Chapter 11

Constant Voltage Transformer (CVT)

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Introduction

The constant-voltage transformer (CVT) has a wide application, particularly where reliability and inherent regulating ability against line voltage changes are of prime importance. The output of a constant-voltage transformer is essentially a square wave, which is desirable for rectifier output applications while, also having good circuit characteristics. The main disadvantage to a constant-voltage transformer is efficiency and regulation for frequency and load. The equations presented here for designing a constant-voltage transformers at line frequency have been used at 400 Hz on aircraft, and as high as 20 kHz.

Constant-Voltage Transformer, Regulating Characteristics

The basic two-component (CVT) Ferroresonant regulator is shown in Figure 11-1. The inductor, L1, is a linear inductor and is in series with C1 across the input line. The voltage across capacitor, C1, would be considerably greater than the line voltage, because of the resonant condition between L1 and C1.
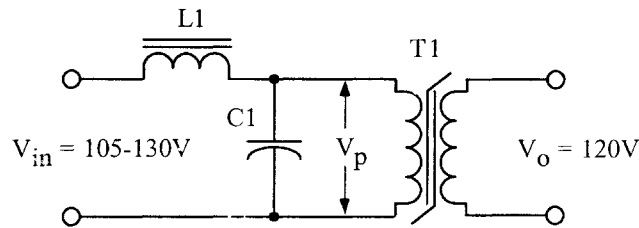
Figure 11-1. Two Component Ferroresonant Voltage Stabilizer.

The voltage, V_p, can be limited to a predetermined amplitude by using a self-saturating transformer, T1, which has high impedance, until a certain level of flux density is reached. At that flux density, the transformer saturates and becomes a low-impedance path, which prevents further voltage buildup across the capacitor. This limiting action produces a voltage waveform that has a fairly flat top characteristic as shown in Figure 11-2 on each half-cycle.
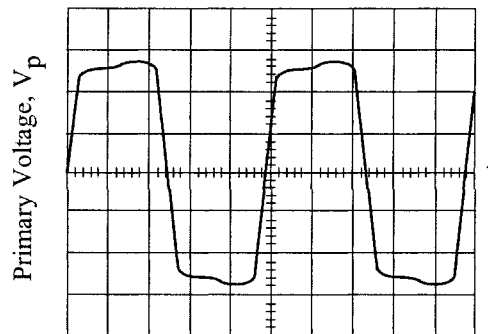
Figure 11-2. Primary Voltage Waveform of a Constant Voltage Transformer.

Electrical Parameters of a CVT Line Regulator

When the constant voltage transformer is operating as a line regulator, the output voltage will vary as a function of the input voltage, as shown in Figure 11-3. The magnetic material used to design transformer, T1, has an impact on line regulation. Transformers designed with a square B-H loop will result in better line regulation. If the output of the line regulator is subjected to a load power factor (lagging) with less than unity, the output will change, as shown in Figure 11-4.
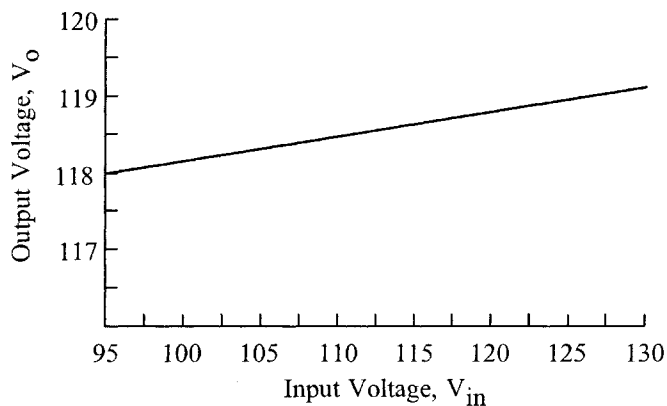
Figure 11-3. Output Voltage Variation, as a Function of Input Voltage.
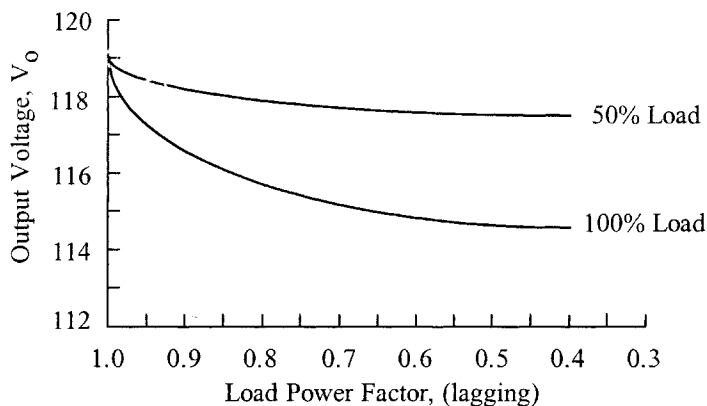
Figure 11-4. Output Voltage Variation, as a Function of Load Power Factor.

