SCREENING-FACTOR VALUES OF OVERHEAD-LINE GROUND WIRES AND COUNTERPOISES

By

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Telecommunication circuits closely parellelling high-voltage power transmission lines are susceptible to electrostatic, electromagnetic or conductive interferences adversely affecting normal telecommunication service. These effects of interference give rise in the telecommunication circuits to voltages and currents, which produce the phenomena generally referred to as *disturbance* and *danger*.

Of these two concepts it is the disturbance which is responsible for producing unwanted signal components deteriorating the quality of telecommunication. Disturbance is primarily caused by the upper harmonics present in the high-voltage transmission voltage. By danger an effect of interference is understood, which may jeopardize the telecommunication equipment or the life of the operators. Danger may arise due to conductive or electromagnetic interference. In the present paper only the problems of electromagnetic interference will be discussed.

Electromagnetic interference is produced when in the telecommunication circuits a voltage is induced by the currents flowing in the high-voltage power transmission lines. In this respect, the case of earth faults is primarily decisive, since the induction produced by normal service currents under balanced three-phase load conditions is equal to zero (in any point sufficiently remote from the power line). Hence, an electromagnetic field only exists in the immediate vicinity of the high-voltage transmission line, where the fields produced by the three phases do not fully compensate each other. The conditions are entirely different in earth-return systems or three-phase systems containing zero-sequence circuits, i.e. whenever an earth fault occurs. In such cases the current producing interference flows in the phase conductors of the high-voltage transmission line towards the fault and returns through the earth. Thus, the current giving rise to interference is an earth-return, or zero-sequence current.

By the electromagnetic field of the high-voltage line a voltage, termed *longitudinal electromotive force*, is induced in the circuit consisting of the telecommunication line and earth. Its magnitude can be calculated from the following relation:

$$E = k \cdot Z_m \cdot I_{op} \tag{1}$$

where

E = longitudinal electromotive force (volts r.m.s.) induced in the telecommunication line concerned,

k = resultant screening factor, in which the effects reducing the induced e.m.f. and considered in the calculation are taken into account. These reducing effects are brought about by currents flowing in the various closed loops (compensating circuits), producing an electromagnetic field partially cancelling the inducing field,

Z_m = mutual impedance (ohms) between the telecommunication line examined and the inducing high-voltage transmission line,

I_{op} = three-times the zero-sequence current ($I_{op} = 3\,I_0$ amp., r.m.s.) flowing in the inducing high-voltage line under the particular conditions of interference examined.

In the case of overhead transmission lines, with respect to interference the circuit elements acting as *compensating conductors* are the overhead *ground wires* and *counterpoises*. The possible variations in the number of compensating conductors, their material, cross-sectional area, and other factors (such as geometrical arrangement of conductors, soil resistivity, permeability of steel wires, etc.) have given the incentive to investigate the screening effect which is to be obtained by the various means available and to summarize the results in the present paper.

In discussing the case of high-conductivity ground wires the examinations will not be extended beyond the compensating effect to the mechanical problems, or to those associated with de-icing, etc. Neither will the economical aspects be dealt with here.

1. Basic relations referring to the screening factor

The arrangement shown in Fig. 1 consists of three earth-return lines, indicating the positive directions of current flows. Explanation of symbols used:

p: inducing line (high-voltage transmission line),
k: compensating conductor (e.g. ground wire or counterpoise),
t: induced line (telecommunication line).

In the course of the described examinations a homogeneous soil, horizontal lines of infinite length, earth-return currents flowing parallel to the inducing line and a current of constant magnitude along the full length of the inducing line are assumed.

The chain of thought leading to the definition of the screening factor may be summarized as follows: a current I_p flowing in the inducing line produces an e. m. f. U_k in the open-circuited compensating conductor and an electromotive force U_t in the induced line. If the compensating conductor forms a closed loop, the value of U_k will be zero, and that of U_t is reduced to E_t, because I_k flowing in the compensating conductor is opposed to I_p. The ratio of E_t to U_t is the *screening factor.*

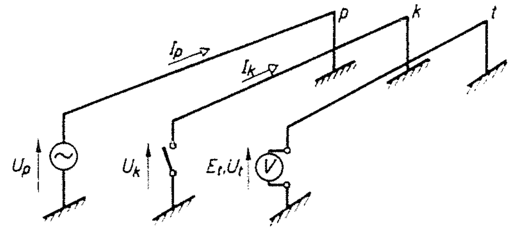

Fig. 1. Basic scheme of compensating conductor application

The *voltage equations* applying to a *closed-loop* compensating conductor are the following:

$$U_k = 0 = I_p Z_{pk} + I_k Z_{kk}\,; \qquad I_k = -\, I_p \frac{Z_{pk}}{Z_{kk}}$$

$$E_t = I_p Z_{pt} + I_k Z_{kt} = I_p Z_{pt} - I_p \frac{Z_{pk}}{Z_{kk}} Z_{kt} = I_p Z_{pt} \left(1 - \frac{Z_{pk} Z_{kt}}{Z_{pt} Z_{kk}}\right) \tag{2}$$

In the above equations the Z impedances marked with a suffix consisting of identical letters indicate the earth-return *self-inductances* of the circuit referred to by the letters of the suffix, while those marked with a suffix consisting of different letters designate the earth-return *mutual inductances* of the circuits referred to by the letters of the suffix, the impedances in all cases being unit-length values.

For an open-circuited compensating conductor the following relation is valid:

$$U_t = I_p Z_{pt} \tag{3}$$

The value of the screening factor is obtained as the quotient of relations (2) and (3):

$$k = \frac{E_t}{U_t} = 1 - \frac{Z_{pk} Z_{kt}}{Z_{pt} Z_{kk}} \tag{4}$$

From the above it immediately follows that the value of the screening factor is always *less than unity* and the compensating effect will be the more favourable the lower its value is.

2. Screening factor of more than one compensating conductor

If the compensating system consists of several conductors and the earth-return (or zero-sequence) self- and mutual inductances are known, for the exact determination of currents and voltages as many simultaneous equations are required as the number of conductors of which the system consists.

In these cases the calculation will proceed as follows: let it be assumed that, in addition to the inducing line p and to the telecommunication line t, the system consists of three compensating conductors (v, w, q). All self- and mutual inductances are known. Each value is marked with a combined suffix as in the former case. The current I_p flowing in the inducing line is also considered as known. The calculations can be simplified by taking the direction of current I_p as reference and its magnitude as a pure real number (i.e. $I_p = 1.0 + j0.0$, if the calculation is made with relative units).

The current flowing in each compensating conductor may be computed from the voltage equations of the three compensating conductors:

$$\begin{aligned} &\text{for conductor } v\text{: } 0 = I_p Z_{pv} + I_v Z_{vv} + I_w Z_{wv} + I_q Z_{qv} \\ &\text{for conductor } w\text{: } 0 = I_p Z_{pw} + I_v Z_{vw} + I_w Z_{ww} + I_q Z_{qw} \\ &\text{for conductor } q\text{: } 0 = I_p Z_{pq} + I_v Z_{vq} + I_w Z_{wq} + I_q Z_{qq} \end{aligned} \tag{5}$$

All Z values and also I_p being known, the above equations constitute a linear, inhomogeneous set of equations in three unknown quantities. The unknown values of I_v, I_w, I_q can be found by applying Cramer's rule.

With the current values thus found the expression giving the longitudinal e. m. f. induced in the telecommunication line will be:

$$E_t = I_p Z_{pt} + I_v Z_{vt} + I_w Z_{wt} + I_q Z_{qt} \tag{6}$$

It should be noted that all quantities in the equations are *complex values*.

3. Remarks concerning the solution of the simultaneous equations

Due to the complex quantities involved, the solution of simultaneous linear equations (5) is rather cumbersome. If more than three compensating conductors are to be considered, the calculations become increasingly lengthy.

Still, the only method leading to exact results is that of solving the simultaneous voltage equations. This method has also been adopted for considering the counterpoise and ground wire.

Cases exceeding the complexity of Eq. (5), i. e. problems involving more than three unknown quantities are seldom encountered in practice. The quickest and most practicable way of solving simultaneous linear equations is that of using a *digital computer*, and this method was adopted for dealing with the tasks described below.

