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EMC OF POWER ELECTROTECHNICAL SYSTEMS – ELECTROMAGNETIC COUPLING (PART I.)

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Abstract: *The paper deals with the general analysis of one part of the electromagnetic compatibility (EMC) problem - the electromagnetic coupling applied in the field of power electrical systems. Theoretical analysis of above mentioned problem, based on the impact investigation of the electromagnetic wave propagation, is described in part I. Obtained results can be used for predictive stating of EMC quality of individual new electrotechnical products.*

Key words: *Electrical electromagnetic compatibility, Electromagnetic coupling, Electrical systems, Electrical drives*

INTRODUCTION

The electromagnetic coupling is typical for galvanically separated electrical circuits, between which exists the exchange of the electromagnetic energy in the form of the radiated and absorbed power.

1 THEORETICAL ANALYSIS

Let the mutual influence of two separated circuits is investigated. We come out from the first two Maxwell's equations in general form, defined by the vector potential. Let it will be supposed, that the energy exchange is done through the air.

$$\overline{E} = -\nabla \varphi - \frac{\partial \overline{A}}{\partial t} \tag{1}$$

$$\overline{B} = \nabla \times \overline{A} \tag{2}$$

The potential φ and magnetic vector potential $\overline{A}$ investigation is leading to the solution of the partial-differential equations of the second order. The volume density of the environ charge is defined by ρ and the current density of conductor surface by $\overline{J}$.

$$\nabla^2 \varphi - \frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0} \tag{3}$$

$$\nabla^2 \overline{A} - \frac{1}{c^2}\frac{\partial^2 \overline{A}}{\partial t^2} = -\frac{\overline{J}}{-\varepsilon_0 c^2} \tag{4}$$

Also next condition must to fulfilled by the searched solution:

$$\nabla . \overline{A} = -\frac{1}{c^2}\frac{\partial \varphi}{\partial t} \tag{5}$$

The relations for potential φ and magnetic vector potential $\overline{A}$ expressed for position 1 in dependence on the source parameters at the point 2 can be obtained by mathematical solving. For solution simplification it will be supposed, that the length $\overline{l}_i$ of conductor element is so small in comparison with the vector length $\overline{r}_{12} = \overline{r}_i$, that the distances of the beginning and finishing points of conductor element of length, measured from the point 1, are the same. Situation is pictured in Figure 1. The direction of current density vector $\overline{J}$ is coincident with the direction of unit conductor vector $\overline{l}^0$.

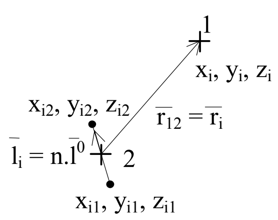

Fig. 1: Investigated point and element of the conductor length

$$\varphi(1,t)=\int\frac{\rho(2,t-\frac{r_{12}}{c})}{4\pi\varepsilon_0 r_{12}}dV_2 \tag{6}$$

$$\overline{A}(1,t)=\int\frac{\overline{J}(2,t-\frac{r_{12}}{c})}{4\pi\varepsilon_0 c^2 r_{12}}dV_2 \tag{7}$$

Let for the purpose of electrotechnical equipment EMC investigation the expression for magnetic vector potential $\overline{A}$ will be related to the elementary radiator represented by the electrical dipole with the dipole moment $\overline{p}$. The variables $\overline{p}'$ and $\overline{p}''$ represent first and second derivation of the dipole moment vector according the time.

$$\overline{p}_i=q\overline{l}_i=\int idt\overline{l}_i \tag{8}$$

$$\overline{p}_i^{'}=\frac{dq}{dt}\overline{l}_i=i\overline{l}_i \tag{9}$$

$$\overline{p}_i^{''}=\frac{di}{dt}\overline{l}_i \tag{10}$$

The optional current course can be expressed by Fourier series as sum of the DC component and k components of individual harmonic functions:

$$\begin{aligned} i &= C_0+\sum_{k=1}^{n\to\infty}C_k\sin(k\omega t+\psi)= \\ &= I_0+\sum_{k=1}^{n\to\infty}I_{mk}\sin(k\omega t+\psi) \end{aligned} \tag{11}$$

