Introduction to Magnetic Elements in Power Converters.

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I. Introduction

Inductive power components are divided in several kind of devices.

- Inductors: defined by the inductance, they are used in multiple power circuits. They are used for conversion of electrical energy into magnetic energy in an intermediate stage in a power converter. Actually, they make use of the equation:

$$U_L = L\frac{dI_L}{dt} \qquad (1)$$

- Chokes: a particular kind of power inductor, used in low-pass filters. Usually intended for allowing line frequencies and filtering high frequencies.
- Transformers: when the principle of magnetic induction is used, the transformers provide galvanic isolation between two parts of a circuit. Also, they are used for matching impedances, level adaptation etc.Text goes here

II. Magnetic materials

a) *Parameters for design of an Inductor*

There are several things to consider; L, Imax, frequency and Losses. Once a material is selected, the design procedure is basically as follows:

- B_{SAT} Saturation of flux density. It is related with Peak current => power level of the application. The current and the number of turns provide the value of H. in a given material, there is a relationship of B and H (MATERIAL). In order to ensure $B<B_{SAT}$, H must be limited.
- But, however, depending on the desired inductance L, then for the existing parameters (B), a given cross sectional area will be selected (SIZE).
- Air gap also affects this relationship, but also decreases inductance, so there is a 3 parameters adjustment to be considered (g, N, Ae).
- But, additionally, also losses depend on these parameters, so for each material there will be an optimum.

b) *Parameters for design of an transformer*

- Turns ratio need to be ensured.
- In addition, the transformer must not saturate. This means that the magnetizing inductor must not saturate. So, for a given frequency, it implies a given voltage between terminals. But a current flowing from primary to secondary does not saturate the transformer, even for high values.
- The losses must be considered. this is what limits the power flowing from primary to secondary.

c) *Soft Materials*

Transformer core requires magnetization, demagnetization and reverse magnetization during operation. The energy expended in doing so in the form of hysteresis losses should be minimum. This corresponds to low coercive force on the magnetization curve of the material and small area of hysteresis loop. See Figures 1 and 2.

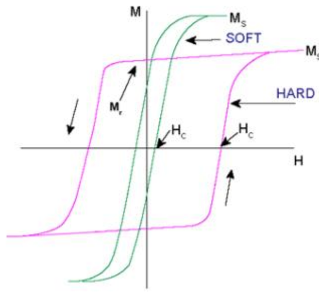

Figure 1.a) Sallen-key filter. b) Multiple feedback filter. [2]

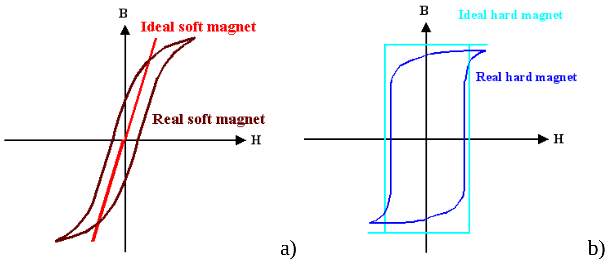

Figure 2.a) Soft Magnet. b) Hard magnet. [3]

III. Ferrites vs other materials

The basic materials are ferrites, powdered metals (powdered iron, permalloys) and bulk metals (Steel, Fe alloys, amorphous cores).

Frequency of Operation	Material	Flux Density to Ensure low loss
50Hz – 1kHz (<200 Hz)	Grain orien-ted steel/Fe	1.7T@50Hz 0.7T@400Hz
50Hz – 1 kHz (<500 Hz)	Fe-Si alloys	1.5T
1kHz - 250 kHz (=10 kHz)	Amorphous cores	< 1.5T
10 kHz – 2MHz (=100kHz)	MnZn Ferrite	< 0.4 T
200kHz – 100 MHz (1-10MHz)	NiZn Ferrite	< 0.3 T

100 kHz – 100 MHz (1-10 MHz)	Powdered Iron	< 1T
Full	Air	Infinity (largest winding losses)

Table I

a) Ferrites

The low flux density does not make Ferrites attractive at lower frequencies. However, other material, if used at the higher frequencies, will have to be operated at still lower flux density to control core loss, increasing their size compared to Ferrites.