4. The screening factor of ground wires and counterpoises

The most common compensating conductors of overhead transmission lines are the ground wires and counterpoises. Since these compensating conductors are in the close vicinity of the inducing phase conductors and at a distance practically *equal* from the latter to that of the induced telecommunication line, it may be assumed with good approximation that $Z_{pt} = Z_{kt}$. Hence, the relation for the screening factor given under (4) takes the simple form of

$$k = 1 - \frac{Z_{pk}}{Z_{kk}} \tag{7}$$

In the following calculations this relation will be used.

5. Short summary of screening-factor calculations performed with the Elliott-803B digital computer

For the Elliott-803B digital computer an autocode programme was prepared to calculate the complex quantities Z_{pk}, Z_{kk} and k contained in Eq. (7) for various combinations of ground wires and counterpoises. The programme is suitable for computing the zero-sequence impedance of the phase conductors as modified by the effect of the compensating conductors, the amount of this modification with respect to the original value, as well as the sum of currents flowing in the compensating conductors, expressed in relative units with respect to the short-circuit current ($3\ I_0$) flowing in the phase conductors. For examinimg the simultaneous effect of ground wires and counterpoises the programme makes use of the simultaneous linear equations (5).

In the course of calculations, the following arrangements of conductors on the transmission-line towers will be considered:

a) with no or with only one ground wire:

120 kV, single-circuit, three-phase overhead line with 250/40 sq. mm ACSR phase conductors in triangular arrangement (Fig. 2),

b) with two ground wires:

120 kV, single-circuit, three-phase overhead line with 150/25 sq. mm ACSR phase conductors in horizontal arrangement (Fig. 3).

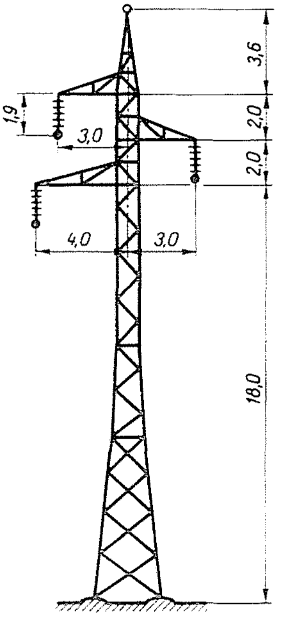

Fig. 2. 120-kV transmission-line tower with one ground wire

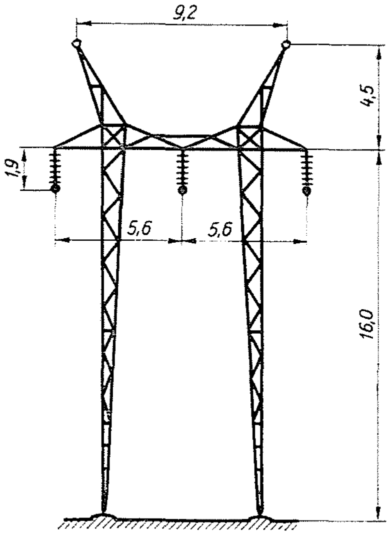

Fig. 3. 120-kV transmission-line tower with two ground wires

Studies were conducted to determine the effect of conductor arrangement on the magnitude of the screening factor. The results obtained have shown that with conventional conductor arrangements of the 120—220 kV transmission-line towers the variation of the screening factor remains within 0.5 per cent, all the other factors remaining unchanged.

6. Modification of the zero-sequence impedance of an overhead transmission line under the effect of compensating conductors

Using the symbols adopted in Section 1, the following voltage equations can be written for the system of conductors consisting of phase conductors and compensating conductors (the quantities now being considered as *zero-sequence values)*:

$$U_p = I_p Z_{pp} + I_k Z_{pk}$$

$$U_k = 0 = I_p Z_{pk} + I_k Z_{kk}$$

Expressing the current flowing in the compensating conductors and subtituting it into the equation of U_p:

$$I_k = - I_p \frac{Z_{pk}}{Z_{kk}}$$

$$U_p = I_p Z_{pp} - I_p \frac{Z^2_{pk}}{Z_{kk}} = I_p \left(Z_{pp} - \frac{Z^2_{pk}}{Z_{kk}} \right)$$

The *modified* zero-sequence current of the phase conductors will be:

$$Z_p = \frac{U_p}{I_p} = Z_{pp} - \frac{Z^2_{pk}}{Z_{kk}} \quad \text{and} \quad \varDelta Z\,\% = \frac{|Z_p| - |Z_{pp}|}{|Z_{pp}|} 100 \tag{8}$$

Resolving the impedances into real and imaginary components:

$$R_p + jX_p = R_{pp} + jX_{pp} - \frac{(R_{pk} + jX_{pk})^2}{R_{kk} + jX_{kk}}$$

Performing the operations, the following component equations will be obtained:

$$R_p = R_{pp} + \frac{R_{kk}(X^2_{pk} - R^2_{pk}) - 2R_{pk} X_{pk} X_{kk}}{R^2_{kk} + X^2_{kk}} \quad \text{and}$$

$$\varDelta R\,\% = \frac{R_p - R_{pp}}{R_{pp}} 100 \tag{9}$$

$$X_p - X_{pp} - \frac{X_{kk}(X^2_{pk} - R^2_{pk}) + 2R_{pk} X_{pk} R_{kk}}{R^2_{kk} + X^2_{kk}} \quad \text{and}$$

$$\varDelta X\% = \frac{X_p - X_{pp}}{X_{pp}} 100 \tag{10}$$

With conventional conductor arrangements and soil resistivity values falling within the range of 1 to 1000 ohm. meters, X_{pk} is always bigger than R_{pk}, and thus, $(X^2_{pk} - R^2_{pk})$ will always be positive. Consequently, *the inductive component* (X_p) *of the modified zero-sequence impedance is always smaller than the inductive component* (X_{pp}) *of the zero-sequence impedance of the phase conductors.*

The relation between the zero-sequence resistive components is not so simple. This can be found from Eq. (9) by examining the numerator of the fraction indicating the magnitude of correction:

$$R_{kk}(X^2_{pk} - R^2_{pk}) - 2R_{pk} X_{pk} X_{kk} \gtrless 0,$$

from which, after suitable rearrangement:

$$\frac{R_{kk}}{X_{kk}} \gtreqless \frac{2R_{pk}\,X_{pk}}{X_{pk}^2 - R_{pk}^2} = \frac{2\,\dfrac{R_{pk}}{X_{pk}}}{1 - \dfrac{R_{pk}^2}{X_{pk}^2}}$$

Writing the tangents of the *complementaries* of the internal angles of the self- and mutual impendances:

$$\frac{R_{kk}}{X_{kk}} = \operatorname{tg}\beta_{kk} \quad \text{and} \quad \frac{R_{pk}}{X_{pk}} = \operatorname{tg}\beta_{pk} \, ,$$

the following relations are obtained:

$$\operatorname{tg}\beta_{kk} \gtreqless \frac{2\operatorname{tg}\beta_{pk}}{1 - \operatorname{tg}^2\beta_{pk}}$$

$$\operatorname{tg}\beta_{kk} \gtreqless \operatorname{tg} 2\beta_{pk} \tag{11}$$

With soil resistivity and geometrical conditions (arrangement of ground wire) unchanged, the value of $\operatorname{tg} 2\beta_{pk}$ is a constant $= C$. Thus, if $\operatorname{tg}\beta_{kk}$ is bigger than C, then R_p *is bigger than* R_{pp} (with steel ground wires), if however it is smaller than C, then also R_p *is smaller than* R_{pp}. The latter condition generally applies to compensating conductors of good conductivity. In the case of 1×50 sq. mm steel ground wire:

$R_{kk} = 15.149$ ohm/km

$X_{kk} = 4.929$ ohm/km

$$\operatorname{tg}\beta_{kk} = \frac{15.149}{4.929} = 3.075$$

$R_{pk} = 0.1485$ ohm/km

$X_{pk} = 0.7758$ ohm/km

$$\operatorname{tg}\beta_{pk} = \frac{0.1485}{0.7758} = 0.1915$$

$$\beta_{pk} = 10^\circ\, 50'$$

$$\operatorname{tg} 2\beta_{pk} = \operatorname{tg} 21^\circ\, 40' = 0.3975$$

Since 3.075 is bigger than 0.3975, R_p will also be bigger than R_{pp}.