If the constant voltage transformer is subjected to a line voltage frequency change the output voltage will vary, as shown in Figure 11-5. The regulation of a constant-voltage transformer can be designed to be better than a few percent. Capability for handling a short circuit is an inherent feature of a constant-voltage transformer. The short-circuit current is limited and set by the series inductance, L. The regulation characteristics at various lines and loads are shown in Figure 11-6. It should be noted that a dead short, corresponding to zero output voltage, does not greatly increase the load current; whereas for most transformers, this dead short would be destructive.
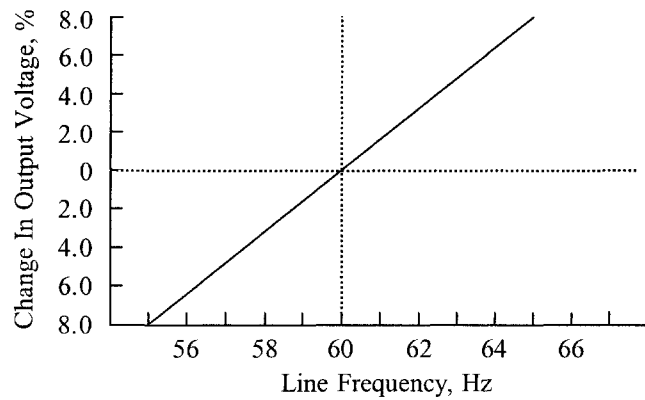
Figure 11-5. Output Voltage Variation, as a Function of Line Frequency Change.
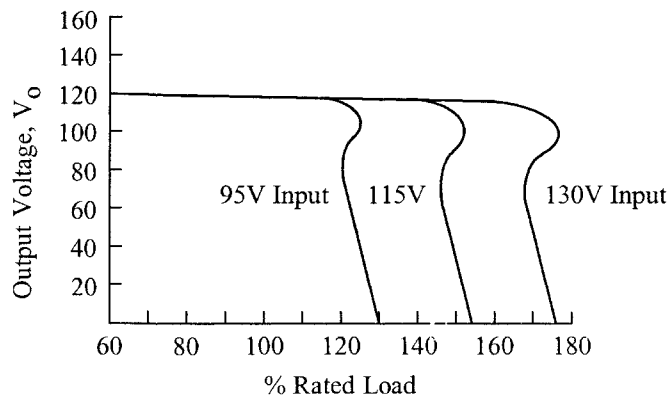
Figure 11-6. Output Voltage Variation, as a Function of Output Voltage vs. Load.

Constant-Voltage Transformer, Design Equations

Proper operation and power capacity of a constant-voltage transformer (CVT) depends on components, L1 and C1, as shown in Figure 11-7. Experience has shown that the, LC, relationship is:

$$LC\omega^2 = 1.5 \qquad [11\text{-}1]$$

Figure 11-7. Basic, Constant Voltage Transformer Circuit.

The inductance can be expressed as:

$$L = \frac{R_{o(R)}}{2\omega}, \quad \text{[henrys]} \quad \text{[11-2]}$$

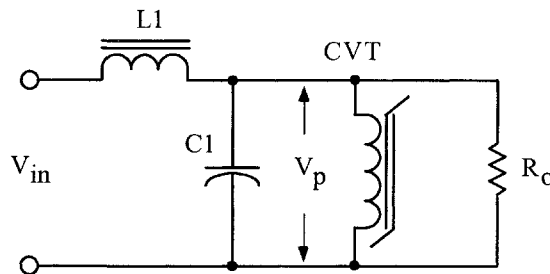The capacitance can be expressed as:

$$C = \frac{1}{0.33\omega R_{o(R)}}, \quad \text{[farads]} \quad \text{[11-3]}$$

Referring to Figure 11-7, assume there is a sinusoidal input voltage, an ideal input inductor, L1, and a series capacitor, C1. All voltage and currents are rms values. V_{in} is the voltage value just before the circuit starts to regulate at full load; $R_{o(R)}$, is the reflected resistance back to the primary, including efficiency; η is the efficiency, and, P_o, is the output power.

