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APPLICATION OF INTERVAL METHODS TO UNCERTAINTY ANALYSIS OF HVDC TRANSMISSION LINES FIELDS

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ABSTRACT

Uncertainty is a major issue facing electric utilities in planning and decision making. Modeling uncertainty can be based on two general approaches. 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 probability distributions. Interval mathematics provides a tool for the practical implementation and extension of the unknown but bounded concept. The calculation of HVDC transmission lines fields is used as an example to illustrate the use of interval mathematics. Ground- level electric field values are calculated using the traditional single point numbers as well as interval numbers. Various geometries for monopolar and bipolar dc lines are considered. The values from the two methods are compared to prove the validity of interval analysis to, practically, model uncertainties associated with HVDC transmission lines field analysis. Procedures devised to reduce the width of the resulting interval bounds either through rearranging the governing expressions or through derivation of interval probability are discussed.

Keywords: Uncertainty, Interval Mathematics, HVDC Transmission Lines Fields

1. INTRODUCTION

Clearances used in the design and/or analysis of overhead transmission lines 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

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the mechanical clearance buffer based on historical practices, field study, and engineering judgment [1]. As a result, there are many uncertainties associated with utility decisions in this regard. HVDC electric fields are currently a source of environmental and public health concerns [2-4]. These fields depend mainly on the line clearances and their values and distributions; thus, should be treated as uncertain as it is no longer valid to assume that the input parameters are known with certainty.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.

Modeling uncertainty can be based on two general approaches. 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 probability distributions[5,6]. Interval mathematics provides a tool for the practical implementation and extension of the unknown but bounded concept. 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[6]. Interval mathematics have been recently used in load flow studies to account for load uncertainty[7,8]
In this paper, the calculation of HVDC transmission line electric field values and distributions is used as an example to illustrate the use of interval mathematics. These calculations are performed on different HVDC transmission line arrangements. Lateral electric field 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. A procedure is devised in order to reduce the width of the resulting interval bounds. In addition, different interval bounds are produced with different probabilities.

II. MODELING UNCERTAINTY

Uncertainty is a major issue facing electric utilities in planning and decision making. Substantial uncertainties exist concerning HVDC transmission line clearances and associated environmental effects such as the electric field in the vicinity of the lines.
Modeling uncertainty in utility calculations can be based on two general approaches [5-9]. 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 [5,9].
Interval mathematics provides a 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 as will be shown later.
The uncertainties associated with transmission lines electric fields 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.

III. 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 [6]. An interval number can then be formally defined as follows: [a. b], where a ≤ 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:

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

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 [5,9].

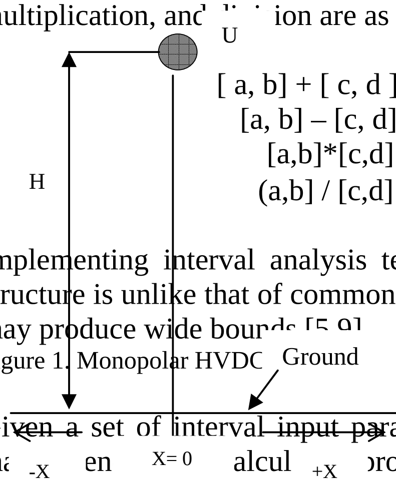


Figure 1. Monopolar HVDC

Figure 2: Bipolar HVDC arrangement

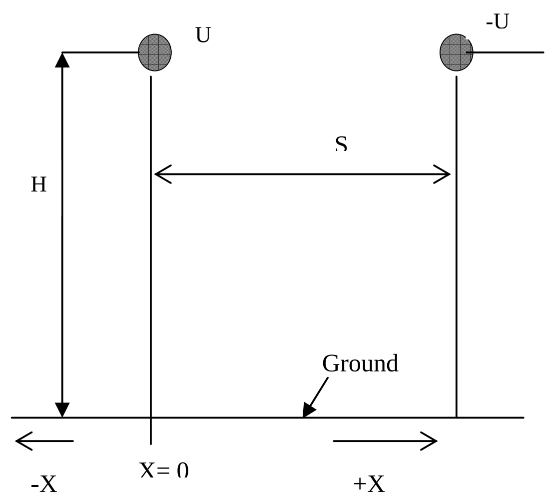
Given a set of interval input parameters, the bounds of the resulting interval computations may depend on the calculation procedure as well as the input parameters. Therefore, an effort has to be made to reduce the width of the resulting interval bounds. Normally, the approach to produce better bounds has been to rearrange the expression so that each interval parameter appears only once in the equation [5]. The approach is illustrated in reference [6].

