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ON POLARITY OF THE ELECTROMOTIVE FORCE INDUCED BY THE GEOMAGNETIC FIELD AND ON NECESSITY TO REVISE J. FLEMING'S RULE

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О полярности ЭДС, индуцируемой геомагнитным полем,
и о необходимости уточнения правила Дж. Флеминга

Отмечается противоречивость полученных разными авторами результатов при рассмотрении процесса индуцирования ЭДС в движущемся вертикальном проводе. Анализируются факторы, влияющие на результат. Проведен обзор опубликованных данных о полярности геомагнитных полюсов, и описан простой эксперимент, позволяющий на основе общепринятых положений теории электромагнетизма проверить их достоверность. Детально рассмотрен процесс электромагнитной индукции, и выявлено противоречие в формулировке одного из основных законов электромагнетизма — правила правой руки, приводящее к ошибкам при рассмотрении геофизических явлений. Предлагаются варианты формулировки этого закона, полностью адекватные физической реальности.

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Inferences drawn by various authors from consideration of EMF induction in a moving vertical conductor are shown to be contradictory. Factors affecting the inference are analyzed. Published data on polarity of geomagnetic poles is reviewed and a simple experiment allowing their verification on the basis of universally accepted concepts of the electromagnetic theory is described. The process of electromagnetic induction is considered in detail and contradiction is revealed in the formulation of one of the basic electromagnetic laws, the right-hand rule, which leads to mistakes in treatment of geophysical phemomena. Alternative formulations of this law fully adequate to physical reality are proposed.

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Rule 3. What we should seek in the subject of our investigation is not what others think of it or what we ourselves believe it to be but what we can clearly witness or reliably deduce for knowledge cannot be gained otherwise.

René Descartes. Rules for the Direction of the Mind

On Polarity of the Electromotive Force Induced by the Geomagnetic Field and on Necessity to Revise J. Fleming's Rule

INTRODUCTION

Out of a great deal of geophysical problems we shall consider one which is sometimes treated from the opposite points of view in the literature. Let a vertical conductor (e. g., a radio antenna of a car) move at a constant velocity in the magnetic field of the Earth from the east to the west. It is required to determine the direction and value of the constant electromotive force (EMF) arising in the conductor. At first glance, this is a simple problem. To solve it, one should know the values and directions of the vector of the geomagnetic field lines in the given area and the car velocity vector and then to find the EMF from these data by the right-hand rule formulated by J. Fleming. Eichenwald [1, p. 274] gives the following solution to this problem: «The Earth's field is directed from the south to the north; as the conductor moves from the east to the west, the electromotive force is induced in the downward direction. Consequently, in the case under consideration the upper end of the conductor will have a higher potential than its lower end». Considering the same problem, Kalashnikov [2, p. 215] writes: «The magnetic field of the Earth is directed from the south to the north. Therefore, we find (e. g., by the right-hand rule) that the EMF is directed downwards. This means that the lower end of the conductor will have a higher potential (will be positively charged) and its upper end will have a lower potential (will be negatively charged)». A similar approach to induction phenomena in the geomagnetic field is described by J. Orear [19]. Considering northbound flight of a plane, he writes that the geomagnetic field induces between the wing ends the EMF directed from the west to the east while the ends of the wings carry the charges, positive at the easterly end and negative at the westerly end.

Thus, the first two authors initially state that the EMF will be directed downwards. According to the theory of electromagnetism, the EMF must always be directed from the higher potential point, which corresponds to a positive charge, to the lower potential point, which corresponds to a negative charge. Note that our planet is surrounded with an electric field adequate to the negative surface charge (i. e., also directed downwards), which the authors do not mention at all.

Then, however, after the first two sentences in the above quotation, Kalashnikov writes something quite opposite, at first glance, namely, that the negative charge is above and the positive charge is below, which corresponds to the upward direction of the EMF. He probably proceeds from the fact that it is this distribution of the charges which one observes when investigating the electric field of the Earth. Strange as it is, the Fleming's right-hand rule may really lead to these opposite conclusions.

