On the Loop Sensors for the Electromagnetic Field Measurement

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Abstract-In this paper we present an overview of the electromagnetic field loop sensors measurement performances. The loop sensors are much utilised in electromagnetic field measurements (magnetic field measurement, simultaneous magnetic and electric field measurements). The knowledge of the influence of the dimensions' sensor on measurement performances of the electromagnetic field is important both in sensor optimisation, and in the selection of the sensor for a certain application. The results of time domain measurements of the magnetic field near some appliances, made with an active magnetic field sensor, are presented.

I. Introduction

The loop is a very important configuration for the electromagnetic field sensors [1]. The loop sensor is used for the measurement of the magnetic field in a very large amplitude domain (nT÷mT) and frequency range (Hz÷GHz). Moreover, the double loaded loop sensor is utilised for simultaneous magnetic and electric fields measurements [2], [3]. The basic requirements for the electromagnetic field sensors are: great sensitivity and dynamic range; small uncertainty (minimal perturbation of the measured field and averaging effect); great spatial resolution; immunity of the perturbing factors (eg. parasitic sensitivity at E of a loop sensor used for H measurement), etc. The great diversity and applications of loop magnetic field sensors are due to: the shape (circular, square); the configuration (full loop antenna, half loop antenna); the dimension (radius) of the loop; the number of the turns, the inner medium (air, core); the number of the loads (single loaded loop sensor, double loaded loop sensor, multiple loaded or resistively loaded), etc. The dimension of the loop is a very important parameter. The smaller the dimension of the sensor, the smaller the perturbation errors [4], the higher the degree of spatial resolution will be, higher frequencies may be measured, but the sensitivity of the sensor will decrease. Thus, an optimisation of the measurement probe must be made.

II. The loop as magnetic field sensor (single loaded loop)

The equivalent circuit of electrical small loop receiving antenna (kb<1) loaded in a single point (ϕ_1) with the impedance Z_{L1}, is shown in Fig.1.

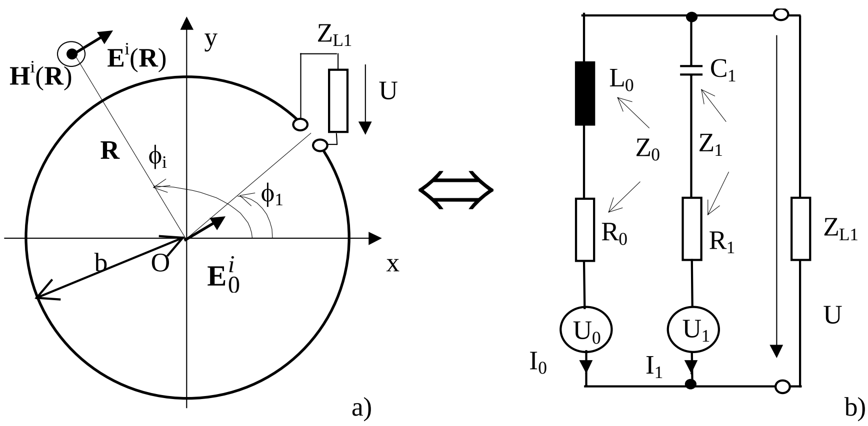

Figure 1. Configuration and equivalent circuit of a single loaded loop antenna

In the equivalent circuit of the receiving loop (Fig. 1b) two sources appear: one owing to the magnetic field (source U_0); the other one owing to the electric field (source U_1).
The parasitic sensitivity at the electric field of the loop sensor (U_1) must be reduced when only H field is measured. The parasitic response to the electric field is reduced by a special configuration of the sensor (Moebius configuration) or using shielded loops. If the loop is electrically very small (kb<<1), the influence of the electric field can be neglected.

$$kb << 1 \Leftrightarrow 2\pi \frac{f}{c} b << 1 \qquad (1)$$

where f is the frequency, c is the speed of light and b is the radius of the loop.
From (1) the high frequency limit for measurements or the maximum radius for a certain upper frequency can be determined. Under these conditions (kb<<1) for U_1 we obtain the well-known formula:

$$U_1 = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{S} \qquad (2)$$

where B is the magnetic induction and S is the loop area.
Because the loop measures the field component perpendicular on its area (it has directivity), by using two perpendicular loops we obtain a biaxial (2D) sensor and with three orthogonal loops the root mean value (r.m.s.) of the magnetic field vector (B) may be obtained.

