MEASUREMENT OF THE ZERO-SEQUENCE CURRENT DISTRIBUTION ON A TRANSMISSION LINE

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In case of a short-circuit, where also a *zero-sequence current* flows through the fault, the distribution of the zero-sequence current flowing from the ground wires to earth varies in the vicinity of the fault. The types of faults in a system with effectively grounded neutrals are the single-phase and double-phase-to-ground faults.

According to the fault statistics of the 120 and 220 kV national grid, the most frequently occurring type of fault is the single-phase-to-ground one (e.g. due to flashovers of insulator strings). In these cases one part of the zero-sequence fault current flows directly into the earth through the steel structure of the transmission-line tower directly affected by the fault, while the other part passes through the steel structure of the same tower into the ground wire (or wires) and is *distributed* in either direction of the line. In case of flashovers the impedance across the faulty line and ground wires is practically equal to that of the arc, while between the faulty line and earth a somewhat higher resistance, i.e. the grounding resistance of the tower is inserted. Thus, in the span adjacent to the faulty tower the current flowing in the ground wires is higher and, receding from the faulty tower, gradually decreases to a definite value referred to in the followings as *steady-state value.*

The difference of currents flowing in the ground wires in any two adjacent spans is equal to the current flowing into the earth through the tower. This current is called *tower-current.* The section of the transmission line along which the value of zero-sequence current varies from span to span is called *the section with end-effect.* The extension of this section is not exactly known and only estimated values exist.

When instead of a line termination the fault occurs at an intermediate tower and the line is fed from one side, the end-effect appears not only in the section lying on the side of the feeding point, but also on the side opposite to the feeding point. Obviously in that case the steady-state value to which the current in the ground wire decays is equal to zero.

No theoretical difficulties are encountered in determining the length of the section with end-effect and the values of tower-currents, especially when the faulty line is sufficiently long to permit the circuit carrying the fault current to be considered as being terminated by their characteristic impedances. In such cases these circuits may be treated as ladder networks and all parameters can be determined by means of the methods developed in the theory of communication techniques.

Although requiring considerably more calculation work, in principle, it is possible to determine the current distribution between ground wire and earth for each span of the section with end-effect. The calculation should be started from the faulty tower, and the tower currents for each tower can, one by one, be determined.

These kinds of calculations are not only tedious and subjected to possible numerical errors, but their reliability is also doubtful, due to the following practical reasons:

a) to keep the extent of calculation work within reasonable limits some neglections affecting accuracy must be introduced;

b) the errors in the basic data (e.g. soil conductivity, grounding resistance of towers, etc.) may be considerable;

c) the factors determining the current distribution (e.g. self-impedance of ground wires, mutual impendance between ground wires, phase conductors and earth, grounding resistance of towers, etc.) may show random variations according to site and time;

d) the effect of local inhomogeneities (e.g. contact resistance between ground wires and towers, soil inhomogeneities, presence of grounded metallic objects, such as near by railway lines, etc.) cannot be taken into account because of the difficulties of their assessment and to the variability of these inhomogeneities.

The picture which can be obtained by calculation yields qualitative information only: it is inadequate for finding definite answers to questions either on power transmission or interference problems. Neither the sporadic references supply sufficient information for practical use, not to mention the difficulties in trying to adapt these informations to our local conditions, for lack of practice in this field.

Therefore, it seemed advisable to clear up the conditions by means of field measurements. It is obvious that the results of a single series of measurements cannot be generalized and, hence, no attempt is made to draw conclusions valid for all cases. Instead, an endeavour was made to fill up the qualitative picture with practical data. The paper is, therefore, restricted to the description of the measurements performed.

1. Objectives of the measurements

The objectives of the measurements may be summarized as follows:

a) Determination of *the extension of the section with end-effect* for an artificial fault produced in the middle of an overhead line and supplied from one end.

b) The *relative values* of currents flowing in the ground wire within the section with end-effect, related to the steady-state ground-wire current (flowing in the middle of the faulty line section) and to the total zero-sequence current.

c) The effect of specific soil resistivity and grounding resistance of towers on the magnitude of currents.

d) Assessing the accuracy of a practical method based on Carson's theory and used for computing the zero-sequence impedances.

e) Determination of the average *screening factor* within the section with end-effect and being of importance with respect to the interference imposed on communication lines.

2. Connections for the measurement

a) For the purpose of producing the zero-sequence current between the feeding point and the artificial fault the use of a *de-icing transformer* seemed most practicable. Among the 120 kV single-circuit overhead transmission lines fed from Ajka Power Station the *Ajka—Söjtör* line was selected as being the most suitable with respect to both system operating conditions and those of the measurement.

The line was supplied from the outdoor station of the Ajka Power Plant through a de-icing transformer. This unit having a ratio of 19/10.5 kV was fed from the 10.5 kV busbars, thus a voltage of 5.8 kV was obtained across the 10.5 kV terminals of the transformer. This voltage was connected between one phase of the selected overhead line and ground at the feeding point in Ajka. The connection diagrams are shown in Figs. 1 and 2.

b) As the site of the artificial fault *one of the anchor towers* (Tower No. 132) of the transmission line was chosen. The distance between the feeding point and this anchor tower was 30.7 km. Here the phase conductors were disconnected and the middle conductor, chosen for symmetrical reasons, was metallically connected to the ground wires and to the tower.

c) The measurements for each span were performed on the line section between the towers of No. 119 and No. 138, over a length of about 5 kilometres.

d) In the middle of the "faulty" section between Ajka and Sümeg additional measurements were made to obtain the steady-state value of current flowing in the ground wires.

