Loop Antennna Calibration Methods in Low-frequency

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Abstract—**Several methods have been proposed for the calibration of an electrically small circular loop antenna in the MF and HF bands. They are the 'standard field method,' 'three-antenna method,' 'impedance method,' and so on. In this paper, the advantages and disadvantages of each method are discussed.**

Keywords-loop antenna calibration; magnetic antenna factor; three-antenna method; impedance method; standard field method; TEM-cell; Helmholtz-coil

I. INTRODUCTION

In the fields of electromagnetic interference and electromagnetic compatibility (EMI / EMC), it is important to measure the electric and the magnetic field strength radiated / emitted from an electric device accurately. In order to achieve this, the antenna factor of a receiving antenna must be accurately determined.

In the MF and HF bands (especially below 30 MHz), loop antennas are used for the estimation of the radiated magnetic field strength from the electric device such as the high-voltage power transmission line, induction heating (IH) system, etc. Recently, a loop antenna and the magnetic antenna factor have been widely used for the evaluation of the power line communication (PLC) system, the radio frequency identification (RF-ID) tag system, the RF shoplifting alarm system, the wireless power transfer (WPT) system, and the signal for radio-controlled clocks.

In the low frequency band, a loop antenna works as an electrically small antenna because the wavelength at a low frequency below 30 MHz is longer than 10 m. Hence, the measurements are performed under the near-field condition. Since the antenna factor is defined under the far-field condition, each of the conventional calibration methods—for example, 'standard field method [1] [2] [3] [4] [5]', 'three-antenna method [6]' and 'impedance method [7]'—have been devised to realize quasi-far-field conditions. In the standard field method, a quasi-plane field is realized and applied to the loop antenna. In this paper, a TEM-cell [8] is used to apply the magnetic field to the loop antenna. In the three-antenna method, three loop antennas are prepared. Three transmission S-parameters are measured for every antenna pair using these loop antennas. In general, in this method, the averaged magnetic field strength over the area of loop antenna [9] is used to obtain the quasi-plane magnetic field. The magnetic antenna factor is calculated from these transmission S-parameters and the averaged magnetic field strength inside the loop. In the impedance method, it is possible to obtain the magnetic antenna factor of an electrically small loop antenna from the input impedance and the output voltage estimated by Faraday's law. Thus, these calibration methods are based on different concepts, and hence, it is interesting to compare the results by each method. We will be able to discuss the advantages and disadvantages of the each method.

II. DEFINITION OF MAGNETIC ANTENNA FACTOR

The magnetic antenna factor AF_{m} is defined as:

$$AF_{\mathrm{m}}(f) = \frac{H(f)}{V_{\mathrm{o}}(f)} \tag{1}$$

where H is the incident plane magnetic field on the antenna element and V_{o} is the output voltage across a load (50 Ω). This means that we must obtain the characteristics under the far-field condition even though the wavelength is very long. The antenna factor, naturally, depends on the frequency *f*.

III. STRUCTURE OF CALIBRATED LOOP ANTENNA

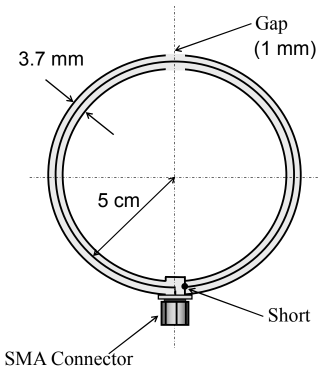

Figure 1. Structure of a shielded loop antenna.

The structure of the calibrated loop antenna used in our study is shown in Fig. 1. This is an ordinary shielded loop antenna and the diameter of the loop is 10 cm. The diameter of the antenna element made of a semi-rigid cable is 3.7 mm. The end of the coaxial line is shorted (0 Ω). An SMA connector (male type) is used for the connection to a generator or receiver. The width of the top gap, which is the feeding point of the loop antenna element, is approximately 1 mm.

IV. CALIBRATION METHODS FOR LOOP ANTENNA

In this paper, three calibration methods for the loop antenna have been adopted for comparison. They are called 'three-antenna method,' 'impedance method,' and 'standard field method.' In this section, each calibration method is described simply.

A. Three-Antenna Method

It is not easy to apply the plane wave to a loop antenna or even obtain a quasi-far-field condition in the low frequency range. Therefore, the averaged magnetic field [9] over the area of the receiving loop antenna is generally used when two loop antennas are located parallelly in free space, as shown in Fig. 2.