ON THE GEOMAGNETIC FIELD

To understand this paradoxical situation and to find a correct answer, one should, firstly, know the correct direction of the Earth's magnetic field lines and, secondly, properly apply laws of electromagnetism. It is adopted in the theory of electromagnetism that magnetic field lines emerge from the northern magnet pole and enter the southern magnet pole. Therefore, the first thing to be done was to ascertain which true physical magnetic pole occurs in the northern hemisphere. It turned out that the most authoritative school and university textbooks on physics, scientific literature and even encyclopedias offer what seems controversial information on which exactly magnetic poles occur in the northern and southern hemispheres of the Earth. This made the author study the available literature, analyze the current status of the problem, and investigate experimentally whether the universally accepted locations of the Earth's magnetic poles were justified.

A few foreign and all Russian textbooks, the Great Soviet Encyclopedia [3], and some other books [1, p. 197; 2, p. 215; 4–6; 7, p. 144; 8, p. 118] state that the northern hemisphere is the location of the southern magnetic pole of the Earth. When this statement is illustrated by a picture of magnetic field lines, it is shown that they enter this pole.

Other books [9–11, 15], including the Great Soviet Encyclopedia [9], make quite the opposite statement, namely, that the northern hemisphere is the location of the northern magnetic pole of the Earth. However, it is quite possible that the southern magnetic pole is actually meant in this case because in the accompanying illustrations, for example, in [11], the magnetic field lines are shown to enter the pole. As to the conflict of names, it might be due to the existing tradition to name the magnetic poles of the Earth according to the hemisphere where the pole is located. This is the case, for example, in astronomy and meteorology, and even, surprising as it is, in geophysics [15].

Neither of the above statements is substantiated in terms of physics in any of the books, which makes the reader form a false impression that this issue is insignificant and the poles may be named arbitrarily. For example, the fundamental geophysical encyclopedia «Terrestrial Magnetism» by B. M. Yanovsky reads that «that which is closest to the northern geographic pole is called the northern magnetic pole and that which is closest to the southern geographic pole is called the southern magnetic pole» [15]. In addition, this book as well as many other physics dictionaries and textbooks only informs the reader that the Earth has magnetic poles, where the magnetic needle is vertically directed, and reads nothing at all about their polarity and, consequently, the direction of the Earth's magnetic field lines.

The Earth is a very sophisticated system of geophysical magnetic and electric fields, where parameters of all components must strictly correspond to the definitions adopted in the electromagnetic field theory. It is only in this case that the physical field theory can adequately describe the observed physical phenomena. As is known, the physical field theory has thoroughly elaborated mathematical techniques. In its turn, the theory of electromagnetism is one of the cornerstones of modern natural sciences and technology, in particular, geomagnetism. Undoubtedly, arbitrary location of the poles is intolerable, since the wrong idea of where they are makes it impossible to understand geophysical phenomena extremely important for inhabitants of the Earth.

ON THE FLEMING'S RULE

The field theory is based on the concept that the northern magnetic pole and the positive electric charge are the sources of the magnetic and electric fields, respectively, while the southern magnetic pole and the negative charge are the sinks. Below, to avoid confusion, the magnetic poles meeting this criterion will be called true physical ones. In addition, it is agreed in the field theory that electric current is motion of positive charges from the positive pole of the current source to the negative one. Accordingly, the potential must be considered high at the positive pole and low at the negative one.

Based on this, J. Fleming established a fundamental physics law — the right-hand rule, by which the direction of the electric current and the polarity of the voltage induced in a conductor as it crosses magnetic field lines emerging from the northern pole are uniquely related to the direction of its motion. This law underlies practical electrical engineering. Electric motors and generators widely used by people all attest to validity of this law. In the field theory, to the right-hand rule there corresponds a formal mathematical tool — a right-handed vector product of the magnetic field induction vector and the conductor velocity vector, which is used to calculate the required electric field vector.