$$P_o = \frac{V_s^2}{R_o}, \quad \text{[watts]} \quad \text{[11-4]}$$

$$R_{o(R)} = \frac{(V_p)^2 \eta}{P_o}, \quad \text{[ohms]} \quad \text{[11-5]}$$

It is common practice for the output to be isolated from the input and to connect C1 to a step-up winding on the constant-voltage transformer (CVT). In order to use smaller capacitor values, a step-up winding must be added, as shown in Figure 11-8. The penalty for using a smaller capacitor requires the use of a step-up winding. This step-up winding increases the VA or size of the transformer. This can be seen in Equation 11-6. The energy in a capacitor is:

$$\text{Energy} = \frac{CV^2}{2}, \quad \text{[watt-seconds]}$$
$$C = \frac{2(\text{Energy})}{V^2}, \quad \text{[farads]} \qquad \text{[11-6]}$$
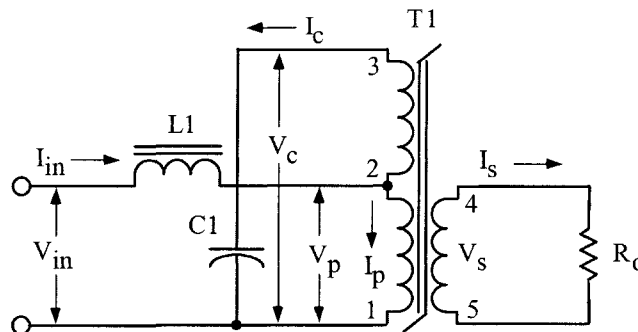
Figure 11-8. CVT, with a Capacitor Step-up Winding.

The secondary current, I_s, can be expressed as:

$$I_s = \frac{P_o}{V_s}, \quad \text{[amps]} \quad [11\text{-}7]$$

With the step-up winding, the primary current, I_p, is related to the secondary current by the following Equation [Ref. 3]:

$$I_p = \frac{I_s\left(V_{s(4-5)}\right)}{\eta\left(V_{p(1-2)}\right)}\left(1 + \sqrt{\frac{V_{p(1-2)}}{V_{c(1-3)}}}\right), \quad \text{[amps]} \quad [11\text{-}8]$$

The current, I_c, through the capacitor, is increased by, K_c, because of the effective higher frequency. Due to the quasi-voltage waveform as shown in Figure 11-2, the equivalent ac impedance of the resonant capacitor is reduced to some value lower than its normal sine wave value. This is due to an increase in odd harmonics.

$$I_c = K_c V_c \omega C, \quad \text{[amps]} \quad [11\text{-}9]$$

Where, K_c, can vary from 1.0 to 1.5.

Empirically, it has been shown that for good performance the primary operating voltage should be:

$$V_p = V_{in}(0.95), \quad \text{[volts]} \quad [11\text{-}10]$$

When the resonating capacitor is connected across a step-up winding, as is Figure 11-8, both the value of the capacitor and the volume can be reduced. C_n, is the new capacitance value, and, V_n, is the new voltage across the capacitor.

$$C_n V_n^2 = C_{(1-2)} V_{(1-2)}^2$$

The apparent power, P_t, is the sum of each winding, VA:

$$P_t = \left(VA_{(1-2)}\right) + \left(VA_{(2-3)}\right) + \left(VA_{(4-5)}\right), \quad \text{[watts]} \quad [11\text{-}11]$$

The line voltage regulation of a constant-voltage transformer is:

$$\Delta V_p = 4.44 \Delta B_s A_c f N_p \left(10^4\right), \quad \text{[volts]} \quad [11\text{-}12]$$

The output voltage regulation of a constant-voltage transformer, for a change in line voltage, is a function of the squareness of the B-H loop, as shown in Figure 11-9. The saturation flux density, B_s, is dependent on the annealing process of the magnetic material. It seems that each manufacturer has his own annealing process, which has an impact on the saturation flux density, B_s.
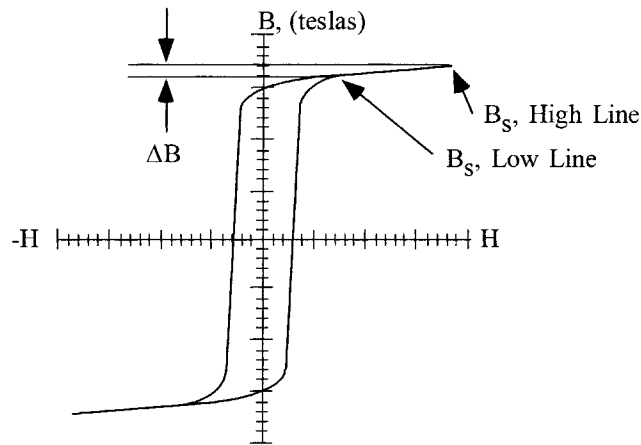
Figure 11-9. B-H Loop of a CVT at High and Low Line.