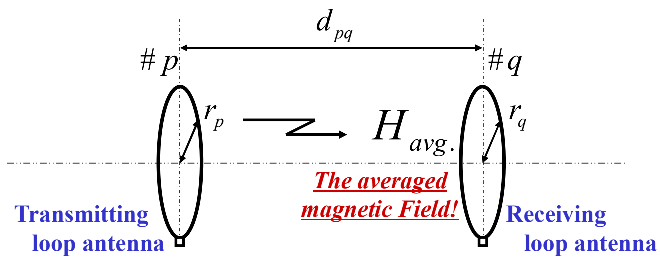

Figure 2. Antenna setup in the three-antenna method.

The 'three-antenna method' using the averaged magnetic field is expressed as:

$$AF_{m\,i}(f)=\left|\sqrt{\frac{-S_{nl}}{S_{in}S_{li}}\frac{\alpha_{in}\alpha_{li}}{\alpha_{nl}}}\right|,$$
$$(i,n,l)=(1,2,3),(2,3,1),(3,1,2)$$
$$\alpha_{pq}=\frac{\sqrt{1+k^2R_{pq}^2}}{j2\pi f\mu_0\pi Z_0R_{pq}^3}\left\{1+\frac{15\left(r_pr_q\right)^2}{8R_{pq}^4}+\frac{315}{64}\frac{\left(r_pr_q\right)^4}{R_{pq}^8}+\cdots\right\},$$
$$R_{pq}=\sqrt{d_{pq}^2+r_p^2+r_q^2},$$
$$(p,q)=(1,2),(2,3),(3,1) \tag{2}$$

where a subscript i shows the antenna number 1, 2 and 3, respectively; AF_{mi} is the magnetic antenna factor of antenna #i; k, wave number ($2\pi/\lambda$) in free space; S_{21}, S_{32}, S_{13} are transmission S-parameters among antennas; ω is the angular frequency; μ_0 is the permeability of free space; Z_L, matched load to the transmission line (50 Ω); r_1, r_2, r_3 are the radii of loop antennas; and d_{12}, d_{23}, d_{31} are the distances between these two loop antennas.

B. Impedance Method

The equivalent circuit of the shielded loop antenna in Fig. 1 is shown in Fig. 3-(a). It is remodeled using the equivalent source and the transmission line theory as shown in Fig. 3-(b).

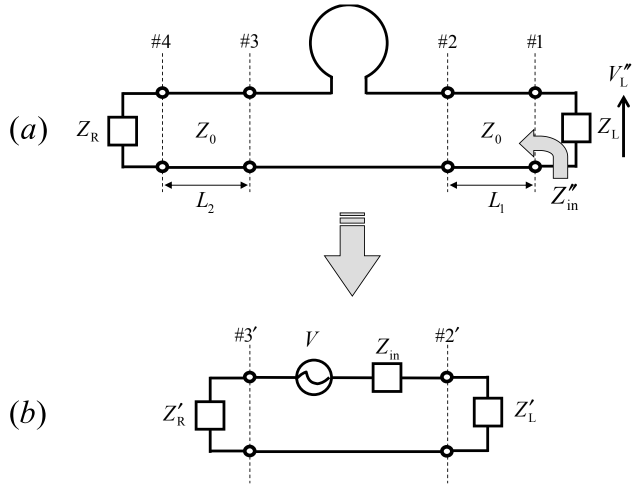

Figure 3. Equivalent circuits of shielded loop antenna. (a) Equivalent circuit of the loop antenna shown in Fig. 1; (b) Remodeled circuit of Fig. 3-(a).

In Fig. 3-(a), Z_0 is the characteristic impedance of the transmission line (50 Ω); L_1 and L_2, the half-length of the loop element; Z_R, the load impedance at one end of the compensation circuit (short / 0 Ω); and Z_L, the matched load to the line impedance (50 Ω). In Fig. 3-(b), Z_{in} is the input impedance of the loop antenna element, and Z'_R and Z'_L are expressed as (3) and (4), respectively.

$$Z'_R=Z_0\frac{Z_R+Z_0\tanh(jkL_2)}{Z_0+Z_R\tanh(jkL_2)} \tag{3}$$

$$Z'_L=Z_0\frac{Z_L+Z_0\tanh(jkL_1)}{Z_0+Z_L\tanh(jkL_1)} \tag{4}$$

On the other hand, the open circuit voltage V of the loop antenna element is expressed by Faraday's law as:

$$V=-j\omega\pi r^2\mu_0H \tag{5}$$

where H is the magnetic field strength of the incident plane wave.

