IMPACT OF CABLE SHEATH SIZING, MATERIAL AND CONNECTIONS UPON THE SAFETY OF ELECTRICAL POWER INSTALLATIONS

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ABSTRACT

When an earth fault occurs at an installation, the resulting current must return to its source via metallic routes (such as a cable sheath) and through the soil/ground. The latter part flows through the local earthing system and creates a temporary elevated potential, called the Earth Potential Rise (EPR). This in turn can cause equipment damage and potentials that create a shock risk to nearby people and animals.
In the new European Earthing Standard EN50522 and IEC 61936-1, an understanding of the role of the cable sheath in returning some of the earth fault current is one of the factors that determine whether a 'Global Earthing System' exists.
In order to analyse such circuits effectively a spreadsheet based routine has been developed for 11kV cables. The first step was to calculate the necessary cable parameters to a high degree of accuracy. Then a number of representative circuits were analysed in detail using software packages, numerical methods and formulae. Finally, formulae of sufficient accuracy were used in a spreadsheet routine. This allows the effect of important variables upon the ground return current to be calculated. Its use has already led to new ideas about the design of earthing systems.
The aim is to develop new design rules and policies and extend the spreadsheet to cover a wider range of circuits (such as at higher voltages) and other parts of the earthing calculations carried out at the design stage.

1. INTRODUCTION

To assess the safety at an electrical installation, knowing its earth resistance and the fault current, we need to establish how current flows through the local electrode system into the ground. For circuits with a continuous metallic earth return path, it is known that part of the fault current returns to source that way. Standards such as EN 50522 [1] and IEC 61936-1[2] recognise this and its importance in determining whether a 'Global Earthing System' exists.
In this paper, in order to accurately account for the effect of the cable sheath and armour return path a spreadsheet based routine is presented. The accuracy of the calculator has been validated against established commercial software and standard formulae.
The paper is organised to cover the data gathering and code development (Section 2), use of the spreadsheet (Section 3) and finally conclusions and future work.

2. STEPS IN DEVELOPING THE SPREADSHEET ROUTINE

The end requirement is to be able to accurately assess how the earth fault current splits between its available return paths. These include the local earth mat/soil and the connected metallic return (cable armour, sheath and any associated pipes or dedicated earth conductors).
To analyse the majority of typical power company circuits, three arrangements are used in existing standards [3]. These include:

a. Fault at a remote substation supplied by a continuous cable circuit, earthed at each end.
b. Circuit initially of unearthed overhead line that converts to underground cable. The fault occurs at the substation on the end of the cable. (The same for the reverse arrangement, i.e. the cable at the start and the fault at the end of the overhead line).
c. An unearthed overhead line with a fault at a substation at its end. In the circuit there is a section of underground cable and of interest is how much current is diverted through its sheath to create an EPR at its ends.

An example of the first scenario is shown in Figure 1 and examples of all three are visible in Figure 2.

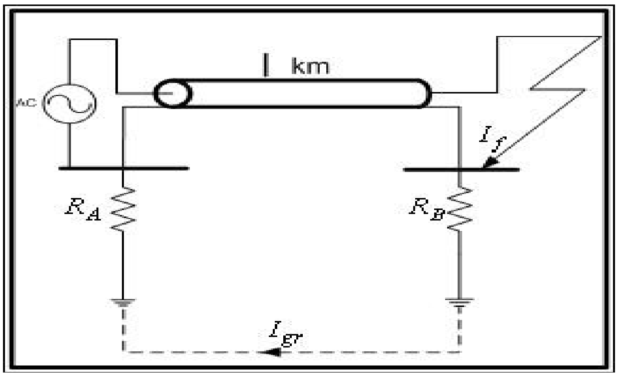

Figure 1. Example of a typical fault scenario.

2.1 Typical formulae

Equations are available to permit analysis of the arrangements described. For example the ones below from ENA S34 [3, Appendix B] calculate the ground return current for the circuit of Figure 1 for a three phase, unarmoured cable. Equation 1b is in simplified form.

$$I_{gr} = -I_f \left[\frac{l(z_c - z_{mp,c})}{lz_c + R_A + R_B} \right] \quad \text{1a}$$

$$I_{gr} = -I_f \left[\frac{lr_c}{lz_c + R_A + R_B} \right] \quad \text{1b}$$

The constants required to use this and the more complex equations include:

r_c: cable sheath resistance in Ω/km
z_c: cable sheath impedance in Ω/km
$z_{mp,c}$: cable core to sheath mutual impedance
$z_{mp,1}$: cable core to sheath of another cable (different phase)
r_a : cable armour resistance, L_a : cable armour inductance

Other factors that need to be available to change include length l(km), R_a and R_b (source and distribution substation earth resistance).

