Measurement of Self-Capacitance for Windings on High-Permeability Ferrite Cores

V. Yurshevich, S. Lomov and J. Jankovskis

Faculty of Electronics and Telecommunications, Riga Technical University,
12 Azenes str., LV-1048, Riga, Latvia

Abstract - Two methods of self-capacitance determination for windings on high-permeability ferrite cores are described. The first one is connected with the measurements on three frequencies, the second - with the measurements on a single frequency with and without additional capacitance. The methods are free from error associated with frequency and amplitude dependencies of the complex magnetic permeability components of ferrites. The potentialities of these methods are shown by data obtained for measuring windings (single-layer windings on toroidal cores) which are broadly used in magnetic measurements. In such a complicated case when the components of complex magnetic permeability are strongly frequency dependent, the offered methods ensure the acceptable accuracy of measurements even for small self-capacitance (in order of 1 *pF*).

Introduction

The self-capacitance C_o is the parasitic parameter of the windings (inductors). By increasing the frequency the influence of C_o also increases and the problem of estimation of C_o influence becomes actual. In this paper only measuring windings (MW) will be considered. MW is the single-layer winding which is winded on the toroidal core to measure its magnetic properties, for example, magnetic spectra (MS) - the frequency dependence of the components of complex magnetic permeability (CMP) $\overline{\mu} = \mu_1 - j\mu_2$ (Fig.1). In this case the estimation of C_o influence is obligatory because the errors of MS measurements caused by inaccurate accounting of C_o influence may be comparable with errors of CMP measurement method.

Sufficiently full review of C_o measuring resonant methods is done in [1] and for other methods - in [2]. The methods described in these papers are based on two main simplifications: the inductance L and C_o (Fig. 2.a) are not changing with frequency and the inductor is linear (its parameters do not depend on the current). In many cases it is also assumed that inductor's loss are small. This makes such methods unsuitable for MW used for high-permeability ($\mu_1 \geq 2000$) ferrites MS measurements. Firstly, the practice shows that in this case it is necessary to measure C_o in region II of MS (Fig. 1) where μ_1 (it means also L of MW) significantly changes with frequency. Secondly, in measuring instruments used in such methods (Q-meters, bridges) the measurement and adjustment of current through the MW, as usual, is impossible. Then, changing the frequency, changes the impedance of MW (mainly because of changes of μ_1 and μ_2) and consequently the current through it. The significant dependence of CMP of mentioned ferrites on the magnetic fields in specimen causes the changes of MW parameters, which may be mistakenly accredited to C_o influence. Let us consider the frequency dependence of C_o. It is known that C_o of inductors without cores may vary only in the

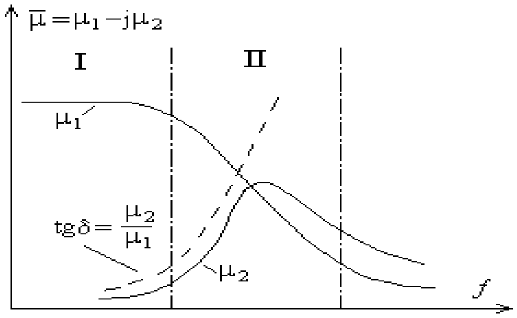

Fig. 1. Typical magnetic spectrum of high-permeability ferrite.

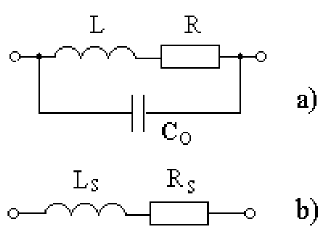

Fig. 2. Equivalent circuits of the measuring winding.

vicinity of self-resonance frequency f_o, namely at $f/f_o > 0.6 - 0.7$. The permittivity ε of a core must have influence on C_o. For manganese-zinc (MnZn) ferrites the value of ε is very high and it strongly changes with frequency in I and II regions of MS. However, if MW is separated from the core even with thin layer of dielectric, the influence of ε can be neglected. In this work it is accepted that C_o of MW does not depend on f right up to frequencies $(0.6 - 0.7) f_o$.

