CHAPTER 11

High Frequency Inductors and Transformers

11.1 Design of Magnetic Components for Power Electronics

Magnetic components, inductors and transformers, are an indispensible part of most power electronic converters. In this situation the power electronic equipment designer/user must be knowledgeable about the design and fabrication of these components in order to specify and use them properly in a given-application.

11.2 Magnetic Material and Cores

Magnetic Core Materials

Two broad classes of materials are used for magnetic cores for inductors and transformers. One class of materials are comprised of alloys principally of iron and small amounts of other elements including chrome and silicon. These alloys have large electrical conductivity compared with ferrities and large values of saturation flux density, near 1.8 tesla (*T*) (one $T = 1\ Wb/m^2$). Two types of loss are found in iron alloy materials, hysteresis loss and eddy current loss. Iron alloys core materials (often termed magnetic steels) are usually used only in low-frequency (2 kHz or less for transformers) applications because of eddy current loss. Iron alloy magnetic materials must be laminated to reduce eddy current loss even at modest frequencies such as 60 Hz. Cores are also made from powdered iron and powdered iron alloys. Powdered iron cores consist of small (less than a skin depth in their largest dimension even at moderately high frequencies) iron particles electrically isolated from each other and thus have significantly greater resistivity than laminated cores. Thus powered iron cores have lower eddy current loss than laminated cores and can be used to higher frequencies.

The second broad class of materials used for cores are ferities. Ferrite materials are basically oxide mixtures of iron and other magnetic elements. They have quite large electrical resistivity but rather low saturation flux densities, typically about 0.3 T. Ferrites have only hysteresis loss. No significant eddy current loss occurs because of the high electrical resistivity. Ferrites are the material of choice for cores that operate at high frequencies (greater than 10 kHz) because of the low eddy current loss.

11.3 Hysteresis Loss

The hysteresis loss increases in all core materials increases with increases in ac flux density, B_{ac}, and operating or switching frequency, *f*. The general form of the loss per unit volume (sometimes termed the specific loss), $P_{m,\,sp}$, is

$$P_{m,sp} = kf^a(B_{ac})^d$$

where *k*, *a*, and *d* are constants that vary from one material to another. This equation applies over a limited range of frequency and flux density with the range of validity being dependent on the specific material. The flux density B_{ac} in equation is the peak value of the ac waveform as shown in figure a if the flux density waveform has no time average. When the flux density waveform has a time-average B_{avg} as shown in Fig. b, then the appropriate value to use in equation is $B_{ac} = B - B_{avg}$. Core manufacturers provide detailed information about core loss usually in the form of graphs of specific loss $P_{m,\,sp}$ as a function of flux density B_{ac} with frequency as a parameter. An example of such a graph is shown in figure a for the ferrite material 3F3, and equation for this material is

$$P_{m,\,sp} = 1.5 \times 10^{-6} f^{1.3} (B_{ac})^{2.5}$$

with $P_{m,\,sp}$ in mW/cm^3 when *f* is in kHz and B_{ac} is in mT. In selected METGLAS alloys, the core losses may be comparable to ferrites, in spite of the fact that the amorphous alloys have much lower resistivity that ferrites and thus will have eddy current losses. For the METGLAS alloys 2705 M, the core losses are given by

$$P_{m,\,sp} = 3.2 \times 10^{-6} f^{1.8}(B_{ac})^2$$

The units in equation *b* are the same as in a. At a frequency of 100 kHz and a flux density B_{ac} of 100 mT, the 3F3 ferrite characterised by equation a would have $P_{m,\,sp} = 60$ mW/cm^3 while for the 2705 M alloy, $P_{m,\,sp} = 127$ mW/cm^3.

11.4 Skin Effect Limitations

When a magnetic core is made from conducting materials such as magnetic steels time-varying magnetic fields applied to the core will generate circulating current as is diagrammed in figure a. Using the right-hand rule, it can be seen that these currents, generically termed eddy currents, flow in directions such that secondary magnetic fields are produced that oppose the applied (primary) magnetic field. These opposing fields tend to screen the interior of the core from the applied field, and the total magnetic field in the core decays exponentially with distance into the core as is shown in figure b.

The characteristic decay length in the exponential is termed the skin depth and is given by

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

where $f = \omega/2\pi$ is the frequency (in hertz) of the applied magnetic field, μ is the magnetic permeability of the core material, and σ is the conductivity of the magnetic material If the cross-sectional dimensions of the core are large compared to the skin depth, then the interior of the core carries little or none of the applied magnetic flux as is diagrammed in figure b and the core is ineffective in its intended role of providing a low reluctance return path for the applied magnetic field. Typical values of the skin depth are quite small even at low frequencies (typically 1 mm at 60 Hz) because of the large permeability of the materials and the skin depth becomes more of a problem as the applied frequency increases.

