Spotting the earth connection and short circuits between the electric conductors, using D.C. bridges for resistance measurements

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Abstract. The paper establishes the necessary connections meant to spot the earth connections and short circuits between the conductors of a power line, using the DC bridges meant for measuring resistances between conductors at the ends of the power line. Since it is a relative method, it imposes an exact knowledge of the faulty power line setting. For values of the resistances measured between the conductors of the power line having over 1Ω at one end, the measurement will be carried out with a Wheatstone bridge, and for values below 1Ω with a Thomson bridge. In order to accurately determine the place of the fault, it measured the distances from the end of the line up to the fault and then we performed a correction calculation for this distance.

1. Introduction
During the exploitation of power lines, there may arise simple faults (permanent short circuits or conductor breaks) or complex ones (short circuits or earth connections with a high value of the fault resistance, conductor breaks with a low fault resistance, short circuits accompanied by earth connections, etc.) [1-4]. Before spotting the fault, it has to be brought to a simple form, using the procedure of “burning” the faulty line. After this operation, we used one of the specific methods of spotting the fault [2, 5-8].

The paper introduces an original method of spotting the short circuits and earth connections of the cable or aerial power lines, using the d.c. bridges for measuring resistances [9]. In this respect, it determined relations for the calculation of the distance between the end of the line and the place of the fault, the fault resistance not implied.

2. Spotting the earth connection of a conductor in an electric line, using D.C. bridges

2.1. Spotting the earth connection without an auxiliary conductor
The method given henceforth can only be used if the power line has at least one good conductor. It is supposed that the power line of length \( l \) in Figure 1, was affected by an earth connection at distances \( l_x \) and \( l_y \) with respect to the ends of the line [2].
In order to spot the earth connection of conductor CF we connect the E and F ends of conductors B - E and C - F and then, with a d.c. bridge we measure at the end of cable I resistances $R_{BD}$ and $R_{CO1}$. If we ignore the contact resistances and the resistances of the connecting conductors between the I end of the cable, plot $O_1$ and the bridge, the result is:

$$R_{BO1} = R_{BE} + R_{FG} + R_{GO1} \quad [\Omega]$$  \hspace{1cm} (1) \\
$$R_{CO1} = R_{CG} + R_{GO1} \quad [\Omega]$$  \hspace{1cm} (2)

In these relations, $R_{GO1}$ is the equivalent resistance of the circuit made of the resistance of the earth at the end of line $l$ of the cable, used in spotting the fault, the resistance of the circuit through the earth and the fault resistance of the cable. Resistances $R_{BE}$, $R_{FG}$ and $R_{CG}$ are determined by means of relations:

$$R_{BE} = \rho_e \cdot \frac{k_p \cdot l}{s_e} \cdot R_l = R_{BE} \quad [\Omega]$$  \hspace{1cm} (3) \\
$$R_{FG} = \rho_e \cdot \frac{k_p \cdot (l - I_x)}{s_e} \quad [\Omega]$$  \hspace{1cm} (4) \\
$$R_{CG} = \rho_e \cdot \frac{k_p \cdot l_x}{s_e} \quad [\Omega]$$  \hspace{1cm} (5)

where $k_p$ is a correction coefficient for the length of the conductors of the cable power lines.

Coefficient $k_p$ represents the ratio between the real length $l_{pr}$ [m] of the conductor along a distance equal to the $p$ [m] twist step:

$$k_p = \frac{l_{pr}}{p} \quad (6)$$
Coefficient \( k_p \) can be determined according to distance \( D_c \) [m] between the conductors (Figure 2), if we know step \( p \), by means of relation \[7\]:

\[
k_p = \sqrt{1 + \frac{4}{3} \left( \frac{\pi D_c}{p} \right)^2}
\]

