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Electrodynamic Induction in Electrostatic Field

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Abstract

This paper described the principle of electrodynamic induction in the electric field. According to that principle, induced electric current in the perfect conductor that connects two plane-parallel metal plates is proportional to a rate of the flux changes through plates. This principle is possible to apply in the variable and invariable electric field, as well as in the electrostatic field, regardless of the method for generating changes of flux. Besides that, here is given a mathematical model and equivalent scheme that allows calculating the electrical circuits on this principle. There is an apparent similarity between this principle and Faraday's law of induction in a magnetic field. A characteristic example of the application of this principle is a generator of alternative currents in the electrostatic field, which is similar to a well-known electromagnetic generator.

Keywords: electrostatic induction; electrodynamic induction.

1. Introduction

According to the known Gauss's law [1], an electrostatic induction on the surface of the metallic body induces electric charge proportional to the flux of the field through the surface [2]. Changes of the flux will redistribute electrical charges and generate electrical currents. These currents could be directed and utilized with appropriate shapes of the metal body. We have shown that in conductor connected between two thin parallel metal plates induces electric current proportional to the rate of the changes of flux through the plates. This principle of induction could be applied regardless of how does change of flux produces: by changing intensity of the electric field, by moving plates in the electrostatic field or by moving the source of the electrostatic field in the vicinity of the plates.

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This induction of current in the electric field we named electrodynamic induction in the electric field, because of similarities with the known Faraday’s law of electrodynamic induction in the magnetic field [3].

2. Materials and Methods

In the experiment, we will use two identical, relatively thin and parallel metal plates of arbitrary shapes and areas, located in the air on a relatively small distance, as shown in Figure 1. Surfaces of the plates that stand opposite one another we named internal surfaces and surfaces exposed to the electric field we named external surfaces. Internal surfaces of plates at some arbitrary place are connected with short and thin metallic conductor, whose resistance and inductance could be considered negligible. The distance between the plates should be so small that it can be considered that electric field flux is equal through both plates. We will use a uniform electric field, which has the same intensity at each point of space, therefore we can say that the same flux passed through both plates and that electric charges are uniformly distributed on the surfaces of plates. Equal flux through both plates is a supposition of essential meaning for this principle of induction.

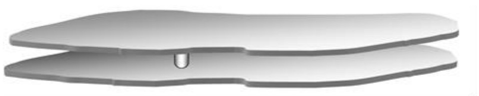
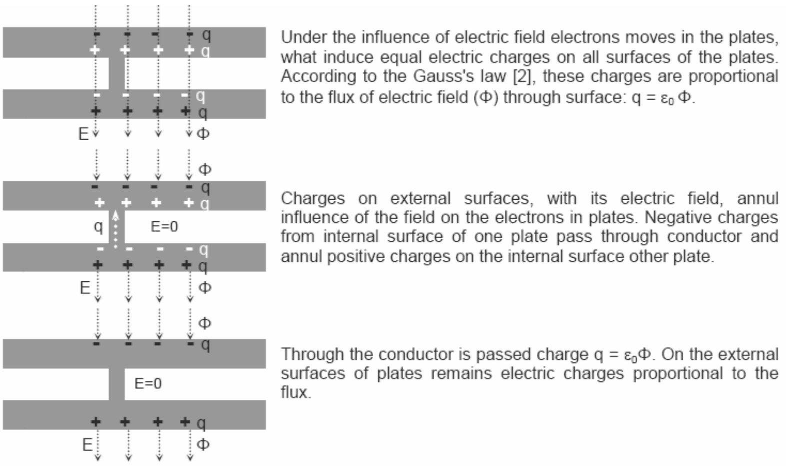


Figure 1: Two plates connected with the conductor, used in the experiment

The principle of electrodynamic induction we will prove by analysis of the process of redistribution of the electric charge in plates and conductor during a change of flux.

3. Results

Let's suppose, plates are exposed to the electric field and flux Φ was reached instantaneously after the exposition. Under electric field influence, in a very short period after that moment occurs process shown on a cross-section of plates in figure 2.