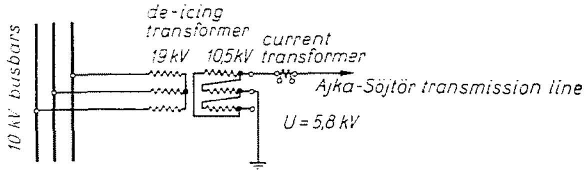

Fig. 1. Connection diagram of the current supply for the measurement

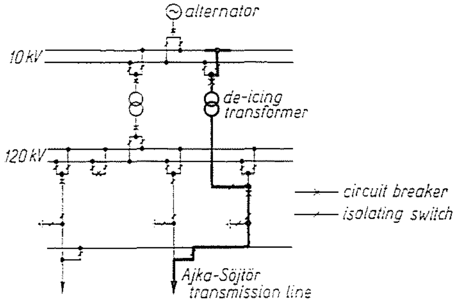

Fig. 2. Connection diagram of the supply end at Ajka Power Station

3. Calculation of currents

a) Based on Appendix 2, the resultant impedance — *without* considering the earthing of ground wires at each tower — is 27.4 ohms.

The voltage at the terminals of the de-icing transformer on the overhead-line side at the Ajka Power Station was 5.97 kV.

Thus, the *computed* value of the current flowing through the overhead line was

$$I = \frac{5970}{27.4} = 218 \text{ amp.}$$

b) The steady-state value of the current flowing in the ground wires can also be determined by calculation.

Establishing the voltage equations, for the phase conductor:

$$u = I \cdot z_{0c} + 2I_g \cdot z_{0g} \,,$$

and for an equivalent conductor, by which, due to the symmetrical conditions, the two ground wires may be substituted:

$$0 = I \cdot z_{0m} + 2I_g \cdot z_{0g}$$

hence,

$$-\frac{2I_g}{I} = \frac{z_{0m}}{z_{0g}},$$

(the negative sign indicating the opposite current-directions) and disregarding the phase angle:

$$2\frac{I_g}{I} = \frac{|z_{0m}|}{|z_{0g}|} = \frac{0.324}{2.41} = 0.1345 = 13.45\%\ ,$$

thus, each of the ground wires carries 6.72 per cent of the calculated current (218 amp), i.e.

$$I_g = 14.6 \text{ amp.}$$

The above values will later be compared with the measured values.

Explanation of symbols used in the voltage equations:

I = (zero-sequence) fault current flowing in the phase conductor;
I_g = current flowing in each ground wire;
z_{0c} = zero-sequence self-impedance of each phase conductor;
z_{0m} = zero-sequence mutual impedance between phase conductor and ground wires;
z_{0g} = zero-sequence self-impedance of ground wires.

The calculation of impedances is given in Appendix 2.

4. Measured magnitudes

a) The *fault current* (injected current) was measured at the feeding point.

b) The same current was also measured at Tower No. 132 by means of current transformers mounted in the tie-conductors connecting the middle phase conductor to each ground wire.

c) The tie-conductors and connections were arranged at Tower No. 132 so as to permit, by means of cable-type current transformers, the measurement of currents flowing *in the ground wires* towards Ajka and Söjtör, as well as that passing directly *into the ground* through the top of each tower.

d) The ground wires were released and isolated from the clamp fittings at the towers of No. 119 to No. 138. Then, by means of cable-type current transformers mounted in the jumpers, set up between each ground wire and the tower, the *tower currents* were measured.

e) At Tower No. 58 lying in the middle of the investigated line-section the *steady-state currents* were measured by means of current transformers mounted into the ground wires.

For measuring the tower currents and those flowing in the ground wires a great number of current transformers with low inserted impedance were required. The low inserted impedance of these current transformers had to be specified to minimize the effect of the measurement on the current distribution. For this purpose suitably modified loading coils used for communication cables were adopted. The inserted impedance of these loading coils, when used as cable-type current transformers, is 10^{-4} ohms.

5. Works performed on the towers

a) *Tower No. 132 with artificial fault*

At Tower No. 132 all three phase-conductors were *disconnected* on the Söjtör side.

Between the middle phase-conductor and each of the two ground wires *metallic connections* were established and *current transformers* were inserted

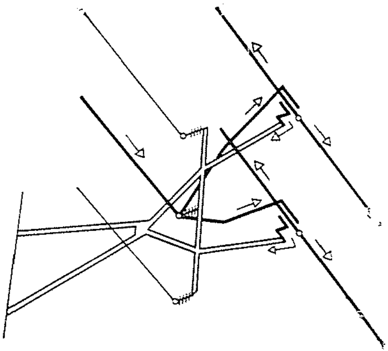

Fig. 3. Schematic layout of connections at the tower with artificial fault

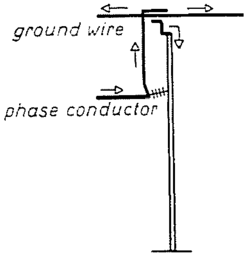

Fig. 4. Side-view sketch of the tower with artificial fault

into these tie-connections. The schematic layout of connection is shown in Figs. 3 and 4. The actual arrangement can be seen on the photograph of Fig. 5.