Dipole moment and its time derivations then have the forms:

$$\begin{aligned} \overline{p}_i &= (\int I_0 dt)\overline{l}_i+\sum_{k=1}^{n\to\infty}(\int I_{mk}\sin(k\omega t+\psi)dt)\overline{l}_i= \\ &= I_0 t l_i \overline{l}_i^0-\sum_{k=1}^{n\to\infty}\frac{l_i I_{mk}}{k\omega}\cos(k\omega t+\psi)\overline{l}_i^0= \\ &= I_0 t l_i \overline{l}_i^0-\sum_{k=1}^{n\to\infty}p_k\cos(k\omega t+\psi)\overline{l}_i^0 \end{aligned} \tag{12}$$

$$\begin{aligned} \overline{p}_i^{'} &= I_0 l_i \overline{l}_i^0+\sum_{k=1}^{n\to\infty}I_{mk}\sin(k\omega t+\psi)\overline{l}_i=I_0 l_i\overline{l}_i^0+ \\ &+\sum_{k=1}^{n\to\infty}k\omega p_k\sin(k\omega t+\psi)\overline{l}_i^0 \end{aligned} \tag{13}$$

$$\overline{p}_i^{''}=\sum_{k=1}^{n\to\infty}(k\omega)^2 p_k\cos(k\omega t+\psi)\overline{l}_i^0 \tag{14}$$

The next equation describes the magnetic vector potential $\overline{A}_i$ of electric dipole.

$$\overline{A}_i(1,t)=\frac{1}{4\pi\varepsilon_0 c^2}\frac{\overline{p}_i^{'}(t-\frac{r_i}{c})}{r_i} \tag{15}$$

By its substitution into the equation (2) the resulting relation for magnetic intensity vector $\overline{H}_i$ of the electromagnetic field will be obtained. It can be expressed by the components of the 3D Cartesian system,

$$\overline{H}_i=\frac{\overline{B}_i}{\mu}=\frac{\nabla\times\overline{A}_i}{\mu}=\frac{1}{\mu}\begin{vmatrix}\overline{i}^0 & \overline{j}^0 & \overline{k}^0 \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_{ix} & A_{iy} & A_{iz}\end{vmatrix}=$$

$$=\frac{1}{\mu}\left[(\frac{\partial A_{iz}}{\partial y}-\frac{\partial A_{iy}}{\partial z})i+(\frac{\partial A_{ix}}{\partial z}-\frac{\partial A_{iz}}{\partial x})j+(\frac{\partial A_{iy}}{\partial x}-\frac{\partial A_{ix}}{\partial y})k\right] \tag{16}$$

$$\begin{aligned} H_{ix} &= \frac{v^2}{4\pi c^2}\left[-\frac{y_i p_{iz}^{'}(t-\frac{r_i}{c})}{r_i^3}-\frac{y_i p_{iz}^{''}(t-\frac{r_i}{c})}{cr_i^2}+\right. \\ &\left.+\frac{z_i p_{iy}^{'}(t-\frac{r_i}{c})}{r_i^3}+\frac{z_i p_{iy}^{''}(t-\frac{r_i}{c})}{cr_i^2}\right] \end{aligned} \tag{17}$$

$$\begin{aligned} H_{iy} &= \frac{v^2}{4\pi c^2}\left[-\frac{z_i p_{ix}^{'}(t-\frac{r_i}{c})}{r_i^3}-\frac{z_i p_{ix}^{''}(t-\frac{r_i}{c})}{cr_i^2}+\right. \\ &\left.+\frac{x_i p_{iz}^{'}(t-\frac{r_i}{c})}{r_i^3}+\frac{x_i p_{iz}^{''}(t-\frac{r_i}{c})}{cr_i^2}\right] \end{aligned} \tag{18}$$

$$\begin{aligned} H_{iz} &= \frac{v^2}{4\pi . c^2}\left[-\frac{x_i p_{iy}^{'}(t-\frac{r_i}{c})}{r_i^3}-\frac{x_i p_{iy}^{''}(t-\frac{r_i}{c})}{cr_i^2}+\right. \\ &\left.+\frac{y_i p_{ix}^{'}(t-\frac{r_i}{c})}{r_i^3}+\frac{y_i p_{ix}^{''}(t-\frac{r_i}{c})}{cr_i^2}\right] \end{aligned} \tag{19}$$

where

$$v=\frac{1}{\sqrt{\varepsilon\mu}} \qquad c=\frac{1}{\sqrt{\varepsilon_0\mu_0}} \tag{20}$$

are the velocities of electromagnetic wave extension inside the investigated environs and inside the vacuum. If we will suppose in following that the electromagnetic wave is air-borne spread then the next relations can be simplified. In such case $v = c$. The magnetic intensity vector $\overline{H}$, as one component of the electromagnetic wave, is possible to express according the equation (21). Where for the conductor length, the electromagnetic field of which is investigated, the relation is valid, equation (22).