2.2 Source data

For each cable, detailed, reliable construction dimensions were obtained from the Electricity Company or manufacturer. The geometric data is fundamental in determining the self and mutual impedances and so must be accurate. Then accurate electrical material constants (resistivity, permittivity and permeability) for the cables were obtained from cable reference books [4].

2.3 Calculation of cable self and mutual impedances

It is vital for the cable self and mutual impedances to be correct, because all subsequent calculations rely on them. Each cable had two models produced independently; one used commercial software and the other EMTP. These were produced by different teams of researchers (in different continents), in order to avoid any common errors and allow cross checking. Each team provided the self and mutual impedances from their model. The results were compared and any discrepancies investigated. Comparisons were also made with values available from other sources [3] for some of the cables modeled. This process allowed the effect of relaxing some modeling features, such as core shape (sector or circular) and stranding, to be quantified. It also allowed comparison of the parameters for single core cables laid flat or in trefoil and at different depths.

2.4 Validation or correction of circuit formulae

The reliable self and mutual impedance data was then used in a number of formulae and analytical routines to calculate the proportion of ground return current with respect to the full fault current. For each circuit configuration (e.g. that of Figure 1), the ground return current was calculated by up to six different methods. This included ATP version of EMTP [5], earthing circuit software [6], standard formulae – mainly from ENA S34 [4] and BS 7354 [7], graphical methods (nomograms as in S34) and a distributed parameter approach [8]. In each case the studies were carried out for a representative range of input variables (circuit length, substation resistance, etc). Close correlation was generally obtained between the EMTP and earthing circuit analysis software, but adjustment to many of the standard formulae was necessary to obtain a sufficient degree of accuracy.

3. USE OF THE SPREADSHEET ROUTINE

A sample view of the spreadsheet is shown in Figure 2. The three different circuit configurations modelled can be seen.

The calculator is straightforward to use and allows selection of the cable type from a drop down menu, then the cable length, injected current, source and faulted substation earth resistances are input.

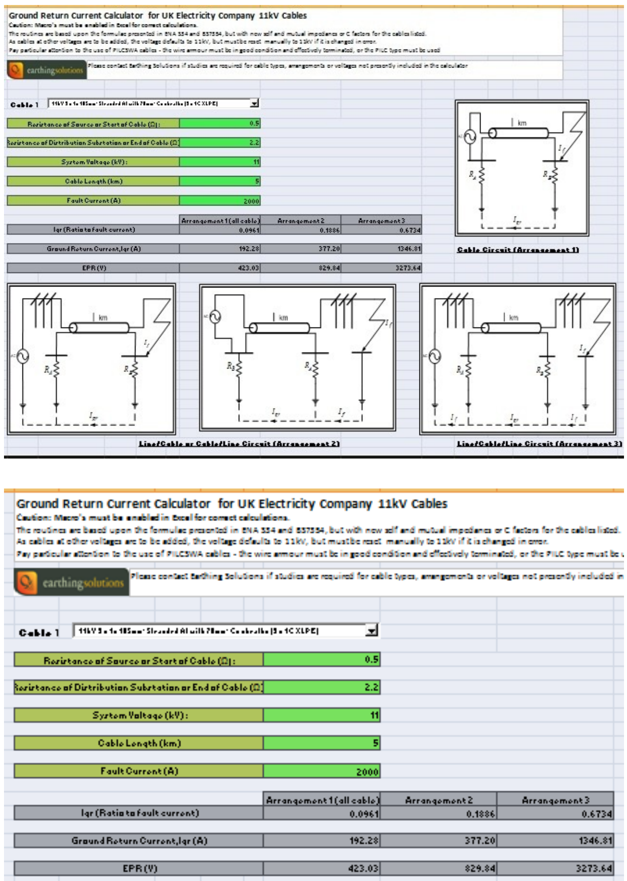

Figure 2. Sample screens of spreadsheet calculator.

More importantly, examples of some of the findings so far are now described.

3.1 Comparison with sample values from EN 50522

The subject is covered in Informative Annex I of this new standard and Table 1 shows a comparison of the typical ground return current values presented there against those for similar cables as modeled in our calculator. These are not necessarily of the same cable specification and we have not yet modeled the full range of cables covered in EN 50522.

Table 1. Typical ground return current as a proportion of the total earth fault current. Based upon typical source (0.5Ω) and installation earth resistances and cable lengths between 1km and 5km.

Cable (all for 10kV to 20kV usage range)	Ground return current in % (EN50522)	Ground return current in % (ES calculator)
95mm² 3 core copper in 1.2mm lead sheath	20 to 60	7 to 63
95mm² 3core aluminium in 1.2mm aluminium sheath	20 to 30	2 to 20
3 off 95mm² 1 core copper with 16mm² screen	50 to 60 (16mm² screen)	20 to 20 (35mm² screen)

The table does vividly illustrate the value of a site specific calculation, because the range given in EN 50522 is very wide and would add a significant degree of uncertainty if used in design studies.