Constant-Voltage Transformer, Design Example

Design a constant-voltage line regulator (CVT) with the following specifications.

1. Input voltage .... = 105-129 volts
2. Line frequency .... = 60 hertz.
3. Output voltage, V_s .... = 120 volts
4. Output VA .... = 250 watts.
5. Transformer current density, J .... = 300 amps/cm^2
6. Capacitor voltage, V_c .... = 440 volts
7. Capacitor coefficient, K_c .... = 1.5
8. Efficiency goal, $\eta(100)$ .... = 85%
9. Magnetic Material .... = Silicon
10. Saturating flux density, B_s .... = 1.95 tesla
11. Window utilization, K_u .... = 0.4
12. Temperature rise goal, T_r .... = 50°C

Step No. 1 Calculate the primary voltage, V_p.

$$V_p = V_{in(min)}(0.95), \quad [\text{volts}]$$
$$V_p = (105)(0.95), \quad [\text{volts}]$$
$$V_p = 99.75, \quad [\text{volts}]$$

Step No. 2 Calculate the reflected resistance, $R_{o(R)}$ back to the primary, including efficiency η.

$$R_{o(R)} = \frac{(V_p)^2 \eta}{P_o}, \quad [\text{ohms}]$$

$$R_{o(R)} = \frac{(99.75)^2 (0.85)}{250}, \quad [\text{ohms}]$$

$$R_{o(R)} = 33.8, \quad [\text{ohms}]$$

Step No. 3 Calculate the required capacitance, C1.

$$C = \frac{1}{0.33 \omega R_{o(R)}}, \quad [\text{farads}]$$

$$C = \frac{1}{0.33(377)(33.8)}, \quad [\text{farads}]$$

$$C = 238(10^{-6}), \quad [\text{farads}]$$

Step No. 4 Calculate the new capacitance value, using the higher voltage, V_c.

$$C_{(1-3)} = \frac{C_{(1-2)}(V_{(1-2)})^2}{(V_{(1-3)})^2}, \quad [\text{farads}]$$

$$C_{(1-3)} = \frac{(238(10^{-6}))(99.75)^2}{(440)^2}, \quad [\text{farads}]$$

$$C_{(1-3)} = 12.3(10^{-6}), \quad [\text{farads}]$$

A standard motor run capacitor is a 12.5 μf/440v.

Step No. 5 Calculate the capacitor current, I_c.

$$I_c = 1.5 V_c \omega C, \quad [\text{amps}]$$

$$I_c = 1.5(440)(377)(12.5(10^{-6})), \quad [\text{amps}]$$

$$I_c = 3.11, \quad [\text{amps}]$$

Step No. 6 Calculate the secondary current, I_s.

$$I_s = \frac{P_o}{V_s}, \quad [\text{amps}]$$

$$I_s = \frac{250}{120}, \quad [\text{amps}]$$

$$I_s = 2.08, \quad [\text{amps}]$$

Step No. 7 Calculate the primary current, I_p.

$$I_p = \frac{I_s\left(V_{s(4-5)}\right)}{\eta\left(V_{p(1-2)}\right)}\left(1+\sqrt{\frac{V_{p(1-2)}}{V_{c(1-3)}}}\right), \quad [\text{amps}]$$

$$I_p = \frac{2.08(120)}{(0.85)(99.75)}\left(1+\sqrt{\frac{99.75}{440}}\right), \quad [\text{amps}]$$

$$I_p = 4.35, \quad [\text{amps}]$$

Step No. 8 Calculate the apparent power P_t.

