Development of AC Transmission Line Audible Noise Prediction Formulas Using Evolutionary Computations

Kwang-Ho Yang, June-Ho Park, Gi-Hyun Hwang, and Jeong-Boo Kim

Abstract

The audible noise produced by corona discharge in high voltage transmission lines is the most important line design consideration. In this paper, more accurate and useful formulas for predicting the A-weighted audible noise during heavy and light rain in alternative current (AC) transmission lines are proposed through comparison with the existing formulas. The proposed formulas are developed by the applications of evolutionary computations (ECs) to audible noise data base from long-term measurement.

I. Introduction

The audible noise (AN) produced by corona is one of the many constraints in the design of high voltage transmission lines. To aid the line designer in deciding a suitable conductor geometry, several formulas for calculating AN levels have been already reported [1]. However the most of the existing formulas cannot be widely applied due to some constraints in use. Therefore, in this paper, more accurate and useful AN prediction formulas are proposed.

A large quantity of measured data is needed to develop a formula. For the purpose of building AN data base, long-term measurement has been accomplished in single phase corona test cage ($6\times6\times20$ m) and full-scale Kochang test line (700 m, 3 spans) for about 11 years from 1987 to 1997. The data base was analyzed by the statistical methods. As the result, A-weighted AN levels, cumulative probability distributions (exceedance levels), frequency spectra and lateral profiles are obtained [2, 3, 4]. The above statistical exceedance levels ($L_{5\%}$ and $L_{50\%}$) and line parameters, G, N, d and D, in section III were applied to the evolutionary computations (ECs) of genetic algorithm (GA) and genetic programming (GP) for obtaining each formula. To evaluate the requirements of all prediction formulas, both formulas obtained from the calculations in this paper and the existing formulas were verified for five operating and test line configurations for which data from long-term AN measurements are available [1, 3]. Finally, more accurate formulas which can be used in the line design field and the assessment of environmental effect are proposed.

The BPA (Bonneville Power Administration, USA) Corona and Field Effects Program using the Markt-Mengele Method was used to calculate conductor surface gradients (G) [5].

II. General Theory for Predicting Audible Noise

1. Sound Propagation and Attenuation

Acoustic power levels (PWL_i) for each phase of a line is the term that is needed to calculate sound levels, and it can be calculated for any phase of any line from 3-phase sound level data ($SLT_{mea.}$). However, three parameters have to be considered before these PWL_is are calculated: 1) the relationship between PWL_i and $SLT_{mea.}$: 2) the effect of air absorption on attenuation: 3) radial distances from the conductors to the calculation point.

2. Derivation of the Equation for Computing the PWLi for a Line Source

To calculate the acoustic power levels from laboratory, test cage and test line requires the derivation of a equation for converting measured sound level data to acoustic power level. The general equation for calculating the acoustic power energy for a given source is:

$$J = \frac{A}{S} = \frac{A}{4\pi R^2} \tag{1}$$

where J : Power intensity (W/m^2)
A : Power generated by source (W)
S : Surface area surrounding source (m^2)
R : Radial distance from point source (m)

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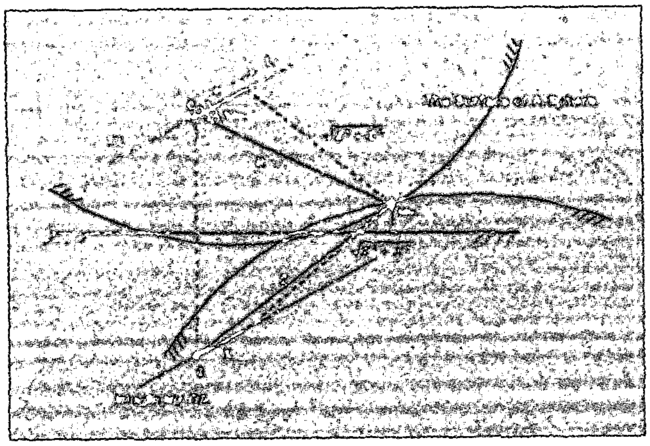


Fig 1. Calculation of SPLs from each phase.

