistance series path. This shows values of copper impedance. Very little current flows through the excitation branch.

Measure $V_{sc.}$, I_{sc}, and a third parameter that represents the real, in-phase, dc component, P_{sc} or R_{sc}.

Then calculate the impedance values.

$$|Z_{SE}| = \frac{V_{sc}}{I_{sc}}$$

$$pf = \cos\theta = \frac{P_{sc}}{V_{sc} I_{sc}} = \frac{R_{sc}}{V_{sc}/I_{sc}}$$

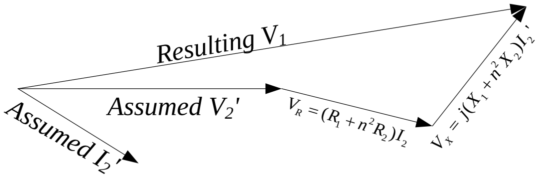
$$\theta = \angle Z_E$$

$$\begin{aligned} Z_{SE} &= R_{eq} + jX_{eq} \\ &= (R_p + a^2 R_s) + j(X_p + a^2 X_S) \end{aligned}$$

Because of the connections, we cannot separate primary & secondary impedance, but usually this is not necessary.

The impedances cause a shift in the angles associated with the current and voltage. Because of the inductance, the current is shifted by the impedance.

Begin with the output voltage as a reference along the real axis. Multiply the sum of the resistances by the shifted current with angle to obtain the resistive voltage drop. Add the resistance voltage drop to the reference voltage. Multiply the current by the sum of the reactances to obtain the voltage shift. The reactance voltage will be shifted 90 degrees from the resistance voltage drop. The resultant is the vector sum of the reference voltage, resistance voltage, and reactance voltage.



6.3.3 Example tests

Consider a transformer with the following results from the tests. The measurements were made on the primary.

Ratings	Open Circuit Values	Short Circuit Values
20 kVA	V=8,000V	V=489V
8000/240V	I=0.214A	I=2.5A
60 Hz	P=400W	P=240W

Open circuit

Determine the values associated with magnetizing current.

$$pf = \cos\theta = \frac{P_{oc}}{V_{oc} I_{oc}} = \frac{400}{(8000)(0.214)} = 0.234 \text{ lagging=76.5°}$$

$$Y_E = \frac{I_{oc}}{V_{oc}} \angle -\theta = \frac{0.214}{8000} \angle -76.5^\circ = 0.0000062 - j0.0000261\Omega$$

$$Y_E = \frac{1}{R_c} - j\frac{1}{X_m}$$

$$\therefore R_c = 159k\Omega, X_m = 38.4k\Omega$$

Short circuit

Determine the values associated with series current.

$$pf = \cos\theta = \frac{P_{sc}}{V_{sc} I_{sc}} = \frac{240}{(489)(7.5)} = 0.196 \text{ lagging=78.7°}$$

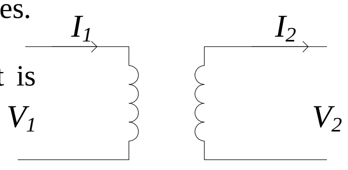
$$Z_{se} = \frac{V_{sc}}{I_{sc}} \angle \theta = \frac{489}{2.5} \angle 78.7 = 38.4 + j1.92\Omega$$

$$R_{eq} = 38.4\Omega \quad X_{eq} = 1.92\Omega$$

These are the values associated with both windings in series. The primary and secondary cannot be easily separated.

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.

$$V_P = aV_S$$

$$I_P = I_S / a$$

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

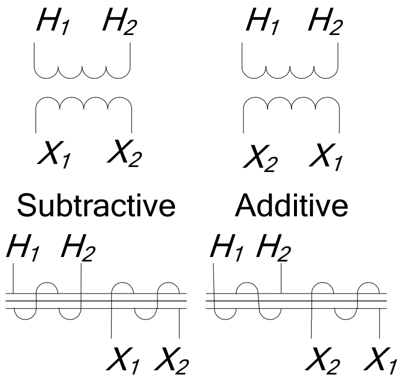
$$Z_P = a^2 \frac{V_S}{I_S} = a^2 Z_S$$

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

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.



