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Detection of potential electric field induced by a toroid with low frequency current

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The article presents the results of experiments on direct measurement of the electric field in the toroid hole with alternating current of 50 Hz. In the first experiment, a shielded charge-sensitive sensor in the form of a metal rod was used. It was found that in the case of traditional single-point grounding, the screen is not equipotential and completely blocks the sensor operation. Forced equipotentiality of the screen is achieved using two-point grounding, and the sensor inside the screen successfully records the alternating electric field. The result of the experiment is explained by the presence of a non-stationary vortex-free vector potential on the toroid axis, which exerts a force effect on free electrons in the metal probe. In the second experiment, a slider rheostat was used. Such a scheme allows us to abandon the grounded screen and the experiment is simplified as much as possible. The conclusions obtained as a result of the experiments complement the idea of the vector potential and its properties and can be used in solving problems of electromagnetic compatibility.

Keywords: generalized electrodynamics, vector potential, magnetic field of a toroid, Aharonov-Bohm effect, electromagnetic compatibility.

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Introduction

Toroidal transformers are often used in electrical and radioelectronic devices. This raises the problem of electromagnetic compatibility of devices and equipment, requiring a detailed study of the generated electric and magnetic fields.

An experiment with a toroidal solenoid (toroid) carrying a current with a frequency of 50 Hz is described in [1]. The toroid winding is enclosed in a solid grounded shield. As a result, a potential electric field was detected and measured by the electrometric method on the axis of the inner hole of the toroid (outside the shielded region). It is shown that this effect is not related to electromagnetic leakage fields. Its origin is explained by the field of the non-stationary vector potential $\mathbf{A}(t)$. The question of the correspondence of the field of vector $\mathbf{A}$ to the

Helmholtz decomposition theorem into solenoidal $\mathbf{A}_s$ and potential $\mathbf{A}_p$ components is discussed:

$$\mathbf{A} = \mathbf{A}_s + \mathbf{A}_p \quad (1)$$

The $\mathbf{A}_p$ component is usually excluded by the Coulomb or Lorentz gauges. However, as it turned out, it possesses certain physical content and paradoxical properties. This coincides with the conclusion made in [2]: "...the vector potential is more important than the electric and magnetic fields. Vector potential fields can generate electric fields in a contactless manner through conducting substances." A similar conclusion is made in [3]. The properties of the $\mathbf{A}_p$ vector field have also been investigated in various works, and the information obtained has been systematized in monographs [4, 5].

The aim of the present study is the direct experimental measurement, by two methods, of the potential electric field in the hole of a toroid with alternating current and outside it, as well as the theoretical explanation of the experimental results.

Note that the methods of measuring the electric field in the present work differ from the method used in [1]. Comparison of the results obtained by different methods allows a conclusion to be drawn about their reliability.

Experiment on measuring the potential electric field by a charge-sensitive sensor

Fig. 1 presents a schematic of the experiment on measuring the electric field in the inner hole of a toroidal solenoid carrying an alternating current with a frequency of 50 Hz. The basis of the solenoid is a laminated steel core shaped as a hollow cylinder with a relative magnetic permeability of 11000. The quasi-static electric field sensor is a conducting steel rod with a resistance of $0.1\ \Omega$, connected to a charge amplifier. The signal of this sensor does not depend on the capacitance of the connecting cables, but only on the sensor's own capacitance and the magnitude of the field acting on it.

The schematic of this experiment differs fundamentally from that described in [1]: here, the toroid is not shielded, whereas the sensor is shielded. The shield is made of a polyvinyl chloride tube with an inner diameter of 50 mm, on the outer surface of which a conductive layer of graphite varnish $20\ \mu\text{m}$ thick is applied. There is an air gap of 20 mm thickness between the sensor and the shielding surface. If the field of the $\mathbf{A}_p$ vector is capable of penetrating through a conductive surface, then the results of experiments with different types of shields should not differ.

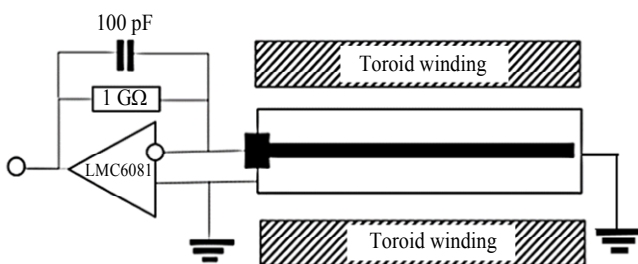


Fig. 1. Schematic of the experiment with a charge-sensitive sensor

Initially, an experiment was conducted with the shield grounded at one point. It showed a complete absence of the sensor signal. When analyzing the reasons for such a result, measurements of the potential difference between the distal and proximal ends of the electrostatic shield were carried out. It was found to be 780 mV. Consequently, such a shield is not equipotential. It is necessary to ensure its equipotentiality. For this purpose, the shield must be grounded at both ends, as shown in Fig. 1. However, with two grounding points of a non-equipotential metal shell, alternating currents will flow through it. To prevent these currents from causing measurement interference, they must be minimized. For this purpose, the shield must be made sufficiently high-resistance (e.g., tens of kilohms); then the currents flowing in it will be negligibly small, allowing their induction on the sensor to be disregarded.

