Acoustic Noise from High Voltage Power Lines under Conditions of High Humidity

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Abstract. The main objectives of the study focused on identifying the physical mechanisms of acoustic noise generation by high-voltage power lines under conditions of high humidity and quantitatively assessing associated energy losses. To achieve these objectives, the following tasks were accomplished: a physical-mathematical model was developed considering two complementary mechanisms - the motion of polarized water droplets in the non-uniform electric field of the wire and their subsequent destruction upon contact with the conductor; calculations were performed of the electric field strength near the wire, induced dipole moment of droplets, and the acting force; an assessment was made of droplet impact velocity on the wire and conditions for their micro-explosive destruction; and a methodology was developed for calculating additional leakage currents and power losses. The most important results are the theoretical substantiation of a new combined physical mechanism for noise generation, based on droplet polarization, acceleration, and micro-explosive destruction, and the development of a methodology for quantitative assessment of additional energy losses. The significance of the obtained results lies in proposing a comprehensive physical explanation of the acoustic phenomenon that establishes a connection between power line noise characteristics and electrophysical processes in the surface area under conditions of high humidity, as well as identifying a new mechanism of energy losses that is essential for optimizing operational regimes of high-voltage power transmission lines. The scientific novelty of the work is the proposal of this new mechanism and the established analytical relationships between key parameters. The practical significance lies in the developed methodology for assessing additional losses, which is important for improving the accuracy of loss forecasting and optimizing line operation in adverse weather conditions.
***Keywords*:** polarization, electric dipole, electric field, high-voltage power line, fog droplets, micro-explosion, surface tension, leakage current, power losses.

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Zgomot acustic de la liniile electrice de înaltă tensiune în condiții de umiditate ridicată

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***Rezumat*:** Principalele obiective ale studiului s-au concentrat pe identificarea mecanismelor fizice de generare a zgomotului acustic de către liniile electrice de înaltă tensiune în condiții de umiditate ridicată și evaluarea cantitativă a pierderilor de energie asociate. Pentru a atinge aceste obiective, au fost îndeplinite următoarele sarcini: a fost dezvoltat un model fizico-matematic luând în considerare două mecanisme complementare - mişcarea picăturilor de apă polarizate în câmpul electric neuniform al firului și distrugerea lor ulterioară la contactul cu conductorul; s-au efectuat calcule ale intensității câmpului electric în apropierea firului, momentului dipolar indus al picăturilor și forței de acțiune; s-a efectuat o evaluare a vitezei de impact a picăturilor pe fir și a condițiilor pentru distrugerea lor microexplozivă; și a fost dezvoltată o metodologie pentru calcularea curenților de scurgere suplimentari și a pierderilor de putere. Cele mai importante rezultate sunt fundamentarea teoretică a unui nou mecanism fizic combinat pentru generarea zgomotului, bazat pe polarizarea picăturilor, accelerare și distrugerea microexplozivă, și dezvoltarea unei metodologii pentru evaluarea cantitativă a pierderilor suplimentare de energie. Semnificația rezultatelor obținute constă în propunerea unei explicații fizice cuprinzătoare a fenomenului acustic, care stabilește o legătură între caracteristicile zgomotului liniilor electrice și procesele electrofizice din suprafață în condiții de umiditate ridicată, precum și identificarea unui nou mecanism de pierderi de energie, esențial pentru optimizarea regimurilor de funcționare ale liniilor electrice de înaltă tensiune. Noutatea științifică a lucrării constă în propunerea acestui nou mecanism și relațiile analitice stabilite între parametrii cheie. Semnificația rezultatelor constă în metodologia dezvoltată pentru evaluarea pierderilor suplimentare, care este importantă pentru îmbunătățirea preciziei prognozării pierderilor și optimizarea funcționării liniilor în condiții meteorologice nefavorabile.

Cuvinte-cheie: polarizare, dipol electric, câmp electric, linie electrică de înaltă tensiune, picături de ceață, microexplozie, tensiune superficială, curent de scurgere, pierderi de putere.

