Chapter 12

Three-Phase Transformer Design

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Introduction

Three-phase power is used almost exclusively for generation, transmission, and distribution, as well as for all industrial uses. It is also used on aircraft, both commercial and military. It has many advantages over single-phase power. The transformer can be made smaller and lighter for the same power handling capability, because the copper and iron are used more effectively. In circuitry, for conversion from ac to dc, the output contains a much lower ripple amplitude, and a higher frequency component, which is 3 times and 6 times the line frequency, and which, in turn, requires less filtering.

Primary Circuit

The two most commonly used primary circuits for three-phase transformers are the Star, or Y connection, as shown in Figure 12-1, and the other being known as the Delta (Δ) connection, as shown in Figure 12-2. The design requirement for each particular job dictates which method of connection will be used.

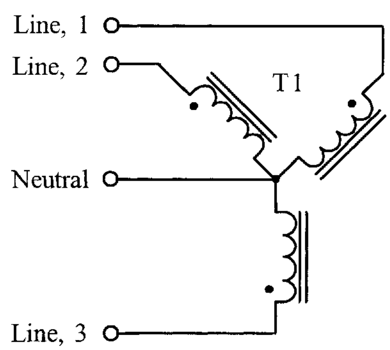

Figure 12-1. Three-Phase Transformer, Connected in Star.

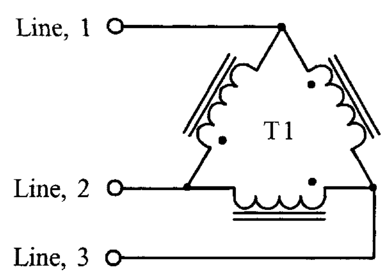

Figure 12-2. Three-Phase Transformer, Connected in Delta.

Comparing Transformer, Physical Size

The schematic diagram in Figure 12-3, shows the connection of three single-phase transformers: (a) Operating from a three-phase power source and a single three-phase transformer; and (b) Operating from a three-phase power source connected in a delta-delta configuration. The single three-phase transformer, T4, would be lighter and smaller than a bank of three single-phase transformers of the same total rating. Since the windings of the three-phase transformer are placed on a common magnetic core, rather than on three independent cores, the consolidation results in an appreciable saving in the copper, the core, and the insulating materials.

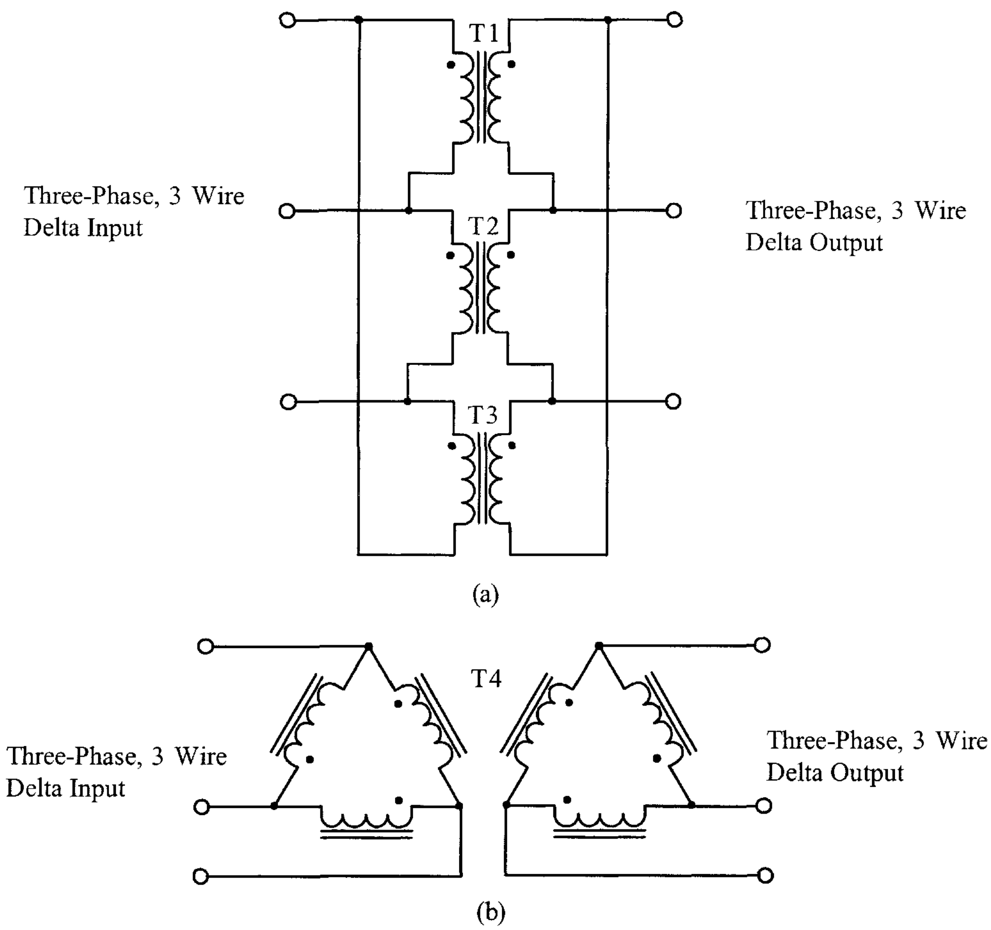

Figure 12-3. Comparing Three Single-Phase Transformers Connected in Three-Phase Delta.

