Addressing Uncertainties for Accurate Determination of Corona Power Loss of HVDC Power Lines

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Abstract- **Accurate determination of corona power loss on HVDC power lines usually represents a difficult problem for utilities. This is due to the numerous uncertainties associated with the corona phenomena. Such uncertainties may include line clearances values, conductor surface coefficient and atmospheric conditions. Interval mathematics provides a tool for the practical implementation and extension of the "Unknown but Bounded" concept. The paper presents the application of Interval Mathematics to, rigorously, address uncertainties associated with corona losses. While several methods exist to determine corona power loss, these methods usually require data which may be uncertain in nature. To account for such uncertainties, the interval mathematics is developed with the integration of input parameters' uncertainties, in interval format, into the governing expressions earlier by several electric utilities. The effects of uncertain inputs within the proposed model are examined for various assumed levels of overall uncertainties. To assess the relative contribution of each uncertain input, an interval sensitivity analysis is carried out. Electric field upon the conductor surface, corona current and corona power loss values are calculated using the traditional single point numbers as well as interval numbers. The values from the two methods are compared to prove the validity of interval analysis to, practically, model uncertainties associated with HVDC transmission lines corona loss analysis. Successful implementation of the proposed method is described for two geometries; monopolar and bipolar dc lines.**

I. INTRODUCTION

Corona power losses are one of the major issue concerning the design and/or analysis of HVDC overhead transmission lines. These losses depend mainly on the voltage type, line clearances values, conductor surface coefficient and atmospheric conditions [1-8]. Clearances are employed to ensure all activities in the vicinity of energized lines are adequately insulated to allow that activity and the overhead lines to coexist. Typically, utilities assign a deterministic value for the mechanical clearance buffer based on historical practices, field study, and engineering judgment [9]. Dirt, contaminations and bugs on the conductor surface, damage during construction/transportation, moisture on the conductor affect the roughness factor of the conductor [7]. Atmospheric conditions are very significant for corona power losses on transmission lines operation as humidity and hoar frost increase these losses [5, 6]. As a result, there are many uncertainties associated with utility decisions in this regard. These values should be treated as uncertain as it is no longer valid to assume that the input parameters are known with certainty. Utilities need to understand the potential effects of variations in these parameters on the final outcome of their studies.

Uncertainty can be looked upon as a condition in which the possibility of errors exists as a result of having less than total information about the surrounding environment. They are beyond the utility's foreknowledge or control. Substantial uncertainties exist concerning HVDC transmission line clearances, conductor roughness factor, the atmospheric conditions and associated environmental effects which in turn may affect the electric field in the vicinity of the lines, corona current and corona power loss. The reasons for the variations in transmission line clearances are numerous including environmental conditions, loading conditions, deviations during the design and erection stages, or simply errors in measurements [8-11]. Similarly, conductor roughness factor is changed due to the environmental conditions, surface contaminations and the aging of the conductors. Also, temperature and pressure are naturally varied according to the seasonal atmospheric conditions. The observation of atmospheric variable effects on corona loss is further complicated by the fact that no single weather factor occurs by itself but rather in every changing combinations and quantities with other weather factors [10]. Consequently, the validity of the results generated is questionable.

Modeling uncertainty in utility calculations can be based on two general approaches [12-16]. The first is a probabilistic approach where probability distributions for all of the uncertainties are assumed. The second approach is called "Unknown but Bounded" in which upper and lower limits on the uncertainties are assumed without a probability structure. A probability distribution may be assumed in some cases since no particular distribution is known, all values are assumed to be equally likely between given limits. In this type of situation a uniform distribution is the most appropriate. Another approach to modeling uncertainty is referred to as unknown but bounded. In this case upper and lower bounds on the uncertainties are assumed without probability distributions. The concept was defined in general in earlier references [12-16]. Interval mathematics provides a powerful tool for the practical implementation and extension of the unknown but bounded concept. Confidence intervals cannot be calculated in this case because there are no probability distributions. However, probability intervals can still be developed [13].