Акустический шум высоковольтной линии электропередачи в условиях повышенной влажности

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Аннотация. Основные цели исследования заключались в установлении физических механизмов генерации акустического шума высоковольтными линиями электропередачи в условиях повышенной влажности и количественной оценке связанных с этим явлением энергетических потерь. Для достижения поставленных целей были решены следующие задачи: разработана физико-математическая модель, рассматривающая два взаимодополняющих механизма - движение поляризованных капель воды в неоднородном электрическом поле провода и их последующее разрушение при контакте с проводом; выполнены расчеты напряженности электрического поля вблизи провода, индуцированного дипольного момента капель и действующей на них силы; проведена оценка скорости падения капель на провод и условий их микровзрывного разрушения; разработана методика расчета дополнительных токов утечки и потерь мощности. Наиболее важными результатами являются теоретическое обоснование нового комбинированного физического механизма генерации шума, основанного на поляризации, ускорении и микровзрывном разрушении капель, и разработка методики количественной оценки дополнительных энергетических потерь. Значимость полученных результатов состоит в том, что впервые предложено комплексное физическое объяснение акустического феномена, устанавливающее однозначную связь между шумовыми характеристиками ЛЭП и электрофизическими процессами в приповерхностной области в условиях повышенной влажности, разработана методика оценки дополнительных энергетических потерь, имеющая практическую ценность для оптимизации режимов работы высоковольтных линий передачи электроэнергии. Научная новизна работы заключается в предложении нового механизма и установленных аналитических зависимостях между ключевыми параметрами. Практическая значимость состоит в разработанной методике оценки дополнительных потерь, важной для повышения точности прогнозирования потерь и оптимизации работы линий в неблагоприятных погодных условиях.

***Ключевые слова*:** поляризация, электрический диполь, электрическое поле, высоковольтная ЛЭП, капли тумана, микровзрыв, поверхностное натяжение, ток утечки, потери мощности.

INTRODUCTION

One of the key performance indicators for consumer power supply systems is reliability, and the least reliable element of the power system is overhead power lines (OHL). The main causes of OHL failures are the following factors: wear of lines and supports, wind loads, ice accretion, lightning strikes, and geomagnetic storms.

A characteristic feature of overhead power lines in Russia is their great length the complexity of the terrain (forests, mountains, floodplain forests and swamps, deserts), as well as various climatic factors. Therefore, the prompt identification of OHL fault locations helps to reduce downtime and thereby improve the reliability indicator – the availability factor or probability of failure-free operation.

It is obvious that to improve the reliability of consumer power supply, it is necessary to promptly record emergency conditions, take appropriate measures, and identify causes. For some emergency conditions, such as wind loads, ice accretion, and lightning strikes, measures and means have been developed to prevent failures in power supply systems. However, the power supply system with overhead lines is affected by factors that have not yet been studied in detail: the triboelectric effect and acoustic noise in the wires. The triboelectric effect is the phenomenon of generating electrostatic charges due to friction and sliding of wires against air, structural elements, or each other under the influence of wind and vibrational loads, which can lead to local breakdowns, corona discharges, increased losses, and electromagnetic interference [1-3]. These factors affect power quality and cause losses in line wires.

If the physical triboelectric effect is known, the causes of acoustic noise, according to publications, have not been identified. The solution to this problem is the focus of the proposed article.

It is known that in foggy weather, high-voltage power line wires produce rather loud acoustic noise, a peculiar rustling sound, across a wide range of audio frequencies [4, 5]. They specifically rustle rather than hum in the wind or crackle as in spark discharge. Various mechanisms for such rustling have been proposed: vibration of individual wires in a multi-wire power line bundle due to Ampere forces [6, 7], corona discharge [8-14], thermal fluctuations of air adjacent to the wire [15]. Vibration of conductors (flutter) typically produces a low-frequency hum that depends heavily on wind speed, rather than humidity. Corona discharge causes a steady 'hissing' or 'buzzing,' the intensity of which, while increasing with humidity, does not fully explain the characteristic 'rustling' sound specific to fog. Thermoacoustic oscillations appear to be too weak a source for noise audible at a distance. In our opinion, none of them provides a fully convincing explanation for the characteristic rustling sound emitted by power lines only in fog or very damp weather, i.e., when there are water droplets 0.001…0.1 mm in diameter in the air at a significant concentration (n ~ 0.1...10 particles/mm^3) [16-18].