A cutaway view of a single-phase transformer, showing the window area and iron area of two types of core configuration, is shown in Figure 12-4 and Figure 12-5. The EI lamination, shown in Figure 12-4, is known as a shell type, because it looks like the core surrounds the coil. The C core, shown in Figure 12-5, is known as a core type, because it looks like the coil surrounds the core.

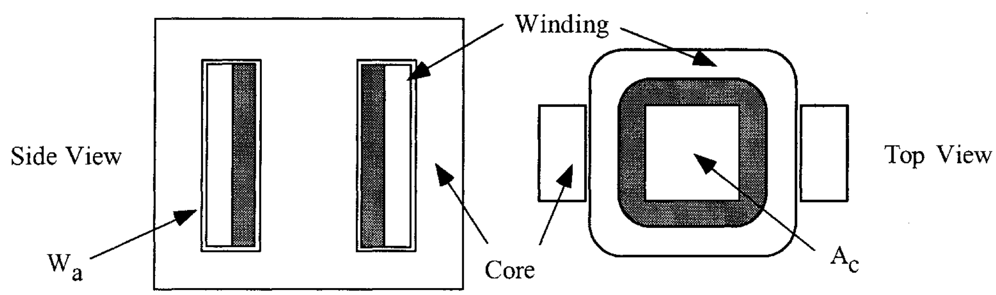

Figure 12-4. Illustrating a Shell Type Transformer.

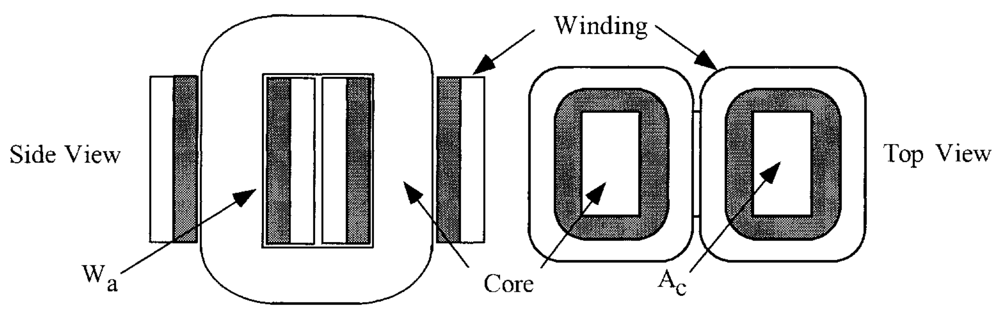

Figure 12-5. Illustrating a Core Type Transformer.

Cutaway views of a three-phase transformer are shown in Figure 12-6. These cross-sectional views show the window and iron areas. The three-legged core is designed to take advantage of the fact that, with balanced voltages impressed, the flux in each phase leg, adds up to zero. Therefore, no return leg is needed under normal conditions. When the transformer is subjected to unbalanced loads, or unbalanced line voltages, it may be best to use three single-phase transformers, because of the high-circulating currents.

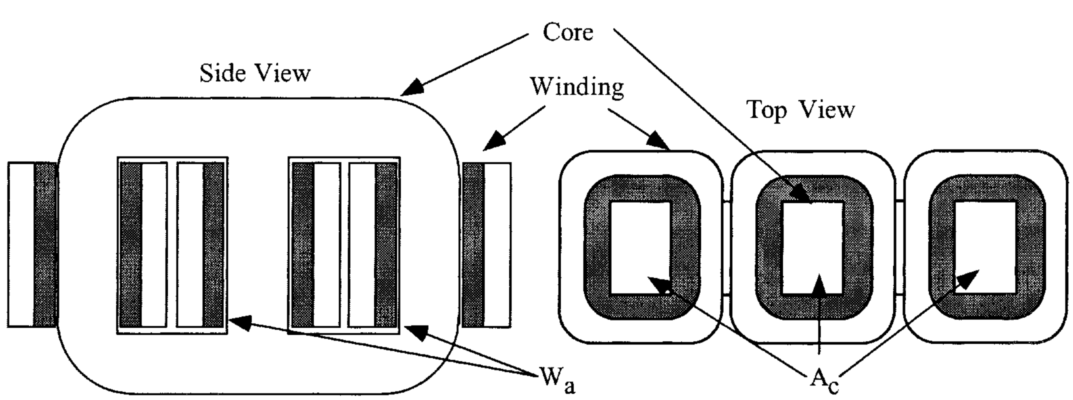

Figure 12-6. Cutaway View of a Three-Phase Transformer.

