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The relation between dielectric breakdown and transported power density in high-voltage transmission lines

(A relação entre ruptura dielétrica e densidade de potência transportada em linhas de transmissão de alta tensão)

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Three-phase electric power systems can transmit large amounts of power, typically in the range of 2000 MVA with a voltage of 765 kV. Under such extreme conditions, the air surrounding the transmission lines is ionized, which significantly increases the conductivity. The present contribution proposes a simple model which allows one to estimate the ionization and the electric conductivity of the air as a function of the power density flowing in the power line system. Near the transmission lines, it is shown that the air conductivity is increased by several orders of magnitude relative to normal conditions. In this scenario, the dielectric breakdown is favored by avalanche processes and lightning stroke probability is significantly increased.
Keywords: air ionization, transmission lines, lightning.

Sistemas elétricos de potência trifásicos podem transmitir grandes quantidades de energia, tipicamente na faixa de 2000 MVA com uma tensão de 765 kV. Sob tais condições extremas, o ar em torno das linhas de transmissão se ioniza, aumentando significativamente a sua condutividade. A presente contribuição propõe um modelo simples, que permite estimar a ionização do ar e a condutividade elétrica, como uma função da densidade de potência que flui no sistema de linhas de energia. Perto das linhas de transmissão, mostra-se que a condutividade do ar é aumentada por várias ordens de grandeza em relação ás condições normais. Neste cenário, a ruptura dielétrica é favorecida por processos de avalanche e a probabilidade de impacto de relâmpagos é discutida de forma significativa.
Palavras-chave: ionização do ar, linhas de transmissão, descargas atmosféricas.

1. Introduction

The environmental conditions are important to estimate the frequency of lightning strokes incidence on transmission lines [1]. The overvoltage produced by lightning in transmission lines is among the most important causes of shutdown. The increase of the electric field near the power transmitting conductors is the main cause of lightning. It induces corona-discharges, a phenomenon in which the air surrounding the power conductors ionises, leading to a significant increase of air conductivity near the transmission line. Astinfeshan *et al.* [2] considered the influence of corona-discharge on overvoltages produced by lightning strokes terminating on the transmission line. Using finite-difference time-domain (FDTD) electromagnetic calculations, Thang *et al.* [1] calculated the critical electric field value for which a corona-discharge starts. Indeed, corona discharge is affected by a large number of parameters, such as conductor diameter, conductor surface condition, weather, altitude, temperature and line voltage [3]. The ionised air surrounding the conductor acts as a virtual conductor and increases the effective diameter of the metallic conductor [4, 5].

For the dielectric breakdown to take place in a given insulator, the applied electric field must exceed a critical value at which the medium starts to behave as a conductor. The critical electric field of the air is strongly influenced by the air density and atmospheric conditions. Under normal conditions, the dielectric breakdown of the air occurs at approximately 3 MV/m [4, 5]. The critical electric field (E_o) on the surface of a cylindrical conductor of radius r_o for initiating a corona discharge is approximately given by [5]

$$E_o = 2.594 \times 10^6 m \left[1 + \left(\frac{0.1269}{r_o^{0.4346}}\right)\right],$$

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where m is a coefficient depending on the surface state of the conductor. A critical electric field on the surface of a conductor of radius $r_o = 5$ mm, for initiating corona-discharge was determined to be $E_0 = 1.8$ MV/m, using $m = 0.3$. D'Alessandro and Gumley estimated that the value of the corona radius is 30-38 cm from the surface of the conductor [4, 5].

The present contribution proposes a simple model which allows one to estimate air ionisation and electric conductivity as a function of the power density flowing in the power line system. Usually, the dielectric breakdown is considered as a function of the total electric field near the transmission lines produced by the transmission line voltage superimposed to the atmospheric electric field. Under these assumptions, the influence of the electric current transported by the transmission line is being neglected. The theoretical model presented here considers the effect of the electromagnetic power density transported by the transmission lines in the nearby environment on the air ionisation, allowing to predict the increase of the air conductivity within the Drude model.

The content of this paper can be described as follows: in Sections II and III we will briefly review the basic formulae of electric and magnetic fields generated by linear conductors above ground planes. In Section IV we will present the expression for the volumetric electromagnetic energy density. In Section V we will discuss the effects of electromagnetic energy density in the air ionisation, and finally, in the last Section a few conclusions and remarks are added.

2. Electric fields produced by three-phase conductors above ground

The three-phase transmission lines are modeled as an array of conductors above a ground plane, where $V(\mathbf{x},\mathbf{y})$ is the electric potential measured in volts, $\mathbf{E}(\mathbf{x},\mathbf{y})$ is the electric field, measured in V/m and $\lambda(\mathbf{x},\mathbf{y})$ is the linear charge density, measured in C/m.