For a 1×250/40 sq. mm ACSR ground wire of similar arrangement:

$R_{kk} = 0.5025$ ohm/km

$X_{kk} = 1.9580$ ohm/km

$\operatorname{tg} 2\beta_{pk} = 0.3975$

$$\operatorname{tg}\beta_{kk} = \frac{0.5025}{1.9580} = 0.2565$$

Since 0.2565 is smaller than 0.3975, R_p will also be smaller than R_{pp}.

In the above numerical examples a soil resistivity of 10 ohm. metres has been assumed. Obviously, the effect of the compensating conductor on the losses will always be such that through the modified zero-sequence impedance of the phase conductors (considering the same zero-sequence voltage) a higher zero-sequence current will flow, and also the zero-sequence losses produced by this increased current in the resistive branch R_p will be higher than that produced in R_{pp} by the original current belonging to the system in which no compensating conductors are used.

Using the data of the above numerical examples, if $U = 1.0 + j0.0$: for a 1 × 50 sq.mm steel ground wire:

$$R_{pp} = 0.2565\,; \quad |I_{pp}| = \frac{U}{|Z_{pp}|} = \frac{1}{1.1759} = 0.85\,; \quad I_{pp}^2 R_{pp} = 0.1925$$

$$R_p = 0.2966\,; \quad |I_p| = \frac{U}{|Z_p|} = \frac{1}{1.1589} = 0.863\,; \quad I_p^2 R_p = 0.2210$$

for a 1 × 250/40 sq. mm ACSR ground wire:

$$R_{pp} = 0.2565; \quad |I_{pp}| = 0.85; \quad I_{pp}^2 R_{pp} = 0.1925$$

$$R_p = 0.2273\,; \quad |I_p| = \frac{U}{|Z_p|} = \frac{1}{0.8713} = 1.148; \quad I_p^2 R_p = 0.2995$$

It can be seen that the *zero-sequence losses had increased* in both cases.

7. Screening-factor calculations

The screening-factor values were investigated for the combinations and in function of the variables listed below:

7.1 *Steel ground wires (see Section 8):*

variables: a) one or two ground wires,
b) cross-sectional area of ground wires,
c) soil resistivity,
d) relative permeability.

7.2 *ACSR ground wires (see Section 9):*

variables: a) one or two ground wires,
b) cross-sectional area of ground wire,
c) soil resistivity.

7.3 *Counterpoise (see Section 10):*

variables: a) material of counterpoise,
b) cross-sectional area of counterpoise.

7.4 *Combined use of ground wire and counterpoise (see Section* 11*):*
variables: a) material of counterpoise and ground wire,
b) cross-sectional area of counterpoise and ground wire.

In the course of the calculations 50 different cases have been investigated.

In the following the results will be described partly by means of figures and partly in tabulated form. The tables contain the following data:

a) the *screening-factor* values,

b) the *modification* of the absolute value as well as of the resistive and inductive component of the overhead-line zero-sequence impedance, brought about by the compensating conductors, with respect to, and given in the percentage of, the original values (i.e. without compensating conductors), for the determination of which the relations (9), (10) and (8) have been used,

c) the currents flowing in the compensating conductors, given in *complex form* and in *relative units*, taking the current $3I_0$ flowing in the phase conductors as being equal to $1.0 + j0.0$.

8. Screening-factor values of steel ground wire

8.1 *Effect of the number and cross-sectional area of ground wires*

The variation of the screening factor was investigated with one and two steel ground wires of 50, 70 and 95 sq. mm cross-sectional areas (Fig. 4 and 5). For the relative permeability the value of 60 and for that of soil resistivity the value of 10 ohm. metres were assumed. The results are summarized in Tables I to V.

8.2 *Effect of soil resistivity*

The influence of soil resistivity on the screening factor was examined for soil resistivity values of 1, 10, 100 and 1000 ohm. metres (Fig. 6). Two steel ground wires of 50 sq. mm each and a relative permeability of 60 were assumed. The results are compiled in Tables VI to X.

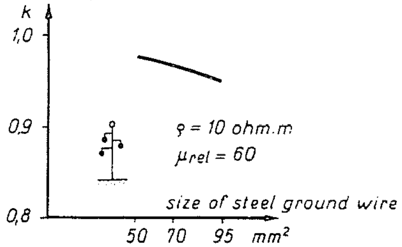

Fig. 4. Screening-factor values of steel ground wire (one ground wire)

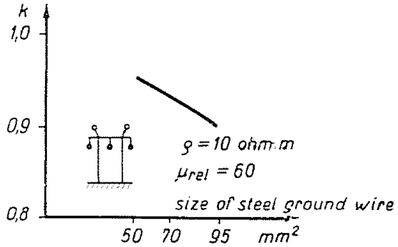

Fig. 5. Screening-factor values of steel ground wire (two ground wires)

Table I

sq. mm	Screening factor one steel ground wire(s)	 two steel ground wire(s)
50	0.9771	0.9543
70	0.9664	0.9338
95	0.9475	0.8988

Table II

sq. mm	Modification of resistive component (in per cent) one steel ground wire(s)	 two steel ground wire(s)
50	+11.32	+16.25
70	+13.30	+18.61
95	+14.95	+20.15

Table III

sq. mm	Modification of inductive component (in per cent) one steel ground wire(s)	 two steel ground wire(s)
50	−2.18	−4.37
70	−3.06	−6.04
95	−3.56	−8.70

Table IV

sq. mm	Modification of absolute value of impedance (in per cent) one steel ground wire(s)	 two steel ground wire(s)
50	−1.45	−2.53
70	−2.15	−3.80
95	−3.40	−6.01

Table V

	Current flowing in ground wires (in relative units)	
Cross sectional area (sq. mm)	one steel ground wire	two steel ground wires
50	−0.0239−j0.0434	−0.0493−j0.0817
70	−0.0351−j0.0523	−0.0712−j0.0965
95	−0.0545 −j0.0619	−0.1081−j0.1105

Table VI

Soil resistivity (ohm. metre)	Screening factor
1	0.9628
10	0.9543
100	0.9487
1000	0.9360

Table VII

Soil resistivity (ohm. metre)	Modification of resistive component (in per cent)
1	+ 7.65
10	+16.25
100	+21.40
1000	+41.40

Table VIII

Soil resistivity (ohm. metre)	Modification of inductive component (in per cent)
1	—3.25
10	—4.37
100	—4.61
1000	—6.71

Table IX

Soil resistivity (ohm. metre)	Modification of absolute value of impedance (in per cent)
1	—1.88
10	—2.53
100	—2.89
1000	—4.06

Table X

Soil resistivity (ohm. metre)	Current flowing in ground wires (in relative units)
1	—0.0390—j0.0581
10	—0.0493—j0.0817
100	—0.0558—j0.0924
1000	—0.0726—j0.1259

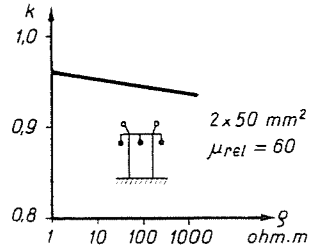

Fig. 6. Screening-factor values of steel ground wire (two ground wires)

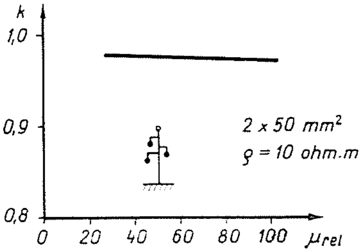

Fig. 7. Screening-factor values of steel ground wire (one ground wire)

8.3 *Effect of the relative permeability of steel ground wires*

The variation of the screening-factor values was investigated, assuming relative permeabilities of 30, 40, 50, 60, 70, 80, 90 and 100 (Fig. 7) and a single steel ground wire of 50 sq. mm. Soil resistivity was 10 ohm. metres. The results are shown in Tables XI to XV.

