The theory of electromagnetic field motion.
4. Electromagnetic field motion and electrodynamics

L.N. Voytsehovich

The article shows the possibility and necessity of extension the principle of electromagnetic field motion to electrodynamics processes. It was also shown on the basis of known electromagnetic paradoxes that Maxwell's law of electromagnetic induction is the special case of Faraday's law of electromagnetic induction. Physical nature and conditions of motion of electromagnetic field components were considered.

4.1. Introduction

We have considered in article [1] the motion of invariable in time electric and magnetic fields created by moving physical sources. The basis of the theory describing these phenomena is Einstein's theory of special relativity, and more particularly, Lorentz transformations of the electromagnetic field. Contrary to it, electrodynamics considers the electromagnetic field that varies in time or even that has lost its relation with the initial source and propagates in space and time. Such processes are the subject of an absolutely different theory of electromagnetism, Maxwellian electrodynamics. Paradoxes emerge at the joint of theories, whose consideration is one of the problems posed in present article.

Here is what A. Einstein [2] writes on this paradoxical situation: "It is known that Maxwellian electrodynamics , as it is usually understood now, leads to asymmetry being applied to moving bodies what, apparently, is not inherent to this phenomenon. Let`s consider, for example, electrodynamic interaction between a magnet and a conductor. The observable phenomenon depends only on relative movement of the conductor and the magnet, whereas usual opinion draws sharp distinction line between these two cases in which either one, or other body is in motion. Because, when the magnet is in motion and the conductor is at rest, the electric field with certain density of energy emerges in the magnet vicinity generating current at the position of the conductor. But if the magnet is at rest and the conductor moves, in the vicinity of magnet no electric field is generated. However, we find an electromotive force in the conductor, for which there is no corresponding energy *per se,* but which causes, assuming equality of relative movement in the two discussed cases, electric currents in the same direction and at the same density, as in the first case".

Feynman writes about the same paradoxical situation [3, p. 54]: “We do not know any other such an example in physics when a simple and exact general law demanded for the real understanding of the analysis in terms *of two different phenomena*. Such beautiful generalization is usually found to have an origin from a deep common fundamental principle”.

This “Common fundamental principle” underlying the electromagnetic field origination and transformation may be motion of electromagnetic field components. It is necessary to admit that any change in the magnetic flux through a loop occurs through motion of magnetic force lines outwards or inwards the loop depending on whether there is a reduction or increase in the magnetic flux. For a current carrying wire the magnetic force lines are moving outward the wire when the current is increased and to the wire when it is reduced. Similarly it is for a single charge when magnetic flux lines diverge from the charge if it is accelerated and converge if it is retarded.

Since in such processes electromagnetic field components, both electric and magnetic, are generally non-zero at each point of the electromagnetic field, all the expressions obtained in [1], which link electromagnetic field components with the intrinsic velocity, should be also valid from the mathematical point of view for dynamic processes. In that case we can find values of electric and magnetic component necessary for calculation of the intrinsic field and the intrinsic velocity using Maxwell’s equations as initial. Then the solution of the inverse problem – the calculation of electromagnetic field component using obtained values is easily possible and will be correct a priori.

This reasoning proves that it is *possible* to extend the principle of motion of electromagnetic field components to dynamic processes. Proceeding from such a formal mathematical approach, it is impossible to do anything more. We are interested not only in possibility, but also *necessity* of extension of this principle to the area of dynamic processes. For this purpose it is necessary to consider cases when Maxwell’s classical theory cannot explain adequately the effects proved experimentally but they are easily explained from positions of the principle of electromagnetic field motion. At the same time, the reason of seeming contradictions and paradoxes of the theory we shall search in the limited and specific character of Maxwell’s theory which does not take into account the principle of electromagnetic field motion.

The purpose of the present work is to indicate from the physical point of view the validity of the principle of motion of electromagnetic field components not only for the case when field moves together with its source, but also for electrodynamic processes.

4.2. Classical form of the law of electromagnetic induction

Let's consider the law of electromagnetic induction, one of the laws underlying Maxwell's classical theory. It is this law that is one of the basic sources of paradoxes in the electromagnetism theory.

