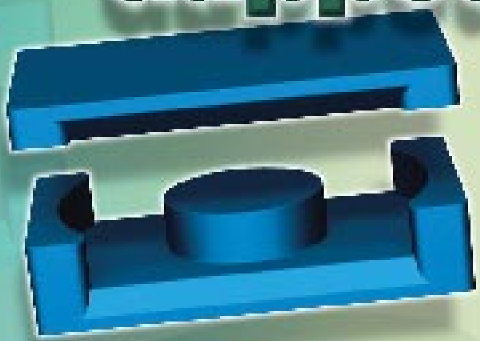
DC-Bias Specifications For Gapped Ferrite Cores



By Mauricio Esguerra, Ferrite Division, EPCOS AG, Munich, Germany

The well-known problem of defining the minimum inductance value for a target roll-off and dc current is addressed in the frame of a hysteresis model.

The widespread use of gapped ferrite cores for inductive components subject to a superposed dc current poses a challenge to the way the required properties are specified. The importance of attaining a precise definition of target values is driven by the need of miniaturization, on one hand, and the slow progress of material performance, on the other. This is because incrementing key material properties requires advancement in both material composition and processing in to push the limits.

The conventional way to formulate a dc-bias specification for a gapped core based on measurements shown in Fig. 1.

1) A target roll-off in the range of 10% to 30% is linked to a dc flux density as estimated from the dc current and the gapping factor b, defined by the reciprocal difference between the effective and the initial permeabilities: (Eq. 1, 2)

$$B = \frac{\mu_0}{\beta}\frac{NI}{l_e}$$

$$\beta = \frac{1}{\mu_e} - \frac{1}{\mu_i} \approx \frac{g}{l_e}$$

N stands for the number of turns, I for the current, le for the effective magnetic length of the core and g for the air gap. Note that the validity of Equation 1 improves with increasing air gaps.

2) It is then verified if the resulting value is distant enough, e.g. 20%, from the material saturation figure as judged by empirical data. The roll-off referred to the lower tolerance limit of the inductance minus a safety margin is then assigned to this current.

The above described semi-quantitative procedure can be improved by taking into account the material behavior under dc-bias. To this end, a model of the nonlinear magnetic response describing the permeability roll-off as a

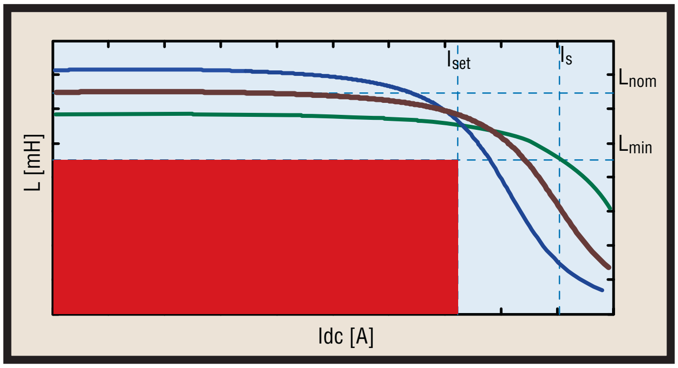


Fig. 1. *Conventional definition of a dc-bias specification: the setting current I_{set} is defined with an empirical distance from the current corresponding to the material saturation I_s according to Eq. 1. The specified inductance limit L_{min} corresponds to the roll-off for the lower tolerance with a safety margin.*

function of flux density is needed. One possibility is the classical model by Gans [1], which describes a universal function that depends on initial permeability and saturation. However, only a certain type of materials follows the Gans curve because features such as the squareness of the hysteresis loop (which is reflected in the inductance vs. current curve) are missing. Therefore, a closer representation has to start from hysteresis modeling.

