

## **Chapter 18**

### **Quiet Converter Design**

The author would like to thank **Dr. V. Vorperian**, Senior Engineer, Power and Sensor Electronics Group, Jet Propulsion Laboratory (JPL), for his help with the Quiet Converter design equations.

## Table of Contents

|   |  |
|---|--|
| 1. Introduction .....   |  |
| 2. The Voltage-fed Converter .....                                      |  |
| 3. Regulating and Filtering .....                                       |  |
| 4. The Current-fed Converter .....                                      |  |
| 5. The Quiet Converter .....  |  |
| 6. Regulating and Filtering .....                                       |  |
| 7. Quiet Converter Waveforms .....                                      |  |
| 8. Technology on the Move .....   |  |
| 9. Window Utilization Factor, $K_u$ .....                               |  |
| 10. Temperature Stability.....  |  |
| 11. Calculating the Apparent Power, $P_t$ .....                         |  |
| 12. Quiet Converter Design Equations .....                              |  |
| 13. Transformer Design, Using the Core Geometry, $K_g$ , Approach ..... |  |
| 14. Design Review .....   |  |
| 15. References .....  |  |

## Introduction

A few designers have known about the Resonant Converter described here for many years. This type of Resonant Converter has been built mainly in the range of 200 watts to 2 kilowatts, and has been used as a static inverter. However, it has remained relatively obscure in the general literature. The Quiet Converter was developed at Jet Propulsion Laboratory (JPL), Division 38, to power very sensitive instruments. The Quiet Converter produces a sinusoidal voltage across a parallel resonant tank. The dc output voltage is obtained after rectification and filtering of the sinusoidal secondary voltage. The regulation is achieved by controlling the duty-cycle of the switching transistors. A comparison of the standard type of PWM control with the Quiet Converter and its amplitude modulation (AM), is shown in Figure 18-1. The inherent low noise from this converter is how the nickname, Quiet Converter, came about. The low noise can easily be reduced, even further, by the addition of a Faraday Shield and common-mode inductors. Programs at Jet Propulsion Laboratory (JPL) that have successfully used the low noise environment of the Quiet Converter are, WF/PC-II, Articulated Fold, Mirror Actuators, (Hubbell Space Telescope), MISR (Earth Orbiting System), Raman, and Mars 05 ONC, CCD Camera.

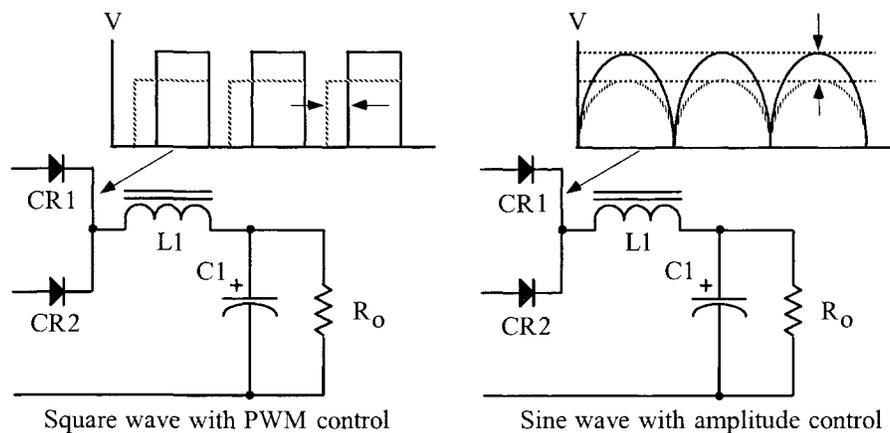
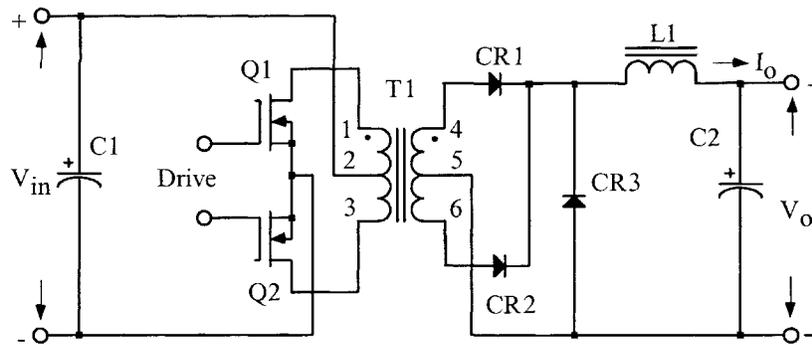


Figure 18-1. Comparing PWM and Amplitude Control.

## The Voltage-fed Converter

The voltage-fed converter circuit is the most widely-used, converter topology. In a voltage-fed converter, the power source,  $V_{in}$ , is connected directly to the transformer through a transistor, Q1, as shown in Figure 18-2. When the transistor, Q1, is switched on, the full source voltage is applied to the transformer, T1, primary, (1-2). The transistor saturation will be ignored. Conversely, when Q2 is switched on, the full source voltage is applied to the other half of the transformer, T1, primary, (2-3).

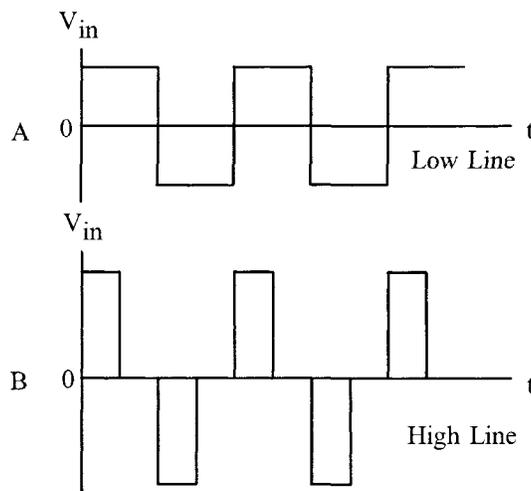


**Figure 18-2.** Typical, Voltage-fed Power Converter.

In Figure 18-2, the switching drive circuit alternately saturates and cuts off the semiconductors' switches, Q1 and Q2, causing an alternating voltage to be generated across the primary winding of transformer, T1, and then delivered to the secondary to be rectified and filtered before going to the load. The primary source voltage,  $V_{in}$ , is directly impressed onto the primary of the transformer, T1, and therefore, the voltage across the transformer, T1, is always a square wave.

### Regulating and Filtering

The most effective method of regulation for a voltage-fed converter is pulse width modulation (PWM). A constant output voltage can be obtained for a changing input voltage, by reducing the on time,  $T_{on}$  of Q1 and Q2, as shown in Figure 18-3. The pulse width voltage is applied to the output filter, L1C2, averaging circuit to provide the proper output voltage,  $V_o$ .



