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Ferrites in HF-applications

MEASUREMENTS TO CORE MATERIALS

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General

This chapter is the sixth in a series of articles on ferrite materials in HF-applications. The first article is an introduction to this field with an overview of some widely applied materials and most important properties. The second article is on materials back-ground and most important HF-application formulas. The third article is on HF inductors and transformers. The fourth article is an introductory to transmission-line transformers. The fifth article is on examples of transmission-line transformers and their analysis.
It is advisable to read the first three articles in the above order first especially since next chapters are building on information and formula's already explained earlier and referencing to this.

Introduction

When designing transformers or inductors we need to now the qualities of the constituents. In case of transistors and integrated circuits it usually is the print on the housing that tells us the particular type and with these type numbers the manufacturer will supply further information. Type numbers usually are a unique coding that tells one component from an other and manufacturers recognize and respect this coding.
This is not the situation with ferrites and other inductor core materials. Since these materials differ widely on parameters and it is usually more than one parameter that determines fitness to a specific application, it is important to tell one material from an other to make sure the right material is being applied in the right application. An impression on ferrite types and qualities may be found in the introductory article on Ferrites in HF applications and in Ferrite materials and properties.
Unfortunately many ferrite and iron-powder core materials for HF applications are looking very much alike after manufacturing. Many manufacturers only deliver bare and un-coded materials and when some type of (color) coding is being applied, this usually is specific to a particular manufacturer and even within this color-coding scheme, a wide color variation from batch to batch may exist to indicate a specific material type.
When acquiring a specific material, the supplier therefore will have to guarantee this material and it is up to the designer and end-user to keep materials apart or marking-up locally. When marking is lost or to determine a particular material from an unknown source, only measurement will tell materials apart and that is what we will discuss in this particular article. A great many materials are being around and within a specific material one may find many different shapes. Although the measurements in this chapter will focus on popular toroidal inductor shapes, formulas and tests also apply to other shapes and variations.

Basic induction formula

Basic formula for an inductor on a magnetic core:

$$L = n^2 .m_r .m_0 .A / l \quad (H) \qquad (4)$$

To design / characterize an inductor we need to identify n = number of turns, A = core area and l = magnetic path length. Factor 'm_0' = general permeability = 4 . p . 10^{-7} and m_r = relative permeability, to be specified by the manufacturer. If any of these parameters is unknown, we have to measure.

Measuring A and l
This is a mechanical measurement with the caliper and should be performed to the bare material. When factory coated, this may be included since coating usual have a thickness of around 10 mm. The area is determined with:

$$A = (D - d) .h / 2 \qquad (20)$$

and magnetic path length with:

$$l = (D + d) .p / 2 \qquad (21)$$

with D = outside diameter, d = inside diameter and h = height of the toroide, all dimensions as always in meters, unless specifically indicated otherwise.
Sometimes the toroide is not exactly round so the average diameters should be taken; this may also apply to the core height. In view of the usual factory tolerance, measuring A/l within 5 % is already very accurate.

Measuring relative permeability
Measuring relative permeability is a bit tricky since this parameter is depending on the magnetic field strength (induction), frequency and temperature. Measurements have to be performed within a temperature range of 20 - 25 °C for the outcome to comply with factory specifications. This is especially important when measuring ferrite materials as these exhibit a relatively large temperature coefficient for permeability.

Properties of ferrite materials are also depending on magnetic field strength; at higher flux permeability is following a hysteresis path with a specific shape for each (ferrite) material. Therefore all magnetic parameters are being measured at a very low flux of 0,1 mT (milli-Tesla) or lower. This is an industrially agreed method to directly compare permeability of materials by different manufacturers.

Core materials however will also be applied at large(r) field strength even up to the point where saturation sets in. Manufacturers therefore will specify the complete hysteresis curve (B-H curve); these measurements however are beyond the scope of this discussion.

Measuring initial permeability m_i

Since frequency is one of the factors determining final permeability, manufacturers have agreed to measure the initial permeability at such low frequency that even the higher permeability materials (lowest maximum frequency) will not be affected. This agreed frequency is 10 kHz., with a magnetic field strength of 0,1 mT.

Relative permeability of any core material may be determined by measuring inductance of an inductor with a low number of turns. Ideally this measurement will be performed with a dedicated measuring bridge, running at 10 kHz. When this is not available, a very acceptable method consists of determining resonant properties of the inductor using a known capacitor, a LF frequency generator and an AC voltmeter. An example of this test set-up, the magnetic core under test and ten turns of a test inductor is schematically shown in figure 3.

