Typical expected values of the fault resistance in power systems

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Abstract-**This article presents a range of possible values for the fault resistance in transmission power systems, considering six existing models for the arc resistance and a model for the grounding impedance of the towers. Resistance by possible additional objects in the path of the fault current was not considered. Known the short circuit level (without fault impedance), the fault resistance was calculated with the above mentioned models, for line-to-line and line-to-ground faults. This calculation was made for diverse nominal voltages and diverse short circuit levels for solid faults. The obtained range might be useful to improve the way of computing the settings for the corresponding protective devices.**

Index Terms- **Arc resistance, grounding resistance, fault resistance, short circuit level.**

I. INTRODUCTION

SHORT circuit current may be limited by a fault impedance, which may be composed by three elements: electric arc, tower grounding, and the presence of objects in the fault path. Electric arc is a non-linear phenomenon that depends on diverse factors; however, there is a tradition considering the arc as a resistance, dependent on the arc current, in order to compute the short circuit currents in a simple way [1-13]. The effective grounding impedance of towers is mainly resistive, its inductive part is greater when there are ground wires [14-20], and its value is assumed to be not dependent on the fault current. Impedance of possible additional objects interposed in the path of the fault current is usually considered mainly resistive, and its value might be zero or very high [1]; by this reason, fault impedance may be described as an unpredictable quantity [21].

For transmission line protection, fault resistance (R_F) is assumed to be composed by the arc resistance (R_A) and the effective grounding resistance of the towers (R_G) [11-14]. A range of values for R_F was computed in this article, by using existing models for R_A and for the effective grounding impedance of the towers (Z_G), and by assuming the short circuit level without fault impedance (I_{SCL}) as known. The obtained range for R_F may be considered typical for the nominal voltages used as examples; however, it was considered necessary to emphasize that the R_F values may be out of the studied range because the factors that affect R_A and Z_G are very diverse and, additionally, there could be other objects interposed in the path of the current.

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II. APPLIED MODELS

A. Models for the arc resistance

A.1. Model 1

This model probably is the most well-known, and it was proposed by A. Warrington in 1931 [1,2]:

$$R_{A1} = \frac{28707.35 \cdot L}{I^{1.4}} \tag{1}$$

R_{Aj}: Arc resistance (Ω), according to model j ($j=1...6$).
L: Arc length (m).
I: Rms value of the fault current (A).

A.2. Model 2

This model is based on the analysis of Mason [11] about the results of Warrington [1], Strom [6] and other authors:

$$R_{A2} = \frac{1804.46 \cdot L}{I} \tag{2}$$

A.3. Model 3

This model is based on a article written by Goda et al. [3]:

$$R_{A3} = \left(\frac{950}{I} + \frac{5000}{I^2}\right) \cdot L \tag{3}$$

A.4. Models 4 and 5

These models are based on articles written by Terzija and Koglin [4-5]:

$$R_{A4} = \frac{G \cdot L}{I} \tag{4}$$

$$R_{A5} = \left(\frac{855.30}{I} + \frac{4501.58}{I^2}\right) \cdot L \tag{5}$$

G: Constant (between 1080.38 and 1350.47 V/m).

A.5. Model 6

This is in a book written by Blackburn and Domin [12]:

$$R_{A6} = \frac{1443.57 \cdot L}{I} \tag{6}$$

A.6. Some details about these models

a) Each model was developed from experiments done with a specific range of currents, but they have been used in a wider range. In this work, the value of the fault resistance was calculated of two ways: Method A, considering that each model is valid for the whole range of currents, and Method B, considering that each model is only valid for the specific range of currents of the corresponding experimental tests (table I).