In the setup used, the toroid height was $h = 0.085\ \text{m}$, the effective (measured) value of the EMF on the toroid axis $\bar{\varepsilon} = 780\ \text{mV}$, which corresponds to the expected effective value of the electric field strength:

$$\bar{E} = \frac{\bar{\varepsilon}}{h} = 9.17\ \text{V/m}.$$

Calibration of the probe together with the charge amplifier (CA) was performed by connecting a voltmeter to the grounding circuit. The transfer coefficient was determined as the ratio of the actually measured voltage at the CA output to the voltage applied to the shield ends: $K = 0.03$. When a voltage of 220 V with a frequency of 50 Hz is applied to the toroid winding, a sensor with an equipotential screen and a CA records the effective voltage $\bar{U} = \bar{\varepsilon} = 0.235\ \text{V}$. Considering the transfer coefficient, this corresponds to the electric field strength $\bar{E}_x = 9.17\ \text{V/m}$. When the voltage supplied to the toroid was varied using a variable autotransformer (LATR), a linear dependence between the input voltage and the output signal was established.

A sensor located outside the toroid does not register an electric field, which is consistent with numerous measurements using closed loops located entirely outside the hole.

Experiment using a slide rheostat

It is highly desirable to measure the electric field using the simplest possible technical means, avoiding various types of interference and noise. To achieve this goal, a slide rheostat with a resistance of 10 k Ω and a length almost exactly matching the height of the toroid was used. The same toroid as in the first experiment was used in this experiment. The contact point B with the resistive layer changes as the slider moves (Fig. 2).

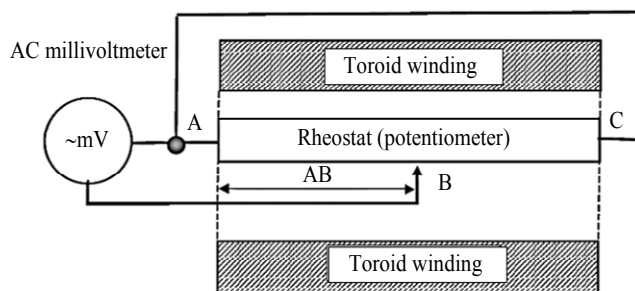


Fig. 2. Schematic of the experiment with a rheostat

If the equipotentiality of the rheostat is ensured by short-circuiting its contacts A and C with a low-resistance conductor, then even under the action of induction on the resistive layer of the rheostat, the potential throughout the entire layer from A to C will be the same. Let us call this technical solution an "equipotential rheostat." Slider B is connected to point A through an AC millivoltmeter. The part of the conductor running from point B to the voltmeter is located inside the toroid. It plays the role of a charge-sensitive probe, as in the first experiment. In this part of the conductor of length $AB = x$, an EMF is induced, which the instrument measures. As the rheostat slider moves, x changes and, accordingly, the measured rms voltage (induction EMF) arising on this section changes. A rheostat with a known nonlinear resistance characteristic $R(x)$ was used in the experiment. The electric field strength E on the toroid axis, calculated using the formula

$$E(x) = \frac{U(x)}{l_0} \frac{R_0}{R(x)}$$

proved to be practically constant and equal to 13 V/m. Here l_0 and R_0 are, respectively, the

length and maximum resistance of the rheostat, and $U(x)$ is the measured voltage. As a result, a linear graph of the dependence of the induction EMF on the position of the rheostat slider was obtained (Fig. 3).

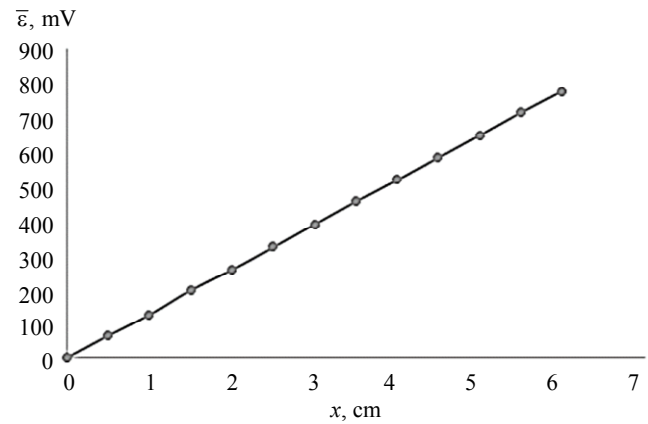


Fig. 3. Dependence of the measured EMF on the length of section $AB = x$

Thus, both experiments register the presence of a potential electric field on the axis of the toroid through the winding of which an alternating current flows.

