ESTIMATION OF SUBSTATION EARTH IMPEDANCE IN A GLOBAL EARTHING SYSTEM

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ABSTRACT

As part of an urban distribution substation earthing design, it is often necessary to calculate the earth impedance contribution from the connected underground cable / earthing networks. This may allow a global earthing system to be proven, the earthing design to be simplified and electrode installation costs to be reduced. The existing calculation method employed by UK Power Networks makes assumptions which can be overly conservative. A novel calculation procedure is proposed based upon the minimum earth impedance that can be expected from a distributed network once the 'effective area' is covered. If the radius of the network around the substation can be estimated and the soil resistivity in the area is known, the earth impedance contribution from the network can be estimated. Results from the existing and proposed calculation methods are compared with data obtained from site for twenty substations and show the proposed method to be in closer agreement with the actual (measured) value. The method is also evaluated for substations connected to more sparse networks and where there is a predominance of underground cables with insulating outer coverings. Further work is identified to refine the method.

INTRODUCTION

UK Power Networks distribute electricity in Southeast England including London and many other large conurbations. In these urban areas there will often exist large area, interconnected underground cable and earthing systems which resemble a global earthing system (GES) as defined in BS EN 50522 [1]. A calculation tool has recently been developed for routine earthing designs at new 11kV distribution substations [2]. It is important to calculate the earth impedance contribution from the connected underground cable network, especially those with lead sheaths in contact with the ground. A detailed calculation could be made, e.g. using computer simulation, but this level of detail cannot generally be justified for distribution substations. Present calculations use equations from BS 7430 [3] and ENA EREC S34 [4] for horizontal electrodes and give conservative approximations. These often provide inflated earth impedance and earth potential rise (EPR) resulting in overdesign and unnecessary installation cost. This paper develops a new calculation method and compares the results to measurement data from test substations.

EXISTING METHOD TO CALCULATE THE EARTH IMPEDANCE CONTRIBUTION FROM A CONNECTED NETWORK

During the earthing design for a new substation, as well as calculations for the local substation electrode resistance, it is beneficial to consider the contribution provided by any connected underground cable sheaths / screens and remote substation electrodes. A parallel network contribution may be provided directly by older cable types, e.g. paper insulated lead sheathed cables (PILC) which have a water permeable outer serving. The lead sheath can be effectively in contact with the soil and act as a horizontal earth electrode. Even modern cable networks with insulated outer coverings can provide an indirect contribution by virtue of their screens connecting to other distribution substation electrodes connected along each feeder. In urban networks the HV earthing system commonly connects to LV earthing systems that will provide an additional contribution.

In the existing calculation tool the network contribution earth impedance is calculated using a simplified and conservative approach. This requires examination of cable records to determine the types and lengths of underground cables connected at the location of the proposed substation. The earth impedance is calculated based on the conservative assumption that only a single cable is providing a contribution, normally the longest PILC cable identified from the cable records. Knowing its length, sheath cross-sectional details and the local soil resistivity the earth impedance can be calculated using an equivalent ladder network model similar to the approach used in ENA TS 41-24 [5] and BS EN 50522. These standards include graphs of earth impedance against horizontal electrode length for a range of soil resistivity. For cables with electrode effect the distributed leakage earth resistance is included. For modern cables with insulated outer coverings, leakage earth resistance is applied only at each distribution substation at user defined distances along the feeder. In both cases the longitudinal impedance of the cable earthed screens are included in the calculation.

The local substation electrode resistance is calculated for each standard arrangement over a range of soil resistivity using the CDEGS software [6] and the values stored in the design tool. The overall earth impedance seen from the substation is the parallel combination of the substation electrode resistance and the network contribution.

PROPOSED CALCULATION METHOD USING THE EFFECTIVE AREA

It is known that the earth impedance of a horizontal electrode decreases with increasing length, up to an ‘effective length’ beyond which no significant contribution is seen [7]. This is due to the series impedance of the electrode becoming comparable and then dominant compared to the shunt earth resistance. At a certain length, known as the effective length, the earth impedance reaches a final minimum value.

The concept of effective length may be extended to an area, e.g. the area covered by a PILC type cable network in a conurbation. A simple approximation would be to consider a number of 11kV feeders radiating from a substation in different directions extending to a circular area with radius, x.

Calculations were made to estimate the effective area of a dense underground cable network using a simplified representation of a central substation with eight radial electrodes of length x(m) with x varied from 500m to 5000m to represent different size conurbations. The arrangement used for the simulations is shown in Figure 1. The impedance Z_A was calculated using CDEGS software as seen from the centre of the arrangement for different soil resistivities and the results are provided in Figure 2.