IV. HVDC TRANSMISSION LINE FIELDS

HVDC transmission lines ionized fields have been a source for environmental and biological public concerns [2-4,10,11]. Calculation of HVDC fields, even without space charges, is important to determine the ionized field quantities. The calculation of HVDC fields is used here as an example to illustrate the use of interval mathematics. Electric field 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 space charge) dc conductors can be readily determined by several

techniques including conformal transformation, method of images, and simplified equations such as those formulated by N. Knudson, Anneberg HVDC testing stations [10]. Knudson's method for computing the space charge- free field above flat ground plane covers the following two cases : monopolar and bipolar which are shown in figures 1 and 2. The resulting formulas are given below for the two arrangements where:

X is the lateral distance from conductor
H is the height above ground of conductor
U is the voltage of conductor
R is the radius (or equivalent radius) of conductor
S is the separation of conductors
K is the coupling factor between the two conductors



Case 1 (Monopolar Line)

The first arrangement is a monopolar HVDC configuration with distances as shown in Figure 1. The electric field at ground is[10],

$$E = \frac{U}{H} \frac{2}{\ln\left(\frac{2H}{R}\right)} \left[\frac{H^2}{H^2 + X^2} \right] \tag{5}$$

Case 2 (Bipolar Line):

The second arrangement is a bipolar HVDC configuration with distances as shown in Figure 2. The electric field at ground is[10],

$$E = \frac{U}{H} \frac{2}{(1\text{-}K)\ln\left(\frac{2H}{R}\right)} \left[\frac{H^2}{H^2 + X^2} - \frac{H^2}{H^2 + (X - s)^2} \right] \tag{6}$$

where

$$K = \frac{\ln\left[\frac{\sqrt{(2H)^2 + S^2}}{S}\right]}{\ln\left[\frac{2H}{R}\right]}$$

and

$$R = \frac{A}{2}\sqrt[n]{\frac{nd}{A}} \tag{7}$$

5. RESULTS

This section presents the results of HVDC transmission line field calculations for the two cases 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 distances that fall within certain lower and upper limits. Method B will use interval mathematics to determine the interval outcome resulting from interval numbers representing the ranges of distances. The bounds of intervals that represent distance 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[12]. In addition, in order to reduce the interval bounds the calculations are carried out using modified formulas expressed as follows for the monopolar case;

$$E = \frac{U}{H}\frac{2}{\ln\left(\frac{2H}{R}\right)}\left[1 + \frac{X^2}{H^2}\right]^{-1} \tag{8}$$

and the modified form for the bipolar case is;

$$E = \frac{U}{H}\frac{2}{(1-K)\ln\left(\frac{2H}{R}\right)}\left[\left(1 + \frac{X^2}{H^2}\right)^{-1} - \left(1 + \frac{(X-s)^2}{H^2}\right)^{-1}\right] \tag{9}$$

5.1 Interval Bounds

Monopolar case

The following values will be used in the calculations: U=600 kV, H = 12.2m, 4x30.5mm subconductors, 45.7cm bundle diameter, and S= 13.2m. A tolerance of 5% is assumed in the input parameters. In case 1, H is considered to be the only interval parameter. H will have a minimum of 10.98 m and a maximum of 13.42 m, then using method A the value of E (at X=0), e.g., will have a minimum of 18.55 kV/m and a maximum of 20.92 kV/m. For method B, H is represented as the interval number [10.98, 13.42] m. When this interval number is used to compute E using equation 8 the interval result for E is [18.55, 20.92] kV/m. This demonstrates the accuracy of interval techniques in producing accurate bounds for the output result. When eqn. 5 is used, the interval result for *E* is [15.19, 25.55] kV/m which reflects the fact that some interval computations may result in overly wide bounds. The result will have a width of 10.36 using eqn. 5 compared with 2.37 using eqn. 8. Normally, the approach to producing better bounds has been to rearrange the expression to reduce the appearance of each interval parameter. It is clear that the resulting interval bounds are drastically improved by using the modified equations. 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*=12 meters, the result will be *E* = 20.06 kV/m, which falls within the range of minimum and maximum values of *E* obtained earlier using either eqn 5 or eqn 8.

