**Khmelnik S.I.**

# The Electromagnetic Wave in a Charged Capacitor

## Abstract

The electromagnetic wave is shown to propagate in a charged capacitor with the mathematical description of this wave being a solution to the Maxwell equations. It is demonstrated that there is a stationary flow of electromagnetic energy in the charged capacitor, and the energy accumulated in the capacitor which is known as the potential electric energy, is the electromagnetic energy stored in the capacitor in the form of stationary flow.

## Contents



## 1. Introduction

The electromagnetic field of a capacitor in an alternative current circuit is investigated in [1]. In this paper, the electromagnetic field in a capacitor being charged as well as the field existing in the charged capacitor are examined.

We also use the Maxwell equations in the GHS system of unit written in the following form with $\varepsilon,\ \mu$ differing from 1:

$$\mathrm{rot}(E)+\frac{\mu}{c}\frac{\partial H}{\partial t}=0, \tag{1}$$

$$\mathrm{rot}(H)-\frac{\varepsilon}{c}\frac{\partial E}{\partial t}=0, \tag{2}$$

$$\mathrm{div}(E)=0, \tag{3}$$

$$\mathrm{div}(H)=0, \tag{4}$$

where

$H,\ E$ are the current, the magnetic field strength, and the electric field strength, respectively;

$\varepsilon,\ \mu$ are the dielectric permeability and the magnetic permeability, respectively.

## 2. System of Equation Solution

As in [1], let us consider a solution to the Maxwell equations (1.1-1.4). In the cylindrical coordinate system $r,\ \varphi,\ z$ these equations take the form:

$$\frac{E_r}{r}+\frac{\partial E_r}{\partial r}+\frac{1}{r}\cdot\frac{\partial E_\varphi}{\partial \varphi}+\frac{\partial E_z}{\partial z}=0, \tag{1}$$

$$\frac{1}{r}\cdot\frac{\partial E_z}{\partial \varphi}-\frac{\partial E_\varphi}{\partial z}=v\frac{dH_r}{dt}, \tag{2}$$

$$\frac{\partial E_r}{\partial z}-\frac{\partial E_z}{\partial r}=v\frac{dH_\varphi}{dt}, \tag{3}$$

$$\frac{E_\varphi}{r}+\frac{\partial E_\varphi}{\partial r}-\frac{1}{r}\cdot\frac{\partial E_r}{\partial \varphi}=v\frac{dH_z}{dt}, \tag{4}$$

$$\frac{H_r}{r}+\frac{\partial H_r}{\partial r}+\frac{1}{r}\cdot\frac{\partial H_\varphi}{\partial \varphi}+\frac{\partial H_z}{\partial z}=0, \tag{5}$$

$$\frac{1}{r}\cdot\frac{\partial H_z}{\partial \varphi}-\frac{\partial H_\varphi}{\partial z}=q\frac{dE_r}{dt} \tag{6}$$

$$\frac{\partial H_r}{\partial z}-\frac{\partial H_z}{\partial r}=q\frac{dE_\varphi}{dt}, \tag{7}$$

$$\frac{H_\varphi}{r}+\frac{\partial H_\varphi}{\partial r}-\frac{1}{r}\cdot\frac{\partial H_r}{\partial \varphi}=q\frac{dE_z}{dt} \tag{8}$$

where

$$v=-\mu/c, \tag{9}$$

$$q=\varepsilon/c, \tag{10}$$

- $E_r,\ E_\varphi,\ E_z$ are the electric intensities;
- $H_r,\ H_\varphi,\ H_z$ are the magnetic intensities.

For brevity, the following abbreviated forms will be used below:

$$co=\cos(\alpha\varphi+\chi z), \tag{11}$$

$$si=\sin(\alpha\varphi+\chi z), \tag{12}$$

where $\alpha,\ \chi$ are constants. Let us write the unknown functions in the following form:

$$H_r.=h_r(r)co\cdot(\exp(\omega t)-1),\tag{13}$$
$$H_\varphi.=h_\varphi(r)si\cdot(\exp(\omega t)-1),\tag{14}$$
$$H_z.=h_z(r)si\cdot(\exp(\omega t)-1),\tag{15}$$
$$E_r.=e_r(r)si\cdot(1-\exp(\omega t)),\tag{16}$$
$$E_\varphi.=e_\varphi(r)co\cdot(1-\exp(\omega t)),\tag{17}$$
$$E_z.=e_z(r)co\cdot(1-\exp(\omega t)),\tag{18}$$

Here, the bias current is

$$J_z=\frac{d}{dt}E_z=-\omega\cdot e_z(r)co\cdot\exp(\omega t)\tag{19}$$

Fig. 1 shows these variables as a function of time and their time derivatives for $\omega=-300$: $H_z$ is shown with solid lines, $E_z$ with dashed lines, and $J_z$ with a dotted line. This provides good evidence that in the system of equations (1-8) the amplitudes of all strength components simultaneously approach a constant value and the current amplitude tends to zero with $t\Rightarrow\infty$. These conditions correspond to the capacitor charging via a fixed resistor.