**Figure 18-3.** Primary Voltage of a PWM Controlled Converter.

## The Current-fed Converter

The main difference between a voltage-fed converter and a current-fed converter is the series inductor,  $L1$ , shown in Figure 18-3. The inductor,  $L1$ , is commonly called a feed-choke or series inductor. It has an inductance large enough in value to maintain a continuous current through the circuit under all conditions of line and load.

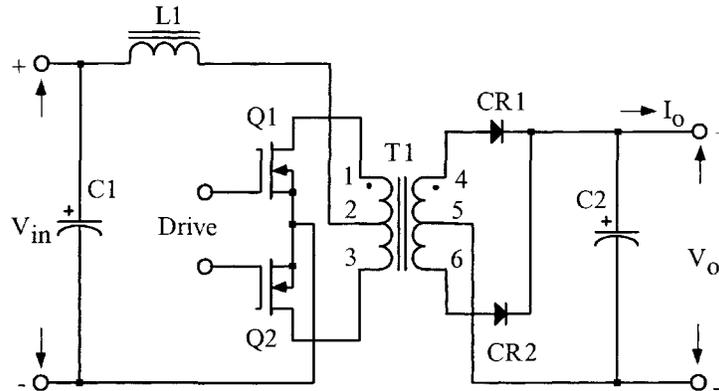


Figure 18-4. Typical Current-fed Power Converter Circuit.

## The Quiet Converter

Simple additions to the circuit, in Figure 18-4, change the performance dramatically, and it becomes a whole new converter. The new converter is shown in Figure 18-5. The changes are: 1. The transformer,  $T1$ , core material has been changed to molypermalloy powder core, (MPP). The reason for using a powder core is because it has a built-in gap required for the tank circuit and these cores are available with temperature stabilized permeability. The use of a gap ferrite would perform just as well, but the design must be stable over temperature. 2. A commutating winding has been added to the series inductor,  $L1$ . 3. A capacitor,  $C3$ , was added for the required parallel tuned tank. The tuning capacitor,  $C3$ , should be of high quality with a low ESR and stable. The capacitors that were used in the flight power supplies, were plastic film, type CRH, to MIL-C-83421.

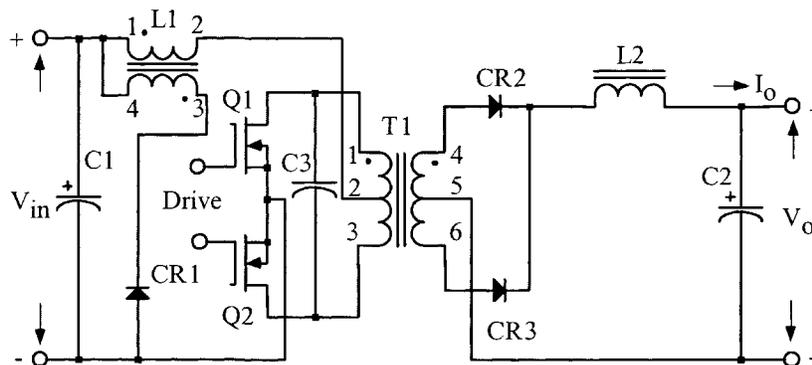


Figure 18-5. Current-fed Parallel Resonant Converter.

With properly designed components, the output voltage of transformer, T1, will always be a sine wave. The sine wave is accomplished by using a tuned parallel resonant tank circuit, (T1C3), to the natural running frequency of the converter. The series inductor, L1, isolates the input dc source from the sine wave voltage across the primary of the transformer, T1.

### Regulating and Filtering

The current-fed resonant converter, shown in Figure 18-5, requires a minimum of dead time, (dwell), for the circuit to function properly. The series inductor, L1, when connected, as shown in Figure 18-4, requires continuous conduction of both Q1 and Q2, along with a small amount of overlap. In this way, there would always be continuous current flowing in L1. If there is any disruption of current in the series inductor, L1, no matter how small, it would destroy the switching transistors, Q1 and or Q2.

In order to incorporate pulse width modulation (PWM), or a drive circuit that has inherent dead time that neither transistor is conducting, there must be a means to commutate the current in the series inductor, L1. Adding a winding to the series inductor, L1, is a simple way to commutate the current. When the current flowing in winding, (1-2), is interrupted, the current will now be commutated to the added winding, (3-4). This is done when connected with proper phasing, through a diode CR1, then, back to the dc source to complete the path, as shown in Figure 18-5. Now, when either transistors, Q1 or Q2, are interrupted, the added winding of the series inductor, L1, commutates the current back into the dc source, thus preventing the destruction of the switching transistors Q1 and Q2.

### Quiet Converter Waveforms

The current-fed, sine wave converter waveforms will be referenced from Figure 18-6. In Figure 18-7 through Figure 18-15, refer back to (A)–(J) points in Figure 18-6. The waveforms presented here are copies drawn from an actual photo taken with an oscilloscope camera.

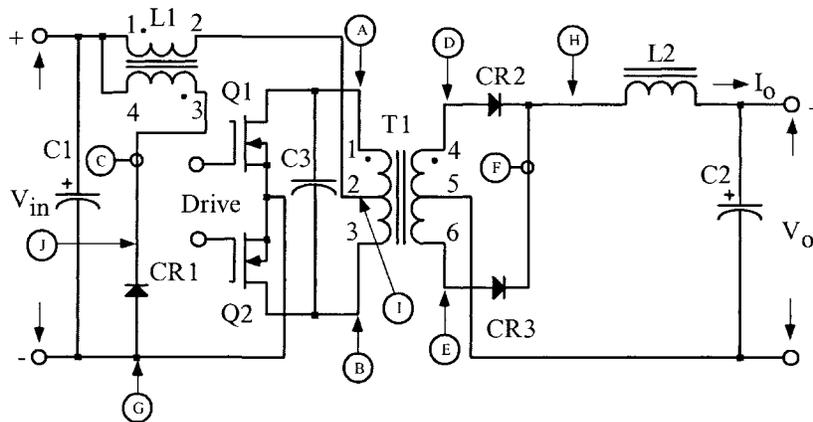
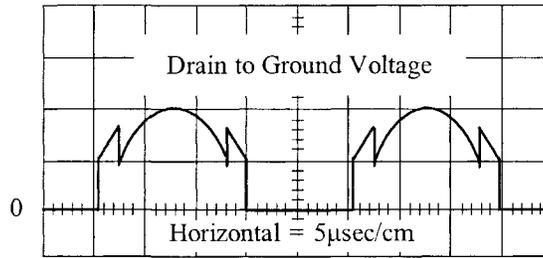
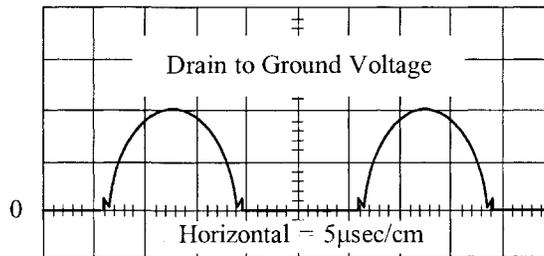


Figure 18-6. Quiet Converter Schematic with Reference Points.