The law of electromagnetic induction in the differential form is successfully applied to describe electromagnetic waves and at the same time does not cause any paradoxes, logic contradictions in theoretical electrodynamics:

$$\operatorname{rot}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4.1}$$

where **E** is the electric field strength, **B** is the magnetic field induction, *t* is time.

A different situation with the law of electromagnetic induction is in the integrated form:

$$\oint_L \mathbf{E}\cdot d\mathbf{l} = -\frac{d}{dt}\int_S \mathbf{B}\cdot d\mathbf{s}, \tag{4.2}$$

where L is the loop encompassing surface S, $d\mathbf{l}$ and $d\mathbf{s}$ are vectors of elements of the length of loop L and of its surface S, respectively.

The left part of equation (4.2) is equal to electromotive force $\mathcal{E}$ in loop L by definition:

$$\mathcal{E} = \oint_L \mathbf{E}\cdot d\mathbf{l}. \tag{4.3}$$

The integral in the right part of (4.2) is equal to the rate of change of magnetic flux $\mathbf{\Phi}$ through loop L:

$$\mathbf{\Phi} = \int_S \mathbf{B}\cdot d\mathbf{s}. \tag{4.4}$$

Application of the law of electromagnetic induction in form (4.2) leads to numerous paradoxes, contradictions of the theory with experimental results. Let`s consider these paradoxes and then analyze the causes of their occurrence.

4.3. Paradoxes related to the law of electromagnetic induction

1. The oldest and most widely known device is a **unipolar generator** known as Faraday generator, operation principle of which gives rise to the paradox. We described the unipolar generator in [1]. **Magnetohydrodynamic generator** (MHD-generator) is actually a version of the unipolar generator. The MHD-generator can be converted into the unipolar generator, if sliding contact K_2 ([1], fig. 2.1) is moved from axis OK_2 to the disk surface and approached to contact K_1 and the disk radius is infinitely increased. It is no matter what material of the disk is used, but it would be a conductor. It may be a metal, a conducting liquid (electrolyte) or a gas (plasma), anyway the EMF is generated when a conducting medium moves in a magnetic field. The EMF is usually calculated on the basis of the Lorentz force, without causing any difficulties and, from the physical point of view, it is quite correct. At the same time, EMF calculation using formula (4.2) which is admitted now as an absolutely valid general equation in Maxwell's theory leads to a zero result.

On the basis of the fact that the Lorentz force, in particular, allows to explain operation of a unipolar and MHD-generator, Maxwell's equations are sometimes supplemented with Lorentz force equation. However, such an addition does not eliminate contradictions of the modern view on Maxwell's theory: in certain cases it is possible to explain the electromagnetic induction phenomenon only on the basis of equation (4.2), in others - only on the basis of the Lorentz force, and in the third ones it is possible to use both approaches. We notice that Faraday did not have such problems, however, the matter hereof will be considered hereinafter.

2. Attempts to apply the law of electromagnetic induction in the form of (4.2) to some devices, where change in the magnetic flux through closed electric circuit L does not lead to EMF occurrence in the circuit results in another type of paradox. Below we consider examples of this type of paradoxes.

2.1. Application of expression (4.2) to the **electric circuit in figure 4.1**, leads to an incorrect result. This example changed insignificantly was taken from Feynman [3, p. 55].

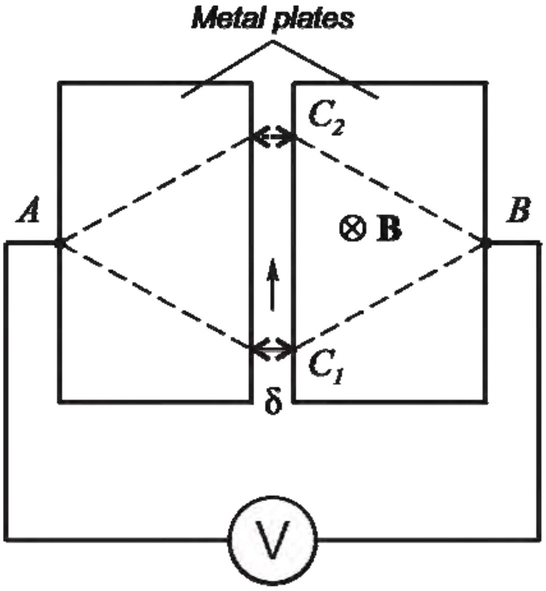

Fig. 4.1. Example of the circuit, increase in magnetic flux which does not result in EMF