For the circular cross-section conductors, without space between the insulation layers, distance \( D_c \) [m] between the conductors is equal to the exterior diameter \( D_e \) [m] of the insulation. By means of formulae \(1\), \( 2\), \( 3\), \( 4\), \( 5\) we obtain distance \( l_c \):

\[
l_c = l - \frac{s_e}{2 \cdot \rho_e \cdot k_p} \cdot (R_{BO1} - R_{CO1}) \quad [\text{m}]
\]

If we short circuit the \( B \) and \( C \) ends of conductors \( EB \) and \( FC \), and we measure resistances \( R_{EO2} \) and \( R_{FO2} \) in the same way, we obtain:

\[
l_y = l - \frac{s_e}{2 \cdot \rho_e \cdot k_p} \cdot (R_{BO1} - R_{CO1}) \quad [\text{m}]
\]

By means of formulae \(4,7\) of \[7\], \(8\) and \(9\) we have:

\[
l_x = \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{EO2} - R_{FO2}) \quad [\text{m}]
\]

\[
l_y = \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{BO1} - R_{CO1}) \quad [\text{m}]
\]

Expressions \(8\), \(9\), \(10\), \(11\) can also be written as \[7\]:

\[
l_x = \left[ l - \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{EO2} - R_{FO2}) \right] \cdot l \quad [\text{m}]
\]

\[
l_y = \left[ l - \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{BO1} - R_{CO1}) \right] \cdot l \quad [\text{m}]
\]

\[
l_x = \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{EO2} - R_{FO2}) \cdot l \quad [\text{m}]
\]

\[
l_y = \frac{1}{2 \cdot k_p \cdot R_i} \cdot (R_{BO1} - R_{CO1}) \cdot l \quad [\text{m}]
\]

For the aerial power lines \( k_p = 1 \). In this case, the spotting of the earth connection for a conductor of the line can be carried out using the pairs of relations:

\[
l_x = l - \frac{s_e}{2 \cdot \rho_e} \cdot (R_{BO1} - R_{CO1}) \quad [\text{m}]
\]

\[
l_y = l - \frac{s_e}{2 \cdot \rho_e} \cdot (R_{BO2} - R_{FO2}) \quad [\text{m}]
\]

\[
l_x = \frac{s_e}{2 \cdot \rho_e} \cdot (R_{EO2} - R_{FO2}) \quad [\text{m}]
\]

\[
l_y = \frac{s_e}{2 \cdot \rho_e} \cdot (R_{BO1} - R_{CO1}) \quad [\text{m}]
\]
\[ l_x = \left[ 1 - \frac{1}{2} \cdot R_i \cdot \left( R_{BO1} - R_{CO1} \right) \right] \cdot l \quad \text{[m]} \quad (20) \]

\[ l_y = \left[ 1 - \frac{1}{2} \cdot R_i \cdot \left( R_{EO2} - R_{FO2} \right) \right] \cdot l \quad \text{[m]} \quad (21) \]

\[ l_x = \frac{1}{2} \cdot R_i \cdot \left( R_{EO2} - R_{FO2} \right) \cdot l \quad \text{[m]} \quad (22) \]

\[ l_y = \frac{1}{2} \cdot R_i \cdot \left( R_{BO1} - R_{CO1} \right) \cdot l \quad \text{[m]} \quad (23) \]

Distances \( l_x \) and \( l_y \) will be corrected using the procedure given in [7].

2.2. Spotting the earth connection using an auxiliary conductor

If all the conductors of the power line are earth connected this method can be used if we replace conductor \( B - E \) (Figure 1) by an auxiliary conductor having the parameters \( R_{la}, \rho_{ca} \) and the dimensions \( l_a \) and \( s_{ca} \). So: \( R_{BE} = R_c \). This equality, as well as relations (1), ..., (5) and (4.2) of [7], if one of the power lines in the cable has failed, lead to the conclusion that:

\[ l_x = \frac{1}{2} \left[ l + \frac{s_c}{k_p \cdot \rho_c} \cdot \left( R_{la} + R_{CO1} - R_{BO1} \right) \right] \quad \text{[m]} \quad (24) \]