BH curves become flatter with increase in temperature, so your selected maximum flux density should be around the knee point of the BH curve at the highest operating temperature of the core otherwise the transformer will move towards saturation with rise in temperature.

Ferrites have the highest permeabilities vs other materials.

For MnZn ferrites, given its polycrystalline nature, the BSAT is much smaller and more "resistive" than in the case of metal alloys. These are soft materials (small coercitivity)

b) Powdered Iron

Not good for transformers (inherent distributed air gap in the magnetic circuit due to the separation between particles by the bonding material). Much higher Curie temperature (770ºC vs. 100-450ºC).

Distributed gap, so the adjustment of inductor is done only but number of turns (less degrees of freedom in the design).

Large saturation value (relatively small inductors), but small permeability (because of distributed gap, thus relatively large windings => higher copper losses).

In addition, iron powder present a softer saturation curve [5], therefore might be interesting for variable inductor applications (however, this is a comparison against non-gapped ferrite; for gapped ferrites, the curve also is softer)

c) Cost Comparison

Roughly, cost can be esteemed as [5]:

Material	Cost multiplier
Powdered iron	1.0
Powdered alloy	3.4 to 4.0
Ferrite (ungapped)	3.4 to 4.3
High flux	3.1
MPP	15 to 20

Table II: Core material cost comparison.

IV. Ferrite Characteristics

The recent developments in power electronic conversion, namely the development of power devices based in WBG (SiC and GaN) impose some requirements in reactive components [1]. In the case of ferrites in magnetic materials in inductive components include high frequency operation and high pulsed power. For high pulsed power, this implies high saturation. For both high pulsed power and HF operation, this implies high temperature.

- For MnZn ferrites, the typical B_{SAT} levels are 530mT@25ºC (430mT@100ºC). But these are measurements as per the IEC standards at 10 kHz and at large H values (1000A/m), whether the usual H values are 100-200 A/m.
- For MnZn ferrites, the typical core losses are 350mW/cm3 @1MHz/50mT/ sinewave/25ºC (1000mW/cm3 @1MHz/50mT/sinewave/100ºC).
- Besides power losses, the winding losses must be taken into account, considering skin and proximity effects among others.

a) Dependence of B_{SAT} with constructive parameters of the magnetic materials

B_{SAT} is a function of Magnetization per unit of volume. It depends on the chemistry and on the density of the magnetic cells:

$$B_{SAT}\,\alpha\,\frac{M}{Vol},\ \text{where}\ H = \frac{B}{\mu_0} - M \qquad (2)$$

For MnZn ferrites (crystalline lattice of cubic spinel structure), in order to maximize the saturation, the iron content must be maximized.

b) Dependence of core losses with constructive parameters of the magnetic materials

In MnZn ferrites, the losses are a function of the composition and the microstructure of the grains. Core losses are divided into:

- Hysteresis losses
- Eddy current,
- Ferriresonance losses.

c) Hysteresis losses

They depend on the magnetic material crystalline cell. The hysteresis losses are proportional to the flux density and can be depicted as the area inside the hysteresis loop. High hysteresis losses are accompanied by the presence of unwanted harmonics[4].

d) Eddy losses

They depend on the morphology of structure (50% of overall losses in HF applications). The key is to avoid current loops in the material. In laminated steel, the plates are perpendicular to flux flow, to avoid direct loops.

To decrease Eddy losses, the resistivity of the material must be increased. This can be done if:

- Grain is finer (more surface of interfaces)
- Increase density (more material)
- Increase some specific dopants

At the highest operating frequencies where further gauge or particle reduction is impractical, ferrites are the only available materials. [4]

> *Given the importance of [Eddy] loss, which means inefficiency, the loss mechanism is still not fully understood. Consequently, it deserves a separate phrase to describe loss more clearly. [1]*

For real application, the magnetic flux is important, however the theoretical comparison of flux density might not be helpful for particular application design.

Usually, the available ferrite cores are not large size (unlike alloyed tape-wound material)

e) Resonance Losses

The residual losses are not too well understood and perhaps represent an expression of our ignorance of the system. They apparently are tied in partially to absorption of energy from the system by gyromagnetic resonance [4].

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