The fact that our planet has its own magnetic field with two poles was established by W. Gilbert in 1600. Until then it had been believed that the

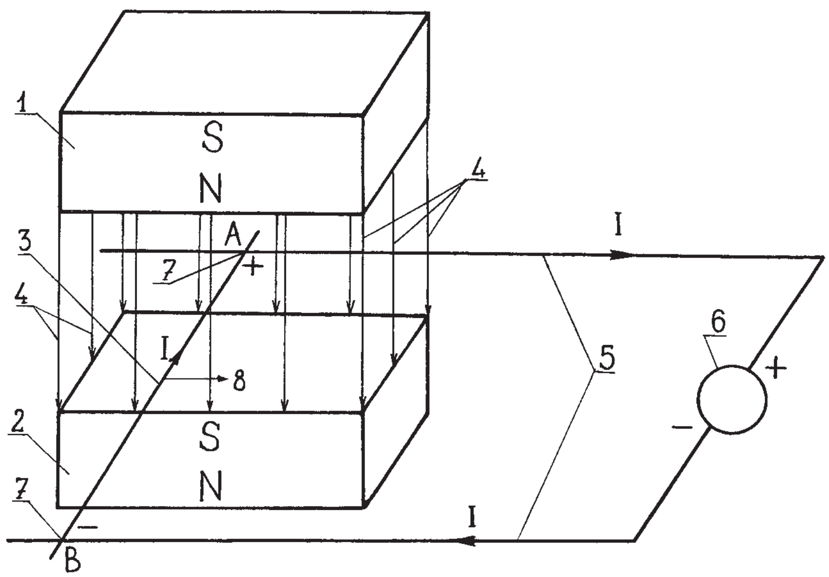

Fig. 1.

compass needle was attracted by stars. At present the compass still remains the most important instrument in what concerns terrestrial magnetism. It is its indications which underlie the present-day ideas of where the Earth's poles are located. It is therefore obvious that all you need for testing the validity of these deep-rooted ideas, which probably resulted from Ampere's investigations, is to find out whether the magnetic compass needle point seeking North is actually the northern or southern true physical magnetic pole. Clearly, if it is the northern one, there is the southern true physical magnetic pole at point of its attraction. To this end, it is necessary to calibrate the magnetic compass needle. This can be done with reference physical poles, which are easily obtained in a simple experiment based on universally accepted laws of the theory of electromagnetism.

The experiment on finding the reference true physical magnetic poles is schematically depicted in the figure. The conductor 3 moves between the poles 1 and 2 toward the needle 8, crossing the magnetic field lines 4. At points A and B its ends are connected by the sliding contacts 7 to the fixed conducting guides 5, whose ends are connected to the positive and negative terminals of the voltmeter 6. Let us mentally place the open right-hand palm between the poles so that the magnetic field lines emerging from the northern pole enter the palm and the thumb is aligned with the conductor motion direction. Then, according to the most widely applied formulation of the right-hand rule [8, p. 148], four stretched fingers will indicate the **direction of the *electromotive force* (?!) and the electric current,** induced during the motion of the conductor. In exact accordance with the Faraday's law of electromagnetic induction, EMF arises in the conductor 3 and the conductor becomes a source of current I, whose direction for the case in question is shown by arrows in Fig. 1.

However, application of the law gives rise to questions.

As is known, two versions of the right-hand finger arrangement are used:

1) The one described above, widely used in the literature on physics and electrical engineering, when the palm is open and stretched with the thumb fully swung aside.

2) Sometimes the authors stick to the following formulation: «If the thumb, the forefinger, and the middle finger are arranged at the right angles with one another and if the forefinger is aligned with the direction of the magnetic field and the thumb with the direction of the motion, the middle finger will indicate the direction of the electromotive force» [18].

What follows equally applies to both positions despite the indicated differences.

In addition, three versions of the right-hand rule formulation are encountered in textbooks and scientific literature. Some authors say that the Fleming's rule indicates **the direction of the current** [7, p. 154]. Others say that the rule indicates **the direction of the electromotive force** [14, 18]. A third and the largest group of authors believe that the rule simultaneously indicates **the direction of the current and the electromotive force** [2, p. 214; 8, p. 148].

There is no doubt about adequacy of the physical reality of the part of the formulation related to the electric current. It fully agrees with the other basic laws of electromagnetism — the corkscrew rule and the right-hand rule.