With the results of the measurements made at end II of the cable, we can obtain in the same way:

\[ l_y = \frac{1}{2} \left[ l + \frac{s_c}{k_p \cdot \rho_c} \cdot \left( R_{la} + R_{FO2} - R_{EO2} \right) \right] \quad \text{[m]} \quad (25) \]

For the aerial power lines \( k_p = 1 \) and relations (24) and (25) become:

\[ l_x = \frac{1}{2} \left[ l + \frac{s_c}{\rho_c} \cdot \left( R_{la} + R_{CO1} - R_{BO1} \right) \right] \quad \text{[m]} \quad (26) \]

\[ l_y = \frac{1}{2} \left[ l + \frac{s_c}{\rho_c} \cdot \left( R_{la} + R_{FO2} - R_{EO2} \right) \right] \quad \text{[m]} \quad (27) \]

Irrespective of the type of power line, we obtain, in the same way the relations:

\[ l_x = \frac{1}{2} \left[ l + \frac{1}{R_i} \cdot \left( R_{la} + R_{CO1} - R_{BO1} \right) \right] \cdot l \quad \text{[m]} \quad (28) \]

\[ l_y = \frac{1}{2} \left[ l + \frac{1}{R_i} \cdot \left( R_{la} + R_{FO2} - R_{EO2} \right) \right] \cdot l \quad \text{[m]} \quad (29) \]

The next step is to correct the distances obtained above.

3. Spotting the short circuits between power lines, using D.C. bridges

3.1. Spotting short circuits without an auxiliary conductor

Unlike the procedures used at present in spotting short circuits, the method given henceforth can be applied using the apparatus the power line servicing teams are endowed with. Spotting the short circuit between two conductors of a power line can be done by measuring the electric resistances at the two ends of the line.
We suppose there arose a permanent short circuit between the two conductors of a cable power line (Figure 3) so, $R_s = 0 \, \Omega$. In this case:

$$R_{BC} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad R_{BC} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad [\Omega]$$ (30)

$$R_{EF} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad R_{EF} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad [\Omega]$$ (31)

The groups of relations (30) and (31) result in:

$$I_s = \frac{R_{BC}}{R_{BC} + R_{EF}} \cdot l \, [m]$$ (32)

$$I_y = \frac{R_{EF}}{R_{BC} + R_{EF}} \cdot l \, [m]$$ (33)

![Figure 3. Three-phase power line with a short circuit between two conductors.](image)

Generally $R_s \neq 0$, therefore the values of resistances $R_{BC}$ and $R_{EF}$ are influenced by the resistances at the place of the short circuit, according to the relations:

$$R_{BC} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} + R_s \quad R_{BC} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad [\Omega]$$ (34)

$$R_{EF} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} + R_s \quad R_{EF} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} \quad [\Omega]$$ (35)

With formulae (4.103) of [7], (34) and (35), by eliminating the fail resistance $R_s$, we obtain the distances from the two ends of the power line to the place of the fail:

$$I_s = \frac{l}{2} \left( 1 + \frac{R_{BC} - R_{EF}}{2 \cdot R_s} \right) \cdot l \, [m]$$ (36)

$$I_y = \frac{l}{2} \left( 1 + \frac{R_{EF} - R_{BC}}{2 \cdot R_s} \right) \cdot l \, [m]$$ (37)

Spotting the short circuit can also be done by two measurements at one end of the cable. If the measurements are carried out at end $I$, we short circuit conductors $A - D$ and $B - E$ at end $II$. We measure the resistances $R_{BC}$ and $R_{AC}$ with a d.c. bridge. They can be determined with expressions (34) and (38):

$$R_{AC} = 2 \cdot \rho_c \cdot k_p \cdot \frac{l}{s_c} + R_s \quad [\Omega]$$ (38)