Assuming that a line source is described by a collection of independent point sources in Fig. 1, the acoustic power energy for the line source would be the sum of the individual power energy's of the point sources. Thus Eq. (1) for a line source becomes:

$$J = \int \frac{Adx}{4\pi(R^2+x^2)} + K\int \frac{Adx}{4\pi(Z^2+x^2)} \tag{2}$$

where A : Power generated per unit length of conductor (W/m)
x : Variable distance along conductor (m)
Z : Distance from calculating point to image of line (m)
K : Reflection coefficient (≒ 1)

Evaluating Eq. (2), assuming the measuring point is close to the ground (i.e. R = Z):

$$J = \frac{A(K+1)}{2\pi R} \tan^{-1}\frac{L}{2R} \tag{3}$$

where L : Length of line (m)

The measured sound pressure level (SPLi) of each single phase is defined as:

$$SPLi = \sqrt{CJ\delta} \tag{4}$$

Substituting Eq. (3) into Eq. (4):

$$SPLi = [\frac{A\delta C(K+1)}{2\pi R} \tan^{-1}\frac{L}{2R}]^{1/2} \tag{5}$$

where δ : Air density (kg/m^3)
C : Sound wave propagation velocity in air (m/s)

Solving Eq. (5) in terms of $dB_{20\mu Pa}$ and assuming K=0, Eq. (6) can be derived for an infinite transmission line.

$$\begin{aligned} SPLi(dB) &\approx A(dB) - 10\log R + 10\log(\tan^{-1}\frac{L}{2R}) \\ -7.8 &= PWL_i - 10\log R - 5.7 \end{aligned} \tag{6}$$

$$SLT_{cal.} = 10 \log [\sum_{i=1}^{P} 10^{\frac{SPLi}{10}}] \tag{7}$$

where P : The number of total phases

The total A-weighted sound level ($SLT_{cal.}$) due to the noise from all phases can now be calculated using Eq. (6) and (7). But this calculated total sound level is a few dBA higher than $SLT_{mea.}$, therefore, the difference between $SLT_{cal.}$ and $SLT_{mea.}$ is subtracted from the calculated PWL_i to obtain $SLT'_{cal.}$ [6].

Ⅲ. Description of The Existing Formulas

1. General Type of Experimental Formula

Audible noise calculation methods can be divided into two general types: Type 1) those which are specific to a particular category of line geometry and specific to a voltage class, Type 2) those which can be applied to different geometries. And also data used in the Type 1 and Type 2 formulation may come from tests on 3-phase in operating or test lines and come from tests on 1-phase test line or test cage, respectively. Therefore, in case of Type 2 formulation, Eq. (6) was used to separate the noise of individual phases, and Eq. (7) was used to sum the contributions of each phase to determine the overall audible noise level. AC audible noise prediction formulas of the whole world are shown in Table 1. A general formulation for the audible noise level is Eq. (8) [1].

$$SLT'_{cal.} = k_1f_1(G) + k_2f_2(N) + k_3f_3(d) + k_4f_4(D) + k_0 \tag{8}$$

2. Nomenclature

- G (kV/cm) : Surface gradient of conductor-bundle
- N : Number of subconductors in a phase bundle
- d (cm) : Diameter of subconductors
- D (m) : Lateral or radial distance from line to point at which audible noise level is to be calculated
- PWL_i : A-weighted sound powers of the noise produced by one phase of the line
- $SLT'_{cal.}$: Modified AN calculation level of the noise from all phases
- $SLT_{mea.}$: Measured AN level from all phases
- $SLT_{cal.}$: Calculated AN level from all phases
- SPLi : Measured sound pressure level of each phase
- $f_1(G)$, $f_2(N)$, $f_3(d)$, $f_4(D)$: Functions of the parameters, G, N, d and D
- k_1, k_2, k_3, k_4 : Coefficients of functions
- k_0 : Adjustment factor depending on values of G, N and d
- $L_{5\%}$, $L_{50\%}$: The level which is exceeded 5% and 50% of the time, respectively, one year during rain

Table 1. Comparative AC Audible Noise Formulas ($N \geq 3$).