Hysteresis Model and Reversible Permeability

The model proposed by the author [2] consists of solving the Hodgdon [3] hysteresis differential equation in the formulation H(B) with the major loop, as a particular solution. For the branches of the major loop a heuristic description has been found, which fits the lower $H_L(B)$ and upper $H_U(B)$ branches for soft magnetic materials: (Eq. 3a, 3b)

$$H_L(B) = \frac{B}{\mu_0 \mu_c} \cdot \frac{1}{1-\left(\frac{B}{B_s}\right)^a} + H_c$$

$$H_U(B) = \frac{B}{\mu_0 \mu_c} \cdot \frac{1}{1-\left(\frac{B}{B_s}\right)^b} - H_c$$

The fit parameters are besides the saturation B_S, coercive field H_c and permeability at the coercive field μ_c, the two squareness exponents *a* and *b*. The reversible permeability can be derived from the equations for asymmetric minor loops in the limit $\hat{B} \to 0$ and for a ≈ b, valid for most power ferrites as follows: (Eq. 4)

$$\mu_{rev}(B_{dc}) = \left(\frac{1+(a-1)\cdot\left(\frac{B_{dc}}{B_s}\right)^a}{\left[1-\left(\frac{B_{dc}}{B_s}\right)^a\right]^2} \cdot \frac{1}{\mu_c} + \frac{1}{\left(1-\frac{B_{dc}}{B_s}\right)\cdot\left[2-\left(1-\frac{B_{dc}}{B_s}\right)^{a_o \cdot B_s}\right]} \cdot \left(\frac{1}{\mu_i} - \frac{1}{\mu_c}\right) \right)^{-1}$$

To compare the model with measured curves, a relationship between the non-directly measurable dc flux density B_{dc} and the applied dc field H_{dc} is necessary: (Eq. 5)

$$H_{dc} = \frac{1}{\mu_0 \mu_c} \frac{B_{dc}}{1-\left(\frac{B_{dc}}{B_s}\right)^a}$$

These equations yield curves in excellent agreement with measured values for a variety of soft ferrite materials [4].

Roll-off at Saturation

With the help of Equation 4, the permeability vs. dc field for cores with air gap can be calculated. For the inductance, the effective reversible permeability follows from Equations 2 and 4: (Eq. 6)

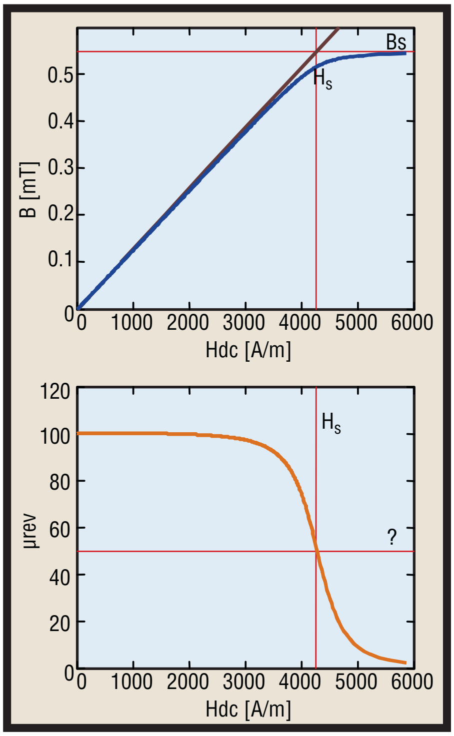


Fig. 2. *The saturation field strength H_s, defined in the upper graph as the cross point of the shearing line (black) and the material saturation, is shown in the lower graph to correspond to a roll-off value to be determined.*

$$\mu_{rev_e} = \frac{1}{\mu_{rev}} + \beta$$

and for the effective dc field: (Eq. 7)

$$H_{dc_e} = H_{dc} + \frac{\beta}{\mu_0} B_{dc}$$

The above equations can then be applied to answer the following question: If the shearing line described by Equation 1 is prolonged to cross the saturation curve, which roll-off corresponds to the resulting value for the effective field (dubbed H_s for "saturation field," Fig. 2)? The result depicted in Fig. 3 clearly shows that for sufficient large gaps, such that roughly [4] (Eq. 8)

$$\mu_e < \frac{\mu_i}{20}$$

the roll-off is 50%. This can be proofed both theoretically [4] and by measurements on a gapped toroids (Fig. 4: R9.5 in material T38, μi=10000, μe=270) for which the dc current has been rescaled by a factor (Eq. 9)

$$I_{dc} \bullet \frac{N}{l_e} \frac{\mu_0}{\beta}$$

following Equation 2 and 7, yielding values in Tesla. The saturation value can then be read at the 50% saturation yielding 410 mT in excellent agreement with the directly measured value. Of course, values higher than the saturation do not have any physical meaning.

