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TRANSFORMERS

WHAT EVERY ENGINEER SHOULD KNOW Rev 4

by

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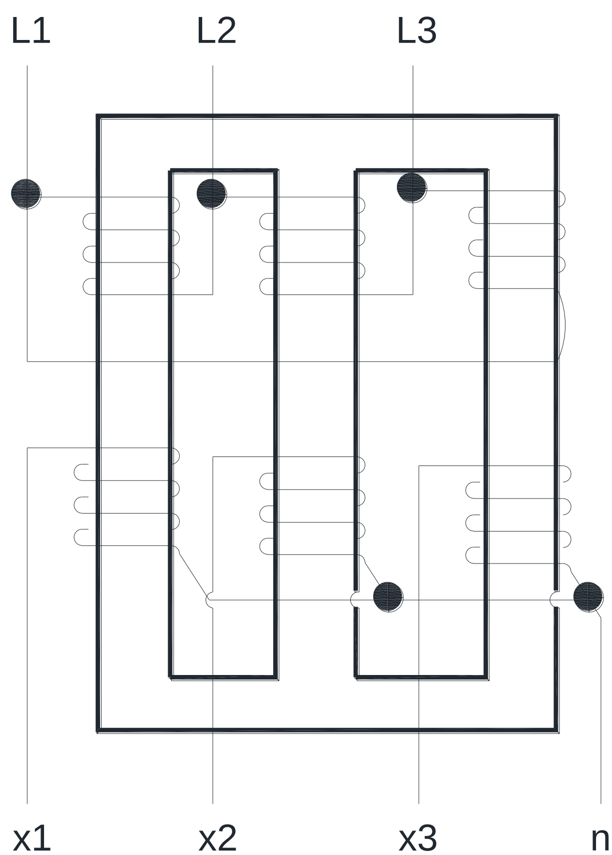

TRANSFORMERS

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PREFACE

There are many different types of transformers. They are different because they are designed for different specific purposes. Among them are:

- Power transformers- used to convert power from one voltage level to another. They include: control voltage transformers and distribution transformers.
- Buck and boost transformers- used to make relatively small corrections in voltage levels.
- Instrument transformers which include: Current transformers & Potential transformers
- Transformers that are submersed in oil for cooling purposes.

For our purposes here we will limit our discussion to low voltage control & power transformers. However, the basic principles apply to all types of transformers.

The purpose of this tutorial is to provide basic information to those who are not familiar with transformers and also as a refresher course for those who may want to reinforce their understanding of transformers. This course is also intended to provide guidance for transformer specification.

Symbol index

a	**Turns ratio**
$\frac{d\Phi}{dt}$	**Rate change of magnetic flux with respect to time**
i_1	**Current in line 1**
N_p	**Number of turns in transformer primary**
Φ	**Magnetic flux**
P_1	**Power in**
Pf	**Power factor**
P	**Primary**
ph	**Phase**
s	**secondary**
V	**Voltage**
VA	**Volts-Amps power**
w	**watts**

1. INTRODUCTION TO FARADY'S LAW

A transformer is an electrical device governed by the laws of electromagnetism. A transformer is comprised of a common core which allows a magnetic flux to flow through it and thus couples two or more stationary coils. A two winding ideal transformer is shown in Figure 1. An ideal transformer is assumed to have no losses in the core and none in the windings. The schematic symbol for this transformer is shown in figure 2.