$$P_t = \left(VA_{(1-2)}\right)+\left(VA_{(2-3)}\right)+\left(VA_{(4-5)}\right), \quad [\text{watts}]$$

$$VA_{(1-2)} = V_p I_p = (99.75)(4.35) = 434, \quad [\text{watts}]$$

$$VA_{(2-3)} = \left(V_c - V_p\right)I_c = (340)(3.11) = 1057, \quad [\text{watts}]$$

$$VA_{(4-5)} = V_s I_s = (120)(2.08) = 250, \quad [\text{watts}]$$

$$P_t = (434)+(1057)+(250), \quad [\text{watts}]$$

$$P_t = 1741, \quad [\text{watts}]$$

Step No. 9 Calculate the area product, A_p.

$$A_p = \frac{P_t\left(10^4\right)}{K_f K_u f B_s J}, \quad [\text{cm}^4]$$

$$A_p = \frac{(1742)\left(10^4\right)}{(4.44)(0.4)(60)(1.95)(300)}, \quad [\text{cm}^4]$$

$$A_p = 279, \quad [\text{cm}^4]$$

Step No. 10 Select an EI lamination from Chapter Three. The closest lamination to the calculated area product, A_p, is the EI-175.

1. Core Number .... = EI-175

2. Magnetic Path Length, MPL .... = 26.7 cm

3. Core Weight, W_{tfe} .... = 3.71 kilograms

4. Mean Length Turn, MLT .... = 25.6 cm

5. Iron Area, A_c .... = 18.8 cm^2

6. Window Area, W_a .... = 14.8 cm^2

7. Area Product, A_p .... = 278 cm^4

8. Core Geometry, K_g .... = 81.7 cm^5

9. Surface Area, A_t .... = 652 cm^2

Step No. 11 Calculate the number of primary turns, N_p.

$$N_p = \frac{V_p(10^4)}{K_f B_s f A_c}, \quad [\text{turns}]$$

$$N_p = \frac{(99.75)(10^4)}{(4.44)(1.95)(60)(18.8)}, \quad [\text{turns}]$$

$$N_p = 102, \quad [\text{turns}]$$

Step No. 12 Calculate the primary bare wire area, $A_{wp(B)}$.

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

$$A_{wp(B)} = \frac{(4.35)}{(300)}, \quad [\text{cm}^2]$$

$$A_{wp(B)} = 0.0145, \quad [\text{cm}^2]$$

Step No. 13 Select a wire from the Wire Table in Chapter 4.

$$AWG = \#16$$

$$A_{w(B)} = 0.0131, \quad [\text{cm}^2]$$

$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 132, \quad [\text{micro-ohm/cm}]$$

Step No. 14 Calculate the primary resistance, R_p. Use the MLT from the core data and the micro-ohm per centimeter found in Step 13.

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

$$R_p = (25.6)(102)(132)(10^{-6}), \quad [\text{ohms}]$$

$$R_p = 0.345, \quad [\text{ohms}]$$

Step No. 15 Calculate the primary copper loss, P_p.

$$P_p = (I_p)^2 R_p, \quad [\text{watts}]$$

$$P_p = (4.35)^2(0.345), \quad [\text{watts}]$$

$$P_p = 6.53, \quad [\text{watts}]$$

Step No. 16 Calculate the required turns for the step-up capacitor winding, N_c.

$$N_c = \frac{N_p(V_c - V_p)}{V_p}, \quad [\text{turns}]$$

$$N_c = \frac{(102)(440 - 99.75)}{99.75}, \quad [\text{turns}]$$

$$N_c = 348, \quad [\text{turns}]$$

Step No. 17 Calculate the capacitor step-up winding bare wire area, $A_{wc(B)}$.

$$A_{wc(B)} = \frac{I_c}{J}, \quad [\text{cm}^2]$$

$$A_{wc(B)} = \frac{(3.11)}{(300)}, \quad [\text{cm}^2]$$

$$A_{wc(B)} = 0.0104, \quad [\text{cm}^2]$$

Step No. 18 Select a wire from the Wire Table in Chapter 4.

$$AWG = \#17$$

$$A_{w(B)} = 0.0104, \quad [\text{cm}^2]$$

$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 166, \quad [\text{micro-ohm/cm}]$$

Step No. 19 Calculate the capacitor winding resistance, R_c. Use the MLT from the core data and the micro-ohm per centimeter found in Step 18.