The electric field created by the transmission lines is superimposed to the local atmospheric electric field. Therefore, the larger the electric potential $V(x, y)$ of the transmission line conductors respective to the ground plane, the greater the electric field in the surrounding medium, increasing the corona-discharge effect near the transmission lines. The electric field produced by a single linear conductor loaded with a linear charge density λ in free space is given by

$$\mathbf{E}_\rho = \frac{\lambda}{2\pi\varepsilon_o\rho}\widehat{a}_\rho, \qquad (1)$$

where ε_o is the vacuum permissivity (8.854×10^{-12} F/m) and $\mathbf{E}_\rho$ is the electric field on conductor (V/m), $\widehat{a}_\rho$ is the unit vector pointing towards the radial direction in cylindric coordinates (ρ, φ, z).

Applying the method of images for an array of conductors above a perfectly conducting ground plane (see Fig. 1) and using the expression $\mathbf{E} = -\nabla V$ we can easily obtain the expression for the total electric field generated in a high-voltage three-phase power system

$$\begin{aligned} \mathbf{E}_{tot} &= \sum_{k=1}^{N} \frac{V_{ok}e^{i\theta_k}}{\ln\left(\frac{2.h_k}{a_k}\right)}(E_{kx}\hat{a}_x + E_{ky}\hat{a}_y)\ , \\ E_{kx} &= \left[\frac{x}{x^2+(y-h_k)^2} - \frac{x}{x^2+(y+h_k)^2}\right]\ , \\ E_{ky} &= \left[\frac{(y-h_k)}{x^2+(y-h_k)^2} - \frac{(y-h_k)}{x^2+(y+h_k)^2}\right], \end{aligned} \qquad (2)$$

where $N = 3$ is the number of conductors, $i = \sqrt{-1}$ is the imaginary unit, θ is the relative phase of the conductors ($\theta = 0, \frac{2\pi}{3}, -\frac{2\pi}{3}$ in three-phase system), h different height from the ground conductors, the distances x and y are horizontal and vertical axis, respectively, (V_o) is the potential difference of a given conductor relative to the ground and a is the radius of the conductor.

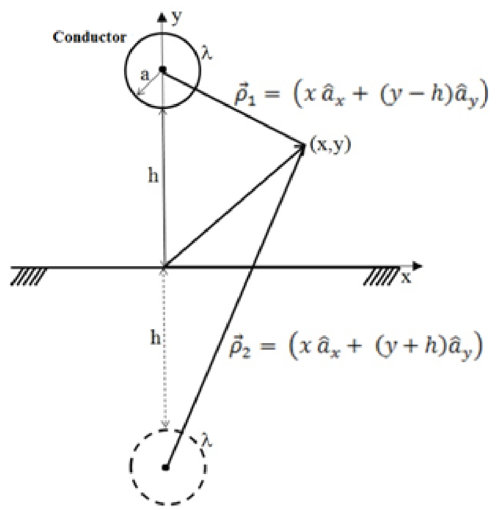

Figure 1 - Method of images to calculate the electric field of a linear conductor.

The thunderstorms have charge distributions described by models like *dipole/tripole structure*. The charge distribution in a storm cloud is associated with the atmospheric electric field generated by the global atmospheric electric circuit, which can be measured using Field Mill sensors. The charge distribution in the cloud produces an electric field near the high-voltage transmission system [6]. The present model is described schematically in Fig. 2, where we have considered that all the transmission line conductors are at the same height respective to the ground.

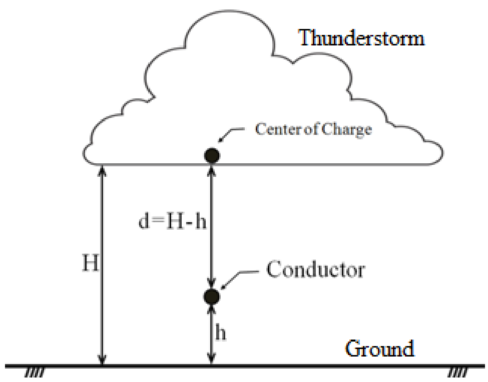

Figure 2 - Distribution of the heights of the phase conductor and the center of the cloud charges.

