DATATRONICS

Magnetics Design

Specification, Performance and Economics

WHITE PAPER

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SPECIFICATION, PERFORMANCE AND ECONOMICS

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Introduction

The design, development and delivery of magnetic components for production is a complex process; it involves various organizations, skills and people. The design development process begins once performance requirements are specified. Upon approval of a design proposal, the procurement of materials for a prototype build is initiated. During this stage of development, specifications are not final, technical options remain open and provisions for a cost-effective production can be made. Specifications must be reviewed and design trade-offs evaluated to ensure that the technical requirements are economically attainable.[1] This paper discusses electrical specification parameters with consideration given to performance and tolerance in relation cost.

Electrical Specification

Initially the electrical specifications are tentative as there may be ambiguity about what are the minimum allowable performance requirements. One approach in the development of an electrical specification is to specify performance parameters. Limits are given for parameters such as input/output voltages, currents, frequency and leakage inductance, *etc*. Another approach is to provide information about the circuit in which the device will function. The functional approach can more appropriately optimize the design by understanding its performance requirement within the circuit.[1]

The size of a magnetic device and its cost are considered to be directly related. Although this is partially true for transformers there is pressure to make them smaller. High power density requirements increase cost of transformers. Size reduction is achieved by careful specification and by good design practice.[1] Transformers can be designed to operate at efficiencies exceeding 99%, however, at this very high efficiency level there is a cost and sometimes a size penalty.

During the development of the electrical specification, the mechanical design of the equipment from which the initial size of the magnetic device is estimated occurs concurrently. The core type choice of a design depends on electrical considerations and on the preference of the designer. Core types have been developed for specific applications, consequently they have drawbacks and advantages depending on circuit type and winding technique.

Magnetic material properties most significant to design economics are losses as a function of frequency, flux density, saturation flux and permeability.[1] The power handling capacity of a magnetic device is dependent upon its ability to dissipate heat. The following parameters are to be considered in development of an electrical specification.

Voltage

Core loss is a function of the voltage applied across the primary winding of a transformer. The operating flux density level, or B level, is determined by Equation 1. Once the frequency and B level are known, core loss can be estimated from the material core loss curves.

$$B_{max} = \frac{E \times 10^8}{4 f N A_e}$$

Equation 1

where *E* is the applied voltage, *f* is the operating frequency, *N* is the number of turns and A_e cross sectional of the core.

Directly related to voltage is the turn area product. A decrease in the cross sectional area requires an increase in the size of the core in order to maintain a constant turn area product. The size of the core is generally determined by the turn area product. The applied voltage for a particular wire size has a direct correlation to core size and cost. Voltage as it increases, affects spacing and dielectric considerations between windings due to efforts in maintaining stress levels within ratings. Winding cost and core size increase as the induced or applied voltages increases. [1]

Frequency

A simple rearrangement of Equation 1 yields the number of turns. It can be observed that for a given value of B level and cross-sectional area, an increase in frequency requires fewer turns. To take advantage of this benefit a designer may select a core with a smaller cross-sectional area.

$$N = \frac{E \times 10^8}{4 f B_{max} A_e}$$

Equation 2

Less cross-sectional area means a smaller core and bobbin accordingly the cost is reduced. However, under this condition an increase in frequency increases core loss which may require the use of a higher grade more expensive material. Also, an increase in frequency augments the effect of parasitic elements in the windings *i.e. distributed capacitance, leakage inductance and skin effect* which may require the use of more expensive Litz[1] wire and a more complex winding construction.

Current

The size of the conductors that make up the windings, typically copper magnet wire, is determined by the RMS current. The current requirement affects cost by contributing to the required size of the core, winding cost and packaging.

The current carrying capacity of copper wire or current density is normally expressed in circular mils per ampere. The current density is specified by the manufacturer based on 1000 circular mils per ampere (*c.m./A*). In practice a lower current densities are used depending on the application and winding construction; current densities as low as 200 *c.m./A* may be adequately used.[7] In a practical design the voltage drop, insulation temperature limit, thickness, thermal conductivity, air convection and temperature must be taken into account.

Solid wire is typically used for magnetics operating at below 100 kHz with RMS current levels under 20 amps. Copper foil is a good choice for low voltage high current windings.

Magnet wire is available as rectangular, round or square. The rectangular and square types in general have larger diameters and allow for a higher density of materials in a given area. Generally, the diameter of the wire can vary in thickness from a few microns to several centimeters.

The price of magnet wire is determined by weight, base price of copper plus adders. The adders are highest for smaller gauge wire and diminish as the gauge increases. The adders for square wire are more than round wire. The greater cost of square wire in the smaller gauges is an economic issue of a design.[1]

The diameter of copper wire or wire gauge is specified by American Wire Gauge (AWG) which ranges from 0.162" (6 AWG) to 0.00124" (48 AWG). Windings of fine wire require coil finishing as an additional assembly process which adds to the labor cost. Heavier gauges are wound one winding at time on slow moving equipment which results in a higher labor rate per turn.[1]

[1] Litz wire consists of multiple fine strands of insulated solid wire twisted together to form a single conducting bundle.