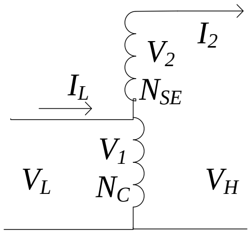
Step-up

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.

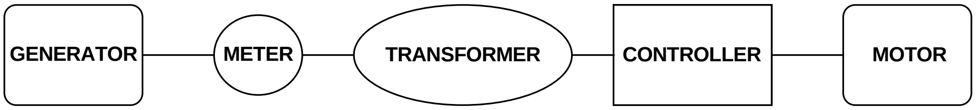
345 KV	700 KV	1 MV	>500 KV DC

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 Per Unit Notation

Per unit notation is used to reduce the complexity when working with circuits that have multiple voltage levels. Both Ohm's law and the power relationship permit a third term to be calculated from only two terms.

Two parameters are selected as the reference or base values. These are generally S and V. A different base V is used on each side of a transformer. The base current and base impedance can be determined from these two values

$$I_{base} = \frac{S_{base}}{V_{base}}$$

$$Z_{base} = \frac{V_{base}^{\ 2}}{S_{base}}$$

All the circuit equipment voltages and currents are then converted to per unit (percentage) values before normal circuit calculations are made

$$S_{pu} = \frac{S_{equip}*100}{S_{base}}$$

$$V_{pu} = \frac{V_{equip}*100}{V_{base}}$$

$$I_{pu} = \frac{I_{equip}*100}{I_{base}}$$

$$Z_{pu} = \frac{Z_{equip}*100}{Z_{base}}$$

As an example, transformer impedance is usually rated in per unit values. To find the actual impedance, combine the above equations

$$Z_{equip} = \left(\frac{Z_{pu}}{100}\right) Z_{base}$$

$$Z_{equip} = \left(\frac{Z_{pu}}{100}\right) \frac{V_{base}^{\ 2}}{S_{base}}$$

An example illustrates the relationship between per unit values and short circuit capability.

Transformer, S_{base}=10kVA, V_{base}=120, Z_{pu}=2%

$$Z_{equip} = \frac{\left(\frac{2}{100}\right)120^2}{10000} = 0.0288\Omega$$

$$SCC = 10000\left(\frac{100}{2}\right) = 5000kVA = \frac{S_{base}}{Z_{pu}}$$

$$I_{sc} = \frac{V}{Z_{equip}} = \frac{SCC}{V_{base}} = \frac{V_{base}}{Z_{equip}} = 4167A \text{ (use pre-fault voltage)}$$

Another application is determining performance on each side of a transformer. An example illustrates the relationship between per unit values and determination of impedance of a machine on each side of a transformer. Determine the impedance of Transformer 2 using Transformer 1 as the base.

Transformer, S_{base}=10kVA, V_{base}=120, Z_{pu}=2%

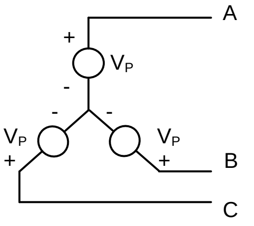
Transformer 2, S= 5kVA, V=240, Z=1.5%

$$\frac{Z_{equip}}{S_{equip}} = \frac{Z_{base}}{S_{base}}$$

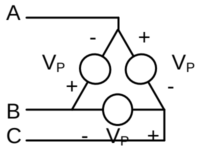
$$Z_{base} = S_{base}\frac{Z_{equip}}{S_{equip}} = 10kVA\left(\frac{.02\Omega}{5kVA}\right) = 0.04\Omega$$

6.9 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° 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

6.10 Temperature, altitude, and cooling

Resistance changes with temperature. As resistance and temperature go up, the capacity of the transformer goes down. Therefore, transformers have rating factors based on ambient temperature and the internal rise in temperature due to current through the resistance.

The ANSI transformer kVA ratings are based on a daily average ambient temperature of 30 C and a maximum of 40 C. Transformers can be specified to have a temperature rise of 55 C, 65 C, or 55 C/65 C. A unit rated at 55 C/65 C rise will deliver 12% more KVA at 65 C rise than at 55 C rise. When a transformer rated at 55 C rise is operated at a lower temperature rise, the rated capacity is increased as follows:

Temperature Rise	Percent Capacity
35 C	135
40 C	125
45 C	116
50 C	108

Transformer cooling methods

Transformers are classified according to their method of cooling. Dry-type transformers are designed without oil around the core and windings. Small dry-type transformers may be mounted in end frames with the coils exposed for indoor operation, or they may be provided with a metal housing for protection. Such transformers are cooled by the natural circulation of air around their coils and core.

