CORRECTION OF ELECTRODYNAMICS IN THE QUESTION OF THE MAGNETIC FIELD WORK

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ABSTRACT

On the basis of a more general expression of the energy conservation law in inhomogeneous current-carrying systems, the erroneousness of the widespread opinion has been revealed, as if the magnetic field does not perform work. It is shown that magnetic forces and their moments perform two types of work, corresponding to the forward and rotational motion of charges, and their velocities play the role of vector potentials of these fields. The corresponding "longitudinal" and "vortex" components of the magnetic field are found and the error in the interpretation of their isopotential lines as force lines is revealed. The incorrectness of a number of related concepts is discussed, including the inconsistency of attempts to materialize force fields, and the force effects analogous to magnetism are predicted for the rotational motion of nonmagnetic materials.

Keywords: current-carrying systems, magnetic fields, electric and magnetic dipoles, their forces and moments, polarization and magnetization, vector potentials, longitudinal and vortex field, their work.

1. INTRODUCTION

It is generally accepted that "the magnetic field, unlike the electric field, does not work on charges moving in it, since the force acting on the charge is perpendicular to its velocity" [1]. Since, in closed circuits, there are no other driving forces except those emanating from magnetic fields, the electrodynamics based on Maxwell's equations [2] can not give an intelligible answer to the question of what forces work, for example, in electromagnetic lifts and Rotating electrical machines?

To answer this question, we need a theory capable of eliminating the existing separation of mechanics and thermodynamics, hydro-aerodynamics and electrodynamics that operate only on external or internal or only free energy, and give a unified description of the laws of transport and transformation of any forms of energy with any kind of work performed by them (ordered and unordered, external and internal, mechanical and non-mechanical, useful and dissipative). Such a theory, called energodynamics [3], was developed only in 2008 and tested by deriving the basic principles, laws and equations of all the disciplines mentioned above.

This interdisciplinary theory of the speed and productivity of real processes has changed many perceptions of processes occurring in current-carrying systems, eliminating the strange separation of electromechanics [4] from Maxwell's theory of the electromagnetic field [2]. The task of this article is to demonstrate how a useful work is performed by a magnetic field and how many many-sided notions about the physical nature of processes occurring in current-carrying systems are justified.

2. FEATURES OF THE DESCRIPTION OF CURRENT-CARRING SYSTEMS FROM THE POSITION OF ENERGODYNAMICS

Without exception, all field theories, faced with the problem of an infinite number of degrees of freedom of continuous media, solve it by dividing them into an infinite number of elementary volumes, which are considered homogeneous with sufficient accuracy. This method is most clearly formulated in the hypothesis of I. Prigozhin's local equilibrium [5], which presupposes the presence of equilibrium in such elements (in spite of the absence of a necessary and sufficient sign of it-the cessation of any macroprocesses), the sufficiency of their description by the same set variables, as in equilibrium (despite the presence of gradients of any intensity in this case), and the possibility of applying to them all the equations of classical physics (despite the inevitable transition to inequalities). This is done for the obvious purpose - to exclude from consideration internal processes occurring in spatially inhomogeneous media, which would allow us to apply the usual apparatus of mechanics, which operates with the concepts of forces and moments external to the object under study [6]. The electrodynamics also applies to this method, which considers the unit volume of a di-electrician or a magnet as an object of investigation, and the processes in any part of it are homogeneous [7].

Meanwhile, in any inhomogeneous system where the local density $\rho_i = \partial\Theta_i/\partial V$ of any extensive quantity $\Theta_i = \int\rho_i dV$ (mass M, entropy S, charge Q, number of moles of *k-th* substances N_k, pulse **P**, its moment **L** etc.) is not equal to its average value etc. $\bar{\rho}_i = \Theta_i/V$, there are always regions in which the processes take place in the opposite direction. Indeed, in view of the obvious equality $\int\rho_i(\mathbf{r},t)dV = \int\bar{\rho}_i\, dV = \Theta_i$, we have:

$$\int[\rho - \bar{\rho}]dV = 0. \qquad (1)$$

The integral (1) vanishes for $\rho \neq \bar{\rho}$ only in the case when the deviations $\rho - \bar{\rho}$ in opposite parts of the system have the opposite sign and mutually compensate. With respect to current-carrying systems, this means the presence of currents of the opposite direction in them, which leads to the appearance of torques in them, not considered in the Maxwell equations.