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad (3)$$

where B_x, B_y, and B_z are the r.m.s. values of the three orthogonal components of the magnetic field vector.
The plane (2-D probe) or spatial (3-D probe) isotropicity is important in the measurement of complex magnetic fields without the rotation of the probe.
Referring to the frequency domain of measurement, if the frequency increases, the number of turns decreases and the shielding mode is more complex [5].
One of the important applications of the loop sensor is for the time domain measurement of the magnetic field [6]. The equivalent circuit of the loop sensor may be simplified as in Fig 2a, where Z_c is the load impedance. Figure 2b shows the frequency characteristic of the field sensor response. There are two situations: U_h proportional to $\partial H/\partial t$ for $f << Z_c/2\pi L$; U_h proportional to H for $f >> Z_c/2\pi L$. These linear characteristics (the straight lines 1 and 2 in figure 2b) are separated by critical frequency f_{cr}.

$$f_{cr} = \frac{Z_c}{2\pi L} \qquad (4)$$

The good performances of spatial resolution, the accuracy, and the upper frequencies require a small radius of the loop. To increase the sensitivity, which decreases for a small radius, the active sensor is used.

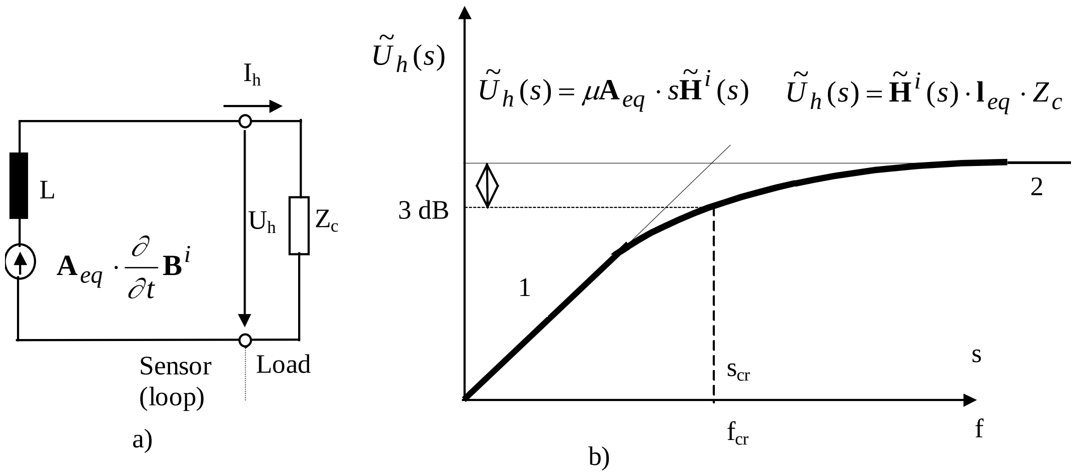

Figure 2. a) The equivalent circuit of the loop sensor; b) The frequency characteristic of the sensor

Figure 3 shows two types of active magnetic field meter. Because the input impedance of the voltage amplifier is great, the response (voltage $U_{out,1}$ in figure 3a) is proportional to the time derivative of the H. If a response proportional to H (voltage $U_{out,2}$) is desired, then an integrating circuit is used. In

Figure 3b, by using a current amplifier (low input impedance), the response (voltage U_{out}) is proportional to H. In this case, it is very important to decrease the critical frequency to extend the inferior frequency domain (e.g. to about 50 Hz to visualize the magnetic fields generated by the power line). To decrease the parasitic influence of the electric field, a screening and a symmetrical configuration of the active sensor is used.
The authors made an active magnetic field meter using the principle given in Fig. 3b. The response of this sensor is proportional to H in 40 Hz ÷ 150 kHz frequency range and it is adequate to measure the magnetic fields generated by the power supply.