TABLE I: RANGE OF CURRENTS FOR METHOD B

Model	Range of currents (A)
1	135 - 960
2	1000 - 20000
3	5000 - 50000
4	2000 - 12000
5	2000 - 12000
6	70 - 20000

b) In this work, a maximum value and a minimum value are used for the arc length (L). Therefore, for Method A:

- b.1) Model 2 and model 4 are complementary by using model 2 with maximum length (L_{MAX}), and model 4 with minimum length (L_{MIN}) and G=1080.38 V/m.
- b.2) Model 3 and model 5 are complementary by using model 3 with L_{MAX} and model 5 with L_{MIN}.
- b.3) Model 6 is equivalent to the use of G=1443.57 V/m; therefore, its result is an intermediate value between model 2 and model 4, and its calculation is not strictly necessary.
- b.4) Model 1 must be computed with L_{MAX} and L_{MIN}; this implies the calculation of two different resistances.
- b.5) By this analysis, only the calculation of a subset of models is strictly necessary; however, the results of the 6 models are shown in this article in order to see their differences.

c) The analyzed models, with the exception of model 1, can be considered particular cases of the general model stated by Ayrton in 1901 [7], by using the adequate value of the constants A, B, C, D:

$$R_A = \frac{A + B \cdot L}{I} + \frac{C + D \cdot L}{I^2} \tag{7}$$

B. Model for the effective grounding impedance of the towers

This article only considers the case of transmission lines with ground wires. Hence, for a line-to-ground fault at a tower, a part of the fault current circulates by the individual tower grounding and other one circulates by the ground wires. This implies that the effective grounding impedance (Z_G) is different from the individual grounding resistance of the tower (R_T). Minimal value of the effective grounding impedance (Z_{GMIN}) is assumed to be for faults at a substation, and its maximum value (Z_{GMAX}) is assumed to be for faults in a line without contribution from the remote end. An analysis of the recommendations for the model of Z_G [15-17,22-24] was done specifically for this article, and by such analysis: Z_{GMIN} is assumed to be equal to r multiplied by the parallel equivalent of R_E with Z_P/N_G, and Z_{GMAX} is assumed to be the parallel equivalent of R_T with Z_P.

R_E: Grounding resistance of the substation.

Z_P: Equivalent impedance of a ladder network formed by an infinite number of individual grounding resistances of towers and grounding wires whose length is the average line span.

N_G: Number of lines arriving to the substation.

r: Quotient of the fault current that does not return through the grounding wires that arrive to the substation divided by the total current of the line-to-ground fault.

The values of Z_P and r are:

$$Z_P = 0.5 \cdot Z_W + \sqrt{\left(0.5 \cdot Z_W\right)^2 + Z_W \cdot R_T} \tag{8}$$

$$r = 1 - \frac{Z'_{WL}}{Z'_W} \tag{9}$$

Z'_W: Self impedance per unit length of the grounding wires.

Z_W: Self impedance of the grounding wires for an average line span d_T ($Z_W = d_T \cdot Z'_W$).

Z'_{WL}: Mutual impedance per unit length between the grounding wires and the phase conductors of the line.

III. RANGE OF USED VALUES

R_E was assumed to be between 0.01 and 5 Ω [20,22], but only its minimal value (0.01 Ω) is needed for this article because it only influences the value of Z_{GMIN}. R_T was assumed to be between 1 and 800 Ω [12-13,25-27]; its minimal value (1Ω) is needed to calculate Z_{GMIN} and its maximum value (800 Ω) is needed to calculate Z_{GMAX}.

Table II shows the range used for the other parameters. These values were estimated from the analysis of the constructive characteristics that were reviewed for a wide variety of transmission lines [25-34].

Arc lengths are different for line-to-line faults (L_{L-L}) and for line-to-ground faults (L_{L-G}). L_{MIN} was assumed to be the minimal distance required for a 50 % of probability of the arc occurrence at the corresponding nominal voltage (with standard atmospheric conditions) [35]. A large arc lengthening might exist by convection, wind action and/or electromagnetic attraction (the arc might evolve in the time), and this affect L_{MAX}. By this reason, a value of L_{MAX} was assumed for the instantaneous action of the protections and other one for the delayed action. L_{MAX} for the instantaneous protections was considered to be equal to the minimal distance of separation (between phases or between phase and ground, according to the case) plus 6 meters of initial lengthening, which was estimated considering a wind speed of 30m/s during 0.1s. L_{MAX} for delayed protections was assumed to be 5 times the minimal separation distance between phases, or between phase and ground, according to the case; such multiple is arbitrary and it is based on a qualitative appreciation of the available information (in the literature and in videos). The criteria enunciated for L_{MAX} have an exception for line-to-ground faults at 69kV because the value for instantaneous protections would be greater than the value for delayed protections; by this reason, there was only used the arc length calculated for the delayed protection.