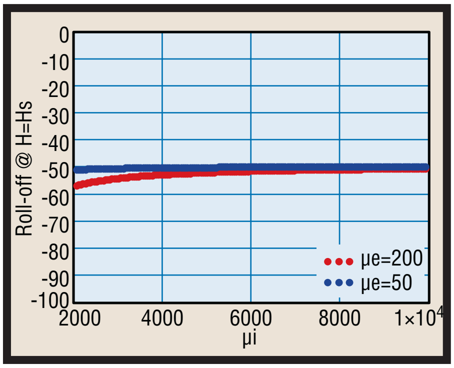


Fig. 3. *Calculated roll-off value for the saturation field H_s as a function of initial permeability for given effective permeability values μ_e= 200 and 50.*

When applying the above procedure to core shapes other than rings, a distribution of cross-sectional areas has to be taken into account. This means that the corresponding flux density distribution of the core has to be calculated section by section. This is shown for a highly inhomogeneous shape, such as EP13 in Fig. 5, along with a rescaling of the current by the minimum cross-sectional area, which represents the bottleneck in terms of saturation. (Eq. 10)

$$I_{dc} \bullet \frac{N}{l_e} \frac{\mu_0}{\beta} \frac{A_e}{A_{min}}$$

Remarkably, the corrected EP13 curves and the ring core coincide exactly at the –50% roll-off, yielding the same material saturation figure.

Distance to Saturation

The results presented so far show that the dc bias can be precisely defined relative to the saturation point. With Equations 4 and 6, curves for the roll-off vs. the relative distance to saturation have been calculated for typical material parameters at different temperatures, as shown in Fig. 6. With the help of these curves, the choice of roll-off can be converted via the relative distance into a corre-

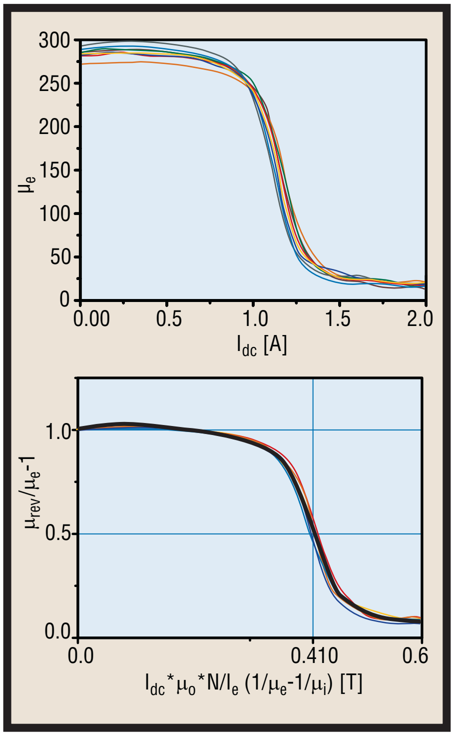


Fig. 4. *Permeability vs. dc-bias measurement for gapped R9.5 cores in the highperm material T38 at T=21°C (upper graph). The rescaling of the current axis (Eq. 8) yields a material saturation value at the 50% roll-off of 410 mT.*

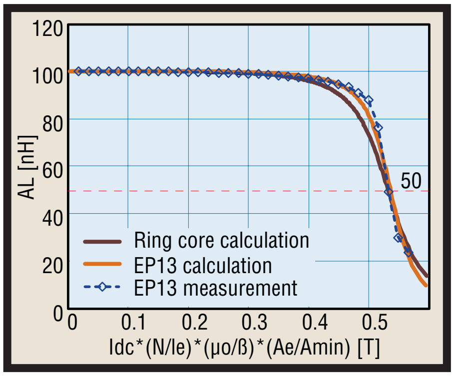


Fig. 5. *A_L-value vs. dc-bias measurement for gapped EP13 cores in the highsat material N45 at T=25°C with A_L=100 nH.*

sponding current, based on the knowledge of material and core parameters.