Thus, the authors suppose that well-known methods of C_o measurements are not valid for MW on high-permeability ferrites. In the region of low frequencies (f < 10 - 15 *MHz*) MW has considerable advantages comparing with other transducers. Therefore, the problem of elaboration of C_o measurement methods for above-mentioned MW is important.

First method: determination of C_o from measurements on three frequencies

The essence of C_o determination methods will be explained as applied to MS measurements. To obtain the necessary formulae in such measurements usually use the equivalent circuit of MW shown in Fig. 2.a, where L is "true" inductance of MW – inductance which is free from influence of C_o as well as loss; R - resistance which is equivalent to loss in a ferrite and MW. The dielectric loss are not accounted because MW, as a rule, is separated from specimen by a good dielectric. Let us assume that the direct results of measurements at each frequency $\omega = 2\pi f$ are the parameters L_S, R_S of series equivalent circuit of MW (Fig. 2.b). The parameters of circuits shown in Fig. 2.a and 2.b are related by well-known equations:

$$L_S = L[1 - \omega^2 LC_o(1 + tg^2\delta)] \big/ [(1 - \omega^2 LC_o)^2 + (\omega^2 LC_o tg\delta)^2], \qquad (1)$$

$$R_S = R \big/ [(1 - \omega^2 LC_o)^2 + (\omega^2 LC_o tg\delta)^2], \text{ where } tg\delta = R/\omega L, \qquad (2)$$

$$tg\delta_S = R_S/\omega L_S = tg\delta \big/ [1 - \omega^2 LC_o(1 + tg^2\delta)]. \qquad (3)$$

These equations may be used for C_o determination. After measurements on a single frequency, we obtain two equations ((1) and (2) or (1) and (3)), containing three unknown values – L, R (or $tg\delta$) and C_o. Measurements on another frequency give four equations and five unknown values and so on. To obtain the determinantal simultaneous equations one needs an additional condition. As such one we can use the reality that in the case of relaxation type of MS the dependence of ferrite $tg\delta$ from frequency is almost linear. For other MS this is valid on frequencies close to the main maximum of absorption curve μ_2. If measurements are performed on frequencies f_1, f_2, f_3 in mentioned frequency region (or in region of almost linear $tg\delta_S(f)$ dependence), then for $f_2 = (f_1 + f_3)/2$ we may accept that $tg\delta_2 = (tg\delta_1 + tg\delta_3)/2$, where $tg\delta_i$ is the $tg\delta$ value on frequency f_i. So we obtain the system of six equations ($L_{S1} = \ldots$, $tg\delta_{S1} = \ldots$; L_{S2}, $tg\delta_{S2}$; L_{S3}, $tg\delta_{S3}$) and six unknown values (L_1, $tg\delta_1$; L_2; L_3, $tg\delta_3$; C_o), which may be solved for C_o.

To simplify expressions we introduce such symbols: $tg\delta_i \to t_i$, $tg\delta_{Si} \to t_{Si}$, $L_{Si} \to l_i$. As the condition is associated with $tg\delta$, the following transformations were made: from equation (3) we express value L, and put it in (1). As a result we have: $t[(1 + t_S^2)\omega^2 lC_o + 1] = t_S$. The solution of system of three such equations: $t_1[(1 + t_{S1}^2)\omega_1^2 l_1 C_o + 1] = t_{S1}$; $0.5(t_1 + t_3)[(1 + t_{S2}^2)\omega_2^2 l_2 C_o + 1] = t_{S2}$; $t_3[(1 + t_{S3}^2)\omega_3^2 l_3 C_o + 1] = t_{S3}$ gives for C_o the quadratic equation:

$$\begin{aligned} &C_o^2(t_{S1}A_2A_3 + t_{S3}A_1A_2 - 2t_{S2}A_1A_3) + C_o[(t_{S1}(A_2 + A_3) + t_{S3}(A_1 + A_2) - 2t_{S2}(A_1 + A_3)] + \\ &+ t_{S1} + t_{S3} - 2t_{S2} = 0, \quad \text{where } A_i = (1 + t_{Si}^2)\omega_i^2 l_i. \end{aligned} \qquad (4)$$

