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Optimum transmitted power spectral distribution for broadband power line communication systems considering electromagnetic emissions

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A B S T R A C T

The study prior to the installation of a power-line communication (PLC) system requires detailed knowledge of the channel properties, such as transfer function, noise levels, and channel capacity in order to assess the services that can be provided. The channel capacity is greatly affected by the transmitted power over the available frequency range. At the same time, the values of transmitted power determine the electromagnetic field magnitude to the vicinity of the system. The simultaneous operation of different systems which share parts of the same frequency range, in the context of smart grid communications, has to be regulated in order to avoid excessive interference scenarios. Therefore, an algorithm that calculates the optimum power allocation of the transmitted power for PLC systems is proposed. The algorithm takes into account the maximum permitted values of electric field emitted from the PLC system and determines the transmitted power. The proposed algorithm is implemented for several test cases, while the corresponding channel capacities are calculated. It is shown that the proposed scheme better exploits the available frequency range and the transmission margins.

1. Introduction

Economical feasible technologies, such as power line communication (PLC) systems can be used in order to serve the increasing necessity for data transfer. This technology utilizes the existing electrical power grid infrastructure, hence it does not require investments for backbone creation. Future power systems in the form of smart grids are expected to incorporate information and communication technology (ICT) in order to enhance their reliability, offering to PLC technology a major chance for large scale implementation [1–6]. Several proposed methods require data communication and PLC systems could be utilized to do so.

The design of power grids was conducted aiming to deliver electric power at very low frequencies. However, PLC technology can utilize frequencies up to several MHz. Also power grids extent to vast areas with numerous branches. For that reason PLC signals suffer from attenuation and multipath propagation, problems similar to those appearing in wireless communication systems [7–10]. This makes the rigorous investigation of several aspects prior to a PLC system installation necessary [11–18]. The data capacity of the PLC communication channels could determine PLC utilization levels, which mainly depends on the existing noise, the transmitted power, the available frequency range and the transfer function of the channel.

Focusing on the transmitted power, it is affected and determined by the parameters of the system and by the fact that several systems that make use of the same frequency range have to be able to operate, respectively. Hence, the transmitted power levels have to comply with rules ensuring electromagnetic compatibility (EMC). The operation of PLC devices must not create interference to other communication devices at their vicinity. The procedure to determine the effect of a PLC device operation to its vicinity includes the measurement of the associated electric field at specific distance from the system [19]. The measured values have to not exceed predetermined values that are specified by organizations responsible for EMC. Several organizations have suggested maximum values for electric field magnitude created by PLC systems. However, as of today there is no common adopted values. The existing suggestions come from either state services or other organizations from various countries, such as Germany, Norway, BBC & NATO and the FCC from USA [20]. Emissions produced by power lines and PLC system operation have attracted some research interest.

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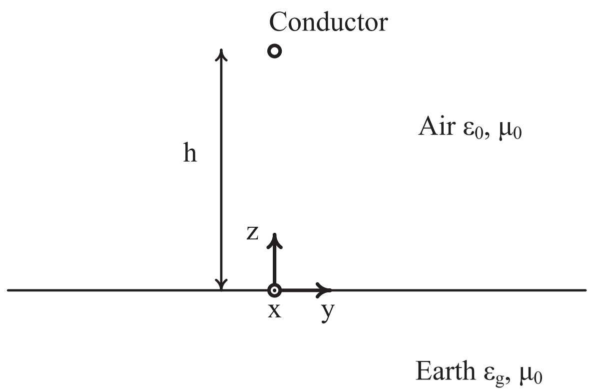

Fig. 1. Conductor at a height *h* from the surface of the earth.

In particular emission calculation methods have been investigated in [21–24]. However, the calculations of electromagnetic emissions were not used in order to optimize the overall transmitted power and hence the channel capacity. The channel capacity is highly affected by the overall transmitted power. Studies in the literature have adopted the water filling algorithm which prerequisites the overall transmitted power for the whole frequency range as an input and clearly do not take into account the limits for electromagnetic emissions [25–27]. Unlike this method, the proposed scheme takes into account electromagnetic emissions' limits in order to accurately compute the overall transmitted power.

In order to better exploit the available frequency range and permitted values for transmitted power, a new approach is presented. This approach takes into consideration all the parameters of a PLC arrangement installed in overhead MV networks. Furthermore, by adjusting the transmitted power for all available frequencies it fully exploits the available frequency range and at the same time does not exceed the predetermined values of emitted electric field in order to comply with EMC regulations. In Section 2 a theoretical formulation of the electric field emitted by a transmission line, both adopting a single and multiphase approach, is presented. Subsequently, Section 3 focuses on the theoretical approach regarding the electric field emitted by a broadband PLC system, while Section 4 presents the maximum allowed transmitted power calculation algorithm. All the conducted simulations are included in Section 5. Finally, the more important conclusions are shown in Section 6.