A_L-Tolerances

When considering the effect of A_L-tolerances, it is important to first note that based on a statistical tolerance simulation analysis, the tolerance is proportional to the A_L-value itself:

(Eq. 11)

$$A_L = A_{L_{nom}} (1 \pm Tol)$$

(Eq. 12)

$$Tol = \frac{6 \cdot C_{pk}}{\mu_o} \cdot \frac{l_e}{A_e} \cdot \sqrt{\frac{1}{sym}\left(\frac{\sigma_{\mu_i}}{\mu_i^2}\right)^2 + \left(\frac{\sigma_g}{l_e}\right)^2} \cdot A_{L_{nom}}$$

The constant involves the standard deviation for the permeability $\sigma_{\mu i}$ and the air gap σ_g, a factor sym for symmetric (=1) or asymmetric (=2) grinding as well as the target −Cpk-value. The above equation gives a generally valid relationship to be considered for designs. However, concrete values will change from vendor to vendor, even though an IEC-standard for A_L–values and its tolerances is in preparation.

Dc-bias Specification

Since the target of an application is to have a certain inductance:

(Eq. 13)

$$L = A_L \cdot N^2 = \mu_0 \mu_e \frac{A_e}{l_e} N^2$$

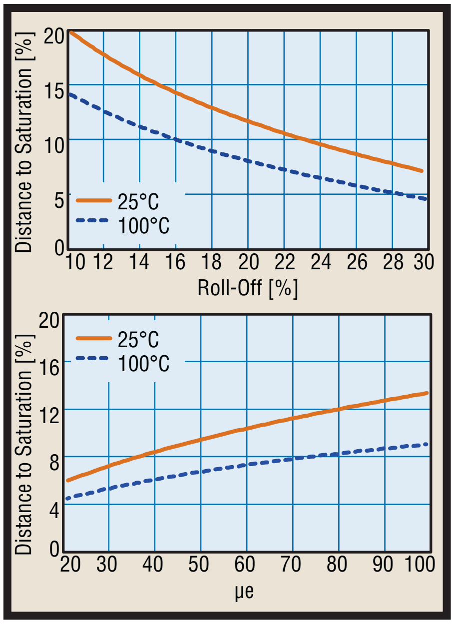


Fig. 6. *Distance to saturation for N87 material as a function of roll-off (for an RM8 with μ_e=75.6, see example) and as a function of μ_e for a roll-off of 20% at T= 25°C and T=100°C.*

the selection of A_L–value and of the number of turns is a degree of free-

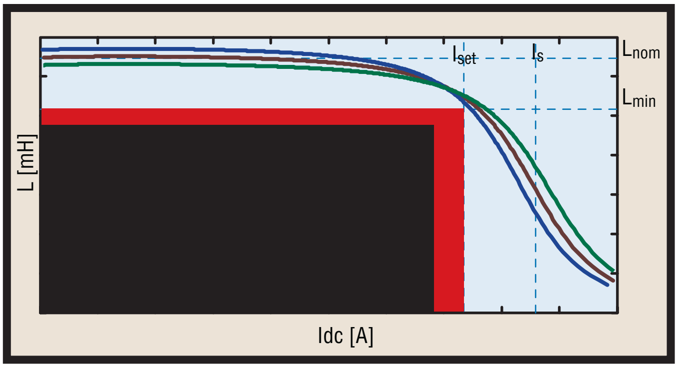


Fig. 7. *Specification example for an RM8 core in N87 with A_L=160 nH +/-3% at T=25°C. The red area corresponds to the set current and limit inductance as per the proposed procedure while the black corresponds to a conventional specification.*

dom. In the frame of the present discussion, the upper tolerance limits the maximum attainable dc current and needs to be kept as small as possible. Therefore, the following specification procedure is recommended (Fig. 7):

1) The target roll-off RO with respect to the nominal inductance is defined as the lower inductance limit: (Eq. 14)

$$L_{\min} = L_{nom} \cdot (1 - RO)$$

2) The current corresponding to the target roll-off referred to the upper tolerance (of μ_e) is the setting parameter: (Eq. 15)

$$I_{set} = B_s \frac{l_e}{N} \frac{A_{\min}}{A_e} \frac{\left(\frac{1}{\mu_e(1+Tol)} - \frac{1}{\mu_i} \right)}{\mu_0} \cdot (1 - DTS)$$

The above procedure provides a valid specification for all possible A_L–values within the limits, provided the tolerance range is smaller than the roll-off: (Eq. 16)

$$2 \cdot Tol < RO$$

Otherwise, the inductance vs. dc-current curve corresponding to the lower A_L-tolerance limit would lie outside the minimum inductance value defined by Equation 13.