$$\overline{H} = \sum_{i=1}^{m\to\infty}\overline{H}_i = \bar{i}^0\sum_{i=1}^{m\to\infty}H_{ix} + \bar{j}^0\sum_{i=1}^{m\to\infty}H_{iy} + \bar{k}^0\sum_{i=1}^{m\to\infty}H_{iz} =$$

$$= \overline{H}_x + \overline{H}_y + \overline{H}_z = \frac{1}{4\pi}\frac{\left[\overline{p}_i^{'} + \left(\frac{r_i}{c}\right)\overline{p}_i^{''}\right]_{t-\frac{r_i}{c}} \times \overline{r}_i}{r_i^3} \tag{21}$$

$$l = \sum_{i=1}^{m\to\infty} l_i \tag{22}$$

Individual axis components of the magnetic vector intensity $\overline{H}_i$, expressed by harmonic and DC components of dipole moment, have the following forms after modifications:

$$H_{ix\sin} = \frac{I_{mk}}{4\pi r_i^3}[((z_i - z_{i0})(y_{i2} - y_{i1}) - (y_i - y_{i0})(z_{i2} - z_{i1}))$$
$$\left(\sin(k\omega t - \frac{k\omega r_i}{c} + \psi) + \frac{r_i}{c}k\omega\cos(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)] \tag{23}$$

$$H_{iy\sin} = \frac{I_{mk}}{4\pi r_i^3}[((x_i - x_{i0})(z_{i2} - z_{i1}) - (z_i - z_{i0})(x_{i2} - x_{i1}))$$
$$\left(\sin(k\omega t - \frac{k\omega r_i}{c} + \psi) + \frac{r_i}{c}k\omega\cos(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)] \tag{24}$$

$$H_{iz\sin} = \frac{I_{mk}}{4\pi r_i^3}[((y_i - y_{i0})(x_{i2} - x_{i1}) - (x_i - x_{i0})(y_{i2} - y_{i1}))$$
$$\left(\sin(k\omega t - \frac{k\omega r_i}{c} + \psi) + \frac{r_i}{c}k\omega\cos(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)]$$

$$H_{ix0} = \frac{I_0}{4\pi r_i^3}\left[(z_i - z_{i0})(y_{i2} - y_{i1}) - (y_i - y_{i0})(z_{i2} - z_{i1})\right] \tag{26}$$

$$H_{iy0} = \frac{I_0}{4\pi r_i^3}\left[(x_i - x_{i0})(z_{i2} - z_{i1}) - (z_i - z_{i0})(x_{i2} - x_{i1})\right] \tag{27}$$

$$H_{iz0} = \frac{I_0}{4\pi r_i^3}\left[(y_i - y_{i0})(x_{i2} - x_{i1}) - (x_i - x_{i0})(y_{i2} - y_{i1})\right] \tag{28}$$

where

$$x_{i0} = \frac{x_{i2} + x_{i1}}{2} \qquad y_{i0} = \frac{y_{i2} + y_{i1}}{2} \qquad z_{i0} = \frac{z_{i2} + z_{i1}}{2} \tag{29}$$

$$r_i = \sqrt{(x_i - x_{i0})^2 + (y_i - y_{i0})^2 + (z_i - z_{i0})^2}$$

Electric intensity $\overline{E}_i$ vector calculation, as the second component of electromagnetic field, will be deduced from condition (5). The found solution of the partial-differential equation of the second order for magnetic vector potential $\overline{A}$ must fulfill this condition.

$$\nabla.\overline{A}_i = -\frac{1}{4\pi\varepsilon_0 c^2}\frac{\left(\overline{p}_i^{'}(t - \frac{r_i}{c}) + \left(\frac{r_i}{c}\right)\overline{p}_i^{''}(t - \frac{r_i}{c})\right)\overline{r}_i}{r_i^3} =$$
$$= -\frac{1}{c^2}\frac{\partial\varphi_i}{\partial t} \tag{30}$$

