Corona Discharge Loss Reduction Method Developed on the Basis of a Three-Dimensional Model of Power Line Strength

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***Abstract*—An analysis of corona losses in extra-high voltage networks was carried out. It was found that corona losses constitute a significant part of losses in power lines. A method of calculating the electric field strength on the overhead line wire, taking into account its sag, has been developed. The obtained results make it possible to assume that the value of corona losses is not uniformly distributed along the length of the span. In the vicinity of the suspension point, the corona intensity is the highest and decreases until a certain distance along the wire, and then tends to increase again. The obtained values of intensities show that if we exclude the possibility of corona on the wire sections with the highest intensity, then the losses on the line span are reduced by 10%. The variants of reduction of working electric field intensity on the surface of overhead line wires are considered.**

Keywords—transmission line, corona losses, electric field strength, power line capacitance, height of wire suspension, power line support, protective coated wires.

I. Introduction

Among the current trends in the world there is a desire to improve the efficiency of production, transmission and consumption of electricity. This statement can be confirmed by the example of eco-design of transformers implemented in Ukraine [1]. One of the priority tasks of optimization of power networks is to optimize the operation of transmission lines, because their share in the total amount of electricity losses in Ukraine is the largest part of the total amount of electricity losses. Power transmission line losses can be divided into heating losses and corona losses. Heating losses are related to the design of the overhead line and its load (current). For a particular line, the wire cross-section determines its ohmic impedance and, accordingly, the heat loss. In the case of corona losses, the situation is slightly different. This type of loss depends on the voltage on the line and the radius of the wire used. It would seem that the corona losses should be constant at the nominal voltage. However, this type of loss depends not only on the voltage of the line but also on its structural design. The corona start strength of a transmission line is rated and the annual average corona losses are calculated using the rated strength. However, such a calculation does not take into account the possibility of changes in this intensity along the length of the span.

II. Analysis of Existing Solutions

Common solutions to reduce technical losses in transmission lines are to choose the optimal cross-section, to increase the number of components in the line and to choose the effective support spacing [2]. However, it is obvious that this is not enough to achieve the lowest possible losses.

In real operation conditions, there are a number of objective restrictions that do not allow to provide these conditions. In particular, an increase in the number of components in the phase will lead to complication of the phase design, which will cause the need to increase the mechanical strength of the support structure, which, in turn, will affect its cost.

Paradoxically, the second method, if used incorrectly, can only increase the level of losses, as will be discussed below.

The problem of economical operation of 220 kV grids and above at their low load is currently related not only and not so much to losses in wires from load currents, as to corona losses. The average annual losses of power and energy on the corona of ALs 330 and 500 kV make 12%, and those of AL 750 kV - 14% of the total losses (on the corona and from the load currents), while the losses in the wires are calculated for the natural power Pnat. Since in reality, the average overhead line loads are two times less than Pnat, the corona losses of 330 and 500 kV overhead lines will amount to 35 %, and those of 750 kV overhead lines to 39 % of the total losses. Power losses to the corona depending on the type of weather vary by 1-2 orders of magnitude, so it is most effective to reduce their maximum values, which take place during frost, rain and snow. Under these conditions, the reduction of power and energy losses in the grid will be determined mainly by the reduction of losses on the corona. Specific corona losses under different climatic conditions are obtained by experimental methods and given in the relevant tables of reference books and guidelines for accounting corona losses.

In contrast to load losses, corona losses are of a different nature and are determined by the peculiarities of operation of overhead insulation of power transmission lines. Measures Subscribe to DeepL Pro to edit this document. Visit www.DeepL.com/pro for more information. aimed at reduction of corona losses are also of a special nature, the basis of which are various methods of regulation of the operating voltage of the network. It is obvious that under market conditions compensation of energy losses due to corona should be formed according to other rules than for load losses. According to the Law "On electric power", grid companies pay for power losses in their grids with the exception of those losses that depend on load and are included in the nodal prices for electric power. Commercial and conditionally constant technological losses, including corona losses, are paid by consumers. The source of funds to pay for this component of losses is the grid tariff. The norm for losses is established by the tariff services and all deviations from it are included in profit or losses, which should determine the interest of grid companies in losses reduction. Today different methods of evaluation and decrease of load losses in 110-6,10 kV power grids are developed. In contrast to the load component of electric power losses, corona losses require further research and improvement of accounting methods. The main weather factors, decisively influencing the value of power losses, do not have clear boundaries in identification, which reduces the reliability of calculation methods.