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

$$R_c = (25.6)(348)(166)(10^{-6}), \quad [\text{ohms}]$$

$$R_c = 1.48, \quad [\text{ohms}]$$

Step No. 20 Calculate the capacitor step-up winding copper loss, P_c.

$$P_c = (I_c)^2 R_c, \quad [\text{watts}]$$

$$P_c = (3.11)^2 (1.48), \quad [\text{watts}]$$

$$P_c = 14.3, \quad [\text{watts}]$$

Step No. 21 Calculate the turns for the secondary, N_s.

$$N_s = \frac{N_p V_s}{V_p}, \quad [\text{turns}]$$

$$N_s = \frac{(102)(120)}{99.75}, \quad [\text{turns}]$$

$$N_s = 123, \quad [\text{turns}]$$

Step No. 22 Calculate the secondary bare wire area, $A_{ws(B)}$.

$$A_{ws(B)} = \frac{I_s}{J}, \quad [\text{cm}^2]$$

$$A_{ws(B)} = \frac{(2.08)}{(300)}, \quad [\text{cm}^2]$$

$$A_{ws(B)} = 0.00693, \quad [\text{cm}^2]$$

Step No. 23 Select a wire from the Wire Table in Chapter 4.

$$AWG = \#19$$

$$A_{w(B)} = 0.00653, \quad [\text{cm}^2]$$

$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 264, \quad [\text{micro-ohm/cm}]$$

Step No. 24 Calculate the secondary winding resistance, R_s. Use the MLT from the core data and the micro-ohm per centimeter found in Step 23.

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

$$R_s = (25.6)(123)(264)(10^{-6}), \quad [\text{ohms}]$$

$$R_s = 0.831, \quad [\text{ohms}]$$

Step No. 25 Calculate the secondary winding copper loss, P_s.

$$P_s = (I_s)^2 R_s, \quad [\text{watts}]$$

$$P_s = (2.08)^2 (0.831), \quad [\text{watts}]$$

$$P_s = 3.59, \quad [\text{watts}]$$

Step No. 26 Calculate the total copper loss, P_{cu}.

$$P_{cu} = P_p + P_s + P_c, \quad [\text{watts}]$$
$$P_{cu} = (6.53) + (3.59) + (14.3), \quad [\text{watts}]$$
$$P_{cu} = 24.4, \quad [\text{watts}]$$

Step No. 27 Calculate the watts-per-kilogram, W/K, for the appropriate core material. See Chapter 2.

$$W/K = 0.000557 f^{(1.68)} B_s^{(1.86)}, \quad [\text{watts-per-kilogram}]$$
$$W/K = 0.000557 (60)^{(1.68)} (1.95)^{(1.86)}, \quad [\text{watts-per-kilogram}]$$
$$W/K = 1.87, \quad [\text{watts-per-kilogram}]$$

Step No. 28 Calculate the core loss in watts, P_{fe}.

$$P_{fe} = (W/K) W_{tfe}, \quad [\text{watts}]$$
$$P_{fe} = (1.87)(3.71), \quad [\text{watts}]$$
$$P_{fe} = 6.94, \quad [\text{watts}]$$

Step No. 29 Calculate the total losses, P_Σ.

$$P_\Sigma = P_{cu} + P_{fe}, \quad [\text{watts}]$$
$$P_\Sigma = (24.4) + (6.94), \quad [\text{watts}]$$
$$P_\Sigma = 31.34, \quad [\text{watts}]$$

Step No. 30 Calculate the transformer surface watt density, ψ.

$$\psi = \frac{P_\Sigma}{A_t}, \quad [\text{watts-per-cm}^2]$$
$$\psi = \frac{(31.34)}{(652)}, \quad [\text{watts-per-cm}^2]$$
$$\psi = 0.0481, \quad [\text{watts-per-cm}^2]$$

Step No. 31 Calculate the temperature rise, T_r.

$$T_r = 450 (\psi)^{(0.826)}, \quad [^\circ C]$$
$$T_r = 450 (0.0481)^{(0.826)}, \quad [^\circ C]$$
$$T_r = 36.7, \quad [^\circ C]$$

Step No. 32 Calculate the transformer efficiency, η.

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

$$\eta = \frac{(250)}{(250 + 31.3)}(100), \quad [\%]$$

$$\eta = 88.9, \quad [\%]$$

Step No. 33 Calculate the window utilization, K_u.

$$K_u = \frac{N_p A_{wp(B)\#16} + N_c A_{wc(B)\#17} + N_s A_{ws(B)\#19}}{W_a}$$

$$K_u = \frac{((102)(0.0131)) + ((348)(0.0104)) + ((123)(0.00653))}{(14.6)}$$

$$K_u = 0.394$$

Series AC Inductor, Design Example
(Also See Chapter 9)

Step No. 33 Design a series, linear ac inductor with the following specifications:

1. Applied voltage .... = 129 volts

2. Line frequency .... = 60 hertz

3. Current density, J .... = 300 amp/cm^2

4. Efficiency goal, $\eta(100)$ .... = 85%

5. Magnetic material .... = Silicon

6. Magnetic material permeability, μ_m .... = 1500

7. Flux density, B_{ac} .... = 1.4 tesla

8. Window utilization, K_u .... = 0.4

9. Waveform factor, K_f .... = 4.44

10. Temperature rise goal, T_r .... = 50°C

Step No. 34 Calculate the required series inductance, L1. See Figure 11-8.

$$L1 = \frac{R_{o(R)}}{2\omega}, \quad [\text{henrys}]$$

$$L1 = \frac{(33.8)}{2(377)}, \quad [\text{henrys}]$$

$$L1 = 0.0448, \quad [\text{henrys}]$$

Step No. 35 Calculate the inductor reactance, X_L.

$$X_L = 2\pi f L1, \quad [\text{ohms}]$$
$$X_L = (6.28)(60)(0.0448), \quad [\text{ohms}]$$
$$X_L = 16.9, \quad [\text{ohms}]$$

Step No. 36 Calculate the short-circuit current, I_L.

$$I_L = \frac{V_{in(\text{max})}}{X_L}, \quad [\text{amps}]$$
$$I_L = \frac{(129)}{(16.9)}, \quad [\text{amps}]$$
$$I_L = 7.63, \quad [\text{amps}]$$

Step No. 37 Calculate the apparent power, P_t or VA, of the input series inductor, L1. Use the high line voltage of 129 volts and the normal running current, I_p, from Step 7.

$$VA = V_{in(\text{max})} I_{L(n)}, \quad [\text{watts}]$$
$$VA = (129)(4.35), \quad [\text{watts}]$$
$$VA = 561, \quad [\text{watts}]$$

Step No. 38 Calculate the area product, A_p.

$$A_p = \frac{VA(10^4)}{K_f K_u f B_{ac} J}, \quad [\text{cm}^4]$$
$$A_p = \frac{(561)(10^4)}{(4.44)(0.4)(60)(1.4)(300)}, \quad [\text{cm}^4]$$
$$A_p = 125, \quad [\text{cm}^4]$$

Step No. 39 Select an EI lamination from Chapter Three with the closest calculated area product, A_p.

1. Core Number .... = EI-138
2. Magnetic Path Length, MPL .... = 21 cm
3. Core Weight, W_{tfe} .... = 1.79 kilograms
4. Mean Length Turn, MLT .... = 20.1 cm
5. Iron Area, A_c .... = 11.6 cm^2
6. Window Area, W_a .... = 9.15 cm^2
7. Area Product, A_p .... = 106 cm^4
8. Core Geometry, K_g .... = 24.5 cm^5
9. Surface Area, A_t .... = 403 cm^2
10. Winding length, G .... = 5.24 cm
11. Lamination tongue, E .... = 3.49 cm

Step No. 40 Calculate the number of inductor turns, N_L.

$$N_L = \frac{V_{in(max)}\left(10^4\right)}{K_f B_{ac} f A_c}, \quad [\text{turns}]$$

$$N_L = \frac{(129)\left(10^4\right)}{(4.44)(1.4)(60)(11.6)}, \quad [\text{turns}]$$

$$N_L = 298, \quad [\text{turns}]$$

Step No. 41 Calculate the required gap, L_g.

$$l_g = \left(\frac{0.4\pi N_L^2 A_c \left(10^{-8}\right)}{L}\right) - \left(\frac{MPL}{\mu_m}\right), \quad [\text{cm}]$$

$$l_g = \left(\frac{(1.26)(298)^2(11.6)\left(10^{-8}\right)}{0.0448}\right) - \left(\frac{21}{1500}\right), \quad [\text{cm}]$$

$$l_g = 0.276, \quad [\text{cm}] \text{ or } l_g = 0.109, \quad [\text{mils}]: \text{This would be 50mils in each leg.}$$

Step No. 42 Calculate the fringing flux, F.

$$F = \left(1 + \frac{l_g}{\sqrt{A_c}} \ln \frac{2(G)}{l_g}\right)$$

$$F = \left(1 + \frac{0.276}{\sqrt{11.6}} \ln \frac{2(5.24)}{0.276}\right)$$

$$F = 1.29$$

Step No. 43 Using the fringing flux, recalculate the series inductor turns, $N_{L(new)}$.

