Measurement of Magnetic Spectra of Ferrites: Introducing a Correction for Ferrites Dielectric Parameters

V. Yurshevich, S. Lomov

Faculty of Electronics and Telecommunications, Riga Technical University,
E-mail: jursevic@rsf.rtu.lv

Abstract. *At measurement of magnetic spectra of high-permeability ferrites with highly pronounced dielectric properties the frequency-depended systematic error of absorption curve* $\mu_2(f)$ *determination appears if the influence of electrical field induced in core is not accounted. It is ascertained that this error may reach 10÷20% which is greater than measurement error of many methods. The way of the error reducing, associated with the calculation of the part of dielectric and conductive losses in total (measured) losses, is proposed. In these calculations the known distribution of components of electromagnetic field in toroidal core is used. After corresponding correction the absorption curve more precisely characterizes just the magnetic losses.*

Keywords: ferrites, magnetic spectra, dielectric and conductive losses.

1. Introduction.

Ferrites of common use (for inductors, transformers, and etc.) are natural magnetodielectrics, that is, they naturally combine magnetic and dielectric properties. In artificial magnetodielectrics (powdered magnetics) a binding material is quite a good dielectric (with small dielectric permittivity ε and loss tangent $\tan\delta_D$), but in high-permeability ferrites the dielectric parameters are far from satisfactory. For example, the manganese-zinc (Mn-Zn) ferrite with initial magnetic permeability $\mu_a = 2000$ at the frequency $f = 1$ *MHz* has magnetic permeability $\mu = 2100$, magnetic loss tangent $\tan\delta_M = 0.3$, $\varepsilon = 22000$ and dielectric loss tangent $\tan\delta_D = 3.2$. The presence of highly pronounced dielectric properties in such ferrites manifests itself at a measurement of magnetic spectra (frequency dependence of the components of the complex magnetic permeability) and the accuracy of the measurements may decrease if this is not taken into account.

Let's restrict the consideration to the case of a measuring winding (single-layer winding uniformly wound on a toroidal specimen under test) as a primary transducer. Such a winding usually is used from very low frequencies till 1…5 *MHz*. If the self-capacitance of the winding is reduced and its influence is taken into account, the frequency range may be extended till 10…20 *MHz*. This overlaps the range of practical use of high-permeability ($\mu_a \geq 2000$) Mn-Zn ferrites.

On the one hand, the influence of the ferrite dielectric parameters on measurement of magnetic spectra is associated with the effect of the electric field created by transducer. This component of the influence has long been taken into account: the measuring winding and specimen are separated by thin layer of a good dielectric or "electrically thin" specimen is placed in the antinode of magnetic field of the other transducers. This is quite enough for nickel-zinc ferrites with much less values of ε and $\tan\delta_D$. Similar measures are used also for Mn-Zn ferrites, but they are deficient, because another aspect of the influence is associated with the phenomenon of electromagnetic induction. Alternating magnetic field induces the circuital electrical field, that is, besides the magnetic losses also the dielectric and conductive losses arise in ferrite and they may be significant for ferrites with highly pronounced dielectric parameters.

2. Effect of the dielectric parameters.

The real component μ_1 of the complex magnetic permeability $\overline{\mu} = \mu_1 - j\mu_2$ is determined from the change of an inductance of the measuring winding, and the imaginary part μ_2 - from the change of the winding losses. In this case the equivalent circuit of the measuring winding shown on Fig.1

usually is used, where $L=\mu_1 L_0$ - inductance of the winding with the ferrite under test; L_0 - inductance without the ferrite; R_f - high-frequency resistance of the winding conductor; R_M - resistance equivalent to magnetic losses in a ferrite; C_0 - self-capacitance of the winding; R_d - resistance equivalent to dielectric losses in the electrical field of the measuring winding.

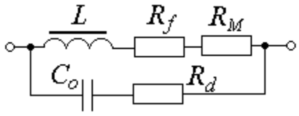

Fig.1. Equivalent circuit of a measuring winding.

The circuital electrical field does not effect directly on the inductance of the winding (the inductance is a parameter of a system "conductor – magnetic field"), that is, does not effect on the measured μ_1. An indirect influence may take place, firstly, because the measured inductance is the effective one L_{eff} and, if the circuital electrical field changes C_0, it will also change L_{eff}; secondly, due to influence of the eddy currents. But as was mentioned, the measuring winding is separated from a ferrite by a thin layer of good dielectric, so the equivalent circuit of C_0 may be presented as the series connection of a small capacitance C_{01} through this dielectric and a large capacitance C_{02}, through the ferrite. Resulting C_0 is smaller than C_{01} and actually is defined by its parameters. The influence of the eddy current on the inductance of winding with ferrite core is the second order effect (this is evident also from the following analysis).