The effect of a storm cloud will be approximated by the presence of an atmospheric electric field created by a point charge located at the bottom of the storm cloud, situated at a distance d from the conductors

$$\mathbf{E_{atm}} = \frac{\mathbf{Q}\cos(\theta)}{\mathbf{2}\pi\varepsilon_{\mathbf{o}}\mathbf{d^2}}\widehat{\mathbf{a}}_{\mathbf{r}}, \tag{3}$$

where $\mathbf{E_{atm}}$ is the atmospheric local electric field (V/m), θ is the angle formed between the center of charge and conductor(in this case $\theta \simeq 0$).

3. Magnetic fields produced by three-phase conductors above ground

The three-phase conductors studied here admit a variable electric current during peak of electricity supply. Ignoring the effects of lightning conductors, it is possible to calculate the magnetic field intensity ($\mathbf{H}$) in the transmission line from Ampere's Law and the method of charge image. The result is

$$\begin{aligned} \mathbf{H} &= \sum_{k=1}^{N} \frac{I_k.e^{i\theta_k}}{2\pi}(H_{kx}\hat{a}_x + H_{ky}\hat{a}_y) \ , \\ H_{kx} &= \left[\frac{(y-h_k)}{(x^2+(y-h_k)^2)} + \frac{y+h}{(x^2+(y+h_k)^2)}\right] \ , \\ H_{ky} &= \left[\frac{x}{x^2+(y-h_k)^2} - \frac{x}{x^2+(y+h_k)^2}\right]. \end{aligned} \tag{4}$$

The Poynting vector $\mathbf{S}$ (measured in W/m^2), which represents the power carried by the conductor per unit area, can be obtained from the equation below

$$\mathbf{S}_{mean} = \frac{1}{2}\Re e(\mathbf{E} \times \mathbf{H}^*), \tag{5}$$

where $\mathbf{H}^*$ is the complex conjugate of the magnetic intensity vector $\mathbf{H}$. Solving the equation for the mean power density transported along the transmission lines we have

$$\mathbf{S}_{mean} = \frac{1}{2}\Re e(E_x H_y^* - E_y H_x^*)\widehat{\mathbf{z}}, \tag{6}$$

corresponding to average power density in (W/m^2), oriented in the longitudinal direction of the conductor. To discuss the effects of a mean power density in transmission lines, it is necessary to review the basic aspects of electromagnetic energy density, which is done in the following section.

4. Volumetric electromagnetic energy density

As the electric and magnetic fields can store energy, we can calculate the volumetric electromagnetic energy density in the region next of conductor. The total energy density (u) in a region occupied by an electromagnetic wave is $u = u_E + u_B$. For plane electromagnetic waves, $\mathbf{E}$ and $\mathbf{B}$ have the following relationship [7]

$$\mathbf{B} = \frac{1}{c}\widehat{\mathbf{k}} \times \mathbf{E}. \tag{7}$$

In Eq. (7), $\widehat{\mathbf{k}}$ is a unitary vector in the propagation direction, $c \approx 3 \times 10^8$ m/s is the speed of light. Therefore the density of electromagnetic energy in (J/m^3) is given by

$$u = \frac{|\ \mathbf{S}\ |}{c}, \tag{8}$$

where $|\ \mathbf{S}\ |$ is the module of mean power density in (W/m^2) [7]. The air will ionise when the density of electromagnetic energy is sufficient to match the called ionisation potential expressed in (eV). The next section will analyze the behavior of electromagnetic energy density (u) compared to the rate of air ionisation.

5. Discussion and results

High-voltage transmission lines also transport large power densities, increasing the rate of air ionisation in the nearby region. It is assumed here that the three-phase conductors have radius of 6.0 cm, being approximately equidistant 14 m and 54 m from the ground (see Fig. 3).

The center of charges from the cloud (H) is located 1500 m above the ground (see Fig. 4). Looking at Fig. 4, the dotted line represents the intensity of the electric field generated solely by the three-phase conductors, assuming a transmission line potential of 765 kV.

The solid line represents the intensity of the electric field generated by the conductors superimposed to the critical atmospheric electric field (2023 kV/m), which is capable of producing corona-discharges. The electric fields in the side conductors is minimal, but the electric field near central conductor increases to 1500 kV/m.

Figure 5 shows the behavior of the magnetic field, obtained by $\mathbf{B} = \mu_0\mathbf{H}$, for transmitted powers of 500, 1000 and 2000 MVA.