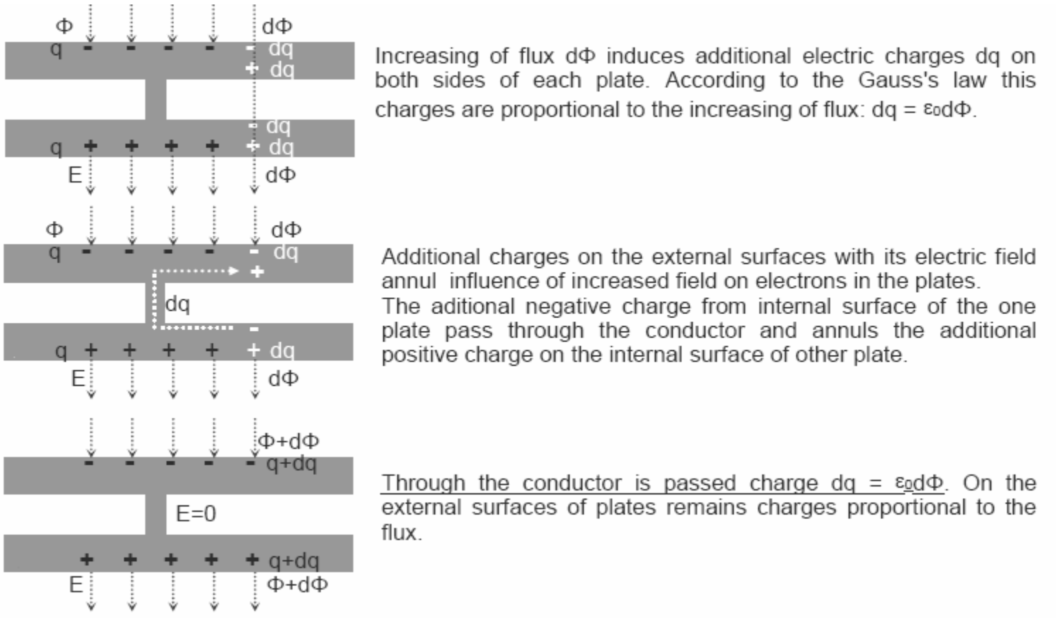
Under the influence of electric field electrons moves in the plates, what induce equal electric charges on all surfaces of the plates. According to the Gauss's law [2], these charges are proportional to the flux of electric field (Φ) through surface: $q = \varepsilon_0 \Phi$.

Charges on external surfaces, with its electric field, annul influence of the field on the electrons in plates. Negative charges from internal surface of one plate pass through conductor and annul positive charges on the internal surface other plate.

Through the conductor is passed charge $q = \varepsilon_0\Phi$. On the external surfaces of plates remains electric charges proportional to the flux.

Figure 2: Process of redistribution of charge after the moment of applying of the electric field

Further changes of flux will perturb this balance and causes the movement of electrons. Let suppose that flux through both plates instantaneously increased for the infinitesimally small value dΦ. In a very short interval after that will occur process as shown in figure 3.

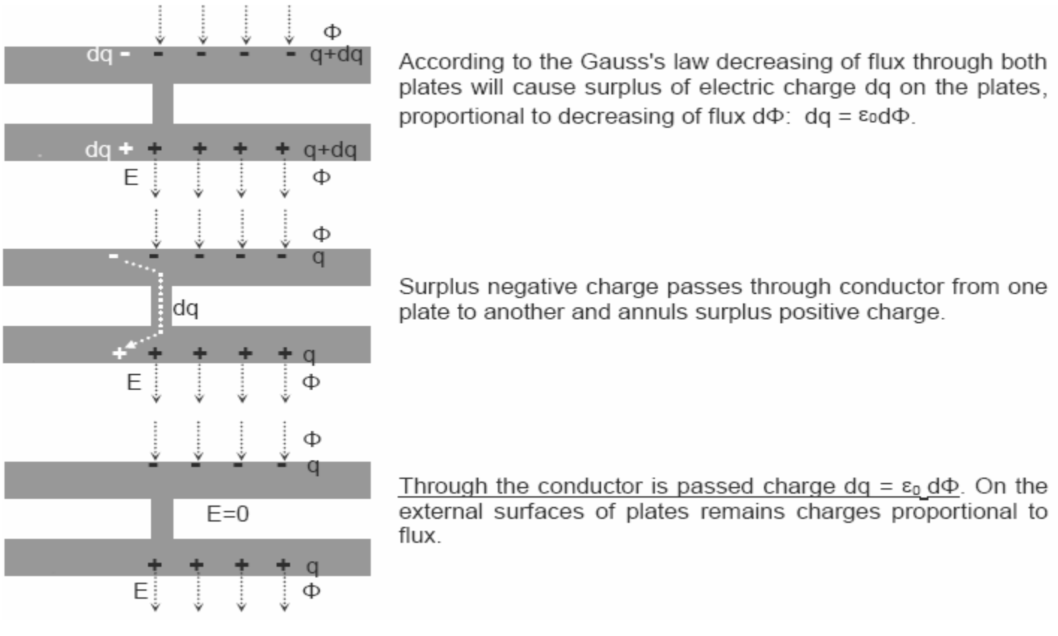


Increasing of flux dΦ induces additional electric charges dq on both sides of each plate. According to the Gauss's law this charges are proportional to the increasing of flux: $dq = \varepsilon_0 d\Phi$.