Two metal plates are placed in homogeneous magnetic field **B**, perpendicular to plates. The plates are connected to voltmeter V and by means of sliding contact form closed circuit VAC_1B. Clearance δ between the plates is considered to be negligibly small. When the sliding contact moves from position C_1 to position C_2 the area of the circuit and, hence, the magnetic flux through it, essentially increases, but the EMF in the circuit does not appear contrary to the law of electromagnetic induction (4.2).

2.2. Another similar example is a **solenoid with winding terminals** placed in a stationary magnetic field. Instead of winding terminals a sliding contact can be used which moves along the coil winding like rheostat sliding contact. The voltmeter is used to measure the EMF at the winding terminals or the sliding contact. When the voltmeter is connected to various taps or the contact slides on winding coils the magnetic flux in the voltmeter circuit changes proportionally to the number of the coils connected to the voltmeter, but the EMF in the circuit does not occur.

2.3. The most convincing example which proves a specific character of the law of electromagnetic induction in form (4.2) is **Herring paradox** [4] (the reference was taken from article [5]). Experiments on checking Herring paradox were repeated in various versions. To illustrate Herring paradox we use the scheme presented in work [6] (fig. 4.2).

Metal ring 1 encompasses the magnetic field directed orthogonally to the page surface and is designated by points. For the sake of clarity the magnetic field is considered to be created by a two-piece solenoid, what will be useful subsequently. In the gap between the halves of the solenoid a metal ring is located. If the magnetic field is created by the magnetized iron core, the ring could be absent, its role will be played by the iron core surface.

In initial position the electric circuit contacts designated by arrows are located in such a manner that the circuit completely encompasses the magnetic flux (fig. 4.2*a*). Then, the contacts start to move in the direction designated by arrows and in final position (fig. 4.2*b*) the magnetic flux is appeared to be located completely outside the circuit. According to the law of electromagnetic induction in the form (4.2), the EMF must be induced in the electric circuit and measured by voltmeter when contacts move, however it does not occur.

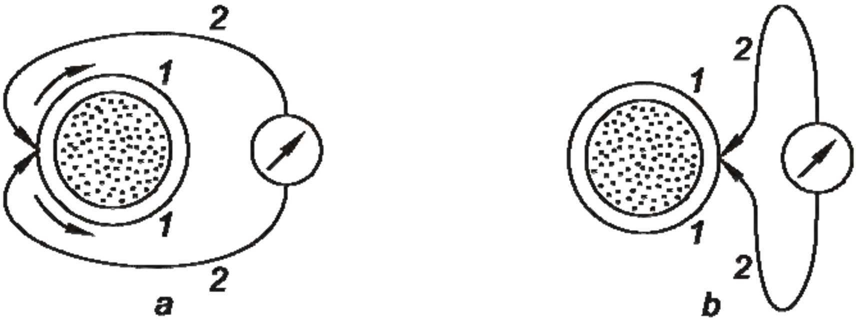

Рис. 4.2. Herring paradox.
1 – metal ring; 2 – electric circuit.

Let`s change a little the experiment represented in fig. 4.2. With that end in view, let`s remove the metal ring (fig. 4.3), and connect the terminals of the electric circuit to a straight piece of wire 3 which can freely move across the magnetic field in the gap inside the solenoid, in direction indicated by arrow. The initial and final position of wire 3 coincides with positions of mobile contacts in figures 4.2*a* and 4.2*b,* accordingly.

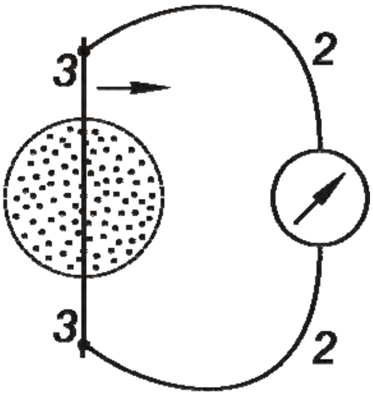

Fig.4.3 To Herring paradox

In the case shown in fig. 4.3, unlike the case in fig. 4.2, the voltmeter shows presence of the EMF in a loop according to (4.2) though the magnetic flux in the electric circuit in both cases changes equally.