Consideration of this most important position, called in the energy dynamics "the principle of the opposite direction of processes" [8], requires the introduction of specific parameters of the spatial inhomogeneity of the systems under study. To find them, let's pay attention to the position of the center of some extensive value Θ_i, defined by its radius vector $\mathbf{R}_{io} = \Theta_i^{-1}\int\bar{\rho}\,\mathbf{r}dV$, where **r** is the traveling (Euler) spatial coordinate (Fig. 1), we find that the deviation of the system from equilibrium is accompanied by a displacement of its center $\mathbf{R}_i$ and the formation of a certain "moment of distribution"

$$\mathbf{Z}_i = M\Delta\mathbf{R}_i = \int(\rho_i - \bar{\rho})\mathbf{r}dV, \qquad (2)$$

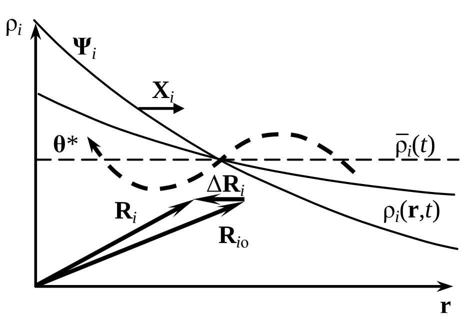

Fig.1. To Generation of Distribution Moment

where $\Delta\mathbf{R}_i = \mathbf{R}_i - \mathbf{R}_{io}$ is the shoulder of the moment $\mathbf{Z}_i$, which we called the "displacement vector" [3,8].

Such moments arise when any extensive parameters are redistributed. Their introduction allows us to express quantitatively the deviation of the system as a whole from an equilibrium of any kind (thermal, mechanical, material, etc.). The total differential of the moment Zi in the general case can be decomposed into three independent components:

$$d\mathbf{Z}_i = \mathbf{R}_i d\Theta_i + \Theta_i d\mathbf{r}_i + d\boldsymbol{\theta}_i \times \mathbf{Z}_i, \qquad (3)$$

where $\Delta R_i \equiv |\Delta \mathbf{R}_i|$ - modulus of the displacement vector; $\Delta \mathbf{r}_i = \mathbf{e}_i \Delta r_i$ is the displacement vector of the center of the quantity Θ_i in the direction of the unit vector $\mathbf{e}_i$; Θ_i is the spatial (Eulerian) angle characterizing the orientation of the vector $\mathbf{Z}_i$.

This means that any *i*-form of the energy $\mathcal{E}_i$ of any independent component or phase of a nonequilibrium system possessing a specific material carrier Θ_i can perform not one but three types of work carried out either by introducing an energy carrier Θ_i through the boundaries of the system from the outside without violation of its homogeneity ($d\Theta_i \neq 0$; $\Delta \mathbf{r}_i = 0$); by redistribution of these parameters Θ_i between different parts of the same system when co-storage of their values for the system as a whole ($d\Theta_i = 0$, $d\mathbf{r}_i \neq 0$), and by reorienting the displacement vectors $\Delta \mathbf{R}_i$, ($d\mathbf{e}_i \neq 0$; $\Delta \mathbf{r}_i = 0$). The first group includes the processes of electrification of the system (entering a charge Q into it), which are similar to the thermodynamic processes of equilibrium heat exchange, volume deformation, mass transfer, etc. [9]; To the second - the processes of polarization of matter in the broadest sense of this term as the creation of spatial inhomogeneity in it [3], the third - the processes of ordering the orientation of the dipoles of substances or rotation of systems with anisotropy of any properties [8]. Thereby $\mathcal{E}_i$. Is in general a function of three independent arguments Θ_i, $\mathbf{r}_i$ and $\boldsymbol{\theta}_i$, i.e. $\mathcal{E}_i = \mathcal{E}_i(\Theta_i, \mathbf{r}_i, \boldsymbol{\theta}_i)$, and the total energy differential of the system as their sums $\mathcal{E} = \Sigma_i \mathcal{E}_i$ can be represented in the form of the identity [3]:

$$d\mathcal{E} \equiv \Sigma_i \overline{\psi}_i \, d\Theta_i - \Sigma_i \mathbf{F}_i \cdot d\mathbf{r}_i - \Sigma_i \mathbf{M}_i \cdot d\boldsymbol{\theta}_i. \quad (4)$$

