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THE ANALYSIS OF ELECTROMOTIVE FORCE APPEARANCE IN A LINEAR UNIPOLAR GENERATOR

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Abstract: On the basis of Lorenz transformation, the mathematical analysis of known results of practical research of a unipolar generator has been given. The analysis shows that the obtained experimental results have strict theoretical substantiation and they are not exceptions to the basic rules of transformation of vectors of an electromagnetic field into any inertial coordinate system. The necessary conditions for the appearance of electromotive force in unipolar generators of various constructions have been given.

Key words: Lorenz transformation, mathematical analysis, electromagnetic field, unipolar generator.

1. Introduction

Experiments with a unipolar generator were extensively discussed in scientific and technical literature for a long period of time [1]–[5]. Different approaches were proposed to theoretically substantiate the phenomenon of appearance of electromotive force within mobile electroconductive medium in the presence of a static magnetic field.

Special attention was paid to the problem of finding consistency between the experimental results and the basic principles of the classic theory of electromagnetic fields for mobile mediums. But still some experimental data cannot be fully supported and explained by applying the above mentioned theoretical principles.

Increasingly sophisticated experimental methods and devices were developed and employed in order to find an acceptable explanation to the physical phenomenon of appearance of electromotive force. Despite the fact that this phenomenon was first investigated by Faraday back in 1831 [7], all the subsequent efforts did not result in a more clear understanding of its nature.

The complete and thorough theoretical substantiation of known experiments with unipolar generators probably need to be done through employing a strict mathematical model, which would cover all the aspects of the discussed phenomenon to the highest degree and open new opportunities for its analyses. Lorenz transformation meets these requirements.

Let us summarize the outcomes of six different experiments with a unipolar generator. During each of the experiments, the relative motion between a conductive medium, a source of electromagnetic field and a measuring circuit would result in either presence or absence of an electromotive force [5]:

1. The conductive medium is mobile, the source of electromagnetic field as well as the measuring circuit are immobile – the electromotive force is present;
2. The source of electromagnetic field is mobile, the conductive medium as well as the measuring circuit are immobile – the electromotive force is absent;
3. The source of electromagnetic field as well as the measuring circuit are mobile, the conductive medium is immobile – the electromotive force is present;
4. The conductive medium as well as the source of magnetic field are mobile, the measuring circuit is immobile – electromotive force is present;
5. The measuring circuit is mobile, the conductive medium as well as the source of magnetic field are immobile – the electromotive force is present;
6. The conductive medium as well as the measuring circuit are mobile, the source of electromagnetic field is immobile – the electromotive force is absent.

It should be noticed that in above mentioned experiments the appearance of electromotive force doesn't depend on the type of the motion of conductive medium (rotational or translational).

2. Analysis of the phenomenon

Before analyzing the results of these experiments, let us consider a relationship between vectors of electromagnetic field located at an arbitrary selected point in space and referenced to different coordinate systems (Fig. 2).

Let's define a stationary coordinate system as *x*, *y*, *z*. Another coordinate system, which is moving at constant speed ***v*** with respect to stationary one in the direction ***x***, is defined as *x'*, *y'*, *z'*. Accordingly, the electromagnetic field vectors are defined as **E**, **B, E', B'**.

The relationship between the electric field strength in different inertial coordinate systems is determined by Lorenz transformation [6]:

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B} \,, \tag{1}$$

where **E, B** – are correspondingly the vectors of electric field strength and magnetic induction in the stationary coordinate system; **E'** – the electric field strength vector in the mobile coordinate system; **v** – the vector of linear velocity of the mobile coordinate system.

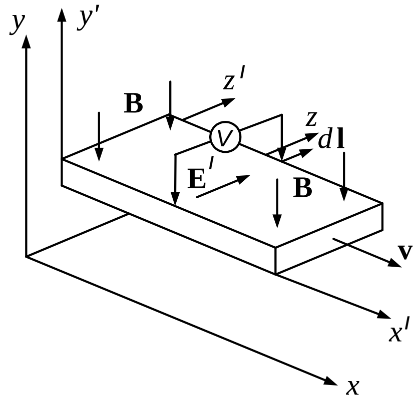

Fig. 1. A linear unipolar generator

Let us assume that there is no electric field in the stationary coordinate system, or **E** (*x, y, z*) = 0, and the vector of magnetic induction has a constant value, or **B** (*x, y, z*) = const. From (1) it follows, however, that there would be some presence of electric field if referenced to the mobile *x'*, *y'*, *z'* coordinate system.