Analyzing the features of all the paradoxes presented above, it is possible to notice that the EMF in a loop is always generated when elements of the loop move physically through the magnetic field that is the loop elements cross the magnetic field. In the considered cases it does not matter whether the magnetic flux through the electric loop changes (fig. 4.3) or not (the case of a unipolar generator).

4.4. Faraday law of electromagnetic induction

Faraday did not have a problem in similar situations as was mentioned above. It is the unipolar generator known also as Faraday disk or Faraday generator that is considered to be the first generator in the world designed by Faraday on the basis of his conception of electromagnetic induction. Faraday always explained the electromagnetic induction by the wire crossing the magnetic field. Or he explained it by the magnetic field crossing wire.

Let's consider Faraday`s work [7] in which he formulates the law of electromagnetic induction for the first time on the basis of experimental results. We will reproduce this work in short using more modern terminology.

Two parallel wires are located closely to each other. One of them, which is stationary, is used to excite the magnetic field by the constant electric current. The other wire serves as measuring wire. Voltage is induced in the measuring wire when it moves away or approaches relative to the current carrying wire. Faraday explains the effect by the fact that the moving measuring wire crosses magnetic flux lines, which, in turn, are excited by the electric current. The same effect is achieved when the electric current increased or reduced. Faraday writes [7] that “the magnetic curves are as if moving (if one can say so) across an induced wire”. When the current is switched on or off the magnetic flux lines “can be imagined as pulled together and coming back along direction to the disappearing current”.

The words presented above contain the essence of the law of electromagnetic induction in its understanding by Faraday. Faraday, as it is known, did not use mathematics in the research, therefore we present this law in the mathematical form. For this purpose, after substitution of the expression for electric field (2.5) into equation (4.3) we obtain:

$$\mathcal{E} = -\int_L [\mathbf{V}_m \mathbf{B}] \bullet d\mathbf{l}, \qquad (4.5)$$

where $\mathbf{V}_m$ is the magnetic field intrinsic velocity relative to motionless loop L.

For the case when the magnetic field is motionless and the field source itself is motionless too, with loop L moving at velocity $\mathbf{V}$, we obtain from (4.5) taking into account that $\mathbf{V}=-\mathbf{V}_m$:

$$\mathcal{E}=\int_L[\mathbf{V}\mathbf{B}]\bullet d\mathbf{l}. \tag{4.6}$$

It should be noted that, unlike (4.2), loop L is not necessarily closed.

The law of electromagnetic induction in forms (4.5) and (4.6) is actually a mathematical form of Faraday law of electromagnetic induction which he formulated in work [7]. This law in form (4.6) is now widely used to solve various problems, first of all applied ones.

Expression (4.2) is a specific solution of equation (4.6) if this equation is applied to the closed circuit. To demonstrate this it is necessary to define the rate of magnetic flux change $d\Phi/dt$ inside the circuit when element of the length of the circuit $d\mathbf{l}$ moves at velocity $\mathbf{V}$ in magnetic field $\mathbf{B}$ at the point where element $d\mathbf{l}$ is located. Integrating on loop L, we obtain required expression (4.2) taking into account (4.4). Another way to derive expression (4.2) is to use Stokes theorem taking into account (4.1). The both ways to obtain (4.2) are enough widely presented in the literature on electromagnetic theory, and also in the literature devoted to the solution of applied problems and, therefore, a more detailed solution is not given here.

Another more modern argument in favor of validity of Faraday concept concerning magnetic field motion when the magnetic flux changes through a loop is the Poynting vector representing energy flux density of the electromagnetic field.

As it is known, when the magnetic flux through a loop increases, the Poynting vector is directed into the loop, whereas it is directed to the outside when the magnetic flux is reduced. For all physical phenomena the energy flux is always related to any physical object moving in space depending on the nature of the phenomenon. Not always the direction of this motion coincides with energy flux direction, but one or another movement is always present. If one denies that in case 2 the change in the magnetic flux occurs at the expense of movement of magnetic flux lines it will be unique case of purely "mathematical" energy flux without motion of a material object, the magnetic field in the present case. On the contrary, if one accepts that the change in magnetic flux occurs at the expense of movement of magnetic flux lines, with direction of movement coincides with the Poynting vector direction, the case 2 submits to the general laws of physics. Certainly, absolutely the same arguments and conclusions on field movement also relate to the electric field.