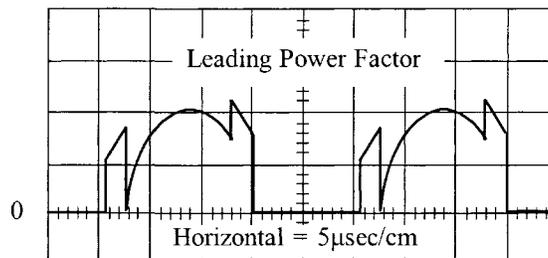
**Figure 18-7.** Drain to Ground, Voltage Waveform of Q1 and Q2.

The drain voltage waveform of Q1 is shown in Figure 18-7. Waveform is taken between points A and G. The converter is properly tuned to the natural frequency.



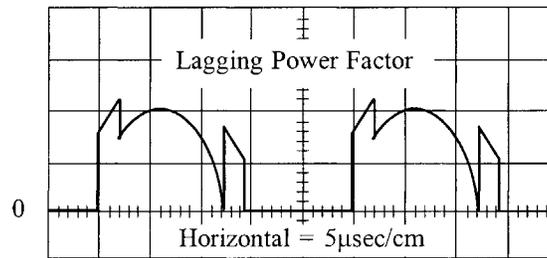
**Figure 18-8.** Drain to Ground, Voltage Waveform of Q1 and Q2.

The drain voltage waveform of Q1 is shown in Figure 18-8, with minimum dead time. Waveform is taken between points A and G. The converter is properly tuned to the natural frequency.



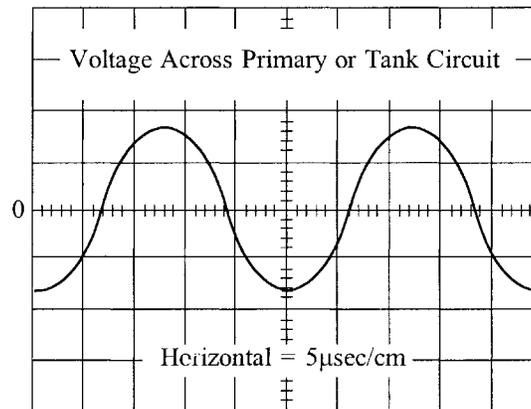
**Figure 18-9.** Drain to Ground, Voltage Waveform of Q1 and Q2.

The drain voltage waveform of Q1 is shown in Figure 18-9. Waveform is taken between points A and G. The converter is improperly tuned to the natural frequency. The resonant tank capacitor is too small in value.



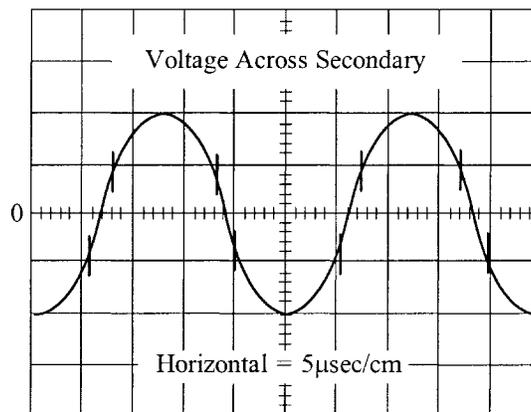
**Figure 18-10.** Drain to Ground, Voltage Waveform of Q1 and Q2.

The drain voltage waveform of, Q1, is shown in Figure 18-10. Waveform is taken between points A and G. The converter is improperly tuned to the natural frequency. The resonant tank capacitor is too large in value.



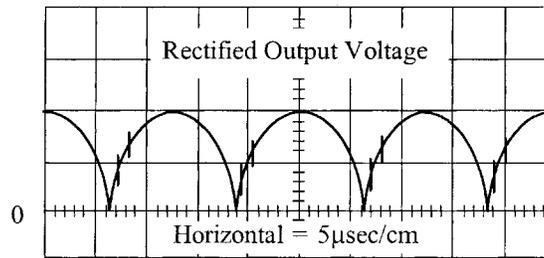
**Figure 18-11.** Voltage Waveform Across Transformer Primary.

The primary voltage waveform is shown in Figure 18-11, across transformer, T1. Waveform is taken between points A and B. The converter is properly tuned to the natural frequency.



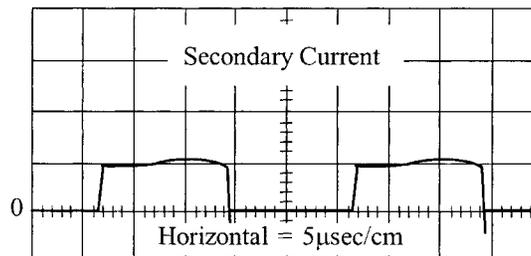
**Figure 18-12.** Voltage Waveform Across Transformer Secondary.

The secondary voltage waveform of transformer, T1, is shown in Figure 18-12. Waveform is taken between points D and E. The converter is properly tuned to the natural frequency.



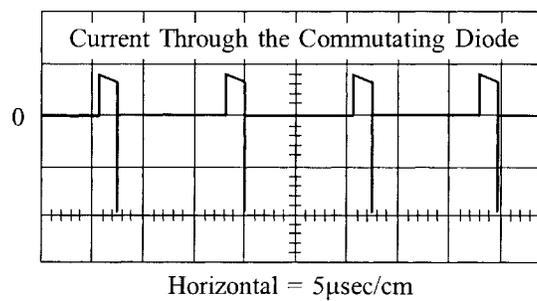
**Figure 18-13.** Secondary Rectified Voltage Waveform at CR2 and CR3.

The secondary, rectified voltage waveform, at the cathodes of, CR2 and CR3, is shown in Figure 18-13. Waveform is taken at point H. The converter is properly tuned to the natural frequency.



**Figure 18-14.** Secondary Current Waveform.

The secondary current waveform is shown in Figure 18-14. The current waveform is taken at point F.



**Figure 18-15.** Current Through the Commutating Diode, CR1.

Commutating diode current waveform is shown in Figure 18-15. The current is through the series inductor L1 winding (3-4). Waveform is taken at point C. The converter is properly tuned to the natural frequency.

## Technology on the Move

As technology moves ahead, instruments become more sophisticated, smaller in size, and require less power. Less power normally relates to lower current. Lower current requires smaller wire to carry the current. There is a practical point where the wire size can no longer be reduced, even though the current is very small. Reliability is affected when the wire size becomes very small. It becomes a handling and termination problem. If a larger wire size can be tolerated, and it does not impact the size a great deal, then, the larger wire should be used. The smallest wire size that seems to be tolerable, depending on the application, ranges from #35 to #39 AWG and this would be from a specialty house.