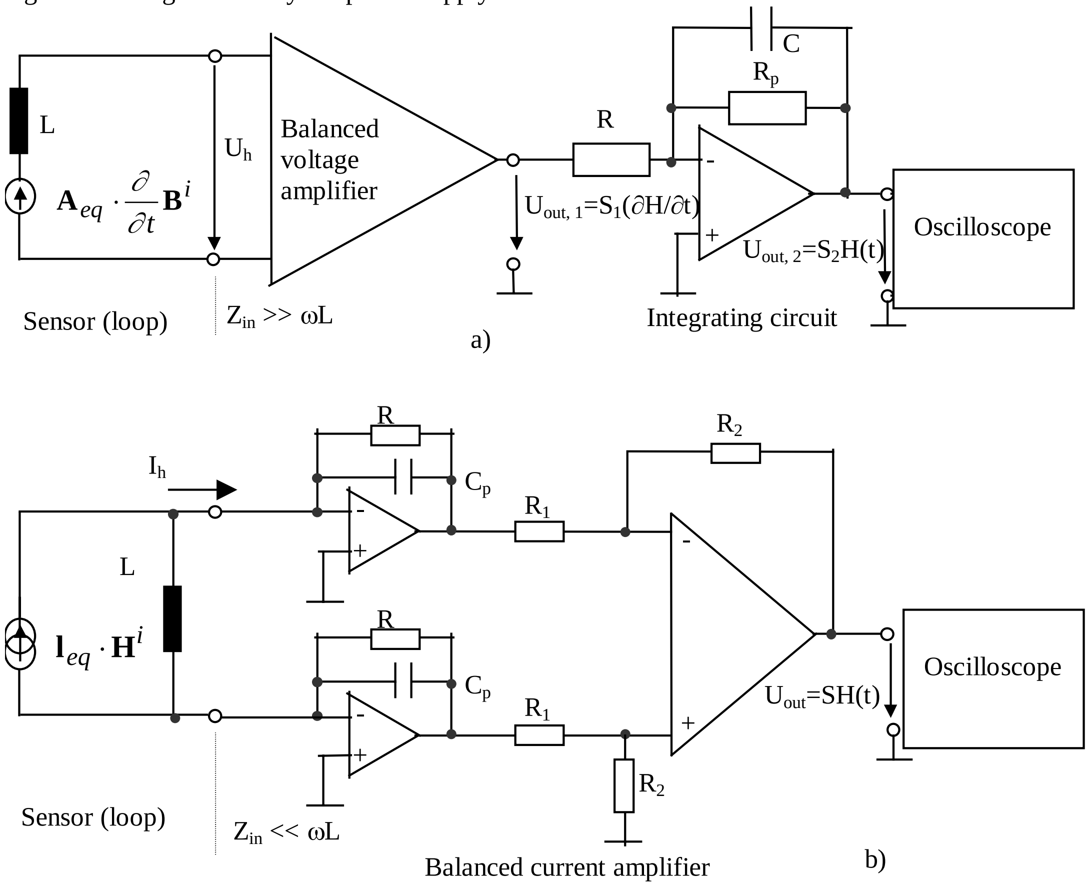

Figure 3. The active loop sensors: a) loop sensor with voltage amplifier; b) loop sensor with current amplifier

The time domain measurement results of the background magnetic field (50 Hz and harmonics) in laboratory and the magnetic field generated by a hairdryer at 30 cm distance are shown in Fig. 4.

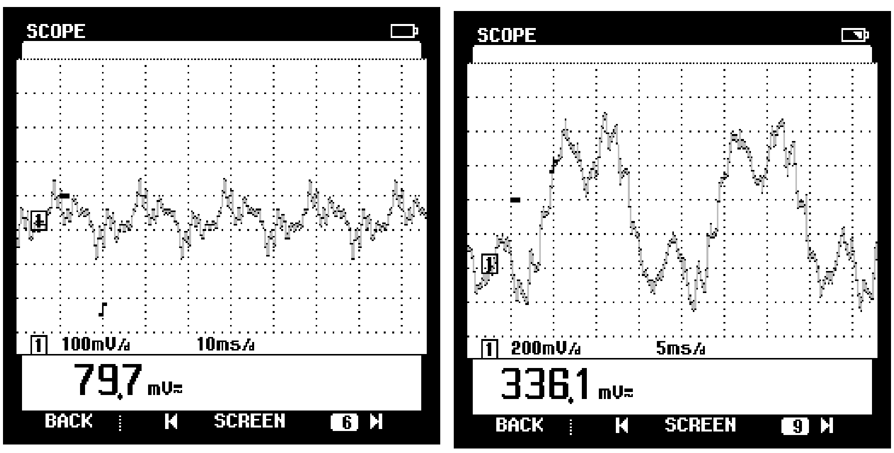

Figure 4. The time domain measurement of H: a) Background H field; b) H generated by a hairdryer

The peak-to-peak value of the background magnetic field is of about 208 nT and the root mean square value of this field is 66 nT. The peak-to-peak value of the magnetic field generated by a hairdryer at 30 cm distance is of 963 nT and the root mean square is 279 nT.