Recall that in the case of a closed electric circuit the current I runs in a circle in one direction from the negative to the positive side of the supply (i. e., the conductor 3 in our case) and from the positive to the negative side of the circuit (i. e., the fixed conductors 5 and the voltmeter). The voltmeter indicates the potential difference (voltage) between the poles and their polarities. Knowing the polarity of the voltmeter indications, we find the direction of the current in the electric circuit. In our case the current runs through the conductor 3 from the near end (point B) to the far end (point A). Knowing the direction of the current and the direction of the conductor motion and using the right-hand rule, that is, the vector product, we can find the positions of the reference northern and southern true physical magnetic poles and appropriately label them. With the positive polarity of the voltmeter indications and the motion directed along the arrow 8 in Fig. 1, the northern reference true physical magnetic pole must be above the conductor and the southern reference physical magnetic pole under the conductor.

Now, bringing the compass near the northern reference pole and knowing that the point of the compass magnetic needle seeking it must be of the opposite polarity, we can uniquely determine the true physical pole of the compass needle point seeking the northern reference physical magnet pole. The described experiment shows that it is the southern pole. Consequently, the northern hemisphere which the north point of the compass needle turns should be though of as the location of the southern true physical magnetic pole.

Solving the above problem and using the right-hand rule, both Eichenwald and Kalashnikov assumed that the magnetic field is directed from south to north, which corresponds to the location of the southern true physical magnetic pole in the northern hemisphere. Then, all they did was right and the conflict in results stemmed from the formulation of the Fleming's rule.

To solve the problem in question, it is necessary to find the direction of the electromotive force, i. e., the potential difference, rather than the direction of the current. Here it suddenly turned out that the statement about determination of the EMF direction by the above method was ambiguous and, thus, admitted of opposite interpretations in the case under consideration, which naturally led to opposite results and in addition contradicted two other laws of electromagnetism — the corkscrew rule and the left-hand rule. Obviously, this is why the results of the above two authors are in conflict.

ON ELECTROMAGNETIC INDUCTION

To eliminate the contradiction, it is necessary to examine thoroughly the physical essence of the electromagnetic induction process. The Fleming's rule is formulated for a closed direct-current electric circuit. Therefore, it is reasonable to refer to the universally adopted theory of physical processes occurring in such an electric circuit, as it is set forth in some textbooks [16, 17, 20, 21]. Direct electric current (conduction current) is orderly motion of free electric charges in a conductor. For it to occur, there must be the primary electric field (i. e., primary EMF) inside the conductor. Under the effect of this field positive charges will travel from the regions of the field with a high (positive) potential to the regions with a lower potential and negative charges will travel in the opposite direction. As is known, only electrons travel in metals. The charges tend to be arranged so that the secondary electric field generated by them will completely balance out the distribution of the primary electric field inside the conductor. As a result, equilibrium static equalization of the potentials throughout the entire conductor volume will take place. If the conductor ends are not connected to external load, the induced secondary charges will concentrate at the ends of the conductor producing secondary EMF, and the electric current ceases. If a load-carrying external electric circuit is connected to the conductor, the charges induced at its ends will travel from one pole to the other generating electric current. Electrostatic equilibrium should be prevented to maintain continuous orderly motion of free charges. This requires that in the conductor there should be a constantly active primary electric field doing work to counteract the force of the secondary electrostatic field tending to equalize potentials at all points of the conductor. However, it is radically impossible that this work should be done through spending the energy of the electrostatic field of any charges because equilibrium is inevitably established in such a field. This work should be done through spending other types of energy of nonelectrostatic origin, e. g., mechanical, chemical, thermal, etc. Thus, for the orderly motion of free charges (electric current) not to cease, constant action of the primary EMF, which is conventionally called extraneous, should be provided in the conductor through conversion of energy of some kind into the energy of the primary extraneous electric field. In the case under consideration the primary EMF is excited in the conductor 3 by the mechanical energy spent for its motion.