## Window Utilization Factor, $K_u$

When designing a transformer or inductor, the window utilization factor,  $K_u$ , is the amount of copper that appears in the window area. See Chapter 4. The window utilization factor,  $K_u$ , is influenced by five main factors:

1. Wire insulation,  $S_1$ .
2. Wire lay fill factor,  $S_2$ .
3. Effective window area,  $S_3$ .
4. Winding insulation,  $S_4$ .
5. Workmanship.

These factors multiplied together will give a normalized window utilization factor of  $K_u = 0.4$ .

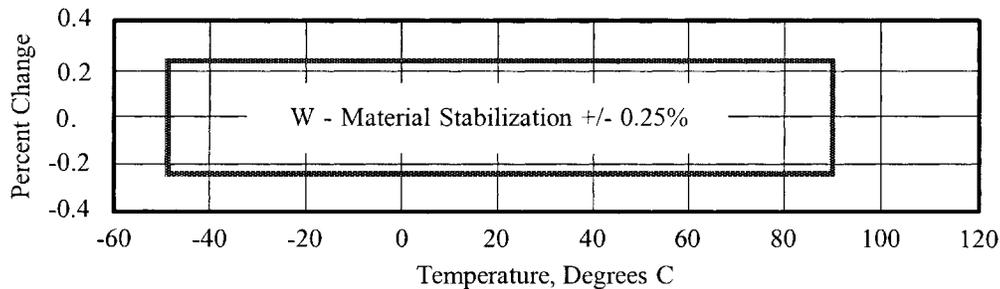
$$K_u = (S_1)(S_2)(S_3)(S_4) = 0.4 \quad [18-1]$$

The design of the current-fed sine wave converter is much more detailed and complex, compared to the simple voltage-fed, square wave converter. The sole reason to use the Quiet Converter is because of its inherent low noise, (EMI). The noise of the Quiet Converter can be, reduced even further by adding a primary and a secondary Faraday Shield. When a Faraday Shield is added between the primary and secondary, the transformer must be designed to accommodate the shield. Transformer size is, mainly determined by the loads. The window utilization,  $K_u$ , has to be adjusted during the design to accommodate the Faraday Shield. When the core size is selected for the transformer, it will be a little larger core, do to the added space required by the Faraday Shield.

After the preliminary design, the engineer will select the proper core size for the power transformer. The core geometry,  $K_g$ , will select the molypermalloy powder core size. After the molypermalloy powder core size has been selected, the engineer will now select a core with a permeability best-suited for the application. The molypermalloy powder cores come with a range of permeability from 14 to 550, all with the same core geometry,  $K_g$ .

## Temperature Stability

For the Quiet Converter to function properly over a wide temperature range, the components must be stable over that temperature range. The components that control the oscillator frequency must be stable. The LC tank circuit must be stable and not drift with temperature. Molypermalloy powder cores are offered with stabilized permeability, with code letters M, W, and D from Magnetics, Inc. The W material temperature stability is shown in Figure 18-16.



**Figure 18-16.** Typical, Stabilized Molypermalloy Material.

## Calculating the Apparent Power, $P_t$

The apparent power,  $P_t$ , is the power associated with the geometry of the transformer. The designer must be able to make allowances for the rms power in each winding. The primary winding handles,  $P_{in}$ , the secondaries handle,  $P_o$ , to the load. Since the power transformer has to be designed to accommodate the primary power,  $P_{in}$ , and the secondary,  $P_o$ , then by definition,

$$P_t = P_{in} + P_{\Sigma}, \quad [\text{watts}]$$

$$P_{\Sigma} = P_{o1} + P_{o2} + \dots + P_{on}$$

$$P_{in} = \frac{P_{\Sigma}}{\eta}, \quad [\text{watts}] \quad [18-2]$$

$$P_t = \frac{P_{\Sigma}}{\eta} + P_{\Sigma}, \quad [\text{watts}]$$

$$\eta = \text{efficiency}$$

The designer must be concerned with the apparent power-handling capability,  $P_t$ , of the transformer core and winding. The apparent power,  $P_t$ , may vary by a factor ranging from 2 to 2.828 times the input power,  $P_{in}$ , depending upon the type of circuit in which the transformer is used. If the current in the transformer becomes interrupted, such as a center-tapped secondary or push-pull primary, its effective rms value changes. Transformer size is thus determined not only by the load demand, but also by application, because of the different copper losses incurred owing to current waveforms.

Because of the different winding configurations, the apparent power,  $P_t$ , of the transformer will have to be summed to reflect these differences. When the winding has a center tap and produces a discontinuous current, then the power in that winding, whether it is primary or secondary, has to be multiplied by the factor,  $U$ , to correct for the rms current in that winding. If the winding has a center tap, then,  $U = 1.41$ ; if not, then,  $U = 1$ . Summing the output power of a multiple-output transformer would be:

$$P_{\Sigma} = P_{o1}(U) + P_{o2}(U) + \dots + P_{on}(U) \quad [18-3]$$

### Quiet Converter Design Equations

The transformer secondary voltage,  $V_s$ , is:

$V_o$  = Output voltage

$V_d$  = Diode Drop

$$V_s = (V_o + V_d), \quad [\text{volts}] \quad [18-4]$$

The maximum secondary true power,  $P_{s(\max)}$ , is:

$$P_{s(\max)} = V_s (I_{o(\max)}), \quad [\text{watts}] \quad [18-5]$$

The minimum secondary true power,  $P_{s(\min)}$ , is:

$$P_{s(\min)} = V_s (I_{o(\min)}), \quad [\text{watts}] \quad [18-6]$$

The secondary apparent power,  $P_{sa}$ , is:

$U = 1.41$ , center tapped winding

$U = 1.0$ , single winding

$$P_{sa} = V_s (I_{o(\max)})(U), \quad [\text{watts}] \quad [18-7]$$

If, there is more than one output, then, sum the total secondary maximum apparent load power,  $P_{sa\Sigma}$ .

$$P_{sa\Sigma} = P_{sa01} + P_{sa02} + \dots, \quad [\text{watts}] \quad [18-8]$$

If, there is more than one output, then, sum the total secondary maximum load power,  $P_{ot(\max)}$ .

$$P_{ot(\max)} = P_{o01(\max)} + P_{o02(\max)} + \dots, \quad [\text{watts}] \quad [18-9]$$

If, there is more than one output, then, sum the total secondary minimum load power,  $P_{ot(\min)}$ .

$$P_{ot(\min)} = P_{o01(\min)} + P_{o02(\min)} + \dots, \quad [\text{watts}] \quad [18-10]$$

The maximum reflected secondary load resistance,  $R_{(\max)}$ , is:

$R_{(\max)}$  = Resistance Value

$\eta$  = Efficiency

$$R_{(\max)} = \frac{(V_{in})^2 (\eta)}{P_{ol(\min)}}, \quad [\text{ohms}] \quad [18-11]$$

The required series inductor inductance,  $L1$ , is:

$f$  = fundamental frequency

$$L1 = \frac{(R_{(\max)})}{3\omega}, \quad [\text{henrys}] \quad [18-12]$$

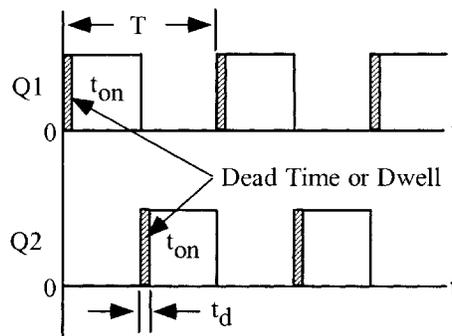
The total period,  $T$ , is:

$$T = \frac{1}{f}, \quad [\text{seconds}] \quad [18-13]$$

The maximum transistor on time,  $t_{on(\max)}$ , is:

Transistor drive circuits such as a pulse width modulator (PWM), will have a minimum of dead time,  $t_d$ . Dead time or dwell is shown in Figure 18-17.

$$t_{on(\max)} = \left(\frac{T}{2}\right) - t_d, \quad [\mu\text{sec}] \quad [18-14]$$



**Figure 18-17.** Transistor Drive Waveforms, Showing Dead Time or Dwell.

The conversion ratio,  $K_a$ , is:

$$K_a = \frac{(4t_{on(\max)} - T)}{T \text{Sin}\left(\frac{t_{on(\max)} 180}{T}\right)} \quad [18-15]$$

The peak voltage,  $V_{c(pk)}$ , on the resonant capacitor, C3, as shown in Figure 18-5, is:

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$V_{c(pk)} = \frac{\pi(K_a V_{in} K_b)}{2}, \text{ [volts] [18-16]}$$

The primary rms voltage,  $V_{p(rms)}$ , is:

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$V_{p(rms)} = \frac{0.707(V_{c(pk)})}{K_b}, \text{ [volts] [18-17]}$$

The primary maximum reflected secondary current,  $I_{ps}$ , is:

$$I_{ps} = \frac{P_{ot(max)}}{V_{p(rms)}\eta}, \text{ [amps] [18-18]}$$

The secondary reflected loads to the primary,  $R_{SR}$ , is:

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$R_{SR} = \frac{K_a V_{p(rms)} (K_b)^2}{I_{sp}}, \text{ [ohms] [18-19]}$$

Note: The capacitance reactance affects the total percentage of harmonic distortion when:

$$\omega R_{SR} C = 1, \approx [12\%], \quad \omega R_{SR} C = 2, \approx [6\%], \quad \omega R_{SR} C = 3, \approx [4\%]$$

As a general rule:

$$C_x = \frac{2}{2\pi f (R_{SR})}, \text{ [farads] [18-20]}$$

The resonant capacitance,  $C_x$ , is:

$Q_T$ , is a variable that provides the engineer a little latitude with the capacitance value. ( $1 < Q_T < 3$ )

$$C_x = \frac{Q_T}{2\pi f (R_{SR})}, \text{ [farads] [18-21]}$$

The reactance,  $X_{cx}$ , of capacitor,  $C_x$ , is:

Use a standard capacitor.

$$X_{cx} = \frac{1}{2\pi f C_x}, \text{ [ohms] [18-22]}$$

The capacitor rms current,  $I_{cx(rms)}$ , is:

$$I_{cx(rms)} = \frac{(0.707)(V_{c(pk)})}{X_{cx}}, \quad [\text{amps}] \quad [18-23]$$

The total primary current,  $I_{p(rms)}$ , is:

$$I_{p(rms)} = \sqrt{\left( (I_{p(rms)})^2 + (I_{cx(rms)})^2 \right)}, \quad [\text{amps}] \quad [18-24]$$

The primary tank inductance,  $L_x$ , is:

$$L_x = \frac{1}{(2\pi f)^2 C_x}, \quad [\text{henrys}] \quad [18-25]$$

The total transformer apparent power,  $P_t$ , is:

$$P_t = (\text{Primary VA}) + (\text{Secondary VA}) + (\text{Capacitor VA}), \quad [\text{watts}]$$

$$P_t = \left( \frac{P_{oi(\max)}(U)}{\eta} \right) + (P_{sa\Sigma}) + (K_b V_{p(rms)} I_{cx}), \quad [\text{watts}] \quad [18-26]$$

The core geometry,  $K_g$ , is:

$K_f$  is the waveform factor = 4.44

$B_{ac}$  is the operating flux density and its value is an engineering judgment based on the frequency and core material.

$$K_g = \left( \frac{P_t}{0.000029 (K_f)^2 (f)^2 (B_{ac})^2 \alpha} \right), \quad [\text{cm}^5] \quad [18-27]$$

## Transformer Design, Using the Core Geometry, $K_g$ , Approach

The following information is the Design specification for a 2.2 watt push-pull transformer, operating at 32kHz, using the  $K_g$  core geometry approach. For a typical design example, assume a push-pull, full wave bridge circuit, with the following specification:

1. Input voltage,  $V_{(min)}$  ..... = 22 volts
2. Output voltage #1,  $V_{s01}$  ..... = 5.0 volts
3. Output current #1,  $I_{s01(max)}$  ..... = 0.2 amps
4. Output current #1,  $I_{s01(min)}$  ..... = 0.1 amps
5. Output voltage #2,  $V_{s02}$  ..... = 12.0 volts
6. Output current #2,  $I_{s02(max)}$  ..... = 0.1 amps
7. Output current #2,  $I_{s02(min)}$  ..... = 0.05 amps
8. Frequency,  $f$  ..... = 32 kHz
9. Switching dead time,  $t_d$  ..... = 0.625 $\mu$ sec
10. Efficiency,  $\eta$  ..... = 95%
11. Regulation,  $\alpha$  ..... = 1.0 %
12. Diode voltage drop,  $V_d$  ..... = 0.5 volt
13. Operating flux density,  $B_{ac}$  ..... = 0.05 tesla
14. Core Material ..... = MPP
15. Window utilization,  $K_u$  ..... = 0.4
16. Temperature rise goal,  $T_r$  ..... = 15°C
17. Waveform coefficient,  $K_f$  ..... = 4.44
18. Notes:

Using a center tapped winding,  $U = 1.41$

Using a single winding,  $U = 1.0$

Step 1. Calculate the total secondary voltage,  $V_s$ , for each output.

$$V_s = (V_o) + (2V_d), \quad [\text{volts}]$$

$$V_{s01} = (5.0) + (1.0) = 6.0, \quad [\text{volts}]$$

$$V_{s02} = (12) + (1.0) = 13.0, \quad [\text{volts}]$$

Step 2. Calculate the maximum secondary true power,  $P_{s(max)}$ .