From Fig. 3 and (5), AF_m of this shielded loop antenna is expressed as:

$$AF_{\mathrm{m}}(f) = \frac{H}{V''_{\mathrm{L}}} = j\frac{Z'_{\mathrm{R}} + Z_{\mathrm{in}} + Z'_{\mathrm{L}}}{\omega\mu_0 \pi r^2 Z_{\mathrm{L}}} \frac{Z_{\mathrm{L}} + Z_0}{Z'_{\mathrm{L}} + Z_0} e^{jkL_1} \tag{6}$$

where

$$Z_{\mathrm{in}} = \frac{Z_0(Z''_{\mathrm{in}} - Z'_{\mathrm{R}}) + (Z''_{\mathrm{in}} Z'_{\mathrm{R}} - Z_0^{\,2})\tanh(jkL_1)}{Z_0 - Z''_{\mathrm{in}}\tanh(jkL_1)}, \tag{7}$$

V''_{L} is the voltage across the load impedance Z_{L}; and Z''_{in}, the input impedance at #1 in Fig. 3-(a) when the loop antenna is transmitting.

Only Z''_{in} is unknown in these equations. If the input impedance Z''_{in} of the loop antenna is measured, AF_{m} of the shielded loop antenna is given by (6).

C. Standard Field Method

In the standard field method, a quasi-plane field as the standard electromagnetic field is realized and applied to a loop antenna. The standard field can be generated by various ways [1] [2] [3] [4] [5]. These differ with respect to the instruments and methods used to generate the standard electromagnetic field. In this paper a TEM-cell [8] is used to generate the standard magnetic field. The structure of the TEM-cell is shown in Fig. 4.

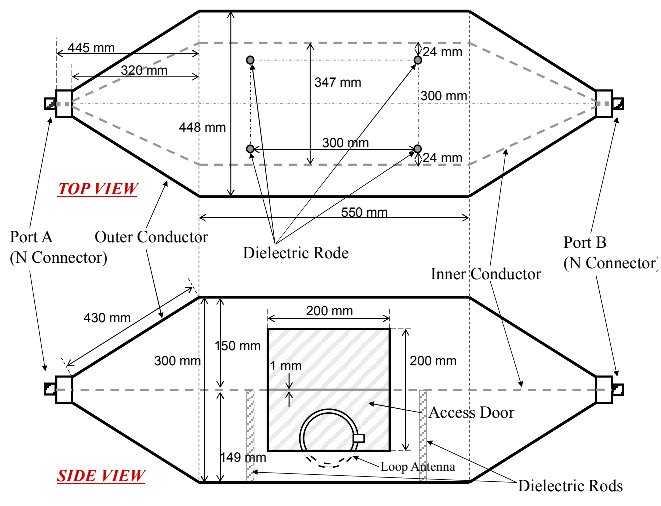

Figure 4. Design of rectangular TEM-Cell and antenna setup.

The magnetic field strength H at the center of the TEM-cell between the upper or lower wall and the inner conductor is determined using the equation

$$H = \frac{\sqrt{P \cdot R_{cell}}}{120\pi \cdot d} \tag{8}$$

where P is the net power flowing through the cell; R_{cell}, the real part of the cell's complex characteristic impedance; and d, the distance between the upper or lower plates and the septum (the inner conductor in Fig. 4). AF_{m} of the loop antenna is obtained from (8), the measured output voltage across the load (50 Ω) V_{o}, and (1).

V. Calibration Result and Comparison

These calibration methods are used with the shielded loop antenna shown in Fig. 1, and the comparison is made among the results by the three calibration methods. The frequency range is from 150 kHz to 30 MHz.

In the three-antenna method the transmission S-parameters among the loop antennas are measured by using a vector network analyzer with a calibration kit. A pair of loop antennas (A round-robin measurement among three loop antennas is performed.) is set in free space as shown in Fig. 2 and the distance between the antennas is 20 cm. AF_{m} of all antennas are calculated from the measured transmission S-parameters using (2). In this paper three loop antennas with the same structure as shown in Fig. 1 are prepared.

In the impedance method, the input impedance of the shielded loop antenna is measured by a calibrated probe of an impedance analyzer. AF_{m} is obtained from the measured input impedance and the radius of the loop by (6).

In the standard field method, the shielded loop antenna is placed at the center in the lower space of the TEM-cell, as shown in Fig. 4. In Fig. 4, Port A is connected to a function generator with a coaxial cable to generate the standard field in the cell. Port B is connected to a power sensor to measure the net power P flowing through the cell. It is assumed that the reflection at Ports A and B and attenuation in the cell is small in this frequency band because the difference between P and P_{direct} is in the order of 0.01 dB (P_{direct} is the absolute power when the power sensor is connected to the generator directly.). The output voltage V_{o} of the loop antenna across the load impedance is also measured by a power sensor and calculated using the equation given below:

$$V_{\mathrm{o}} = \sqrt{P_{\mathrm{Antenna}} \cdot Z_{\mathrm{PowerMeter}}} \tag{10}$$

where P_{Antenna} is the output power of the loop antenna and $Z_{\mathrm{PowerMeter}}$ is the load impedance of a power meter (50 Ω). The separation d between the cell's lower plate and the septum of the TEM-cell is 149 mm.