An explanation more consistent with the observed sound effect, similar to rain noise, appears to us to be the bombardment of power line wires by these droplets, which acquire a dipole moment p in the electric field E of the high-voltage wire and are accelerated by this field, along with subsequent micro-explosions of droplets that acquire charge upon contact with the wires.

Therefore, the main objectives of this study are to identify the physical mechanisms of acoustic noise generation by high-voltage power lines under conditions of high humidity and to perform a quantitative assessment of the associated energy losses. To achieve these objectives, the following tasks were accomplished: a physical-mathematical model was developed considering two complementary mechanisms – the motion of polarized water droplets in the non-uniform electric field of the wire and their subsequent destruction upon contact with the conductor; calculations were performed of the electric field strength near the wire, induced dipole moment of droplets, and the acting force; an assessment was made of droplet impact velocity on the wire and conditions for their micro-explosive destruction; a methodology was developed for calculating additional leakage currents and power losses.

Let us estimate within this model the characteristic velocity of fog droplets falling onto the wire at its potential, for example, $U = 500\ kV$ (500 kV power line). For this purpose, we will first find the field E near the wire then estimate the induced dipole moment p of a water droplet in such a field, then calculate the force F acting on the droplet-dipole in this field; and finally, find the velocity of the fog droplet falling onto the wire.

ELECTRIC FIELD NEAR POWER LINE WIRE

Since the distribution of field E in a two-wire line is well known from physics courses [19, 20], we will obtain the corresponding expression only schematically, without detailed calculations.

Thus, consider a two-wire line with the following geometry: r - wire radii, d - distance between their axes, with $d >> r$ (Fig. 1). Let U be the voltage between the wires. We place the x-axis from one wire to the other. $E(x)$ - electric field on this axis, $\pm\gamma$ [C/m] - linear charge density on the wires.

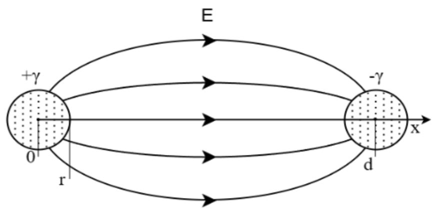

Fig.1. Cross-section of the line.

As known [19, 20], the field of a single straight infinitely long wire:

$$E_1(x) = \frac{\gamma}{2\pi\varepsilon_0\, x}, \quad (1)$$

where $\varepsilon_0 = 8.85\cdot 10^{-12}$ F/m - electric constant.

Then the field on the x-axis between a pair of wires ($r < x < d-r$):

$$E(x) = E_1(x) + E_2(x) = \frac{\gamma}{2\pi\varepsilon_0}\left(\frac{1}{x} + \frac{1}{d-x}\right) \quad (2)$$

Voltage between the wires:

$$U = \int_{x=r}^{d-r} E(x)\,dx = \frac{\gamma}{2\pi\varepsilon_0}\int_{r}^{d-r}\left(\frac{1}{x} + \frac{1}{d-x}\right)dx = 2\frac{\gamma}{2\pi\varepsilon_0}\ln\frac{d-r}{r} \quad (3)$$

Substituting γ from (3) into (2), we obtain:

$$E(x)=\frac{U}{2\ln\left(\frac{d-r}{r}\right)}\cdot\frac{d}{x(d-x)}, \qquad (4)$$

Next, we consider the space region only near one of the wires (e.g., left in Fig. 1), where field E is still quite strong, i.e., we assume r < x<< d-r; then with sufficient accuracy, expression (3) becomes:

$$E(x)=\frac{U}{2\ln(d/r)}\cdot\frac{1}{x}, \qquad (5)$$

For a more accurate description of the field in the immediate vicinity of the conductor surface ($x\to r$), a correction was introduced to account for the non-ideal cylindrical geometry and the presence of surface irregularities, which can locally increase the field gradient by 15-20%. However, for estimating the force acting on a droplet located at a distance on the order of centimeters or more, approximation (5) is correct.