The minimum values for Z'_W and the maximum values for Z'_{WL} are necessary to compute Z_{GMIN}, and they were estimated with two grounding wires (ACSR 240/40 at 20°C) and with a soil resistivity of 20 Ωm. The maximum values for Z'_W were estimated with a soil resistivity of 10000 Ωm, with a grounding wire (extra-high-strength steel, 3/8", at 100°C) for instantaneous protections and at its admissible short circuit temperature (200 °C) for the delayed protections (except in case of 765 kV, that was estimated by two grounding wires of this type because all the lines analyzed for this case had two grounding wires). The value used for N_G is 16.

TABLE II: RANGE FOR THE VARIABLES THAT DEFINE THE VALUES OF Z_{GMIN} (UPPER ROW), AND THE VALUES OF Z_{GMAX} FOR INSTANTANEOUS PROTECTIONS (MIDDLE ROW) AND DELAYED PROTECTIONS (LOWER ROW)

V_N (kV)	L_{L-L} (m)	L_{L-G} (m)	Z'_W (Ω/km)	Z'_{WL} (Ω/km) *	d_T (m)
69	0.23	0.15	0.120 + j0.577	0.059 + j0.362	94
	7.83	5.80	6.098 + j2.502	-	246
	9.15	5.80	8.129 + j2.502		
115	0.37	0.23	0.120 + j0.573	0.059 + j0.342	101
	8.49	7.83	6.098 + j2.502	-	322
	12.5	9.15	8.129 + j2.502		
230	0.70	0.42	0.120 + j0.568	0.059 + j0.320	126
	11.0	8.77	6.098 + j2.502	-	451
	25.0	13.9	8.129 + j2.502		
400	1.23	0.70	0.120 + j0.563	0.059 + j0.290	152
	13.6	10.3	6.098 + j2.502	-	503
	38.2	21.5	8.129 + j2.502		
765	2.06	1.33	0.120 + j0.511	0.059 + j0.236	213
	18.0	13.6	3.078 + j1.489	-	512
	60.0	38.1	4.094 + j1.489		

*: Only the maximum values of Z'_{WL} are required (they are required to compute the minimum fault impedance).

For each nominal voltage (V_N), the range for the short circuit level without fault impedance (I_{SCL}) is between 0.1 and 50 kA. Such range is greater than the usually required values because the objective is to observe the behavior of the results in the range of currents as wide as possible. The range assumed for the angle of the corresponding current is shown in table III. The lower angle values were used to obtain the maximum arc resistance values and vice versa.

TABLE III: RANGE FOR THE ANGLE OF I_{SCL}

V_N (kV)	Line-to-ground	Line-to-line
69 y 115	71.6º…87.1º (X/R: 3…20)	78.7º…87.1º (X/R: 5…20)
230	71.6º…87.7º (X/R: 3…25)	78.7º…87.7º (X/R: 5…25)
400	76.0º…88.1º (X/R: 4…30)	81.9º…88.1º (X/R: 7…30)
765	78.7º…88.6º (X/R: 5…40)	84.3º…88.6º (X/R: 10…40)

IV. METHOD FOR COMPUTING THE ARC RESISTANCE

For the described models, the arc resistance is a decreasing function of the fault current:

$$R_A = g(I) \tag{10}$$

Arc resistance allows to calculate the fault current by using the Thevenin equivalent circuit. A way for expressing this calculation is:

$$I = h(R_A) = \left| V_{TH} / (Z_{TH} + R_A + Z_G) \right| \tag{11}$$

Thevenin voltage (V_{TH}) is the line-to-line voltage for line-to-line faults and the line-to-neutral value for line-to-ground faults. Thevenin impedance (Z_{TH}) is the sum of the impedances of positive and negative sequence for line-to-line faults, and the average of the three sequence impedances for line-to-ground faults. Z_G is zero for line-to-line faults. I_{SCL} is the value of $h(R_A)$ for $R_A = 0$ (and with $Z_G = 0$, for line-to-ground faults).