8.4 *Conclusions*

a) The examinations have shown that the screening-factor values of steel ground wires fall within the range of *0.90 to 0.98.*

The reduction in the absolute value of the overhead-line zero-sequence impedance, due to the effect of ground wires, amounts from 1.6 to 6 per cent. The resistive component of the impedance is always larger than the original value of the line without ground wires.

Table XI

Relative permeability	Screening factor
30	0.9805
40	0.9793
50	0.9782
60	0.9771
70	0.9760
80	0.9751
90	0.9742
100	0.9735

Table XII

Relative permeability	Modification of resistive component (in per cent)
30	+12.39
40	+12.03
50	+11.67
60	+11.32
70	+10.90
80	+10.54
90	+10.18
100	+ 9.80

Table XIII

Relative permeability	Modification of inductive component (in per cent)
30	—2.00
40	—2.07
50	—2.13
60	—2.19
70	—2.24
80	—2.28
90	—2.32
100	—2.36

Table XIV

Relative permeability	Modification of absolute value of impedance (in per cent)
30	—1.21
40	—1.29
50	—1.37
60	—1.45
70	—1.52
80	—1.58
90	—1.64
100	—1.69

Table XV

Relative permeability	Current flowing in ground wire (in relative units)
30	—0.0206—j0.0464
40	—0.0218—j0.0455
50	—0.0229—j0.0449
60	—0.0239—j0.0434
70	—0.0249—j0.0423
80	—0.0258—j0.0412
90	—0.0266—j0.0401
100	—0.0273—j0.0389

b) The real component of current flowing back in the ground wires is 2 to 11 per cent, and its imaginary component is 4 to 11 per cent of the full fault current ($3I_0$). The imaginary component is always larger than the real part.

In spite of the fact that the *imaginary component* of the current flowing in steel ground wires is always the larger component, it may be neglected in the calculation of the screening factor. This can be explained as follows (Fig. 8):

— the current $3I_0$ flowing in the phase conductors is $1.0 + j0.0$ in relative units,

— the maximum value of the imaginary component of current flowing in the ground wires is $j0.1$, also expressed in relative units,

— the resultant of the two components, when making use of the approximation $\sqrt{a^2 + b} \cong a + \frac{b}{2a}$ (if $\frac{b}{a^2} \leqq 0.2$, the error is less than 5 per cent), will be in the present case by

$$a^2 = 1.0^2$$

$$b = 0.1^2$$

$$\sqrt{1 + 0.01} = 1 + \frac{0.01}{2} = 1.005 \cong 1.0\,;$$

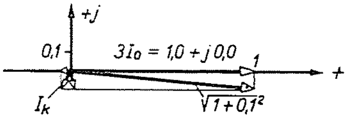

Fig. 8. Explanatory scheme for the approximative determination of the screening factor

when subtracting from this value the *real* component of the current flowing in the ground wires, with good approximation, the screening factor is obtained.

c) An increase of soil resistivity will result in a *slight* reduction of the screening factor. Increasing the soil resistivity by 4 orders of magnitude, a reduction of a mere 2.8 per cent was found.

The variation of the relative permeability of the steel ground wire in the range investigated has caused *no essential change* in the screening factor.

9. Screening-factor values of ACSR ground wires

9.1 *Effect of the number and cross-sectional area of ground wires*

The variation of the screening factor was investigated with one and two ACSR ground wires of 150/25 and 250/40 sq. mm cross-sectional areas (Figs. 9 and 10). A soil resistivity of 10 ohm. metres has been assumed for the study. The results are summed up in Tables XVI to XX.

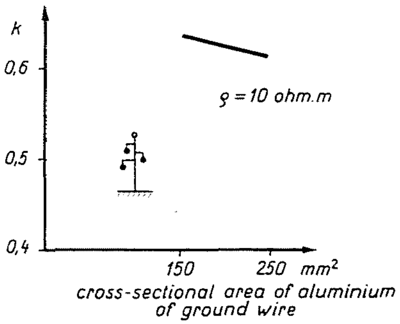

Fig. 9. Screening-factor values of ACSR ground wire (one ground wire)

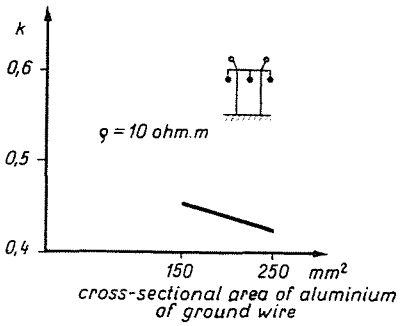

Fig. 10. Screening-factor values of ACSR ground wire (two ground wires)

Table XVI

Screening factor		
sq. mm	one ACSR ground wire(s)	two
150/25	0.6370	0.4556
250/40	0.6117	0.4270

Table XVII

Modification of resistive component (in per cent)		
sq. mm	one ACSR ground wire (s)	two
150/25	— 3.72	— 8.98
250/40	—14.70	—18.61

Table XVIII

Modification of inductive component (in per cent)		
sq. mm	one ACSR ground wire (s)	two
150/25	—25.40	—37.55
250/40	—26.55	—38.70

Table XIX

Modification of absolute value of impedance (in per cent)		
sq. mm	one ACSR ground wire (s)	two
150/25	—24.80	—34.80
250/40	—25.82	—36.80

Table XX

Current flowing in ground wires (in relative units)		
Cross-sectional area (sq. mm)	one ACSR ground wire	two ACSR ground wires
150/25	—0.3655—j0.0570	—0.5494—j0.0674
250/40	—0.3888—j0.0239	—0.5740—j0.0293

9.2 *Effect of soil resistivity*

The variation of the screening factor in the function of soil resistivity was investigated, assuming soil resistivity values of 1, 10, 100 and 1000 ohm. metres (Fig. 11). The calculations were performed with one and two ACSR ground wires. The results are shown in Tables XXI to XXV.

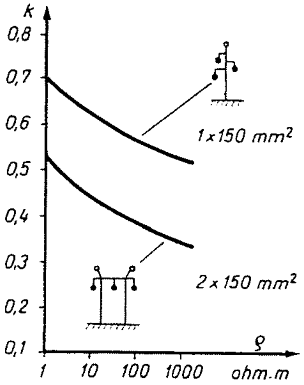

Fig. 11. Screening-factor values of ACSR ground wire

Table XXI

Screening factor		
Soil resistivity (ohm. metre)	one ACSR ground wire(s)	two
1	0.7043	0.5339
10	0.6370	0.4556
100	0.5808	0.3966
1000	0.5334	0.3507

Table XXII

Modification of resistive component (in per cent)		
Soil resistivity (ohm. metre)	one ACSR ground wire(s)	two
1	—8.96	—12.70
10	—3.72	— 8.98
100	+2.47	— 5.11
1000	+9.15	— 1.51

Table XXIII

Modification of inductive component (in per cent)		
Soil resistivity (ohm. metre)	one ACSR ground wire(s)	two
1	—18.35	—28.35
10	—25.40	—37.55
100	—31.55	—44.85
1000	—36.92	—50.75

Table XXIV

Modification of absolute value of impedance (in per cent)		
Soil resistivity (ohm. metre)	one ACSR ground wire(s)	two
1	—17.61	—26.30
10	—24.80	—34.80
100	—30.00	—41.80
1000	—35.10	—47.50

Table XXV

Current flowing in ground wires (in relative units)		
Soil resistivity (ohm. metre)	one ACSR ground wire	two ACSR ground wires
1	—0.2966—j0.0362	—0.4684—j0.0490
10	—0.3655—j0.0570	—0.5494—j0.0674
100	—0.4234—j0.0701	—0.6106—j0.0751
1000	—0.4724—j0.0783	—0.6580—j0.0775

9.3 *Conclusions*

It can be stated from the results that the screening factor varies within the range of 0.61 to 0.64 with a single ground wire and within 0.43 to 0.45 with two ground wires.

The reduction in the absolute value of the overhead-line zero-sequence impedance lies around 25 and 35 per cent with one and two ground wires, respectively. When a single ground wire is used, with high soil-resistivity values (100 to 1000 ohm. metres) the resistive component of the impedance increases, whereas in all other cases it decreases, and this decrease may be as much as 15 per cent. The variations in this case are also related to the original values of lines without ground wires.