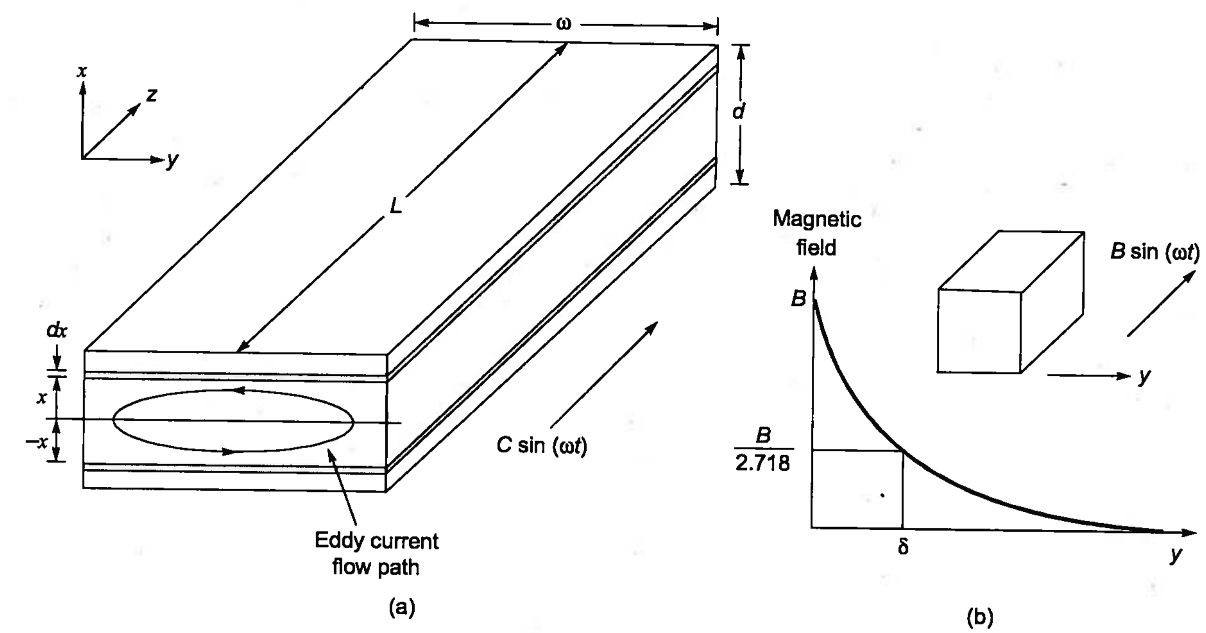

Figure-11.1 : *(a) Eddy currents generated in a thin transformer lamination by an applied time-varying magnetic field and (b) decay of the magnetic field versus depth y into the interior of a thick bar of magnetic material.*

Most magnetic steel have a small percentage of silicon added to the iron to increase the resistivity of the material and thus increase the skin depth. Addition of more than a few percent of silicon, however, reduces the magnetic properties such as saturation flux density more than it increases the resistivity. Hence a reasonable compromise for transformers for 50/60 Hz applications is an iron alloy of 97% iron–3% silicon and a lamination thickness approximately of 0.3 mm.

11.5 Eddy Current Loss in Laminated Cores

The eddy currents generated in the conductive core dissipate power, generically termed eddy current loss, in the core and raise its temperature.

The specific eddy current loss, $P_{ec,\,sp}$ (loss per unit volume) are given by

$$P_{ec,\,sp} = \frac{d^2\omega^2B^2}{24\rho_{core}}$$

11.6 Coppwer Windings

The conductor windings in an inductor or transformer are made from copper because of its high conductivity. The high ductility of the copper makes it easy to bend the conductors into tight windings around a magnetic core and thus minimize the amount of copper and volume needed for the windings. High conductivity contributes to minimizing the amount of copper needed for the windings and thus to the volume and weight of the windings. At the current densities used in inductors and transformers, electrical loss is a significant source of heat even though the conductivity of copper is large. The heat generated raises the temperature of both the windings an the magnetic core. The amount of dissipation allowable in the windings will be limited by maximum temperature considerations just as was described for the core loss.