The solution of (4) allows to obtain C_o value. Experimental results are presented below. The weaknesses of this method are the limitation of the used frequency range for resonant MS (in this range $tg\delta_S$ must changes with frequency almost linearly) and the influence of possible frequency dependence of C_o.

Second method: determination of C_o from measurements on single frequency

More precise results may be obtained if all measurements are carried out on the same frequency: in this case influence of possible frequency dependence of C_o is excluded. As was mentioned above, the measurements on a single frequency give two equations with three unknown values. The additional condition may be obtained if the following (second) measurements are performed on the same frequency but under different circumstances. The change of the magnetic biasing or magnetization reversal field is not rational: the corresponding relationships usually are not known precisely, but their measurements are not free from influence of C_o.

The second measurements may be done if the small capacitance C_{ad} is connected in parallel to MW. In result we obtain four equations (l_1, t_{S1}; l_2, t_{S2}) with three unknown values (L, t, C_o), since the parameters L and t at the same frequency are constant if C_{ad} is so small that do not change noticeably a current in the parallel circuit L, R, C_o. The presence of one "unnecessary" equation gives the opportunity to obtain the formula for C_o in different ways. One of the possible solutions:

$$C_o = [\omega^2 l_1 C_{ad}(1+t_{S12}) + t_{S12} l_{12} - 1] \big/ \omega^2 l_1 [1 - t_{S12} - (1+t_{S1}^2)\omega^2 l_1 C_{ad}], \tag{5}$$

where $t_{S12} = t_{S1}/t_{S2}$, $l_{12} = l_1/l_2$. Experimental results are presented below. The weakness of this method is difficulties with the determination of the influence of additional capacitor on C_o.

Experimental results

It is necessary to note the contradiction arising when account of C_o influence is required. On the one hand, it is desirable to reduce C_o and, on the other hand, the error of C_o measurement sharply increases with C_o decreasing. This tendency is true for all measuring methods. For instance, in well-known method of double tuning at the resonance [1] at frequency ratio $n = 4$ the relative error $\Delta C_o / C_o$ increases from $\pm 28\%$ for $C_o = 5\ pF$ to $\pm 270\%$ for $C_o = 0.5\ pF$. As practice shows, the ordinary MW for high-permeability ferrites MS measurements have C_o values in range 0.5 - 2 *pF*.

The possibilities of the first method may be shown by using the results of C_o measurements for MW winded on the toroidal cores of MnZn ferrite with initial magnetic permeability $\mu_a = 3000$; the dimensions of toroidal core are $20 \times 12 \times 6\ mm$; number of turns $w = 24$. The preliminary measurements of MS showed that dependence $tg\delta_S(f)$ is almost linear in range 0.7 - 1.7 *MHz*. In this range C_o was determined using (4) for three similar specimens and several frequency sets, for example, from (0.7 - 0.85 - 1.0) *MHz* till (1.3 - 1.5 - 1.7) *MHz*. As it was expected, the scattering of obtained C_o values is high enough and increases with decreasing the frequency (decreasing of the ratio f/f_o). For frequency interval 1.2 - 1.7 *MHz* the calculated values of C_o were located in the range from 0.3 to 1.6 *pF* but the great part of results were concentrated about mean value C_{om} = 0.95 *pF* at scattering $\pm 0.4\ pF$. It should be pointed out that the mentioned scattering is not the weakness of the method. This is the objective phenomenon: the precise measurements of small C_o at the limited value of f/f_o is a difficult problem (the influence of C_o is slight and the relationship between the effective parameters is complicated) Thus, the elements of statistical approach are natural for such measurements.