The time gradient of potential at the investigated place is necessary to express from the above-mentioned equation.

$$\frac{\partial\varphi_i}{\partial t} = \frac{1}{4\pi\varepsilon_0}\frac{\left(\overline{p}_i^{'}(t - \frac{r_i}{c}) + \left(\frac{r_i}{c}\right)\overline{p}_i^{''}(t - \frac{r_i}{c})\right)\overline{r}_i}{r_i^3} \tag{31}$$

The relation for potential will be received after the integration.

$$\varphi_i = \frac{1}{4\pi\varepsilon_0}\frac{\left(\overline{p}_i(t - \frac{r_i}{c}) + \left(\frac{r_i}{c}\right)\overline{p}_i^{'}(t - \frac{r_i}{c})\right)\overline{r}_i}{r_i^3} + K \tag{32}$$

Integral constant K expresses a possible existence of the electrostatic field. It should be omitted during the investigation of electromagnetic wave spreading and so the final formula can be simplified.

By substitution of the obtained dependencies for potential φ and magnetic vector potential $\overline{A}$ into the equation (1) and by its modification the searched formula for electric field intensity $\overline{E}$ vector caused by harmonic pulsating dipole can be expressed.

$$\overline{E} = \sum_{i=1}^{m\to\infty}\overline{E}_i = \bar{i}^0\sum_{i=1}^{m\to\infty}E_{ix} + \bar{j}^0\sum_{i=1}^{m\to\infty}E_{iy} + \bar{k}^0\sum_{i=1}^{m\to\infty}E_{iz} = \overline{E}_x + \overline{E}_y + \overline{E}_z =$$

$$= -\frac{1}{4\pi\varepsilon_0 r_i^3}\left[-\overline{p}_i(t - \frac{r_i}{c}) - \left(\frac{r_i}{c}\right)\overline{p}_i^{'}(t - \frac{r_i}{c}) - \right. \tag{33}$$

$$\left. -3\frac{\left(\left(\overline{p}_i(t - \frac{r_i}{c}) + \left(\frac{r_i}{c}\right)\overline{p}_i^{'}(t - \frac{r_i}{c})\right)\overline{r}_i\right)\overline{r}_i}{r_i^2} + \frac{\overline{p}_i^{''}(t - \frac{r_i}{c})}{c^2}\left(r_i^2 - \overline{r}_i\overline{r}_i\right)\right]$$

Note, that above-mentioned condition (22) for total length of the investigated current conductor is valid, too. The individual axis components of electric intensity $\overline{E}$ vector of electromagnetic wave can be calculated on the basis of following relations.

$$E_{ix} = -\frac{1}{4\pi\varepsilon_0 r_i^3}\left[\left(p_{ix}(t-\frac{r_i}{c}) + \left(\frac{r_i}{c}\right)p_{ix}^{'}(t-\frac{r_i}{c})\right)\left(1-3\frac{x_i^2}{r_i^2}\right) + \left(\frac{r_i^2 - x_i^2}{c^2}p_{ix}^{''}(t-\frac{r_i}{c})\right)\right] \tag{34}$$

$$E_{iy} = -\frac{1}{4\pi\varepsilon_0 r_i^3}\left[\left(p_{iy}(t-\frac{r_i}{c}) + \left(\frac{r_i}{c}\right)p_{iy}^{'}(t-\frac{r_i}{c})\right)\left(1-3\frac{y_i^2}{r_i^2}\right) + \left(\frac{r_i^2 - y_i^2}{c^2}p_{iy}^{''}(t-\frac{r_i}{c})\right)\right] \tag{35}$$

$$E_{iz} = -\frac{1}{4\pi\varepsilon_0 r_i^3}\left[\left(p_{iz}(t-\frac{r_i}{c}) + \left(\frac{r_i}{c}\right)p_{iz}^{'}(t-\frac{r_i}{c})\right)\left(1-3\frac{z_i^2}{r_i^2}\right) + \left(\frac{r_i^2 - z_i^2}{c^2}p_{iz}^{''}(t-\frac{r_i}{c})\right)\right] \tag{36}$$