Phase Current, Line Current, and Voltage in a Delta System

In a Three-Phase Delta Circuit, such as the one shown in Figure 12-7, the line voltage and line current are commonly called phase voltage and phase current. The line voltage, $E_{(Line)}$, will be the same as the actual winding voltage of the transformer. However, the line current, $I_{(Line)}$, is equal to the phase current, $I_{(Phase)}$, times the square root of 3.

$$I_{(line)} = I_{(phase)}\sqrt{3}, \quad \text{[amps]} \quad [12\text{-}1]$$

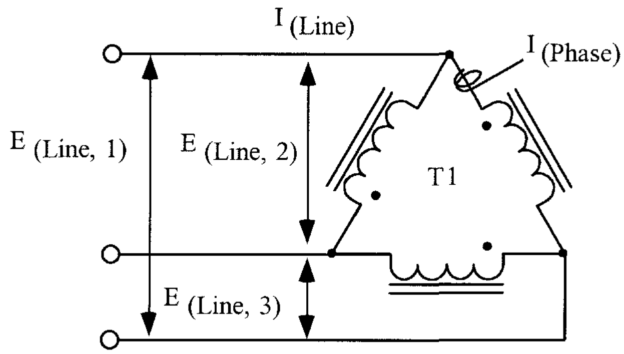

Figure 12-7. Voltage and Current Relationship of a Three-Phase Delta Circuit.

Phase Voltage, Line Voltage, and Current in a Wye System

The relationship between the Line voltage, and Line current, and the winding, or Phase voltage and Phase current, in a Three-Phase Wye Circuit can be seen in Figure 12-8. In a Wye System, the voltage between any two wires in the line will always be the square root of three times the phase voltage, $E_{(Phase)}$, between the neutral, and any one of the lines.

$$E_{(phase)} = \frac{E_{(line)}}{\sqrt{3}}, \quad \text{[volts]} \quad [12\text{-}2]$$

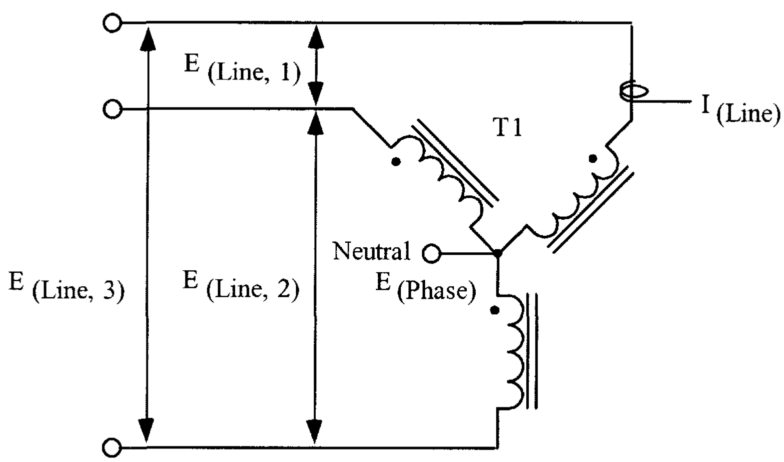

Figure 12-8. Voltage and Current Relationship for a Three-Phase Wye Circuit.

Comparing Multiphase and Single-Phase Power

Three-phase power distribution has a significant advantage over the single-phase. Most high power equipment and industrial complexes will use three-phase power. One of the biggest advantages in using three-phase power distribution has to do with smaller magnetic components handling the same power as single-phase. This can be seen in aircraft, and shipboard equipment, as well as fixed ground installations. One of the basic reasons for selecting three-phase is the transformer size. Another reason is, if dc is a requirement, the capacitor and inductor filtering components are both smaller. The odd shape of a three-phase transformer could be troublesome, as well as keeping balanced loads to minimize circulating currents.

The single-phase, full wave bridge circuit is shown in Figure 12-9. The ripple voltage frequency is always twice the line frequency. Only 50% of the total current flows through each rectifier. The three-phase, Delta full wave bridge circuit is shown in Figure 12-10. The ripple voltage frequency is always 6 times the line frequency. Only 33% of the total current flows through each rectifier. Looking at the ripple in Figure 12-10, it is obvious the LC components will be smaller.

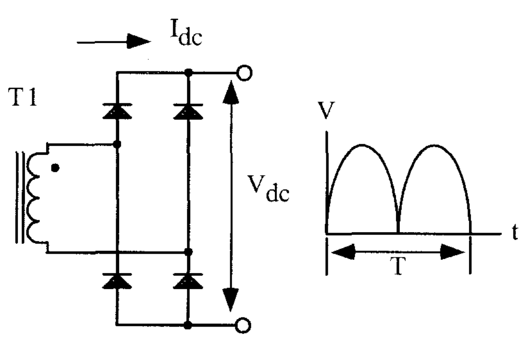

Figure 12-9. Single-Phase Full Wave Bridge.

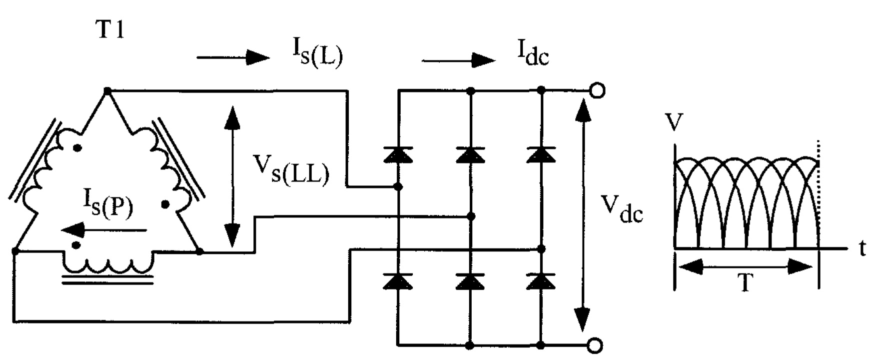

Figure 12-10. Three-Phase, "Delta" Full Wave Bridge.