The simplified model would be expected to be a conservative representation in most situations where, in practice, the earth electrode coverage within a built-up area would typically be denser and consist of 11kV cable sheaths / armours and 11kV distribution substation electrodes. In the majority of cases LV cable screens / armours, LV earth electrodes and fortuitous metallic objects such as pipes, structural steelwork, etc., will also be connected and provide a contribution.

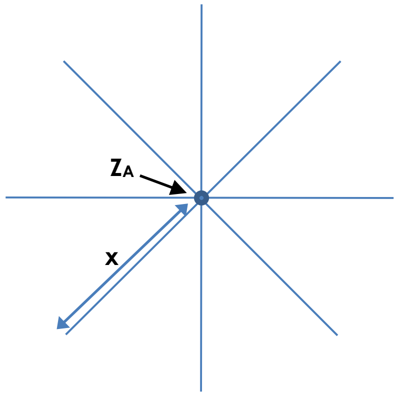

Figure 1. Cable Network Approximation – Earth Impedance Calculated at Z_A

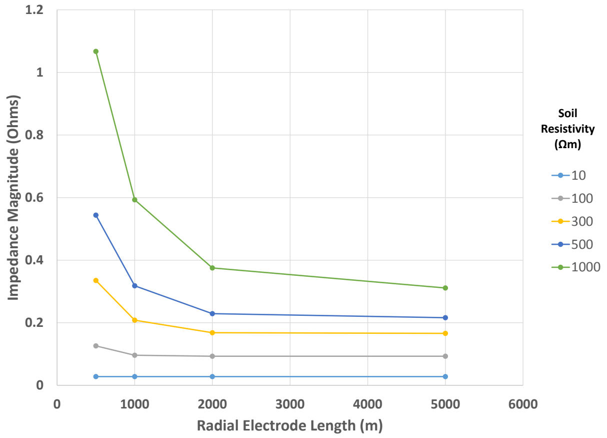

Figure 2. Calculated Earth Impedance Magnitude for Cable Network Model from Figure 1

From Figure 2 it is evident that the effective area radius and the final minimum earth impedance is dependent on the soil resistivity. A summary of the effective area radii and minimum impedances from the curves in Figure 2 is provided in Table 3. This table could be used to provide estimates of the earth impedance contribution from underground cable networks where the substation is part of a large interconnected network for different sized conurbations.

Table 1. Summary of Effective Area Earth Impedances

Soil Resistivity (Ωm)	Effective Area Radius (m)	Minimum Earth Impedance (Ω)
10	<500	0.030
50	500	0.065
100	1000	0.100
300	1500	0.170
500	2000	0.230
1000	>2000	0.310

MEASUREMENTS AT TEST SUBSTATIONS

Ten 11kV distribution substations were selected across the UK Power Networks distribution network which were part of a large urban underground network and also near to open soft ground suitable for measurements to be carried out. At each substation the overall earth resistance was measured using the fall-of-potential method [1] and a standard digital earth tester. The soil resistivity was also measured at each substation location using the Wenner Array [1]. At two of the substations the results from the earth tester were compared to higher current injection equipment and were found to be consistent.

Results were also available from previous UK Power Networks substation measurements at a further ten substations including distribution and primary substations. The measured earth resistances for all twenty substations are provided in Table 2. For each site the uniform equivalent soil resistivity is also provided and this can be seen to range from 5 to 190Ωm with an average of 63Ωm. In each case the measured earth resistance was found to be lower than that calculated using the existing approach.

Table 2. Summary of Measured and Calculated Earth Impedances (Substations A to T)

Substation Name	Uniform Soil Equivalent Resistivity (Ωm)	Measured Earth Impedance (Ω)	Calculated Earth Impedance (Ω) (Existing Method)	Calculated Earth Impedance (Ω) (Proposed Method)
A	93	0.085	0.51	0.100
B	112	0.160	0.69	0.170
C	128	0.172	0.64	0.170
D	63	0.075	0.35	0.100
E	182	0.177	0.65	0.170
F	35	0.053	0.35	0.065
G	17	0.055	0.21	0.065
H	23	0.111	0.26	0.065
I	20	0.068	0.26	0.065
J	129	0.148	0.70	0.170
K	13	0.077	0.09	0.065
L	18	0.030	0.08	0.065
M	140	0.288	27.90	0.170
N	191	0.046	53.00	0.170
O	36	0.052	0.59	0.065
P	55	0.100	0.18	0.065
Q	50	0.046	0.12	0.065
R	40	0.060	0.47	0.065
S	94	0.113	18.90	0.100
T	11	0.034	0.07	0.065