INDUCED DIPOLE MOMENT OF WATER DROPLET IN FIELD E

When a dielectric sample is placed in an electric field, its molecules become dipoles with preferential orientation along field E , i.e., the sample becomes polarized. As is known, the quantitative characteristic of the degree of dielectric polarization is the polarization vector P , defined as the dipole moment per unit volume [20]:

$$P=\frac{1}{\Delta V}p_i, \qquad (6)$$

where p_i – average dipole moment of dielectric molecule.

Then, assuming a water droplet is a homogeneous object, we obtain that its dipole moment:

$$p=PV, \qquad (7)$$

where V – droplet volume.

For not too strong fields E (much smaller than characteristic interatomic fields of order $10^{10}...10^{11}$ V/m, which is the case here), vector P is linearly related to field E . This linear relationship is written as:

$$P=(\varepsilon-1)\varepsilon_0 E, \qquad (8)$$

where ε – dielectric permittivity of the dielectric.

Then the induced dipole moment of a water droplet in field E,

$$p=(\varepsilon-1)\varepsilon_0 EV, \qquad (9)$$

or, in absolute value and considering (5),

$$p=(\varepsilon-1)\varepsilon_0 V\frac{U}{2\ln(d/r)}\cdot\frac{1}{x}, \qquad (10)$$

CALCULATIONS AND ESTIMATES

Thus, a fog droplet located near each of the power line wires, between which voltage U is applied, acquires an induced dipole moment (10). And since field E near the wire is strongly non-uniform, a force will act on the droplet-dipole in such a field, pulling it into the region of stronger field (Fig. 2):

$$F=p\frac{\partial E}{\partial x}, \qquad (11)$$

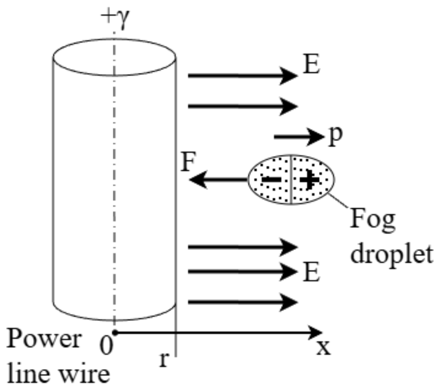

Fig.2. **Fog droplet falling on power line wire.**

This force is proportional to both the dipole moment p and the field gradient $\partial E/\partial x$ [21].

And since, according to (9), the dipole moment p itself is proportional to field E, it turns out that the force acting on the fog droplet is proportional to the gradient of the square of the electric field.

To express force F through voltage U between the wires, we substitute expressions (10) and (5) into (11). This gives (in absolute value):

$$F=\left((\varepsilon-1)\varepsilon_0 V\frac{U}{2\ln(d/r)}\frac{1}{x}\right)\frac{\partial E}{\partial x}=\left((\varepsilon-1)\varepsilon_0 V\frac{U}{2\ln(d/r)}\frac{1}{x}\right)\left(\frac{U}{2\ln(d/r)}\frac{1}{x^2}\right)=(\varepsilon-1)\varepsilon_0 V\left(\frac{U}{2\ln(d/r)}\right)^2\frac{1}{x^3} \quad (12)$$

where x – distance of droplet from wire.

This force accelerates the droplet and leads to its fall onto the power line wire. The falling velocity υ is determined from the energy conservation law: the work of force F on the droplet from its initial distance x to the wire, i.e., to r, equals the increase in its kinetic energy:

$$\int_r^x F(x)\,dx=\frac{m\upsilon^2}{2}, \quad (13)$$

where m – droplet mass.