Both ground wires had to be isolated from the tower; and the current-carrying tie-connections of the ground wires had to be separated from the tower tops.

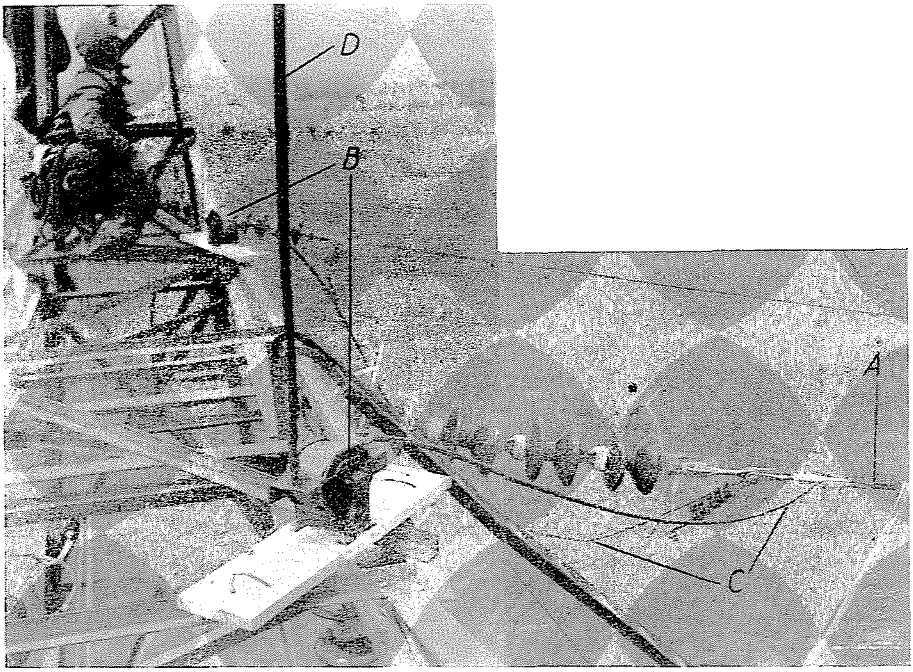

Fig. 5. Actual arrangement of artificial fault connections and mounting of current transformers on the tower

A = middle-phase conductor
B = current transformers
C = connection between middle-phase and current transformer
D = connection between current transformer and ground wire

At each tower top a *four-branched node* was established and the current in each branch was measured.

The arrangement of the fittings and conductors is shown in Fig. 6, while the view of the tower during mounting can be seen in Fig. 7.

b) *Suspension towers*

The serial numbers of towers involved in the measurement towards Ajka were as follows: No. 119 to No. 131, i.e. thirteen towers; those towards Söjtör: No. 133 to No. 138, i.e. six towers.

At all of the suspension towers mentioned the ground wires *had to be removed* from their clamp fittings mounted on the tower tops.

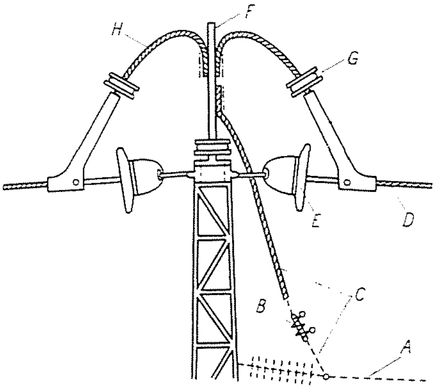

Fig. 6. Detailed arrangement of fittings and connections at the tower top with artificial fault

A = middle-phase conductor
B = current transformer
C = connection between middle-phase conductor and ground wire
D = ground wire
E = single-disc insulator
F = fitting
G = cable-type current transformer
H = tie-conductor

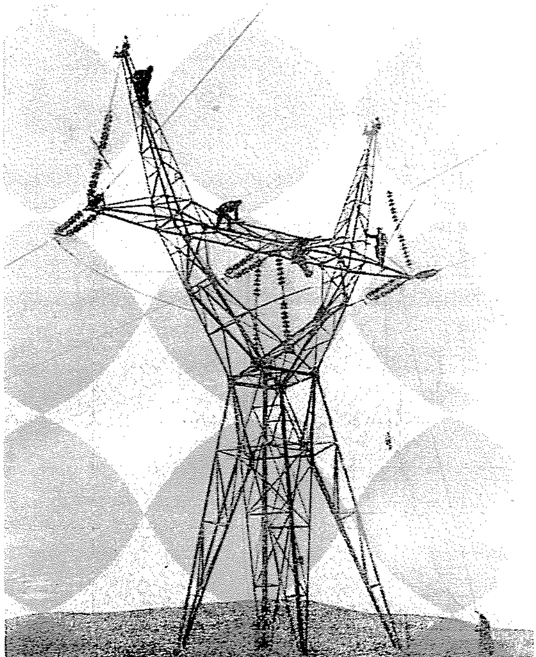

Fig. 7. Mounting work performed on the tower with artificial fault

Between each ground wire and clamp fitting an *insulation* was inserted, so at these points no current could flow from the ground wire to the tower.