$$E_{ix\sin} = -\frac{(x_{i2}-x_{i1})}{4\pi\varepsilon_0 r_i^3}\left[\left(\frac{I_m}{k\omega}\cos(k\omega t - \frac{k\omega r_i}{c} + \psi) - \left(\frac{r_i}{c}\right)I_m \sin(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)\left(1-3\frac{(x_i - x_{i0})^2}{r_i^2}\right) + \frac{k\omega I_m \cos(k\omega t - \frac{k\omega r_i}{c} + \psi)}{c^2}\left(r_i^2 - (x_i - x_{i0})^2\right)\right] \tag{37}$$

$$E_{iy\sin} = -\frac{(y_{i2}-y_{i1})}{4\pi\varepsilon_0 r_i^3}\left[\left(\frac{I_m}{k\omega}\cos(k\omega t - \frac{k\omega r_i}{c} + \psi) - \left(\frac{r_i}{c}\right)I_m \sin(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)\left(1-3\frac{(y_i - y_{i0})^2}{r_i^2}\right) + \frac{k\omega I_m \cos(k\omega t - \frac{k\omega r_i}{c} + \psi)}{c^2}\left(r_i^2 - (y_i - y_{i0})^2\right)\right] \tag{38}$$

$$E_{iz\sin} = -\frac{(z_{i2}-z_{i1})}{4\pi\varepsilon_0 r_i^3}\left[\left(\frac{I_m}{k\omega}\cos(k\omega t - \frac{k\omega r_i}{c} + \psi) - \left(\frac{r_i}{c}\right)I_m \sin(k\omega t - \frac{k\omega r_i}{c} + \psi)\right)\left(1-3\frac{(z_i - z_{i0})^2}{r_i^2}\right) + \frac{k\omega I_m \cos(k\omega t - \frac{k\omega r_i}{c} + \psi)}{c^2}\left(r_i^2 - (z_i - z_{i0})^2\right)\right] \tag{39}$$

$$E_{ix0} = -\frac{(x_{i2}-x_{i1})I_0 T}{4\pi\varepsilon_0 r_i^3}\left(1 - \frac{3(x_i - x_{i0})^2}{r_i^2}\right) \tag{40}$$

$$E_{iy0} = -\frac{(y_{i2}-y_{i1})I_0 T}{4\pi\varepsilon_0 r_i^3}\left(1 - \frac{3(y_i - y_{i0})^2}{r_i^2}\right) \tag{41}$$

$$E_{iz0} = -\frac{(z_{i2}-z_{i1})I_0 T}{4\pi\varepsilon_0 r_i^3}\left(1 - \frac{3(z_i - z_{i0})^2}{r_i^2}\right) \tag{42}$$

Their concrete expressions are given by the next equations for individual harmonics and DC component of dipole moment.

Also equation (29) is valid again. From the electromagnetic field theory it is known, that the harmonic electromagnetic wave, by means of which the electromagnetic impact to the other electrotechnical equipments is giving out, is characterized by the phase constant α, damping coefficient β, certain velocity v, wave length λ and depth of penetration δ for given environs, as it is listed in Table 1.

Optional environs	Ideal dielectric environs ($\gamma = 0$)
$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}(1+\sqrt{1+(\frac{\gamma}{\omega\varepsilon})^2})}$	$\alpha = \omega\sqrt{\mu\varepsilon}$
$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}(-1+\sqrt{1+(\frac{\gamma}{\omega\varepsilon})^2})}$	$\beta = 0$
$v = \frac{\omega}{\alpha} = \frac{1}{\sqrt{\frac{\mu\varepsilon}{2}(1+\sqrt{1+(\frac{\gamma}{\omega\varepsilon})^2})}}$	$v = \frac{\omega}{\alpha} = \frac{1}{\sqrt{\mu\varepsilon}}$
$\lambda = \frac{v}{f} = \frac{1}{f\sqrt{\frac{\mu\varepsilon}{2}(1+\sqrt{1+(\frac{\gamma}{\omega\varepsilon})^2})}}$	$\lambda = \frac{v}{f} = \frac{1}{f\sqrt{\mu\varepsilon}}$
$\delta = \frac{1}{\beta} = \frac{1}{\omega\sqrt{\frac{\mu\varepsilon}{2}(1+\sqrt{1+(\frac{\gamma}{\omega\varepsilon})^2})}}$	$\delta = \frac{1}{\beta} = \infty$

Tab. 1: Basic parameters of electromagnetic waves

Characteristic impedance defines the environs, inside which the harmonic wave is propagated.

$$\dot{Z}_v = \sqrt{\frac{j\omega\mu}{j\omega\varepsilon+\gamma}} = \frac{\dot{\overline{E}}}{\dot{\overline{H}}} \tag{43}$$

Radiated electromagnetic wave falls on cover of the impacted equipment during its way. The penetration, refraction and reflection of electromagnetic wave occur here in dependence on the interface parameters. Such a way the resulting impact wave effect on the investigated equipment can be reduced. Situation, during the wave incidence, shows Figure 2.