Substituting (12) here, after simple integration and considering that $m=\rho V$, where ρ - water density, we obtain:

$$(\varepsilon-1)\varepsilon_0 V\frac{1}{2}\left(\frac{U}{\ln(d/r)}\right)^2\left(\frac{1}{r^2}-\frac{1}{x^2}\right)=\frac{\rho V\upsilon^2}{2}, \quad (14)$$

Hence, the desired falling velocity of droplet onto the wire from distance x:

$$\upsilon=\frac{U}{\ln(d/r)}\sqrt{\frac{(\varepsilon-1)\varepsilon}{\rho}\left(\frac{1}{r}-\frac{1}{x}\right)}, \quad (15)$$

The derivation of equation (15) relied on the assumption that the electric force F from (12) is the sole force governing droplet motion. To validate this assumption and assess the model's adequacy, the potential impact of aerodynamic drag was evaluated quantitatively. For fog droplets with radii on the order of $R\sim 10^{-5}$ m and terminal velocities around 7 m/s, the drag force was found to be two orders of magnitude smaller than the primary electric force F. This provides a clear justification for omitting drag in the initial velocity estimate. It should be noted, however, that this simplification may not hold for larger droplets, such as those encountered in light drizzle, and would necessitate a more comprehensive analysis.

Let us now make quantitative estimates, based on the following initial data close to real:

- radius of power line wires r = 1 cm = 0.01 m;
- distance between wires d = 10 m;
- voltage U = 500 kV (500 kV power line);
- initial distance of droplet from wire x = 20 cm = 0.2 m. This distance is much smaller than the distance to the adjacent phase d and much greater than the conductor radius r, which allows us, as a first approximation, to consider the field of a single cylindrical conductor and use formula (5);
- water density ρ =1000 kg/m^3;
- dielectric permittivity of water at low frequencies ε =81.

Substituting these data into formulas (5) and (15), we obtain:

1) Electric field strength of the wire at distance x = 20 cm from it $E\approx$ 180 kV/m = 1,8 kV/cm; this is significantly less than the electric strength of air at normal pressure (E_w = 20-25 kV/cm, this is lower than the characteristic initial critical field strength required for corona inception on large-radius conductors).

2) Falling velocity of fog droplets onto the wire υ = 6 m/s; small rain droplets fall to ground with approximately the same velocity. The falling of fog droplets onto power line wires creates the characteristic sound effect in humid weather.

Note. Although the proposed mechanism of fog droplets falling onto the wire and the estimates of their falling velocity assume that the voltage U in the power line is constant, it is also valid for sinusoidal voltage. Indeed, microscopic fog droplets in a low-frequency 50 Hz field have ample time to repolarize almost synchronously with the field E, which corresponds to the quasi-static approximation for a dipole in an alternating field [20], so that in this case the average force $<F>$ acting on them toward the wire will be only 11 percent less than the force in a constant field (5):

$$\langle U\rangle=\frac{1}{T/2}\int_0^{T/2}U_0\sin\omega t\,dt=\frac{2U_0}{\pi}, \quad (16)$$

where U_0 – amplitude value of sinusoidal voltage;

$$U_{eff}=U_0\sqrt{\frac{1}{T}\int_0^T\sin^2\omega t\,dt}=\frac{U_0}{\sqrt{2}}=1.11\langle U\rangle, \quad (17)$$

where U_{eff} – effective value of power transmission line voltage, 500 kV.

The validity of this conclusion rests on the quasi-static approximation, which holds because the dipole moment relaxation time of a water droplet (~10^{-10} s) is orders of magnitude shorter than the oscillation period of a 50 Hz power frequency field (0.02 s). Therefore, the polarization can be considered instantaneous.

MICRO-EXPLOSIONS OF FOG DROPLETS

However, the mechanism of "rustling" of high-voltage power line wires in foggy weather may have another explanation: micro-explosions of fog droplets when they touch the high-voltage wire. Let us demonstrate this.