Multiphase Rectifier Circuits

Table 12-1 lists voltage and current ratios for the circuits, shown in Figures 12-11 through Figures 12-14 for inductive output filters. These ratios apply for sinusoidal ac input voltages. Values shown do not take into consideration voltage drops which occur in the power transformer or rectifier diodes.

Table 12-1. Three-Phase Voltage and Current Ratios for Rectifier Circuits.

Three Phase Rectifier Circuit Data			
Delta-Delta Full Wave, Figure 12-11			
Item	Factor		
Primary VA	1.050	x	dc watts output
Secondary V/ leg	0.740	x	average dc output voltage
Secondary I/leg	0.471	x	average dc output current
Secondary VA	1.050	x	dc watts output
Ripple Voltage %	4.200		
Ripple Frequency	6f		
Delta-Wye Full Wave, Figure 12-12			
Item	Factor		
Primary VA	1.050	x	dc watts output
Secondary Line to Line	0.740	x	average dc output voltage
Secondary V/ leg	0.428 to Neutral	x	average dc output voltage
Secondary I/leg	0.817	x	average dc output current
Secondary VA	1.050	x	dc watts output
Ripple Voltage %	4.200		
Ripple Frequency	6f		
Delta-Wye Half Wave, Figure 12-13			
Item	Factor		
Primary VA	1.210	x	dc watts output
Secondary Line to Line	0.740	x	average dc output voltage
Secondary V/ leg	0.855 to Neutral	x	average dc output voltage
Secondary I/leg	0.577	x	average dc output current
Secondary VA	1.480	x	dc watts output
Ripple Voltage %	18.000		
Ripple Frequency	3f		
Delta-Wye 6 Phase Half Wave, Figure 12-14			
Item	Factor		
Primary VA	1.280	x	dc watts output
Secondary Line to Line	1.480	x	average dc output voltage
Secondary V/ leg	0.740 to Neutral	x	average dc output voltage
Secondary I/leg	0.408	x	average dc output current
Secondary VA	1.810	x	dc watts output
Ripple Voltage %	4.200		
Ripple Frequency	6f		
Root mean square values to the average dc.			
Sine-wave , infinite inductance, no transformer or rectifier losses.			

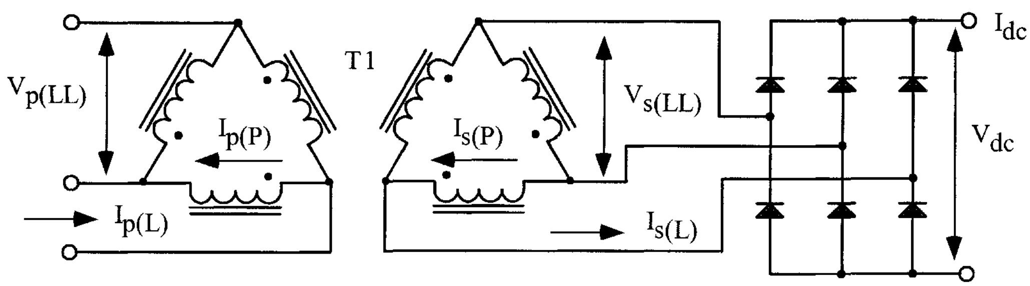

Figure 12-11. Three-Phase, "Delta-Delta" Full Wave Bridge.

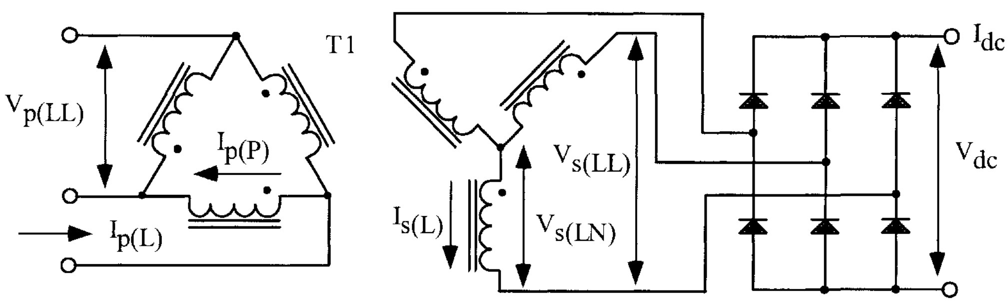

Figure 12-12. Three-Phase, "Delta-Wye" Full Wave Circuit.

