PHYSICS

ECTS

EDUCATION IN ENGLISH

Module 3

Electricity and Magnetism

$$I = \oint_L \vec{H} d\vec{l}$$

A. G. Bovtruk, S. L. Maximov,

S. M. Menaylov, A. P. Polischuk, P. I. Chernega

PHYSICS

Module 3

Electricity and Magnetism

Manual

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У той час, коли Україна приєднується до Болонського процесу та вступає до «Європи знань», видання англомовних навчальних посібників є вкрай необхідним. Даний посібник розроблено для використання на всіх формах занять з курсу загальної фізики в умовах кредитно-модульної системи.

Модуль 3 «Електрика та магнетизм» складається з навчальних елементів, які містять теоретичне ядро, задачі для аудиторної та індивідуальної роботи, а також лабораторний практикум. Розглянуто програмні питання з основ електрики та магнетизму.

Для студентів інженерно-технічних спеціальностей вищих технічних навчальних закладів.

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Having joined in Bologna process Ukraine requires creating new books on physics (in English in particular). The book is developed for all forms of studying physics on the Credit-based Modular System basis in higher school.

"Physics. Module 3. Electricity and Magnetism" presents the essential principles of electricity and magnetism. It contains Study Units which include theoretical information, test questions, sample problems, laboratory works and individual home tasks.

It is designed for students of engineering specialities.

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PREFACE

Aim of Studying Physics

The discipline «Physics» is aimed at studying basic physical phenomena and laws, mastering fundamental concepts and theories of classical and modern physics, up-to-date research methods, and finally formation of scientific outlook. Therefore, the ***tasks*** are the following:

- learning objective laws of the world and connections between physical phenomena;
- mastering ways and methods of problem solving;
- acquaintance with experimental equipment, formation of practical skills of experiment performance;
- formation of skill to see the concrete physical essence to be applied in practice.

As a result of studying the discipline «Physics», students are supposed to ***know***:

- physical meaning and definition of every term and concept used;
- basic physical phenomena, laws, theories, and spheres of their practical application in engineering;
- major methods of physical research;
- the system of units of physical magnitudes.

Students ought to get the following ***skills***:

- to apply physical laws to solve practical problems;
- to use physical laws and research methods while studying engineering and special disciplines;
- to carry out physical measurements;
- to estimate errors.

Physics is the basis for studying all other technical disciplines in higher educational institutions. It explains and gives comprehension of physical phenomena, familiarizes students with its concepts, models and laws. The aim of studying physics, as well as higher mathematics, is to give students a thorough grounding for further mastering engineering subjects.

Foreword to Module M3
Electricity and magnetism

This manual represents the third module of the discipline "Physics". It helps master essential principles of electromagnetism.

As a result of studying this module, students must ***know*** the definitions of such concepts as *vector of electric and magnetic field intensity, potential of electric field, capacitance, current strength, current density vector, voltage, basic laws of electromagnetism, formulation of Gauss theorem, laws of electromagnetic induction.*

Students must get ***skills*** to apply research and theoretical methods of electrodynamics, plot graphs, estimate errors of physical measurements, and use theoretical knowledge for practical problem solving.

It is necessary to ***understand***, that electric and magnetic phenomena are closely connected with each other.

The differential and integral calculus is widely used in the module but at first year students' level. The module "Electricity and magnetism" consists of the following **Study Units** (**SU**):

Preliminary SU — Brief physical data, Glossary;
SU 1 — Electrostatics;
SU 2 — Direct electric current;
SU 3 — Magnetic field in vacuum;
SU 4 — Stationary magnetic field in substance, electromagnetic induction;
SU 5 — Laboratory works;
SU 6 — Individual home tasks;
Supplementary SU — Key words, Help tables.

The Preliminary unit contains the basic concepts and laws of mechanics, molecular physics and thermodynamics that are necessary to study efficiently this module and a glossary with explanations of terminology in mathematics and physics.

