UDC 621.3

ELECTROMAGNETIC FIELD ENERGY FLUX IN TRANSFORMER

D. Špaldonová
Technical University of Košice
Park Komenského, 3, 04200, Košice, Slovak Republic. E-mail: darina.spaldonova@tuke.sk

This paper deals with the electromagnetic field energy flux in the basic electric components and engines by the means of Maxwell's theory of the electromagnetic field. The ideas of this process are often incorrect because basic electric components and engines is uncommon studied and it paid only minimal attention. However, the knowledge of this process is very important for precisely understanding of its operation. The shell transformer, as one of the often used electric engine, was selected to illustrate the application of this theory on the computing the electromagnetic field energy flux. At the first, electric intensity $\mathbf{E}(t)$ and magnetic intensity $\mathbf{H}(t)$ of the electromagnetic field in the transformer core and in its winding was expressed. At the second, the density of the transmitted electromagnetic field energy per unit time i.e. the density of power, known as Poynting's vector, was calculated for the transformer winding as well as its core. Next, the transmitted electromagnetic field energy per unit time, i.e. the transmitted power was calculated for once again for the transformer core and for its winding too. So in this work was demonstrated how the energy spread actually in one of the electric engine – in the transformer.

Keywords: Theory of electrical engineering, Theory of electromagnetic field, Electromagnetic field energy, Electromagnetic field energy flux in the basic electric components, Electromagnetic field energy flux.

ДОСЛІДЖЕННЯ ПОТОКУ ЕЛЕКТРОМАГНІТНОЇ ЕНЕРГІЇ У ТРАНСФОРМАТОРАХ

Д. Спалдонова
Технічний університет Кошице
вул. Парк Коменского, 3, м. Кошице, 04200, Словаччина. E-mail: darina.spaldonova@tuke.sk

Розглянуто питання дослідження потоку енергії в електромагнітному полі на основі аналізу елементарних електричних компонентів та електромагнітних перетворювачів на базі електромагнітної теорії Максвела. Оскільки вивченню принципів роботи базових електричних компонентів та електричних перетворювачів приділяється недостатньо уваги, то й при аналізі процесу перетворення потоку енергії в електромагнітному полі часто допускаються помилки. Однак знання цього процесу є досить важливим для точного розуміння роботи електричних перетворювачів енергії. Для ілюстрації можливостей застосування даної теорії для розрахунку потоку електромагнітної енергії було обрано броньовий трансформатор як один із найчастіше використовуваних електромагнітних перетворювачів. По-перше, було отримано вирази для опису напруженості електричного поля $\mathbf{E}(t)$ та напруженості магнітного поля $\mathbf{H}(t)$ осердя трансформатора та його обмоток. По-друге, було розраховано щільність переданої електромагнітним полем енергії за одиницю часу, тобто щільність потужності, відому як вектор Пойнтінга, для обмоток і осердя трансформатора. На наступному кроці було повторно розраховано передану електромагнітним полем енергію за одиницю часу, тобто передану потужність, для осердя та обмоток трансформатора. Таким чином, було показано реальне розподілення потоків енергії в одному з типів електричних перетворювачів – трансформаторі.

Ключові слова: теорія електротехніки, теорія електромагнітного поля, енергія електромагнітного поля, потік енергії електромагнітного поля.

INTRODUCTION. The flux of the electromagnetic field energy in the electric circuits, basic electric components and engines is uncommon studied and it paid only minimal attention, so that ideas of this process are often incorrect. However, the knowledge of this process is very important for precisely understanding of its operation.

The best way to describe this process is by the means of Maxwell's theory of the electromagnetic field, because the differential values describe electromagnetic field in each point of space where it exist and not only in the points of electric circuit as integral values do.

The shell transformer, as one of the often used electric engine, was selected to illustrate the application of this theory on the computing the energy flux.

