Transformer Design in ACDC Power Conversion

1. Backdrop

A key component in ACDC power conversion is the transformer within the isolation stage.

The requirements imposed on this component are typically:

- Isolation to meet safety-agency compliance
- Low core loss
- Low conduction Loss
- Low – nominally zero – common-mode noise generation

These characteristics are examined in the sections as follow.

2. Isolation

In ACDC conversion, the transformer is usually the main component straddling the isolation gap required between primary and secondary, and it must thus be designed with particular care from an electrical safety viewpoint, with the principal standards documentation here being IEC60950. Additionally, if medical-grade isolation is required, then the IEC60601 standards material becomes relevant.

Isolation requirements imply clearance and creepage requirements relating to transformer terminations, as well as usage of multiple layers of insulation between primary and secondary (or usage of solid material of 0.4mm thickness unless a test regimen is undertaken), as well as usage of approved materials. An important aspect is that the core material is usually classed as conductive, requiring due consideration in terms of spacing requirements and/or taping needs. In terms of transformer construction spacing requirements then translate to usage of some or all of the following approaches:

- Taping approaches – usually as implemented in “margin wound” transformers – to maintain the required clearance and creepage distances between windings that use conventional enamelled wire
- Triply- or quad-insulated wire for at least one winding, with suitable mechanical protection against chafing
- Wire former/bobbin that guarantees adequate isolation whilst allowing usage of conventional enamelled wire. This approach is used in several ICERGi designs and is treated in more detail below, being particularly well suited to cases where low turns counts are used.

The approach used will depend on the size of the transformer, the standards set for which compliance is required, and availability of suitable devices in approved materials.

3. Core Loss Characteristics

Core loss is primarily a function of peak flux and frequency, with effects due to pulse of low duty cycle being modelled using concepts such as “effective frequency”. Loss graphs for materials are typically plotted for combinations of peak flux at various frequencies, typically for sinusoidal excitation and with limited data available for non-sinusoidal excitation. Loss plots are also invariably for toroids, which have the advantages of a homogenous cross-section and without “complications” such as uneven flux in the vicinity of gaps. Specific published loss estimates for cores of non-toroidal form factor usually give an upper bound that can be ~40% above the figures that can be deduced from the graphs associated with performance of the material in toroids.

A particular challenge with core loss is that it is primarily a function of applied volt-seconds per turn on the associated winding, with converters designed for high-efficiency operation using synchronous switches, one can have effectively the same core loss figure at full power as at zero-load. In practice, conditions of near-zero load are addressed using burst mode techniques, so the greatest challenge in the context of core loss and its impact on percentage efficiency can apply at load levels in the region of 5%-40% unless some pulse thinning or comparable approaches are used.

Core loss in inductors used in multilevel converters is reduced materially given the low volt-seconds values applied to the inductor – as well as which there is near-complete cancellation at various voltage levels. For example, in a four-level three-cell converter operating with 400V output, there is effective cancellation and resulting minimal Vs applied to the inductor at input/output voltage ratios of ⅓ and ⅔, i.e. at input voltage levels of 133V and 277V. For an input voltage that traverses these conditions following the line voltage, one can estimate values of core loss using the Steinmetz-type equation with an exponent of typically 2.5-3.0 for losses due to peak flux density.

At the operating frequencies involved in ICERGi-designed power converters, the design of inductors and transformers is usually loss-limited rather than limited by saturation. A loss-limited design, where peak flux densities in normal operation are usually limited to absolute levels of less than 100mT, naturally has greater margin for transient effects given that ferrite saturation levels are typically >400mT at the relevant operating temperatures, and powdered-iron or alloy materials show saturation levels >1T and with soft roll-off.

Some loss curves for relevant materials are as shown in figure 1a and 1b.

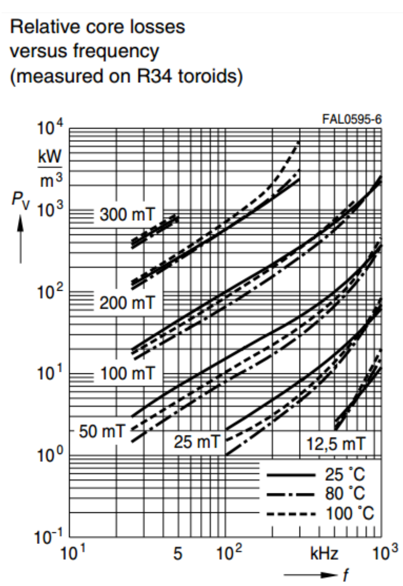
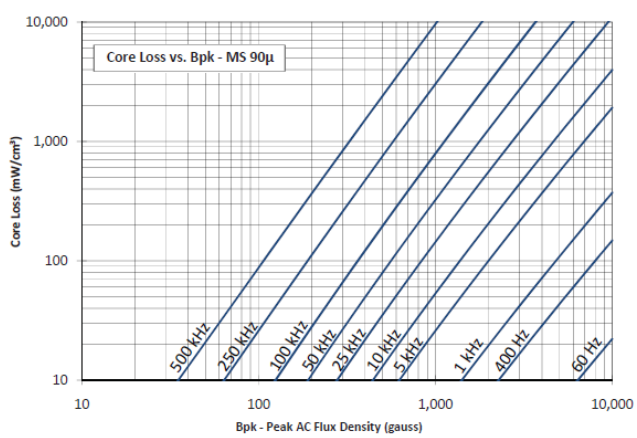