This analysis is based on the use of phasors. Therefore, the effect of non-sinusoidal waveforms is not considered. The value used for the Thevenin voltage is the nominal value.

The iterative method for computing the solution is very simple: the first value of I for computing R_A with equation (10) is I_{SCL}; with such value of R_A, then I is updated by using equation (11); and with such value of I, R_A is updated by using equation (10). This iterative process is repeated until the convergence is achieved. The error for the current must be lower than 0.1 % as convergence criterion.

In a graphic way, the solution for the equations (10) and (11) is at the intersection of the curves (Fig. 1). Generally there is only one solution; nevertheless, in case of two solutions, only the solution with lower value of R_A has been considered in this article (the computing method forces such solution).

In practice, the possibility of no intersection of the curves is negligible. If this happen for the maximum arc lengths, the recommendation of this article is to evaluate the biggest arc length that allows an intersection of the curves and to use the results of such intersection. An example of this is shown at the section V.B.3.

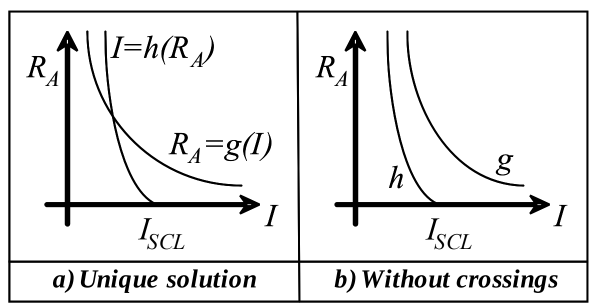

Fig. 1. Examples of the relationship between the equations 10 and 11.

V. RESULTS

A. Effective grounding impedance of the towers

Table IV shows the results of the effective grounding impedance of the towers (Z_G). The effective grounding resistance of the towers (R_G) is simply the real part of the impedance value.

Minimum value of Z_G is practically zero and its maximum value is near to 45Ω (+/-10Ω). This maximum value is moderate, in comparison with the average individual grounding resistance of the towers (R_T =800 Ω); this is due to the presence of the grounding wires. Angle of Z_{GMAX} is small, but the value in ohms of its reactive component is not negligible, and it might influence the apparent reactance seen by the distance protections.

TABLE IV: EFFECTIVE GROUNDING IMPEDANCE OF THE TOWERS

V_N (kV)	Minimum value (mΩ)	Maximum values (Ω) for instantaneous protections (upper row) and delayed protections (lower row)
69	2.51 /12.40º = 2.45 + j0.54	35.2 /10.9º = 34.6 + j6.67
		39.9 /8.34º = 39.5 + j5.79
115	2.73 /13.12º = 2.66 + j0.62	40.2 /10.9º = 39.4 + j7.58
		45.5 /8.30º = 45.0 + j6.57
230	3.07 /13.09º = 2.99 + j0.70	47.3 /10.8º = 46.5 + j8.88
		53.5 /8.26º = 53.0 + j7.69
400	3.51 /13.55º = 3.41 + j0.82	49.9 /10.8º = 49.0 + j9.35
		56.4 /8.24º = 55.8 + j8.09
765	4.02 /13.44º = 3.91 + j0.93	36.6 /12.6º = 35.7 + j7.99
		41.2 /9.73º = 40.6 + j6.96

B. Arc resistance

B.1. General description of the graphs of results

Fig. 2 and Fig. 3 show the results of the arc resistance (R_A) in function of the short circuit level (I_{SCL}, without fault impedance). The minimum values of resistance are equal in both figures. The maximum values of Fig. 2 and Fig. 3 correspond to the instantaneous and delayed protections, respectively. Each graph in both figures indicates the results of the arc models for the minimal and maximum values of R_A. For example, Fig. 2 shows that for line-to-ground faults at 230kV whose I_{SCL} is 1 kA, the value of R_A is between 0.36Ω and 23Ω for Method A, with minimal values in the range between 0.36Ω and 0.76Ω, and maxima values between 9.5Ω and 23Ω (according to the considered arc model). The corresponding case in Fig. 3 indicates that the maximum value for delayed protections is 42Ω (with values between 16Ω and 42Ω, according to the considered arc model).