For the measurement of the current flowing from the ground wire into the tower, i.e. the tower current, each ground wire was connected to the tower through a flexible *tie-conductor*. The mounting arrangement used is given in Fig. 8.

c) *Tower No.* 58

This tower is 13.2 kilometres from the feeding point Ajka and from previous soil resistivity measurements it was assumed that in this section the steady-state value of ground-wire current was attained, i.e. no current was flowing through the tower structures to earth. During mounting one of the two connecting fittings of each grounding wire was replaced by a single-disc insulator: the jumpers of ground wires had also to be disconnected from the towers. Each jumper was equipped with a cable-type current transformer (Fig. 9).

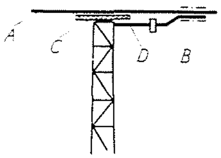

Fig. 8. Side-view sketch of suspension tower tops

A = ground wire
B = cable-type current transformer
C = insulator
D = connecting cable

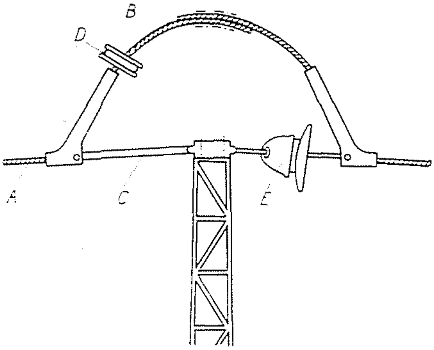

Fig. 9. Detailed arrangement of connections at top of Tower No. 58

A = ground wire
B = tie-conductor
C = connecting fitting
D = cable-type current transformer
E = single-disc insulator

6. Results of measurements

a) *Measurements at Tower No. 132*

During each of the test periods the distribution of currents at the "faulty" tower No. 132 was measured. The values obtained are summarized in Table I.

Table I

Current distribution at the faulty tower No 132

1.	Test period	1.	2.	3.	4.	5.	6.
2.	Current fed-in at Ajka (amp)	225.6	226.6	228.8	228.0	224.4	223.2
3.	*At Tower No. 132 :*						
	Right-side current (amp)	113.0	113.2	113.6	113.0	113.2	113.0
	Left-side current (amp)	114.4	115.0	115.0	112.8	112.6	112.4
	Total (amp)	227.4	228.2	228.6	225.8	225.8	225.4
4.	*On the right side :*						
	Current flowing into the tower (amp)	25.4	24.4	24.4	27.5	27.4	27.3
	Current towards Ajka (amp)	55.0	55.6	55.4	57.5	56.4	50.1
	Current towards Söjtör (amp)	31.6	32.4	32.4	39.5	38.1	37.9
	Total (amp)	112.0	112.4	112.2	124.5	121.9	121.3
5.	*On the left side :*						
	Current flowing into the tower (amp)	27.1	25.5	25.9	26.1	26.7	26.7
	Current towards Ajka (amp)	49.8	48.6	48.4	55.0	54.0	53.8
	Current towards Söjtör (amp)	32.5	33.5	33.5	34.7	34.2	33.9
	Total (amp)	109.4	107.6	107.8	115.8	114.9	114.4
6.	Total of right-side and left-side currents (amp)	221.4	220.0	220.0	240.3	236.8	235.7

First the table indicates the current readings taken at Ajka Power Station. The next row contains the currents measured by means of the current transformers mounted on the tower and also the sum of these currents. The maximum deviation of the sums of currents from the readings taken at Ajka is 0.98 per cent.

The designations "left" and "right" used here and in the following always refer to the ground wire fitted to the respective side of the tower *looking toward the feeding point.*

In the next two rows the distribution of currents flowing in the indicated directions, i.e. towards Ajka, Söjtör and into the tower, respectively, as well as their sums are shown. The last row of the table contains the sum of all currents. The difference in this sum and the fed-in current varied between 1.85 and 5.55 per cent.

b) *Measurement of tower currents ; computation and measurement of currents flowing in the ground wires*

The readings could not be taken at the towers simultaneously, because the measuring instruments had to be transferred from place to place. Nevertheless, there was no need to relate these values to a common reference basis, since — as it may be seen from the 2nd row of Table I — the deviations of the readings taken at different times remained within the range of measuring errors.

The measurements were not extended to explore phase conditions, thus the current values were treated as algabraic and not as vector quantities. This procedure is fully justified by the data of Table I, showing that the maximum deviation between the sum of branch currents and the current fed into the circuit at Ajka is 5.55 per cent.

By successive subtraction of the measured tower currents from that flowing at Tower No. 132 into the ground wire toward Ajka and Söjtör, respectively, the current values flowing in the ground wires in each span could be determined by calculation. The result of this calculation is listed in Table II and III, further in Fig. 10.