For above-mentioned MW C_o were measured on frequencies 0.6 and 0.75 *MHz* also by second method at C_{ad} = 2.4 and 4.1 *pF*. It is obtained that C_{om} = 1.1 *pF* at real scattering $\pm 0.4\ pF$. The rise of C_{om} may be explained by increase of current in parallel circuit L, R, C_o (Fig. 2.a) after connection of C_{ad} (that is at approaching to self-resonance). In this case according to amplitude dependence of μ_1 the inductance of MW increases and this change, in fact, is ascribed to influence of C_o.

For MW on the same cores but with *w* = 72 the self-capacitance has been measured at the same frequencies and the same C_{ad}. It was obtained that C_o = 1.4 ± 0.3 *pF*. At the three-hold increasing of *w* the self-capacitance increases only for 40%. This means that contribution to C_o from MW leads and parasitic capacitance of measuring network is noticeable.

In this study the results of MS measurements were used for C_o determination by the first method. If C_o determination is not associated with MS measurements, one must use the measuring method which allows to monitor and adjust the current through MW (at MS measurements this is an obligatory condition), otherwise the amplitude dependence of complex magnetic permeability may introduce the uncertainty in the results. Besides that such a method allows to correct an increase of the current in parallel circuit L, R, C_o when C_{ad} is connected.

The great scattering of results and its increase with decreasing of f may be explained easily on the basis of Fig.3: when loss and f/f_o are small, the parameters L_S and $tg\delta_S$ are changing insignificantly and almost in the same extent. Then the equations (3) and (4) contain the differences between the closely spaced quantities and even small errors of L_S and $tg\delta_S$ determination involve the significant scattering of C_o values. From this the importance of the increasing of measurement accuracy follows (the individual calibration of measuring instruments, the accounting of main accompanying factors: the parameters of instruments' input, the parasitics of measuring network a. o.). For example, even after simplest performance of these operations the scattering of C_o decreased to $\pm 0.25\ pF$ for MW with $w = 24$.

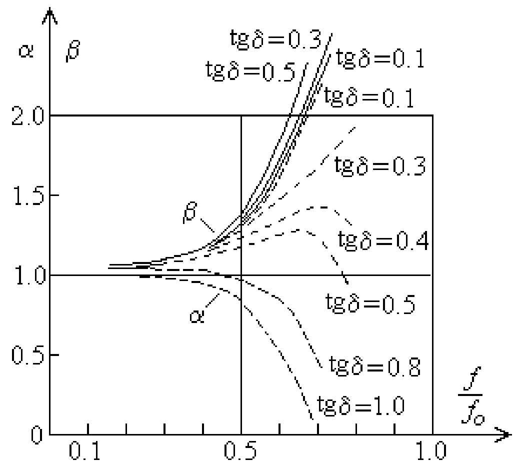

Fig. 3. Frequency dependence of parameters α, β; $\alpha = L_S/L$; $\beta = tg\delta_S/tg\,\delta$.

Conclusion

The offered methods allow to measure with acceptable accuracy even small C_o on frequencies where the components of complex magnetic permeability of ferrites are changing strongly. The well-known methods are unsuitable for this case as they are not taking into account these changes and, in fact, the corresponding changes of MW L_S and $tg\delta_S$ are accredited to influence of self-capacitance. As it was mentioned, the results of MS measurements were used for C_o determination by the first method. This is undoubted advantage of the method if C_o values are necessary for correction of MS measurements. If the measurements of C_o are not associated with MS, the allowable range of frequencies may be easily found from the frequency dependence of parameter $tg\delta/\mu_a$. One can find these curves in handbooks. The weakness of the second method is connected with the using of additional capacitor. However, the comparison of the results obtained by both methods showed that this influence is insignificant if one uses the miniature capacitors and $f/f_o < 0.6$.

These methods were developed mainly for MS measurements. But they conceptually are valid also for other windings on high-permeability ferrite cores – for windings of transformers and chokes.

References

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