The description of the processes running in the transformer is usually concentrated on the specifying of magnetic flux $\Phi(t)$ enclosing in its ferromagnetic core. The electromagnetic field is understood as constant in the space and changing in the time only. This implies the incorrect idea that the electromagnetic field energy spread from the transformer primary winding through the ferromagnetic core to the secondary winding while energy of the electric field in primary winding transform to the energy of magnetic field in the core and then transform to the energy of the electric field in secondary winding. This idea is wide extended up to this day nevertheless that it has been adverted on the inaccuracy of such an idea several times.

Basic relationships. The base for the expression of electromagnetic field energy flux is the integral form of the first two of Maxwell's equations. The first of them is Faraday law

$$\oint_{l_E} \mathbf{E}(t).\mathrm{d}\mathbf{l}_E = u_{\mathrm{i}}(t), \qquad (1)$$

where $u_{\mathrm{i}}(t)$ is the induced voltage, which is

$$u_i(t) = -\int_S \frac{\partial \mathbf{B}(t)}{\partial t}.\mathrm{d}\mathbf{S} = -\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t} \qquad (2)$$

and the second one is Ampere law

$$\oint_{l_H} \mathbf{H}(t).\mathrm{d}\mathbf{l}_H = i_C(t), \qquad (3)$$

where

$$i_C(t) = i_v(t) + i_p(t) \qquad (4)$$

and there $i_v(t)$ is the conduction current, which is expressed as

$$i_v(t) = \int_S \mathbf{J}(t).\mathrm{d}\mathbf{S}; \qquad (5)$$

$i_p(t)$ is the displacement current, which is expressed as

$$i_p(t) = \int_S \frac{\partial \mathbf{D}(t)}{\partial t}.\mathrm{d}\mathbf{S}.$$

The density of the transmitted electromagnetic field energy per unit time i.e. the density of power is defined by Poynting's vector as

$$\mathbf{N}(t) = \mathbf{E}(t) \times \mathbf{H}(t) \qquad (6)$$

and the transmitted electromagnetic field energy per unit time, i.e. the transmitted power is

$$P(t) = \oint_S \mathbf{N}(t).\mathrm{d}\mathbf{S} = \oint_S [\mathbf{E}(t) \times \mathbf{H}(t)].\mathrm{d}\mathbf{S}. \qquad (7)$$

So we need to know both the electric intensity $\mathbf{E}(t)$ and the magnetic intensity $\mathbf{H}(t)$ to be able to calculate process of electromagnetic field energy flux.

Shell transformer. The shell transformer is one of the often used electric engines, so it was selected to illustrate the application of Maxwell's theory of electromagnetic field to compute its electromagnetic field energy flux.

Let us consider a shell transformer in the idle state (Fig. 1) whose primary winding radius is R_0, its height is l_0, its winding thickness is δ and it is negligible in comparison to other sizes of the primary winding. The transformer core is made from the ferromagnetic material whose permeability is μ and cross section of its middle column is S_0. The primary winding is connected to the voltage $u(t)$.

We will examine the electromagnetic field energy flux in both basic parts of the transformer – in its winding and in its ferromagnetic core.

Denote:

– the points of the outer primary winding surface as A_1 and the points on its inner surface as A_2;

– the points of the core outer surface as B (Fig. 2).

Electromagnetic field in the transformer is best described in the cylindrical coordinate system [r, α, z] illustrated on the Fig. 2.