In large and medium size dry-type transformers, additional cooling is provided by air ducts through the winding. In forced air cooled transformers, the winding and core are provided with many ducts through which air is forced at high speed by a blower.

With the exception of small transformers less than 30 kVA and some instrument transformers, it is the general practice to use oil-immersed power transformers. The coils and core are mounted in a tank filled with oil, which serves the double purpose of helping to insulate the transformer and of carrying heat caused by the transformer losses to the cooling surfaces where it is dissipated.

In certain locations, oil is prohibited because of potential fire hazards. In such cases, inhibited transformer oils are used. These are non-combustible synthetic insulating liquids, which do not give off explosive gasses when decomposed by an electric arc. Askarel is the trade-name of a common inhibited transformer oil.

There are several variations to cooling systems on oil immersed transformers. Acronyms indicate the different designs. The following list is the most common power transformer cooling classes. There is typically a 12% increase each time the transformer is uprated by enhanced cooling. The enhanced types are separated by a slash (/).

Type	Cooling
OA	Oil-immersed, self cooled
OW	Oil-immersed, water-cooled
OA/FA	Oil-immersed self-cooled/forced aid-cooled
OA/FA/FOA	Oil-immersed, self-cooled/forced-air-cooled/forced oil-cooled
FOA	Oil-immersed, forced oil-cooled with forced air cooled
FOW	Oil-immersed, forced-oil-cooled with water cooled

Derating for altitude

Altitudes above 33a00 feet (1000 meters) require derating of air-cooled transformers due to the reduced cooling capacity of the less dense air. The permissible temperature rise shall be reduced by the following amounts for each 330 feet (100meters) of altitude in excess of 3300 feet (1000 meters).

Cooling	Type	Percent
Oil immersed, self cooled	OA	0.4
Oil immersed, forced air cooled	FA	0.6
Dry type, self cooled	A	0.5
Dry type, forced air cooled	AFA	1.0

Percent impedance limit

The impedance of large power transformers is a design parameter used to control fault current. A higher impedance unit will limit the amount of current that can flow under a fault condition. The downside is losses are higher resulting in higher utility costs.

The following table uses the voltage rating of the primary and secondary to correlate with the maximum allowed impedance.

Winding Insulation in kV		**Impedance limit in Percent**			
High Voltage kV	*Low Voltage kV*	*Cooling OA, OW OA/FA* OA/FA/FOA**		*Cooling FOA FOW*	
		Min	*Max*	*Min*	*Max*
15	15	4.5	7.0	6.75	10.5
25	15	5.5	8.0	8.25	12.0
34.5	15	6.0	8.0	9.0	12.0
	25	6.5	9.0	9.75	13.5
46	25	6.5	9.0	9.75	13.5
	34.5	7.0	10.0	10.5	15.0
69	34.5	7.0	10.0	10.5	15.0
	46	8.0	8.0	12.0	16.5
92	34.5	7.5	10.5	11.25	15.75
	69	8.5	12.5	12.75	18.75
115	34.5	8.0	12.0	12.0	18.0
	69	9.0	14.0	13.5	21.0
	92	10.0	15.0	15.0	23.25
138	34.5	8.5	13.0	12.75	19.5
	69	9.5	15.0	14.25	22.5
	115	10.5	17.0	15.75	25.5
161	46	9.5	15.0	13.5	21.0
	92	105	16.0	15.75	24.0
	138	11.5	18.0	17.25	27.0
196	46	10	15.0	15.0	22.5
	92	11.5	17.0	17.25	25.5
	161	12.5	19.0	18.75	28.5
230	46	11.0	16.0	16.5	24.0
	92	12.5	18.0	18.75	27.0
	161	14.0	21.0	21.0	30.0

*The impedances are expressed in percent on the self-cooled rating of OA/FA and OA/FA/FOA.