Table II

Tower currents and ground-wire currents in the line section on the side towards Ajka

Serial No. of towers	Resistance of tower grounding (ohms)		Tower current (amp)			Serial No. of spans	Ground-wire currents (amp) calculated from the tower currents		
	right	left	right	left	total		right	left	total
132.	8.0	13.0	25.00	26.00	51.00	1.	56.50	54.50	111.00
131.	4.0	4.0	16.35	18.70	35.05	2.	40.15	35.80	75.95
130.	11.0	13.0	10.40	7.15	17.55	3.	29.75	28.65	58.40
129.	9.0	9.0	4.55	6.00	10.55	4.	25.20	22.65	47.85
128.	15.0	18.0	3.05	3.95	7.00	5.	22.15	18.70	40.85
127.	13.0	10.0	2.65	2.85	5.50	6.	19.50	15.85	35.35
126.	10.0	8.0	2.20	2.45	4.65	7.	17.30	13.40	30.70
125.	8.5	8.5	2.10	0.90	3.00	8.	15.20	12.50	27.70
124.	12.0	13.0	1.45	1.45	2.90	9.	13.75	11.05	24.80
123.	6.0	6.0	0.70	0.20	0.90	10.	13.05	10.85	23.90
122.	19.0	23.0	0.25	0.25	0.50	11.	12.80	10.60	23.40
121.	16.0	15.0	—	—	—	12.	12.80	10.60	23.40
120.	13.5	12.0	—	—	—	13.	12.80	10.60	23.40
119.	19.5	25.0	—	—	—				

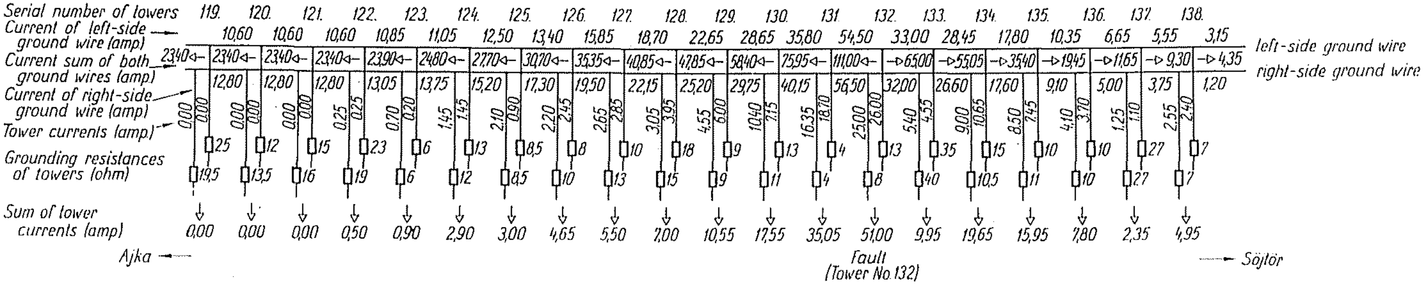

Fig. 10. Grounding resistance of towers, tower currents and ground-wire currents in the vicinity of the fault

Table III

Tower-currents and ground-wire currents in the line section on the side towards Söjtör

Serial No. of towers	Resistance of tower grounding (ohms)		Tower current (amp)			Serial No. of spans	Ground-wire currents (amp) calculated from the tower currents		
	right	left	right	left	total		right	left	total
132.	8.0	13.0	25.00	26.00	51.00				
						1.	32.00	33.00	65.00
133.	40.0	35.0	5.40	4.55	9.95				
						2.	26.60	28.45	55.05
134.	10.5	15.0	9.00	10.65	19.65				
						3.	17.60	17.80	35.40
135.	11.0	10.0	8.50	7.45	15.95				
						4.	9.10	10.35	19.45
136.	10.0	10.0	4.10	3.70	7.80				
						5.	5.00	6.65	11.65
137.	27.0	27.0	1.25	1.10	2.35				
						6.	3.65	5.55	9.30
138.	7.0	7.0	2.55	2.40	4.95				
						7.	1.20	3.15	4.35

Table II contains the current readings obtained for the section between Tower No. 132 and Ajka, while Table III gives the respective readings for the section towards Söjtör. The grounding resistances of the towers are also indicated in the same tables. The measurement of the latter resistances was performed closely before the current readings were taken.

c) *Measurement of steady-state current at Tower No. 58*

The readings of ground-wire currents taken by means of installed current transformers were as follows:

on the right-hand side	13.90 amp,
on the left-hand side	13.80 amp,
total	27.70 amp.

7. Conclusions

a) Length of line section with end-effect

If in the line section with end-effect the difference between the currents flowing in the span adjacent to the "faulty" tower and the steady-state ground-wire currents is taken as 100 per cent, then in the subsequent spans the percentage values of difference currents were found as shown in Table IV.