Inductance

The nominal value of inductance (L) can only be approximately defined. The A_L value is a factor of inductance per turn (N) squared in nano-henries (nH) for a given core:

$$L = N^2 x A_L \ (nH)$$

Equation 3

Introducing a mechanical gap between core halves of a two piece ferrite core makes the A_L value adjustable. Because the air gap can be ground to any length, any value of A_L value can be provided within the limits permitted by the core.[6] The A_L value tolerance of an un-gapped ferrite core is typically about $\pm$25% or greater. Once the core is gapped the tolerance is typically about $\pm$10% and in some materials less than $\pm$5%.

The measured A_L value of a core will depend slightly on the coil used for measurement. Ferromagnetic inductance measurements are subject to variations depending on the measuring method and the magnetizing conditions in a given method.[6]

Variations in material permeability, assembly and gapping process contribute to deviation in inductance for a given design. In many applications the higher inductance the better for optimum circuit performance. In this case a minimum inductance with margin may be properly specified. Specifying a tight tolerance on inductance ($\pm$10%) can have economic consequences in production. A tolerance of less than $\pm$5% incurs significant cost penalties.

Resistance

At low frequencies the DC resistance (DCR) is the most important parameter to be considered in the winding of a magnetic device. The resistance per unit length of the wire is inversely proportional to the winding window area. A bigger window area yields a smaller per length of wire if the number of turns is the same.[2]

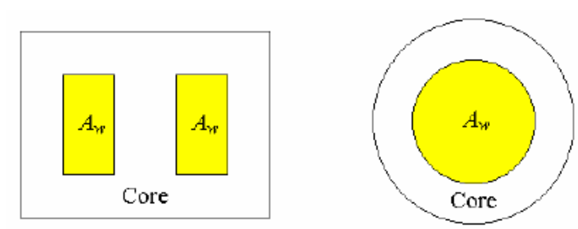

Figure 1. Window Area, A_w

The arrangement of the wire in a winding is a vital factor in determining the DCR of the copper in the winding. Fully utilizing the winding space to have the maximum cross-sectional area of wire is the ideal arrangement for lower DCR.[2] In transformers with high voltage isolation requirements between windings nearly 1 cm of window breadth is lost severely impacting window utilization. The increased separation results in higher leakage inductance between primary and secondary windings.

Winding resistance, *R,* is determined by the cross-sectional area and the length of the conductor given by equation 4

$$R = \frac{\rho l}{A} \quad \Omega$$

Equation 4

where resistivity of copper, *ρ,* is equals to 1.724×10^{-6} Ω-cm at 20 ℃, l is the length and A is the cross-sectional area of the wire.

The resistivity of copper varies with temperature by a coefficient of 0.00393 per ℃. The calculated winding resistance accuracy is only about 10 to 20 percent. The manufacturing tolerances of copper wire are between 10 to 20 percent. Measurement of DC resistance can be as much as 50 percent from the calculated value. Variations in tension during winding and in per-unit-length resistance cause variations in winding resistance.[1]

At higher frequencies AC resistance becomes a very important factor. AC resistance frequently exceeds DC resistance and can overwhelm the design if not managed properly. A copper foil winding typically has far greater window utilization and typically has the lowest DCR of any other alternative, and copper foil is the low loss alternative.

Specifying a tight tolerance on DC resistance should not be considered until nominal values have been established from measurements made on prototype units. Coils that fail DC resistance in production cannot be reworked and must be scrapped. Specifying a DC resistance tolerance of ±20% incurs no significant cost penalty. However, specifying a tolerance of ±10% may have some economic consequences, more so on smaller gauge wire. A tight tolerance on DC resistance should be specified only after careful consideration and if not necessary it should be avoided. In most cases specifying a maximum DC resistance is sufficient.[1]

Leakage Inductance

Leakage inductance is a very important issue in transformer design because it impedes the basic operation of a transformer. Leakage inductance is proportional to the height of the winding and inversely proportional to width of the winding. It is also, inversely proportional to the square of the number of interface sections of the windings.[2]

Leakage inductance is determined by the number of turns and the geometry of the winding. Leakage inductance cannot be accurately calculated. In production there are variations in leakage inductance because physical dimensions cannot be consistently maintained. A nominal value of leakage inductance is established only after measurement and design verification of prototype units. Coils that fail leakage inductance cannot be reworked and must be scrapped. A maximum specification of leakage inductances is adequate for most circuit requirements. Where a circuit requires tight control a ±25% from a nominal value can be adequately specified.[1]

Capacitance

There are two types of capacitance requirements associated with transformers, the inter-winding and the distributed capacitance. Inter-winding capacitance causes coupling of noise from primary to secondary and capacitive loading to ground. Distributed capacitance creates series and parallel resonance with the mutual inductance of a transformer. In a filter inductor the distributed capacitance, beyond resonance, passes the high frequency component from the switching frequency to the output. In high voltage applications the distributed capacitance is a serious problem and it is associated with the high frequency performance of a transformer. Winding techniques that reduce leakage inductance increase winding capacitance.

In production there are variations in both capacitance parameters because physical dimensions cannot be consistently maintained. There are also variations in dielectrics constants of the insulation between conductors which effect capacitance. Coils that fail capacitance requirements cannot be reworked and must be scrapped. Nominal values of capacitance parameters cannot be accurately predicted and can be established only after measurement and design verification of prototype units. Once capacitance parameters have been characterized and nominal values established a tolerance of about ± 25% can be maintained without economic consequences.[1]

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