Figure 1a – Illustrative loss curves for TDK-Epcos N49 material



Note – the mW/cm³ figure is equivalent to a KW/m³ figure. 10000G=1T

Figure 1b – Illustrative loss curves for Arnold “Super MSS” material

Temperature dependence of core losses can also be observed. Most ferrite materials are optimised for 100C operation. N95/3C95 and equivalents are materials with relatively constant loss in a working range from 25C-100C, whereas many other materials have significantly higher losses (2x or 3x) at 25C as compared with 100C. Magnetic devices using such materials usually heat up on initial operation, stabilising at an equilibrium condition over time.

4. Conduction Loss Minimisation

There is typically a tradeoff between core loss and conduction loss. Core loss is reduced by have a large number of turns giving low peak-flux – and a large number of turns corresponds to high copper loss at higher power. Copper loss is really associated with the I^2R factor – where the "R" term here needs to take account of the extra losses associated with AC operation, including from skin-effect, proximity effect and the like.

The "shape" of the efficiency-power curve is impacted quite significantly by the policy adopted in effecting the necessary tradeoff – with core loss being approximately constant with output power and copper loss varying with the square of current (or of power, given constant voltage operation).

Achieving high copper fill factor is important, as is the performance gain associated with Litz wire of moderate strand diameter. Coming up with a bobbin structure that guarantees the required spacing using standard (unjacketed) wire is valuable, and ICERGi has made use of proprietary structures in this context. An approach is as shown in figure 2.

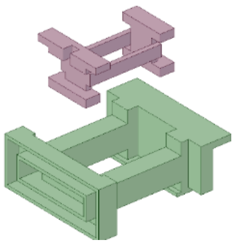


Figure 2 – showing "tunnel bobbin" design as may be used in resonant converters to achieve defined leakage inductance and provide for usage of unjacketed Litz wire.

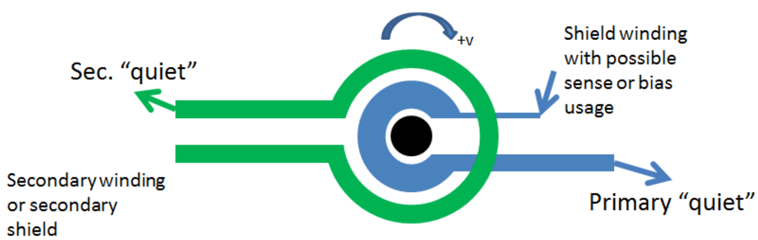
5. Shielding and Balance

In many structures – such as phase-shifted full bridge and many instances of resonant converters – the winding undergoes rapid transitions in voltage, both in terms of the common-mode voltage of the centre-point of the winding with respect to a "quiet" level and in terms of the voltage across the winding. In a common scenario, the core can be "referenced" to the primary side and tied to the quiet level on the primary with foil or similar techniques.

Ferrite cores are however quite resistive, and it may not suffice to rely on a “grounded” core for containment of the time-varying electric field associated with the transformer primary winding. The optimal approach can be to wrap the primary winding in a layer of foil. This layer can function as a sense winding of due allowance is made for leakage inductance effects or if an external series inductor is provided.

In many converters, usage of a voltage-doubler secondary winding can be convenient. The secondary winding thus can be a single winding without the need for centre tap, and with one end at a quiet point, namely the midpoint of two capacitors. With a “one end quiet” secondary winding and with the gap distance as is normal for ACDC converter isolation requirements, low common-mode noise can typically be assured by careful winding such that the potential across sections of interwinding capacitance is equal.

These aspects are shown in figure 3.



Assume V_t is voltage generated due to flux, per turn
Then average primary voltage in top semicircle is $+V_t*(3/4)$ and average secondary voltage is $V_t/4$ – thus voltage of Vt/2 applied across interwinding capacitance in top semicircle.
In lower semicircle average primary voltage is $V_t/4$ and average secondary voltage is $+V_t*(3/4)$ - thus voltage of -Vt/2 applied across interwinding capacitance in top semicircle – hence cancellation.
Alternative implementations may need balancing half-turns or more complex structures

Figure 3 – Showing shielding and balance considerations associated with isolation-stage transformer design.

6. Summary

Transformer design is critical in the context of obtaining excellent performance in ACDC power conversion. Safety is of course paramount, and then losses and noise issues need to be managed. Losses come from core loss and resistive factors in the transformer structure, with care needed in minimising AC losses, typically through usage of stranded wire. Guaranteeing safety isolation whilst achieving low common-mode noise is also critical. Low inherent common-mode noise translates to low required values of Y-capacitance (associated with low values of line-frequency leakage current) and to small values of required inductance on common-mode filter chokes.

Line frequency leakage current is unpleasant from the viewpoint of user “sensation” and from audio noise concerns, with low values also being particularly specified in medical deployments. Common-mode chokes with high inductance requirements are invariably quite dissipative particularly at low-line, and minimising losses here through careful transformer design is thus important.