With formulae (4.103) of [7], (34) and (38) we obtain:
\[ l_x = \frac{2 \cdot R_i + R_{BC} - R_{AC}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

\[ l_y = \frac{R_{AC} - R_{BC}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

Similarly, we can determine the relations for spotting short circuit (39) and (40), using the values of resistances \(R_{DF}\) and \(R_{EF}\) at end \(II\) of the cable, when points \(B\) and \(C\) are connected:

\[ l_y = \frac{2 \cdot R_i + R_{EF} - R_{DF}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

\[ l_x = \frac{R_{DF} - R_{EF}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

3.2. Spotting short circuits using an auxiliary conductor

When all the conductors of the power line are in short circuit, the method of fail spotting by two measurements at the same end of the cable can only be used with the help of an auxiliary conductor, having resistance \(R_{la}\). In order to use this method, instead of conductor \(A - D\) we use the auxiliary conductor. Measuring resistances \(R_{AC}\) and \(R_{BC}\) at end \(I\), with a bridge between points \(D\) and \(E\), having the values:

\[ R_{AC} = R_{la} + R_i + R_x \quad [\Omega] \]  

\[ R_{BC} = 2 \cdot R_{la} + R_x \quad [\Omega] \]  

by eliminating the fail resistance we obtain:

\[ l_x = \frac{R_{la} + R_i + R_{BC} - R_{AC}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

We then short circuit conductors \(A - D\) and \(B - E\) at end \(I\) and measure resistances \(R_{DF}\) and \(R_{EF}\), used to determine \(l_y\):

\[ l_y = \frac{R_{DF} - R_{EF}}{2 \cdot R_j} \cdot l \quad [\text{m}] \]  

4. Experimentation of the method

The experimental verification of the method of fail spotting in power lines, which this paper deals with, has been carried out on a laboratory model, having the parameters given in table 1, and the diagram in figure 3. The simulation of the effect resistance \(R_i\) has been done with a laboratory variable resistance connected between points \(G\) and \(H\).

The experimental data and the results of the calculations done with formulae (36) and (37) in order to spot the short circuits in power lines are given in table 1. The relative short circuit spotting errors have been calculated by means of formulae:

\[ \varepsilon_{x\text{r}} = \frac{l_x - l_{xm}}{l_{xm}} \cdot 100[\%] \]  

\[ \varepsilon_{y\text{r}} = \frac{l_y - l_{ym}}{l_{ym}} \cdot 100[\%] \]
Table 1. The determination of distances $l_x$ and $l_y$ from the ends of the power line to the place of the short circuit $l_x=2\text{m}; l_y=0.6\text{m}; R_s=123.528\Omega$.

| $R_s$ (Ω) | $R_{BC}$ (Ω) | $R_{EF}$ (Ω) | $l_x$ (m) | $l_y$ (m) | $\varepsilon_x$ (%) | $\varepsilon_y$ (%) |
|-----------|--------------|--------------|-----------|-----------|---------------------|---------------------|
| 0         | 28.04        | 65.38        | 0.6002    | 1.3998    | +0.0333             | +0.0333             |
| 20        | 47.98        | 85.35        | 0.5998    | 1.4001    | -0.0333             | -0.0333             |
| 40        | 67.90        | 105.20       | 0.6006    | 1.3994    | +0.1000             | +0.1000             |
| 60        | 87.80        | 125.50       | 0.5962    | 1.4036    | -0.6333             | -0.6333             |
| 80        | 107.60       | 145.50       | 0.5942    | 1.4058    | -0.9667             | -0.9667             |
| 100       | 128          | 165.45       | 0.5990    | 1.4010    | -0.1667             | -0.1667             |

5. Conclusions
The analysis of the calculation results referring to the short circuit spotting leads to the conclusion that for fail resistances whose values are below or equal to the resistance of the conductor, the spotting errors are very small and therefore relations (36) and (37), as well as the method we suggested can be used in practice.

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