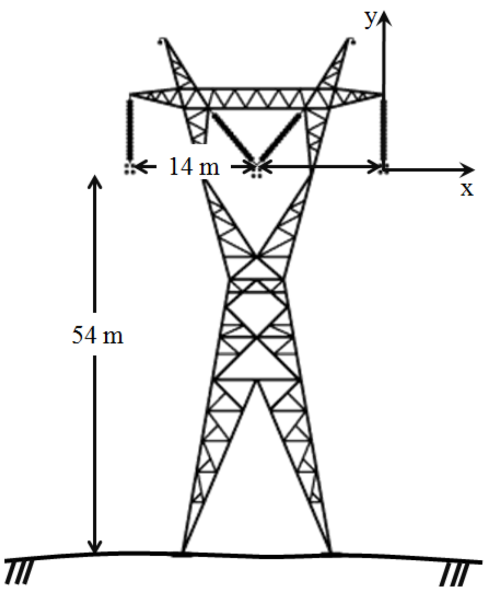

Figure 3 - Tower profile of 765 kV transmission line.

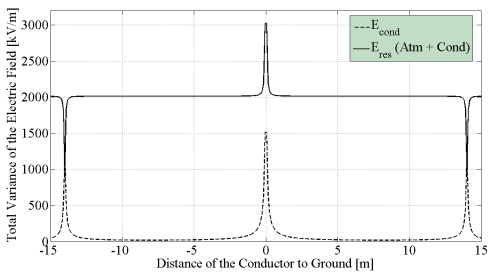

Figure 4 - Resulting electric field on conductor with 765 kV.

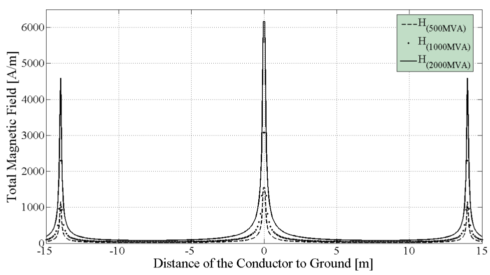

Figure 5 - Magnetic field of conductors with 765kV, and total transmitted power of 500 MVA, 1000 MVA and 2000 MVA.

Figure 6 shows the mean power density for the center conductor of the 765kV transmission lines. The magnitude of the mean power density in the neighborhood of the conductors for a three-phase system is in the range of 5×10^9 W/m^2 for transmitted power of 2000 MVA. The distance around the line conductor in which the electric field exceeds 2200 V/m, at which the dielectric breakdown of the air takes place, is approximately 20 cm.

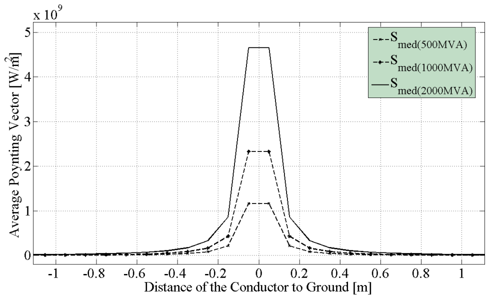

Figure 6 - Mean power density for the center conductor of the transmission line 765 kV.

When the electric field is large enough, electrons are accelerated and collide with other atoms or molecules, increasing the number of charge carriers in the environment in an exponential manner. This process is called electron avalanche [8]. As the corona-discharge on a transmission line is generated and sustained by the mechanisms of air ionisation, the air ionisation rate can be correlated with the density of electromagnetic energy around the conductor.

If the electric field in the conductor is enhanced by the electric field of the atmosphere, electrons are accelerated and collide with other atoms, releasing more electrons, increasing the amount of electrons in the environment. This process is called *ionisation through particle collision* [8, 9].

In what follows, the kinetic theory of gases will be considered, assuming that the air composition is 78% (minimum ionisation energy required of 15.6 eV) Nitrogen and 21% (12.1 eV) Oxygen, the mean ionisation energy is 14.7 eV [10]. When an electron gets enough energy and collides with other electrons, it will create an avalanche effect, initiating the process of air ionisation [11]. Considering the number of molecules per cubic meter near the conductor, a good estimate of the air conductivity in the neighborhood of the conductor will be made.

Under standard atmospheric conditions and before dielectric breakdown, i.e., without the existence of lightning channels, the air conductivity (in S/m) is in the range $10^{-15} < \sigma_{air} < 10^{-11}$ [12, 13]

For a transmission line carrying a total power of 2000 MW, the density of electromagnetic energy around the conductor in J/m^3, given by Eq. (7), is shown in Fig. 7. For a conductor of radius 6 cm, the electromagnetic energy near the surface of the conductor is approximately 16 J/m^3.