III. The loop as a magnetic and electric field sensor (double loaded loop)

In the case of the single loaded loop antenna (Fig. 1), the electric field sensitivity of the loop must be decreased because only H is measured. The sensitivity at electric field of the loop may be used to measure E and H with a single sensor. Thus, using a loop loaded in diametrically opposed points with equal charges, by summing and subtracting the two voltages, we can measure simultaneously E and H fields [2], [3], [7].

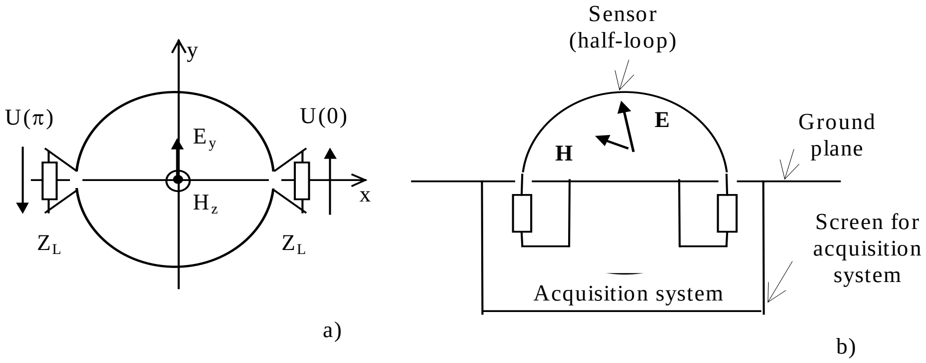

Figure 5**.** Double loaded loop antenna a) Symmetrical or equilibrated configuration (full loop); b) Asymmetrical configuration (half-loop and ground plane).

Referring to Fig. 5a, the values of the sum and difference of the two voltages obtained at interstices are:

$$U(0)+U(\pi)=\pi b^2 j\omega \frac{1}{c} E_0^i = \pi b^2 j\omega\mu_0 H_z \quad (5)$$

$$U(0)-U(\pi)=2\pi b j\omega C Z_L E_0^i = 2\pi b j\omega C Z_L E_y \quad (6)$$

where C is the capacitance of the loop.

Thus, the magnetic field perpendicular to the loop plane (H_z) and the electric field tangent at the interstices (E_y) are measured. To collect the voltage from the two diametrically opposed loads, so as not to form supplementary loops in the field area to be measured, an optical transmission line [8] or an asymmetrical configuration is used. The asymmetrical configuration (half-loop and ground plane) given in Fig. 5b has the advantages of a simple connection mode for the two voltages and the possibility to shield the electronic processing system.

By using the shield of the magnetic antenna for the measurement of the electric field, we made a sensor for the measurement of the electric and magnetic fields in the 40 Hz ÷100 kHz frequency range [9]. In this way the frequency range of the sensors for the electric and magnetic field measurements is extended under 100 kHz and it is possible to measure the fields generated by power line.

With three double-loaded loop antennas orthogonally situated it is possible to measure three components of E and three of H, and to calculate the resultant magnetic field vector and the resultant electric field vector using relation (3).

Referring to multiple loaded loop antenna, if the number of loads increases a uniform resistive loading is obtained [10]. This type of antenna may be used for time domain measurements in the case of fast, impulsive electromagnetic fields.

IV. Conclusions

There is a great diversity of loop sensors used for electromagnetic field measurements. Through the choice of a certain configuration (number of turns, number and value of the loads, etc) and through optimisation, the loop sensors become suitable in many measurement applications. The dimension of the probe determinates the basic measurement performances. Time domain measurements of H, very important in many domains, require a flat response in a large frequency domain and a great dynamic range. By using an active magnetic field sensor made by ourselves, we measured in the time domain the ambient magnetic field in a laboratory and the magnetic field generated by a hairdryer.

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