These figures draw the attention to the fact that when high-conductivity ground wires are used, *the fault current may considerably increase*, due to the reduced zero-sequence impedance. To some extent this increase counterbalances the decrease of the screening factor.

The real component of the current flowing back in the ground wires is 37 to 39 and 55 to 57 per cent of the full fault current ($3I_0$) with one and two ground wires, respectively. The imaginary component is *very small* with respect to the real part and amounts to only 2 to 7 per cent. As regards the effect of the imaginary component the same remarks apply as stated in Section 8.4/b.

In that case, an increase in soil resistivity produces a *more pronounced* decrease in the values of the screening factor. Increasing the soil resistivity by 4 orders of magnitude the screening factor will be reduced by 25 and 35 per cent, with one and two ground wires, respectively.

10. Screening-factor values of counterpoises

10.1 *Calculation method for considering the effect of counterpoises*

As regards interference, a counterpoise may be considered as a *ground wire*. When exact calculations are required, the depth of the counterpoise should be substituted in the equations by a negative sign. The purpose of the counterpoise is to provide a good metallic connection between individual tower earthings. Although the counterpoise is continuously earthed (be it either a bare conductor or a scrapped underground cable with cores and sheath metallically connected), it can be stated in accordance with the references that a counterpoise can be calculated and treated in the same way as a ground wire. This consideration applies not only to the case when only a counterpoise is used, but also to the *combined use* of counterpoise and ground wire.

Accordingly, relation (7) can also be used for the calculation of the screening factor of a counterpoise. Z_{kk} is used also here to denote the zero-sequence self-impedance of the counterpoise, i.e. applying the approximative Carson—Clem formula and considering a single counterpoise (with suffix q denoting the counterpoise):

$$Z_{qq} = 3R_q + 0.1485 + j\,0.435 \lg \frac{D_e}{GMR_q} \text{ ohm/km} \tag{12}$$

where

R_q = resistance of counterpoise (ohm/km),
D_e = depth of fictive earth return (metres) where $D_e = 659 \sqrt{\frac{\varrho}{f}}$,
ϱ = soil resistivity (ohm. m),
f = frequency (c/s),
GMR_q = geometric mean radius of counterpoise (metres), where

$$GMR_q = r_q \cdot e^{-\frac{\mu}{4}}$$

r_q = half of outer diameter of counterpoise (metres),
μ = relative permeability of steel conductor.

Interpretation of Z_{pk} for the present case: zero-sequence mutual impedance between the set of phase conductors and counterpoise: its value is also obtained from the relevant Carson—Clem formula:

$$Z_{pq} = 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{GMD_q} \text{ ohm/km}, \tag{13}$$

where GMD_q indicates the geometric mean distance (in metres) between each phase conductor and the counterpoise:

$$GMD_q = \sqrt[3]{D_{aq} \cdot D_{bq} \cdot D_{cq}} \tag{14}$$

(Explanation of suffixes: a, b, c refer to the phase conductors, q to the counterpoise, and p to the system composed of the phase conductors).

Thus, the system composed of phase conductors and counterpoise is reduced to the case of a system consisting of phase conductors and ground wires.

In the course of the calculations the counterpoise was assumed to be placed at a depth of 0.8 metres below the ground level.

10.2 *Effect of material and cross-sectional area of the counterpoise*

The variation of the screening factor was investigated for a single counterpoise made of 50 and 240 sq. mm steel, and of 185/60 and 250/40 sq. mm ACSR, respectively.

The selection of the above cross-sectional areas was based on the following consideration: by investigating the steel cross-sections of 50 and 240 sq. mm the question can immediately be answered whether using steel is at all worth while i.e. a material of poor conductivity, even of a large cross-sectional area, for the purpose of counterpoises. The numerical results obtained with ACSR stranded wires of 185/60 and 250/40 sq. mm cross-sectional areas give information on which values are to be expected when scrapped 1 kV underground 4-core *aluminium* cables of $3\times 50 + 1\times 25 = 175$ sq. mm and $3\times 70 + 1\times 35 = 245$ sq. mm are used as counterpoise. The cross-sectional area of stranded wires and cables being very close to each other and identity of the geometrical arrangement ensure good comformity of the results. Practically, the only difference between an underground cable and stranded ACSR wire is in their GMR values, but also here the effect caused by the core insulation of an aluminium-core cable is somewhat counterbalanced by that of the steel core of an ACSR stranded wire, the result being in both cases an increase in the outer diameter. Obviously, in practice, there is no need to use ACSR stranded wires and the only reason for considering this type of conductor is to reduce by one the number of factors involved in the calculations.

In the course of the investigations the relative permeability of the steel cable was assumed to be 60. Soil resistivity of 10 ohm. metres was throughout considered. The results are summarized in Tables XXVI to XXX.

10.3 *Conclusions*

The conclusions drawn from above (Sections 8.4 and 9.3) as regards steel and ACSR compensating conductors (acting in that particular case as counterpoise wires) fully retain their validity. It may be noted that a buried compensating conductor possesses a *less favourable screening effect* with respect to an overhead ground wire of equal size (Tables XXXI and XXXII).

This reducing effect is due to the change in the mutual impedance Z_{pk}, this in turn being the consequence of the increased GMD defining the value of Z_{pk}.

In respect of using steel conductors as counterpoise wires, it can be stated that the screening effect of a steel conductor (as regards interference), whether *used as ground wire or counterpoise, is equally very poor* (excluding the line sections with end-effect). Anyhow, the excellent mechanical properties of steel conductors only become effective in overhead line applications, and are of no advantage when buried in the ground. The screening effect is low even if steel wires of large cross-sectional areas were used.

Table XXVI

Screening factor			
Steel		ACSR	
50 sq. mm	0.9815	185/60	0.7400
240 sq. mm	0.9145	250/40	0.7338

Table XXVII

Modification of resistive component (in per cent)			
Steel		ACSR	
50 sq. mm	+4.40	185/60	−12.39
240 sq. mm	+1.24	250/40	−16.30

Table XXVIII

Modification of inductive component (in per cent)			
Steel		ACSR	
50 sq. mm	−1.22	185/60	−11.90
240 sq. mm	−4.30	250/40	−11.95

Table XXIX

Modification of absolute value of impedance (in per cent)			
Steel		ACSR	
50 sq. mm	−0.92	185/60	−11.94
240 sq. mm	−4.01	250/40	−12.18

Table XXX

Current flowing in counterpoise (in relative units)			
Steel		ACSR	
50 sq. mm	−0.0189−j0.0280	185/60	−0.2601−j0.0100
240 sq. mm	−0.0860−j0.0310	250/40	−0.2662−j0.0075

Table XXXI

Investigation of 50 sq. mm steel					
Used as	Screening factor	$\frac{R_p-R_{pp}}{R_{pp}}100$	$\frac{X_p-X_{pp}}{X_{pp}}100$	$\frac{\lvert Z_p\rvert-\lvert Z_{pp}\rvert}{\lvert Z_{pp}\rvert}100$	$\frac{I_{\text{comp. cond.}}}{3I_0}$
ground wire	0.9771	+11.32	−2.19	−1.45	−0.0239−j0.0434
counter-poise	0.9815	+4.40	−1.22	−0.92	−0.0189−j0.0280

Table XXXII

Investigation of 250/40 sq. mm ACSR					
Used as	Screening factor	$\frac{R_p-R_{pp}}{R_{pp}}100$	$\frac{X_p-X_{pp}}{X_{pp}}100$	$\frac{\lvert Z_p\rvert-\lvert Z_{pp}\rvert}{\lvert Z_{pp}\rvert}100$	$\frac{I_{\text{comp. cond.}}}{3I_0}$
ground wire	0.6117	−14.70	−26.55	−25.82	−0.3888−j0.0239
counter-poise	0.7338	−16.30	−11.95	−12.18	−0.2662−j0.0075

11. Combined application of a counterpoise and ground wire

11.1 *Method of calculation using simultaneous equations for considering the combined effect of a counterpoise and ground wire*

Briefly summarizing the statement described in Section 10.1, counterpoise wires are used for connecting and, thereby reducing, the tower footing resistances, as well as for minimizing the effects of interference. Counterpoises are buried 0.5—1 metre deep under the ground surface. In the calculations a depth of 0.8 metres was assumed. Good approximation is obtained when leaving the continuous earthing of counterpoise wires out of consideration, thus the counterpoise may be treated as an overhead ground wire.