Study Units 1–4 include theoretical material, test questions, sample problems, as well as problems for work in class. Study Unit 5 gives instructions on how to perform laboratory works. Study unit 6 contains problems to be solved by students on their own. Supplementary Units are aimed at facilitating the module study.

For effectiveness, we advise using self-check questions. Each question is supplied with information where to find an answer in the case of necessity. Concepts, which are studied in the module, are basic for all engineering specialties, they are used and intensified in technical electrodynamics.

Study Unit 1

ELECTROSTATICS

Having worked through the Study Unit, students will know fundamentals and notions of electrostatics, will be able to formulate, write, analyze laws of electrostatics and apply theoretical knowledge to solve problems

1.1. Electric charges and their interaction

For a long time people know that a lot of bodies are capable to electrify — to acquire an electric charge. It is also well known that there exist two kinds of electric charges — "*positive*" and "*negative*" (these names and signs were chosen arbitrary by Benjamin Franklin). Charges of the same signs ("*like charges*") repel each other and charges of the different signs ("*unlike charges*") attract each other.

We shall use the letter ***q*** as the general symbol fora charge. The SI unit for a charge is the coulomb (C), which will be defined later.

An electric charge is an important property of elementary particles for which it may have one of three values: $-1.6 \cdot 10^{-19}$ C; 0; $+1.6 \cdot 10^{-19}$ C. A charge $1.6 \cdot 10^{-19}$ C was named an *elementary charge* and denoted with the latter ***e***. It is one of the most important constants of nature. Thus, the charge of an electron $e = -1.6 \cdot 10^{-19}$ C, of a proton $e = +1{,}6 \cdot 10^{-19}$ C. But it is not clear thus far, why an elementary charge has this and not other value.

Any charge of a macroscopic body is equal to the sum of elementary charges and is said to be quantized. It means that it may have only discrete values multiple to an elementary charge: $q = Ne.$ But an elementary charge being so small, a charge of a body may be considered as continuously changable.

An absolute value of an electric charge does not depend on an inertial reference frame it is measured in. It means that an *electric charge is relativistically invariant, i.e. its magnitude does not depend on its motion or state of rest.*

A great number of experiments have proved the ***law of electric charge conservation*****: the total charge of an electrically isolated system cannot change:**

$$\sum_i q_i = \text{const.}$$

A system is called *electrically isolated* if no charges penetrate through the surface confining it.

For convenient description of electric phenomena, an ideal notion of a point charge is used. A *point charge* is a charged body whose dimensions are small compared with the distances to other charged bodies.

Interaction of point charges is determined by *Coulomb's law* (established experimentally in 1785):

Two stationary point charges interact in a vacuum with the force directly proportional to the magnitude of each of them and inversely proportional to the square of the distance between them.

Taking into account the direction of forces action, Coulomb's law in SI is expressed by the formulas (Fig. 1.1 corresponds to the case of like charges):

$$\vec{F}_{12} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 \cdot q_2}{r_{12}^2} \cdot \frac{\vec{r}_{12}}{r_{12}} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 \cdot q_2}{r_{12}^2} \vec{e}_{12}; \qquad (1.1)$$

$$\vec{F}_{21} = -\frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 \cdot q_2}{r_{21}^2} \cdot \frac{\vec{r}_{21}}{r_{21}} = -\frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 \cdot q_2}{r_{21}^2} \vec{e}_{21}, \qquad (1.2)$$

where q_1, q_2 — magnitudes of interacting charges, $\varepsilon_0 = 8{,}85 \cdot 10^{-12}\ C^2/N \cdot m^2$ (or F/m) — electric constant (or permittivity constant) in SI; $\frac{\vec{r}_{12}}{r_{12}} = \vec{e}_{12}$ $\left(\frac{\vec{r}_{21}}{r_{21}} = \vec{e}_{21}\right)$ — the unit vector, the absolute value of which is equal to one $|\vec{e}_{12}| = |\vec{e}_{21}| = e_{12} = e_{21} = 1$.