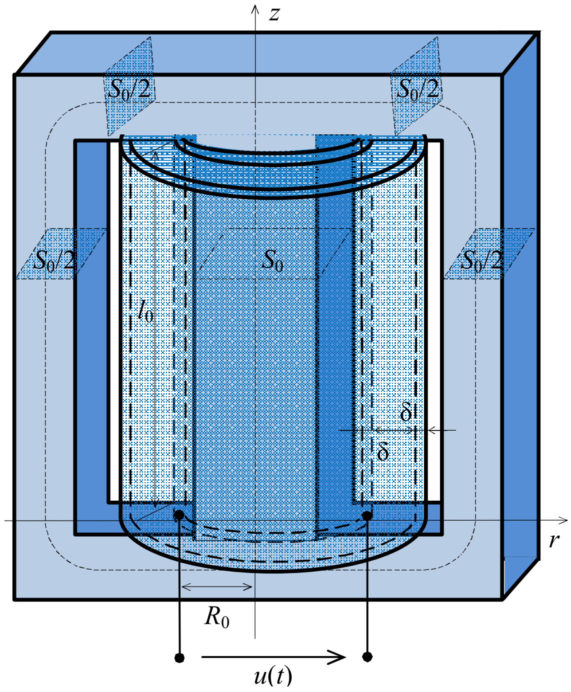

Figure 1 – Shell transformer

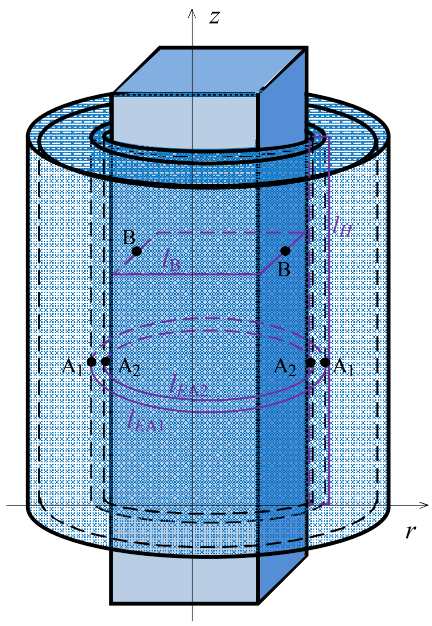

Figure 2 – Points of transformer winding surfaces and core surface

Transformer winding. The electric intensity E(t) in the transformer primary winding may be determined by the means of Faraday law. Under this law

– the voltage inducted in one of the primary winding turns is

$$u_i(t) = \oint_{l_E} \mathbf{E}(t).\mathrm{d}\mathbf{l}_E; \qquad (8)$$

– the total voltage inducted in all N turns of the primary winding is

$$u_{\text{ic}}(t) = N\oint_{l_E} \mathbf{E}(t).\mathbf{dl}_E = -u(t)\,. \qquad (9)$$

If the primary winding resistivity as well as its thickness δ be neglected, then the electric intensity $E_{A1}(t)$ in the points A_1 of the outer primary winding surface and electric intensity $E_{A2}(t)$ in the points A_2 of the inner primary winding surface (Fig. 2) will be the same:

$$E_{A1}(t) = E_{A2}(t) = E(t)$$

and the length of one winding turn l_{E1} for the points A_1 of the outer primary winding surface and l_{E2} for the points A_2 of the inner primary winding surface (Fig. 2) will be the same too:

$$l_{E1} = l_{E2} = l_E = 2\pi R_0.$$

Each of the primary winding turn is an electrical line of force, so that electric intensity $E(t)$ is tangent to the l_E and have a constant size $E(t)$ at any point of l_E.

Then it will be

$$u_{\text{i}}(t) = -N\oint_{l_E} \mathbf{E}(t).\mathbf{dl}_E = -N\oint_{l_E} E(t)\text{d}l_E = -NE(t)\oint_{l_E} \text{d}l_E = = -NE(t)l_E = -NE(t)2\pi R_0\,,$$

so we get

$$E(t) = \frac{-u(t)}{N2\pi R_0} \quad \text{and} \quad \mathbf{E}(t) = \frac{-u(t)}{N2\pi R_0}\boldsymbol{\alpha}_0\,. \qquad (11)$$

The magnetic intensity $H(t)$ in the transformer primary winding may be determined by the Ampere law, i.e.

$$\oint_{l_H} \mathbf{H}(t).\mathbf{dl}_H = i_{\text{v}}(t) = Ni(t)\,.$$

Elected closed integration curve l_H closely surrounds winding turns and its area is vertical to the winding turns area (Fig. 2). If the primary winding thickness δ is neglected, then the length of the curve l_H will be

$$l_H = 2l_0.$$

The magnetic intensity $H(t)$ is tangent to the l_H at any point too, but its size is $H_{A1}(t)$ in the points A_1 of outer surface and $H_{A2}(t)$ in the points A_2 of inner surface of the primary winding and they are