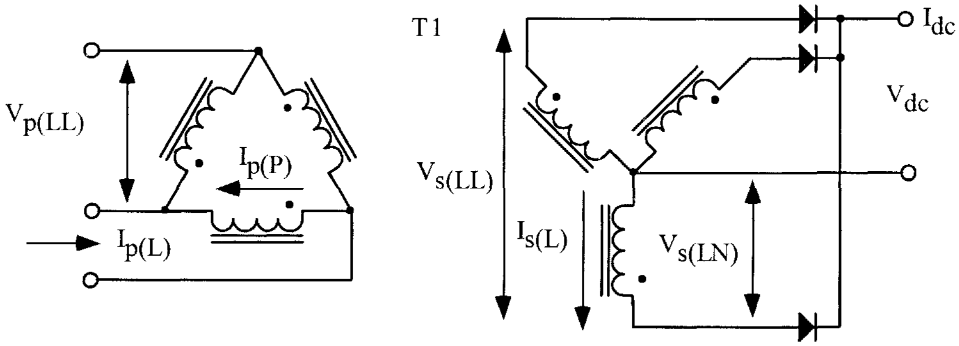

Figure 12-13. Three-Phase, "Delta-Wye" Half Wave Bridge.

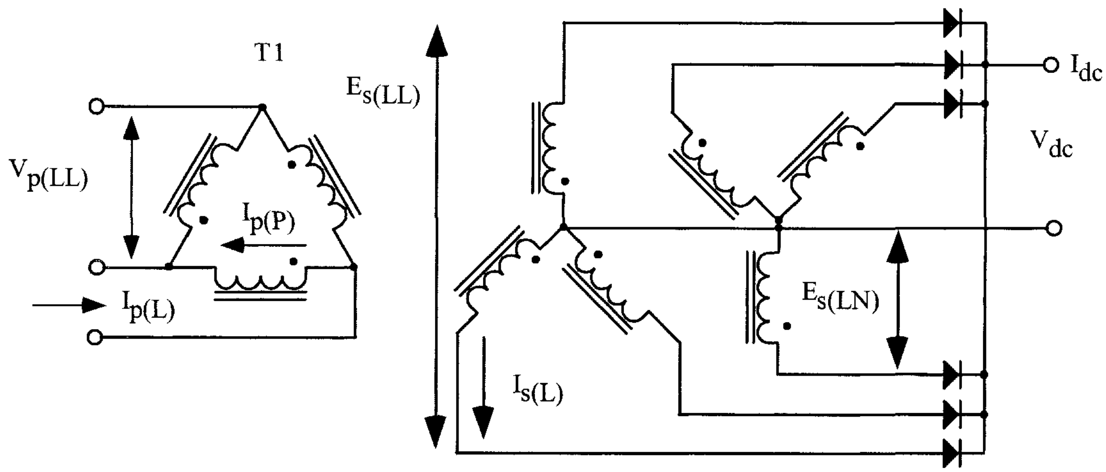

Figure 12-14. Three-Phase, "Delta-Wye" Six Phase Star.

Area Product, A_p, and Core Geometry, K_g, for Three-Phase Transformers

The area product, A_p, of a three-phase core is defined differently than that for a single-phase core. The window area, W_a, and iron area, A_c, for a single-phase transformer is shown in Figure 12-4 and 12-5. The window area, W_a, and iron area, A_c, for a three-phase transformer is shown in Figure 12-6. The area product, A_p, of a core is the product of the available window area, W_a, of the core in square centimeters (cm^2) multiplied by the effective, cross-section area, A_c, in square centimeters (cm^2), which may be stated as:

$$\text{Single-phase: } A_p = W_a A_c, \quad [\text{cm}^4] \quad [12\text{-}3]$$

This is alright for a single-phase transformer. For three-phase transformers, because there are basically two windows area, W_a, and three iron areas A_c, the window utilization is different, and the area product, A_p, changes to:

$$\text{Three-phase: } A_p = 3\left(\frac{W_a}{2} A_c\right), \quad [\text{cm}^4] \quad [12\text{-}4]$$

This reduces to:

$$A_p = 1.5\left(W_a A_c\right), \quad [\text{cm}^4] \quad [12\text{-}5]$$

It is basically the same thing for the core geometry, K_g, for a single-phase transformer and the core geometry, K_g, for a three-phase transformer. The core geometry, K_g, for a single-phase transformer is:

$$\text{Single-phase: } K_g = \left(\frac{W_a A_c^2 K_u}{\text{MLT}}\right), \quad [\text{cm}^5] \quad [12\text{-}6]$$

In the three-phase transformer, core geometry, K_g, is:

$$\text{Three-phase: } K_g = 3\left(\left(\frac{W_a}{2}\right)\frac{A_c^2 K_u}{\text{MLT}}\right), \quad [\text{cm}^5] \quad [12\text{-}7]$$

This reduces to:

$$K_g = 1.5\left(\frac{W_a A_c^2 K_u}{\text{MLT}}\right), \quad [\text{cm}^5] \quad [12\text{-}8]$$

Output Power Versus Apparent Power, P_t, Capability

The apparent power, P_t, is described in detail in Chapter 7. The apparent power, P_t, of a transformer is the combined power of the primary and secondary windings which handle, P_{in} and P_o, to the load, respectively. Since the power transformer has to be designed to accommodate the primary, P_{in}, and the secondary, P_o:

$$P_t = P_{in} + P_o, \quad \text{[watts]} \quad [12\text{-}9]$$

$$P_{in} = \frac{P_o}{\eta}, \quad \text{[watts]} \quad [12\text{-}10]$$

Substituting:

$$P_t = \frac{P_o}{\eta} + P_o, \quad \text{[watts]} \quad [12\text{-}11]$$

$$P_t = P_o\left(\frac{1}{\eta} + 1\right), \quad \text{[watts]} \quad [12\text{-}12]$$