The uncertainties associated with transmission lines electric fields and corona loss analysis could be more effectively understood if the input parameters were treated as interval numbers whose ranges contain the uncertainties in those parameters. The resulting computations, carried out entirely in interval form, would then literally carry the uncertainties associated with the data through the analysis. Likewise, the final outcome in interval form would contain all possible solutions due to the variations in input parameters. Thus, it is possible to perform sensitivity analysis by assigning interval bounds to any or all of the input parameters and observing the effects on the final interval outcome.

This paper presents the application of interval mathematics as a new method to address uncertainties associated with corona losses of HVDC transmission lines. Uncertainties in the parameters are integrated into the governing expressions formulated by N. Knudson, Anneberg HVDC testing stations, as interval numbers, to determine the interval maximum conductor surface gradient, interval corona current and interval corona power loss. These values are calculated using the traditional single point numbers as well as interval numbers. A comprehensive uncertainty level analysis is presented. The relative significance of each uncertain input is established through an interval sensitivity analysis. In this study, two configurations for monopolar and bipolar HVDC transmission lines are tested and encouraging results are reported.
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II. INTERVAL MATHEMATICS

Interval mathematics provides a useful tool in determining the effects of uncertainty in parameters used in a computation. In this form of mathematics, interval numbers are used instead of ordinary single point numbers. An interval number is defined as an ordered pair of real numbers representing the lower and upper bounds of the parameter range [13]. An interval number can then be formally defined as follows: [a. b], where $a \leq b$. In the special case where the upper and lower bounds of an interval number are equal, the interval is referred to as a point or degenerate interval. In this case, interval mathematics is reduced to ordinary single point arithmetic.

Given two interval numbers, [a, b] and [c, d], the rules for interval addition, subtraction, multiplication, and division are as follows:

$$[a, b] + [c, d] = [a + c, b + d] \qquad (1)$$
$$[a, b] - [c, d] = [a-d, b-c] \qquad (2)$$
$$[a,b]*[c,d] = [min(ac,ad,bc,bd), max(ac,ad,bc,bd)] \qquad (3)$$
$$(a,b] / [c,d] = [a,b] * [l/d, l/c], \quad where\ 0 \notin [c, d] \qquad (4)$$

Implementing interval analysis techniques confronts some obstacles because its algebraic structure is unlike that of common single point arithmetic. Accordingly, interval computations may produce wide bounds [12-16].

Given a set of interval input parameters, the bounds of the resulting interval computations may depend on the calculation procedure as well as the input parameters. Therefore, an effort has to be made to reduce the width of the resulting interval bounds. Normally, the approach to produce better bounds has been to rearrange the expression so that each interval parameter appears only once in the equation [12, 13].

III. METHOD OF CALCULATION FOR HVDC TRANSMISSION LINES FIELDS AND CORONA LOSS

HVDC transmission lines ionized fields and corona loss have been a source for economic, environmental and biological public concerns [8,10,11]. Calculation of HVDC fields, even without space charges, is important to determine the ionized field quantities and corona power loss. The calculation of HVDC fields and corona power loss are solved here using interval mathematics. Electric field, corona current and corona power loss values are calculated using the traditional single point numbers as well as interval numbers. The values from these two methods are compared to prove the validity of interval analysis.

Means of analyzing dc electrostatic fields are well known. Electric fields in the vicinity of corona-free (i.e. without free charge) dc conductors can be readily determined by several techniques including conformal transformation, method of images, and other simplified equations such as those formulated by N. Knudson, Anneberg HVDC testing stations [10]. Knudson's method covers the following two cases: monopolar and bipolar lines which are shown in figure (1) and figure (2). These formulas are given below for the two arrangements.