Now let us turn to the consideration of the fundamental physical nature of the extraneous electric field. It is necessary to proceed directly from the law of electromagnetic induction experimentally discovered by M. Faraday. As is known, he was the first to find out that induction of the electric current by the magnetic field in a conductor was due to their relative motion. The induced current is invariant in a sense, i. e., it does not matter what actually moves, the conductor or the magnetic field. It will be the same when the moving conductor crosses the lines of the fixed magnetic field and when the lines of the moving magnetic field cross the fixed conductor. On the other hand, the laws adopted in the theory of electromagnetism, e. g., the right-hand and left-hand rules or the Lorentz force, are not invariant. They allow correct results only when the magnetic field is fixed and the conductor moves. And this should be borne in mind.

It is usually stated in textbooks and scientific publications that when a conductor crosses the magnetic field, the free charges that are present in it move to the ends of the conductor under the effect of the Lorentz force and generate an electric field in the conductor. Therefore, the process of induction is traditionally described with using quite dissimilar notions of the force and the field. The authors of some authoritative textbooks, e. g., N. Papaleksi [17] and E. Purcell [21], pointed out inadequacy of this approach and came up with alternative approaches in their textbooks. The paradox that arose in the theory of electromagnetism was best characterized by R. Feynman. In his widely known physics course he wrote that science did not know any other example when analysis in terms of two different phenomena would be required for gaining a proper insight into a simple and accurate general law. He continued that in such cases quite beautiful generalization based on a single profound fundamental principle would usually come to light, but in this case no whatever profound principle was seen [20].

To my mind, however, the notion of the electromagnetic field introduced by Faraday is a sufficiently profound and comprehensive principle. As is shown below, the consistently applied notion of the field is enough to gain a proper insight into the process of induction.

It is known that the notion of the Lorentz force applies by definition only to charges moving in a magnetic field. If there are no charges, there is no force. Accidental presence or absence of charges or charge-containing matter in space is not significant. It is in principle incapable of affecting the physical process of generation of an electric field in space during relative motion of the magnetic field. The processes of generation and transformation of electromagnetic fields are undoubtedly determined by the space-time properties insufficiently studied so far. Therefore, preference should be definitely given to Faraday's conception of the field. The more so as it was on its basis that Maxwell introduced the notion of the displacement current. This provided further considerable development of the theory of electromagnetism. Investigation of the process of unipolar induction and experimental observation of an electric field generated during rotation of a magnetized rotor [12, 13] made it possible to put forward a hypothesis that a particular kind of electric field is generated in space during relative motion of a magnetic field [13]. Therefore, our further consideration is based on this hypothesis. This new kind of electromagnetic field has rather specific properties, which were first described in detail in [13]. It is not impossible that in future this new approach will allow a new treatment of the induction process in the time-varying magnetic field.

In this approach induction of the EMF is described as follows. The electric field arising in the space occupied by the conductor 3 in motion relative to the magnetic field is an extraneous primary electrodividing force that makes free electric charges move toward the ends of the conductor. It is directed from end B (higher potential) to end A (lower potential). The charges formed at the ends of the conductor generate an oppositely directed secondary electric field in the conductor, which fully counterbalances the primary electric field. In this case end A gets a higher potential (is charged positively) and end B gets a lower potential (is charged negatively). Connecting a voltmeter to the ends of the conductor one can directly measure this secondary EMF. It is this EMF which electric engineers need for developing various devices and which is meant when the Fleming's rule is used. However, it is evident from the above experiment that the right-hand finger-tips point to the high-potential (positively charged) end of the conductor 3 (point A), as is shown in Fig. 1. Thus, to the finger bases there corresponds the lowest-potential (negatively charged) end of the conductor 3 (point B). Since it is the practice in the theory of electromagnetism to determine the EMF direction by the direction of the motion of the test positive charge, which is taken to be the direction of the current flow in the electric circuit, it is obvious that in our case the test charge inside the conductor 3 should have moved under the effect of the secondary EMF in the direction opposite to the stretched fingers (from the finger-tips, i. e., the positive pole, to the finger bases, i. e., the negative pole), which is in conflict with reality. Thus, the secondary EMF in the conductor is actually directed against the fingers and is opposite to the electric current flowing with the fingers. On the other hand, in the external part of the electric circuit, which alone is of interest for electrical engineers, the directions of the electric current and the EMF between higher-potential (positively charged) point A and lower-potential (negatively charged) point B coincide in full compliance with the commonly accepted definitions. This is probably the cause of the confusion in the formulation of the Fleming's rule. What actually coincides in the conductor 3 with the direction of the right-hand fingers is the B-to-A direction of the primary extraneous electric field providing the flow of the current I (in the direction indicated by arrows in Fig. 1).