$$P_{s(max)} = V_s (I_{o(max)}), \quad [\text{watts}]$$

$$P_{s01(max)} = 6.0(0.2) = 1.2, \quad [\text{watts}]$$

$$P_{s02(max)} = 13.0(0.1) = 1.3, \quad [\text{watts}]$$

Step 3. Calculate the minimum secondary true power,  $P_{s(\min)}$ .

$$P_{s(\min)} = V_s (I_{o(\min)}), \text{ [watts]}$$

$$P_{s01(\min)} = 6.0(0.1) = 0.6, \text{ [watts]}$$

$$P_{s02(\min)} = 13.0(0.05) = 0.65, \text{ [watts]}$$

Step 4. Calculate the secondary apparent power,  $P_{sa}$ .

$$P_{sa} = V_s (I_{o(\max)})(U), \text{ [watts]}$$

$$P_{sa01} = 6.0(0.2)(1.0) = 1.2, \text{ [watts]}$$

$$P_{sa02} = 13.0(0.1)(1.0) = 1.3, \text{ [watts]}$$

Step 5. Calculate the secondary total maximum apparent load power,  $P_{sa\Sigma}$ .

$$P_{sa\Sigma} = P_{sa01} + P_{sa02}, \text{ [watts]}$$

$$P_{sa\Sigma} = (1.2) + (1.3), \text{ [watts]}$$

$$P_{sa\Sigma} = 2.5, \text{ [watts]}$$

Step 6. Calculate the secondary total maximum load power,  $P_{ot(\max)}$ .

$$P_{ot(\max)} = P_{o01(\max)} + P_{o02(\max)}, \text{ [watts]}$$

$$P_{ot(\max)} = (1.2) + (1.3), \text{ [watts]}$$

$$P_{ot(\max)} = 2.5, \text{ [watts]}$$

Step 7. Calculate the secondary total minimum load power,  $P_{ot(\min)}$ .

$$P_{ot(\min)} = P_{o01(\min)} + P_{o02(\min)}, \text{ [watts]}$$

$$P_{ot(\min)} = (0.6) + (0.65), \text{ [watts]}$$

$$P_{ot(\min)} = 1.25, \text{ [watts]}$$

Step 8. Calculate the secondary maximum reflected load resistance,  $R_{(\max)}$ .

$R_{(\max)}$  = Resistance Value

$\eta$  = Efficiency

$$R_{(\max)} = \frac{(V_{in})^2 (\eta)}{P_{ot(\min)}}, \text{ [ohms]}$$

$$R_{(\max)} = \frac{(22)^2 (0.95)}{1.25}, \text{ [ohms]}$$

$$R_{(\max)} = 368, \text{ [ohms]}$$

Step 9. Calculate the inductance of the series inductor, L1.

$$L1 = \frac{R_{(\max)}}{3\omega}, \text{ [henrys]}$$

$$L1 = \frac{(368)}{3(2(3.14)(32000))}, \text{ [henrys]}$$

$$L1 = 0.000610, \text{ [henrys]}$$

Step 10. Calculate the total period, T.

$$T = \frac{1}{f}, \text{ [seconds]}$$

$$T = \frac{1}{32,000}, \text{ [seconds]}$$

$$T = 31.25, \text{ [micro-seconds]}$$

Step 11. Calculate the maximum transistor on time,  $T_{on(\max)}$ . Dead time is shown in Figure 18-17.

$$t_{on(\max)} = \left(\frac{T}{2}\right) - t_d, \text{ [usec]}$$

$$t_{on(\max)} = \left(\frac{31.25}{2}\right) - 0.625, \text{ [usec]}$$

$$t_{on(\max)} = 15, \text{ [usec]}$$

Step 12. Calculate the conversion ratio,  $K_a$ .

$$K_a = \frac{(4t_{on(\max)} - T)}{T \text{Sin}\left(\frac{t_{on(\max)} 180}{T}\right)}$$

$$K_a = \frac{(4(15) - (32.25))}{(32.25) \text{Sin}\left(\frac{(15)180}{32.25}\right)}$$

$$K_a = 0.866$$

Step 13. Calculate the peak voltage,  $V_{c(pk)}$ , on the resonant capacitor, C3, as shown in Figure 18-5.

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$V_{c(pk)} = \frac{\pi(K_a V_{in} K_b)}{2}, \text{ [volts]}$$

$$V_{c(pk)} = \frac{(3.1415)(0.866)(22)(2)}{2}, \text{ [volts]}$$

$$V_{c(pk)} = 59.85, \text{ [volts]}$$

Step 14. Calculate the primary rms voltage,  $V_{p(rms)}$ .

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$V_{p(rms)} = \frac{0.707(V_{c(pk)})}{K_b}, \text{ [volts]}$$

$$V_{p(rms)} = \frac{0.707(59.85)}{2}, \text{ [volts]}$$

$$V_{p(rms)} = 21.2, \text{ [volts]}$$

Step 15. Calculate the primary maximum reflected secondary current,  $I_{ps}$ .

$$I_{ps} = \frac{P_{ot(max)}}{V_{p(rms)}\eta}, \text{ [amps]}$$

$$I_{ps} = \frac{2.5}{(21.2)(0.95)}, \text{ [amps]}$$

$$I_{ps} = 0.124, \text{ [amps]}$$

Step 16. Calculate the secondary reflected loads to the primary,  $R_{SR}$ .

$K_b = 2$ , center tapped winding.

$K_b = 1$ , single winding.

$$R_{SR} = \frac{K_a V_{p(rms)} (K_b)^2}{I_{sp}}, \text{ [ohms]}$$

$$R_{SR} = \frac{(0.866)(21.2)(2)^2}{0.124}, \text{ [ohms]}$$

$$R_{SR} = 592, \text{ [ohms]}$$

Note: The capacitance reactance effects the total percentage of harmonic distortion when:

$$\omega R_{SR} C = 1, \approx [12\%], \quad \omega R_{SR} C = 2, \approx [6\%], \quad \omega R_{SR} C = 3, \approx [4\%]$$

As a general rule:

$$C_x = \frac{2}{2\pi f (R_{SR})}, \text{ [farads]}$$

Step 17. Calculate the resonant capacitance,  $C_x$ .

$$C_x = \frac{2}{2\pi f (R_{SR})}, \text{ [farads]}$$

$$C_x = \frac{2}{(6.28)(32000)(592)}, \text{ [farads]}$$

$$C_x = 1.68(10^{-8}), \text{ [farads]}$$

$$C_x = 0.0168 \text{ use a } 0.015, \text{ [micro-farads]}$$

Step 18. Calculate the reactance,  $X_{cx}$ , of capacitor,  $C_x$ . Use a standard capacitor. Let,  $C_x$ , equal  $0.015\mu\text{f}$ .

$$X_{cx} = \frac{1}{2\pi f C_x}, \quad [\text{ohms}]$$

$$X_{cx} = \frac{1}{(6.28)(32,000)(0.015(10^{-6}))}, \quad [\text{ohms}]$$

$$X_{cx} = 332, \quad [\text{ohms}]$$

Step 19. Calculate the capacitor current,  $I_{cx(\text{rms})}$ .