For the calculation of the screening factor when counterpoises are used in combination with ground wires, the following impedances are required:

Z_{vv} = zero-sequence self-impedance of the system of ground wires (v, w),

Z_{pv} = zero-sequence mutual impedance between the system of phase-conductors (a, b, c) and that of ground wires (v, w),

Z_{qq} = zero-sequence self-impedance of the counterpoise (q),

Z_{pq} = zero-sequence mutual impedance between the system of phase-conductors (a, b, c) and counterpoise (q),

Z_{vq} = zero-sequence mutual impedance between the system of ground wires (v, w) and counterpoise (q).

The approximative Carson—Clem formulae giving the values of the above impedances, using the suffixes indicated, will be:

— for one ground wire:

$$Z_{vv} = 3R_v + 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{GMR_v} \text{ ohm/km} \tag{15}$$

— for two ground wires:

$$Z_{vv} = \frac{3}{2} R_v + 0.1485 + j0.435 \cdot \lg \frac{D_e}{\sqrt{GMR_v \cdot D_{vw}}} \text{ ohm/km} \tag{16}$$

— for one ground wire in the case of 1×3 phases and 2×3 phases, respectively, as well as

— for two ground wires in the case of 1×3 phases:

$$Z_{pv} = 0.1485 + j0.435 \cdot \lg \frac{D_e}{\sqrt[3]{D_{av} D_{bv} D_{cv}}} \text{ ohm/km} \tag{17}$$

— for two ground wires in the case of 2×3 phases:

$$Z_{pv} = 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{\sqrt[6]{D_{av} \cdot D_{bv} \cdot D_{cv} \cdot D_{aw} \cdot D_{bw} \cdot D_{cw}}} \text{ ohm/km} \tag{18}$$

— for one counterpoise:

$$Z_{qq} = 3R_q + 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{GMR_q} \text{ ohm/km} \tag{19}$$

$$Z_{pq} = 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{\sqrt[3]{D_{aq} \cdot D_{bq} \cdot D_{cq}}} \text{ ohm/km} \tag{20}$$

— for one or two ground wires and one counterpoise:

$$Z_{vq} = 0.1485 + j\,0.435 \cdot \lg \frac{D_e}{D_{vq}} \text{ ohm/km} \tag{21}$$

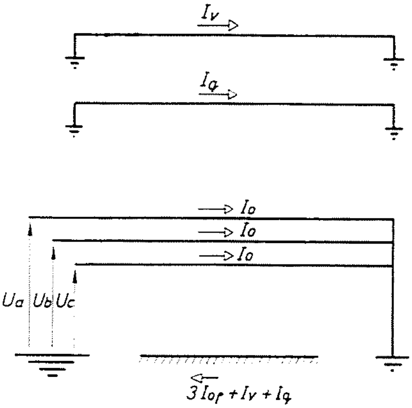

Fig. 12. Combined use of counterpoise and ground wire

As regards interpretation of the various quantities, reference is made to the suffixes and to the quantities dealt with in Section 10.1.

When substituting the quantities into the formulae, care must be taken that the distances (D_e, GMR, D) be of identical dimensions.

After the computation of the above quantities the required simultaneous equations can easily be written. Z_{vv}, Z_{pv} and Z_{vq} appearing in the equations are quantities considering the ground wires (if two of them are concerned) as one single system.

The set of simultaneous linear equations given below applies to the zero-sequence network of a single-circuit three-phase system incorporating one ground wire and one counterpoise, as shown in Fig. 12:

$$\begin{aligned}
U_a &= I_0 (Z_{aa} + Z_{ab} + Z_{ac}) + I_v Z_{va} + I_q Z_{qa} \\
U_b &= I_0 (Z_{ba} + Z_{bb} + Z_{bc}) + I_v Z_{vb} + I_q Z_{qb} \\
U_c &= I_0 (Z_{ca} + Z_{cb} + Z_{cc}) + I_v Z_{vc} + I_q Z_{qc} \\
0 &= I_0 (Z_{va} + Z_{vb} + Z_{vc}) + I_v Z_{vv} + I_q Z_{qv} \\
0 &= I_0 (Z_{qa} + Z_{qb} + Z_{qc}) + I_v Z_{vq} + I_q Z_{qa}
\end{aligned} \tag{22}$$

Eq. (22) can also be written in another form. Here, forming a common group from the three phase conductors, utilizing the symmetry conditions and applying the notations of Eqs. (15) to (21):

$$\begin{aligned} U_n &= 3I_0 \cdot Z_{pp} + I_v \cdot Z_{pv} + I_q \cdot Z_{pq} \\ 0 &= 3I_0 \cdot Z_{pv} + I_v \cdot Z_{vv} + I_q \cdot Z_{vq} \\ 0 &= 3I_0 \cdot Z_{pq} + I_v \cdot Z_{vq} + I_q \cdot Z_{qq} \end{aligned} \tag{23}$$

From Eq. (23), the relative values of I_v and I_q with respect to $3I_0$ will be

$$\frac{I_v}{3I_0} = - \frac{Z_{qq} \cdot Z_{pv} - Z_{vq} \cdot Z_{pq}}{Z_{vv} \cdot Z_{qq} - Z_{vq}^2} \tag{24}$$

$$\frac{I_q}{3I_0} = - \frac{Z_{vv} \cdot Z_{pq} - Z_{vq} \cdot Z_{pv}}{Z_{vv} \cdot Z_{qq} - Z_{vq}^2} \tag{25}$$

Now, the sum of currents flowing in the compensating conductors can be determined, in relative units too:

$$\frac{I_v}{3I_0} + \frac{I_q}{3I_0} = \frac{I_{\text{comp}}}{3I_0} = i_{\text{comp}} \tag{26}$$

The screening factor, however, may also be written in the following form:

$$k = \frac{3I_0 - I_{\text{comp}}}{3I_0} = 1 - \frac{I_{\text{comp}}}{3I_0} = 1 - i_{\text{comp}} \tag{27}$$

Thus, subtracting from the real current unit the current expressed in relative units (in *complex* form) flowing in the compensating conductors, the screening factor is obtained. Hence, the screening factor is again a complex quantity, but since in the computed examples, the imaginary parts are much smaller in every case than the real parts, only the absolute values of the screening factors have been given, which deviate but slightly from the corresponding real parts.

Similarly to Eq. (8), the *modified* zero-sequence impedance of phase-conductors can be calculated for the case of combined use of ground wire and counterpoise:

$$Z_p = Z_{pp} - \frac{Z_{pq}^2 Z_{vv} + Z_{pv}^2 Z_{qq} - 2Z_{pv} Z_{pq} Z_{vq}}{Z_{vv} Z_{qq} - Z_{vq}^2} \tag{28}$$

In the following, the various cases associated with the combined use of ground wires and counterpoise are investigated for different materials of ground wires and for stranded ACSR counterpoise wires, in compliance with the considerations outlined above. The screening factors as well as the absolute values of zero-sequence resistance, inductance and impedance of phase conductors, as modified by the effect of the compensating conductors, expressed in percentage of the original values, as well as the currents flowing in the compensating conductors, expressed in relative units, are given for each particular case. The current distribution between grond wires and counterpoise, in terms of relative units, are separately stated as well.

It should be noted that no detailed description of the investigations concerning the combined use of ground wires with a steel counterpoise is given here, because virtually no screening effect is to be expected from a steel counterpoise as has already been stated in Section 10.3. A summarized evaluation of these investigations is, however, given in Section 11.4, in the Tables XLVII to XLIX and in Figs. 15 to 18.

11.2 *Combined use of steel ground wire and ACSR counterpoise*

a) *Calculations*

The variation of the screening factor was investigated when an ACSR counterpoise wire of 250/40 sq. mm (or, as described in Section 10.2, an equal-size aluminium stranded wire or underground cable) is used in combination with one or two steel ground wires of cross-sectional areas of 50, 70 and 95 sq. mm.