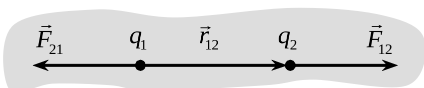

Fig. 1.1

$\vec{F}_{12}$ — the force acting on the second charge from the first one, and $\vec{F}_{21}$ — the force acting on the first charge from the second one. As $\vec{r}_{12} = -\vec{r}_{21}$ ($\vec{e}_{12} = -\vec{e}_{21}$), then $\vec{F}_{12} = -\vec{F}_{21}$.

The form of the force of interaction, which is the same for both charges, is

$$F = \left|\vec{F}_{12}\right| = \left|\vec{F}_{21}\right| = \frac{1}{4\pi\varepsilon_0} \frac{\left|q_1 \cdot q_2\right|}{r_{12}^2}. \tag{1.3}$$

Coulomb's law holds for distances from 10^{-15} to 10^{7} m and no exceptions have ever been found. It is one of the main experimental facts the teaching of electricity is based on.

Experiments show that if we have n charges, they interact in pairs according to the *principle of superposition*: the force of interaction of two charges does not depend on the presence of other charges. It means that the resultant force that acts on the charge q_0 (Fig. 1.2) is equal to the vector sum of forces with which each charge acts separately on q_0:

$$\vec{F} = \vec{F}_{10} + \vec{F}_{20} + \ldots + \vec{F}_{n0}. \tag{1.4}$$

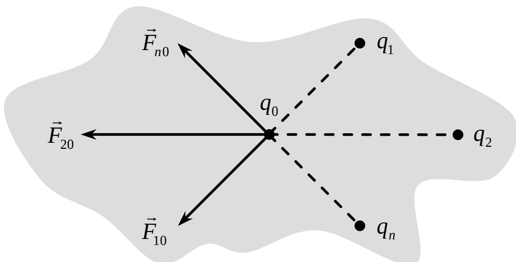

Fig. 1.2

The principle of superposition permits to find the force of interaction not only of point charges, but any charged bodies. In such a case, a charged body should be divided into small parts that may be considered as point charges, and for their interaction Eq. (1.4) should be used.

1.2. Electric field in vacuum and its characteristics

1.2.1. Electric field Intensity. Electric force lines

Electric charges interact at a distance. Therefore, a question arises: how does this interaction happen? In the mid-19th century Michael Faraday introduced the notion of an electric field as medium, with the help of which interaction between electric charges takes place. According to Faraday's theory, each stationary charge sets up an electric field in the surrounding space. This field acts on another charge and vice versa. A field produced by stationary charges is called an *electrostatic field*. Electrostatic field is a particular case of an electromagnetic field, with the help of which an interaction between any charges occurs.

Thus, the main property of an electric field is to act with a force on a charge placed in it. A quantitative (force) characteristic of this action is a vector quantity that is called the electric field intensity (or electric intensity, or electric field strength) $\vec{E}$.

The *electric field intensity* at a given point of a field is equal to the ratio of the force $\vec{F}$, acting on the side of the field on the test charge q_0, placed at this point, to the magnitude of this test charge:

$$\vec{E} = \frac{\vec{F}}{q_0} \tag{1.5}$$

(the *test charge* q_0 is called a positive point charge that does not distort the field under investigation).

As it follows from Eq. (1.5), the SI unit for the electric field intensity is the newton per coulomb (N/C) or, as it will be shown later, the volt per meter (V/m).