The numerical simulation using the method of moment is performed for the shielded loop antenna. In this method the thin-wire approximation is used and the piecewise sinusoidal function is adopted as an expansion and weighting function. In this simulation a plane electric field E = 1 V/m is applied to the element of the shielded loop antenna. The antenna factor is calculated as the ratio of the magnetic field strength H (= E/120π) to the output voltage V_{o} across the load impedance Z_{L}=50 Ω. The calculated result will be used as a reference value for comparison with the experimental results.

The obtained four results are shown in Fig. 5, and it can be found that all the calibration results agree with each other. The frequency range is from 150 kHz to 30 MHz. Furthermore, the differences between the numerical simulation result and each of the three calibration results are shown in Fig. 6.

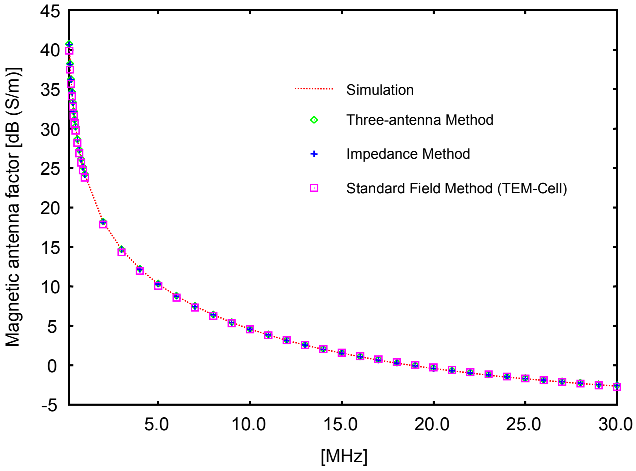

Figure 5. Magnetic antenna factors obtained by the three calibration methods and numerical simulation.

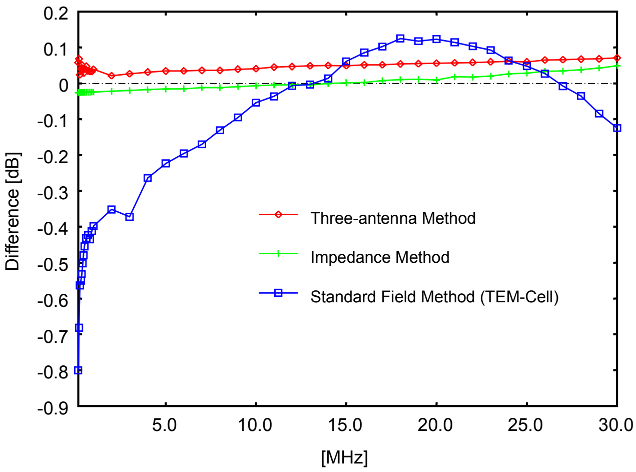

Figure 6. Magnetic antenna factor: deviation of the measured AF_m from the simulation?

In this figure it is found that the difference between these calibration results is within 1 dB. In particular the results of the three-antenna method and impedance method agree well, and the difference of the results is within ±0.1 dB, approximately. Since the dynamic range of the power sensor is not sufficiently enough below 1 MHz in the standard field method, a considerable difference from the other results is obtained. It is expected that the difference may be reduced by using a receiver with the wide dynamic range, such as a measuring receiver.

Performing this comparison the character of each calibration method became clear. In the three-antenna method, we can obtain the AF_m very accurately using a vector network analyser while we have to prepare three antennas and perform three measurements. In the impedance method, we need to know the structure of loop antenna in detail. It is necessary the loop antenna is calculable type. In the standard field method, the size of loop antenna is restricted by the size of the TEM-cell, and the characteristic impedance Z_{cell} of the TEM-cell and the distribution of magnetic field strength in the cell should be evaluated. It is expected that these affect uncertainty of the standard field method. In the case of standard field method, there are various methods [1] [3] [4] [5]. These methods also have the advantages and disadvantages.

In this paper uncertainties are not described. The uncertainties are going to be estimated and compared in the next work.

VI. CONCLUSIONS

In this paper three calibration methods for the magnetic antenna factor of a shielded loop antenna in the frequency range from 150 kHz to 30 MHz were compared. The magnetic antenna factors agree with each other and the differences are within 1 dB. Each of these calibration methods is based on the different concept. Hence, it is important that such a comparison is performed using the same loop antenna. The results also show that all three calibration methods can efficiently calibrate loop antennas. In the future the uncertainties of these calibration methods will be estimated and compared.

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