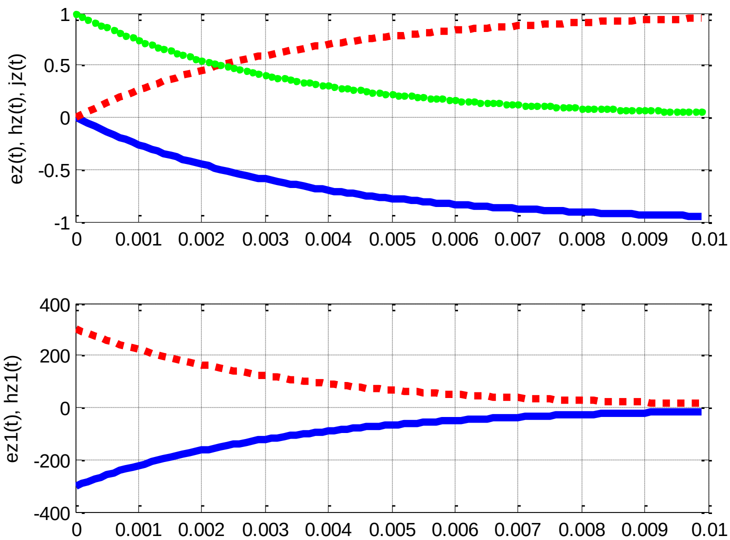

Fig.1. (SSMB6.1)

After the capacitor becomes charged, the current stops to flow. However, as shown below, the stationary flow of electromagnetic energy persists.

Direct substitution of functions (13-18) makes it possible to transform the system of equations (1-8) with four arguments $r$, $\varphi$, $z$, $t$

into a system of equations with one argument $r$ and unknown functions $h(r),\ e(r)$. This system of equations has the form:

$$\frac{e_r(r)}{r}+e_r'(r)-\frac{e_\varphi(r)}{r}\alpha-\chi\cdot e_z(r)=0\,, \tag{21}$$

$$-\frac{1}{r}\cdot e_z(r)\alpha+e_\varphi(r)\chi-\frac{\mu\omega}{c}h_r=0, \tag{22}$$

$$e_r(r)\chi-e_z'(r)+\frac{\mu\omega}{c}h_\varphi=0, \tag{23}$$

$$\frac{e_\varphi(r)}{r}+e_\varphi'(r)-\frac{e_r(r)}{r}\cdot\alpha+\frac{\mu\omega}{c}h_z=0, \tag{24}$$

$$\frac{h_r(r)}{r}+h_r'(r)+\frac{h_\varphi(r)}{r}\alpha+\chi\cdot h_z(r)=0\,, \tag{25}$$

$$\frac{1}{r}\cdot h_z(r)\alpha-h_\varphi(r)\chi-\frac{\varepsilon\omega}{c}e_r=0, \tag{26}$$

$$-h_r(r)\chi-h_z'(r)+\frac{\varepsilon\omega}{c}e_\varphi=0, \tag{27}$$

$$\frac{h_\varphi(r)}{r}+h_\varphi'(r)+\frac{h_r(r)}{r}\cdot\alpha+\frac{\varepsilon\omega}{c}e_z(r)=0\,. \tag{28}$$

It is identical to the similar system of equations for a capacitor in an alternative current circuit [1]. The solution of this system is also identical to the solution obtained in [1] and has the following form:

$$e_\varphi(r)=\mathrm{kh}(\alpha,\ \chi,\ r), \tag{30}$$

$$e_r(r)=\frac{1}{\alpha}\left(e_\varphi(r)+r\cdot e_\varphi'(r)\right), \tag{31}$$

$$e_z(r)=r\cdot e_\varphi(r)\frac{q}{\alpha}, \tag{32}$$

$$h_\varphi(r)=-\frac{\varepsilon\omega}{c}e_r(r)\frac{1}{\chi}, \tag{33}$$

$$h_r(r)=\frac{\varepsilon\omega}{c}e_\varphi(r)\frac{1}{\chi}, \tag{34}$$

$$h_z(r)\equiv 0\,. \tag{35}$$

where $\mathrm{kh}()$ is the function determined in [1],

$$q=\left(\chi-\frac{\mu\varepsilon\omega^2}{c^2\chi}\right). \tag{36}$$

Thus, the solution of the Maxwell equations for a capacitor being charged and for a capacitor in a sinusoidal current circuit differs only in that the former includes exponential functions of time and the latter contains sinusoidal time-functions.