The designer must be concerned with the apparent power handling capability, P_t, of the transformer core and winding. The apparent power, P_t, varies with the type of circuit in which the transformer is used. If the current in the rectifier is interrupted, its effective rms value changes. Transformer size is thus determined, not only by the load demand, but also by current wave shape. An example of the primary and secondary, VA, will be done to compare the power-handling capability required by each three-phase rectifier circuit in Table 12-1 and Figures 12-11 through 12-14. This comparison will negate transformer and diode losses so that $P_{in} = P_o$ ($\eta = 1$) for all three-phase rectifier circuits.

1. Delta-Delta, Full Wave, Figure 12-11.

$$P_t = P_o\left(\frac{P_{VA}}{\eta} + S_{VA}\right), \quad \text{[watts]}$$

$$P_t = P_o\left(\frac{1.05}{1} + 1.05\right), \quad \text{[watts]} \quad [12\text{-}13]$$

$$P_t = P_o(2.1), \quad \text{[watts]}$$

2. Delta-Wye, Full Wave, Figure 12-12.

$$P_t = P_o\left(\frac{P_{VA}}{\eta} + S_{VA}\right), \quad \text{[watts]}$$

$$P_t = P_o\left(\frac{1.05}{1} + 1.05\right), \quad \text{[watts]} \quad [12\text{-}14]$$

$$P_t = P_o(2.1), \quad \text{[watts]}$$

3. Delta-Wye, Half Wave, Figure 12-13.

$$P_t = P_o\left(\frac{P_{VA}}{\eta} + S_{VA}\right), \quad \text{[watts]}$$

$$P_t = P_o\left(\frac{1.21}{1} + 1.48\right), \quad \text{[watts]} \quad [12\text{-}15]$$

$$P_t = P_o(2.69), \quad \text{[watts]}$$

4. Delta-Wye, 6 Phase Half Wave, Figure 12-14.

$$P_t = P_o\left(\frac{P_{VA}}{\eta} + S_{VA}\right), \quad \text{[watts]}$$

$$P_t = P_o\left(\frac{1.28}{1} + 1.81\right), \quad \text{[watts]} \quad [12\text{-}16]$$

$$P_t = P_o(3.09), \quad \text{[watts]}$$

Relationship, K_g, to Power Transformer Regulation Capability

Although most transformers are designed for a given temperature rise, they can also be designed for a given regulation. The regulation and power-handling ability of a core are related to two constants:

$$\alpha = \frac{P_t}{2K_g K_e}, \quad [\%] \quad [12\text{-}17]$$

$$\alpha = \text{Regulation } (\%) \quad [12\text{-}18]$$

The constant, K_g, is determined by the core geometry, which may be related by the following equations:

$$K_g = 1.5\left(\frac{W_a A_c^2 K_u}{\text{MLT}}\right) = \frac{P_t}{2K_e\alpha}, \quad [\text{cm}^5] \quad [12\text{-}19]$$

The constant, K_e, is determined by the magnetic and electric operating conditions, which may be related by the following equation:

$$K_e = 2.86 f^2 B^2 \left(10^{-4}\right) \quad [12\text{-}20]$$

From the above, it can be seen that factors such as flux density, frequency of operation, and waveform coefficient, have an influence on the transformer size.

Relationship, A_p, to Transformer Power Handling Capability

According to the newly developed approach, the power handling capability of a core is related to its area product, A_p, by an equation which may be stated as:

$$A_p = \frac{P_t(10^4)}{K_f K_u B_m J f}, \quad [\text{cm}^4] \qquad [12\text{-}21]$$

$$A_p = 1.5(W_a A_c) = \frac{P_t(10^4)}{K_f K_u B_m J f}, \quad [\text{cm}^4] \qquad [12\text{-}22]$$

Where:

$K_f =$ waveform coefficient

$K_f = 4.0$ square wave

$K_f = 4.44$ sine wave

From the above, it can be seen that factors such as flux density, frequency of operation, and window utilization factor, K_u, define the maximum space, which may be occupied by the copper in the window.

Three-Phase Transformer, Design Example

The following information is the Design specification for a three-phase, isolation transformer, using the, K_g, core geometry approach.