$$H_{A1}(t) = \mu_0 B(t) \quad \text{and} \quad H_{A2}(t) = \mu_0\mu_r B(t)\,,$$

so we have

$$H_{A1}(t) = \mu_r H_{A2}(t).$$

Then

$$\oint_{l_H} \mathbf{H}(t).\mathbf{dl}_H = \int_{l_0} \mathbf{H}_{A1}(t).\mathbf{dl}_H + \int_{l_0} \mathbf{H}_{A2}(t).\mathbf{dl}_H =$$

$$= \int_{l_0} H_{A1}(t)\text{d}l_H + \int_{l_0} H_{A2}(t)\text{d}l_H = H_{A1}(t)l_0 + H_{A2}(t)l_0 =$$

$$= \left(\mu_r H_{A2}(t) + H_{A2}(t)\right)l_0 = (\mu_r + 1)H_{A2}(t)l_0,$$

so we get

$$(\mu_r + 1)H_{A2}(t)l_0 = Ni(t)\,,$$

and then

$$H_{A2}(t) = \frac{Ni(t)}{(\mu_r + 1)l_0} \quad \text{and} \quad H_{A1}(t) = \frac{\mu_r Ni(t)}{(\mu_r + 1)l_0}\,;$$

$$\mathbf{H}_{A2}(t) = \frac{Ni(t)}{(\mu_r + 1)l_0}\mathbf{k}\,; \qquad (12)$$

$$\mathbf{H}_{A1}(t) = \frac{\mu_r Ni(t)}{(\mu_r + 1)l_0}(-\mathbf{k})\,. \qquad (13)$$

Subsequently the density of the transmitted electromagnetic field energy per unit time i.e. the density of transmitted power consists of two parts:

$$\mathbf{N}_{A1}(t) = \mathbf{E}(t)\times\mathbf{H}_{A1}(t) = \frac{-u(t)}{N2\pi R_0}\boldsymbol{\alpha}_0 \times \frac{\mu_r Ni(t)}{(\mu_r + 1)l_0}(-\mathbf{k}) = = \frac{\mu_r}{(\mu_r + 1)}\frac{u(t)i(t)}{2\pi R_0 l_0}\mathbf{r}_0\,; \qquad (14)$$

$$\mathbf{N}_{A2}(t) = \mathbf{E}(t)\times\mathbf{H}_{A1}(t) = \frac{-u(t)}{N2\pi R_0}\boldsymbol{\alpha}_0 \times \frac{Ni(t)}{(\mu_r + 1)l_0}\mathbf{k} = = \frac{1}{(\mu_r + 1)}\frac{u(t)i(t)}{2\pi R_0 l_0}(-\mathbf{r}_0). \qquad (15)$$

Therefore it is obvious then the transmitted electromagnetic field energy coming out through the lateral primary winding surfaces $2\pi R_0 l_0$ perpendicular to these surfaces. Energy density transmitted through the outer primary winding surface $N_{A1}(t)$ is directed to the secondary winding (Fig. 3) and energy density transmitted through the inner primary winding surface $N_{A2}(t)$ is directed to the transformer core (Fig. 4). It is important to remember that the energy density $N_{A1}(t)$ directed to the secondary winding is μ_r times greater than the energy density $N_{A2}(t)$ directed to the core.

The transmitted electromagnetic field energy per unit time, i.e. the transmitted power is