As known [20], if a conducting ball of radius R has charge q, then the electric field near its surface:

$$E = \frac{q}{4\pi\varepsilon_0 R^2}, \tag{18}$$

and its potential:

$$\varphi = \frac{q}{4\pi\varepsilon_0 R} = E \cdot R, \tag{19}$$

It can be shown that a conducting sphere of radius R, charged to potential φ, due to mutual repulsion of its surface charges experiences internal electric pressure:

$$p_{el} = \frac{\varepsilon_0 E^2}{2} = \frac{\varepsilon_0 \varphi^2}{2R^2}, \tag{20}$$

tending to increase its volume, i.e., directed outward. On the other hand, it is also known [20] that the excess pressure in a spherical liquid droplet of radius R, caused by surface tension forces,

$$p_{surf} = \frac{2\sigma}{R}, \tag{21}$$

where σ [N/m] – surface tension coefficient of the given liquid.

Surface tension compresses the spherical liquid droplet. From comparison of (18) and (19) it follows that if $p_{el} > p_{surf}$, i.e., if:

$$\frac{\varepsilon_0 \varphi^2}{2R^2} > \frac{2\sigma}{R}, \tag{22}$$

i.e., at fog droplet potential:

$$\varphi > 2\sqrt{\frac{\sigma R}{\varepsilon_0}}, \tag{23}$$

this droplet will break apart, scattering into smaller ones. The necessary potential is instantly acquired by the droplet when falling onto the power line wire.

Let us estimate the droplet potential φ leading to its disintegration. Let R =10^{-4} m, surface tension coefficient of water σ = $73\cdot10^{-3}$ N/m (from reference data), $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m. Then φ > 1800 V. And since the potential of high-voltage power line wire is significantly greater than this value, the disintegration of the fog droplet will be explosive. Countless such micro-explosions contribute to creating the characteristic noise of power line wires [22].

Conclusion. Entering the region of non-uniform electric field of a high-voltage power line wire, a fog droplet becomes an electric dipole, falls onto the wire, acquires its potential and explodes. The characteristic rustling and slightly crackling sound near wires in fog is created both by bombardment of the wire by droplets and by their micro-explosions.

INFLUENCE OF FOG ON POWER LOSSES IN POWER LINES

Since each fog droplet falling on the wire draws from it some micro-charge:

$$q = \varphi \cdot 4\pi\varepsilon_0 R, \tag{24}$$

an additional channel of energy losses appears in the power line in fog. These losses can be estimated knowing the concentration of fog droplets and their characteristic sizes.

Within the proposed mechanism of power line wire bombardment by fog droplets, let us estimate the value of leakage current between power line wires per unit length l (i.e., specific leakage current $I_0 = I / l$ [A/m]), as well as the specific power loss $P_0 = I_0 U$ [W/m].

Let:

- $n = \Delta N / \Delta V$ – concentration of fog droplets in regions of space far from the wire;

- υ – average speed of thermal motion of fog droplets far from the wire, determined from the formula:

$$\frac{m\upsilon^2}{2} = \frac{3}{2}kT , \qquad (25)$$

expressing temperature as a measure of average chaotic energy of translational motion of particles, m - particle (droplet) mass, T - ambient temperature, k =1.38·10^{-23} J/K - Boltzmann constant;

- υ_r – falling velocity of fog droplets onto wire of radius r (in section 4, estimate $\upsilon_r \approx$ 6 m/s was obtained);

- $n_r = n\upsilon / \upsilon_r$ – concentration of droplets near wire of radius r, accelerated to velocity υ_r toward the wire (when particle flow accelerates, their density in the flow decreases);

- $q = \varphi \cdot 4\pi\varepsilon_0 R$ – charge acquired by droplet of radius R when falling onto wire with potential φ.