For the purpose of the calculations the relative permeability of 60 and a soil resistivity of 10 ohm. metres were assumed. The results are compiled in Tables XXXIII to XXXIX.

Table XXXIII

Screening factor		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one steel ground wire(s)	two steel ground wire(s)
50	0.7202	0.7081
70	0.7136	0.6961
95	0.7071	0.6751

Table XXXIV

Modification of resistive component (in per cent)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one steel ground wire(s)	two steel ground wire(s)
50	−7.85	−1.39
70	−6.27	+0.53
95	−4.73	+2.10

Table XXXV

Modification of inductive component (in per cent)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one steel ground wire(s)	two steel ground wire(s)
50	−13.36	−14.71
70	−13.95	−15.80
95	−14.96	−17.58

Table XXXVI

Modification of absolute value of impedance (in per cent)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one steel ground wire(s)	two steel ground wire(s)
50	−13.05	−13.00
70	−13.60	−13.80
95	−14.52	−15.26

Table XXXVII

Current flowing in ground wires (in relative units)		
250/40 sq. mm ACSR counterpoise		
Ground wire sq. mm	one steel ground wire	two steel ground wires
50	−0.0189−j0.0373	−0.0377−j0.0686
70	−0.0280−j0.0453	−0.0553−j0.0820
95	−0.0443−j0.0542	−0.0855−j0.0958

Table XXXVIII

Current flowing in counterpoise (in relative units)		
250/40 sq. mm ACSR counterpoise		
Ground wire sq. mm	one steel ground wire	two steel ground wires
50	−0.2612+j0.0161	−0.2555+j0.0261
70	−0.2589+j0.0178	−0.2506+j0.0296
95	−0.2549+j0.0197	−0.2423+j0.0332

Table XXXIX

Current flowing in compensating conductors (in relative units)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one steel ground wire	two steel ground wires
50	−0.2801−j0.0213	−0.2932−j0.0426
70	−0.2869−j0.0274	−0.3059−j0.0524
95	−0.2992−j0.0345	−0.3278−j0.0625

b) *Conclusions*

The data of Tables XXXIII to XXXIX can be compared with those of Tables I to V (referring to the investigation of steel ground wires). A considerable reduction of the combined screening factor may be observed, the values of the latter being shifted into the range of 0.67 to 0.72. The change of the resistive component of the zero-sequence impedance is of a different character, and its sign is here overwhelmingly negative. The reduction of the inductive component falls within 13 to 18 per cent, that of the absolute value of impedance is within the range of 13 to 15 per cent.

The current flowing in the steel ground wire is about 20 per cent smaller, while the value of current returning in the counterpoise wire goes up to the range of 24 to 26 per cent of the full fault current ($3I_0$). In every case, the imaginary term of the current flowing in the ACSR counterpoise is negative, thus having a sign *opposed to* that of the imaginary term of current flowing in the ground wire. The distribution pattern of the real and imaginary components of currents is shown in Figs. 13 and 14 (indicating the true directions of currents).

It can be stated that the current carried by a counterpoise of good conductivity (e.g. aluminium) is *three times* higher than that flowing back through a steel counterpoise of *equal size*. This ratio is, at the same time, indicative of the compensating effect of counterpoise of different conductivities.

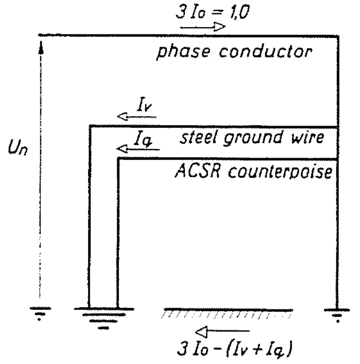

Fig. 13. Real current components

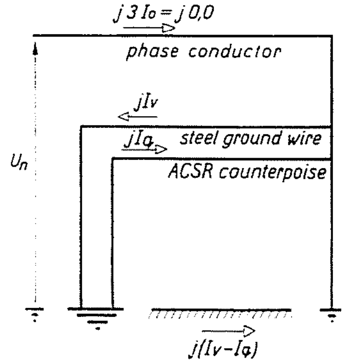

Fig. 14. Imaginary current components

Otherwise, the case of using steel ground wires in combination with good-conductivity counterpoises is the one of major practical importance. ACSR ground wires usually provide for such a high degree of compensation that the need for applying a counterpoise is very unlikely. On the other hand, it frequently occurs that the compensating effect of steel ground wires of existing overhead lines proves to be insufficient and the necessity of its improvement is required. Since a steel counterpoise is capable of influencing the value of the screening factor to but a very limited extent, even if using large size wires, *the most effective means of improvement is the application of a good-conductivity counterpoise.*

11.3 *Combined use of ACSR ground wire and ACSR counterpoise*

a) *Calculations*

The variation of the screening factor was investigated in conjunction with the use of one 250/40 sq. mm ACSR counterpoise (or, as described in Section 10.2, an equal-size *aluminium* stranded wire or underground cable) combined with one and two 150/25 and 250/40 sq. mm ACSR ground wires.

For the purpose of calculations a soil resistivity of 10 ohm. metres was assumed. The results are summed up in Tables XL to XLVI.

Table XL

Screening factor		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire(s)	two
150/25	0.4903	0.3759
250/40	0.4712	0.3541

Table XLI

Modification of resistive component (in per cent)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire(s)	two
150/25	—14.52	—14.50
250/40	—22.80	—22.45

Table XLII

Modification of inductive component (in per cent)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire(s)	two
150/25	—30.78	—39.78
250/40	—31.90	—40.85

Table XLIII

Modification in absolute value of impedance (in per cent)		
250/40 sq. mm ACSR ground wire		
ground wire sq. mm	one ACSR ground wire(s)	two
150/25	—30.00	—36.80
250/40	—31.45	-38.55

Table XLIV

Current flowing in ground wire(s) (in relative units)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire	two ACSR ground wires
150/25	—0.3228—j0.0595	—0.4976—j0.0752
250/40	—0.3453—j0.0289	—0.5237—j0.0367

Table XLV

Current flowing in counterpoise (in relative units)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire	two ACSR ground wires
150/25	—0.1888+j0.0168	—0.1297+j0.0252
250/40	—0.1839+j0.0092	—0.1228+j0.0146

Table XLVI

Current flowing in compensating conductors (in relative units)		
250/40 sq. mm ACSR counterpoise		
ground wire sq. mm	one ACSR ground wire	two ACSR ground wires
150/25	—0.5116—j0.0427	—0.6274—j0.0500
250/40	—0.5292—j0.0197	—0.6466—j0.0222

b) *Conclusions*

The data of Tables XL to XLVI can be compared with those of Tables XVI to XX (referring to the investigation of ACSR ground wires). The value of the combined screening factor, with one ACSR ground wire, is shifted from the range of 0.61 to 0.64 to that of 0.47 to 0.49, while with two ACSR ground wires from the range of 0.43 to 0.45 to that of 0.35 to 0.38. The reduction of the absolute value and of the components of the zero-sequence impedance have become more expressed. Thus, the absolute value of the zero-sequence

Table XLVII

Steel ground wire(s) (one or two 50—70—95 sq. mm stranded wires)			
Investigated quantity	no counterpoise	steel counterpoise	ACSR counterpoise
Screening factor	0.90....0.98	0.83....0.89	0.68....0.72
$\frac{R_p - R_{pp}}{R_{pp}} 100\%$	+11....+20	+11....+18	—8....+2
$\frac{X_p - X_{pp}}{X_{pp}} 100\%$	—2....—9	—6....—12	—13....—18
$\frac{\lvert Z_p \rvert - \lvert Z_{pp} \rvert}{\lvert Z_{pp} \rvert} 100\%$	—1.5....—6	—5....—9	—13....—15
$\frac{-I_{\text{gr. wire, real}}}{3I_0} 100\%$	2....11	2....10	2....9
$\frac{-I_{\text{gr. wire, imag.}}}{3I_0} 100\%$	4....11	4....10	4....10
$\frac{-I_{\text{c. poise, real}}}{3I_0} 100\%$	—	8....9	24....26
$\frac{-I_{\text{c. poise, imag.}}}{3I_0} 100\%$	—	2....3	—2....—3
$\frac{-I_{\text{comp. cond., real}}}{3I_0} 100\%$	2....11	11....18	28....33
$\frac{-I_{\text{comp. cond., imag.}}}{3I_0} 100\%$	4....11	7....12	2....6