4.5. Electric loop

One of the basic conditions of using the law of electromagnetic induction in its classical form (4.2) is the requirement of closure of loop L. This requirement in Maxwell's theory is obligatory, almost sacral. The open loop is excluded from consideration; in extreme case the concept of displacement currents to transform the open loop into a closed one is introduced. Meanwhile, Faraday did not make the demands of the closure of the loop but repeatedly noticed that the current could flow only in the closed loop. Nevertheless, in work [7] mentioned above Faraday describes two parallel wires one of which serves to create magnetic field, and the other one is measuring. These wires, undoubtedly, formed closed loops, but it was insignificant for Faraday to explain causes of induction occurrence.

Nowadays, Faraday experiment could be repeated without using any circuit. Linear current can be obtained, for example, by means of an electron beam in space, and instead of the said measuring wire a ferroelectric bar as electric field sensor can be used, with a laser interferometer registering changes in sensor dimensions. The interferometer signal repeats a signal from Faraday measuring wire. In this situation application of the law of electromagnetic induction in form (4.2) appears to be almost impossible. The displacement current concept which is usually used to substantiate application of equation (4.2) to open loops, in the given case is possible in principle at certain intellectual efforts, but only leads to complication of the problem. At the same time, application of (4.6) does not cause any difficulties.

First of all, let`s make some notes why it is such a form, the form for a closed loop, was adopted in which the law of electromagnetic induction became widely used in spite of all the paradoxes generated by it. The EMF formally, or theoretically, is possible to be measured not only in the closed circuit, but also between any two points of the electromagnetic field. For this purpose it is possible to measure the work expended to move a probe charge between two points, or, using a wire as a natural device integrating the electric field strength along the wire, forming an electric loop, to measure potentials on the ends of the wire using an electroscope and to calculate their difference. However, the inaccuracy of such measurements will be very high because of low energies at which it is necessary to operate. Modern methods to measure the electric field strength, in particular that one described above, were inaccessible in XIX century. At the same time, a galvanometer is possible to be used for the closed circuit and thus provide high measurement accuracy. Besides, the closed electric circuit is very convenient in practical application because it allows to design electric generators and high power motors. Moreover, Maxwell theory based on use of the closed loop predicted the existence of the electromagnetic waves which was confirmed experimentally rather quickly.

These factors, in our opinion, also led to the fact that the equation for the closed electric circuit was included in the system of the basic equations of electrodynamics while equation (4.6) for the open circuit would allow to avoid rather numerous misunderstandings and paradoxes because equations (4.5) and (4.6) always adequately describe the phenomenon of electromagnetic induction. Despite it, the question remains open why expression (4.2), even for the loop, does not always lead to a correct result.

Not quite correct use of the “electric loop” concept is the source of paradoxes.

Maxwell law of electromagnetic induction in form (4.2) includes the closed loop that encompasses a surface through which the magnetic field passes. A loop means a mathematical or geometrical concept. The size and the form of "mathematical" loop must be invariable. Increase or reduction by itself in sizes of an electric loop does not necessarily lead to occurrence of the EMF in the loop; it depends on the way of increasing the sizes. Only when the loop is not mathematical, but the *physical loop* formed by a conductor, change in its sizes by moving elements of the loop can lead to the EMF generation. The equation of electromagnetic induction (4.2) does not demand presence of a physical circuit at all; it is also valid in vacuum. For this reason, applications of the equation of electromagnetic induction to the loop in vacuum and to the physical loop formed by a conductor must be considered separately.

The mathematical loop, unlike the physical one, is only an auxiliary mathematical (geometrical) concept allowing more full and deeply to describe properties of a field not only in space but also in time.

Transformation of mathematical loop only changes the form of mathematical expressions describing the field without any influence on the field.