2. Electric field emitted by a transmission line

2.1. Single phase approach

Considering an overhead conductor at a height h from the surface of the ground, which carries current $Ie^{-\gamma x}$ with angular frequency ω, the electric field to the surrounding area can be calculated by making use of the electric and magnetic Hertz vectors [28], as suggested by Wait [29] for a thin conductor being at a distance from the line separating two mediums with different electromagnetic properties, which in the studied case are the air and the ground as shown in Fig. 1. Concretely, the dielectric constant and magnetic permeability of the air are ε_0, μ_0, respectively and the dielectric constant and magnetic permeability of the earth are ε_g, μ_0, respectively. The electric field per direction can be computed using electric and magnetic Hertz vectors as shown in Eqs. (1)–(3)

$$E_x(x,y,z) = \left(k_0^2 + \frac{\partial^2}{\partial x^2}\right)\Pi_E \tag{1}$$

$$E_y(x,y,z) = \frac{\partial^2 \Pi_E}{\partial y \partial x} + j\mu_0\omega\left(\frac{\partial \Pi_H}{\partial z}\right) \tag{2}$$

$$E_z(x,y,z) = \frac{\partial^2 \Pi_E}{\partial z \partial x} - j\mu_0\omega\left(\frac{\partial \Pi_H}{\partial y}\right) \tag{3}$$

where $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$. Moreover, the electric and magnetic Hertz vector, Π_E Π_H, respectively, are defined as in Eqs. (4) and (5), respectively

$$\Pi_E = -\frac{j\mu_0\omega I}{4\pi k_0^2}\cdot e^{-\gamma x}\cdot \int_{-\infty}^{+\infty}\left[e^{u_0(z-h)} + R(\lambda)e^{-u_0(z+h)}\right]\cdot\frac{e^{-j\lambda y}}{u_0}d\lambda \tag{4}$$

$$\Pi_H = -\frac{j\mu_0\omega I}{4\pi k_0^2}\cdot e^{-\gamma x}\cdot \int_{-\infty}^{+\infty}\left[e^{-u_0 h} + M(\lambda)e^{-u_0 z}\right]\cdot\frac{e^{-j\lambda y}}{u_0}d\lambda. \tag{5}$$

Variable u_0 is computed using Eq. (6). Furthermore, functions $R(\lambda)$ and $M(\lambda)$ are defined using the boundary conditions on the mediums separating line and are given by Eqs. (7) and (8):

$$u_0 = \sqrt{\lambda^2 - \gamma^2 - k_0^2} \tag{6}$$

$$R(\lambda) = \frac{-\lambda^2\gamma^2(1-K)^2 + (\varepsilon_0\omega u_0 - \varepsilon_g\omega u_g K)(\mu_0\omega u_0 + \mu_0\omega u_g K)}{\lambda^2\gamma^2(1-K)^2 + (\varepsilon_0\omega u_0 + \varepsilon_g\omega u_g K)(\mu_0\omega u_0 + \mu_0\omega u_g K)} \tag{7}$$

$$M(\lambda) = \frac{2\lambda\gamma\varepsilon_0\omega u_0(1-K)}{\lambda^2\gamma^2(1-K)^2 + (\varepsilon_0\omega u_0 + \varepsilon_g\omega u_g K)(\mu_0\omega u_0 + \mu_0\omega u_g K)} \tag{8}$$

where $K = (k_0^2+\gamma^2)/(k_g^2+\gamma^2)$, $k_g = \omega\sqrt{\varepsilon_g\mu_0}$ and $u_g = \sqrt{\lambda^2-\gamma^2-k_g^2}$.

The analytical expressions for the components of electric field at each direction of the Cartesian coordinate system at a point with coordinates (x, y, z) are derived by using Eqs. (1)-(5) and Leibniz integral rule and are shown in Eqs. (9)-(11).

$$E_x(x,y,z) = (k_0^2+\gamma^2)\cdot\left(-\frac{j\mu_0\omega I}{4\pi k_0^2}\right)\cdot e^{-\gamma x} \cdot \int_{-\infty}^{+\infty}\left[e^{u_0(z-h)} + R(\lambda)e^{-u_0(z+h)}\right]\cdot\frac{e^{-j\lambda y}}{u_0}d\lambda \tag{9}$$

$$E_y(x,y,z) = \left(-\frac{j\mu_0\omega I\gamma}{4\pi k_0^2}\right)\cdot e^{-\gamma x} \cdot \int_{-\infty}^{+\infty}\left\{\left[e^{u_0(z-h)} + R(\lambda)e^{-u_0(z+h)}\right]\cdot j\lambda\cdot\frac{e^{-j\lambda y}}{u_0}\right\}d\lambda - \left(\frac{\mu_0^2\omega^2 I}{4\pi k_0^2}\right)\cdot e^{-\gamma x}\cdot\int_{-\infty}^{+\infty}\left[e^{-u_0 h}M(\lambda)u_0 e^{-u_0 z}\frac{e^{-j\lambda y}}{u_0}\right]d\lambda \tag{10}$$

$$E_z(x,y,z) = \left(\frac{j\mu_0\omega I\gamma}{4\pi k_0^2}\right)\cdot e^{-\gamma x} \cdot \int_{-\infty}^{+\infty}\left\{\left[u_0 e^{u_0(z-h)} - R(\lambda)u_0 e^{-u_0(z+h)}\right]\cdot\frac{e^{-j\lambda y}}{u_0}\right\}d\lambda + \left(\frac{\mu_0^2\omega^2 I}{4\pi k_0^2}\right)\cdot e^{-\gamma x}\cdot\int_{-\infty}^{+\infty}\left[e^{-u_0 h}M(\lambda)e^{-u_0 z}j\lambda\frac{e^{-j\lambda y}}{u_0}\right]d\lambda \tag{11}$$