The reasons for the variations in *H* are numerous including environmental conditions, loading conditions, deviations during the design and erection stages, or simply errors in measurements [3,10,11]. Similarly, the lateral location *X* may be inaccurately determined; though with a lesser error than *H*. The results for *E* when *H* alone or *X* alone or both are treated as interval numbers are shown in Figure 3 a,b,c. It is clear that the value of *E* is much more influenced by uncertainty in *H* than in *X*.

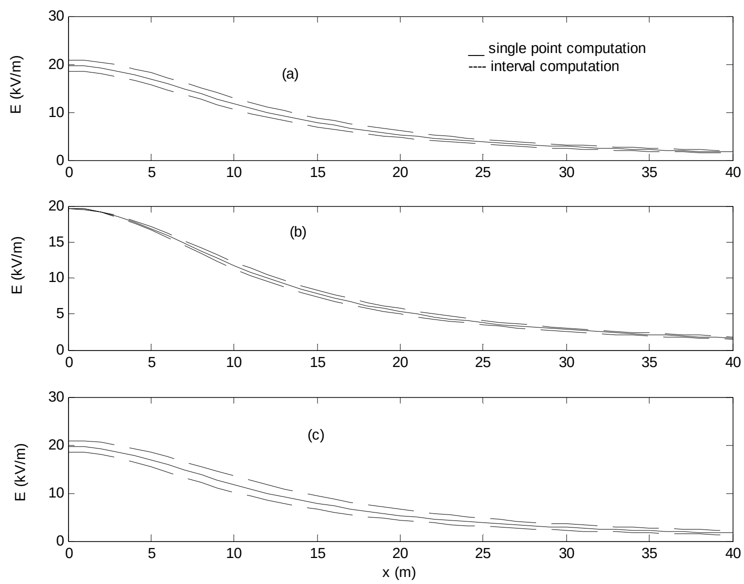


Fig. 3 Lateral electric field profiles with uncertainties-monopolar case
(a) *H* only (b) *X* only (c) both *H* and *X*

Bipolar case

In case 2, there are three parameters which are *H, X, S* . First, it is considered that *S* is the only interval parameter. S will be represented by [12.5399,13.8601] m. The electric field lateral profiles are shown in Fig. 4, where *X* is replaced by *X*+*S*/2. The peak value of *E* using method A is 13.4722 kV/m ;while using method B the interval value is [12.8169,14.1265] kV/m which shows the validity of the interval approach. The slight asymmetry of the field profiles, commonly observed in many outdoor studies [1,3,10,11], may be partly explained by the uncertainty in the value of *S* as observed here at the zero crossing. The *E* profiles with uncertainty in *H* only are shown in Fig.5. It cab be seen that using Eqn. 6 results in incorrect distributions of *E* while the modified Eqn. 10 provides the correct result:

$$E = \frac{U}{H}\,\frac{2}{(1\text{-}K)\ln\left(\frac{2H}{R}\right)}\left[\left(\frac{(X-s)^2 - X^2}{\left(1+\frac{X^2}{H^2}\right)(H^2+(X-s)^2)}\right)\right] \tag{10}$$

Fig.6 shows the *E* profiles when all uncertainties in *H, X, S* are included in the analysis using both eqns 6 and 9. For the single point computation, both the negative and positive peaks equals 13.4722 kV/m and located at ± 9m from the mid distance of the towers (X=0). The interval computation, using Eqn. 9, results in the –ve peak values of -10.3068 kV/m and -16.9331kV/m at -10m and -8m respectively. The +ve peak values are between 11.1345 kV/m and 16.0257 kV/m at 7m and 9m respectively. It is clear that the interval results bounds both peaks in value and location while accounting for all possible uncertainties in the input parameters. When assuming a 5% tolerance in the parameters *H, X, S* , the –ve peak may vary by +25% to -23% and the +ve peak may vary by +25% to -17% of their corresponding single point estimates.