## 3. Field Intensities and Energy Flows

As in [1], the density of energy flows along the coordinates can be determined by the formula:

$$\overline{S} = \begin{bmatrix} \overline{S_r} \\ \overline{S_\varphi} \\ \overline{S_z} \end{bmatrix} = \eta \iint_{r,\varphi} \begin{bmatrix} s_r \cdot si^2 \\ s_\varphi \cdot si \cdot co \\ s_z \cdot si \cdot co \end{bmatrix} dr \cdot d\varphi . \quad (1)$$

where

$$\begin{aligned} s_r &= \left(e_\varphi h_z - e_z h_\varphi\right) \\ s_\varphi &= \left(e_z h_r - e_r h_z\right), \\ s_z &= \left(e_r h_\varphi - e_\varphi h_r\right) \end{aligned} \quad (2)$$

$$\eta = c/4\pi . \quad (3)$$

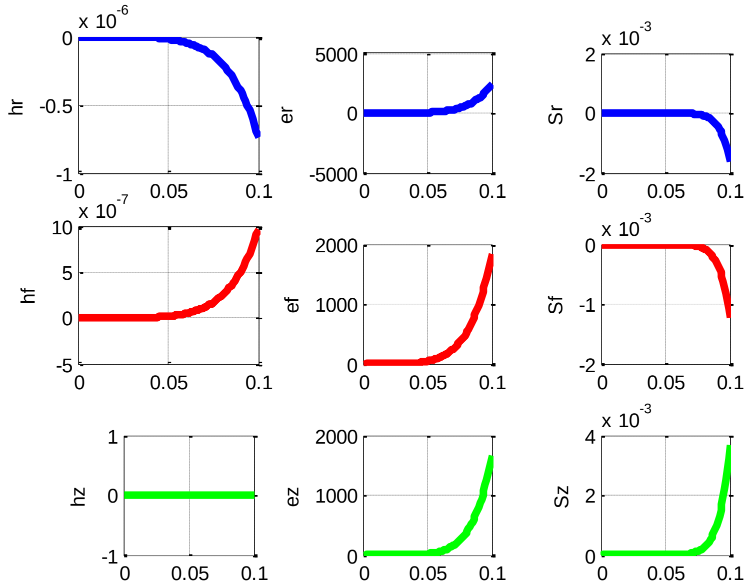

Fig.1. (SSB6(3).m)

Let us consider functions (2) and $e_r(r),\ e_\varphi(r),\ e_z(r)$, $h_r(r),\ h_\varphi(r),\ h_z(r)$. Fig. 2 shows, for example, these functions plotted for $A=1,\ \alpha=5.5,\ \mu=1,\ \varepsilon=2,\ \chi=50,\ \omega=300$. The conditions of this example differ from conditions of a similar example in [1] for a capacitor in an alternative current circuit only in the value of parameter ω which is equal to $\omega = -300$ in this paper (and $\omega = 300$ in [1]). It is evident that these functions differ only in sign.

It must be emphasized once again that these functions are not zero at any time moment, i.e. after the capacitor becomes charged the bias current stops to flow, the electric and the magnetic field components are retained and take a stationary non-zero value.

The stationary electromagnetic energy flow is also retained. Its existence does not contradict our physical understanding [2]. The presence of this flow in a static system was studied by Feynman [3]. He provides an example of an energy flow in a system consisting of an electric charge and a permanent magnet which are fixed and closely spaced.

Fig. 2.

Fig. 3.

Other experiments [4] demonstrating this effect are also available. Fig. 2 shows an electromagnet which retains its attractive force after the current is switched off. Edward Leedskalnin is assumed to use such electromagnets in constructing the famous Coral Castle, see Fig. 3 [4]. In these electromagnets (or solenoids), the electromagnetic energy in not zero at the instant the current is switched off. This energy can be dissipated by radiation and heat loss. However, if these factors are not significant (at least at the initial phase), the electromagnetic energy must be conserved. With electromagnetic oscillations, the electromagnetic energy flow must be induced and propagate WITHIN the solenoid structure. This flow can be interrupted by destructing the structure. In this case, according to the energy conservation law, the work should be done equal to the electromagnetic energy which dissipates on destruction of the solenoid structure. This means that a "destructor" should overcome a force. It is this fact that is demonstrated in the abovespecified experiments. Mathematical models of similar solenoid structures based on the Maxwell equations are examined in [5]. The conditions are identified which are to be met to maintain the electromagnetic energy flow for an unlimited time period.