Here $\overline{\psi}_i \equiv (\partial \mathcal{E}/\partial \Theta_i)$ are the scalar generalized potentials ψ_i (absolute temperature T and pressure p, chemical potentials of *k-th* substances μ_k, their electric φ and gravitational ψ_g potentials, translational $\boldsymbol{\upsilon}_i$ and the rotational $\boldsymbol{\omega}_i$ local velocities, etc.); $\mathbf{F}_i \equiv - (\partial \mathcal{E}/ \partial \mathbf{r}_i)$ – forces in their usual sense; $\mathbf{M}_i \equiv - (\partial \mathcal{E}/\partial \boldsymbol{\theta}_i)$ are their moments.

Unlike other disciplines, identity (4) defines the total energy of the system $\mathcal{E}$ as the most general function of the state, characterizing its ability to perform any of the works mentioned above, the number of arguments of which is equal to the number of independent processes occurring in the system under study.

Representing the result of the joint determination of the "conjugate" parameters $\overline{\psi}_i$ and Θ_i, $\mathbf{F}_i$ and $\mathbf{r}_i$, $\mathbf{M}_i$ and $\boldsymbol{\theta}_i$, it preserves the character of the identity, regardless of what is caused by the change of these parameters: external energy exchange ($d\mathcal{E} \neq 0$) or internal (including relaxation processes) ($d\mathcal{E} = 0$) [1)]. It is at this day the most common and at the same time the most detailed expression of the law of conservation of energy, since not only all forms of energy, but all conceivable types of work performed by them, are included in the number of its components. All this makes identity (4) a unique means of verifying theories based on postulates and model representations of a particular nature.

3. THE WORK OF CHARGING AND PULSE INPUT INTO CURRENT-CARRING SYSTEMS

Consider a current-carrying system that has both an electrostatic and an electrokinetic (magnetic) form of energy. Like a mechanical system, the carrier of electrostatic energy in it is the stationary charge of the system $Q = \int \rho_e dV$ with density ρ_e, and electrokinetic - its momentum $\mathbf{J}_e = Q \overline{\boldsymbol{\upsilon}}_e$, called the current, where $\overline{\boldsymbol{\upsilon}}_e$ - the average velocity of the charge. Like a mechanical impulse, the latter can be decomposed into two independent components corresponding to the translational $\mathbf{w}_e = d\mathbf{R}_e/dt$ and the rotational $\boldsymbol{\omega}_e \equiv d\boldsymbol{\theta}_e/dt$ velocity component υ_e:

$$\boldsymbol{\upsilon}_e \equiv d\mathbf{r}_e/dt = \mathbf{w}_e + \boldsymbol{\omega}_e \times \mathbf{r} \, . \quad (5)$$

Accordingly, $\mathbf{J}_e$ decomposes into the momentum of translational motion, which is the current **I** $= Q\bar{\mathbf{w}}_e$ with density $\mathbf{I}_v = \rho_e \bar{\mathbf{w}}_e$, and at the moment of the amount of rotational motion $\mathbf{L} = Y\bar{\boldsymbol{\omega}}_e$ with density $\mathbf{L}_v = \rho_e \boldsymbol{\omega}_e$, where ρ_ω is the density of the moment of inertia Y.