Theory

First of all, the question of the origin of the potential electric field on the toroid axis should be answered. This phenomenon cannot be explained by leakage fields around the toroid: at a frequency of 50 Hz, the length of the emitted electromagnetic waves is more than 6000 kilometers; consequently, no noticeable potential difference can arise within the toroid. It is obvious that the cause is related to the non-stationary field of the vector potential, since:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}. \quad (3)$$

The induction EMF on the x -axis of the toroid "from end to end" is determined by the formula:

$$\varepsilon = \int_0^h E_x dx = - \int_0^h \frac{\partial A_x}{\partial t} dx = - \frac{\partial A_x}{\partial t} h. \quad (4)$$

Note that here the projection A_x of the potential vector $\mathbf{A}_p$ onto the toroid axis is used,

and it is taken into account that the non-stationary field $E_x(t)$, as follows from experiments, is uniform. In this case, free electrons with charge q move in the metal probe under the action of the force:

$$F_x = qE_x.$$

Since the output voltage of the CA is proportional to the force F_x , the experiment proves the force action of the non-stationary vector potential A_p on charges. This conclusion allows the well-known Aharonov-Bohm effect [6–11] to be explained, but without the quantum concepts that are often used for this purpose.

With a sinusoidal law of alternating current in the toroid with frequency f , the vector potential changes according to the law:

$$A_x = A_{x(\max)} \cos(2\pi ft). \quad (5)$$

Substituting (5) into (4), we obtain

$$A_x = \frac{\varepsilon}{2\pi f h} \sin(2\pi ft)$$

then the amplitude of the potential component of vector $\mathbf{A}$ on the toroid axis can be calculated:

$$A_{x(\max)} = \frac{\bar{\varepsilon}}{\sqrt{2}\pi f h} = 0.0106 \text{ T} \cdot \text{m}.$$

Here $\varepsilon = \bar{\varepsilon}\sqrt{2}$ is considered.

The monograph [4] outlines the concept of generalized electrodynamics, based on the concept of a four-dimensional vector (quaternion) of the magnetic field $(\mathbf{B}, B^*)$. Such a concept corresponds to the Helmholtz theorem on the decomposition of a field into solenoidal and potential components. The potential component of the magnetic field is determined by the scalar function $B^*(x, y, z, t)$ and is related to the vector potential $\mathbf{A}$:

$$\nabla \cdot \mathbf{A} = -B^*. \quad (6)$$

It is clear that here $\mathbf{A} = \mathbf{A}_p$.

The scalar magnetic field (SMF) is induced, in particular, by a toroidal solenoid (Fig. 4). In the ideal case, the vortex (solenoidal) and potential (scalar) magnetic fields of the toroid are

positionally separated: the vortex magnetic field is concentrated inside its winding, and the potential one is concentrated along the axis in the inner hole and is represented by two regions with different signs. In the region of negative SMF, the sources of the potential vector $\mathbf{A}_p$ are located, and in the positive region, the sinks.

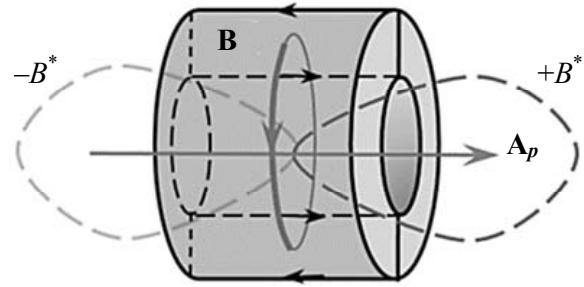


Fig. 4. Magnetic field of a toroidal solenoid

In [3], a system of differential equations of generalized electrodynamics (extended Maxwell's equations) is presented. One of the equations expresses the law of irrotational electromagnetic induction:

$$\nabla \cdot \mathbf{E} = \frac{\partial B^*}{\partial t}, \quad (7)$$

from which it follows that a non-stationary SMF with induction B^* generates a potential electric field of strength $\mathbf{E}$. Note that formula (3) follows from equation (7) taking into account (6). The same monograph presents the results of several experiments confirming the phenomenon of irrotational electromagnetic induction. The experiment described in this article also confirms this phenomenon.

Conclusion

Let us formulate the results obtained in this study:

1. In the first experiment, a potential electric field in the inner hole of a toroid with alternating current was registered using a charge-sensitive sensor. It was shown that in such experiments, it is necessary to ensure the equipotentiality of the electrostatic shield.

2. The phenomenon of penetration of the irrotational vector potential field through an equipotential electrostatic shield has been confirmed, which is important to consider in problems of electromagnetic compatibility.

3. It has been established that in the non-stationary field of the irrotational vector potential, charged particles experience a force action. This result should be considered when interpreting the Aharonov–Bohm effect.

4. In the second experiment, a very simple circuit with a potentiometer was implemented, requiring no grounding. Its advantage lies in the ease of replicating the experiment in order to verify the described phenomenon.

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