$$\mathbf{E}' = \mathbf{v} \times \mathbf{B}\ , \qquad (2)$$

which means that characteristics of electromagnetic field when expressed in mobile coordinate system are different from the characteristics in the stationary one.. This phenomenon is directly related to the energetic relationships of electromagnetic fields. Similar to the mechanical systems in a constant linear motion, the results of different interferences between material bodies do not depend on the selection of the type of coordinate system. The transition from one system to another, however, is accompanied by absorption or discharge of energy and this amount of energy becomes a quantitative measure of motion relativity.

The article [8] contains mathematical transformations in order to obtain expressions for calculating total electromagnetic energy for moving medium by utilizing Maxwell-Minkovsky equations for electrodynamics. The authors, however, neglect the fact that those equations simultaneously refer to the vectors of electromagnetic field belonging to different frames of references and consequently the validity of their work can be questioned.

The problem of computing the energy of electromagnetic field during the transition from one inertial frame of reference to another remains still open and requires further research.

According to (2), a free electrical charge at the point of interest, when referenced to the mobile system *x'*, *y'*, *z'*, would experience an application of some external force of electromagnetic nature. Under the influence of such a force, as defined by (2), within the field described by vector **B** (coordinate system *x*, *y*, *z*) the charge would undergo a rotary motion. This kind of motion is resulted from the changes in direction of the charge's speed vector. The radius of the circular/rotary motion depends on the mass and the full energy of the particle.

It should be emphasized that magnetic field of the charged particle rotating along a circular path (analogues to the phenomenon of creation of whirling current in the conductive medium under the influence of alternating magnetic field) would be in opposition to the external field. Consequently, the free electrical charge, if brought into the field of vector **B**, would be moving with rotary or spiral trajectory.

The mathematical analysis of this phenomenon presents significant difficulties since the coordinate system associated with the free particle during its motion is not inertial, even if particle is entering magnetic field **B** along a linear path. The possibility of employing Lorenz transformation in this case would be determined by the ratio of particle's speed to the speed of light.

The physical processes, which take place in conductive mediums moving with constant speed within a steady magnetic field, have different character when comparing to the ones just described. It is known that by nature, all substances are electrically neutral (they don't possess any uncompensated electrical charges). According to (2), during the motion of conductive medium within a magnetic field some forces would appear, which are equal in magnitude but opposite in direction. These forces would act on positive (ions) and negative (electrons) charges inside the substance. As a result of internal balancing of those forces, the mobile medium would not experience the change in the direction of its motion.

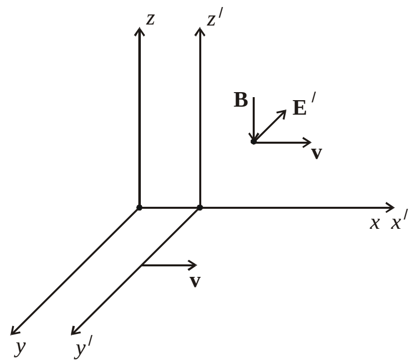

Fig. 2. The electromagnetic field vectors at the arbitrary spatial point in space in different coordinate system.

Inside the substance, however, the process of redistribution of charges would lead to the appearance of internal electrical field, which eventually becomes as strong as external field, but directionally opposite.

The similar phenomenon can be observed when experimenting with electrically charged sphere. The conductive substance, if situated near the sphere, would experience redistribution of charges, and as a result of that, the internal electrical field strength would eventually balance external. In both cases, the resulting electrical field (each in its own frame of reference, related to the conductive substance under study) is absent. In case when conductors were substituted by dielectrics during experiments, the latter would be polarized.

Let us pay attention to the problem of appearance of an electrical voltage between the two arbitrary spatial points when referencing to different coordinate systems (Fig. 3). For this purpose, let's use a known equation:

$$u = \int_a^b \mathbf{E} d\mathbf{l}, \qquad (3)$$

where u – is the voltage between points a and b.