Considerging a volume of about 1 m^3 of air in the surroundings of the conductors, the total electromagnetic energy is approximately 16 J. According to the Peek model [14], which is used to examine the nature of the corona effect and its influence on electromagnetic wave propagation in transmission lines, the loss of energy through the corona effect on a 765 kV transmission line system is approximately 1% of the total electromagnetic energy available in line. This means that 0.16 J of energy ($\simeq 1 \times 10^{18}$ eV) is lost in corona effect.

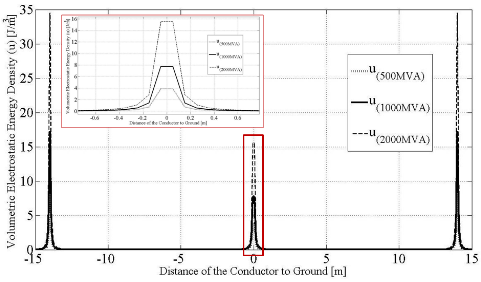

Figure 7 - Volumetric energy density (J/m^3) of the transmission line 765 kV.

Making the ratio of the total electromagnetic energy contained in 1 m^3 of air and the average ionisation energy per molecule of air (approximately 14.7 eV), the number of generated free electrons ($\bar{e}$) per cubic meter is of the order of 6.7938×10^{16}. This number is in fairly good agreement with the result of Ref. [14], showing that the electron density in return strokes is between 10^{13} and 10^{19} $\bar{e}/m^3$.

Assuming that the Drude model is valid, it is possible to estimate the conductivity in (S/m) in terms of intrinsic properties of air [12]. The Drude conductivity is given by

$$\sigma = \frac{n\bar{e}^2\tau}{m_{\bar{e}}}, \tag{9}$$

where n $= 6.7938 \times 10^{16}$ is the number of free electrons per cubic meter, $\bar{e} = 1.6020 \times 10^{-19}$ C is the electron charge, $m_{\bar{e}} = 9.1193 \times 10^{-31}$ kg is the electron mass and τ is the averaged time between collisions. For the air a good estimate for the averaged free time is $\tau = 5.0311 \times 10^{-12}$ s, leading to an electric conductivity $\sigma_{air} = 0.009617$ S/m. Such a value is about 8 orders of magnitude greater than the conductivity of air in standard atmospheric conditions.

According to the *prestrike* condition theorized by Griscom (1958), the return-stroke current is anticipated by the transfer of the charge around the power line conductors. Therefore, the enhanced air conductivity near the transmission line conductors allows for production of small filamentary current steps known as *Stepped Leader Initiation*, generating sparks [11, 14]. An upward-moving discharge would meet the negative leader at some point above ground and, at that point the return stroke would be initiated. A smaller field is probably necessary to launch an upward-moving discharge from a lightning rod, a TV antenna, or transmission line tower, according to the literature [11, 15].

Although some values are roughly estimated, the magnitude of results confirm a larger air ionisation in the neighborhood of the conductors, which results in i) runaway process of breakdown and ii) a region near the conductor which guarantees the corona-discharge effects, acting as a precursor for lightning to occur (see Fig. 8). A return stroke from the conductor can be created when the electric field reaches the critical value, which can be interpreted as the upward leader in a "preionised" channel.

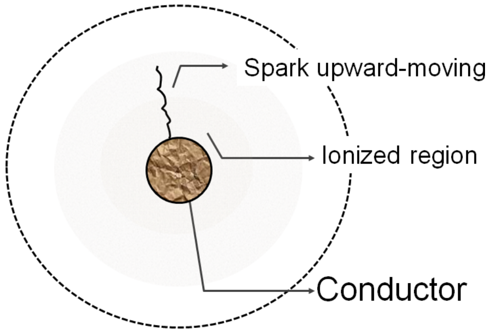

Figure 8 - Spark caused by the high conductivity of the air near the surface of power line conductor in 765 kV.

As a final remark, it is debatable to observe the results of electric field measurements (using Field Mills sensors) under transmission lines, in order to evaluate the effect of the electric field of the three-phase conductors in relation to the atmospheric local electric field. These results may influence the perspective of transmission line projects and correct classification of electric potential available in a system.

6. Conclusion

In summary, using a very simple model, it was shown that standard electric power transmission lines operating in three-phase mode with nominal transmitted powers as large as 2000 MVA and voltages of 765 kV can produce highly favorable conditions for air ionization. The model is based on the power density flowing in the power system, allowing one to estimate the air ionization and electric conductivity of the air in the neighborhood of high power conductors. It was shown that the air conductivity can be increased by several orders of magnitude near the transmission line system, relative to normal conditions. In this scenario, the dielectric breakdown is favored by avalanche processes and lightning stroke probability is significantly raised.

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