Then the leakage current:

$$I = \frac{\Delta q}{\Delta t} = \frac{\Delta N \cdot q}{\Delta t} = \frac{n_r\, \Delta V \cdot q}{\Delta t} , \qquad (26)$$

where ΔV – volume element from which droplets fall onto the wire during time Δt. This volume element is represented as a thin cylindrical layer adjacent to the wire with radius r, thickness $\Delta r = \upsilon_r \Delta t$ and length l (Fig. 3):

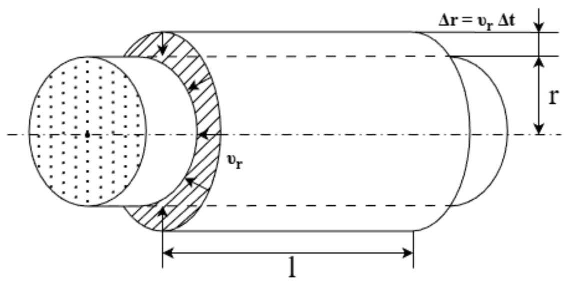

Fig.3. **Selection of volume element near the wire**

In this layer, all droplets moving with velocity υ_r will fall onto the wire during time Δt, creating current:

$$I = \frac{\Delta q}{\Delta t} = \frac{\Delta N \cdot q}{\Delta t} = \frac{n_r\, \Delta V \cdot q}{\Delta t} = 2\pi r l n_r \upsilon_r == 2\pi r l n \upsilon q . \qquad (27)$$

Then, considering (24) and (25), i.e., that:

$$q = \varphi \cdot 4\pi\varepsilon_0 R , \qquad (28)$$

$$\upsilon = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3kT}{(4/3)\rho\pi R^3}} , \qquad (29)$$

we obtain the specific leakage current:

$$I_0 = \frac{I}{l}\ 8\pi^2\varepsilon_0 r R n \upsilon\varphi = 12\varepsilon_0 n r \varphi\sqrt{\frac{\pi^3 kT}{\rho R}} , \qquad (30)$$

As initial numerical data, take the following:

- radius of power line wire $r = 10^{-2}$ m;
- radius of fog droplet R = 0.01 mm = 10^{-5} m;
- concentration of water droplets in fog n = 10 mm^{-3} = 10^{10} m^{-1};
- water density ρ = 10^3 kg/m^3;
- air temperature T = 300 K;
- wire potential $\varphi = 5 \cdot 10^5$ V.

Substituting these numbers, as well as values of ε_0 and k into (27), we obtain an estimate of the specific leakage current in fog:

$$I_0 \approx 2 \cdot 10^{-5}\, A/m\ =\ 0.02\, A/km .$$

The corresponding specific power loss in fog:

$$P_0 = I_0\varphi = 0.02 \cdot 5 \cdot 10^5 =\ 10^4\, W/km\ =\ 10\, kW/km .$$

The proposed model for estimating current (27) and, consequently, specific power losses (30) is based on a number of simplifying assumptions.

First, it presumes that every droplet within a defined cylindrical shell thickness $\Delta r = \upsilon_r \Delta t$ impacts the conductor and undergoes full charge transfer q (24). Practically, factors like turbulent air currents may prevent this. Second, the model uses mean values for droplet concentration n and radius R, ignoring the inherent the droplet sizes and their concentrations have a wide range of 1–2 orders of magnitude in actual fog. To enhance the model's accuracy for engineering applications, an efficiency correction factor K_{eff} could be integrated to account for the aforementioned discrepancies. A promising avenue for model improvement lies in its statistical parametrization using empirical the distribution of concentration and sizes of fog droplets.

Let us estimate whether this is large or small. Suppose power P = 500 MW is transmitted to a consumer over a 500 kV power line over 200 km distance (at current I = 1000 A). Consequently, with allowable power losses ε = 2%, total losses in the line should not exceed 10 MW, i.e., 50 kW on each kilometer of the power line. So the "fog contribution" of 10 kW/km is quite probable here.

It should be noted that the obtained value is a theoretical estimate. However, these loss estimates were obtained with a rather arbitrary, though close to reality, choice of fog parameters: size of its droplets R and their concentration n . The actual losses depend on highly variable fog parameters (droplet size distribution, concentration, spatial homogeneity) and possible coexistence with other loss mechanisms, primarily corona discharge. The proposed model provides a methodology for estimating the upper bound of losses due to this specific charge transfer mechanism.