If a field is produced by a point charge q, then

$$\vec{F} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q \cdot q_0}{r^2}\vec{e}, \tag{1.6}$$

and the electric intensity

$$\vec{E} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2}\vec{e}. \tag{1.7}$$

Formula (1.7) determines the electric intensity of a point charge field at a point distant at $\vec{r}$ from this charge. It follows from (1.7) that the electric intensity at a

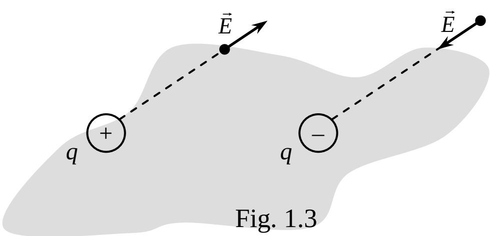

Fig. 1.3

given point does not depend on the presence of the test charge at this point. The *direction* of the vector $\vec{E}$ coincides with the direction of the force acting on a *positive* charge: away from the charge if q is positive, and toward it if q is negative (Fig. 1.3).

It may be shown that the principle of superposition applies to electric fields as well as to electrostatic forces. From Eq. (1.5) we obtain:

$$\vec{E} = \frac{\sum_{i=1}^{n}\vec{F}_i}{q_0} = \frac{\sum_{i=1}^{n}q_0\vec{E}_i}{q_0} = \sum_{i=1}^{n}\vec{E}_i. \quad (1.8)$$

Thus, the *principle of electric field superposition* is: **electric intensity of a system of charges equals the vector sum of the electric intensities that would be produced by each of the charges separately.**

Electric force lines (lines of electric field intensity or $\vec{E}$ lines) are used for graphic representation of an electric field. They are the lines a tangent to which at every point coincides with the direction of the vector $\vec{E}$ (Fig. 1.4).

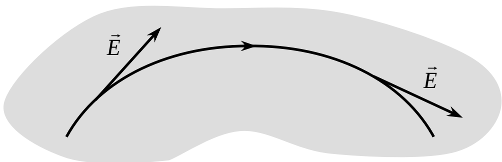

Fig. 1.4

The electric force lines originate at positive charges and terminate at negative charges. In the case of an isolated point charge (Fig. 1.5), there is a set of radial straight lines directed away from the positive charge (where they originate) and toward the negative charge (where they terminate). That is why, the positive charges are said to be a source of vector $\vec{E}$ and negative charges — a sink of this vector. The electric force lines do not cross because the vector $\vec{E}$ has only one direction at each point of a field.

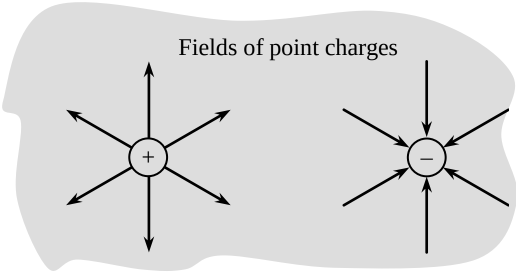

Fig. 1.5

It must be emphasized that these lines are not real, but they provide a nice way to visualize and describe an electric field. They are not also identical to trajectories of charge movement in the field.

Electric force lines may represent not only direction, but the numerical value of the vector $\vec{E}$. For this, the lines are drown with certain *density*: **the number of lines per unit area, measured in a plane that is perpendicular to the lines, is proportional to the numerical value of the vector** $\vec{E}$**.** It means that where the electric force lines are close together, E is large; and where they are far apart, E is small. Fig. 1.6 shows the electric force lines for a non-uniform and uniform field.

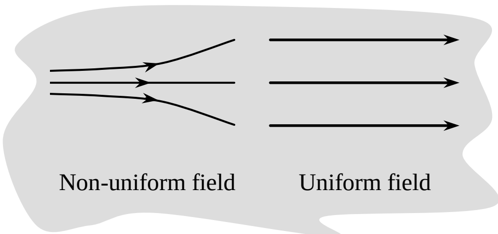

Fig. 1.6

Let us return to Fig. 1.5 showing the pattern of point charge force lines. The density of the lines at any distance r from the charge equals the ratio of the number N of the lines directed away (toward) from the charge to the surface area of the sphere with the radius r, namely the density $= \dfrac{N}{4\pi r^2}$. It is evident that the density reduces inversely proportional to the square of the distance from the charge, that is the same as for the electric intensity of the point charge field (see Eq. (1.7)).

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