Table XLVIII

ACSR ground wire(s) (one 150/25—250/40 sq. mm stranded wire)

Investigated quality	no counterpoise	steel counterpoise	ACSR counterpoise
Screening factor	0.61....0.64	0.57....0.59	0.47....0.49
$\frac{R_p-R_{pp}}{R_{pp}}\,100\%$	—4....—15	—4....—14	—15....—23
$\frac{X_p-X_{pp}}{X_{pp}}\,100\%$	—25....—27	—27....—28	—31....—32
$\frac{\|Z_p\|-\|Z_{pp}\|}{\|Z_{pp}\|}\,100\%$	—25....—26	—26....—28	—30....—31
$\frac{-I_{\text{gr. wire, real}}}{3I_0}\,100\%$	37....39	35....37	32....35
$\frac{-I_{\text{gr. wire, imag.}}}{3I_0}\,100\%$	2....6	2....5	3....6
$\frac{-I_{\text{c. poise, real}}}{3I_0}\,100\%$	—	6	18....19
$\frac{-I_{\text{c. poise, imag.}}}{3I_0}\,100\%$	—	2	—1....—2
$\frac{-I_{\text{comp. cond., real}}}{3I_0}\,100\%$	37....39	41....43	51....53
$\frac{-I_{\text{comp. cond., imag.}}}{3I_0}\,100\%$	2....6	4....7	2....4

impedance decreased in the case of using ACSR counterpoise by about 30 and 40 per cent, respectively, as compared with the former corresponding values of 25 and 35 per cent.

The current flowing in the ground wire is reduced by 10 to 15 per cent, as compared with the case without counterpoise. The current flowing back in the ACSR counterpoise amounts to 18 and 13 per cent of the full fault current ($3I_0$), in the case of one and two ground wires, respectively.

11.4 *Summarized investigation of the combined use of counterpoise and ground wire*

In Tables XLVII to XLIX the results of summarized investigations are shown, which were performed to determine the effect of combining steel and ACSR ground wires with steel and ACSR counterpoises. These results are grouped into ranges, instead of indicating individual values already stated in the foregoing sections, thereby facilitating the judgement of the various cases.

For relative permeability the value of 60, for soil resistivity that of 10 ohm. metres was assumed.

Table XLIX

ACSR ground wires (two 150/25—250/40 sq. mm stranded wires)			
Investigated quantity	no counterpoise	steel counterpoise	ACSR counterpoise
Screening factor	0.43....0.45	0.41....0.43	0.35....0.38
$\frac{R_p-R_{pp}}{R_{pp}}100\%$	−9....−19	−10....−19	−15....−22
$\frac{X_p-X_{pp}}{X_{pp}}100\%$	−38....−39	−38....−39	−40....−41
$\frac{\lvert Z_p\rvert-\lvert Z_{pp}\rvert}{\lvert Z_{pp}\rvert}100\%$	−35....−37	−35....−37	−37....−39
$\frac{-I_{\text{gr. wire, real}}}{3I_0}100\%$	55....57	53....56	50....52
$\frac{-I_{\text{gr. wire, imag.}}}{3I_0}100\%$	3....7	3....6	4....7
$\frac{-I_{\text{c. poise, real}}}{3I_0}100\%$	—	4	12....13
$\frac{-I_{\text{c. posie, imag.}}}{3I_0}100\%$	—	1	−1....−2
$\frac{-I_{\text{comp. cond., real}}}{3I_0}100\%$	55....57	57....57	63....65
$\frac{-I_{\text{comp. cond., imag.}}}{3I_0}100\%$	3....7	4....7	2....5

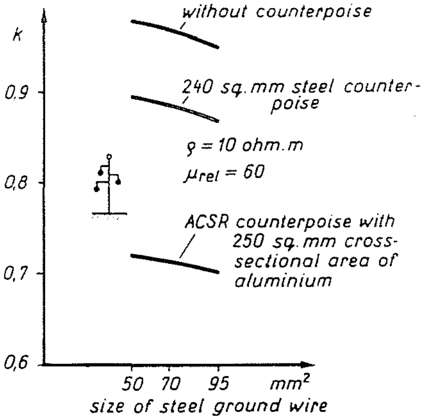

Fig. 15. Combined use of counterpoise and ground wire (one ground wire)

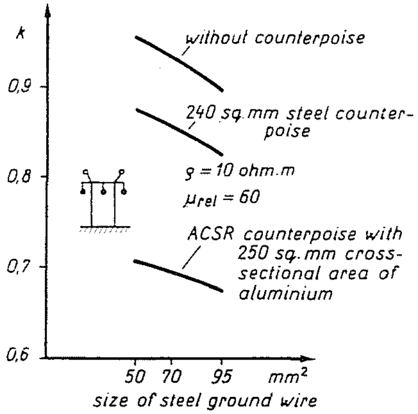

Fig. 16. Combined use of counterpoise and steel ground wire (two ground wires)

Summarizing the conclusions described in Sections 11.2 and 11.3, it can be stated that the combined use of the counterpoise and ground wires offers the greatest practical advantages in cases where the poor screening factor values provided by low-conductivity steel ground wires are to be subsequently improved. Obviously, the application of a *high-conductivity counterpoise* (e.g. an aluminium-core underground cable) *is the most effective means* of reaching this aim, by which the screening factor may be reduced by 30 to 35 per cent. The reduction obtainable with an identical-size steel counterpoise is only about 10 per cent (Table XLVII).

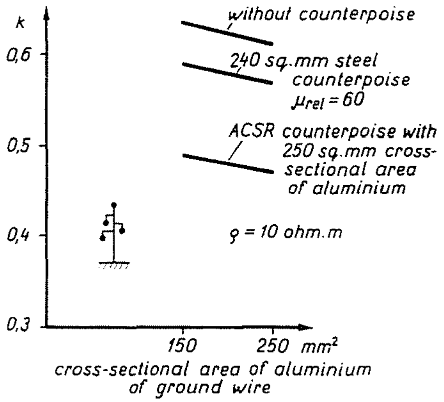

Fig. 17. Combined use of counterpoise and ACSR ground wire (one ground wire)

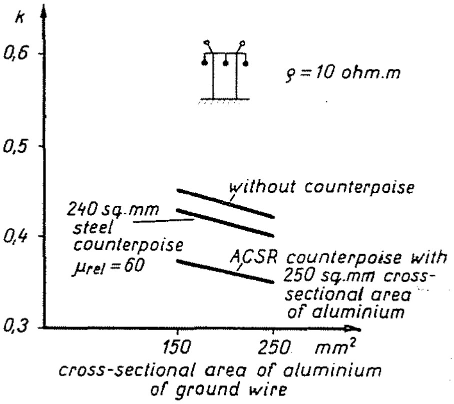

Fig. 18. Combined use of counterpoise and ACSR ground wire (two ground wires)

The screening factors provided by ground wires only, and those when combining the effect of ground wires and a counterpoise made of 240 sq. mm steel and of 250/40 sq. mm ACSR are represented in the following figures:

with one steel ground wire: Fig. 15,
with two steel ground wires: Fig. 16,
with one ACSR ground wire: Fig. 17,
with two ACSR ground wires: Fig. 18.

*

In the References a number of papers and books are listed in which the problems concerning the screening factor of overhead lines are discussed and further numerical results are given.

Summary

In the case of overhead power transmission lines the compensating conductors as means of reducing the effects of interference are represented by overhead ground wires and counterpoises. The paper investigates the variation of screening factors and the effect of compensating conductors modifying the absolute value and components of the zero-sequence impedance of overhead lines in the function of the number, material and size of compensating conductors and other factors (such as soil resistivity, permeability of steel conductors), as well as the complex form of currents flowing in the compensating conductors, given in relative units. The investigations were performed by means of an ELLIOTT digital computer.

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