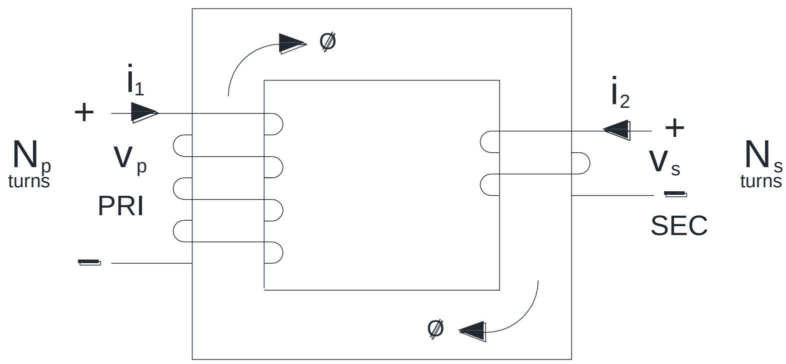


FIGURE 1
IDEAL TRANSFORMER

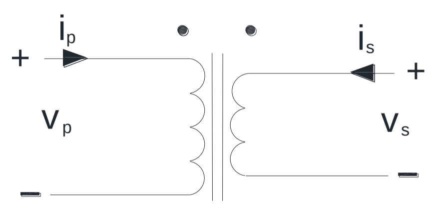


FIGURE 2
SCHEMATIC DIAGRAM
IDEAL TRANSFORMER

The basic components of a transformer are the core, the primary winding N_1 and the secondary winding N_2. The common flux is shown as Φ. Transformer cores can take different shapes, as long as they provide a closed loop for the flux to travel through. In Figure 2, the two dots indicate the polarity of the windings. In this case the two windings are in the same direction so the output is in phase with the input and there is no “phase shift”.

Faraday’s Law of Electromagnetic Induction describes the electrical action that takes place in the transformer. Accordingly, the time varying current i_1 in the primary winding produces a time varying flux which is linked via the core to a secondary coil and induces an emf (electro-motive force or, the term we will use, voltage) in it. Thus, referring to Fig-1, if Ø is the flux linking the N_1 winding, then its induced voltage is given by:

$$V_p = N_p \frac{d\text{Ø}}{dt}$$

or
$$\frac{d\text{Ø}}{dt} = \frac{Vp}{Np} \tag{1}$$

Similarly,

$$\frac{d\text{Ø}}{dt} = \frac{Vs}{Ns} \tag{2}$$

Since the same flux passes by both the primary and secondary windings, we can combine (1) and (2)

$$\frac{Vp}{Np} = \frac{Vs}{Ns} \tag{3}$$

or

$$\frac{Vp}{VS} = \frac{Np}{NS} = \mathbf{a} \tag{4}$$

The number of turns in the primary coil divided by the number of turns in the secondary coil is defined as the “turns ratio” and we will represented it by the letter **a.**

In an ideal transformer power in = power out, thus:

$$P_1 = P_2 \tag{5}$$

or

$$V_p\, i_p = V_s \tag{6}$$

or

$$\frac{Vp}{Vs} = \frac{Np}{Ns} = \frac{is}{ip} = \mathbf{a} \tag{7}$$

Thus, the turns ratio times the primary current i_1 equals the secondary current i_2. If the primary voltage and the turns ratio are known then the secondary voltage is easily determined by dividing the primary voltage by the turns ratio. For example, if the primary winding has 1000 turns and is connected to 600 volts and the secondary has 250 turns, then employing equation 4, the turns ratio is:

$$\mathbf{a} = \frac{N1}{N2} = \frac{1000}{250} = 4$$

and the secondary voltage would be:

$$V_s = \frac{Vp}{a} = \frac{600}{4} = 150 \text{ volts}$$

In a similar example, using the same transformer above, if the load has a resistance of 4Ω**,** then the current flow in the secondary would be:

$$\frac{150V}{4\Omega} = 37.5 \text{ A.}$$

To find the primary current, use equation 7 by employing the turns ratio.

$$37.5 \text{ A} \times \frac{250}{1000} = 9.375$$

Another way of looking at this is Power in = Power out. In this case

600 V x 9.375 A = 150 V x 37.5 A = 5625 watts

A transformer permits voltage to be stepped up or down. A practical example of this is the voltage in power transmission lines. The voltage in a transmission line is stepped up thus requiring less current to be carried by the lines. Remember, the power equals the voltage times the current. If the voltage increases, then to produce the same power, the current will decrease. The smaller currents produce less i^2 R losses and allow for smaller wires in the transmission lines thus reducing the material cost. The voltage is then stepped down when it arrives at the load.

2. TRANSFORMER LOSSES

In the previous section we considered an ideal transformer, which is assumed to have no losses. Transformers actually have the following losses:

A. Iron Losses

a. Core loss (hysteresis)

The repeated magnetization and demagnetization of the core produces a loss because of the repeat alignment of the magnetic domains. This loss, known as hysteresis, is directly proportional to the frequency. The quality of the iron in the core can minimize hysteresis loss.

b. Core loss (eddy current)

The changing magnetic field also induces circulating currents or eddy currents in the core material. To minimize eddy current loss, the core is constructed of laminations or layers rather than a solid material. These layers are then clamped or bonded together.