Method	Gradient(G) $k_1f_1(G)$	No. of Subcon.(N) $k_2f_2(N)$	Conductor Diameter(d) $k_3f_3(d)$	Distance (D) $k_4f_4(D)$	Constant, k_0	Noise Measure in Rain	Type No. in Method
BPA	120 log G	26.4 log N	55 log d	-11.4 log D	-128.4	L_{50}	2
EdF	-	15 log N	4.5	-10 log D	depends on the G	HR	2
ENEL	85 log G	18 log N	45 log d	-10 log D	-71	HR	2
FGH	2	18 log N	45 log d	-10 log D	-0.3	Max	2
GE	-665/G	20 log N	44 log d	-10 log D	-	L_5, L_{50}	2
IREQ	72 log G	22.7 log N	45.8 log d	-11.4 log D	-57.6	Max	2
CRIEPI	-665/G	-	-	-10 log D	depends on the N and d	HR	2
Westinghouse	120 log G	10 log N	60 log d	-11.4 log D	-	-	-
AEP	108 log G	10 log N	102.5log(d/2.54)	-	-94.5	Avg	1
Ontario Hydro	100 log G	-	40 log d	-10 log D	-77.2	HR	1

IV. Application Methods and Prediction Formulas

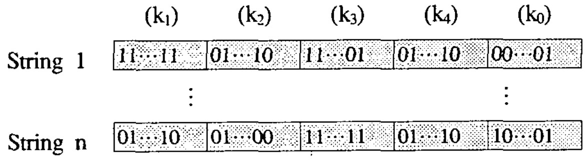
1. Application of Genetic Algorithm

1) Genetic Algorithm: GA, an optimization algorithm based on the principles of genetics and natural selection, was introduced in the early 1970's. It finds the best solution appropriate to the environment by searching the solution space with a probabilistic method and a hierarchical exchange of information between each individual (string). GA does not use real parameters but uses chromosomes composed of string coded genotype. GA simulates the crossover and mutation of natural systems, giving it a global searching capability[7].

2) Tuning Method of AN Measured Data Using GA: To execute the tuning method using GA, strings are composed of all coefficients of a general formula shown in Eq. (8). That is, initial population can be produced as shown in Fig. 2. To compute the fitness, we use the summed absolute value of the difference between calculated outputs ($SLT'_{cal.}$) and desired outputs ($SLT_{mea.}$). The fitness is defined as Eq. (9).

$$Fitness = \frac{1}{1+\sum_{i=1}^{N} |error_i|} \tag{9}$$

where error = $SLT_{mea.}$(desired) - $SLT'_{cal.}$(calculated)
N : The number of tuning data



where n : The number of strings

Fig. 2. Configuration of population.

Table 2. GA and GP Parameters.

	GA	GP
Generations	500	500
Population Size	100	500
Selection Method	Roulette Wheel	Tournament
P_c	0.85	0.70
P_m	0.05	0.01
Length of A String/ Function	60 Bits	16 Functions

That is, using a randomly generated population, we evaluate fitness using Eq. (9) and then execute reproduction, crossover, mutation and iterate this procedure until the solution reach the critical value at which the error is smaller than the predetermined value. GA and GP parameters are shown in Table 2.

3) Prediction Formulas by GA: The type 1 (3-phase, 3P) and type 2 (1-phase, 1P) prediction formulas obtained through application of GA are the same as following equations. SLT'_{3P}s of Eq. (10) and (11) are the Type 1 formulation which can be directly used to calculate the total AN level of lines. And SLT'_{1P}s of Eq. (12) and (13) are the Type 2 formulation which can be used to calculate the AN level produced by each phase of the most kinds of lines. G_{3P} is the average of average-maximum bundle gradients of 3 phases, but G_{1P} means the average-maximum gradient of single phase under consideration. D_{3P} is the radial distance from the center phase to the calculated point, but D_{1P} means the radial distance from the phase under consideration to the calculated point.

$$SLT'_{3PL5,GA} = 106.5\ log(G) + 27.9\ log(N) + 43.3\ log(d) - 11.0\ log(D) - 97.9 \tag{10}$$

$$SLT'_{3PL50,GA} = 111.4\ log(G) + 25.0\ log(N) + 43.6\ log(d) - 11.9\ log(D) - 103.6 \tag{11}$$

$$SLT'_{1PL5,GA} = 105.6\ log(G) + 15.4\ log(N) + 58.6\ log(d) - 10.5\ log(D) - 102.8 \tag{12}$$

Table 3. Parameters of AC Lines Used to Develop Prediction Formulas.