The proposed new types of combined lines [3] are insufficiently tested in real operating conditions, which does not allow us to claim that they are a comprehensive solution to the problem.

III. Calculation of corona losses

As was shown above, the share of corona losses in the value of total losses is rather high. Reducing such losses by 10% gives a reduction in total losses by 1% on average. In our opinion, simple and economically justified solutions to reduce corona losses are promising.

Many works are devoted to the reduction of corona losses. As a rule, all such works involve voltage regulation on power lines and obtaining the effect by reducing the field strength on the wires. In our case, the design features of transmission line construction are considered. All calculations of field strength on power transmission line wires are made on the assumption that the wire is located at a certain fixed height from the ground. When a wire is so placed, its capacitance is calculated, and then the field strength on its surface is calculated. However, this is not the case in real life. The wire is not positioned parallel to the ground. It has several characteristic suspension points, which include the attachment point of the wire to the garland and the point of maximum overhang located at a height corresponding to the height of the line to the ground. In the case of large conductor lengths, these distances are significantly different.

Calculations carried out by us and other authors, for example in [4], have shown that the stress distribution along the span length is a variable value.

Using the author's program "PLE-1" created on the basis of Mathcad software, the calculations of intensity distribution along the length of transmission line span were performed. The intensity distribution along the line length of 380 m is shown in Figure 2.

The results of the calculations shown in Fig. 2 clearly show that the strength varies quite significantly along the span length, approximately by 10%. This allows us to assume that the value of power losses for the corona will change if the corresponding voltage distribution is taken into account. In addition to the sag of wires, when calculating power losses for the corona, it is necessary to take into account the presence of current-carrying objects in the vicinity of the transmission line wires.

Corona power losses can be reduced by decreasing the field strength on the wire, which slows down or stops the process of ambient air ionization and reduces the number of electrons that determine the corona current. The same effect can be achieved by coating the wire with a dielectric dielectric whose permittivity is different from 1. Such coating will stop the process of ambient air ionization and practically eliminate the corona discharge on the wire. This fact is the reason for the use of coated wires on power lines of all voltage classes. Along the length of transmission lines there may be areas with increased corona discharge. Such areas are, for example, mountain crossings or areas with frequent fog. The increased corona losses in such sections are due to changes in weather conditions unfavourable in terms of corona discharge development (fog, increased humidity). Applying protective conductors in such sections can significantly reduce corona losses in the whole line. An example of such lines could be the 330 kV overhead lines passing through the Carpathians. When fog appears, the losses in these lines increase by a factor of 10-15 and can be compared with the heating losses of these lines.

$$\mathrm{ORIGIN} := 1$$

$$\mathrm{LF}(l,f,d) := \left| \begin{array}{l} lf \leftarrow (d-1)\cdot(3-d)\cdot l + f\cdot\left[(d-2)\cdot\dfrac{d-1}{2}\right] \\ lf \end{array} \right.$$