B. Copper Losses

These losses are a direct result of providing power to the load and they will vary with the current drawn by the load. These losses are the i^2 R losses in the primary and secondary windings.

The equivalent schematic shown in figure 3 can be used to represent the losses involved.

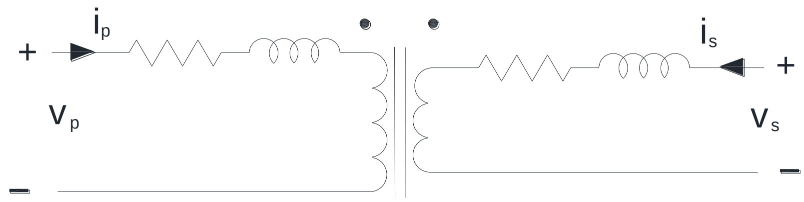


FIGURE 3
EQUIVALENT SCHEMATIC OF A TRANSFORMER

3. EFFICIENCY

The efficiency of transformers is $\frac{\text{power out}}{\text{power in}}$. Since the input = the output + losses then the efficiency can be evaluated as $\frac{\text{power in} - \text{losses}}{\text{power in}}$. It then follows that, If the core and i^2R losses at a given load are known, their values can be used to calculate the efficiency. Efficiency is seriously affected by either over- or under-loading. When overloaded, the efficiency falls off because the copper losses increase as the square of the load current (i^2R). When under loaded the efficiency is poor because of the constant iron loss. The best efficiency occurs when the copper losses equal the iron losses, and this generally occurs approximately at ¾ of full load. Transformers that operate at this level may experience efficiencies in the high 90% range.

4. INSULATION FATIGUE

The AC voltage applied to the e_1 terminals of the transformer alternates based on its frequency. As the voltage changes the magnetism in the core changes proportionately. With this change comes an expansion and contraction of the ferrous material in the transformer. This phenomenon is referred to as magnetostriction. This in turn causes the transformer to vibrate, which produces a hum. In order to mitigate this movement the wire and the core of the transformer are covered with an insulating material such as varnish. This also bonds the components together restricting any movement. While this vibratory movement is small, it can over time cause wear on the insulation of the windings and fatigue to other components which in turn can result in failure of the transformer.

5. POWER FACTOR

Power factor (PF) is the ratio between true power in watts (w) and apparent power in volt-amps (VA).

$$pf = \frac{w}{va} \qquad (8)$$

Resistive loads only produce watts. Not all electrical loads are purely resistive. Some circuits contain components that store electrical energy such as capacitors and inductors. These loads that store energy produce vars. Since a transformer winding has the same properties as an inductor, a portion of the transformer's electrical energy will be considered true power, and a portion will be unusable power (or vars) and for this reason, the apparent power must be considered for calculations. The relationship between watts, vars and VA is given by:

$$va^2 = watts^2 + vars^2 \qquad (9)$$

See the figure below for a graphic representation.

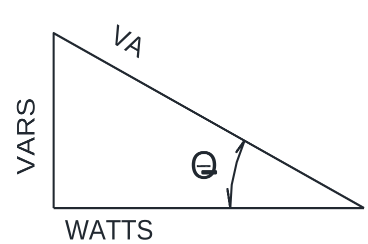


FIGURE 4
RELATIONSHIP WATTS to VARS

6. POWER FACTOR CORRECTION

Unlike the response of voltage due to current across a resistor given by V = iR, an inductor's voltage is given by the equation $V = L\frac{di}{dt}$. A transformer, by the very nature of its windings, will have the same electrical properties as an inductive load. This will cause the current to lag the voltage. Or, we can say the power factor is lagging. This inductive current or lagging current is unusable energy and is not contributing to the watts portion of the load. However, the transformer windings must be able to handle the current associated with the VA, which includes that portion of the unused electrical power, referred to as vars.

Based upon the relationship between watts and vars, as θ approaches 0, the power factor (pf) approaches 1.

$$\text{pf} = \frac{\text{watts}}{\text{VA}} = \text{Cos}\,\theta \tag{10}$$

In order to increase power factor in a transformer the quantity of vars must be reduced. Therefore, a device where the voltage lags the current (the power factor is leading) must be employed. This would be a capacitor.