When referenced to the mobile coordinate system and under conditions $\mathbf{E}(x, y, z) = 0$, $\mathbf{B}(x, y, z) = \text{const}$ and providing there is no conductive medium present, the equation (3) would have the form:

$$u' = \int_a^b \mathbf{E}' d\mathbf{l} = \int_a^b (\mathbf{v} \times \mathbf{B}) d\mathbf{l} \qquad (4)$$

It should be noted, however, that the obtained u' represents a calculated value only and characterizes the computed spatial difference of potentials of electrostatic field, similar to the example with charged sphere. Since free electric charges are absent, the value of u' does not indicate a magnitude of real voltage (the concept of voltage in equation (4) is different from the one used in analysis of electrical circuits).

If the conductive medium is moving within a static magnetic field, then the expression (4) for the coordinate system x', y', z' would become:

$$u' = \int_a^b (\mathbf{E}' - \mathbf{E}'_{in}) d\mathbf{l}, \qquad (5)$$

where $\mathbf{E}'_{in}$ is the vector of internal electric field strength in the conductor.

For the conductive medium, if expressed in the mobile frame of reference x', y', z', $|\mathbf{E}'| = |\mathbf{E}'_{in}|$, and consequently the conductor's electric voltage u' between arbitrary selected points is equal to zero.

In case when both the measuring circuit and the conductive medium move with the same speed with respect to the stationary coordinate system, in which $\mathbf{B} = \text{const}$, the electric voltage between arbitrary points in medium, according to (5), is always zero. It exactly corresponds to the results of experiment 6.

If the measuring circuit is transferred to the coordinate system x, y, z, its electric voltage would be expressed as:

$$u = -\int_a^b \mathbf{E}'_{in} d\mathbf{l} \qquad (6)$$

or

$$u = -\int_a^b (\mathbf{v} \times \mathbf{B}) d\mathbf{l}. \qquad (7)$$

This way, we have obtained an electrical generator of linear construction. The equation (7) can be used to calculate the magnitude of generated electromotive force. It can be noted here that the coordinate system, which is related to the measuring circuit, should not necessarily be stationary (x, y, z). The necessary conditions for appearance of the electrical voltage, besides conductive medium being moved within a magnetic field, consist of having the differrence in speed between measuring circuit and conductive medium. In general, the equation (7) would have the form:

$$u = -\int_a^b (\Delta\mathbf{v}_{12} \times \mathbf{B}) d\mathbf{l}, \qquad (8)$$

where $\Delta\mathbf{v}_{12} = \mathbf{v}_1 - \mathbf{v}_2$, $\mathbf{v}_1$ – is the speed the of conductive medium, $\mathbf{v}_2$ – is the speed of the measuring circuit with respect to a stationary coordinate system. The equation (8) contains the vector of magnetic induction $\mathbf{B}$ measured in the stationary coordinate system.

The measuring circuit consists of a measuring device and connecting conductors, which if all connected together, would form an electrical loop. When measuring circuit is moving within a static magnetic field, the processes inside its conductors are analogous to the ones taking place inside mobile conductive mediums.

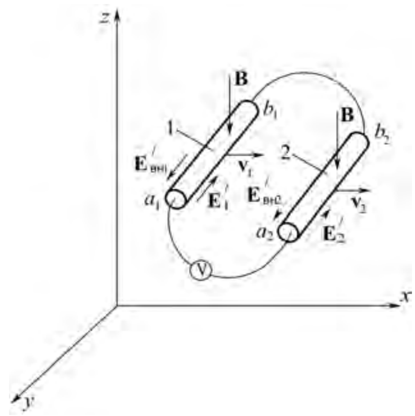

Fig. 4. A "flat" electrical circuit, moving within magnetic field

Taking into account the similar nature of redistribution of electrical charges at an arbitrary cross-sectional area of the conductor along its direction of motion, the specifics of processes taking place in the conductors of the measuring circuit, and also the method of formation of the electrical loop, the analysis of necessary conditions for appearance of electromotive force in a unipolar generator boils down to the analysis of the processes taking place in two different electrically connected conductors, moving within a magnetic field. One such a conductor would correspond to the mobile conductive medium and the other one to the measuring circuit (Fig. 4).