B.2. Comparison between Method A and Method B

Fig. 2 and Fig. 3 indicate that the minimum values of R_A in the Method A are obtained with model 5. For Method B, model 5 is assumed to be valid only for fault currents between 2 and 12 kA; by this, its minimal values are obtained with model 6 for low values of I_{SCL}, with model 5 for intermediate values of I_{SCL}, and with model 3 for highest values of I_{SCL}. The fact of obtaining the minimal values with model 3 in Method B only can be seen easily for line-to-line faults at 765kV because the R_A values are very small for these high values of I_{SCL} and such R_A values leave the graph by the minimum value used in the scale (0.1Ω). In the Method B, the assumed range for the fault current (table 1) is not equal to the range for I_{SCL} by the effect of the fault impedance; this is more evident for the maximum values of R_A for line-to-ground faults because the fault impedances are greater.

The maximum values of R_A with Method A are obtained with model 1 for the lower values of I_{SCL} and with model 2 for the higher values. In Method B, model 1 is assumed to be only valid for fault currents between 0.135 and 0.96 kA, and model 2 for values between 1 and 20 kA; by this, its maximum values are obtained with model 6 for very low values of I_{SCL}, with model 1 for the moderately low values of I_{SCL}, with model 2 for almost all the higher values of I_{SCL}, and with model 3 for line-to-line faults whose I_{SCL} is greater than 20kA approximately. The maximum values with model 6 in Method B have little practical application because they are obtained for negligible values of I_{SCL}.

Fig. 2 and Fig. 3 show that the low and high limits of the graphs tend to be very similar for Method A and Method B. Additionally, the variables that define the value of the fault impedance are unpredictable. By these two reasons, the use of the results of Method A is advisable for the sake of simplicity.

B.3. Shape of the curves

All the curves of the minimal values of R_A, and the curves of the maximum values of R_A for line-to-line faults, tend to be straight lines in the chosen logarithmic scale. This occurs because $R_A = g(I)$ is a hyperbolic function in terms of the fault current, what means a straight line in the logarithmic scale, and in these cases the fault impedance is moderate (and by this, I_{SCL} is similar to the value of the fault current).

The curves of the maximum values of R_A for line-to-ground faults tend to be inclined straight lines for low values of I_{SCL} and to become stable horizontally for high values of I_{SCL}. This occurs because the values of Z_G are very high, and for high values of I_{SCL}, such Z_G value tends to define the value of the fault current; therefore, as the fault current has little changes, the arc resistance also has little changes.

There are two cases without intersection between the curves $R_A = g(I)$ and $I = h(R_A)$. Both were obtained with model 1, for the maximum values of R_A for line-to-ground faults at 69kV, and I_{SCL} equals to 0.1kA (one case is in Fig. 2 and the other one is in Fig. 3). As it was indicated in section IV, the biggest arc length that allows intersection of the curves was computed for such cases, and the result of this intersection was applied to the graph for these values of I_{SCL}.

B.4. Comparison between different nominal voltages

Except in case of the maximum values of R_A for line-to-ground faults, for each I_{SCL} value, the estimated values of R_A tend to be greater while greater is the nominal voltage (V_N). This occurs because the simulated arc length is greater while greater is V_N.

In case of the maximum values of R_A for line-to-ground faults, the simulated values of Z_G are very big and they do not differ very much between the different V_N values. By this, at each I_{SCL} specific value, for the lower values of V_N there is a greater reduction in the fault current; such reduction in the fault current influences more in the function $R_A = g(I)$, increasing the value of R_A, than the influence by the reduction of the simulated arc length for the lower values of V_N.