It can be seen that under the conditions given *the end-effect extended over* 10 *spans, i.e. over a length of* 2.5 *km* towards the feeding point and presumably over the same length in the opposite direction. As it is apparent from the data

Table IV

Serial No. of span	Difference with respect to the steady-state current			
	Line section towards Ajka		Line section towards Söjtör	
	amp	%	amp	%
1.	87.60	100.0	65.00	100.0
2.	52.55	60.0	55.00	84.5
3.	35.00	39.9	35.40	54.4
4.	24.45	27.9	19.45	29.9
5.	17.45	19.9	11.65	17.9
6.	11.95	13.6	9.30	14.3
7.	7.30	8.3	4.35	6.7
8.	4.30	4.9	no reading was taken	
9.	1.40	1.6	,,	
10.	0.50	0.57	,,	
11.	0.00	0.0	,,	

In the line section towards Ajka:

111.00—23.40 = 87.60 amp = 100%

In the section towards Söjtör:

65.00—0.00 = 65.00 amp = 100%

of Table IV, the difference currents flowing in the ground-wires only slightly differ from those of the corresponding spans lying in the opposite direction — especially at some distance from the artificial fault. This means that in the 10th span towards Söjtör the ground-wires were practically free of current.

b) Relative magnitudes of ground-wire currents

If the steady-state current of 23.4 amp flowing in the line section with end-effect towards Ajka is considered as a unity, the relative magnitudes of current flowing in other spans are given in Table V.

The total zero-sequence current fed in at Ajka taken as 100 per cent, the current distribution at Tower No. 132 was found to be as follows:

current flowing into the earth through the tower	22.4%
current flowing into the two ground wires towards Ajka	48.9%
current flowing into the two ground wires towards Söjtör	28.7%

It is to be noted that the current flowing through the tower by the artificial fault did not even reach one quarter of the total fault current and that

Table V

Serial No. of span	Current related to the steady-state value	
	Line section towards Ajka	Line section towards Söjtör
11.	1.00	No reading was taken
10.	1.02	"
9.	1.06	"
8.	1.18	"
7.	1.31	0.186
6.	1.51	0.40
5.	1.75	0.50
4.	2.04	0.83
3.	2.49	1.51
2.	3.24	2.35
1.	4.75	2.78

almost one half of the total fault current flowed into the ground wires towards the feeding point!

In Fig. 11 are shown the currents flowing in the ground wires in the vicinity of the fault.

Thus, when calculating the thermal stresses caused by fault currents in the ground wires, it should be taken into account, that the ground-wire current flowing in the first span adjacent to the fault is five-times the steady-state current of the ground wire! For this reason utmost care must be taken to ensure sound metallic connections at the fittings used for clamping the ground wires to the tower tops, since a higher contact resistance may cause local overheating and consequent damage (burning) of ground wires.

It is very useful for the survey of actual conditions to sketch the percentage distribution of currents over the total measured line section. Fig. 12 indicates the percentage values of currents flowing in the two ground wires, towers and in the earth, for one-side feeding, where the total value of fed-in zero-sequence fault current is taken as 100 per cent. For the sake of simplicity, the phase conductor is not shown in the drawing.

c) Effects resulting from specific soil resistivity and grounding resistance of towers

Since along the measured line section, the soil resistivity was constant, presumably it did not influence the conditions of current distribution.

The grounding resistance of the towers, however, had a considerable effect on the current distribution. This fact becomes clearly apparent in Tables

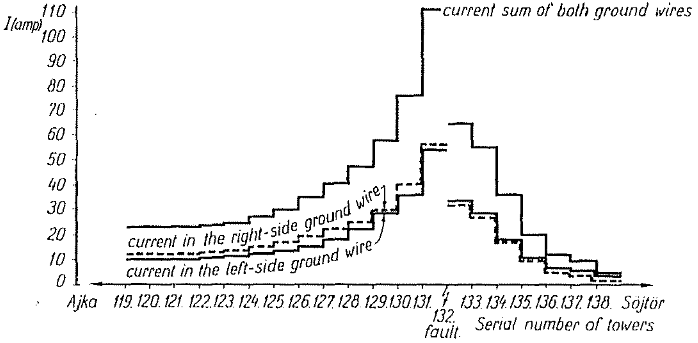

Fig. 11. Current flowing in the ground wires in the vicinity of the fault (stepped curve)

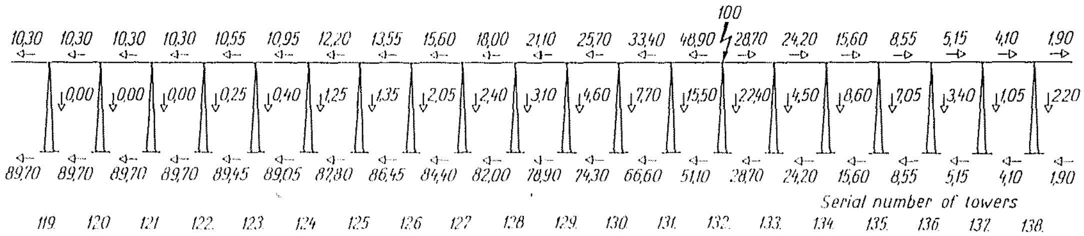

Fig. 12. Percentage values of currents flowing in the ground wires, towers and earth in case of one-sided supply and the fault current taken as 100. For the sake of simplicity the phase conductor is not represented

II and III and in Fig. 11. In the line section towards Söjtör considerably lower tower currents were found to pass into the earth through Towers No. 133 and No. 137, disturbing the regularity of the stepped curve. The grounding resistance of both of these towers was about three times that of other towers.