The through impedance of a two-winding autotransformer can be estimated knowing rated circuit voltages, by multiplying impedances obtained from this table by the factor. $\left(\frac{HV-LV}{HV}\right)$

6.11 Basic impulse level (BIL)

Basic impulse level is the amount of voltage a device should withstand under an impulse or spike condition. It is sometimes referred to as basic insulation level. The number is significantly greater than the nominal rating of the insulation.

The connection and insulation type obviously affects the withstand value. Very large units greater than 500 kVA have greater withstand capability than somewhat smaller units.

Insulation Classes and Dielectric Tests for Distribution & Power Transformers											
Insulation rating	*Rated Voltage Between Terminals of Power-Transformers(a)*			*Low Frequency Tests*		*Oil-immersed transformers 500 kVA or Less*			*Oil-immersed transformers above 500 kVA*		
	1-Phase	*1-Phase*	*3-Phase*	*Oil*	*Dry*	*Chopped Wave*		*Full wave(e)*	*Chopped Wave*		*Full wave(e)*
	Y on 3φ	*Δ on 3φ*	*Δ or Y (c)*	*type*	*type*	*Crest*	*Min time to flashover*	*Crest*	*Crest*	*Min time to flashover*	*Crest*
kV	*kV rms*	*kV rms*	*kV rms*	*kV rms*	*kV rms*	*kV*	*microsec*	*kV*	*kV*	*microsec*	*kV*
1.2	0.69	0.69(d)	1.2	10	4	36	1.0	30	0.54	1.5	0.45
2.5	..	..	2.5	15	10	54	1.25	45	..	..	..
5.0	2.89	2.89(d)	5.0	19	12	69	1.5	60	88	1.6	75
8.66	5.0	5.00(d)	8.66	26	19	88	1.6	75	110	1.8	95
18	8.66	15.0	15.0	34	31	110	1.8	95	130	2.0	110
25.0	14.4	25.0	25.0	50	..	175	3.0	150	175	3.0	150
34.5	19.9	34.5	34.5	70	..	230	3.0	200	230	3.0	200
46.0	26.6	46.0	46.0	95	..	290	3.0	250	290	3.0	250
69.0	39.8	69.0	69.0	140	..	400	3.0	350	400	3.0	350
92	53.l	92	92	185	..	520	3.0	450	520	3.0	450
115	66.4"	113	115	230	..	520	3.0	450	520	3.0	450
138	79.7:	138	138	275	..	750	3.0	650	750	3.0	650
161	93.0	161	161	325	..	865	3.0	750	865	3.0	750
196	113	196	196	395	..	1035	3.0	900	1035	3.0	900
230	133	230	230	460	..	1210	3.0	1050	1210	3.0	1050
287	166	287	287	575	..	1500	3.0	1300	1500	3.0	.1300
345	199	345	690	690	..	1785	3.0	1530	1785	3.0	1550

After ANSI C57.11-1948

(a) Intermediate voltage ratings are placed in the next higher insulation class unless otherwise specified.

(b) Standard impulse tests have not been established for dry-type distribution and power transformers. Accepted values for impulse tests of such apparatus are as follows:

1.2 kv class, 10 kV; 2.5 class, 20 kv; 5.0 class, 25 kv; 8.66 kv class, 35 kV; 15 kv class, 50 kv. These values apply to both chopped-wave and full-wave tests.

(c) Y-connected transformers for operation with neutral solidly grounded or grounded through an impedance may have reduced insulation at the neutral. When this reduced insulation is below the level required for delta operation, transformers cannot be operated delta-connected.

(d) These apparatus are insulated for the test voltages corresponding to the Y-connection, so that a single line of apparatus serves for the Y and delta applications. The test voltages for such delta-connected single-phase apparatus are therefore one step higher than needed for their voltage rating.

(e) 1.5 x 40 microsecond wave.

6.12 Exemplars

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

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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

$r_{ac} = r_{dc} + r_{core} + \cancel{r_{mech}}$ (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

$$r_{ac}(25^\circ C) = r_{dc}(25^\circ C) + r_{core}(25^\circ C) = 1.0105\Omega$$

$$1.0105\Omega = 0.7524\Omega + r_{core}(25^\circ C)$$

$$r_{core}(25^\circ C) = 1.0105\Omega - 0.7524\Omega$$

$$= 0.2581\Omega$$

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.