Case 1: Monopolar Line

The first arrangement is a monopolar HVDC transmission line as shown in Figure (1). The maximum conductor surface gradient is [10],

$$G = \frac{V}{mr \ln(\frac{2H}{r})} \qquad (kV / cm) \qquad (5)$$

Where:
V = is the line voltage in kV
r = is the radius (or equivalent radius) of conductor in cm
m = is the conductor roughness factor
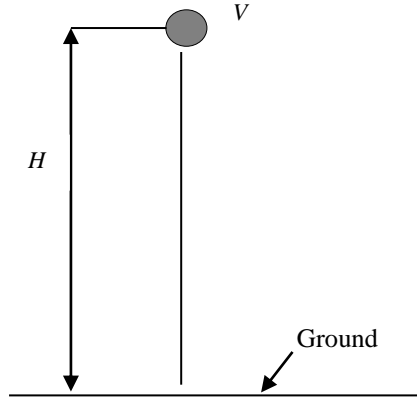H = is the line to ground clearance in cm
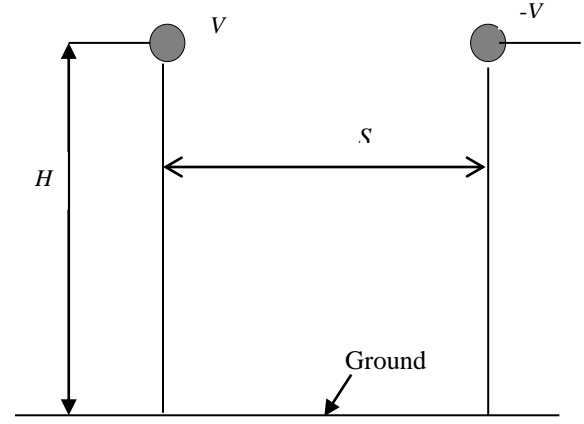
Fig. 1: Monopolar HVDC arrangement

Fig. 2: Biopolar HVDC arrangement

Case 2: Bipolar Line

The second arrangement is a bipolar HVDC transmission line with distances as shown in Figure (2). The corona power loss in kW / circuit km is [10],

$$P_c = VI_c = 2V(k+1)k_c nr 2^{0.25(G-G_o)}, \tag{6}$$

where:

$$G = \frac{V\left[1+(n-1)\left(\frac{r}{R}\right)\right]}{nr \ln\left(\frac{2H}{\left(nrR^{n-1}\right)^{\frac{1}{n}}\sqrt{\left(\frac{2H}{S}\right)^2+1}}\right)}, \tag{7}$$

$$G_o = 22\delta \tag{8}$$

$$\delta = \frac{2.94p}{273+t} \tag{9}$$

$$k = \frac{2}{\pi}\tan^{-1}\left(\frac{2H}{S}\right)$$

Where:
V = is the pole to ground voltage in kV
I_c = is the corona current in mA / km
k = constant related to the amount of the current flows in the interpolar region
k_c = is the conductor surface coefficient varies from less than 0.15 for smooth, clean conductor to more than 0.35 for conductors with imperfections [10]
n = is the number of subconductors
r = is the radius of each subconductor in cm
G = is the maximum conductor surface gradient at operating voltage in kV / cm
G_o = is the corona onset gradient in kV / cm
δ = is the relative air density factor
p = pressure in kPa
t = temperature in ˚C
H = mean height of conductors in cm
S = pole to pole spacing in cm
R = radius of circle passing through centers of all subconductors in a bundle in cm

IV. RESULT AND DISCUSSIONS

This section presents the results of HVDC transmission line field calculation for the monopolar configuration and corona loss calculations for the bipolar case described above. Two methods will be used as follows. Method A represents traditional single-point mathematics. This method will determine the minimum and maximum values for a range of the uncertain parameters that fall within certain lower and upper limits. Method B will use interval mathematics to determine the interval outcome resulting from interval numbers representing these ranges. The bounds of intervals that represent ranges will be the same as the minimum and maximum limits used in Method A. The computations are carried out in the MATLAB environment and the toolbox Intlab is used for interval computation [17].