Example:

A 480v single phase transformer has a pf of 55% and a 5500 watt load. In order to correct it's pf to 95% how many vars must a capacitor contribute?

A graphic representation of the correction process is shown in Figure 5. Notice that the value for watts remains constant. First determine VA for existing system:

VA = watts / pf =5500 / .55 = 10000

Since watts will remain the same we can then determine the VA for required

VA = watts / pf =5500 / .95 = 5789

Next, determine vars (existing and required):

Vars = (va2 – watts2)$^{1/2}$ = (10000 ^{2} – 5500 ^{2})$^{1/2}$ = 8352 existing

Vars = (va2 – watts2)$^{1/2}$ = (5789 ^{2} -5500 ^{2})$^{1/2}$ = 1809 required

Vars (req) = Vars (existing) + correction Vars (x)

x = Vars (reg) - Var (existing)

x = 1809 - 8352 = -6543 vars

The negative sign indicates vars that oppose the inductive

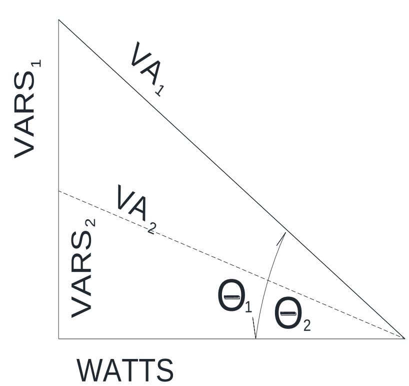


FIGURE 5
GRAPHIC REPRESENTATION

7. K FACTOR

K-Factor rated transformers are transformers designed to operate with specific levels of non-linear loading without de-rating. These transformers do not reduce the harmonics, but they are designed with oversized windings and neutrals that can handle the harmonic currents. And they have better ventilation to more effectively dissipate the harmonic heating effects. In addition, K-Factor transformers have an electrostatic shield to attenuate transient noise.

As shown in the chart below, a transformer's K-Factor is a measure of its ability to operate with non-linear loads without de-rating. Therefore, the K-Factor needed for a specific application depends on the extent to which non-linear loads are employed. Because the cost of manufacturing a transformer increases with the K-Factor, transformers with different K-Factors are available. The most common ratings for K-Factor transformers are K-4, K-13, K-20, and K-30.

K4	linear load 100%	Non-linear 50%	K-factor 4
K13	linear load 100	Non-linear 100%	K-factor 13
K20	linear load 100	Non-linear 125%	K-factor 20
K30	linear load 100	Non-linear 150%	K-factor 30

8. THREE PHASE TRANSFORMER CONSIDERATIONS

For power applications, single phase transformers are inefficient and unsatisfactory. The use of three conductors in a three phase system can provide 173% ($\sqrt{3}$) more power than the two conductors of a single phase system.

A three phase transformer is essentially three single phase transformers built on one magnetic circuit. A three phase transformer has three flux paths. As a result of the three phase relationship, each of the fluxes in these paths is displaced 120^0 from the each other. The three phase transformer has three similar primary and secondary windings.

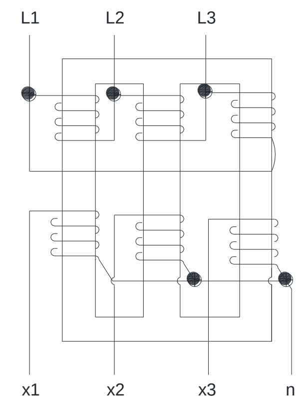


FIGURE 6

THREE PHASE TRANSFORMER

The transformer shown in figure 6 has its primary winds in a delta connection and the secondary windings in a wye connection. The transformer in figure 6 can also be shown as in figure 7.

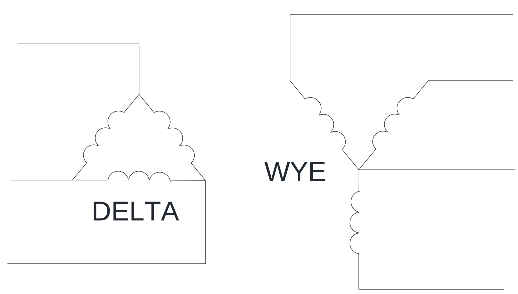


FIGURE 7

TRANSFORMER CONFIGURATIONS

The transformer shown in figure 7 can also be drawn as shown in figure 8.