Additional charges on the external surfaces with its electric field annul influence of increased field on electrons in the plates. The aditional negative charge from internal surface of the one plate pass through the conductor and annuls the additional positive charge on the internal surface of other plate.

Through the conductor is passed charge $dq = \varepsilon_0 d\Phi$. On the external surfaces of plates remains charges proportional to the flux.

Figure 3: Process of charge redistribution after the moment of flux increasing



According to the Gauss's law decreasing of flux through both plates will cause surplus of electric charge dq on the plates, proportional to decreasing of flux dΦ: $dq = \varepsilon_0 d\Phi$.

Surplus negative charge passes through conductor from one plate to another and annuls surplus positive charge.

Through the conductor is passed charge $dq = \varepsilon_0 d\Phi$. On the external surfaces of plates remains charges proportional to flux.

Figure 4: Process of charge redistribution after the moment of flux decreasing.

Suppose that after formation this electrostatic equilibrium, flux through both plates instantaneously decreased for the infinitesimally small value dΦ. After that moment, in a very short interval occurs process as shown in figure 4.

4. Discussion

From this experiment follows conclusion: infinitesimally small change of flux through the plates (dΦ) generate a flow of electric charge (dq) through the conductor proportional to the change of flux:

$$dq = \varepsilon_0 d\Phi$$

We assumed that change of flux occurred instantaneously and the conductor has negligible resistance and inductance. That causes a very fast redistribution of electric charge. As a consequence, we can have assumed that change of flux and the process of charge redistribution occurred in an infinitesimally short interval dt. So, electrical current in the conductor can be expressed as the flow of charges in this interval:

$$i = \varepsilon_0 \frac{d\Phi}{dt}$$

Quotient dΦ/dt is the rate of change of flux, therefore we can conclude that induced electrical current is proportional to the rate of change of flux. From the above, is possible to define the principle of electro-dynamic induction in the electric field that reads:

In a perfect conductor that connects two plane-parallel metal plates, change of electric field flux through the plates will induce an electric current that is proportional to the rate of flux change.

From figure 3 one can see that increase flux causes the movement of electrons in a direction that is opposite to the direction of field vector. On the other side, the reduction of flux causes the movement of electrons in the direction of the field vector (Figure 4). According to the well-known convention, the positive direction of the current is the movement of electrons opposite to the direction of the electric field that causes movement. Therefore, it can be accepted that the positive change of flux generates a positive direction of the current.

Applicability of this principle is possible in the environment with permittivity of vacuum (ε_0) regardless of the method for generating changes of flux, under the condition that the changes of flux through both plates are equal.

Here is shown the simplest example of proof of the principle electrodynamic induction in the electrostatic field. We have proved this principle for every particular case of change of electric field flux, theoretically and in the laboratory.

Using well-known Norton's theorem [4] gives a possibility to define a model for calculating induced current in the cases when plates are connected with a real conductor, which has resistivity and inductivity. According to the Norton's theorem, generating current through an impedance Z from an unknown source can be presented by Norton source that is connected in parallel to impedance Z. The Norton source consists of an ideal current source and its internal impedance [4]. For defining the current of the ideal source (i_g) and its internal impedance (Z_g), we will make the next experiment.

Suppose that plates are connected with impedance Z and the whole area of the plates (S) are exposed to the uniform electric field whose intensity changes in accordance with sine function ($E = E_m \sin\omega t$) and whose lines are perpendicular to the plates. Therefore, changes of flux through plates can be expressed by:

$$\Phi = SE_m \sin \omega t.$$

If we bridged the impedance Z with a perfect conductor, the total current of the ideal source (i_g) will pass through this conductor. In the case when the plates are connected with the perfect conductor induced current in him calculated according to the above-given principle $i_g = d\Phi/dt$. After calculations current of the ideal source is:

$$i_g = \varepsilon_0 \omega S E_m \cos \omega t.$$

If we remove the impedance Z between plates, they become thin parallel metal plates in the uniform electric field. The voltage between the plates can be calculated as the voltage between two equipotential surfaces in a uniform electric field [5]. So, that voltage is proportional to the intensity of field and distance (r) between them:

$$u = rE_m \sin \omega t.$$

In this case whole current i_g flows through the internal impedance of the Norton's source(Z_g). This impedance could be calculated in accordance to Norton's theorem [4] by dividing the amplitude of voltage ($U_m = rE_m$) and amplitude of current of the ideal source ($I_m = \varepsilon_0 \omega E_m S$) and it is:

$$Z_g = \frac{r}{\omega \varepsilon_0 S}.$$

As we know [6] capacitance two plates determine known expression: ($C = \varepsilon_0 S/r$), therefore we can say that the internal impedance of Norton's source is capacitance, determined by the capacitance between the plates:

$$Z_g = \frac{1}{\omega C}.$$

With known electric current and the internal impedance of the Norton's source, in Figure 5 is drawn a scheme of the equivalent electrical circuit for induction in the case when the plates are connected with impedance Z.