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

$$= 1.1138\Omega$$

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

$Z = \underline{V} = \sqrt{}R^2 + X^2$

$$Z_{ac} = \frac{V_{sc}}{I_{sc}} = \frac{800}{75.76} = 10.56\Omega$$

$$X_{ac} = \sqrt{Z_{ac}{}^2 - r_{ac}{}^2}$$

$$X_{ac} = \sqrt{10.56\Omega^2 - 1.1138\Omega^2}$$

$$= 10.501\Omega$$

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

(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

$S = VI^{*} \rightarrow I = S / V$

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

$$\begin{aligned} P_{lossFA} &= 3*(I_{FA}{}^{2}r_{ac} + P_{no-load}) \\ &= 3*(94.697^{2}*1.1138 + 5500) \\ &= 46.46kW \end{aligned}$$

(f) Efficiency

$$\begin{aligned} P_{out} &= 3750kVA*0.85pf \\ &= 3{,}187.5kW \end{aligned}$$

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

Exemplar 6.2

SITUATION:

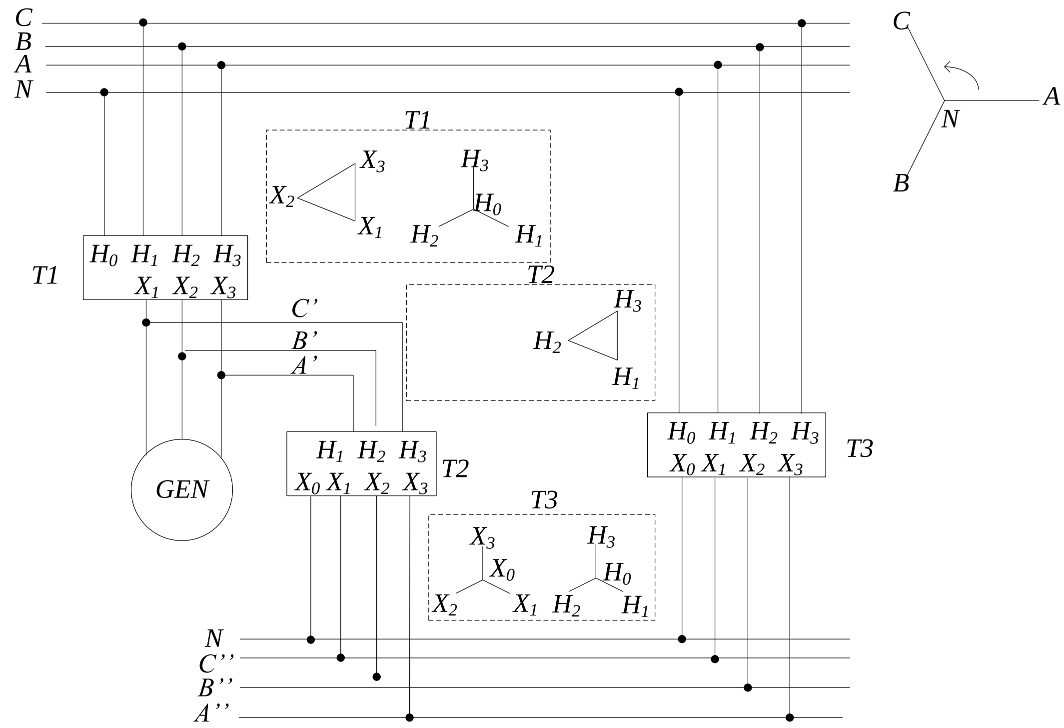
A generating station is connected as shown in Figure Problem 2-7 below. Transformer T_2 was destroyed and must be replaced; however, no records exist of the nameplate, and the proper phase relations must be determined so that a new transformer can be specified.

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.

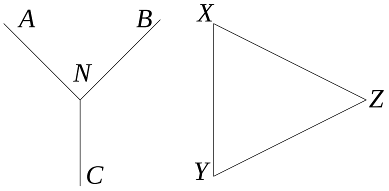
Delta	Delta	Wye	Wye
Phase	Line	Phase	Line
L-L	L-L	L-N	L-L

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.

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