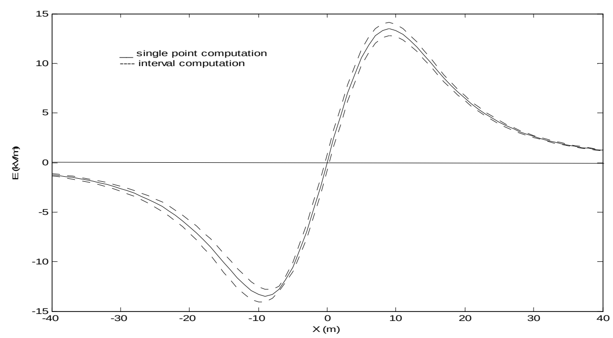


Fig. 4 Bipolar lateral electric field profiles with uncertainties in *S*

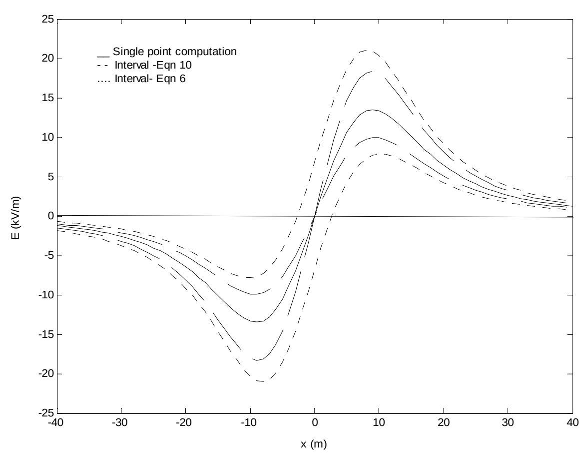


Fig. 5 Bipolar lateral electric field profiles with uncertainties in *H*

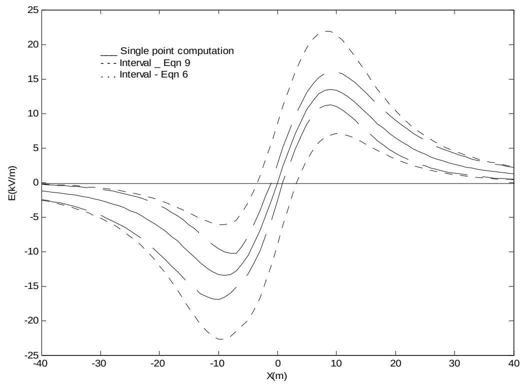


Fig. 6 Bipolar lateral electric field profiles with uncertainties in *H,S,X*

This may partly explain the discrepancies which usually observed in outdoor field measurements when compared with calculations [1,3,10,11]. The above analysis demonstrates the accuracy of interval techniques in producing accurate bounds for the output result. By using interval analysis, there is no need for many simulation runs because the total variation in the output *E* is known given the total variation in the input parameters *H, X, S.*

Another technique for reducing the width of the resulting interval is to develop what is called 'interval probability' [5,9]. This can be accomplished by assuming the resulting interval to be represented by a uniform probability distribution with the lower and upper bounds of the distribution being those of the corresponding interval. In this case, as the exact value lies between these two limits, then the probability is 1. However, a narrower interval within which the exact value lies can be developed with a probability less than 1 (e.g. 0.95 as commonly used). Further development of these procedures will be the subject of another research paper.

6. CONCLUSIONS

Interval mathematics can be used to, rigorously, determine uncertainty in parameters used in a computation of HVDC transmission lines electric fields. 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 electric fields values and distributions of both monopolar and bipolar configurations were used as examples. Field values were calculated using the traditional single point numbers as well as interval numbers. The results from these two methods proved the validity of interval analysis for uncertainty assessment of electric field calculations. Extension of the interval methods to be applied to the uncertainty analysis of HVDC ionized fields, grounding systems and reactive power compensation of distribution systems is underway.

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