In this case, the potential of the electrostatic energy form $\bar{\varphi} \equiv (\partial \mathcal{E}/\partial Q)$ in accordance with (4) will have the meaning of the averaged electric potential of the system φ(r), and the potential of the electrokinetic form of energy is the meaning of the averaged velocity of the internal translational motion $\bar{\mathbf{w}}_e \equiv (\partial \mathcal{E} / \partial \mathrm{I})$ and its internal rotation $\bar{\boldsymbol{\omega}}_e \equiv (\partial \mathcal{E}/\partial \mathbf{L})$ [10]. In this case, the terms of the first sum of the identity (4) will acquire the meaning of the elementary work of introducing the charge $đW_e'$ and the momentum $đW_v'$:

$$đW_e' = \bar{\varphi}\, dQ; \quad đW_v' = \bar{\boldsymbol{\omega}}_e\, d\mathbf{L}_e\,. \tag{6}$$

This work is analogous to the one that takes place in the process of introducing *k-th* substances with a chemical potential μ_k in the number of N_k moles $đW' = \mu_k dN_k$, or the work of the volume deformation of the system $đW_v' = pdV$, which is equivalent to introducing an additional volume dV. To the same category is, in principle, the heat exchange, which consists in replenishing the entropy of the system S as a measure of the momentum of chaotic motion in the system [3]. In electrodynamics of this kind work, expressed in the replenishment of the momentum of the ordered motion of a charge in it, is usually not considered at all.

4. TRANSLATIONAL AND ROTATIONAL VELOCITY OF CHARGES AS VECTOR MAGNETIC POTENTIALS

Let us now clarify the relationship between the moments of the distribution of the charges $\mathbf{Z}_e = Q\Delta\mathbf{r}_e$ and the currents $\mathbf{Z}_m = \mathbf{J}_e\Delta\mathbf{r}_m$ with the electric and magnetic induction vectors **D** and **B**. If we refer these moments, like the vectors **D** and **B**, to a system of unit volume, and discard the indices at $\Delta\mathbf{r}$, then $d\mathbf{Z}_{ev} = \rho_e d\mathbf{r}$ and

$$\nabla \cdot \mathbf{Z}_{ev} = \rho_e; \tag{7}$$

Since $\nabla \cdot \mathbf{D}$ is also equal to ρ_e [7], the moment $\mathbf{Z}_{ev}$ has the same meaning as the electric displacement (induction) vector **D**. Another matter is $\mathbf{Z}_{mv}$, which is the external product of two vectors $\mathbf{j}_e$ and $\Delta\mathbf{r}_m$, i.e. is a rank 2 tensor. The sequential vector of the magnetic induction **B** is also a second-rank tensor, and its divergence

$$\nabla \cdot \mathbf{Z}_{mv} = \nabla \cdot \mathbf{B} = \mathbf{j}_e\,, \tag{8}$$

hose it does not vanish, as postulated by Maxwell's equations [2]. This means that the magnetic field also has sources, and the field **B** can be represented, like any second-rank tensor, by a scalar equal to one-third of the trace of the tensor, its symmetric part vector with the 5-th components, and the vortex vector, equivalent to its antisymmetric part [10]. In other words, the magnetic field is not purely vortical, as Maxwell believed.

We now clarify the relationship between the vector magnetic potential **A** introduced by Maxwell [2] in a formal mathematical way and the rate of rotation of the charge. Consider for this purpose an arbitrary system in which molecular currents form closed structures such as electrical circuits. We represent Q as the sum of the translational $\mathbf{J}_e = Q\bar{\mathbf{w}}_e$ and the rotational pulses $\mathbf{L}_v = \mathrm{Y}\bar{\boldsymbol{\omega}}_e$ of the charge motion. For clarity, consider a long single-layered solenoid with a radius r, along the winding of which a current **I** flows with a density $\mathbf{I}_v = \rho_e \bar{\boldsymbol{\omega}}_e$. Then $\mathbf{L}_e = \int \boldsymbol{\omega}_e \rho_e dV = \int (\mathbf{I}_v/r)dV$, and the angular rotation speed of the charge is the conjugate potential $\bar{\boldsymbol{\omega}}_e$ [11]:

$$\bar{\boldsymbol{\omega}}_e \equiv (\partial \mathcal{E}/\partial \mathbf{L}_e) = Q^{-1}\int(\mathbf{I}_v/r)dV\,, \qquad (9)$$

