# Chapter 9

## Design of High-Frequency Inductors and Transformers


9-1 Introduction

9-2 Basics of Magnetic Design

9-3 Inductor and Transformer Construction

9-4 Area-Product Method

9-5 Design Example of an Inductor

9-6 Design Example of a Transformer for a Forward Converter

9-7 Thermal Considerations

References

Problems

# BASICS OF MAGNETIC DESIGN

- The peak flux density $B_{\max}$ in the magnetic core to limit core losses, and
- The peak current density $J_{\max}$ in the winding conductors to limit conduction losses

# INDUCTOR AND TRANSFORMER CONSTRUCTION

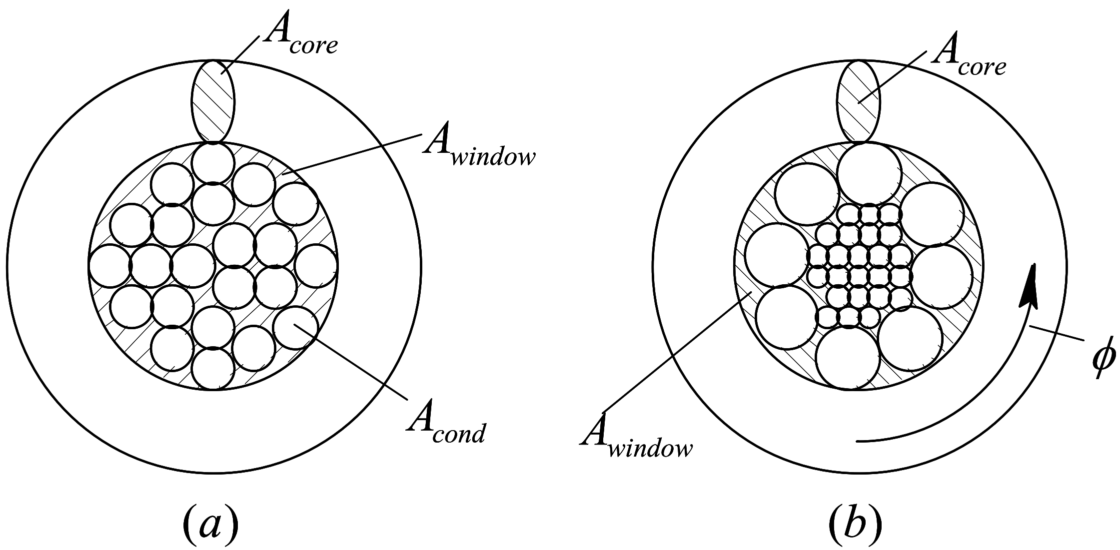


Figure 9-1 Cross-sections.

# AREA-PRODUCT METHOD

**Core Window Area** $A_{window}$

$$A_{window} = \frac{1}{k_w} \sum_y \left( N_y A_{cond,y} \right)$$

$$A_{cond,y} = \frac{I_{rms,y}}{J_{\max}}$$

$$A_{window} = \frac{\sum_y \left( N_y I_{rms,y} \right)}{k_w J_{\max}}$$

**Core Cross-Sectional Area** $A_{core}$

$$A_{core} = \frac{\hat{\phi}}{B_{\max}}$$

inductor: $\hat{\phi} = \frac{L\hat{I}}{N}$ $A_{core} = \frac{L\hat{I}}{NB_{\max}}$

transformer:

$$\hat{\phi} = \frac{k_{conv}V_{in}}{N_1 f_s}$$

$$A_{core} = \frac{k_{conv}V_y}{N_y f_s B_{\max}}$$

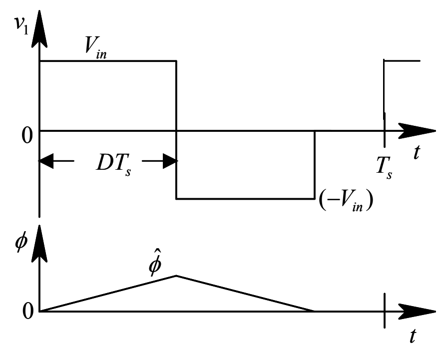


Figure 9-2 Waveforms in a transformer for a Forward converter.