11.7 Winding Loss Due to DC Resistance of Windings

The power $P_{Cu, sp}$ dissipated per unit of copper volume in a copper winding due to its dc resistance is given by

$$P_{Cu, sp} = \rho_{Cu} (J_{rms})^2$$

where $J_{rms} = I_{rms}/A_{cu}$ is the current density in the conductor and I_{rms} is the rms current in the winding. However, it is more convenient to express $P_{Cu, sp}$ as power dissipated per unit of winding volume, $P_{w, sp}$. The total volume V_{cu} of the copper is given by $V_{cu} = k_{Cu}V_w$, where V_w is the total winding volume. Using this result to express $P_{w, sp}$ yields

$$P_{w, sp} = k_{Cu} \rho_{Cu} (J_{rms})^2$$

If the resistivity of copper at 100°C (2.2 x 10–8 Ω-m) is used in equation and J_{rms} is A/mm², the value of $P_{w, sp}$ becomes

$$P_{w, sp} = 22k_{Cu} (J_{rms})^2 (\text{mW/cm}^3)$$

11.8 Skin Effect in Copper Windings

The skin effect occurs in the copper conductors used in inductor and transformer windings in exactly the same manner as described for the magnetic core. Consider the single copper conductor shown in figure a, which is carrying at a time-varying current $i(t)$. This current generates the magnetic fields shown in figure a, and they in turn generate the eddy currents illustrated in fig b.

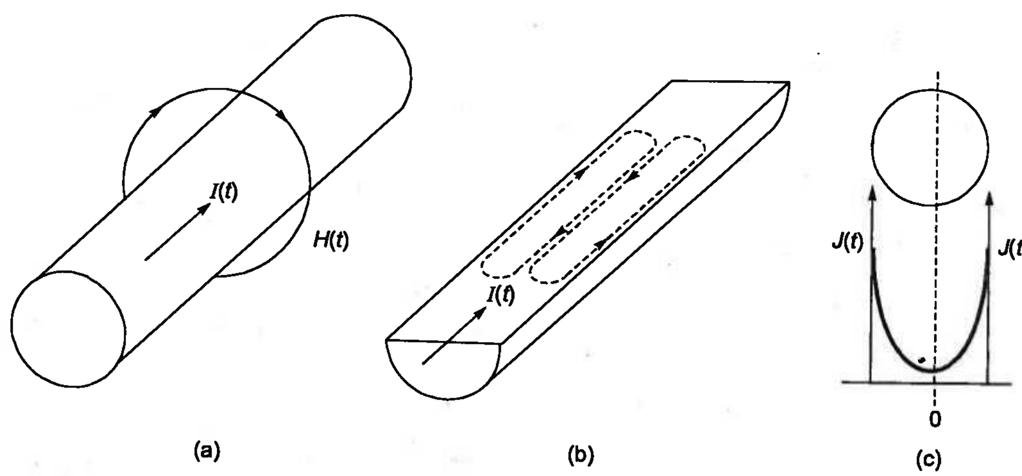

Figure-11.2 : *Isolated copper conductor carrying (a) a current i(t), (b) eddy current generated by the resulting magnetic field, and (c) the consequences of the skin effect on the current distribution*

Skin Depth in Copper at 100°C for Several Different Frequencies				
Frequency	50 Hz	5 kHz	20 kHz	500 kHz
δ	10.6 mm	1.06 mm	0.53 mm	0.106 mm

The net result of this is that the effective resistance of the conductor will be far larger than the dc resistance because the effective cross-sectional area for current flow is small compared to the geometric cross section of the conductor. This will cause the winding losses to be much larger than if it were a dc current.

The solution to this problem is to use conductors with cross-sectional dimensions on the order of the skin depth in size. If d is the diameter of a round conductor or the thickness of a rectangular conductor, calculations have shown that if $d \leq 2\delta$ the consequences of the skin effect can be neglected. Such considerations have led to the development of special conductor arrangements for high-frequency applications. These conductor arrangements include its wire, which was described earlier, and the use of thin foil windings. Eddy current loss in windings are treated in greater detail in later sections of this chapter. The net effect of these losses is to increase the effective resistance of the winding to a value R_{ac}. This modifies equation a to

$$P_{w, sp} = 22k_{Cu} \frac{R_{ac}}{R_{dc}} (J_{rms})^2$$

11.9 Thermal Considerations

Increases in the temperature of the core and winding materials degrade the performance of these materials in several respects. The resistivity of the copper windings increases with temperature, and so the winding loss increases with temperature, assuming a constant current density. In the magnetic materials, the core loss increase s with increasing temperature above approximately 100°C, assuming the frequency and flux density remain constant. The value of the saturation flux density becomes smaller with increases in temperature.