$$I_{cx(\text{rms})} = \frac{(0.707)(V_{c(pk)})}{X_{cx}}, \quad [\text{amps}]$$

$$I_{cx(\text{rms})} = \frac{(0.707)(59.85)}{332}, \quad [\text{amps}]$$

$$I_{cx(\text{rms})} = 0.127, \quad [\text{amps}]$$

Step 20. Calculate the total primary current,  $I_{p(\text{rms})}$ .

$$I_{p(\text{rms})} = \sqrt{\left(I_{p(\text{rms})}\right)^2 + \left(I_{cx(\text{rms})}\right)^2}, \quad [\text{amps}]$$

$$I_{p(\text{rms})} = \sqrt{\left(0.124\right)^2 + \left(0.127\right)^2}, \quad [\text{amps}]$$

$$I_{p(\text{rms})} = 0.177, \quad [\text{amps}]$$

Step 21. Calculate primary tank inductance,  $L_x$ .

$$L_x = \frac{1}{(2\pi)^2 (f)^2 C_x}, \quad [\text{henrys}]$$

$$L_x = \frac{1}{(6.28)^2 (32000)^2 (0.015(10^{-6}))}, \quad [\text{henrys}]$$

$$L_x = 0.00165, \quad [\text{henrys}]$$

Step 22. Calculate the total transformer apparent power,  $P_t$ .

$$P_t = (\text{Primary VA}) + (\text{Secondary VA}) + (\text{Capacitor VA}), \quad [\text{watts}]$$

$$P_t = \left(\frac{P_{ot(\text{max})}(U)}{\eta}\right) + (P_{sa\Sigma}) + (K_b V_{p(\text{rms})} I_{cx}), \quad [\text{watts}]$$

$$P_t = \left(\frac{(2.5)(1.41)}{0.95}\right) + (2.5) + ((2)(21.2)(0.127)), \quad [\text{watts}]$$

$$P_t = 11.6, \quad [\text{watts}]$$

Step 23. Calculate the core geometry,  $K_g$ .  $B_{ac}$  is the operating flux density and its value is an engineering judgment based on the frequency and core material.

$$K_g = \left( \frac{P_t}{0.000029 (K_f)^2 (f)^2 (B_{ac})^2 \alpha} \right), \text{ [cm}^5\text{]}$$

$$K_g = \left( \frac{11.6}{0.000029 (4.44)^2 (32,000)^2 (0.05)^2 (1)} \right), \text{ [cm}^5\text{]}$$

$$K_g = 0.00793, \text{ [cm}^5\text{]}$$

### Design Review

|   |                      |
|---|----------------------|
| Conversion factor, $K_a$ .....                    | 0.866                |
| Tank Capacitance, $C_x$ .....                     | 0.015 $\mu$ f        |
| Tank Capacitance Peak Voltage, $V_{cx}$ .....     | 59.85 volts          |
| Tank Capacitance rms Current, $I_{cx(rms)}$ ..... | 0.127 amps           |
| Primary Inductance, $L_x$ .....                   | 0.00165 henrys       |
| Series Inductor, $L1$ .....                       | 0.000610 henrys      |
| Primary Reflected Current, $I_{ps(rms)}$ .....    | 0.124 amps           |
| Primary rms Voltage, $V_{p(rms)}$ .....           | 21.2 volts           |
| Primary Total rms Current, $I_{tp(rms)}$ .....    | 0.177 amps           |
| Secondary Total Load Power, $P_{ot(max)}$ .....   | 2.5 watts            |
| Transformer Total Apparent Power, $P_t$ .....     | 11.6 watts           |
| Transformer Core Geometry, $K_g$ .....            | 0.0107 $\text{cm}^2$ |

Step 24. From Chapter 3, select a MPP powder core, comparable in core geometry,  $K_g$ .

|                                      |                       |
|--------------------------------------|-----------------------|
| Core part number .....               | 55848-W4              |
| Manufacturer .....                   | Magnetics             |
| Magnetic path length, MPL .....      | = 5.09 cm             |
| Core weight, $W_{tfe}$ .....         | = 9.4 gm              |
| Copper weight, $W_{tcu}$ .....       | = 11.1 gm             |
| Mean length turn, MLT .....          | = 2.8 cm              |
| Iron area, $A_c$ .....               | = 0.226 $\text{cm}^2$ |
| Window area, $W_a$ .....             | = 1.11 $\text{cm}^2$  |
| Area product, $A_p$ .....            | = 0.250 $\text{cm}^4$ |
| Core geometry, $K_g$ .....           | = 0.008 $\text{cm}^5$ |
| Surface area, $A_t$ .....            | = 22.7 $\text{cm}^2$  |
| Permeability, $\mu$ .....            | = 60                  |
| Millihenrys per 1000 turns, AL ..... | = 32                  |

Step 25. Calculate the total number of primary turns,  $N_{tp}$ .

$$N_{tp} = 1000 \sqrt{\frac{L_{(new)}}{L_{(1000)}}}, \quad [\text{turns}]$$

$$N_{tp} = 1000 \sqrt{\frac{1.65}{32}}, \quad [\text{turns}]$$

$$N_{tp} = 226, \quad \text{round-down} \quad [\text{turns}]$$

$$N_p = 113, \quad [\text{each side center tap}]$$

Step 26. Calculate the operating flux density,  $B_{ac}$ .

$$B_{ac} = \frac{V_p(rms)(10^4)}{K_f N_p f A_c}, \quad [\text{tesla}]$$

$$B_{ac} = \frac{(21.2)(10^4)}{(4.44)(113)(32000)(0.226)}, \quad [\text{tesla}]$$

$$B_{ac} = 0.0587, \quad [\text{tesla}]$$

Step 27. Calculate the watts per kilogram, WK, using the MPP 60 perm loss equation in Chapter 2.

$$WK = 0.788(10^{-3})(f)^{(1.41)}(B_{ac})^{(2.24)}, \quad [\text{watts/kilogram}]$$

$$WK = 0.788(10^{-3})(32000)^{(1.41)}(0.0587)^{(2.24)}, \quad [\text{watts/kilogram}]$$

$$WK = 3.09, \quad [\text{watts/kilogram}] \text{ or } 3.09, \quad [\text{milliwatts/gram}]$$

Step 28. Calculate the core loss,  $P_{fe}$ .

$$P_{fe} = \left( \frac{\text{milliwatts}}{\text{grams}} \right) W_{fe} (10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = (3.09)(9.4)(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = 0.0290, \quad [\text{watts}]$$

Step 29. Calculate the volts per turn,  $K_{N/V}$ .