Let us assume that these two conductors are moving in the same direction at the same speed **v** (the electrical loop of constant area is formed). These conditions would justify the following expressions:

$$\mathbf{E}_1' = \mathbf{E}_2'; \ \mathbf{E}'_{in1} = \mathbf{E}'_{in2}; \quad \mathbf{E}'_{a1a2} = \mathbf{E}'_{b1b2} = 0 \tag{10}$$

and, accordingly, the voltage in the formed electrical loop will be equal to:

$$u' = -\int_{a1}^{a2} \mathrm{E}'_{a1a2} d\mathrm{l} = \int_{a1}^{a2} \left(\mathrm{E}'_1 - \mathrm{E}'_{in1} - \mathrm{E}'_{b1b2} + \mathrm{E}'_{in2} - \mathrm{E}'_2\right) d\mathrm{l} = 0 . \tag{11}$$

The magnitude of electrical field strength vectors between spatial points a_1 and a_2, as well as b_1 and b_2 are equal to zero because in both conductors (a_1b_1 and a_2b_2), which are moving in the same direction and at the same speed, a similar by magnitude and direction redistribution of electrical charges along their length is taking place. Besides that, in the part of electrical loops a_1a_2 and b_1b_2 the external electrical field strength described by (2) does not lead to the internal redistribution of electrical charges along the direction of vector $d\mathbf{l}$. Consequently, such conditions of the experiment would not result in generation of electrical voltage in the loop.

In the experiments 2 and 6 the electrical voltage in the loop is equal to zero. It is due to the fact that measuring circuit and electroconductive medium, as parts of the same electrical loop, are in the same frame of reference, which is equivalent to the phenomenon of motion of a loop of constant area in a steady magnetic field.

A linear motion of an electrical loop of constant area within a magnetic field, according to (10) and (11) would not lead to appearance of electromotive force. The only condition for force generation in this case would be the presence of rotary motion of the loop.

The appearance of an electromotive force in any arbitrary electrical loop is possible only when its conductors are crossing the lines of magnetic induction either with different speed, or in different direction or under both conditions simultaneously.

Let us consider the case when conductors of electrical loop are moving relatively to each other in the fashion described in Fig. 5. The generated voltage for such a case would be described by the expression:

$$u = \int_{a1}^{a2} \mathbf{E}_{in} d\mathbf{l} = \int_{a1}^{a2} \left(\mathbf{E}'_1 + \mathbf{E}'_2\right) d\mathbf{l} = \int_{a1}^{a2} \left(\left(\mathbf{v}_1 + \mathbf{v}_2\right) \times \mathbf{B}\right) d\mathbf{l} \neq 0 , \tag{12}$$

where u is the voltage in the stationary coordinate system.

In the case for both conductors move with the same speed with respect to the stationary coordinate system, the generated voltage would be:

$$u = 2\int_{a1}^{a2} \left(\mathbf{v} \times \mathbf{B}\right) d\mathbf{l} . \tag{13}$$

In this experiment, loop's elements a_1a_2 and b_1b_2 do not take part in the voltage generation.

Let us go back to the case of a "flat" electrical loop moving within magnetic field (Fig. 4). Let us assume that conductors a_1b_1 and a_2b_2 are moving in the same direction but with different speeds $\mathbf{v}_1$ and $\mathbf{v}_2$, correspondingly.

The relationship between electrical fields strength for conductors would have the form:

$$\mathbf{E}_1' = \mathbf{E}'_{in1} \neq \mathbf{E}_2' = \mathbf{E}'_{in2} ; \tag{14}$$

$$\mathbf{E}'_{a1a2} = -\mathbf{E}'_{b1b2} = \mathbf{E}'_{in1} - \mathbf{E}'_{in2} = -\mathbf{v}_1 \times \mathbf{B} + \mathbf{v}_2 \times \mathbf{B} = -\Delta\mathbf{v}_{12} \times \mathbf{B} , \tag{15}$$

and the voltage in the loop would be determined by the expression:

$$u = -\int_{a1}^{a2} \mathbf{E}'_{a1a2} d\mathbf{l} = -\int_{a1}^{a2} \left(\Delta\mathbf{v}_{12} \times \mathbf{B}\right) d\mathbf{l} , \tag{16}$$

which is similar to the equation (8). Here, u represents the magnitude of the voltage in the stationary coordinate system.