$$P(t) = \oint_S \mathbf{N}(t).\text{d}\mathbf{S}.$$

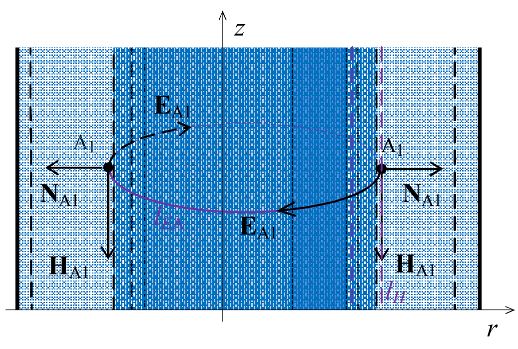

Figure 3 – Energy density $\mathbf{N}_{A1}$

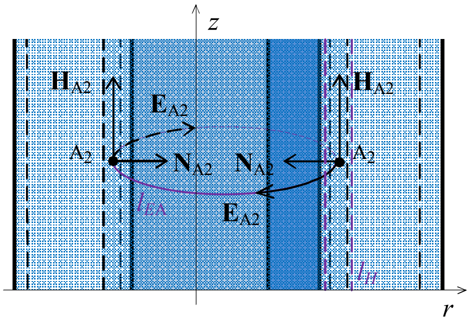

Figure 4 – Energy density $\mathbf{N}_{A2}$

We select the area of cylinder S as the closed integration surface which its bases area is S_1, S_2 and its shell area is S_3.

This area closely surround the outer surface of primary winding for the vector $\mathbf{N}_{A1}(t)$ (Fig. 5) and the inner surface of primary winding for the vector $\mathbf{N}_{A2}(t)$

(Fig. 6).

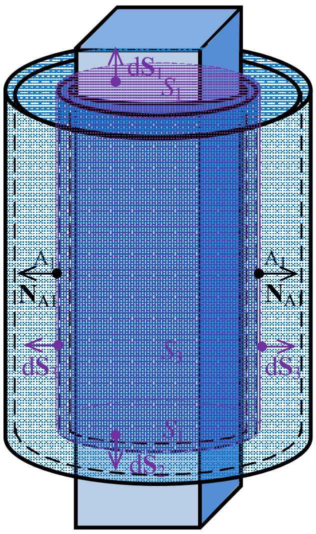

Figure 5 – Integration area for the vector $\mathbf{N}_{A1}$

For the first part of the transmitted electromagnetic field energy per unit time we get

$$P_{A1}(t)=\oint_S \mathbf{N}_{A1}(t).\mathrm{d}\mathbf{S}=$$
$$=\int_{S_1}\mathbf{N}_{A1}(t).\mathrm{d}\mathbf{S}_1+\int_{S_2}\mathbf{N}_{A1}(t).\mathrm{d}\mathbf{S}_2+\int_{S_3}\mathbf{N}_{A1}(t).\mathrm{d}\mathbf{S}_3=$$
$$=\int_{S_3}\mathbf{N}_{A1}(t).\mathrm{d}\mathbf{S}_3=\int_{S_3}N_{A1}(t)\mathbf{r}_0.\mathrm{d}S_3\mathbf{r}_0=\int_{S_3}N_{A1}(t)\mathrm{d}S_3= \quad (16)$$
$$=\int_{S_3}\frac{u(t)i(t)}{S_3}\frac{\mu_r}{(\mu_r+1)}\mathrm{d}S_3=\frac{\mu_r}{(\mu_r+1)}u(t)i(t)$$

and for the second part of the transmitted electromagnetic field energy per unit time we have

$$P_{A2}(t)=\oint_S \mathbf{N}_{A2}(t).\mathrm{d}\mathbf{S}=$$
$$=\int_{S_1}\mathbf{N}_{A2}(t).\mathrm{d}\mathbf{S}_1+\int_{S_2}\mathbf{N}_{A2}(t).\mathrm{d}\mathbf{S}_2+\int_{S_3}\mathbf{N}_{A2}(t).\mathrm{d}\mathbf{S}_3=$$
$$=\int_{S_3}\mathbf{N}_{A2}(t).\mathrm{d}\mathbf{S}_3=\int_{S_3}N_{A2}(t)(-\mathbf{r}_0).\mathrm{d}S_3\mathbf{r}_0=-\int_{S_3}N_{A2}(t) \quad (17)$$
$$=-\int_{S_3}\frac{1}{\mu_r+1}\frac{u(t)i(t)}{S_3}\mathrm{d}S_3=-\frac{1}{\mu_r+1}u(t)i(t)\,.$$

The sign (−) implies that energy is transmitted into the volume V of integration surface S.