Temperature Effects

The material parameters of ferrite materials are known to be strong temperature-dependent. To adapt the above results from a given temperature, i.e. 25°C, the following parameters need to be corrected in their temperature dependence:

B_s: Look up value in material data sheet; the slope of the temperature curve is in the range of –0.8 ... –1.5 mT/°C for power grades and –1.6...-2.3 mT/°C for highperm grades

μ_e: Since the air gap and hence β remain constant throughout the temperature, the value at a different temperature is given by (Eq. 17)

$$\frac{1}{\mu_e(T_2)}=\frac{1}{\mu_e(T_1)}+\frac{1}{\mu_i(T_2)}-\frac{1}{\mu_i(T_1)}$$

DTS: cf. Fig. 6

The adaptation of these parameters mainly affects the setting current given by Equation 15. Because of the comparably large gaps considered here (Eq. 8), the minimum inductance may be considered as temperature-independent. This is desirable from an application point of view and correct as long as $T_2>T_1$. In most cases, $\mu_i(T_2)>\mu_i(T_1)$.

The specification procedure can be therefore complemented with a final step: 3.) Setting current at the temperature T_2 (Eq. 18)

$$I_{set}(T_2)=\frac{B_s(T_2)}{B_s(T_1)}\cdot\frac{1-DTS(T_2)}{1-DTS(T_1)}$$

The advantage of this equation as opposed to a direct calculation for every temperature is that a known specification that has been defined at, say, room temperature can easily be transferred to a different temperature. Even though the ratio of saturation values is the dominating factor (see example below), the DTS term is necessary to have correct setting currents for all temperatures. The specification procedure can be best illustrated by the following example (Fig. 7):

Core: RM8
A_e=64 mm², l_e=38 mm, A_{min}=55 mm²

Material: N87
μ_i(25°C)=2200, μ_i(100°C)=4000

3)B_s(25°C)=465 mT, 3)B_s(100°C)=370 mT

a(25°C)=2.9, a(100°C)=5.1

μ_c(25°C)=5500, μ_c(100°C)=4300

H_c(25°C)=21 A/m, H_c(100°C)=13 A/m

Inductance: L=1.3 mH
A_L=160 nH +/- 3% (μ_e=75.6) and N=90

Roll-off: RO=20%

Result:
1) From Eq. 14 follows

$$L_{min}=1.04mH$$

2) From Fig. 6:

$$DTS(25°C)=12\%\Rightarrow I_{set}(25°C)=1.47A$$

3) For T_2=100°C with DTS (100°C)=8%:

$$\frac{B_s(100°C)}{B_s(T_1)}=0.796;\frac{1-DTS(100°C)}{1-DTS(25°C)}=1.042$$

$$\Rightarrow I_{set}(100°C)=1.27A$$

Conclusion

A well-defined dc-bias specification for ferrite cores with a sufficiently large gap starts from the saturation properties of the core and the material via the 50% roll-off point. Further consideration of tolerances and temperature effects makes it possible in a straightforward manner to have consistent setting currents with one target minimum inductance as required by most applications. The result is a stable specification with higher values in both setting current and minimum inductance as compared to the conventional method.

The equations shown are not limited to the case of large gaps, which represents the most common design case and which can be handled in a simple way. As shown in [4] the model can be also applied even for ungapped cores such as rings. **PETech**

References

1. *R.M. Bozorth, Ferromagnetism, D.van Norstrand Co.Inc., New York: 1951.*
2. *M. Esguerra, "Modelling Hysteresis Loops of Soft Ferrite Materials," International Conference on Ferrites ICF8, Kyoto: 2000, 220-222.*
3. *M. L. Hodgdon, IEEE Trans. Magn. 24 (1988) 3120.*
4. *M. Esguerra, to be submitted to IEEE Trans. Magn.*