On the side towards Ajka no major deviations in the resistance of the tower groundings were found and the stepped curve shows a regular shape.

d) Comparison of the values calculated by means of the Carson's formula with those obtained by the measurement

The deviation between the 218 amp determined by means of the calculation given in Appendix 2 and in Section 3 and the average value of 225 amp obtained by the measurements is 3.2 per cent.

Similarly, when comparing the calculated values of the steady-state currents flowing in the ground wires ($2 \times 14.6 = 29.2$ amp) with those measured at Tower No. 58 ($13.9 + 13.8 = 27.7$ amp), a difference of 5.14 per cent is found.

e) Average screening factor in the section with end-effect

The *screening factor* as defined by the CCIF Recommendations can be determined by the ratio of the difference between the total fault current (I_f) and the current flowing in the considered line section to the total fault current, i.e.

$$k_e = \frac{I_f - \sum I_g}{I_f}$$

When determining I_g, the ground-wire currents must be related to the unit line length, thus

$$\sum I_g = \frac{I_{1g} \cdot l_1 + I_{2g} \cdot l_2 + \dots + I_{ng} \cdot l_n}{l_1 + l_2 + \dots + l_n} = \frac{\sum_{i=1}^{n} I_{ig} \cdot l_i}{\sum_{i=1}^{n} l_i}.$$

The screening factors thus calculated for the line section between Tower No. 132 and Ajka are contained in Table VI and are plotted in Fig. 13 in function of the distance taken from the artificial fault.

Table VI

Distance from the fault (km)	0.5	1	2	3	5
Screening factor: k_e	0.58	0.65	0.74	0.81	0.86

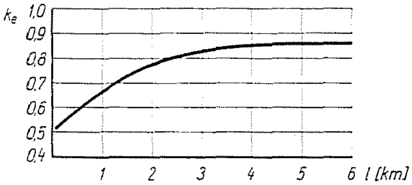

Fig. 13. Value of screening factor (k_e) in function of distance (l) from the fault

The screening factor valid for the line section without end-effect according to relation

$$k = \frac{I_f - I_g}{I_f}$$

is (using the readings taken at Tower No. 58):

$$k \cong 0.9$$

The screening factor k_e valid for the line section with end-effect can also be determined by multiplying the factor k valid for the line section without ind-effect by a factor S_e which serves for taking into account the end-effect in function of line length.

Thus,

$$k_e = k \cdot S_e$$

The values of S_e valid within the considered section are given in Table VII, while the relation $S_e = f(l)$ is plotted in Fig. 14.

Table VII

Distance from the fault (km)	0.5	1	2	3	5
S_e	0.645	0.72	0.82	0.90	0.95

It is apparent from the above that *the end-effect has a reducing effect on the screening factor.* This reduction also manifests itself beyond the section subjected to the end-effect, although to a lesser extent.

*

The results of measurements have shown that in the case of the investigated overhead transmission line the section with end-effect extends to about 10 spans, or 2.5 kilometres on either side of the fault. Almost half of the total fault current flows through the ground wires towards the feeding point, this being an important factor in assessing the expectable thermal stresses imposed on the ground wires. The knowledge of the proportion of fault current flowing through the faulty tower directly into earth is required for calculating the potential rise of the tower structure. The measurements gave information on the effects caused by the resistance of tower groundings. Finally, knowing the end-effect conditions, the screening effect, i. e. the reduction in the magnitude of interference can also be determined.

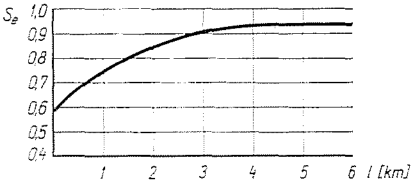

Fig. 14. Value of factor S_e in function of distance (l) from the fault

In the References some specific papers and books are given in which theoretical considerations concerning the problems of current distribution between ground wires and earth, as well as data in the end-effect and the influences of these factors on interference, may be found.

Appendix 1

Technical data of the overhead transmission line Ajka—Söjtör.
Total length of overhead line: 77.3 km.
Length of line section Ajka—Tower No. 132: 30.7 km.
Length of line section Ajka—Tower No. 58: 13.2 km.
Type of tower: single-circuit with two ground wires, H-type suspension towers (Fig. 15).
Transmission line: single-circuit, 120 kV.

Phase conductors:

material	ACSR
equivalent aluminium cross-sectional area:	110 mm^2;
diameter	1.51 cm;
GMR	0.622 cm;
resistance	0.261 ohm/km;

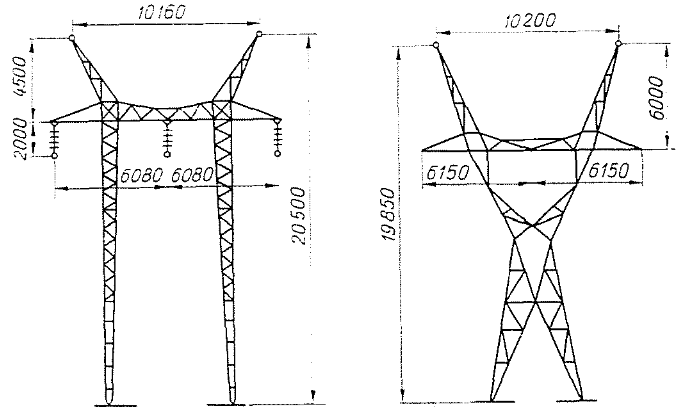

Fig. 15. Schematic diagram of the suspension and anchor towers

clearance between phases:

at suspension towers:	608	mm;
at anchor towers:	615	mm;
continuous current rating:	335	amp.