COMPARISON OF RESULTS

A comparison was made between the measured earth impedance and the calculation using the existing and proposed methods. For example at Substation A the measured impedance was 0.085Ω. This compares with the result from the existing calculation method of 0.51Ω i.e. a difference of 0.425Ω or 500% increase compared to the measured value. Use of the proposed method provides a result of 0.1Ω which is only 18% higher than the measured value. The percentage differences for all twenty sites are presented in Figure 3.

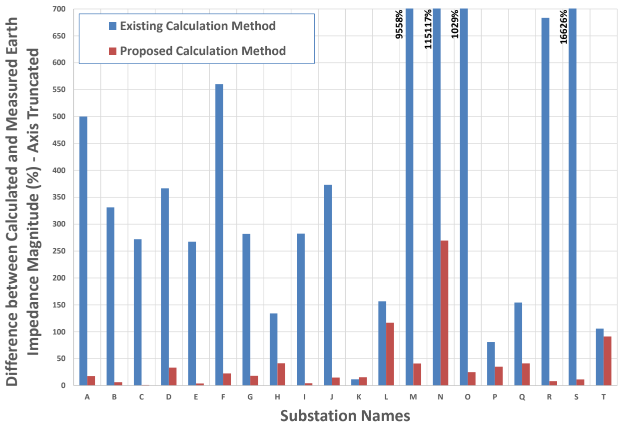

Figure 3. Difference between Measured and Calculated Network Earth Impedance (Substations A to T)

From Figure 3 it can be seen that each of the measured values are significantly lower than the calculations predicted by the existing method confirming that the method is conservative. At 14 of the substations the difference between the calculated and measured values is greater than 350%.

The results from the proposed calculation method can be seen to be in much better agreement with the measured values. At 17 of the substations the difference between the calculated and measured value is ±50%. The calculated earth impedance is still conservative at the majority of sites but the earth impedance contribution is overestimated at 5 substations.

APPLICATION OF THE PROPOSED CALCULATION METHOD TO SUBSTATIONS WITH DIFFERENT CHARACTERISTICS

To investigate how the new approach may be applied to substations with different characteristics a further six sites were selected. These were selected to allow the initial evaluation of substations having the following features:

(a) Substations connected to 11kV cable networks predominantly consisting of modern cables with insulated outer coverings, i.e. those with little or no PILC / PILCSWA type cables. Two new towns (constructed in the past 20 years) were identified and a suitable substation was selected in each of these areas (U and W).

(b) Substations in areas of high soil resistivity. Based on data from the UK Power Networks soil resistivity database, substations W and X were selected from high resistivity areas.

(c) Sparse networks, i.e. substations connected to a relatively small underground cable network in a rural or sub-urban environment. Two islanded sections of 11kV underground network (maximum of 20 distribution substations) were identified and measurements were carried out at two suitable substations (Y and Z).

The measured and calculated results for the six additional substations (U to Z) are provided in Table 3 and Figure 4.

Table 3. Summary of Measured and Calculated Earth Impedances (Substations U to Z)

Substation Name	Uniform Soil Equivalent Resistivity (Ωm)	Measured Earth Impedance (Ω)	Calculated Earth Impedance (Ω) (Existing Method)	Calculated Earth Impedance (Ω) (Proposed Method)	Calculated Earth Impedance (Ω) (Proposed Method – modified for Sparse Networks)
U	17	0.092	1.43	0.065	------
V	16	0.200	1.43	0.065	------
W	225	0.239	2.74	0.170	------
X	186	0.242	0.85	0.170	------
Y	70	0.223	0.54	0.100	0.200
Z	53	0.192	0.36	0.100	0.200

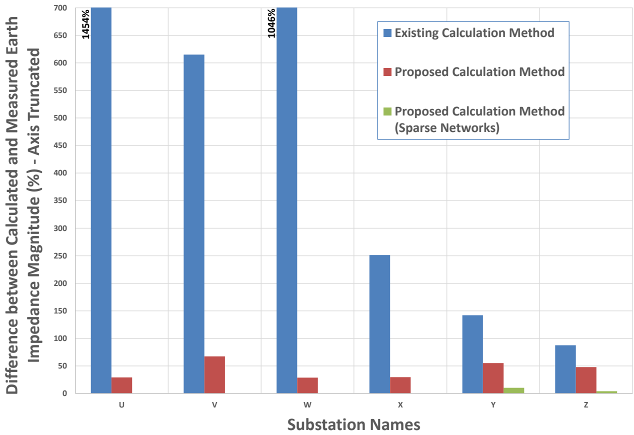

Figure 4. Difference between Measured and Calculated Network Earth Impedance (Substations U to Z)

Sparse Networks

For the two substations connected to a smaller, islanded cable network (Y and Z), the measured impedances are approximately double that predicted by the effective area calculations from Figure 2. This is expected because the networks are not large enough to cover the effective area.