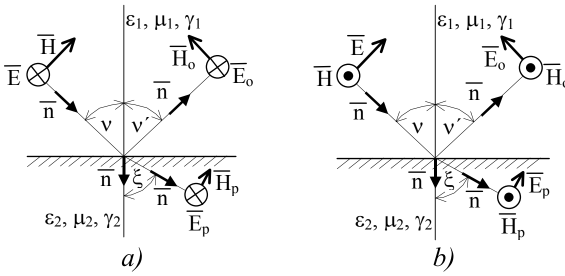

Fig. 2: Electromagnetic wave falling on the interface

For the angles of falling and reflected waves the next relation is valid:

$$\nu = \nu' \tag{44}$$

Also the Snell's law describes relation valid for angles of falling and penetrating waves.

$$\frac{\sin\xi}{\sin\nu'} = \frac{\mu_1 Z_{v2}}{\mu_2 Z_{v1}} \tag{45}$$

The normal vector $\overline{n}_2$ defines interface plain. The pair of vectors $\overline{n}$ and $\overline{n}_2$ define falling plain.

In the case, when the vector $\overline{E}$ is perpendicular to the falling plane and parallel with the interface plane (Figure 2 a)), then:

$$E + E_o = E_p \tag{46}$$

$$H\cos\nu' = H_p\cos\xi + H_o\cos\nu' \tag{47}$$

If we know that relations $H = E/Z_{v1}$, $H_o = E_o/Z_{v1}$, $H_p = E_p/Z_{v2}$ are valid, then

$$\overline{E}_o = \frac{Z_{v2}\cos\nu' - Z_{v1}\cos\xi}{Z_{v2}\cos\nu' + Z_{v1}\cos\xi}\overline{E} \tag{48}$$

$$\overline{E}_p = \frac{2Z_{v2}\cos\nu'}{Z_{v2}\cos\nu' + Z_{v1}\cos\xi}\overline{E} \tag{49}$$

$$\overline{H}_o = \frac{\frac{Z_{v2}}{Z_{v1}}\cos\nu' - \cos\xi}{Z_{v2}\cos\nu' + Z_{v1}\cos\xi}\overline{E} \tag{50}$$

$$\overline{H}_p = \frac{2\cos\nu'}{Z_{v2}\cos\nu' + Z_{v1}\cos\xi}\overline{E} \tag{51}$$

If the vector $\overline{H}$ is perpendicular to the plane of incidence and parallel with the interface plane, as it is shown in Figure 2 b), then:

$$\overline{H}_o = \frac{Z_{v1}\cos\nu' - Z_{v2}\cos\xi}{Z_{v1}\cos\nu' + Z_{v2}\cos\xi}\overline{H} \tag{52}$$

$$\overline{H}_p = \frac{2Z_{v1}\cos\nu'}{Z_{v1}\cos\nu' + Z_{v2}\cos\xi}\overline{H} \tag{53}$$

$$\overline{E}_o = \frac{Z_{v1}\cos\nu' - Z_{v2}\cos\xi}{\cos\nu' + \frac{Z_{v2}}{Z_{v1}}\cos\xi}\overline{H} \tag{54}$$

$$\overline{E}_p = \frac{2Z_{v2}Z_{v1}\cos\nu'}{Z_{v1}\cos\nu' + Z_{v2}\cos\xi}\overline{H} \tag{55}$$

The vector amplitudes of the falling $\overline{E}$ and $\overline{H}$, reflected $(\overline{E}_o, \overline{H}_o)$ and penetrating $(\overline{E}_p, \overline{H}_p)$ planar harmonic waves are expressed by the next equations in the case of its perpendicular falling to the interface plane:

$$E_o = \frac{Z_{v2} - Z_{v1}}{Z_{v2} + Z_{v1}}E \tag{56}$$

$$E_p = \frac{2Z_{v2}}{Z_{v2} + Z_{v1}}E \tag{57}$$

$$H_o = \frac{Z_{v1} - Z_{v2}}{Z_{v2} + Z_{v1}}H \tag{58}$$

$$H_p = \frac{2Z_{v1}}{Z_{v2} + Z_{v1}}H \tag{59}$$

The ratio of the reflected and falling wave amounts is defined by the reflection coefficient $\dot{r}$ in the electromagnetic field theory.