$$N_{L(new)} = \sqrt{\frac{l_g L}{0.4\pi A_c F\left(10^{-8}\right)}}, \quad [\text{turns}]$$

$$N_{L(new)} = \sqrt{\frac{(0.276)(0.0448)}{(1.26)(11.6)(1.29)\left(10^{-8}\right)}}, \quad [\text{turns}]$$

$$N_{L(new)} = 256, \quad [\text{turns}]$$

Step No. 44 Using the new turns, recalculate the flux density, B_{ac}.

$$B_{ac} = \frac{V_{in(max)}\left(10^4\right)}{K_f N_{L(new)} A_c f}, \quad [\text{tesla}]$$

$$B_{ac} = \frac{(129)\left(10^4\right)}{(4.44)(256)(11.6)(60)}, \quad [\text{tesla}]$$

$$B_{ac} = 1.63, \quad [\text{tesla}]$$

Step No. 45 Calculate the inductor bare wire area, $A_{wL(B)}$.

$$A_{wL(B)} = \frac{I_{L(n)}}{J}, \quad [cm^2]$$

$$A_{wL(B)} = \frac{(4.35)}{(300)}, \quad [cm^2]$$

$$A_{wL(B)} = 0.0145, \quad [cm^2]$$

Step No. 46 Select a wire from the Wire Table in Chapter 4.

$$AWG = \#16$$

$$A_{w(B)} = 0.01307, \quad [cm^2]$$

$$\left(\frac{\mu\Omega}{cm}\right) = 132, \quad [micro\text{-}ohm/cm]$$

Step No. 47 Calculate the inductor winding resistance, R_L. Use the MLT from the core data and the micro-ohm per centimeter found in Step 38.

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

$$R_L = (20.1)(256)(132)(10^{-6}), \quad [ohms]$$

$$R_L = 0.679, \quad [ohms]$$

Step No. 48 Calculate the inductor winding copper loss, P_L.

$$P_L = (I_L)^2 R_L, \quad [watts]$$

$$P_L = (4.35)^2(0.679), \quad [watts]$$

$$P_L = 12.8, \quad [watts]$$

Step No. 49 Calculate the watts-per-kilogram, W/K, for the appropriate core material. See Chapter 2.

$$W/K = 0.000557 f^{(1.68)} B_s^{(1.86)}, \quad [watts\text{-}per\text{-}kilogram]$$

$$W/K = 0.000557(60)^{(1.68)}(1.63)^{(1.86)}, \quad [watts\text{-}per\text{-}kilogram]$$

$$W/K = 1.34, \quad [watts\text{-}per\text{-}kilogram]$$

Step No. 50 Calculate the core loss in watts, P_{fe}.

$$P_{fe} = (W/K)W_{tfe}, \quad [\text{watts}]$$
$$P_{fe} = (1.34)(1.79), \quad [\text{watts}]$$
$$P_{fe} = 2.4, \quad [\text{watts}]$$

Step No. 51 Calculate the gap loss, P_g.

$$P_g = K_i E I_g f B_{ac}^2, \quad [\text{watts}]$$
$$P_g = (0.155)(3.49)(0.276)(60)(1.63)^2, \quad [\text{watts}]$$
$$P_g = 23.8, \quad [\text{watts}]$$

Step No. 52 Calculate the total losses, P_Σ.

$$P_\Sigma = P_{cu} + P_{fe} + P_g, \quad [\text{watts}]$$
$$P_\Sigma = (12.8) + (2.4) + (23.8), \quad [\text{watts}]$$
$$P_\Sigma = 39, \quad [\text{watts}]$$

Step No. 53 Calculate the inductor surface area watt density, ψ.

$$\psi = \frac{P_\Sigma}{A_t}, \quad [\text{watts-per-cm}^2]$$
$$\psi = \frac{(39)}{(403)}, \quad [\text{watts-per-cm}^2]$$
$$\psi = 0.0968, \quad [\text{watts-per-cm}^2]$$

Step No. 54 Calculate the temperature rise, T_r.

$$T_r = 450(\psi)^{(0.826)}, \quad [^\circ C]$$
$$T_r = 450(0.0968)^{(0.826)}, \quad [^\circ C]$$
$$T_r = 65, \quad [^\circ C]$$

Step No. 55 Calculate the window utilization, K_u.

$$K_u = \frac{N_{L(new)} A_{w(B)\#16}}{W_a}$$
$$K_u = \frac{((256)(0.0131))}{(9.15)}$$
$$K_u = 0.367$$

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