$$\mathrm{CE}(a,He,do,n,ro,U) := \left| \begin{array}{l} nf1 \leftarrow n \\ nf2 \leftarrow n \\ nf3 \leftarrow n \\ n2f \leftarrow nf1 + nf2 \\ np \leftarrow nf1 + nf2 + nf3 \\ \alpha \leftarrow \dfrac{2\cdot\pi}{n} \\ rr \leftarrow \dfrac{\frac{a}{200}}{\sin\left(\frac{\alpha}{2}\right)} \quad \text{if } a \neq 0 \\ rr \leftarrow 0 \quad \text{otherwise} \\ HET \leftarrow \dfrac{n}{2} \\ Man \leftarrow HET - \mathrm{floor}(HET) \\ \text{if } Man \leq 0 \\ \quad \left| \begin{array}{l} \text{for } i \in 1..np \\ \quad \left| \begin{array}{l} h_i \leftarrow rr\cdot\cos\left[\pi - \alpha\cdot(i-1) + \dfrac{\alpha}{2}\right] \\ D_i \leftarrow rr\cdot\sin\left[\pi - \alpha\cdot(i-1) + \dfrac{\alpha}{2}\right] \end{array} \right. \end{array} \right. \end{array} \right.$$

```
        h_i ← He − h_i
        if i > n
            D_i ← do + D_i  if i ≤ 2·n
            D_i ← 2·do + D_i  if i > 2·n
    D
if Man > 0
    for i ∈ 1..np
        h_i ← rr·cos[π − α·(i − 1)]
        D_i ← rr·sin[π − α·(i − 1)]
        h_i ← He − h_i
        if i > n
            D_i ← do + D_i  if i ≤ 2·n
            D_i ← 2·do + D_i  if i > 2·n
    D
Emx ← 0
for i ∈ 1..np
  for j ∈ 1..np
    if i ≠ j
        dr_i,j ← sqrt((D_i − D_j)^2 + (h_i − h_j)^2)
        hr_i,j ← sqrt((D_i − D_j)^2 + (h_i + h_j)^2)
    otherwise
        dr_i,j ← ro/200
        hr_i,j ← 2·h_i
for d ∈ 1..3
    nf ← 1 + LF(nf1, nf1 + nf2, d)
    kf ← nf1 + LF(nf2, nf2 + nf3, d)
    u1_d ← 1 − LF(1, 1, d)·1.5
    u2_d ← −0.5 + LF(1, 0, d)·1.5
    u3_d ← −0.5 + LF(0, 1, d)·1.5
    for m ∈ 1..np
      for k ∈ 1..np + 1
        if k ≠ np + 1
            ko_m,k ← ln(hr_m,k / dr_m,k)
            V_m,k ← ko_m,k
        otherwise
          if m ≤ nf1
              C1 ← m
              ko_m,k ← u1_d
              Z_m ← u1_d
          if (m > nf1)·(m ≤ n2f)
              ko_m,k ← u2_d
              Z_m ← u2_d
          if (m > n2f)·(m ≤ np)
              ko_m,k ← u3_d
              Z_m ← u3_d
          ko
        ko
    K ← lsolve(V, Z)
    qs ← 0
    qm ← 0
    for i ∈ nf..kf
        fn ← nf
        fk ← kf
        qs ← qs + K_i/(fk − fn + 1)
    for j ∈ nf..kf
        pq_j ← (K_j − qs)/(qs·100)  if K_j < qm
        otherwise
            qm ← K_j
            iq ← j
    qs ← 55.56·qs
    qm ← qm·55.56·U·0.81649·10^−9
    fk ← kf
    Cf_d ← qs·(fk − fn + 1)
    z ← 1
    for j ∈ nf..kf
        Ex ← 0
        Eh ← 0
```

$$\text{for } i \in 1..n$$
$$\quad \text{for } k \in 1..2$$
$$\qquad k1 \leftarrow -1 \quad \text{if } k < 2$$
$$\qquad k1 \leftarrow 1 \quad \text{otherwise}$$
$$\qquad \text{if } (i \neq j)\cdot(k1 \neq -1)$$
$$\qquad\quad t \leftarrow \left(D_i - D_j\right)^2 + \left(h_i + k1\cdot h_j\right)^2$$
$$\qquad\quad Ex \leftarrow Ex - \frac{k1\cdot K_i\cdot\left(D_i - D_j\right)}{t}$$
$$\qquad\quad Eh \leftarrow Eh - \frac{k1\cdot K_i\cdot\left(h_j + k1\cdot h_i\right)}{t}$$
$$\qquad \text{break} \quad \text{otherwise}$$
$$Em_j \leftarrow 2\cdot\sqrt{Ex^2 + Eh^2} + \frac{K_j}{\frac{ro}{100}}$$
$$\text{if } Emx < Em_j$$
$$\quad Emx \leftarrow Em_j$$
$$\quad iE \leftarrow j$$
$$Em_j \leftarrow Em_j\cdot U\cdot 0.81649\cdot 10^{-2}$$
$$K_j \leftarrow \left(K_j\cdot\frac{U}{1.2247\cdot 10^{-3}}\right)\cdot 0.5556\cdot 10^{-10}$$
$$z \leftarrow 1$$
$$Emx \leftarrow Emx\cdot U\cdot 0.81649\cdot 10^{-2}$$
$$rez \leftarrow \begin{pmatrix} iq \\ qm \\ iE \\ Emx \\ Cf_1 \\ Cf_2 \\ Cf_3 \end{pmatrix}$$
$$rez$$