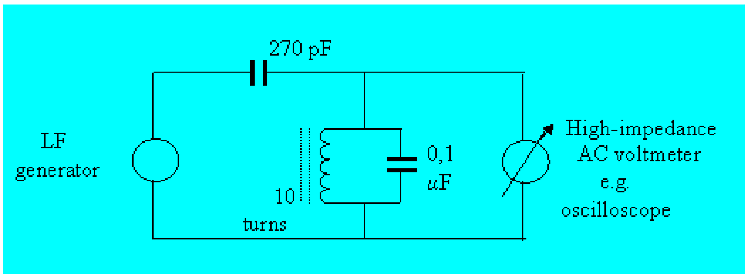

Figure 3. Set-up for determining μ_i

In the set-up of figure 3, resonance will be determined by changing the frequency of the LG generator until maximum amplitude is being measured with the AC-voltmeter. Care should be taken to not change the frequency too quickly as the quality factor of the resonant circuit may be quite high with peak voltage to be easily missed. The resonating capacitor of 0,1 mF should be of relatively high accuracy since the value of this capacitor is determining the accuracy of this measurement set-up to a large extend. Better not apply a decoupling type of capacitor as these usually are specified with a tolerance of -20% to + 50%. Any other capacitor with a +/- 5% specification will do, since measuring frequencies will be relatively low.

From the above formula for the inductance and the general resonance formula $(2\ p\ f_r)^2\ L\ C = 1$, we may determine the initial permeability, with the l and A measurement by the caliper and the f_r reading at the LF generator in Hz.:

$$m_i = (2\ .10^9\ .l) / (f_r^2\ .A) \qquad (22)$$

This measurement set-up will do nicely for a wide range of toroide dimensions and materials with resonance frequencies to range between 1 and 150 kHz. With the generator delivering 0,5 V_{rms} or below, voltage across the inductor will be low enough to stay outside hysteresis effects, so this set-up is measuring the real m_i

Measuring permeability at frequency

At higher frequencies permeability is splitting up into two factors, of which one is the loss factor. Relative permeability therefore may be written as:
$m_r = m' – j.\ m''$,

with m' as the inductivity factor and $j.m''$ as the loss factor.
The complex factor 'j' is determining the relative phase component of 90 ° between the voltage and current at this component. Since pure inductivity makes voltage and current to run 90 ° out of phase, the 'j' term in the permeability makes the inductor loss into an in-phase term again, so we are really discussing loss that will generate heat ('Ohmic' loss).
To determine both m' and m'' at a certain frequency, we need an instrument to measure both factors at the same time. A few examples of such instruments are the measuring bridges by General Radio, Hewlett Packard and Marconi as very accurate and professional instruments. At a (much) lower budget we find instruments by MFJ (e.g. MFJ-259B) and Autek Research (RF-1, RF-Analyst). Different instruments will measure different parameters that may usually be re-worked into and in-phase and a quadrature component.

Since most instruments operate most accurately around a terminating impedance of 50 Ohm, we best start at the lowest measuring frequency with an impedance around 25 Ohm. Since we are measuring inductive loads, impedance will go up at higher frequencies.

As an example we will determine m' and m'' at 1,8 MHz. When we like to see a lower impedance $X_L = 25$ W, impedance should be:

$$L = X_L / 2.p.f = 25 / (2.\ p\ .\ 1{,}8.\ 10^6) = 2{,}21 \text{ mH.}$$

Say we found for the initial permeability in our first measurement $m_i = 100$, we determine the number of turns for this more extensive measurement using formula 4:

$$n = \sqrt{\frac{L \times l}{\mu \times \mu_0 \times A}} = \sqrt{\frac{2{,}21 \times 10^{-6} \times 0{,}093}{100 \times 4 \times \pi \times 10^{-7} \times 97 \times 10^{-6}}} = 4{,}11 \approx 4$$

since each turn through the balun hole is accounting for a complete turn. In this example, l and A are taken from a 36 mm. toroide.

To avoid copper loss we will apply wire with a diameter of 0,8 mm. or more and spread turns out to at least a few diameters apart at the inside of the core. Also input and output wire should not be too close to avoid parasitic capacitance.