Configuration		Line Voltage (kV_{rms})	Cond. Gradient (G)	No. of Phases (P)	Conductor Parameter			Ground Wire Diam.	Line Geometry (m)								Calcul. Distance (D, m)	L_5 ($SLT_{mea.}$, dBA)	L_{50} ($SLT_{mea.}$, dBA)
No. (N)	Type				N	d(cm)	S(cm)		D1	D2	D3	D4	H1	H2	H3	H4			
1	II	765	15.78	6	4	3.84	40.0	1.61	24.6	23.7	22.8	-	22.1	38.1	54.1	-	39.8	57.5	56.8
2	II	765	12.14	6	6	3.84	40.0	1.61	24.6	23.7	22.8	-	22.1	38.1	54.1	-	39.8	51.8	43.2
3	II	765	15.07	6	6	3.04	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	70.9	52.0	43.8
4	II	630	12.47	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	40.2	51.1	46.6
5	II	765	15.17	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	37.1	53.0	49.2
6	II	765	15.17	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	70.9	49.6	44.7
7	II	783	15.57	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	40.2	53.4	50.4
8	II	800	15.87	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	40.2	53.8	51.6

Note 1) G : The average of average-maximum bundle gradients
2) D : Radial distances from the center phase
3) S : Subconductor spacing
4) H : Average height of each phase

$$SLT'_{1PL50,GA} = 122.1\ \log(G) + 12.6\ \log(N) + 59.0\ \log(d) - 11.5\ \log(D) - 122.6 \tag{13}$$

2. Application of Genetic Programming

1) Genetic Programming: The genetic programming (GP) continues the trend of dealing with the problem of representation in GA by increasing the complexity of the structures undergoing adaptation. But we should use heuristic approach to decide the EC operators as mutation probability (P_m), crossover probability (P_c), population size, fitness function and so on. Because choosing improper operators leads to premature convergence of the EC or transform the EC into a random search. Therefore the ECs should be iteratively performed to get a final solution with new proper operators. In summary, the GP solves problems by executing the following three steps[8]:

① Generate an initial population of the functions (F) and terminals (T) of the problem.
② Iteratively perform the following substeps until the termination criterion has been satisfied.
  ⓐ Execute each program in the population and assign it a fitness value
  ⓑ Create a new population of computer programs by applying the following two primary operations.
    - Copy existing computer program to the new population.
    - Create new computer programs by genetically recombining randomly chosen parts of two existing programs.
③ The best computer program that appeared in any generation is designated as the result of GP. This result may be a best solution to the problem.

2) Prediction Formulas by GP and GA: At first, the following three steps in preparing to use GP are used to get a best function of each term of the formula under consideration. The first step is to identify the set of terminals (line parameters). The terminal set (T) is:

$$T = \{G,\ N,\ d,\ D\} \tag{14}$$

The second step is to identify the set of functions that are used to generate the mathematical expressions (S-expressions) that attempt to fit the given 8 and 48 samples of 3-phase and single phase measured data in Table 3, respectively. As shown in Eq. (15), the function set (F) for the problem consists of 5 functions that are the four ordinary arithmetic operations and the common logarithm function. Fig. 3 shows the change of a S-expression after mutation.

$$F = \{+,\ -,\ \times,\ \%,\ \log\} \tag{15}$$

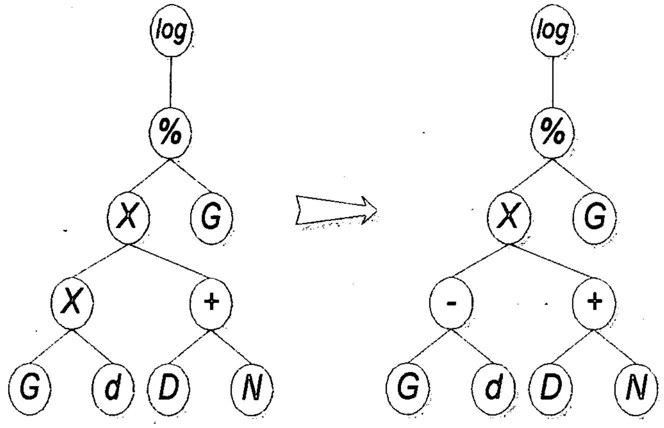
The third step is to identify the fitness measure. The raw fitness for the problem is the sum of the absolute error between the real-measured value, $SLT_{mea.}$ and the calculated value, $SLT'_{cal.}$. Fig. 4 shows the algorithm of the above process by GP and GA applications.