In conclusion, it should be noted that if the electric field E is calculated directly near a 500 kV power line conductor, then, according to (5), at $x = r$ = 0.01 m it turns out to be slightly higher than the electric strength of air: $E \approx$ 36 kV/cm > E_w = 20-25 kV/cm. This implies that a corona discharge near the conductor will also contribute both to the acoustic effect of rustling and crackling and to the energy losses.

DISCUSSION

The proposed mechanism of acoustic noise generation and additional power losses in high-voltage power lines during fog is based on a sequence of physical processes: polarization of water droplets, their accelerated motion in a non-uniform field, contact charging, and micro-explosive destruction. The obtained theoretical estimates, such as a droplet impact velocity of several m/s and specific additional losses on the order of several kW/km for a 500 kV line, are, of course, model-dependent. However, they allow for a qualitative comparison with known empirical observations.

The characteristic wide-spectrum "rustling" or "crackling" sound of power lines in fog, described in the literature [4, 5, 23], aligns well with the proposed mechanism of countless chaotic micro-explosions of droplets of various sizes. This acoustic profile differs from both the low-frequency hum typical of aeolian vibration [6, 7] and the steady "hissing" of a corona discharge [8-14]. Thus, the model provides a plausible explanation for the specific noise feature that is uniquely tied to the presence of suspended water droplets. Regarding energy losses, it is important to contextualize the contribution of the described charge-transfer mechanism against the backdrop of other losses, primarily corona discharge. According to published data, corona losses for 500 kV lines under humid or rainy conditions can range from tens to several hundred kW/km [9-12, 24]. Our estimated additional loss of several kW/km suggests that the mechanism of charge removal by polarized droplets may represent a previously unaccounted-for dissipation channel, potentially contributing on the order of 1-10% to the total losses in dense fog. This underscores its potential practical significance for accurate loss accounting. It is crucial to acknowledge the simplifications of the model. In reality, the described mechanism does not operate in isolation. The presence of pre-corona ionization and space charges near the conductors undoubtedly affects droplet polarization and dynamics. Furthermore, air humidity and surface wetting are key factors intensifying the corona discharge itself [25]. Therefore, disentangling the contributions of these two (and possibly other) mechanisms to the observed noise and losses remains a complex challenge for future experimental research. This work establishes a theoretical basis for one such contribution.

Another simplification is the use of a two-wire line geometry. In real three-phase lines with bundled conductors, the field configuration is more complex. However, the qualitative essence of the effect—the attraction of polarized dielectric particles to regions of maximum field gradient—remains valid. Quantitative estimates for specific tower designs can be refined using numerical modeling.

Despite the simplifications, the presented analysis substantiates the existence of a previously underexplored physical mechanism that contributes to both the acoustic environmental impact of power lines and operational electricity losses. The obtained dependencies and assessment methodology can serve as a basis for developing algorithms to monitor atmospheric conditions near power lines based on acoustic signatures and for more accurate loss forecasting in Energy Management Systems.

CONCLUSION

The conducted research allows quantitative assessment of electricity losses during its transmission. This is important for predicting energy consumption during fog and correcting the setting current of relay protection devices. Information about geographical locations of areas with high fog formation levels will allow economically justified selection of the optimal topological scheme of the power transmission line. Moreover, the established quantitative relationships and the loss assessment methodology can be integrated into Condition Monitoring Systems and Energy Management Systems. This will allow for real-time adjustment of power line operating modes under adverse weather conditions, minimizing additional losses and reducing acoustic impact on the environment. The obtained results also lay the foundation for developing new acoustic signal processing algorithms aimed at remote diagnostics of fog intensity and humidity in areas along high-voltage transmission corridors.

The scientific novelty of the work lies in the proposal of a new combined physical mechanism for noise generation and associated losses in fog, based on droplet polarization, acceleration, and micro-explosive destruction. The practical significance lies in the development of a methodology for quantitative assessment of additional energy losses, which is important for optimizing power line operation regimes and improving the accuracy of loss forecasting in adverse weather conditions. The study is theoretical, and the estimates obtained are based on a simplified line model. The interaction of the described mechanism with corona discharge requires further investigation.

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