Case 1: Monopolar Line

The following values are used in the calculations: V = 600kV, H = 10m, and m = 0.9. A tolerance of 10% is assumed in the input parameters. H and m are considered to be interval parameters. H will have a minimum of 9m and a maximum of 11m while m will have a minimum of 0.81 and a maximum of 0.99, then using method A the value of G (at r = 2.3cm), e.g., will have a minimum of 38.39 kV/cm and a maximum of 48.34 kV/cm. For method B, H and m are represented as the interval numbers [9.0, 11.0] m and [0.81, 0.99] respectively. When these interval numbers are used, the interval result for G is [38.39, 48.34] kV/cm. This demonstrates the validity of interval techniques in producing accurate bounds for the output result. This concept can be used to carry out any field calculation to get exact bounds on the resulting interval. As an example of other values between the limits, let H = 10m and m = 0.9, the result will be G = 42.83 kV/cm, which falls within the range of minimum and maximum values of G obtained earlier. Figure (3) shows the values of the interval conductor maximum surface gradient outcomes compared with the single point estimates values for different conductor radii. It is clear that the estimated values of the outcomes are within the lower and upper bounds of the corresponding interval results.
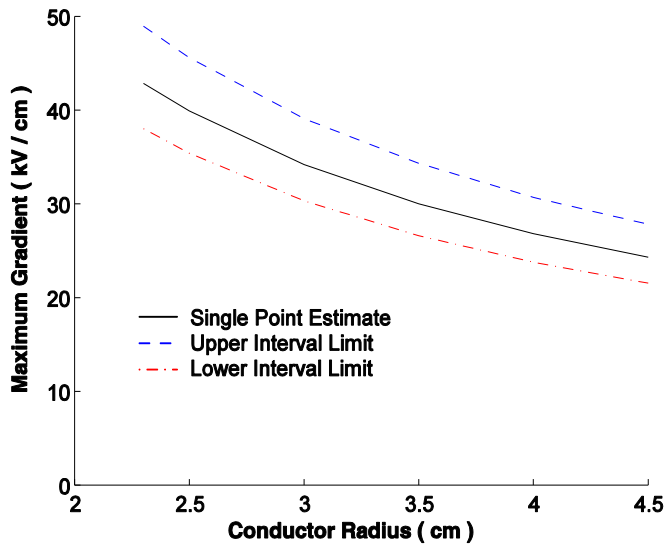
Fig. 3: Maximum Surface Gradient as a function of Conductor Radius for Monopolar Line

In order to assess the uncertainties associated with both parameters H and m, the level of uncertainty of these parameters has been taken to vary by 5% in one case and 15% in another. Table I shows the results of the interval outcomes for different uncertainty level. It is observed that the interval bounds of the different interval outcomes for the higher tolerances contains those of lower tolerances, e.g., the interval outcome of G for a 5% uncertainty is contained within the intervals of the 15% level. It is also noted that the radii of the interval outcomes increase proportional to the increase of the uncertainty level.

TABLE I
INTERVAL MAXIMUM GRADIENT AGAINST CONDUCTOR RADIUS
FOR DIFFERENT UNCERTAINTY LEVELS

Conductor Radius	Maximum Gradient (kV / cm)	
	Tolerance 5%	Tolerance 15%
2.3	[40.4959, 45.4257]	[36.4876, 51.6248]
2.5	[37.7176, 42.3170]	[33.9788, 48.1020]
3	[32.3061, 36.2608]	[29.0929, 41.2378]
3.5	[28.3582, 31.8416]	[25.5292, 36.2276]
4	[25.3424, 28.4650]	[22.8075, 32.3985]
4.5	[22.9583, 25.7952]	[20.6562, 29.3703]

Case 2: Bipolar Line

In case 2, the following values will be used in the calculations: $V = 600$ kV, 2 subconductors, 45.7cm bundle diameter, $H = 15.2$m, $S = 18.3$m, $t = 20$˚C, $p = 101.325$kPa, and $k_c = 0.2$. Here, there are five uncertain parameters which are H, S, k_c, t and p. First, a tolerance of 5% is assumed in all the five parameters. Figures (4-6) show the values of the interval

conductor maximum surface gradient, interval corona current and interval corona loss outcomes compared with the single point estimates values for different conductor radii. It is clear that the estimated values of the outcomes are within the lower and upper bounds of the corresponding interval results. Also, these interval bounds contain all the calculated and measured results obtained by the different techniques mentioned in reference [10] as for example, the measured corona power loss for subconductor radius of 2.3cm was 5.1kW / circuit-km and the calculated corona loss value using the modified POPKOV equation is 3.8kW / circuit-km which falls in the obtained interval power loss range.