The physical loop is actually, unlike a mathematical loop, the device actively influencing magnetic and electric electromagnetic field components: the open loop reduces to zero the electric field component inside the material of the loop and near its surface and concentrates it at the location of loop discontinuity, the closed loop interferes with any change of the magnetic component near the loop and reduces thereby the electric field component.

If Maxwell law of electromagnetic induction in form (4.2) is used for research of electromagnetic phenomena in vacuum it is always meant that loop L remains invariable in time. Otherwise, as long as loop deformation is arbitrary (it is not supported by physical movement of material objects) and can also change unevenly, the magnitude of integral in the left part of (4.2) will also be arbitrary. Another concern if a material object such as an electric field sensor, metal conductor or a ferroelectric sensor described above is connected to the circuit. The material object cannot instantly jump from one point to another and can move only continuously. If loop elements move, there is a possibility to measure the electric field strength at each point of the loop in an inertial frame of reference instantly accompanying the loop element. If the magnetic field varies in time and the loop is stationary, the laboratory frame of reference is such an inertial system which is common for every point of the loop. Then it is possible to sum field strengths at all points of the loop. If the physical loop of conducting material is used instead of a ferroelectric sensor such summation occurs naturally in the form of the EMF at the location of discontinuity in the closed loop.

We consciously avoided application of the Lorentz force concept, this concept, after the relativity theory emerged, complicates the perception of electromagnetic phenomena because a usual electric field in an intrinsic instant reference frame connected to the moving electric charge is always behind the Lorentz force. It does not mean, of course, that we urge to abandon the concept of the Lorentz force in general. The concept of the Lorentz force has been developed historically and in certain cases not leading to misunderstanding it is convenient enough in practice.

Maxwell's law of electromagnetic induction in classical form (4.1), (4.2) is valid when conducting materials (or environments) are absent.

For physical loops made of conducting materials it is possible to consider and classify various conditions when equation (4.2) is applicable. This can be done, in particular, by analyzing the paradoxes considered above. We have drawn a conclusion from the analysis presented before (par. 4.3 of the present chapter) that when motion of conducting electric loop elements through a magnetic field results in change in the magnetic flux through the loop (at the expense of crossing of the magnetic loop and the magnetic field), use of Maxwell's law of electromagnetic induction in form (4.2) is admissible. Otherwise, and also in cases of doubt, it is necessary to use Faraday law of electromagnetic induction in form (4.5) or (4.6). It should be noted that it is possible to make an additional gap in a physical loop and position a foreign EMF source there. This cannot be done for mathematical loop L. A foreign EMF source is considered to be any source in which the EMF is not generated by crossing the magnetic flux by loop elements, but for different reasons, for example, by making use of an electric chemical element, a photo cell, a thermocouple, etc. Such loops, obviously, do not submit to equation (4.2). Further, we shall exclude from consideration those EMF sources for which presence of the magnetic field is not required.

If the magnetic field is available, separate consideration is required for physical loops where free electric charges, entering into the loop, cross magnetic flux lines at some parts of the loop or at all parts of the loop under the influence of foreign forces but not at the expense of time change in the magnetic field. Various versions of unipolar generators (with a mobile and motionless magnetic field), MHD-generators, etc. relate to these cases. Switching of a part of the loop is often considered to be a distinctive feature of these devices, however, it is not the case. In the cases stated above in paragraphs 2.1 and 2.3 there are also switching and change of magnetic flux through the loop, but there is no free charge motion when the loop configuration changes under the influence of foreign forces (because foreign forces are absent), and the EMF is equal to zero. At the same time, if Hall sensor as EMF source is switched as a part of circuit there are no either switching or changes in the magnetic flux, but under foreign electric forces free charges cross magnetic flux lines, and the EMF is generated in the loop.

4.6. Physical reasons of electromagnetic field movement

What causes magnetic flux lines of the electromagnetic field to move?

In the electromagnetism theory the following inequality is almost always accepted by default provided that electromagnetic waves are excluded from consideration:

$$\Delta l \ll c\Delta t\,, \tag{4.7}$$

where Δl is the distance from a field source, or sizes of the source, depending on circumstances , c is the velocity of light, and Δt is a minimum time interval necessary to perform measurements.

Let's consider some cases when inequality (4.7) is not held true. In these cases, the electric or magnetic field does not submit to the laws of electro- or magnetostatics.