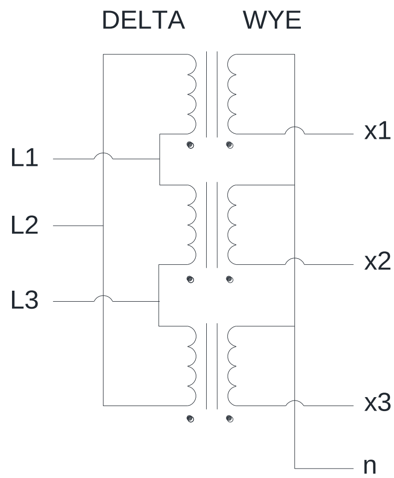


FIGURE 8
TRANSFORMER CONFIGURATIONS

The four possible combinations of transformer windings are:

Wye to wye connection
Wye to delta connection
Delta to delta connection
Delta to wye connection

The wye on the primary side has a disadvantage of unbalanced loads that cannot be effectively carried to the secondary. High Voltage transmission lines are the most common application of wye to wye connections.

The delta to delta connection is most commonly used in step up or step down transmission lines.

For distribution service where a four wire secondary distribution circuit is desired, the delta to wye is the most popular connection.

In a wye connection phase amps = line amps, line volts = phase volts x 1.73

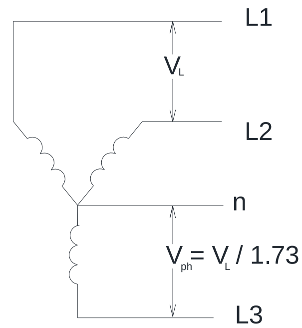


FIGURE 9

V_L & V_P SHOWN IN A WYE CONNECTION

In a delta connection line amps = phase amps x 1.73 and phase volts = line volts

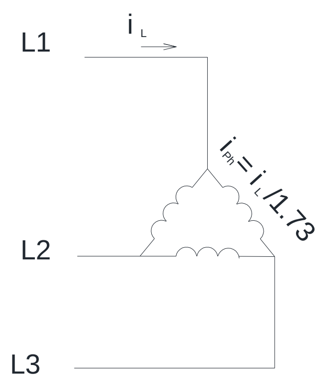


FIGURE 10

i_L & i_P SHOWN IN A DELTA CONNECTION

Calculating the KVA of a three phase Transformer

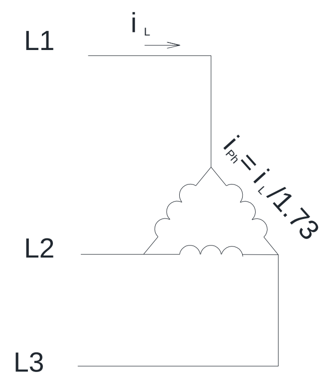
Calculating the KVA of a Delta Transformer

KVA per phase = Vp ip

$= V_L \ x \ i_L / \sqrt{3}$

for 3 phases $= 3(V_L \ x \ i_L)/\sqrt{3}$

$= (V_L \ x \ i_L) \sqrt{3}$



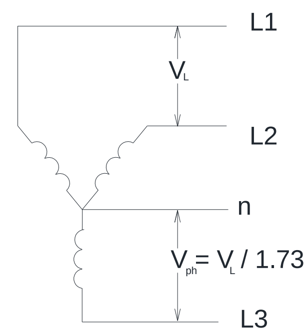
Calculating the KVA of a Y- Transformer

KVA per phase = Vp x ip

$= i_L \times V_L / \sqrt{3}$

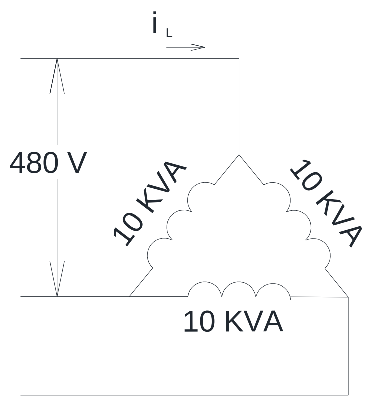
for 3 phases $= 3(V_L \times i_L)/\sqrt{3}$

$= (V_L \times i_L)\sqrt{3}$



Example 1:

The primaries of three 10 KVA transformers are connected in a delta configuration as shown below. The primary line voltage is 480v.