Since permeability is not changing too quickly over frequency we may spread measurements to a few well selected points of interest, e.g. spaced-out radio-amateur frequencies. As soon as impedance is becoming too high (say over 150 Ohm), we take-off turns to arrive at the ball-park impedance around 50 Ohm again. In the example of table 6 we took 4 turns starting at 1,8 MHz., and changed to 2 turns at 14 MHz.

f MHz	n	R_S W	X_S W	L mH	m’	m”
1,8	4	0,87	33,1	2,93	140	3,7
3,6	4	1,27	66,3	2,39	140	2,7
7,1	4	2,87	123,7	1,77	132	3,1
14,2	2	4,45	77	0,86	164	9,5
21,3	2	30,9	113	0,84	161	44
29	2	45,0	123	0,68	129	47

Table 6. Measurements to an example inductor

Our measurements presented the values for R_s and X_s in the 3rd and 4th column. With the first and fourth column we calculate inductance in the fifth column with:
L = X_S / 2 p f

and permeability (m’, sixth column) and loss (m”) according to:

m’ = X_S / (2 p f n² m $_0$ A / l) en

m” = R_S / (2 p f n² m $_0$ A / l)

If we compare the measurement results from table 6 with the materials overview of table 2 in Ferrites for HF applications, we find that the core material under test most probably has been 4C65 ferrite. Looking more in details we also get an impression about realistic tolerances of this material.

Measuring core induction

As we noticed earlier, the relation between B en H (permeability) is also determined by the absolute strength of the magnetic field. At large(r) field strength this relation is no longer linear so it may be useful to determine parameters under various field strength conditions to get an impression of the behavior of this component in a practical system. Earlier we derived a formula for maximum voltage across an inductor to drive this component inside the linear field-strength region. One of the parameters in this formula is saturation field strength, B_{sat}, usually presented by the manufacturer, but may also be measured in the set-up of figure 4.

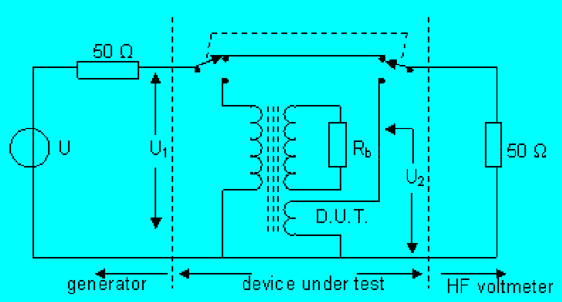

Figure 4. Induction and saturation measurement

The Device Under test (DUT) in this case is a 1 : 1 transformer, possibly a HF balun. In the linear region, the load R_b = 50 Ohm, is transformed from the output tot the input of the DUT, thereby presenting the required termination impedance to the generator. The HF voltmeter may be any device capable of measuring at the required frequency, or an oscilloscope. Best instrument of course is a tuned measuring system to only measure at the desired frequency and ignoring higher harmonics.
For measuring purposes, an additional, low turns measuring coil has been added to the DUT, which will only marginally influence measurement accuracy.

The following steps are to be taken for this measurement:

With the switch in the upper position, a reference measurement U_1 is being made, to be followed by a second measurement with the switch in the lower position to measure U_2.
According to Faraday's law, we may write:
U_2 = n w B A (23)

with:
n = number of turns of the additional coil
A = area of the magnetic material
w = 2 p f with f as the measuring frequency
B = core induction

Reworking this formula for the maximum core induction (we are 'normally' measuring rms values):
$B_{max} = U_2$ Ö2 / (n w A)

In practice it is better to express saturation as related to input voltage U_1 and transformer ratio $T = U_2 / U_1$.
Induction may than be expressed as:
$B_{max} = U_1$ T Ö2 / (n w A) (24)

With this set-up we determine core induction at a specific frequency and input voltage, the latter related to system power according to:
$P = (U_1)^2 / Z_{in}$ (25)

In linear application, inductions should be lower than 0,2 B_{sat}, so maximum allowable system power for this component follows directly from this test set-up.

As an example we tested the Ruthroff 1 : 2,25 transformer as in the last part of our article on [transmission-line transformers.]() This transformer has been constructed using a 36 mm. toroide (A = 1,11 cm^2) of 4A11 (43) type of ferrite material and n = 2 in the measuring coil. At a measuring frequency of 3,6 MHz., we measured T = 0,32.
When we are to apply this transformer in a 50 Ohm environment, at a system power of 1000 W., U_1 will be 224 V. from which we calculate:
B_{max} = 224 . 0,32 . Ö2 / (2 p 3,6 .10^6. 1,11 . 10^{-4}) = 20,2 mT.

Since saturation of 4A11 is specified at 340 mT, we may safely apply this transformer at this system power and frequency and still be within the linear application region. In HF applications above 1 MHz however, it usually is the core loss-power that will determine maximum voltage across the coil instead of the maximum voltage for linearity, we calculated above. Formulas and example calculations may be found at Ferrite materials and properties.
The above linearity test set-up therefore is only is serving as a means to determine saturation level.

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