If the equation (16) is used for computing the electrical voltage in frames of references related to the first or second conductor, the presence of magnitude of the magnetic induction vectors $\mathbf{B}'_1$ or $\mathbf{B}'_2$ in corresponding frames of references is required in the equation.

The most common experiment to investigate the appearance of the electromotive force for the case of conductors' motion within a magnetic field is illustrated in

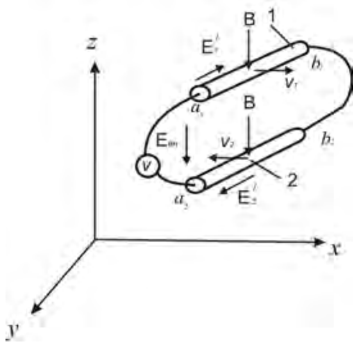

Fig. 5. An electrical loop, formed by conductors, which move in different directions

Fig. 6. Its difference from the scheme of Fig. 4 is that one of the conductors is stationary, or $\mathbf{v}_2 = 0$ (conductors of the measuring circuit). The voltage in the resulting loop corresponds to the coordinate system, which is related to the stationary conductor.

Considering the specifics of the electrical circuit represented in Fig. 6, the voltage in the loop would be equal to:

$$u = -\int_{a1}^{a2} (\mathbf{v}_1 \times \mathbf{B}) d\mathbf{l} \; . \qquad (17)$$

If a stationary coordinate system (x, y, z) is located in such a way that conductor a_1b_1 moves along its coordinate $\mathbf{x}$, then (17) can be expressed in the form:

$$u = -\int_{a1}^{a2} \left(\frac{dx}{dt} \times \mathbf{B} \right) d\mathbf{l} =$$

$$= -\frac{dx}{dt} B_z l = -\frac{dS}{dt} B_z \; , \qquad (18)$$

where l is the working length of the conductor a_1b_1.

Consequently, the phenomenon of appearance of an electromotive force in electrical circuits containing conductors moving within the magnetic field at different speeds can only be explained by looking into the process

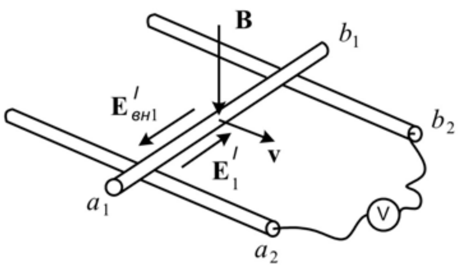

Fig. 6. A set-up to measure electromotive force in the conductor, which is moving within a magnetic field

of changes of the loop's area in time. The absolute value of the area of the loop doesn't have any influence on force generation.

Experiments 3, 4 and 5 correspond to the test conditions as described in Fig. 4 providing $\mathbf{v}_1 \neq \mathbf{v}_2$ and, naturally, the electromotive force has been generated in all the cases. The only difference between experiments 3, 4 and 5 is that the voltage measurement, according to the equation (16), is done in the distinct frames of references, related to either one or another conductor (belonging to either the measuring circuit or the mobile conductive medium) of the generated electrical loop.

3. Conclusions

The transformation of electromagnetic field vectors into different inertial frames of reference as well as analysis of physical processes occurring in electroconductive mediums of electrical circuits represent the key to the understanding of the physical phenomenon of appearance of an electromotive force in linear unipolar generators of various constructions.

The analysis of experimental results with a unipolar generator confirms its correspondence with fundamental rules of electrodynamics of mobile mediums.

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АНАЛІЗ УМОВ ВИНИКНЕННЯ ЕЛЕКТРОРУШІЙНОЇ СИЛИ В ЛІНІЙНОМУ УНІПОЛЯРНОМУ ГЕНЕРАТОРІ

Я. Ковівчак

На основі перетворень Лорентца проведено математичний аналіз відомих результатів практичних досліджень з уніполярним генератором. Показано, що отримані результати мають строге теоретичне обгрунтування. Приведено необхідні умови виникнення електрорушійної сили в уніполярних генераторах різної конструкції.

Yaroslav Kovivchak – Ph D., Associate Professor. Research investigations: theory of electromagnetic field, mathematical modelling.