The type 1 (3P) prediction formulas obtained through applications of GP using the given samples of 8 measured data in Table 3 are the same as following Eq. (16) and (17). Since GP finally selects the best combination of terminals and functions, formulas by GP do not have a general type as Eq. (8) and ones in Table 1. But the type 2 (1P) prediction formulas could not be obtained at this time by GP applications using the given 48 measured data from Table 3.

$$SLT'_{3PL5,GP} = (1+d)\ \log(G) + 2\ \log(N) + (1+d)\ \log(d) + \log(D+d) + (2G+2N+d) \tag{16}$$

$$SLT'_{3PL50,GP} = 3d\ \log(G) + d\ \log(N) + d\ \log(d) + d\ \log(D+d) + 2G \tag{17}$$

Furthermore, in this paper, for the purpose of making the above error to be closer to 0, coefficients (gains) of formulas by GP were finely retuned by applications of GA using the independency between parameters. As a result, coefficients of each term in Eq. (18) and (19) are obtained.



S_{BM} = log d + log (D+N)
(Before Mutation)

S_{AM} = log (G-d) + log (D+N) - log G
(After Mutation)

Fig. 3. A sample S-expression after mutation.

$$SLT'_{3PL5,GP+GA} = 0.93(1+d)\log(G) + 0.94\log(N) + 1.3(1+d)\log(d) + 1.09\log(D+d) + (2.15G+1.09N+1.5d) \quad \textbf{(18)}$$

$$SLT'_{3PL50,GP+GA} = 2.93d\log(G) + 0.99d\log(N) + 0.99d\log(d) + d\log(D+d) + 1.95G \quad \textbf{(19)}$$

V. Verification and Results

1. Method of Verification

To verify the accuracy of all prediction formulas including the existing formulas, the calculated levels, SLT'_{cal}s of each formula for five AC line configurations in Table 4 are compared with the measured levels, SLT_{mea}s. As illustrated in Fig. 5, the lines used to verify have all kinds of AC line configurations. The results of calculations by all formulas and the measured levels in light rain ($L_{50\%}$) and heavy rain ($L_{5\%}$) are given in Table 5 and 7, respectively. And summaries of the absolute errors of differences between measured levels and calculated levels in each case are shown in Table 6 and 8.

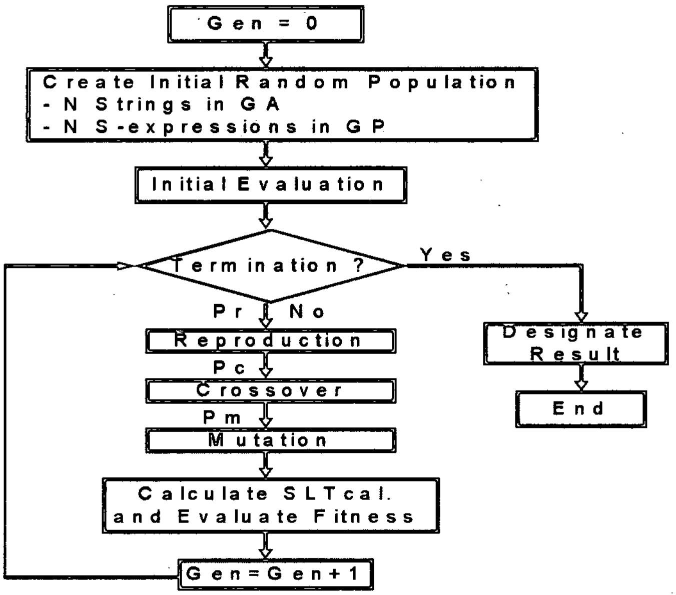


Fig. 4. Flowchart for GA and GP runs.

2. Results

According to the results of verification in Table 6 and 8, it can be known that formulas obtained through applications of GP and GA or only GA are more excellent than the existing ones. And also, the accuracy of formulas by GP with GA are the almost same as ones by GA. Therefore, in this paper, each formula according to the number of phases and rainy conditions is finally proposed with the application conditions as follows.