Then another practical range is assumed, it is considered that still H, S and p are interval parameters with a tolerance of 5% from their single point input parameters. The value of interval temperature t will be represented by [18.0, 30.0] ˚C to express a wide seasonal variation. Finally, the interval value of k_c is assumed to be represented by [0.15, 0.35] to cover the different variation upon the conductor surface condition. It was clear that the interval corona current and interval corona power loss range increased as shown in figures (5-6). The reason for this wide range is the wide range taken in the interval k_c which simulates a practical range to the conductor surface coefficient variation. Prior knowledge of such information could be of significance in utility planning and maintenance strategy.

By using interval analysis, there is no need for many simulation runs as the total variation of the solution considers the simultaneous variations of all inputs in a single run. In order to evaluate the relative influence of each input parameter H, S, k_c, t and p, an interval sensitivity analysis has been carried out. It is clear that some input parameters have no influence on some interval outcomes, e,g., k_c has no effect upon the interval G and interval G_o. Table II shows the different interval outcomes when every input parameter is assumed to vary alone with tolerances of 10% and 15% for a subconductor radius equal 2.3cm. Close inspection of Table II, reveals that p is the most influencing parameter on all the interval outcomes followed by H then k_c then S and finally t. For example, the radius of the interval P_c, when varying p alone, is 2.1162 and 3.2735 for tolerance of 10 and 15% respectively. As for varying H alone, these values are 1.017 and 1.5612 respectively. While, for varying k_c alone, these values are 0.5326 and 0.7988 respectively. Also, for varying S alone, these values are 0.4821 and 0.7364 respectively. Finally, for varying t alone, these values are 0.1409 and 0.2114 respectively. The above results point out to the importance of accurate determination of these parameters as the confidence in the computed interval outcomes depends mainly on the confidence in the input parameters and not on computational procedures.
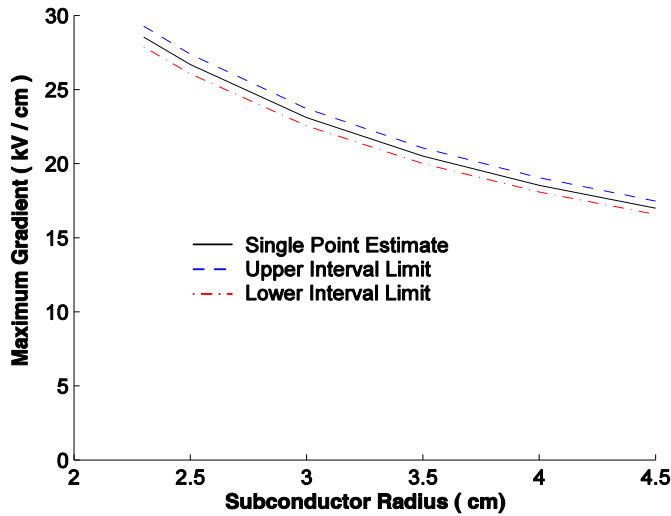
Fig. 4: Maximum Surface Gradient as a function of Conductor Radius for Biopolar Line
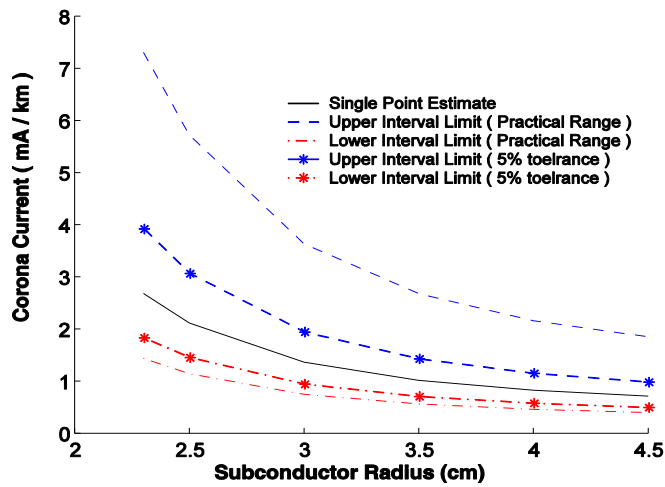