**Core Area-Product** $A_p = A_{core} A_{window}$

inductor: $$A_p = \frac{L\hat{I} I_{rms}}{k_w J_{\max} B_{\max}}$$

transformer: $$A_p = \frac{k_{conv} \sum V_y I_{y,rms}}{k_w B_{\max} J_{\max} f_s}$$

**Design Procedure Based on Area-Product** $A_p$

inductor: $$N = \frac{L\hat{I}}{B_{\max} A_{core}} \qquad L \simeq \frac{N^2}{\Re_g} \qquad \Re_g \simeq \frac{\ell_g}{\mu_o A_{core}} \qquad \ell_g = \frac{N^2 \mu_o A_{core}}{L}$$

transformer: $$N_y = \frac{k_{conv} V_y}{A_{core} f_s B_{\max}}$$

**DESIGN EXAMPLE OF AN INDUCTOR**

In this example, we will discuss the design of an inductor that has an inductance $L = 100\mu H$. The worst-case current through the inductor is shown in Fig. 9-3, where the average current $I = 5.0\,A$, and the peak-peak ripple $\Delta I = 0.75\,A$ at the switching frequency $f_s = 100\,kHz$. We will assume the following maximum values for the flux density and the current density: $B_{\max} = 0.25\,T$, and $J_{\max} = 6.0\,A/mm^2$ (for larger cores, this is typically in a range of 3 to $4\,A/mm^2$). The window fill factor is assumed to be $k_w = 0.5$.

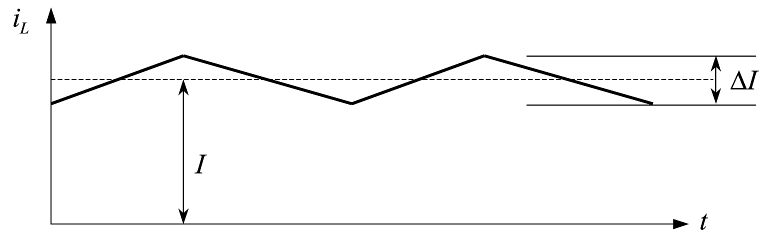


Figure 9-3 Inductor current waveforms.

$$\hat{I} = I + \frac{\Delta I}{2} = 5.375\,A$$

$$I_{rms} = \sqrt{I^2 + \frac{1}{12}\Delta I^2} \simeq 5.0\,A$$

$$A_p = \frac{100 \times 10^{-6} \times 5.375 \times 5}{0.5 \times 0.25 \times 6 \times 10^6} \times 10^{12} = 3587\,mm^4$$

From the Magnetics, Inc. catalog [2], we will select a P-type material, which has the saturation flux density of $0.5T$ and is quite suitable for use at the switching frequency of $100 kHz$. A pot core 26×16, which is shown in Fig. 9-4 for a laboratory experiment, has the core Area $A_{core} = 93.1 mm^2$ and the window Area $A_{window} = 39 mm^2$. Therefore, we will select this core, which has an Area-Product $A_p = 93.1 \times 39 = 3631 mm^4$.

$$N = \frac{100\mu \times 5.375}{0.25 \times 93.1 \times 10^{-6}} \simeq 23$$

Winding wire cross sectional area $A_{cond} = I_{rms} / J_{\max} = 5.0/6.0 = 0.83 mm^2$. We will use five strands of American Wire Gauge AWG 25 wires [3], each with a cross-sectional area of $0.16 mm^2$, in parallel.

$$\ell_g = \frac{23^2 \times 4\pi \times 10^{-7} \times 93.1 \times 10^{-6}}{100\mu} \simeq 0.62 mm$$

Figure 9-4 Pot core mounted on a plug-in board.

**DESIGN EXAMPLE OF A TRANSFORMER FOR A FORWARD CONVERTER**

The required electrical specifications for the transformer in a Forward converter are as follows: $f_s = 100kHz$ and $V_1 = V_2 = V_3 = 30V$. Assume the rms value of the current in each winding to be $2.5A$. We will choose the following values for this design:

$B_{\max} = 0.25\,\text{T}$ and $J_{\max} = 5\,\text{A/mm}^2$. $k_w = 0.5$ $k_{conv} = 0.5$

$$A_p = \frac{k_{conv}}{k_w f_s B_{\max} J_{\max}} \sum_y \hat{V}_{\text{y}} I_{rms,y} = 1800 \text{ mm}^4$$

For the pot core 22×13 [2], $A_{core} = 63.9 \text{ mm}^2$, $A_{window} = 29.2 \text{ mm}^2$, and therefore $A_p = 1866 \text{ mm}^4$.

$$A_{cond,1} = \frac{I_{1,rms}}{J_{\max}} = \frac{2.5}{5} = 0.5 \text{ mm}^2$$

We will use three strands of AWG 25 wires [3], each with a cross-sectional area of $0.16mm^2$, in parallel for each winding.

$$N_1 = \frac{0.5 \times 30}{\left(63.9 \times 10^{-6}\right) \times \left(100 \times 10^3\right) \times 0.25} \simeq 10 \qquad N_1 = N_2 = N_3 = 10$$

## 9-7 THERMAL CONSIDERATIONS

Designs presented here do not include eddy current losses in the windings, which can be very substantial due to proximity effects in inductors. These effects are carefully considered in [1]. Therefore, the area-product method is a good starting point, but the designs must be evaluated for temperature rise based on thermal considerations.