$$K_{N/V} = \frac{N_p}{V_p}, \quad [\text{turns/volt}]$$

$$K_{N/V} = \frac{(113)}{(21.2)}, \quad [\text{turns/volt}]$$

$$K_{N/V} = 5.33, \quad [\text{turns/volt}]$$

Step 30. Calculate the secondary number of turns  $N_s$ .  $\alpha$  is regulation in percent. See Chapter 6.

$$K = \left(1 + \frac{\alpha}{100}\right) = 1.01$$

$$N_{s01} = K_{N/V} V_{s01} K = (5.33)(6.0)(1.01) = 32, \text{ [turns]}$$

$$N_{s02} = K_{N/V} V_{s02} K = (5.33)(13.0)(1.01) = 70, \text{ [turns]}$$

Step 31. Calculate the current density,  $J$ , using a window utilization,  $K_u = 0.4$ .

$$J = \frac{P_t 10^4}{A_p B_m f K_f K_u}, \text{ [amps per cm}^2\text{]}$$

$$J = \frac{(11.6)10^4}{(0.25)(0.0587)(32000)(4.44)(0.4)}, \text{ [amps per cm}^2\text{]}$$

$$J = 139, \text{ [amps per cm}^2\text{]}$$

Step 32. Calculate the secondary required wire area,  $A_{ws}$ .

$$A_{ws01} = \frac{I_{s(01)(rms)}}{J} = \frac{0.2}{139} = 1.44 \times 10^{-3}, \text{ [cm}^2\text{]}$$

$$A_{ws02} = \frac{I_{s(02)(rms)}}{J} = \frac{0.1}{139} = 0.719 \times 10^{-3}, \text{ [cm}^2\text{]}$$

Step 33. Then select the wire from the Wire Table, in Chapter 4. Record  $\mu\Omega/cm$ .

$$A_{ws01} = 1.44 \times 10^{-3}, \text{ use \#26} = 1.28 \times 10^{-3}, \text{ [cm}^2\text{]}$$

$$\#26, \frac{\mu\Omega}{cm} = 1345$$

$$A_{ws02} = 0.719 \times 10^{-3}, \text{ use \#29} = 0.647 \times 10^{-3}, \text{ [cm}^2\text{]}$$

$$\#29, \frac{\mu\Omega}{cm} = 2664$$

Step 34. Calculate the primary required wire area,  $A_{wp}$ .

$$A_{wp} = \frac{I_{ip(rms)}}{J}, \text{ [cm}^2\text{]}$$

$$A_{wp} = \frac{(0.177)}{139}, \text{ [cm}^2\text{]}$$

$$A_{wp} = 1.27 \times 10^{-3}, \text{ [cm}^2\text{]}$$

Step 35. Then select the wire from the Wire Table, in Chapter 4. Record  $\mu\Omega/cm$ .

$$A_{wp} = 1.27 \times 10^{-3}, \text{ use \#26} = 1.28 \times 10^{-3}, \text{ [cm}^2\text{]}$$

$$\#26, \frac{\mu\Omega}{cm} = 1345$$

Step 36. Calculate the total secondary window utilization,  $K_{us}$ .

$$K_{us01} = \frac{(N_{01} A_{w01})}{W_a} = \frac{(32)(0.00128)}{1.11} = 0.0369$$

$$K_{us02} = \frac{(N_{02} A_{w02})}{W_a} = \frac{(70)(0.000647)}{1.11} = 0.0408$$

$$K_{us} = K_{us01} + K_{us02} = 0.0777$$

Step 37. Calculate the primary window utilization,  $K_{up}$ .

$$K_{up} = \frac{(N_p A_w)}{W_a}$$

$$K_{up} = \frac{(226)(0.00128)}{1.11}$$

$$K_{up} = 0.261$$

Step 38. Calculate the total window utilization,  $K_u$ .

$$K_u = K_{up} + K_{us}$$

$$K_u = 0.261 + 0.0777$$

$$K_u = 0.339$$

Step 39. Calculate the primary, winding resistance,  $R_p$ .

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

$$R_p = 2.80(113)(1345)(10^{-6}), \quad [\text{ohms}]$$

$$R_p = 0.426, \quad [\text{ohms}]$$

Step 40. Calculate the primary, copper loss,  $P_p$ .

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

$$P_p = (0.177)^2 (0.426), \quad [\text{watts}]$$

$$P_p = 0.0133, \quad [\text{watts}]$$

Step 41. Calculate the secondary, winding resistance,  $R_s$ .

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

$$R_{s01} = 2.80(32)(1345)(10^{-6}) = 0.121, \quad [\text{ohms}]$$

$$R_{s02} = 2.80(70)(2664)(10^{-6}) = 0.186, \quad [\text{ohms}]$$

Step 42. Calculate the secondary, copper loss,  $P_s$ .

$$P_s = (I_{s(rms)})^2 R_s, \text{ [watts]}$$
$$P_{s01} = (0.2)^2 (0.121) = 0.00484, \text{ [watts]}$$
$$P_{s02} = (0.1)^2 (0.186) = 0.00186, \text{ [watts]}$$

Step 43. Calculate the total secondary, copper loss,  $P_{ts}$ .

$$P_{ts} = P_{s01} + P_{s02}, \text{ [watts]}$$
$$P_{ts} = 0.00484 + 0.00186, \text{ [watts]}$$
$$P_{ts} = 0.0067, \text{ [watts]}$$

Step 44. Calculate the total loss, core and copper,  $P_\Sigma$ .

$$P_\Sigma = P_p + P_{ts} + P_{fc}, \text{ [watts]}$$
$$P_\Sigma = (0.0133) + (0.0067) + (0.0290), \text{ [watts]}$$
$$P_\Sigma = 0.049, \text{ [watts]}$$

Step 45. Calculate the watts per unit area,  $\psi$ .

$$\psi = \frac{P_\Sigma}{A_t}, \text{ [watts per cm}^2\text{]}$$
$$\psi = \frac{(0.049)}{(22.7)}, \text{ [watts per cm}^2\text{]}$$
$$\psi = 0.00216, \text{ [watts per cm}^2\text{]}$$

Step 46. Calculate the temperature rise,  $T_r$ .

$$T_r = 450(\psi)^{(0.826)}, \text{ [}^\circ\text{C]}$$
$$T_r = 450(0.00216)^{(0.826)}, \text{ [}^\circ\text{C]}$$
$$T_r = 2.83, \text{ [}^\circ\text{C]}$$

Step 47. Calculate the,  $Q_t$ , of the tank.

$$Q_t = 2\pi f C_x R_{SR}$$
$$Q_t = (6.28)(32000)(0.015(10^{-6}))(592)$$
$$Q_t = 1.79$$

For more information see Equation [18-20].

## References

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2. S. Lendena, "Current-Fed Inverter." 20<sup>th</sup> Annual Proceedings Power Sources Conference, May 24 1966.
3. S. Lendena, "Single Phase Inverter for a Three Phase Power Generation and Distribution System." Electro-Optical-System, Contract #954272, from Jet Propulsion Laboratory, January 1976.