Design specification:

1. Input voltage, V_{in} .... 208 V, 3 Wire
2. Output voltage, V_o .... 28 V
3. Output Current, I_o .... 10 amps
4. Output Circuit .... Full Bridge
5. Input / Output .... Delta / Delta
6. Frequency, Three Phase, f .... 60 hertz
7. Efficiency, $\eta(100)$ .... 95 %
8. Regulation, α .... 5 %
9. Flux Density, B_{ac} .... 1.4 tesla
10. Magnetic Material .... Silicon M6X
11. Window Utilization $K_u = (K_{up} + K_{us})$ 0.4
12. Diode Drop, V_d .... 1.0 volt

Step No. 1 Calculate the apparent power, P_t.

$$P_t = P_o\left(\frac{1.05}{\eta}+1.05\right), \quad \text{[watts]}$$

$$P_o = I_o\left(V_o+2V_d\right)=(10)(30)=300, \quad \text{[watts]}$$

$$P_t = 300\left(\frac{1.05}{0.95}+1.05\right), \quad \text{[watts]}$$

$$P_t = 647, \quad \text{[watts]}$$

Step No. 2 Calculate the electrical conditions, K_e.

$$K_e = 2.86 f^2 B^2\left(10^{-4}\right)$$

$$K_e = 2.86(60)^2(1.4)^2\left(10^{-4}\right)$$

$$K_e = 2.02$$

Step No. 3 Calculate the core geometry, K_g.

$$K_g = \frac{P_t}{2K_e\alpha}, \quad [\text{cm}^5]$$

$$K_g = \frac{647}{2(2.02)(5)}, \quad [\text{cm}^5]$$

$$K_g = 32, \quad [\text{cm}^5]$$

Step No. 4 This data is taken from Chapter 3. The section is on, EI, Three-Phase Laminations.

Core number 100EI-3P

Iron weight, W_{tfe} .... 2.751 kilograms

Mean length turn, MLT .... 16.7 cm

Iron area, A_c .... 6.129 cm^2

Window area, W_a .... 29.0 cm^2

Area product, A_p .... 267cm^4

Core geometry, K_g .... 39 cm^5

Surface area, A_t .... 730 cm^2

Step No. 5 Calculate the number of primary turns, N_p, using Faraday's Law.

$$N_p = \frac{V_{p(Line)}\left(10^4\right)}{4.44 B_{ac} A_c f}, \quad \text{[turns]}$$

$$N_p = \frac{208\left(10^4\right)}{4.44(1.4)(6.129)(60)}, \quad \text{[turns]}$$

$$N_p = 910, \quad \text{[turns]}$$

Step No. 6 Calculate the primary line current, $I_{p(Line)}$.

$$I_{p(Line)} = \frac{P_o}{3V_{p(Line)}\eta}, \quad \text{[amps]}$$

$$I_{p(Line)} = \frac{300}{3(208)(0.95)}, \quad \text{[amps]}$$

$$I_{p(Line)} = 0.506, \quad \text{[amps]}$$

Step No. 7 Calculate the primary phase current, $I_{p(phase)}$.

$$I_{p(Phase)} = \frac{I_{p(Line)}}{\sqrt{3}}, \quad \text{[amps]}$$

$$I_{p(Phase)} = \frac{0.506}{1.73}, \quad \text{[amps]}$$

$$I_{p(Phase)} = 0.292, \quad \text{[amps]}$$

Step No. 8 Calculate the primary bare wire area, $A_{wp(B)}$. The window area available for the primary is, W_a / 4. The primary window utilization, $K_{up} = 0.2$.

$$A_{wp(B)} = \left(\frac{K_{u(p)}W_a}{4N_p}\right), \quad \text{[cm}^2\text{]}$$

$$A_{wp(B)} = \left(\frac{(0.2)(29.0)}{4(910)}\right), \quad \text{[cm}^2\text{]}$$

$$A_{wp(B)} = 0.00159, \quad \text{[cm}^2\text{]}$$

Step No. 9 The selection of the wire would be from the Wire Table in Chapter 4.

$$AWG\ \#25$$

$$A_{w(B)} = 0.001623, \quad \text{[cm}^2\text{]}$$

$$A_{w(Ins)} = 0.002002, \quad \text{[cm}^2\text{]}$$

$$\frac{\mu\Omega}{\text{cm}} = 1062$$

Step No. 10 Calculate the primary winding resistance. Use the MLT, from Step 4, and the micro-ohm, per centimeter, found in Step 9.

$$R_p = \text{MLT}(N_p)\left(\frac{\mu\Omega}{\text{cm}}\right)(10^{-6}), \quad \text{[ohms]}$$

$$R_p = (16.7)(910)(1062)(10^{-6}), \quad \text{[ohms]}$$

$$R_p = 16.1, \quad \text{[ohms]}$$

Step No. 11 Calculate the total primary copper loss, P_p.

$$P_p = 3\left(I_{p(phase)}\right)^2 R_p, \quad \text{[watts]}$$
$$P_p = 3(0.292)^2(16.1), \quad \text{[watts]}$$
$$P_p = 4.12, \quad \text{[watts]}$$

Step No. 12 Calculate the secondary turns, N_s.

$$N_s = \frac{N_p V_s}{V_p}\left(1 + \frac{\alpha}{100}\right), \quad \text{[turns]}$$
$$V_s = (0.740)(V_o + 2V_d) = (0.740)(28 + 2) = 22.2$$
$$N_s = \frac{(910)(22.2)}{(208)}\left(1 + \frac{5}{100}\right), \quad \text{[turns]}$$
$$N_s = 102, \quad \text{[turns]}$$

Step No. 13 Calculate the secondary bare wire area, $A_{ws(B)}$.

$$A_{ws(B)} = \left(\frac{K_{u(s)} W_a}{4N_s}\right), \quad [\text{cm}^2]$$
$$A_{ws(B)} = \left(\frac{(0.2)(29.0)}{4(102)}\right), \quad [\text{cm}^2]$$
$$A_{ws(B)} = 0.0142, \quad [\text{cm}^2]$$