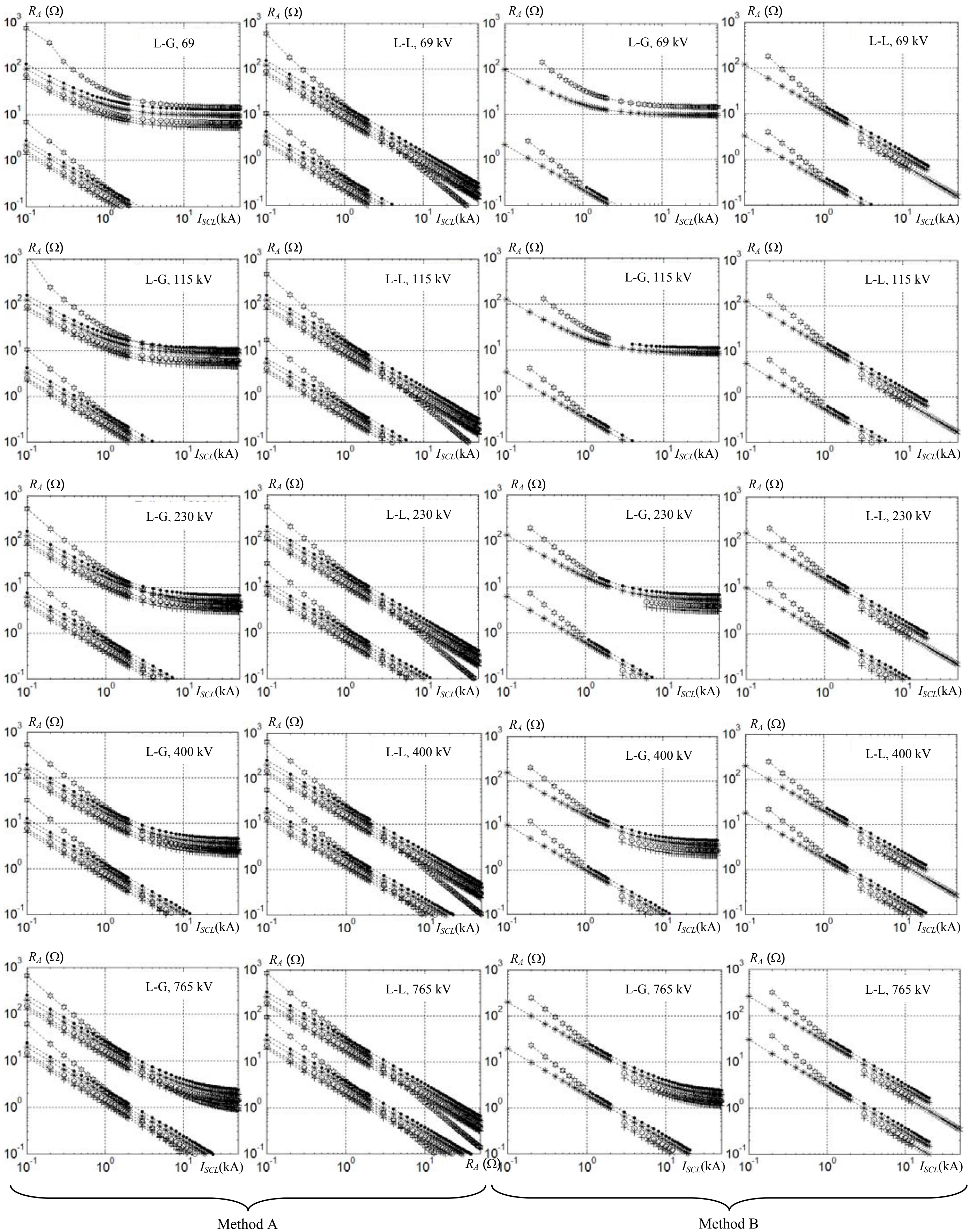

Fig. 2. Minimal and maximal arc resistances for instantaneous protections.
Legend for the arc models: ✡ Model 1, • Model 2, × Model 3, ○ Model 4, + Model 5, ∗ Model 6.