3.2 Effect of cable length and sheath cross section area and material on the required substation earth resistance

One design factor used to determine whether an installation is safe is the earth potential rise for a representative fault condition. Within the UK a threshold value of 430V is often used. Table 2 below shows the range of substation earth resistance values that achieve the 430V value for different cable lengths and for three cables that have the same core size, but different sheath sizes or types. Note that these studies have not accounted for the longitudinal impedance of the faulted cable core that would reduce the fault current and required resistance for longer cables.

The main conclusions are that much higher resistance values can be permitted close up to the source and that the distance away for which this applies depends upon the sheath cross sectional area and material. After a 'knee' point, the resistance value required becomes much less dependent upon cable length. We intend to investigate this effect further to see if design rules can be developed that allow a standard installation within a certain radius, then a set earth resistance figure beyond. These studies will include the impact of the core impedance on the fault current and other factors such as mixed cable circuits. As an example, for the PILCSWA type cable in Table 2, a resistance value of 0.9Ω could apply for substations between 1km and 2km from the source, then 0.6Ω beyond. What is very clear is that lower resistance installation earth resistance values are needed further out from the source.

Table 2. Substation resistance (Ω) required to achieve an EPR of 430V for different lengths and types of cable. Source resistance assumed as 0.5Ω and fault current is 2000A.

Length (km)	3c 185mm² PILCSWA	3 x 1c 185mm², with 70mm² Cu sheath per cable	3 x 1c 185mm², with 35mm² Cu sheath per cable
0.5	500+	500+	500+
0.75	500+	500+	500+
1.0	3.0	500+	500+
1.5	1.2	500+	5.3
2.0	0.93	500+	2.0
3.0	0.75	4.8	1.3
4.0	0.68	2.7	1.1
5.0	0.65	2.2	1.0

3.3 Effect of the steel wire armour of older cables

Older distribution cables at 11kV were typically of the PILCSWA type (paper insulated, lead covered, steel wire armoured). The steel wire armour was included to provide mechanical protection to help avoid physical damage to the lead sheath (this could allow water ingress and failure of the paper phase-phase or phase-earth insulation). Within a power installation, cables were often of the PILC type (paper insulated, lead covered) because they were installed within secure cable tunnels or on surface racks. Newer cables are of the XLPE or EPR type, either three single cores or composite with all three phase within the same stranded copper or aluminium sheath.

As can be seen from the results set out in Table 3 below, the steel wire armour carries out a previously unknown role – it passes almost as much current back to the source as the lead sheath.

Table 3. Ground return current as a % of the total, for PILC and PILCSWA 185mm² 3 core belted cable.

Cable Length (km)	PILC Type Cable, Ground Return Current in %	PILCSWA Type Cable, Ground Return Current in %
1	35	18
2	48	26
3	54	30
4	58	32
5	60	33
6	62	34
8	64	35

This has very important operational implications. Originally it was generally understood (incorrectly) from the UK standards that the calculations were based upon the lead sheath only. The full rigour of our calculations

was required to illustrate this mis-conception.
The operational implications arise due to the steel wire armour either being corroded or not terminated with sufficient diligence. In either case, more of the earth fault current must then flow through the ground and will create a higher EPR than previously considered.
The quality of the cable sheath and armour termination is important, because if poorly made off, then less of the fault return current will use this route and will instead flow through the soil and increase the EPR. Once this factor was identified and included in maintenance checks, many instances of poorly terminated sheath and wire armours were found. An example is shown in Figure 3, where the earth connection is merely clamped to the outer armour wires – i.e. there is not a direct connection to the lead sheath or cable gland (the cable gland is of the insulated type). The implication of this defect is illustrated in Figure 4, where the fault return current found a lower impedance route back to its source and in doing so, punctured the cables lead sheath and created a fault.

Figure 3. Example of poorly terminated cable sheath and steel wire armours.

Figure 4. Cable damage due to poor sheath termination.

4. CONCLUSIONS AND WORK IN PROGRESS

As mentioned above, having a tool that can provide reliable results of fault current distribution quickly, allows a much better understanding of the issues and to gain experience of design options. The intention is to extend the tool to include cables of higher voltages (33kV, 132kV, etc) and different construction (cross bonded, gas filled in pipes etc). The effect of the core impedance in reducing the fault current at the faulted substation can also be partially included. Other design formulae will be included to cover some of the additional calculations required, such as transfer potential along cables.
Although three different types of circuit configuration have been studied, in real systems the cables are not often of the same size or type over their entire length. Studies of circuits that have sections of different cable in series and possibly an earth/ground connection at the junction where they meet, have already been carried out and guidance rules are being developed.
Design rules and policy guidance are also being developed for the Electricity Companies based upon work facilitated by the spreadsheet calculator.

Acknowledgments

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