Further calculations were made to estimate the effective area of a more sparse underground cable network using a simplified representation of a central substation with three radial electrodes of length x(m) with x varied from 100m to 5000m to represent different size semi-rural networks. The arrangement used for the simulations is shown in Figure 5. The impedance Z_{AS} was calculated using CDEGS software as seen from the centre of the arrangement for different soil resistivities.

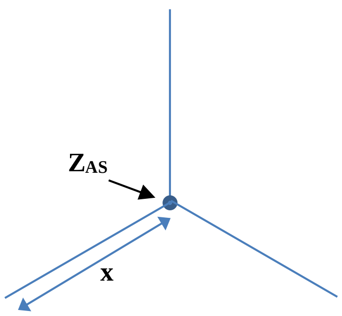

Figure 5. Cable Network Approximation – Earth Impedance Calculated at Z_{AS}

The results indicate that the effective area and the final minimum impedance is dependent on the soil resistivity, i.e. following a similar trend to the results in Figure 2 but the impedance was found to be approximately double those shown in Figure 2 and Table 1.

The results from the 'sparse network' calculations are provided in the final column of Figure 4 for Substations Y and Z where they can be seen to be in good agreement with the measured values.

Areas of High Soil Resistivity

The measured impedance for the two substations (W and X) in areas of high soil resistivity are in better agreement with the measured value compared to the existing calculation method.

Modern Underground Cable Networks

For the two substations where there is predominantly cables with insulated coverings (Substations U and V), from Figure 4, it can be seen that the measured values are significantly higher than predicted by the effective area method (the difference is 29% and 68% respectively). This is expected as the impedance calculated for the effective area assumes bare electrodes extending over the area. This limited data indicates that the effective area method is not suitable where there is a high proportion of cables with insulated coverings. The measured values are however significantly lower than those calculated using the simplified existing method. It may be possible to reduce the conservatism of the existing method by applying a scaling factor to the effective area impedance. The results from these two substations suggest that this factor must be a minimum of four but this would need to be confirmed by results from a larger sample.

CONCLUSIONS

Earth resistance measurements have been taken at ten distribution substations and combined with previous data to create a sample of twenty case study sites. For each substation considered in this investigation the calculated earth impedance using the existing simplified approach is higher than the measured value. This is as expected because the calculations do not include the effect of all of the connected earth electrodes and are inherently conservative.

A novel calculation method is proposed which uses the minimum impedance provided by a network covering the effective area. Providing the underground earthing network covers a relatively large area and is reasonably dense the earth impedance may be predicted with better accuracy if the uniform soil equivalent resistivity and the network radius is known. Comparison of the earth impedance calculated from the effective area method with measured values from the twenty test sites indicates that the method may provide a reasonable, and generally conservative prediction of the network earth impedance contribution.

Measurements at an additional six substations suggest that this approach may be optimistic at substations which are part of a modern polymeric cable network (no electrode effect) or where a PILC type cable network does not cover the effective area. Further calculations based on a sparse network have been made which appear to be more applicable to semi-rural networks. Further work is required to refine and validate this.

The work provides an improved method of calculating the network contribution and has been implemented in the UK Power Networks earthing design tool. Safety factors or alternative calculation methods for areas with a high proportion of plastic sheathed cables or where there are small sections of islanded cable network require further characterisation.

FURTHER WORK

The small sample of substations tested as part of the follow-on work at the six additional sites has indicated that where there is a high proportion of plastic sheathed cables or a PILC network that does not cover the effective area, it may be more difficult to develop a simple improvement on the existing calculation methods included in the UK Power Networks Tool. Further research, including measurements at a larger sample of substations is required to further develop an approach for these types of substation.

Refinement of the sparse network model, together with a comparison with a larger set of measurements is recommended to increase confidence in the use of this approximation for design purposes.

REFERENCES

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