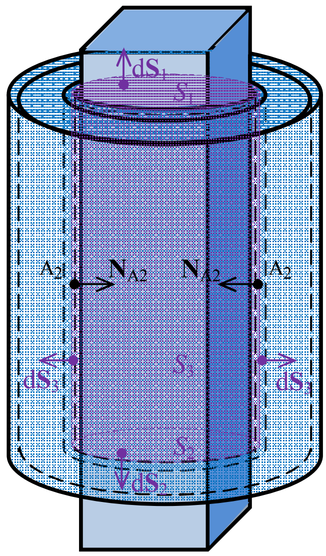

Figure 6 – Integration area for the vector $\mathbf{N}_{A2}$

Therefore the energy supplied to the primary winding per time unit coming out through the lateral primary winding surfaces S_3 perpendicular to these surfaces. The size of the energy $P_{A1}(t)$, which get to the space between the primary and secondary transformer winding per time unit is $\mu_r/(\mu_r + 1)$-part of the energy supplied to the primary winding per time unit and size of the energy $P_{A2}(t)$, which get to the space of the transformer core is $1/(\mu_r + 1)$ – part of the energy supplied to the primary winding per time unit.

Transformer core. Let us identify the points B of the transformer core surface with the points A_2 of the inner surface of the transformer primary winding. Then the electric intensity $E_B(t)$ in the points B of transformer core surface and the electric intensity $E_{A2}(t)$ in the points of the transformer primary winding inner surface will be the same (Fig. 7):

$$E_B(t)=E_{A2}(t)=E(t)=\frac{-u(t)}{N2\pi R_0}\,; \quad (18)$$

$$\mathbf{E}_B(t)=\frac{-u(t)}{N2\pi R_0}\boldsymbol{\alpha}_0 \quad (19)$$

and the magnetic intensity $H_B(t)$ in the points B of transformer core surface will be the same as the magnetic intensity $H_{A2}(t)$ in the points of the transformer primary winding inner surface of the (Fig. 7):

$$H_B(t) = H_{A2}(t) = \frac{Ni(t)}{(\mu_r + 1)l_0}; \qquad (20)$$

$$\mathbf{H}_B(t) = \frac{Ni(t)}{(\mu_r + 1)l_0}\mathbf{k}. \qquad (21)$$

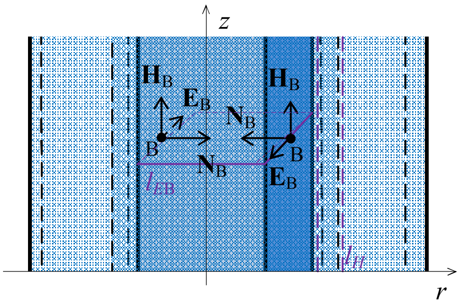

Figure 7 – Energy density N_B

Then the density of the transmitted electromagnetic field energy per unit time i.e. the density of transmitted power $N_B(t)$ and $N_{A2}(t)$ will be the same too:

$$\mathbf{N}_B(t) = \mathbf{N}_{A2}(t) = \frac{1}{(\mu_r + 1)}\frac{u(t)i(t)}{2\pi R_0 l_0}(-\mathbf{r}_0). \qquad (22)$$

The transmitted electromagnetic field energy per unit time, i.e. the transmitted power $P_B(t)$ will be

$$P_B(t) = \oint_S \mathbf{N}_B(t).\mathrm{d}\mathbf{S}.$$

The area of cuboid S was selected as the closed integration area now which its bases area is S_1, S_2 and its shell area is S_3 (Fig. 8). The energy $P_B(t)$ for this elected integration area S will be the same as $P_{A2}(t)$:

$$P_B(t) = \oint_S \mathbf{N}_B(t).\mathrm{d}\mathbf{S} =$$

$$= \int_{S_1} \mathbf{N}_B(t).\mathrm{d}\mathbf{S}_1 + \int_{S_2} \mathbf{N}_B(t).\mathrm{d}\mathbf{S}_2 + \int_{S_3} \mathbf{N}_B(t).\mathrm{d}\mathbf{S}_3 =$$