This scheme defines the relationship between the area of plates, space between plates, induced current and impedance of the load. This is a model that allows calculating of physical and electrical parameters of devices on the principle of induction in electric field. As is obvious from this scheme, for good exploiting of induced currents, the impedance of the load must be smaller than the capacitive impedance of the plates.

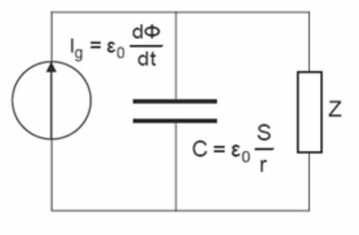


Figure 5: The scheme of equivalent circuit

There is an apparent similarity of here defined principle and the known Faraday's law induction in the magnetic field. According to Faraday's law [3], changes of the flux of the magnetic field in a conductive loop will induce electromotive force, which is proportional to the rate of flux change through the area of the loop. Thus, according to both principles, induced currents are proportional to the rate of change of flux. The similarity suggests that in an electric field is possible to utilize the same methods that are used for the application of Faraday's law. One example is a generator of alternating current, which works on the same principle of electromagnetic generators [7]. Figure 6 presents a model of a generator whose rotor consists of two plates that are mounted to the non-conductive shaft. The plates are exposed to electrostatic or invariable electric field. In our experiment as the source of the electrostatic field we have used the polyvinyl plate charged by friction with piece of textiles. As a source of electric field it is also possible to use two metal plates connected on the DC source. A load resistor is connected between the plates through two sliding ring contacts. By rotating the shaft with angular velocity ω, flux through the plates will change according to the function $\varphi = \Phi_m \cos\omega t$. According to the here presented principle, these changes of flux generates sinusoidal shape current in the load resistor. If we suppose that impedance of the plates is much bigger from load resistance, current in the load could be expressed by the equation $i = \varepsilon_0\ \omega\ \Phi_m \sin\omega t$.

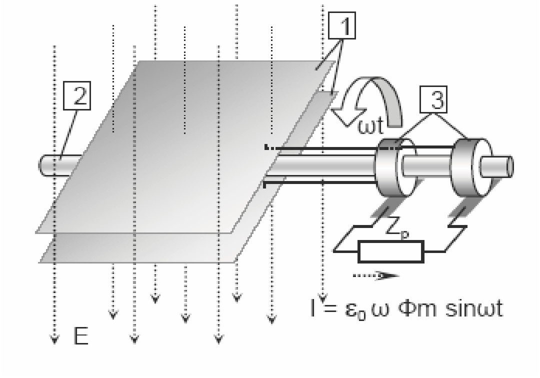


Figure 6: The model of the alternating current generator.

Legend: 1- metal plates; 2-non-conductive shaft; 3 - sliding ring contacts.

Electrodynamic induction in the electric field could be used in the same way as induction in the magnetic field. But there are some limitations. The induced current is so small because of the small value of ε_0 ($8{,}85 \cdot 10^{-12}$). Because of that, generators on this principle generate small current, even in the strong electric field. Here we proved this principle in the environment with permittivity of vacuum (ε_0). We didn’t consider this principle in environments with other permittivity values. Another limitation in the applicability of this principle is the condition that changes of the flux through both plates are equal. So, the plates must be thin and at a small distance. On the other hand, the fact that induced current is proportional to the rate of change of flux gives the possibility of inducing of electric current even if the values of field intensity are very small. Therefore, the principle of induction could be used for the detection of the electrostatic and electromagnetic field, just as Faraday’s law is used for the magnetic field.

5. Conclusion

In this paper is shown principle of electrodynamic induction in the electric field on the specific metal shape. That principle can be applied in the variable and invariable electric field, as well as in an electrostatic field, regardless of the method for generating changes of flux. It is also presented a mathematical model and equivalent scheme that allows calculating the electrical circuits in accordance with this principle. The model defines the relationship between changes of the flux of electric field, area of plates, the distance between them and induced currents. Electrodynamic induction in the electric field could be used in the same way as electrodynamic induction in the magnetic field. There is an obvious apparent similarity between this principle and Faraday’s law of induction in a magnetic field. A characteristic example of the application of this principle is a generator of alternating currents, which is similar to the well-known electromagnetic generator.

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