1. Let`s consider stationary spherically symmetric point charge. The electric field of such a charge is of spherical symmetry because in any other distribution of electric lines of force the total electric field energy increases. Let`s a force be applied to the charge for a time period so as to accelerate it. The field near the charge will also accelerate, however the field will not have time to start moving at a great distance from the charge, and in a charge intrinsic reference frame (instantly accompanying the reference frame) the field will lose spherical symmetry and its energy will increase. This will be also true for some time after force cancellation depending on point of observation. The electric field will start moving at first near the charge and then in remote points, aspiring to the total energy minimum, and, eventually, will get the initial spherical symmetry. Under laboratory conditions when distances are small and a measurement time exceeds a field acceleration time, the electric or magnetic field are usually supposed by default to be rigidly connected to their source and, hence, their velocities are equal.

2. Let`s consider two parallel infinitely long motionless wires. At very large distance l from each other, so that inequality (4.7) is not true, wires are closed by sliding crosspieces. The current source is switched in one of the crosspieces. Near one of the wires between the crosspieces, a probe charge is positioned. When the crosspieces are motionless, there are no forces applied to the probe charge, because the magnetic field created by the current, is motionless. Let`s move simultaneously the crosspieces in one direction for a short time, such that inequality (4.7) was not true. At initial moment there will be reduction in the force lines density behind a

front crosspiece, taken in the direction of motion, that is in magnetic field induction, whereas before a rear crosspiece the density increases.

Earlier, when the crosspieces were motionless, magnetic flux lines in the current circuit were distributed so that magnetic field energy would be minimal at the fixed magnetic flux. With crosspieces motion the magnetic flux lines also started their motion, aspiring to energy minimum. If losses in the loop are small enough, damped oscillation of the magnetic flux lines density along the loop are possible. However, due to radiation losses and eddy currents, the oscillation will eventually stop, and the flux line velocity will be equal to the velocity of the crosspieces, so distribution of the magnetic flux line density (induction) along the loop becomes the same, as it was prior to the start of motion. In the reference frame connected to a probe charge, the electric field and the force applied to the probe charge will be generated. In the reference frame connected to the crosspieces this force will be interpreted as the Lorentz force.

3. Let1s consider a loop which has a very large not only longitudinal but also lateral dimension, for example, round a coil of wire of a very large radius, such that inequality (4.7) is not valid. Current source is switched in the loop. In steady-state conditions magnetic field distribution inside and outside of this circuit corresponds to minimum magnetic field energy at defined magnetic flux value through circuit loop. Let`s change loop current very rapidly, for example, we increase it for short time so that the inequality (4.7) is not valid. As the current in the loop has changed, the magnetic flux crossing the loop will also change. However, because the velocity of light is of finite value the induction will increase in the initial moment only in immediate proximity to the coil with current, whereas in the central areas of the loop the induction will not have time to change. The condition of a minimum of the magnetic field energy will be violated, magnetic flux lines will start moving from the current coil wire until a new minimum of the magnetic field energy will be reached. This example once again shows that the change of a magnetic flux through an electric loop and a magnetic field energy transfer can occur only due to the motion of magnetic flux lines.

Thus, the electric or the magnetic field goes out of the state of rest when the equilibrium state of the field corresponding to a minimum of energy is disturbed. If for any reasons this equilibrium condition of the electromagnetic field energy is disturbed, that field starts moving, due to what new equilibrium state is reached. Motion of the magnetic field and physical elements of the electric circuit relative to each other is necessarily considered to be a unique reason of the EMF to emerge in the circuit.

Conclusions

1. Any change of the electric or magnetic field in time at any point of space occurs only by moving the electric or magnetic flux lines.

2. From par. 1 follows that all conclusions drawn in [1] and also the principle of superposition also extend to electric or magnetic fields varying in time. In other words, one of electromagnetic field sources can be an electric or magnetic field varying in time.

3. Maxwell's theory for electric and magnetic fields varying in time is a specific theory, valid for electromagnetic waves and for some other special cases.

4. The electric or magnetic field goes out of the state of rest when the field equilibrium state corresponding to the minimum of energy is disturbed. When the energy equilibrium state is disturbed, the electromagnetic field starts moving to achieve a new equilibrium state.

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