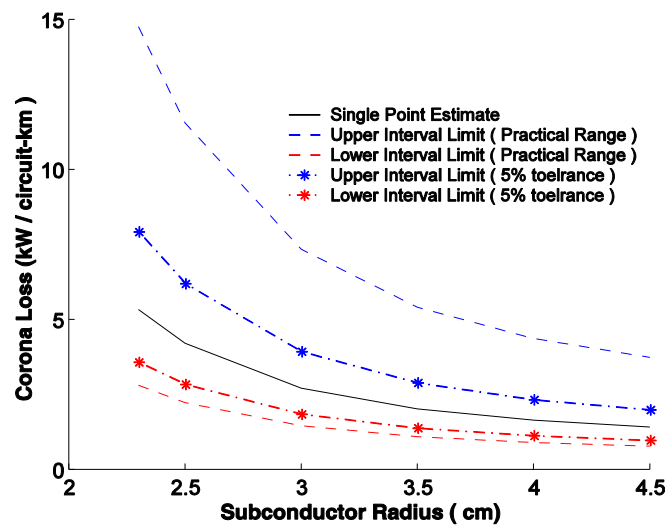Fig. 5: Corona Current as a function of Conductor Radius for Biopolar Line

Fig. 6: Corona Power Loss as a function of Conductor Radius for Biopolar Line

TABLE II
RESULTS FOR SENSITIVITY ANALYSIS OF THE INPUT PARAMETERS

par.	Tol.	10%	15%
t (°C)	G_o (kV/cm)	[22.26, 22.52]	[22.14, 22.59]
	G (kV/cm)	-------	-------
	I_c (mA/km)	[2.61, 2.75]	[2.57, 2.79]
	P_c (kW/circuit-km)	[5.19, 5.47]	[5.12, 5.54]
p (KPa)	G_o (kV/cm)	[20.13, 24.61]	[19.01, 25.72]
	G (kV/cm)	-------	-------
	I_c (mA/km)	[1.82, 3.95]	[1.49, 4.79]
	P_c (kW/circuit-km)	[3.62, 7.85]	[2.98, 9.52]
k_c	G_o (kV/cm)	-------	-------
	G (kV/cm)	-------	-------
	I_c (mA/km)	[2.41, 2.95]	[2.28, 3.08]
	P_c (kW/circuit-km)	[4.79, 5.86]	[4.53, 6.12]
H (cm)	G_o (kV/cm)	-------	-------
	G (kV/cm)	[27.6, 29.58]	[27.17, 30.15]
	I_c (mA/km)	[2.28, 3.21]	[2.11, 3.54]
	P_c (kW/circuit-km)	[4.45, 6.48]	[4.08, 7.2]
S (cm)	G_o (kV/cm)	-------	-------
	G (kV/cm)	[28.16, 28.99]	[27.99, 29.26]
	I_c (mA/km)	[2.51, 2.90]	[2.44, 3.04]
	P_c (kW/circuit-km)	[4.9, 5.87]	[4.72, 6.19]

V. CONCLUSION

Interval mathematics can be used to, rigorously, determine uncertainty in parameters used in the computation of HVDC transmission lines electric fields and corona losses. By using interval analysis, there is no need for many simulation runs because the total variation in the output is known given the total variation in input parameters. The calculation of the HVDC transmission line field calculation for the monopolar configuration and corona loss calculations for the bipolar case were used as examples. These values were calculated using the traditional single point numbers as well as interval numbers. The effects of uncertain inputs within the proposed model were examined for various overall uncertainty levels. The relative contribution of each uncertain input was assessed through an interval sensitivity analysis. The results from these two configurations proved the validity of interval analysis for uncertainty assessment of electric field and corona loss calculations.

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