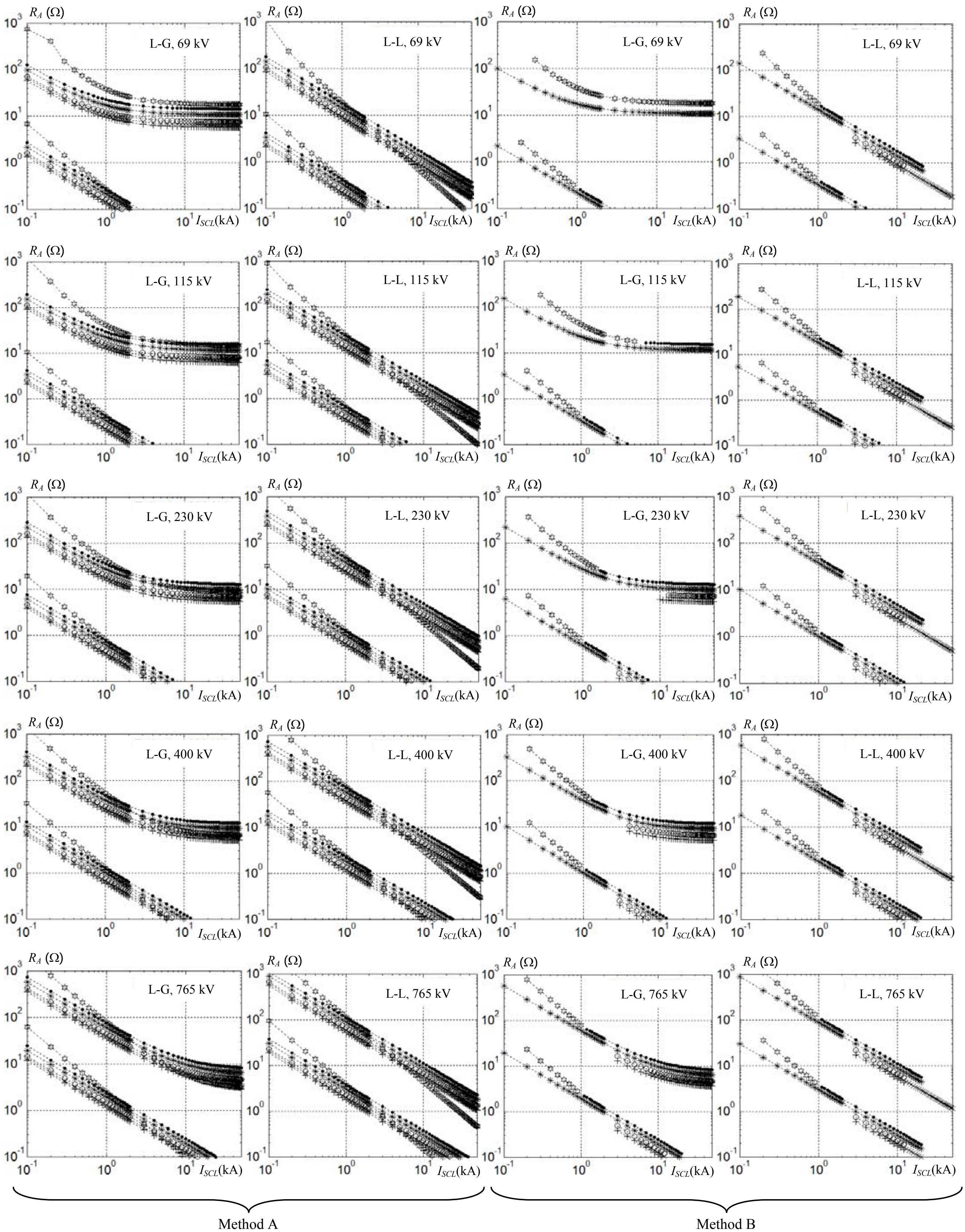

Fig. 3. Minimal and maximal arc resistances for delayed protections.
Legend for the arc models: ✡ Model 1, • Model 2, × Model 3, ○ Model 4, + Model 5, ∗ Model 6.

B.5. Summary of typical values for I_{SCL} greater than 1kA

For each I_{SCL} and V_N, Fig. 2 and Fig. 3 indicate exactly the minimal and maximum estimated values of R_A. Nevertheless, it is also possible to indicate some approximate relations:

a) Except for 69kV and 115kV, the minimal values of R_A are approximately 1Ω at 1kA, 0.1Ω at 10kA, and tend to be lower than 0.1Ω for I_{SCL} greater than 10kA. For 69kV and 115kV, the minimal values of R_A tend to be even lower.