EXAMPLE 1

A. What is the primary phase current?

In a delta connection, the phase voltage = the line voltage. Therefore, the primary phase voltage is 480v. The phase volt-amps would be 10,000 VA. To find the phase current,

I = VA / V = 10000 / 480 = 20.83 A

B. What is the primary line current?

In a delta connection the line current equals the phase current x 1.73

20.83 x 1.73 = 36.04 A

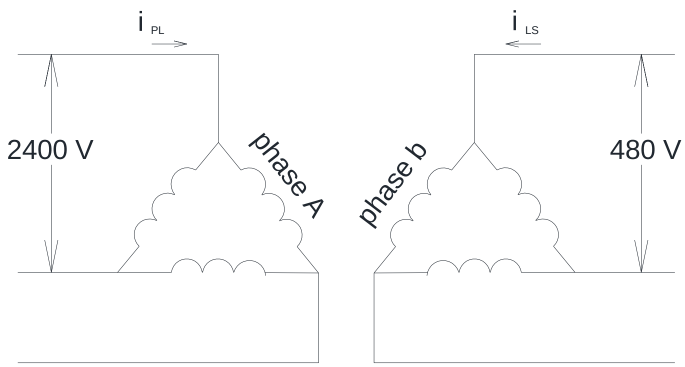
The total power is 3 x 10 KVA = 30 KVA.

Checking by phase current: 20.83 A x 480v = 10,000 VA per phase.

Checking by line current = 36.04 A x 480v x 1.73 = 30,000 VA or 30 KVA

Example 2:

A three phase 2400/480v transformer is connected delta – delta. The secondary line voltage is 480 and the secondary line current is 150 A.



EXAMPLE 2

1. What is the secondary phase current?

In a delta connection phase amps = line amps / 1.73 = 150 / 1.73 = 86.7 A

2. What is the primary line current?

$a = V_p/V_s$ = 2400/480 = 5

primary line current = secondary line current/a = 150/5 = 30 A

3. What is the primary phase current?

The primary phase current = secondary phase current / turns ratio (ref equation 7)

= 86.7 / 5 = 17.3 A

or

primary phase current = primary line current/1.73 = 30/1.73 = 17.3 A

4. What is the kva load on the transformer?

To find the kva load on a 3 phase transformer: 480v x 150 A x 1.73 = 124560 va or 124.5 KVA

9. PHASE DISPLACEMENT

In a three phase transformer when the connections are "Y to Y" or "Δ to Δ", the secondary will
be in phase with the primary. However, there are times when a phase shift is desired. A "Δ to Y" or a "Y to Δ" will produce a 30^o phase shift in the secondary.

Transformer manufacturers use a notation to describe phase shifts. The first symbol, either a Y or a D (for delta), is in capital letters and denotes the primary. The second symbol denotes the secondary and is in a lower case. If a "y" is specified then an "n" may follow denoting a neutral. The next indicator is a number. With reference to the minute hand on a clock, a 1 would denote a 30^0 lag where as an 11 would denote a 30^0 lead. Similarly, a Dd2 would denote a 60^0 lag where as a Dd10 would denote a 60^0 lead.

10. TRANSFORMER PARAMETERS

A. TRANSFORMER REGULATION

Transformer regulation is a measurement of how a transformer will perform under load.

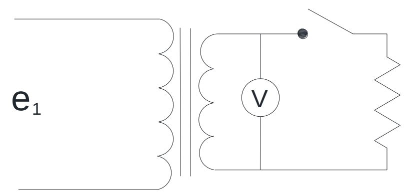


FIGURE 11
TRANSFORMER REGULATION

Measure V_L (with load)
Measure V_{NL} (with no load)

% regulation = 100% $(V_{NL} - V_L) / V_{NL}$

B. % IMPEDANCE

The Z% of a transformer is a crucial parameter when determining the fault current.