(1) Type 1 Prediction Formulas (3-Phase)

$$SLT'_{3PL5,GP+GA} = 0.93(1+d)\log(G) + 0.94\log(N) + 1.3(1+d)\log(d) + 1.09\log(D+d) + (2.15G+1.09N+1.5d) \quad \textbf{(18)}$$

$$SLT'_{3PL50,GP+GA} = 2.93d\log(G) + 0.99d\log(N) + 0.99d\log(d) + d\log(D+d) + 1.95G \quad \textbf{(19)}$$

∘ Application : All line geometries
∘ Noise measure : L_5 and L_{50} in rain
∘ D : The radial distance from the center phase
∘ G : The average of average-maximum bundle gradients of all phases
∘ Range of validity : 500~1150 kV

Table 4. Parameters of AC Lines Used to Verify All Prediction Formulas.

Configuration		Line Voltage (kV_{RMS})	Cond. Gradient (G)	No. of Phases (P)	Conductor Parameter			Ground Wire Diam.	Line Geometry (m)								Calcul. Distance (D,m)	L_5 ($SLT_{mea.}$, dBA)	L_{50} ($SLT_{mea.}$, dBA)
No.	Type				N	d(cm)	S(cm)		D1	D2	D3	D4	H1	H2	H3	H4			
1	II	765	15.07	6	6	3.04	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	27.3	52.5	48.4
2	II	765	15.17	6	6	2.96	40.0	1.61	24.6	23.7	22.8	26.4	24.3	38.6	53.5	75.0	27.3	52.8	48.8
3	I	765	20.1	3	4	2.96	45.7	0.98	13.7	-	22.3	-	18.3	-	30.5	-	29.0	61.8	58.6
4	III	1150	15.2	3	7	4.07	46.4	2.33	22.0	-	18.3	-	16.8	39.1	51.8	-	26.0	60.0	56.5
5	III	525	16.4	3	4	3.51	45.7	-	4.9	-	-	-	12.2	16.4	-	-	30.5	55.0	52.9

Table 5. Results of Calculations and Measurements for Test Models in Light Rain.

Calculation Method ($SLT'_{cal.}$)	Noise Measure (dBA)	Test Model No.									
		Type 1 (3P)					Type 2 (1P)				
		#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
BPA	L_{50}	-	-	-	-	-	49.2	48.8	57.8	57.4	50.7
Formulas by GA	L_{50}	49.1	48.9	59.0	56.0	52.3	48.7	48.3	59.9	56.5	52.9
Formulas by GP+GA	L_{50}	48.6	48.3	58.3	56.5	54.0	-	-	-	-	-
Measured Level ($SLT_{mea.}$, dBA)	L_{50}	48.4	48.8	58.6	56.5	52.9	48.4	48.8	58.6	56.5	52.9

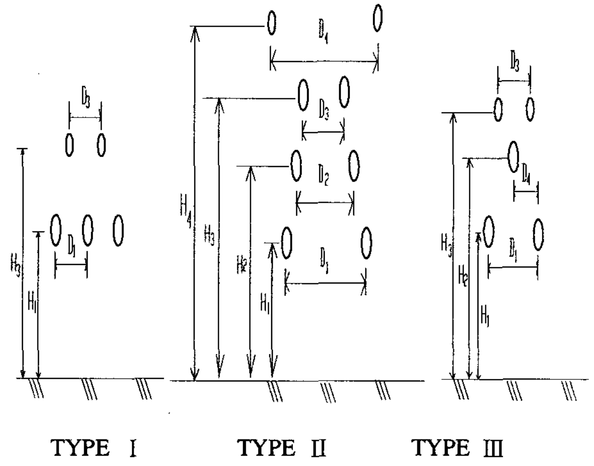


Fig. 5. AC line configurations referenced by Table 4.

Table 7. Results of Calculations and Measurements for Test Models in Heavy Rain (HR).

Calculation Method ($SLT'_{cal.}$)	Noise Measure (dBA)	Test Model No.									
		Type 1 (3P)					Type 2 (1P)				
		#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
BPA	L_5	-	-	-	-	-	52.7	52.3	61.3	60.9	54.2
EdF	HR	-	-	-	-	-	56.2	56.1	61.9	-	57.2
ENEL	HR	-	-	-	-	-	56.2	55.9	61.8	62.7	57.2
GE	L_5	-	-	-	-	-	55.4	55.1	60.0	-	56.1
Formulas by GA	L_5	52.5	52.3	61.3	59.7	55.1	52.5	52.0	61.0	60.1	55.5
Formulas by GP+GA	L_5	53.0	52.9	61.6	58.7	55.5	-	-	-	-	-
Measured Level ($SLT_{mea.}$, dBA)	L_5	52.5	52.8	61.8	60.0	55.0	52.5	52.8	61.8	60.0	55.0

$$4 \le N \le 7$$

$$2.96 \le d \le 4.07$$

- Equivalent rainfall rate : $R_5 = 6.5$ mm/hr.
  $R_{50} = 1.0$ mm/hr.