$$Hpod(F, Hpp, Lpr, a, d, no, ro, U, Ek) :=$$
$$hg \leftarrow 1$$
$$N \leftarrow \frac{Lpr}{hg}$$
$$\text{for } i \in 1..N$$
$$\quad k_i \leftarrow \frac{-Lpr}{2} + (i - 1)$$
$$\quad H_i \leftarrow \left(k_i\right)^2\cdot\frac{Hpp}{\left(\frac{Lpr}{2}\right)^2} + (Hpp\cdot$$
$$\quad He \leftarrow H_i$$
$$\quad G \leftarrow CE(a, He, d, no, ro, U)$$
$$\quad rez_{i,1} \leftarrow d$$
$$\quad rez_{i,2} \leftarrow no$$
$$\quad rez_{i,3} \leftarrow He$$
$$\quad rez_{i,4} \leftarrow G_1$$
$$\quad rez_{i,5} \leftarrow G_2$$
$$\quad rez_{i,6} \leftarrow G_3$$
$$\quad rez_{i,7} \leftarrow G_4$$
$$\quad rez_{i,8} \leftarrow G_5$$
$$\quad rez_{i,9} \leftarrow G_6$$
$$\quad rez_{i,10} \leftarrow G_7$$
$$\quad rez$$
$$CA \leftarrow \frac{\sum_{i=1}^{N} rez_{i,8}}{N}$$
$$CB \leftarrow \frac{\sum_{i=1}^{N} rez_{i,9}}{N}$$
$$CC \leftarrow \frac{\sum_{i=1}^{N} rez_{i,10}}{N}$$
$$Co \leftarrow \frac{CA + CB + CC}{3}$$
$$zv \leftarrow \frac{3436.4}{Co}$$
$$Pn \leftarrow \frac{U^2}{zv\cdot 10^{-3}}$$
$$rez_{N+1,11} \leftarrow CA$$
$$rez_{N+1,12} \leftarrow CB$$
$$rez_{N+1,13} \leftarrow CC$$
$$rez_{N+1,14} \leftarrow Co$$
$$rez_{N+1,15} \leftarrow zv$$
$$rez_{N+1,16} \leftarrow Pn$$
$$rez$$

```
PR := | a ← 30
      | F ← 12
      | Hpp ← 10
      | Lpr ← 380
      | ro ← 21.6/20
      | U ← 500
      | no ← 4
      | d ← 5
      | μ ← 0.8
      | δ ← 1.05
      | Ek ← 24.5·μ·δ·[1 + 0.613/(δ·ro)^0.4]
      | Hpp ← Hpp + 2·F/3
      | T ← Hpod(F,Hpp,Lpr,a,d,no,ro,U,Ek)
      | T
```

Fig. 1. The body of the "PLE-1" program

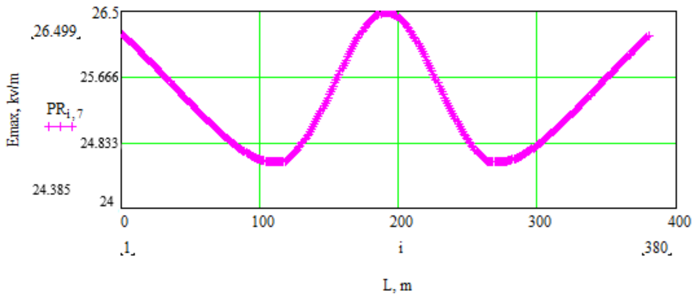

Fig. 2. Dependences of the maximum intensity value on the line span length.

The effectiveness of this solution can be evaluated on the basis of Peak's law:

$$P = \frac{24,1}{\delta}\; f + 25 \;\; \overline{S} \;\; U_F - \;\; 21,2\delta \ln\frac{S}{r_0} m_1 m_2 \;\;{}^{2}\;\; 10^{-5}, kWh/km$$

where δ - relative air density; f - frequency, Hz; r_0 - radius of a single wire, cm; S - distance between wires, cm; U_F - effective value of phase voltage, kV; Uc - corona voltage, kV;

Based on this, we will formulate a formula to determine the efficiency of using the dielectric layer to reduce corona losses:

$$P_{rated} = \frac{24,1}{\delta_{air}}\; f + 25 \;\; \overline{S} \;\; U_F - \;\; 21,2\delta \ln\frac{S}{r_0} m_1 m_2 \;\;{}^{2}\;\; 10^{-5} \;\; l_{span} - \frac{24,1}{\delta_{diel.}}\; f + 25 \;\; \overline{S} \;\; U_F - \;\; 21,2\delta \ln\frac{S}{r_0} m_1 m_2 \;\;{}^{2}\;\; 10^{-5} \;\; * l_{diel.\ sect.}$$

IV. Conclusions

The electric field strength on the conductor surface depends on the location of the line and its structural design.

Calculation based on the formula above showed the reduction of total line losses from 12,304% to 20% depending on the characteristics of the transmission line, which suggests that an additional dielectric layer on the section of the conductor with high voltage is an effective measure to reduce losses in the power system, which confirms the relevance of the use of conductors with protective coating to reduce losses on the corona

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