Step No. 14 The selection of the wire will be from the Wire Table in Chapter 4.

$$AWG\ \#16$$
$$A_{w(B)} = 0.01307, \quad [\text{cm}^2]$$
$$A_{w(Ins)} = 0.01473, \quad [\text{cm}^2]$$
$$\frac{\mu\Omega}{\text{cm}} = 132$$

Step No. 15 Calculate the secondary winding resistance, R_s. Use the MLT, from Step 4, and the micro-ohm per centimeter, found in Step 14.

$$R_s = \text{MLT}(N_s)\left(\frac{\mu\Omega}{\text{cm}}\right)\left(10^{-6}\right), \quad \text{[ohms]}$$
$$R_s = (16.7)(102)(132)\left(10^{-6}\right), \quad \text{[ohms]}$$
$$R_s = 0.225, \quad \text{[ohms]}$$

Step No. 16 Calculate the secondary line current, $I_{s(line)}$.

$$I_{s(line)} = (0.471) I_o, \quad \text{[amps]}$$
$$I_{s(line)} = (0.471)(10), \quad \text{[amps]}$$
$$I_{s(line)} = 4.71, \quad \text{[amps]}$$

Step No. 17 Calculate the secondary phase current, $I_{s(phase)}$.

$$I_{s(phase)} = \frac{I_{s(line)}}{\sqrt{3}}, \quad \text{[amps]}$$
$$I_{s(phase)} = \frac{4.71}{1.73}, \quad \text{[amps]}$$
$$I_{s(phase)} = 2.72, \quad \text{[amps]}$$

Step No. 18 Calculate the total secondary copper loss, P_s.

$$P_s = 3\left(I_{s(phase)}\right)^2 R_s, \quad \text{[watts]}$$
$$P_s = 3(2.72)^2(0.225), \quad \text{[watts]}$$
$$P_s = 4.99, \quad \text{[watts]}$$

Step No. 19 Calculate the transformer regulation, α.

$$\alpha = \frac{P_{cu}}{P_o}(100), \quad [\%]$$
$$P_{cu} = P_p + P_s, \quad \text{[watts]}$$
$$P_{cu} = 4.12 + 4.99, \quad \text{[watts]}$$
$$P_{cu} = 9.11, \quad \text{[watts]}$$
$$\alpha = \left(\frac{9.11}{300}\right)(100), \quad [\%]$$
$$\alpha = 3.03, \quad [\%]$$

Step No. 20 Calculate the watts per kilogram.

$$\text{Watts/kilogram} = K f^{(m)} B_{ac}^{(n)}$$
$$\text{Watts/kilogram} = 0.000557(60)^{(1.68)}(1.40)^{(1.86)}$$
$$\text{Watts/kilogram} = 1.01$$

Step No. 21 Calculate the core loss, P_{fe}. Core weight, W_{tfe}, is found in Step 4.

$$P_{fe} = \text{Watts/Kilogram}\left(\text{W}_{\text{tfe}}\right), \quad \text{[watts]}$$
$$P_{fe} = 1.01(2.751), \quad \text{[watts]}$$
$$P_{fe} = 2.78, \quad \text{[watts]}$$

Step No. 22 Summarize the total transformer losses, P_Σ.

$$P_\Sigma = P_p + P_s + P_{fe}, \quad \text{[watts]}$$
$$P_\Sigma = 4.12 + 4.99 + 2.78, \quad \text{[watts]}$$
$$P_\Sigma = 11.89, \quad \text{[watts]}$$

Step No. 23 Calculate the transformer efficiency, η.

$$\eta = \frac{P_o}{P_o + P_\Sigma}(100), \quad [\%]$$
$$\eta = \frac{300}{300 + 11.89}(100), \quad [\%]$$
$$\eta = 96.2, \quad [\%]$$

Step No. 24 Calculate the watts per unit area, ψ. The surface area, A_t, is found in Step 4.

$$\psi = \frac{P_\Sigma}{A_t}, \quad \text{[watts per cm}^2\text{]}$$
$$\psi = \frac{(11.89)}{(730)}, \quad \text{[watts per cm}^2\text{]}$$
$$\psi = 0.0163, \quad \text{[watts per cm}^2\text{]}$$

Step No. 25 Calculate the temperature rise, T_r. The watts per unit area ψ is found in Step 24.

$$T_r = 450(\psi)^{0.826}, \quad [^\circ\text{C}]$$
$$T_r = 450(0.0163)^{0.826}, \quad [^\circ\text{C}]$$
$$T_r = 15, \quad [^\circ\text{C}]$$

Step No. 26 Calculate the total window utilization, K_u. The window area is found in Step 4.

$$K_u = K_{up} + K_{us}$$
$$K_u = \frac{4 N_p A_{wp(B)(25)}}{W_a} + \frac{4 N_s A_{ws(B)(16)}}{W_a}$$
$$K_u = \frac{4(910)(0.001623)}{29} + \frac{4(102)(0.01307)}{29}$$
$$K_u = (0.204) + (0.184)$$
$$K_u = 0.388$$