Dielectric and conductive losses due to induced electrical field are compensated by the energy of magnetic field, and the appearance of these losses increases the energy consumed by the winding; this means that the resistance of the winding increases. This may be taken into account by introducing into equivalent circuit (Fig.1) the additional resistance R_D in series with R_M. On Fig.1 this resistance is not shown because this equivalent circuit represents the existing approach to μ_2 determination: R_f is subtracted from the measured resistance of the winding , the remainder is accredited to magnetic losses, and μ_2 is calculated on the basis of this remaining resistance. So, at measurement of magnetic spectra of ferrites with pronounced dielectric properties (e.g., high-permeability Mn-Zn ferrites), it is necessary to take into account that the existing method of μ_2 calculation has a systematic error. This error may be significant. The problem of the electromagnetic field components determination in a toroidal ferrite core is solved in [1]. On this basis for particular case (core made of Mn-Zn ferrite with $\mu_a=3000$) the magnetic loss power P_M, dielectric loss power P_D and conductive loss power P_E were calculated. From these calculations it follows that on frequency 5 MHz $P_D \approx 0.8P_M$, $P_E \approx 0.09P_M$. Loss power is in direct proportion to the resistance equivalent to these losses. From the equation for magnetic loss tangent: $\tan\delta_M = R_M/\omega L = \mu_2/\mu_1$ follows that μ_2 is in direct proportion to magnetic loss power: $\mu_2 = I^2 R_M / I^2 \omega L_o$, where I - current in the measuring winding; $\omega = 2\pi f$. At the measurement of magnetic spectra $I=const$, $L_0=const$, hence at any frequency measured μ_2 will differ from μ_2 characterizing magnetic losses as much as measured losses will differ from magnetic losses. Therefore, in the above-mentioned case the systematic error achieves 90%. This value is undoubtedly unreal; the analysis of the reasons of such a result is given below. Even if $P_D + P_E \approx (0.1-0.2)P_M$, the corresponding error is too great and this aspect of a spectra measurement accuracy needs more detailed consideration.

It should be remarked that one may neglect the mentioned error of μ_2 determination if the experimental spectra are used in a design of the elements with ferrite cores: measured losses describe the total losses which take place when a ferrite is used as a material of core. But if the experimental spectra are used for analysis of physical processes of magnetization, such a systematic error is unwanted. This error may be reduced by excluding from measured (total) losses the losses which are not associated directly with the magnetic properties – dielectric and conductive losses. The powers P_D and P_E may be calculated if the distribution of electrical field in a core cross-section is known. The

μ_2 value, which describes just the magnetic properties, may be determined by subtracting P_D and P_E from measured (total) power.

The discussed method of account of ferrite dielectric parameters has a methodological weakness: for calculation of fields and powers the experimental magnetic and dielectric spectra of ferrite are used (others simply do not exist), but curves $\mu_2(f)$ and $\varepsilon_2(f)$ of such spectra are determined from the total losses. But these overestimated values of μ_2 and ε_2, on the one hand, increase the loss powers, on the other hand, decrease the penetration depth of the field in a ferrite. Therefore, in first approximation, it may be believed that calculated powers are precise enough.

In [1] the distribution of the electromagnetic field components in a toroidal core with circular cross-section was found with the solution of Maxwell's equations. The analytical equations for magnetic field intensity $H_z(r,\theta)$ and electrical field components $E_r(r,\theta)$, $E_\theta(r,\theta)$ (where *r, z,* θ - the cylindrical coordinates in a core cross-section, *z* – applicate perpendicular to core cross-section) are presented with Bessel functions. On the basis on these solutions powers P_M, P_D, P_E were calculated for above-mentioned core and it turned out $P_E + P_D \approx P_M$ that can be considered as a evidently unreal result. We have reasons to suppose that the equations $H_z(r,\theta)$, $E_r(r,\theta)$ and $E_\theta(r,\theta)$ have not mistakes. Too high P_D, P_E values are due to incorrect numerical values of the parameters used for calculations. Firstly, the spectrum of initial magnetic permeability is used, but it is easy to check that the intensity of magnetic field in core several times exceeds the allowable value for such spectra. Secondly, in [1] is said that the typical for Mn-Zn ferrites values of $\bar{\varepsilon}$ are used, but in the spectrum of complex permittivity, presented in [1], in region 2…5 *MHz* ε_2 significantly exceed ε_1 (at 5 *MHz* approximately three times), but accordingly to experimental results of many authors (including our data) for Mn-Zn ferrites with $\mu_a = 3000$ in this frequency region ε_2 is noticeably smaller than ε_1.

In [2] the problem of the field distribution was solved for toroidal core with rectangular cross-section using the finite element method. The calculations for another particular specimen give $P_D \approx 0.4P_M$ and $P_E \approx 0{,}17P_M$. These results also seem overestimated but assumed experimental data are described very shortly and it is difficult to determine the reasons of the overestimated values.

From these examples it follows that in high-permeability Mn-Zn ferrites the dielectric and conductive losses conditioned by the induced electrical field are comparable with the magnetic losses. If this shall not be taken into account, measured μ_2 frequency dependence will include the systematic error comparable with the error of measurement method.