Ground wires:

material	Steel,	Grade III.
nominal cross section	50	mm^2;
diameter	0.9	cm;
d.c. resistance	4.4	ohm/km;
clearance between ground wires	1050	cm;

Specific soil conductivity	$4.65 \cdot 10^{-14}$ cgs = = $4.65 \cdot 10^{-3}$	 mho/m.
Specific soil resistivity along the measured line section:	215	ohm · m.

Appendix 2

Calculation of zero-sequence impedance

With respect to the rating of the de-icing transformer and taking into account the given line length of 30.7 kilometres, the zero-sequence circuit had to be composed of *a single phase conductor* and earth, instead of parallelled phase conductors and earth. This also simplified the set-up of the measurements without affecting the characteristic results.

a) *Zero-sequence impedance of a single phase conductor calculated from the Carson's formula*

$$z_{0c} = r + 0.00099 f = j\, 0.0029 \cdot f \cdot lg \frac{D_e}{GMR} \text{ ohm/km};$$

$$r = 0.261 \text{ ohm/km},$$

$$f = 50 \text{ c/s};$$

$$D_e = 6.59 \cdot 10^4 \sqrt{\frac{\varrho}{f}} \text{ cm}; \qquad \varrho = 215 \text{ ohm} \cdot \text{m},$$

$$D_e = 1365 \text{ m}.$$

With these data

$$z_{0c} = 0.31 + j\, 0.770 \text{ ohm/km}$$

b) *Zero-sequence mutual impedance between phase-conductor and ground wires*

$$z_{0m} = 0.00099 f + j\, 0.0029 \cdot f \cdot lg \frac{D_e}{GMD},$$

$$GMD = 835 \text{ cm},$$

$$z_{0m} = 0.0495 + j\, 0.321 \text{ ohm/km}.$$

c) *Zero-sequence self-impedance of ground wires*

For this calculation it was assumed that each ground wire carried a current of 10 amp. The calculation was based on the method described in the book "*Symmetrical Components*" by GESZTI, KOVÁCS and VAJTA.

Computation of the resistive component:
constansts relating to the 50 mm^2 conductor $a = 2.2$,
$m = 3.5$

$$I' = aI = 2.2 \cdot 10 = 22 \text{ amp}$$

Permeability: $\mu' = 20$; $\mu = m\mu' = 3.5 \cdot 20 = 70$;

$$K = \frac{\mu}{r} = \frac{70}{44} = 15.9;$$

value taken from the curve: $S_r = 1.5$,
thus:

$$r_g = r_d \left(1 + \frac{S_r}{100}\right) = 4.4 \cdot 1.015 = 4.46 \text{ ohm/km}$$

Computation of the inductive component:

constants relating to the 50 mm² conductor: $a = 1.75$, $m = 0.93$

$$I' = aI = 1.75 \cdot 10 = 17.5 \text{ amp}$$

Permeability: $\mu' = 30$; $\mu = m\mu' = 0.93 \cdot 30 = 28$;

$$GMR = r \cdot e^{-\frac{28}{4}} = 0.415 \cdot 10^{-3}\,\text{cm}$$

Since there are two ground wires:

$$GMR_1 = \sqrt{GMR \cdot GMD} = \sqrt{0.415 \cdot 10^{-2} \cdot 1050} = 0.66\,\text{cm};$$

$$z_{og} = \frac{r_g}{2} + 0.00099 f + 0.0029 \cdot f \cdot lg \frac{D_e}{GMR} =$$
$$= 2.28 + j\,0.771 \text{ ohm/km}$$

d) *Resultant zero-sequence impedance*

This can be calculated from the formula

$$z_0 = z_{cc} - \frac{z_{0m}^2}{z_{0g}}$$

where

$$z_{0m}^2 = -0.1027 + j\,0.0319,$$

$$\frac{z_{0m}^2}{z_{0g}} = -0.0364 + j\,0.0262,$$

hence,

$$z_0 = 0.3464 + j\,0.7438 \text{ ohm/km}.$$

Thus, for the length 30.7 km, the following impedance is obtained:

$$Z_0 = z_0 l = 30.7\ (0.3464 + j\,0.7438) = 10.65 + j\,22.8 \text{ ohm}.$$

The resultant grounding resistance of Tower No. 132 is 4.6 ohm, so the total resistance of the loop is:

$$Z = 15.25 + j\,22.8 \text{ ohm, or its absolute value } 27.4 \text{ ohm}.$$

e) *The resistance of the earthing grid of Ajka Power Station was neglected.*

Summary

The distribution of the zero-sequence current varies in the vicinity of the fault. After describing a series of measurements carried out on a 120 kV line section, the paper gives the results of measurements relating to the line section with end-effect, the distribution of the zero-sequence current in the ground wire and earth along the section with end-effect, furthermore the heating effect of current in the ground wires.

After dealing with the influence of the grounding resistance of the towers, the paper gives screening factors, corrected so as to take the end-effect into consideration.

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