Thus, a stationary electromagnetic energy flow is formed in a capacitor. Let us consider the structure of this flow in more details. From (2.11, 2.12, 3.1) it follows that at each point in the dielectric the components of energy flows can be determined using the formula:

$$S = \begin{bmatrix} S_r \\ S_\varphi \\ S_z \end{bmatrix} = \begin{bmatrix} s_r \cdot si^2 \\ s_\varphi \cdot si \cdot co \\ s_z \cdot si \cdot co \end{bmatrix} = \begin{bmatrix} s_r \cdot \sin^2(\alpha\varphi + \chi z) \\ s_\varphi \cdot 0.5\sin(2(\alpha\varphi + \chi z)) \\ s_z \cdot 0.5\sin(2(\alpha\varphi + \chi z)) \end{bmatrix}. \tag{4}$$

where, as it follows from (2.30-2.35, 3.2),

$$s_r = \left(-e_z h_\varphi\right) = \frac{q}{\alpha}\frac{\varepsilon\omega}{\chi c} r \cdot e_\varphi(r) \cdot e_r(r)$$

$$s_\varphi = \left(e_z h_r\right) = \frac{q}{\alpha}\frac{\varepsilon\omega}{\chi c} r \cdot e_\varphi^2(r) \tag{5}$$

$$s_z = \left(e_r h_\varphi - e_\varphi h_r\right) = -\frac{\varepsilon\omega}{\chi c}\left(e_r^2(r) + e_\varphi^2(r)\right)$$

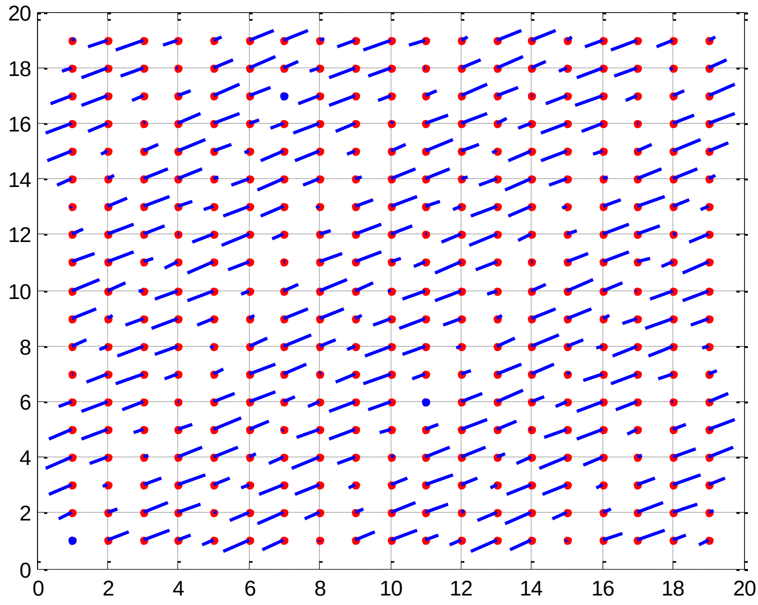
Fig.4. (SSMB.88)

For example, let us consider a development of a cylinder with a given radius $r$. At the circle of this radius vector S always points in the direction of a radius increase and oscillates in value as $\sin^2(\alpha\varphi + \chi z)$. The total vector $\left(\vec{S}_\varphi + \vec{S}_z\right)$ is always at an angle of $\mathrm{arctg}\left(s_z / s_\varphi\right)$ to the radius line and its value oscillated as $\sin\left(2(\alpha\varphi + \chi z)\right)$. Fig. 4 shows the vector field $\left(\vec{S}_\varphi + \vec{S}_z\right)$ for $\alpha = 1.35,\ \chi = 50$. Here, the horizontal line and the vertical line correspond to coordinates $\varphi,\ z$

## 4. Discussion

It is demonstrated that an electromagnetic wave propagates through a capacitor as it is being charged, and the mathematical description of this wave is a solution of the Maxwell equations. In this case, in the dielectric body (i.e. where the field intensities $e_z$ does exist) the electric and the magnetic field intensities components exist. There are also present:

- the circumferential energy flow $S_\varphi$ of variable sign;
- the vertical energy flow $S_z$, of variable sign;
- the radial energy flow $S_r$, always directed from the center. This means that the charged capacitor radiates via the side surface.

The energy flow still persists in the charged capacitor as a stationary electromagnetic energy flow. It is this flow where the electromagnetic energy stored in the capacitor circulates. Hence, the energy which is contained in the capacitor and which is considered to be the electrical potential energy, is the electromagnetic energy stored in the capacitor in the form of the stationary flow.

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