Comparing (6) with the known expression of the vector magnetic potential [7]

$$\mathbf{A} = (\mu_o/4\pi)\int(\mathbf{I}_v/r)dV, \qquad (10)$$

we find that the average rotational velocity of the charge is $\mathbf{A}/Q$, i.e. Is the specific (per unit of charge) magnitude of the vector magnetic potential, differing from it in magnitude only by the factor $\mu_o/4\pi$, where μ_o is the magnetic permeability of the medium. This means that the value of **A**, determined by the expression (10), can not claim to be a generalized potential, since all such quantities are intensive parameters. Thus, the true vector potential of the electrokinetic form of energy is the angular velocity of charge rotation. The value of **A** becomes such only because of its attribution to the current-carrying system of unit volume, as, indeed, the vector of magnetic induction **B**.

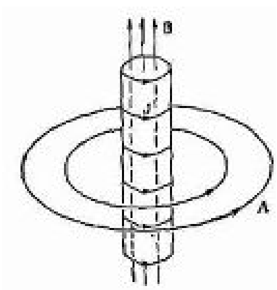

Fig.2. Solenoid field

Like the vector potential A, the angular velocity is directed along the so-called lines of force of the magnetic field, as illustrated in Fig. This circumstance reveals the inconsistency of the traditional (Faraday) interpretation of the lines formed by iron filings around the conductor with current, as lines indicating the action of the magnetic force field. Hence - the idea of them as some kind of material formations that can flex flexibly, stretch and even "loosen up" [4]. If this were so, floating sawdust would certainly come into motion in the direction indicated.

As it turns out, in reality these are lines of constant vector potential, the role of which is played by the angular velocity of rotation of the charge, rather than the extensive value of **A**. That is why the physical meaning of this potential has remained unclear for so long, causing discord of opinions as to the legitimacy and expediency of its introduction In the toolkit of electrodynamics, and the very fact of its existence [7]. Then it becomes understandable also why the induction emf is induced only when the isopotential lines of this field intersect, i.e. its potential is changing.

5. TORQUES OF LORENTZ FORCES

For current-carrying systems, one more category of work is characteristic, expressed by the terms of the third sum (4):

$$đW_e''' = \mathbf{M}_e \cdot d\boldsymbol{\theta}_e, \qquad (11)$$

This work is performed by the torque $\mathbf{M}_e = \mathbf{F}_m \times \Delta \mathbf{r}_e$ of the magnetic forces $\mathbf{F}_m$ and $\boldsymbol{\omega}_e$ - is in ordering the orientation of the circuits with current with respect to the direction of the magnetic field (their Euler angle $\boldsymbol{\theta}^e$). In the particular case of a rectangular frame with that (Fig. 3), this occurs due to the opposite direction of the currents $\mathbf{I}_e$ in its upper and lower branches and the magnetic components of the Lorentz force $\mathbf{F}_1 = \mathbf{I}_e \times \mathbf{B} = - \mathbf{F}_2$.

Similar pairs of forces and perform the work of rotation of various electrical devices. Thus, energy dynamics complements Maxwell's electrodynamics by predicting the ability of a magnetic field to perform not one but three types of work described by three sums of its identity (4). To find out the origin of the torque, we draw attention to the extremely important addition of Maxwell's equation