b) For line-to-line faults, the maximum values of R_A for instantaneous protections are approximately 20Ω at 1kA and 2Ω at 10kA if V_N is 69kV, 115kV or 230kV, and they are approximately 40Ω at 1kA and 4Ω at 10kA if V_N is 400kV or 765kV. The corresponding values for delayed protections are approximately 30Ω at 1kA and 3Ω at 10kA if V_N is 69kV or 115kV, they are approximately 60Ω at 1kA and 6Ω at 10kA if V_N is 230kV, and they are approximately 100Ω at 1kA and 10Ω at 10kA if V_N is 400kV or 765kV.

c) For line-to-ground faults, the maximum values of R_A for instantaneous protections are approximately 60Ω at 1kA and tend to become stable to 25Ω at 3kA if V_N is 69kV, they are approximately 30Ω at 1kA and tend to become stable at 10Ω at 3kA if V_N is 115kV or 230kV, and they are approximately 30Ω at 1kA and 6Ω at 10kA if V_N is 400kV or 765kV. The corresponding values for delayed protections are similar if V_N is 69kV, they are approximately 60Ω at 1kA and tend to become stable to 15Ω at 3kA if V_N is 115kV, 230kV or 400kV, and they are approximately 100Ω at 1kA and 15Ω at 10kA if V_N is 765kV.

Another way for doing a summary of these results is making use of the fact that the sloping part of the curves tend to a straight line in the logarithmic scale, whose expression is:

$$R_A\, I_{SCL} = K \qquad (12)$$

K: Constant.

The curve of maximum values of R_A for line-to-ground faults can be approximated as the intersection of an inclined straight line with a horizontal one. The horizontal straight line is described by the values of stabilization ($I_{SCL,ST}$ and $R_{A,ST}$); therefore:

$$R_A\, I_{SCL} = K, \qquad \text{if } I_{SCL} < I_{SCL,ST} \qquad (13)$$

$$R_A = R_{A,ST}, \qquad \text{if } I_{SCL} \geq I_{SCL,ST} \qquad (14)$$

This summary of the results is different to the described one in the previous items (a, b, c) and it has a greater accuracy and simplicity (Tables V and VI).

TABLE V: APPROXIMATE RESULTS OF R_A FOR LINE-TO-LINE FAULTS, AND I_{SCL} > 1 KA (EQUATION 12).

V_N (kV)	Minimum	Maximum (instantaneous protection)	Maximum (delayed protection)
	K (kV)	K (kV)	K (kV)
69	0.20	15	18
115	0.32	16	24
230	0.60	20	49
400	1.1	25	72
765	1.6	33	112

TABLE VI: APPROXIMATE RESULTS OF R_A FOR LINE-TO-GROUND FAULTS, AND I_{SCL} > 1 KA (EQUATIONS 13 AND 14).

V_N (kV)	Min.	Maximum (instantaneous protection)			Maximum (delayed protection)		
	K (kV)	K (kV)	$I_{SCL,ST}$ (kA)	$R_{A,ST}$ (Ω)	K (kV)	$I_{SCL,ST}$ (kA)	$R_{A,ST}$ (Ω)
69	0.13	54	3	18	66	3	22
115	0.20	52	4	13	72	4	18
230	0.36	49	6	8.2	75	5	15
400	0.60	47	8	5.9	91	7	13
765	1.1	46	16	2.9	130	13	10

VI. CONCLUSION

A range of typical expected values for the fault resistance in electrical transmission systems was computed, by using six existing models for the arc resistance and a model for the effective grounding impedance of the towers. The minimal and maximum expected values for the fault resistance are dependent of the short circuit level and the nominal voltage of the system. The component of the fault resistance associated with the effective grounding resistance of the towers is shown in tables because it is not dependent of the short circuit level, while the component associated with the arc resistance is shown in graphs in function of the maximum short circuit level (without fault impedance). The achieved information can be useful to have a fast estimation of the required range of fault resistances.

The maximum values of the arc resistances were computed considering two different assumptions about the arc lengthening. The considered arc length for the instantaneous protections is lower than for the delayed protections.

For line-to-ground faults, the fault impedance has an inductive part. The angle of the fault impedance is small, but the modules of the possible maximum values are so high that the inductive part of the impedance is not insignificant, and it might affect the behavior of some distance protections.

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