3. Results.

Let's evaluate more accurately the significance of above-mentioned error for toroidal specimen with outer diameter *18 mm*, inner diameter *14 mm* and height *2 mm* made of Mn-Zn ferrite with $\mu_a = 3000$ investigated in [3]. The experimental magnetic spectrum of this specimen calculated by the existing (conventional) method is shown in Fig.2 [3]. The spectrum of complex permittivity $\bar{\varepsilon} = \varepsilon_1 - j\varepsilon_2$ and the conductivity $\sigma = 0.11\ S/m$ were measured just for specimen under test [3]. The calculations of the powers P_M, P_D and P_E were performed with the following formulae from [1]:

$$P_M = \int_V \mu_2\omega|H(r,\theta)|^2\,d\tau,\quad P_D = \int_V \varepsilon_2\omega(|E_r|^2 + |E_\theta|^2)\,d\tau,\quad P_E = \int_V \sigma(|E_r|^2 + |E_\theta|^2)\,d\tau,$$

where $\int_V d\tau = \int_V dl(r\,dr\,d\theta) = \iint [2\pi(0.5(R_2 + R_1) - r\cos\theta)]\,r\,dr\,d\theta$; R_1 and R_2 - inner and outer radius of specimen, respectively; $\omega = 2\pi f$; σ – conductivity of the specimen. The electromagnetic field components are [1]:

$$H(r,\theta) = \frac{J_0(kr)}{2J_0(kR)}a_0 + \sum_{n=1}^{\infty}\frac{J_n(kr)}{J_n(kR)}(a_n\cos(n\theta)),\quad E_r(r,\theta) = \frac{1}{\sigma + j\omega\bar{\varepsilon}}\cdot\frac{1}{r}\sum_{n=1}^{\infty}\frac{J_n(kr)}{J_n(kR)}(-na_n\sin(n\theta)),$$

$$E_\theta(r,\theta) = \frac{-1}{\sigma + j\omega\bar{\varepsilon}} \sum_{n=1}^{\infty} \left[\frac{0.5k\ [J_{n-1}(kr) - J_{n+1}(kr)]}{J_n(kR)} a_n \cos(n\theta) \right] + \frac{1}{\sigma + j\omega\bar{\varepsilon}} \frac{J_1(kr)}{2J_0(kR)} ka_0,$$ where

$J_n(kr)$ - Bessel functions; $k = (\bar{\mu}\bar{\varepsilon}\omega^2 - j\bar{\mu}\sigma\omega)^{0.5}$; $R = kr$; a_n - coefficients of Fourier series [1].

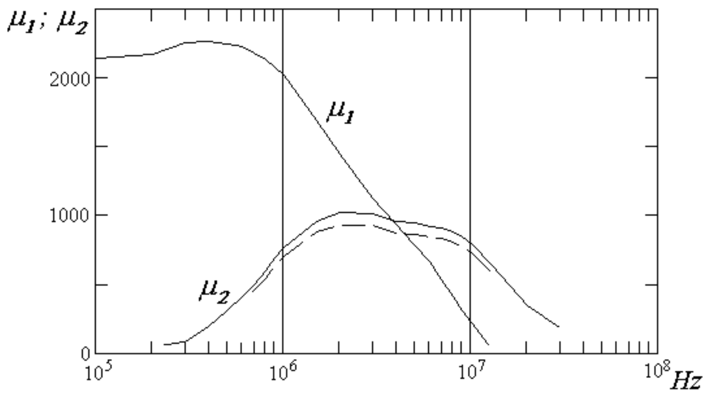

Fig.2. Magnetic spectrum for ferrite under test; — measured values; − − − corrected values.

From these calculations it follows that, e.g., on frequency *5 MHz* $P_D = 0.089 P_M$, $P_E = 0.015 P_M$, and $P_D + P_E = 0.104 P_M$. This estimation is more realistic. Thus, the “true” value of μ_2 on f = *5 MHz* is less by *10.4%* than the measured μ_2 value. So, if the part $P_D + P_E$ in total loss power is calculated, the possibility to correct experimental values of μ_2 on given frequencies occurs. The curve $\mu_2(f)$ which describes just the magnetic losses is calculated in such a manner and is shown on Fig.2 by dotted line. After this correction on the plot $\mu_{2\max} D_m / M_s$ *vs.* f_u [4] (where $\mu_{2\max}$ and f_u - maximal value of μ_2 and the corresponding frequency; D_m - mean size of the ferrite grains; M_s - saturation magnetization) the point, which specifies the ferrite under test as a material, lies closer to expected typical values for magnetically-soft ferrites than without the correction.

4. Conclusion.

It is ascertained that at measurement of magnetic spectra of high-permeability ferrites with highly pronounced dielectric parameters the systematic error may reach *10-20%* if dielectric and conductive losses are not accounted. This error may be reduced by calculating the part of dielectric and conductive losses in total (measured) losses. After corresponding correction the absorption curve of magnetic spectrum more precisely characterizes just the magnetic losses.

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