$$\dot{r} = \frac{\dot{Z}_{v2} - \dot{Z}_{v1}}{\dot{Z}_{v2} + \dot{Z}_{v1}} \tag{60}$$

This coefficient is very important parameter from the EMC viewpoint, because it determines the value of electromagnetic penetrating wave passing through the cover into investigated environs. By its suitable practical utilizing it is possible to achieve improved shielding of the radiated source or impacted equipment.

The ratio of penetrating and falling waves defines the shielding coefficient K_t in the electromagnetic field theory.

$$K_{tE} = \frac{E_p}{E} \qquad \text{or} \qquad K_{tH} = \frac{H_p}{H} \tag{61}$$

The coefficient, which is the most used in practice, is labeled as shielding effectiveness *SE*.

$$SE_E = 20 \log \frac{1}{|K_{tE}|} = 20 \log \left| \frac{E}{E_p} \right| \tag{62}$$

$$SE_H = 20 \log \frac{1}{|K_{tH}|} = 20 \log \left| \frac{H}{H_p} \right| \tag{63}$$

Besides the knowledge about depth of electromagnetic wave penetration, the application of knowledge from electromagnetic field theory is also based on reason about the value reduction of penetrating electromagnetic wave as consequence of its multiple reflections. Such example is shown in Figure 3. However, the main effort should be focused on such state reaching, that the depth of penetration δ would be smaller than the shielding material thickness *d*.

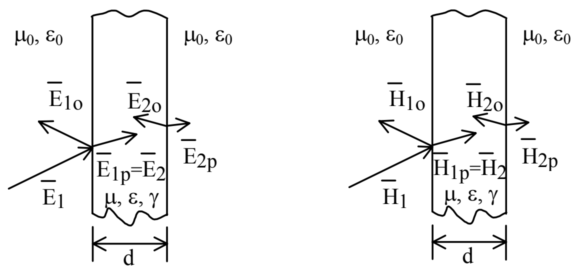

Fig. 3: Multiple reflections of electromagnetic wave

For securing of required shielding efficiency it is possible to derive relation for the value of shielding material wave impedance $Z_T = |\dot{Z}_T|$ calculation:

$$Z_T = 10^{-\frac{SE}{20}} Z_0 \tag{64}$$

where Z_0 is the wave impedance value of air.

Poyting's relation can state the total amount of energy power transferred from the source to the impacted equipment. The *S* represents covering surface of affected system.

$$p = \oint_S (\overline{E}_p \times \overline{H}_p) d\overline{S} \tag{65}$$

2 CONCLUSION

The electromagnetic coupling implication between the two electrical circuits is manifested by the parasitic induced voltage creation at the loop of impacted electrical circuit. This voltage consists of the magnetic and electric components. The induced voltage generated by the magnetic component of electromagnetic wave can be stated in such a way that the values of axis components of magnetic intensity vector will be calculated at the position in the center of impacted loop by the equations (23) up to (28). The induced voltage generated by the electric component of electromagnetic wave can be stated in such a way that the values of axis components of electric intensity vector at the investigated positions will be found by the equations (37) up to (42). If the equations (62) up to (63), describing the shielding efficiency, are taken into consideration then one can find out that the intensity of electromagnetic coupling is directly proportional to the amount and the time change slope of circuit current, which is radiating the electromagnetic energy and to the surface and the length values of disturbed circuit. In the same way electromagnetic coupling intensity depends on the length of this circuit. It is indirectly proportional to the distance between the interference source and the disturbed circuits, to the reflection coefficient and to the permeability and permittivity values of space between the both circuits.

The simulation and measurement results, published in part II, will confirm the correctness of derived equations. Even though they can be used for predictive stating of EMC quality of individual new electrotechnical products. However, the fact is necessary to remind, that if higher number of Fourier series will be used, then the better coincidence with the reality will be obtained. It means that during the electromagnetic coupling investigation, as one part of general EMC investigation, it is necessary to reconsider the compromise between the number of Fourier series components and the required calculation precision.

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