$$= \int_{S_3} \mathbf{N}_B(t).\mathrm{d}\mathbf{S}_3 = \int_{S_3} N_B(t)(-\mathbf{r}_0).\mathrm{d}S_3\mathbf{r}_0 = -\int_{S_3} N_B(t)\mathrm{d}S_3 =$$

$$= -\int_{S_3} \frac{1}{\mu_r + 1}\frac{u(t)i(t)}{S_3}\mathrm{d}S_3 = -\frac{1}{\mu_r + 1}u(t)i(t),$$

so it really is

$$P_B(t) = P_{A2}(t) = -\frac{1}{\mu_r + 1}u(t)i(t). \qquad (23)$$

This means that size of the energy $P_B(t)$, which get to the transformer core is $1/(\mu_r + 1)$ – part of the energy supplied to the primary winding per time unit.

The magnetic intensity $H(t)$ inside the transformer core is constant and such as that one on its surface $H_B(t)$:

$$H(t) = H_B(t) = \frac{Ni(t)}{(\mu_r + 1)l_0}; \qquad (24)$$

$$\mathbf{H}(t) = \frac{Ni(t)}{(\mu_r + 1)l_0}\mathbf{k}. \qquad (25)$$

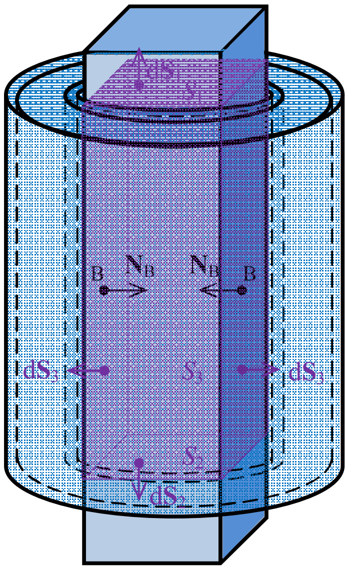

Figure 8 – Integration area for the vector $\mathbf{N}_B$

The magnetic induction $\mathbf{B}(t)$ in the transformer core then will be

$$\mathbf{B}(t) = \mu\,\mathbf{H}(t) = \mu_0\mu_r\,\mathbf{H}(t),$$

the magnetic flux $\Phi(t)$ closed by one of the primary winding turns is

$$\Phi(t) = \int_{S_0} \mathbf{B}(t).\mathrm{d}\mathbf{S}_0 = \int_{S_0} B(t)\mathbf{k}\mathrm{d}S_0\mathbf{k} = \int_{S_0} B(t)\mathrm{d}S_0 =$$
$$= \int_{S_0} \frac{\mu_0\mu_r Ni(t)}{(\mu_r + 1)l_0}\mathrm{d}S_0 = \frac{\mu_0\mu_r}{(\mu_r + 1)}\frac{Ni(t)S_0}{l_0}, \qquad (26)$$

and the whole magnetic flux $\Phi_C(t)$ closed by the all N primary winding turns is

$$\Phi_C(t) = N\Phi(t) = \frac{\mu_0\mu_r}{(\mu_r + 1)}\frac{N^2 i(t)S_0}{l_0}. \qquad (27)$$

This expression is identical with the expression of the whole magnetic flux Φ_C expressed in determining of the coil inductance L in the stationary electromagnetic field:

$$\Phi_C = \frac{\mu_0\mu_r N^2 I S_0}{l_0}, \qquad (28)$$

in which the electromagnetic induction does not exist, so that the whole energy supplied to the primary winding per time unit is transmitted into the coil core and rise the magnetic flux Φ_C.

Therefore it is evident that $1/(\mu_r + 1)$-part of the electromagnetic field energy which get into the transformer core rise the magnetic flux $\Phi_C(t)$.

CONCLUSIONS. The incorrect ideas of the electromagnetic field energy flux in the electric circuits, its basic components and electric engines still appears in the print and electronic media. Mainly it is the idea that the electromagnetic field is constant in the space and changing in the time only. This implies such an incorrect idea as the electromagnetic field energy spread through conductive parts of the electric and magnetic circuits. So in this work was demonstrated how the energy spread actually in one of the electric engine – in the transformer.