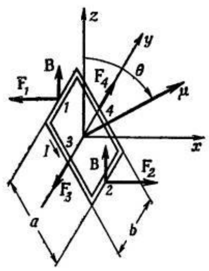

Fig.3. Frame with current in a magnetic field

$$\nabla \times \mathbf{E} = - d\mathbf{B}/dt \qquad (12)$$

which consists in replacing the partial derivative $(\partial \mathbf{B}/\partial t)$ by a total $d\mathbf{B}/dt$. Due to this, a term $(\boldsymbol{\upsilon}_e \cdot \nabla)\mathbf{B}$ appears in it, in which the charge velocity $\boldsymbol{\upsilon}_e$ can be decomposed into the translational $\mathbf{w}_e = d\mathbf{R}_e/dt$ and the rotational $\boldsymbol{\omega}_e$ component (5). The first of them determines the so-called "longitudinal" component of the magnetic field **B**, responsible for the appearance of attractive and repulsive forces of permanent magnets and electromagnets, with the work done at this time $đW_{mv}'' = \mathrm{H} \cdot d\mathrm{B}$, and the other for the appearance of torques $\mathbf{M}_e = \mathrm{rot}(\mathbf{B} \times \mathbf{r}_e)$, which perform the work (11). This work is responsible, in particular, for the process of magnetization of ferromagnets, which appears as a process of ordering the chaotic orientation of directions of angular velocity vectors of circular, atomic, spin or other currents. It is to change the orientation angle θe separate current contour-trench so as to arrange them in one direction. No imaginary "magnetic mass" or any other specific "carriers magnetism" for this is not required.

5. DISCUSSION OF RESULTS

As shown above, many difficulties in understanding electrodynamics can be avoided by adhering to the methodologically unified construction of electrodynamics based on the mechanics of translational and rotational motion of bodies or charges. With this approach, it becomes clear that the translational motion of the charge generates a potential (longitudinal) and its rotational motion produces a vortex magnetic field. According to identity (4), both these velocity fields become force only when the inhomogeneity in the momentum distribution of these forms of motion of charged particles appears in them [4]. Thus, one of the main conclusions of energy dynamics is confirmed, according to which any force fields are generated not by masses, charges and currents in themselves, but by their uneven distribution.

No less important result of this approach is the explanation of the essence of processes occurring in current-carrying systems without involving any hypotheses and postulates for this. Understanding that each form of the energy of the system $\mathcal{E} = \Sigma_i \mathcal{E}_i(\mathbf{Z}_i)$ has a potential and kinetic component with its vector potential $\mathbf{w}_e$ and $\boldsymbol{\omega}_e$ allows us to apply a single algorithm to finding all the properties of these fields without combining them into a single "electromagnetic" field and not resorting to its materialization.

Scalar, vector, and tensor fields were and remain only functions of the distribution of potentials in space, and their strengths are determined by their gradients, which are similar to the gradient of the Grad$\boldsymbol{\upsilon}_e$ velocity, can be decomposed into a potential and a vortex component. The necessity of the existence of such a potential for moving charges was also clear to Ampere [13], and it "should be sought in the form $\mathrm{H} = - \nabla\psi$" [1, p.156]. It remains to be regretted that the attribution to the magnetic field of purely vortex properties delayed the detection of their irrotational (longitudinal) component for more than a century [14].

The approach from the standpoint of energy dynamics disproves the popular opinion that a magnetic field does not perform work. On the contrary, it is found that this field does not one, but three kinds of works $đW_e'$, $đW_{mv}''$ and $đW_e'''$, in the latter case it is produced by the moment of Lorentz forces. Incidentally, it also turns out that Faraday's "lines of force" are actually isotopic lines of the magnetic field. This explains why the work is done only when crossing these lines.

Making the vector magnetic potential **A** and its derivative $\partial\mathbf{A}/\partial t$ a simple sense of the angular velocity of a charge and its acceleration makes it impossible for the electromechanists to avoid using it [4]. At the same time, their refusal to use the expression of Maxwell's electromotive force becomes more comprehensible [2, §598]:

$$Э = \oint(-\nabla\varphi - \partial\mathbf{A}/\partial t + \boldsymbol{\upsilon}_e\times\mathbf{B})d\boldsymbol{\ell}\ ,\ \text{Дж/Кл} \qquad (13)$$

where $d\boldsymbol{\ell}$ is the vector element of the length of the closed electrical circuit.

It becomes obvious that in the stationary process of charge circulation not only the quantity $\partial\mathrm{A}/\partial t$ does not participate, but also the potential gradient $\nabla\varphi$, the circular integral of which always vanishes, and also the Lorentz force $\boldsymbol{\upsilon}_e\times\mathbf{B}$, since the latter is always Is normal to the direction of its motion. Thus expression (13) leaves the question of real forces acting on the current frame virtually open. The very application of the term "electromotive force" to the value $Э$, which makes sense of the work of transferring a single charge in a circular process, does not stand up to criticism either. All this increases the already extensive list of parallels of Maxwell's theory of electromagnetism [15].

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