The impedance of a transformer can be measured by means of a short circuit test. The secondary of the transformer is shorted. The voltage on the primary is gradually increased from zero until the secondary current reaches its rated value.

Z% = 100% x impedance voltage / rated voltage

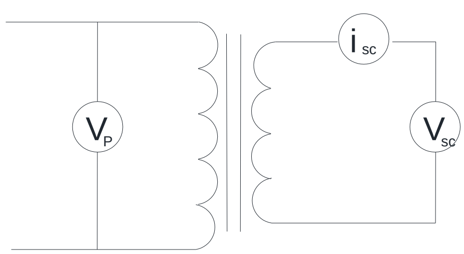
$Z\% = V_{s\text{-}sc} / V_p$

Measure secondary short circuit voltage $V_{s\text{-}sc}$ V_p = rated voltage at primary

Thus a transformer with a primary rating of 600V which requires a voltage of 30V to circulate the rated current in the shorted secondary would have an impedance of Z% = 30/600 = 5%.

C. SHORT CIRCUIT CALCULATIONS

Short circuit calculations are important because they measure the amount of short circuit current that is available. This information is essential to properly size downstream equipment.



$Z\% = Vs\text{-}sc / Vp$ $I_{s\text{-}sc} = 100\%\ I_s / Z\%$ $Z\% = V_s / I_{S\text{-}SC} = V_{S\text{-}SC} / I_S$

FIGURE 12
TRANSFORMER SHORT CIRCUIT

11. TRANSFORMER CIRCUIT PROTECTION

Article 450 of the National Electric Code (NEC, also known as NFPA 70 which is a publication of the National Fire Protection Association) addresses the issue for circuit protection. The main considerations to be aware of are: primary protection, secondary protection and grounding protection.

In all cases, primary circuit protection is required. There are only a few cases where secondary circuit protection is not required due to either the intrinsic properties of the transformer or the strategic primary protection that also protects the secondary. Depending on the application, the NEC will specify the required grounding protection.

12. CLEARENCES

Clearances for transformers basically follow the same rules as those for switchgear and are dictated by the voltage level and personnel accessibility to live parts. A certain amount of free space should be provided around the transformer to allow air movement. The exact clearance dimensions should be in agreement with the pertinent regulatory body. The NEC addresses transformers that are mounted inside control panels as well as transformers that are "stand alone." Generally speaking, clearances are determined by voltage levels and proximity of live parts of the transformer to other components.

13. THERMAL CONSIDERATIONS

As discussed in section 2, transformers have losses. These losses produce heat which is a consideration for the transformer manufacturer. There are two temperature considerations: ambient temperature and temperature rise.

Ambient temperature is normally given as 40^{o} C. Temperature rise is proportional to the sum of the losses (eddy current, hysteresis and i^2R losses) divided by the surface area of the transformer. NEMA has established values for different classes of temperature rise as shown in the following chart. The basic difference between insulation classes is the type of material used for insulation.

NEMA code	Insulation class	temp rise ºC
A	105	55
B	130/150	80
F	180	115
H	220	150

TABLE 1

Insulation class table

14. TRANSFORMER DATA SHEET

The following is information you may expect to see on a transformer data sheet:

DESIGN CRITERIA		Examples
KVA rating	HV / LV1 / LV2	5000 / 2500 / 2500
Pri voltage		10,000
Sec voltage 1	Taps (# and %)	600/ 2x2.5%
Sec voltage 2	Taps (# and %)	600/ 2x2.5%
Freq		60
# of phases		3
type		dry type / fan cooled
Vector group		Dyn11d0
K-factor		K4
Temperature class		F
Efficiency	full load,	manufacturer to advise
	75%	manufacturer to advise
	50%	manufacturer to advise
	25%	manufacturer to advise
wiring		copper
insulation material		manufacturer's std
LOCATION		
Indoor or Outdoor		indoor
Coastal / Offshore		no
Cooling		no
Ambient	temp (min / max)	0 - 35 deg C
Altitude		<1000 m
ENCLOSURE		
NEMA / IP rating		IP 23
Area classification / non hazardous		non hazard
Dimensions		3100 l x 2200 w x 3500 h (mm)
Weight		13000 kg
Methods of lifting		lifting eyes
Methods of mounting		mounting rails
Paint spec		ANSI 61 light gray