ON THE NECESSITY TO REVISE THE FLEMING'S RULE

Thus, obviously, it must be clearly decided which EMF, primary or secondary, is meant in the Fleming's rule. Otherwise that part of the above formulation of the Fleming's rule which says that the EMF is aligned with the fingers is completely wrong because no doubt arises that it deals with the secondary EMF, which is actually of interest for electrical engineers. In addition, it is also in conflict with the other two basic laws of electromagnetism — the corkscrew rule and the left-hand rule. Note, by the way, that it has long been known from the theory of electric circuits that the directions of the current and the voltage in a supply are always opposite and they coincide only in the external electric circuit. This statement is fully valid for the moving conductor, which is a supply in the case under consideration.

Now we can return to the problem in question and investigate into the above contradiction. Undoubtedly, when both authors write that «the electromotive force in the conductor is directed downwards», it means that there is the positive pole at the top and the negative pole at the bottom. This is absolutely correct for the primary electric field and quite agrees with the universally accepted concept of the negative charge of the Earth. But when Kalashnikov also points out that «the lower end of the conductor will have a higher potential (will be positively charged) and the upper one will have a lower potential (will be charged negatively)», it is valid only for induced secondary electric charges counterbalancing the primary field inside the conductor. Such confusion between notions, especially without any comments, should not take place in textbooks.

To eliminate this confusion of long standing in scientific publications and textbooks, which leads to incorrect results in investigation of geophysical phenomena, one should strictly discriminate between the primary EMF, generated by extraneous forces (i. e., a new kind of extraneous electric field which has been treated as the Lorentz force action domain so far), and the secondary EMF of the Coulomb field, generated by the induced electric charges.

To this end, it is necessary to change the formulation of the Fleming's right-hand rule. For example, it could be written in the formulation that «the stretched right-hand fingers (or middle finger), firstly, indicate the direction of the electric current and, secondly, point to the positive pole of the generated secondary EMF». This would be satisfactory for practical electrical engineering but absolutely insufficient for other areas, e. g., geophysics. In addition, as follows from what is said above, it is the primary electric field producing the extraneous electrodividing force that is directed along the stretched right-hand fingers (or middle finger). Therefore, a justified step would be to replace the term «EMF» in the current formulations by the «extraneous EMF» with appropriate explanation.

On the strength of what was said above, I believe it is reasonable to use the following rather rigorous formulations of the right-hand rule for each of the above-mentioned finger configurations:

1. To find the directions of the current and electromotive force induced in the conductor the right-hand palm should be arranged so that the turned-aside thumb coincides with the direction of the conductor motion and the magnetic force lines enter the palm. Then four stretched fingers will indicate the direction of the induced current and the extraneous electromotive force (extraneous electric field) in the moving conductor and will point to the positive pole of the generated secondary electromotive force producing an electric current in the external fixed electric circuit.

2. If the right-hand thumb, forefinger, and middle finger are arranged at a right angle with each other, the forefinger being aligned with the magnetic field and the thumb with the direction of the conductor motion, the middle finger will indicate the direction of the induced electric current and the extraneous electromotive field (extraneous electric field) in the moving conductor and will point to the positive pole of the generated secondary electromotive producing an electric current in the external fixed electric circuit.

CONCLUSION

The aforesaid is important, first of all, for understanding of geophysical phenomena. However, the history of science shows that refinement of fundamental laws and notions in any science will sooner or later open up new possibilities for its development. Therefore, the author considers it his duty to publish the above consideration in order to attract attention of the scientific community to the subject. The scientific community should undoubtedly take part in clearing up this confusion reigning long in textbooks and scientific literature.

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