The widespread perception is that the electromagnetic field energy spread from the transformer primary winding through the ferromagnetic core to the secondary winding while energy of the electric field in primary winding transform to the energy of magnetic field in the core and then transform to the energy of the electric field in secondary winding. Actually the energy supplied to the primary winding coming out through the lateral primary winding surfaces perpendicular to these surfaces. The size of the energy which get to the space between the primary and secondary transformer winding is $\mu_r/(\mu_r+1)$ – part of the energy supplied to the primary winding and size of the energy which get to the space of the transformer core is only $1/(\mu_r+1)$ – part of the energy supplied to the primary winding per time unit. That part of the electromagnetic field energy which get into the transformer core rise the magnetic flux only.

ACKNOWLEDGEMENT

The paper has been prepared by the support of Slovak grant projects KEGA No. 005TUKE-4/2012, KEGA No. 014TUKE-4/2013.

REFERENCES

1. Haňka, L. (1982), Electromagnetic Field Theory. SNTL/ALFA, Praha, Czech Republic.
2. Myslík, J., Electromagnetic Field. BEN technická literatura, Praha, Czech Republic.
3. Kvasnica, J., (1985), Electromagnetic Field Theory. ACADEMIA, Praha, Czech Republic.
4. Tirpák, A. (1999), Electromagnetics. POLYGRAFIA SAV, Bratislava, Slovakia.
5. Mayer, D. (1981), Electromagnetic Field Theory. Edičné stredisko VŠSB, Plzeň, Czech Republic.
6. Neveselý, M. (1995), Electrical Engineering III/2. VŠDS, Žilina, Slovakia.
7. Špaldonová, D., Neveselý, M. and Šuriansky, J. (1999), Electromagnetic Field Transmission and Transformation in the Electric Engines. VA SNP, Liptovský Mikuláš, Slovenia.
8. Thidé, B. (2004), Field Theory. Upsilon Books, Communa AB, Uppsala.
9. Hayt, W.H. and Buck, J.A. (1982), Engineering Electro-magnetics. McGraw-Hill Series in Electrical and Computer Engineering Haňka, L.: Electromagnetic Field Theory. SNTL/ALFA, Praha, Czech Republic.

ИССЛЕДОВАНИЕ ПОТОКА ЭЛЕКТРОМАГНИТНОЙ ЭНЕРГИИ В ТРАНСФОРМАТОРАХ

Д. Спалдонова
Технический университет Кошице
ул. Парк Коменского, 3, г. Кошице, 04200, Словакия. E-mail: darina.spaldonova@tuke.sk

Рассмотрен вопрос исследования потока энергии в электромагнитном поле на основе анализа элементарных электрических составляющих и электромагнитных преобразователей согласно теории Максвелла. Поскольку изучению принципов работы базовых электрических компонентов и электрических преобразователей уделяется недостаточное внимание, то и при анализе процесса преобразования потока энергии в электромагнитном поле часто допускаются ошибки. Однако знание этого процесса является очень важным для точного понимания работы электрических преобразователей энергии. Для иллюстрации возможностей применения данной теории для задач расчёта потока электромагнитной энергии был выбран броневой трансформатор как один из наиболее часто используемых электромагнитных преобразователей. Во-первых, были получены выражения для описания напряжённости электрического поля $\mathbf{E}(t)$ и напряжённости магнитного поля $\mathbf{H}(t)$ сердечника трансформатора и его обмоток. Во-вторых, была рассчитана плотность переданной электромагнитным полем энергии за единицу времени, т.е. плотность мощности, известная как вектор Пойнтинга, для обмоток и сердечника трансформатора. На следующем этапе была повторно рассчитана переданная электромагнитным полем энергия за единицу времени, т.е. переданная мощность для сердечника и обмоток трансформатора. Таким образом, в данной работе было показано реальное распределение потоков энергии в одном из типов электрических преобразователей – трансформаторе.

Ключевые слова: теория электротехники, теория электромагнитного поля, энергия электромагнитного поля, поток энергии электромагнитного поля.

Стаття надійшла 14.04.2013.