(2) Type 2 Prediction Formulas (1-Phase)

$$SLT'_{1PL5,GA} = 105.6\ \log(G) + 15.4\ \log(N) + 58.6\ \log(d) - 10.5\ \log(D) - 102.8 \tag{12}$$

$$SLT'_{1PL50,GA} = 122.1\ \log(G) + 12.6\ \log(N) + 59.0\ \log(d) - 11.5\ \log(D) - 122.6 \tag{13}$$

- Application conditions : the same as the above

Table 6. Deviations and Absolute Errors between Calculated and Measured Levels for Test Models in Light Rain.

Calculation Method ($SLT'_{cal.}$ - $SLT_{mea.}$)	Noise Measure (dBA)	Test Model No.											
		Type 1 (3P)						Type 2 (1P)					
		# 1	# 2	# 3	# 4	# 5	Absolute Error	# 1	# 2	# 3	# 4	# 5	Absolute Error
BPA	L_{50}	-	-	-	-	-	-	+0.8	0.0	-0.8	+0.9	-2.2	0.94
Formulas by GA	L_{50}	+0.7	+0.1	+0.4	-0.5	-0.6	0.46	+0.3	-0.5	+1.3	0.0	+0.0	0.42
Formulas by GP+GA	L_{50}	+0.2	-0.5	-0.4	0.0	+1.1	0.43	-	-	-	-	-	-

Table 8. Deviations and Absolute Errors between Calculated and Measured Levels for Test Models in Heavy Rain.

Calculation Method ($SLT'_{cal.}$ - $SLT_{mea.}$)	Noise Measure (dBA)	Test Model No.											
		Type 1 (3P)						Type 2 (1P)					
		# 1	# 2	# 3	# 4	# 5	Absolute Error	# 1	# 2	# 3	# 4	# 5	Absolute Error
BPA	L_5	-	-	-	-	-	-	+0.2	-0.5	-0.5	+0.9	-0.8	0.58
EdF	HR	-	-	-	-	-	-	+3.7	+3.3	+0.1	-	+2.2	2.33
ENEL	HR	-	-	-	-	-	-	+3.7	+3.1	0.0	+2.7	+2.2	2.34
GE	L_5	-	-	-	-	-	-	+2.9	+2.3	-1.8	-	+1.1	2.03
Formulas by GA	L_5	0.0	-0.5	-0.5	-0.3	+0.1	0.28	-0.1	-0.8	-0.8	-0.1	+0.5	0.46
Formulas by GP+GA	L_5	+0.5	+0.1	-0.3	-1.3	+0.5	0.53	-	-	-	-	-	-

∘ D : the radial distance from the phase under consideration
∘ G : the average-maximum bundle gradient

VI. Conclusions

The proposed formulas for predicting AN from AC lines were developed by applications of evolutionary computations to long-term AN data base. Specially, the proposed Type 1 formulas which are directly used to 3-phase lines and developed by GP application can be applied to both all line geometries and wide range of voltages for rainy weathers. Therefore two constraints of the existing Type 1 formulas are solved. In Table 8, BPA formula among the existing ones is the best one. However the proposed Type 2 formulas by GA applications which are used to calculate AN levels of each phase are more accurate than BPA formulas.

According to the result of applications of GA, it can be known that the natural searching has a considerable effect on finding the best formulas. Formulas by GA take a general type as Eq. (8). However formulas obtained by the applications of GP take a new interesting form due to the best combination of terminals and functions. Furthermore, it has been found that formulas by GP can take fine coefficients of functions and an adjustment factor through additional gain tuning by GA. But the useful type 2 (1P) prediction formulas could not be obtained by GP applications using the given 48 measured data from Table 3. It is not clear at this time what the above reason is. The further verifications and improvements of all proposed formulas will be performed by obtaining more measurement data over a wide range of line parameters, G, N and d.

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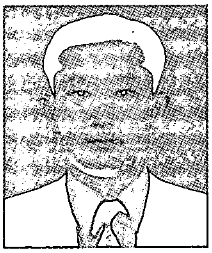

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