NEW DESIGN METHODS TO ACHIEVE GREATER SAFETY IN LOW VOLTAGE SYSTEMS DURING A HIGH VOLTAGE EARTH FAULT

Mark DAVIES
Earthing Solutions – UK
mark@earthing-solutions.co.uk

Trevor CHARLTON
Earthing Solutions – UK
trevor@earthing-solutions.co.uk

Denis BAUDIN
Earthing Solutions - UK
denis@earthing-solutions.co.uk

ABSTRACT

When an earth fault occurs at a high voltage installation, the flow of return current through the soil also impacts upon adjacent installations. We are particularly interested in nearby low voltage installations because these are used to supply places like homes, factories, shops, transport facilities etc., where people can usually directly contact the earth conductor.

One of the methods of achieving safety in a low voltage installation, particularly when the high voltage one has a high fault current or Earth Potential Rise (EPR), is to separate the respective earthing systems. Safety calculations for this arrangement were previously based upon conditions solely at the boundary area and the authors have previously shown that this was an overly cautious approach.

Since that time significant additional studies and measurements at live electrical installations have been carried out and show that the effects described by the authors do occur.

This latest paper presents additional data via a case study that adds further proof. Just as importantly a new calculation method is presented to allow designers to more accurately estimate the transfer potential to LV earthing networks that have a number of distributed earth electrodes. The lessons learnt can be applied to the design of earthing systems such that they achieve both a higher degree of safety and also allow the introduction of a high voltage installation relatively close by.

INTRODUCTION

We showed previously [1] that the present calculation method in UK standards [2] significantly overestimates transfer potential between HV electrodes and multiply earthed LV systems, (including TNC-S or PME). The method invariably creates an overdesigned earthing system with the unnecessary installation and maintenance costs associated with achieving large separation distances. The overestimation is primarily due to an incorrect assumption that the surface potential on the LV electrode nearest to the HV electrode is transferred to the entire LV earthing network. Calculations and measurements have shown that the lower surface potential experienced by other more remote electrodes in the LV network are important and reduce the overall transfer potential to a lower 'average' value. There is presently no method available in standards to calculate this 'averaging' effect.

In this paper such a method is presented via a case study and the results compared to those obtained from commercially available earthing simulation software [3]. The implications to LV earthing system design are then discussed and future work identified.

NEW CALCULATION METHOD

UK [2] and other International Standards contain different approximate formulae to calculate the earth resistance (R) of different shaped electrodes such as a hemisphere (Equation 1). There are also formulae to calculate the surface potential (V_s) at a given distance away from different electrode shapes such as an equivalent circular plate (Equation 2). The equations reproduced here have been included because they have been found to be suitable for this application.

$$R = \frac{\rho}{2\pi r} \qquad \{\text{Equation 1}\}$$

$$V_s = \frac{\rho I}{2\pi r} sin^{-1}(\frac{\rho r}{4R}) \qquad \{\text{Equation 2}\}$$

Where ρ is soil resistivity (Ωm) and r is the radius of the hemisphere or circular plate (m).

The existing approach is to calculate V_s at the LV electrode nearest the HV electrode and assume that this potential is transferred to the entire LV network. In the new method V_s is calculated at the location of each individual electrode in the distributed LV network (or a representative sample of electrodes) and the overall transfer potential calculated using a potential divider circuit. If each LV electrode is of a similar size, e.g. a number of distributed LV earth rods in a PME system, it may be assumed that they each have the same earth resistance. The overall transfer potential is then the average of the potentials calculated on each of the individual electrodes. If one of the LV electrodes has a significantly lower resistance, compared to the others connected to the network, then the overall potential will be more influenced by its potential. This effect can also be estimated using the new method provided that the individual LV electrode resistances are known (either by calculation or measurement).

The new method can theoretically calculate the overall potential on any number of interconnected LV electrodes. In practice the arrangement can be simplified by concentrating first on the areas of highest electrode density and at the extremities of the network, to achieve sufficiently accurate results.

To illustrate the above, calculations using the new method and computer simulation software have been applied to a simple case study.

CASE STUDY

One of the most common HV to LV substation arrangements in the UK consists of an integrated transformer / switch unit on a concrete plinth within a fibreglass enclosure. A typical PME LV network consists of a number of distributed earth rods or horizontal electrodes (tapes) interconnected via an overhead or underground neutral / earth conductor. This theoretical case study is a simplified representation of such a network, but with the LV electrode system designed to help reduce transfer potential. In this case we have simply connected 50% of the electrode towards the remote end of the LV feeder (i.e. in areas of low surface potential).

Arrangement Considered

The case study arrangement is shown in Figure 1.

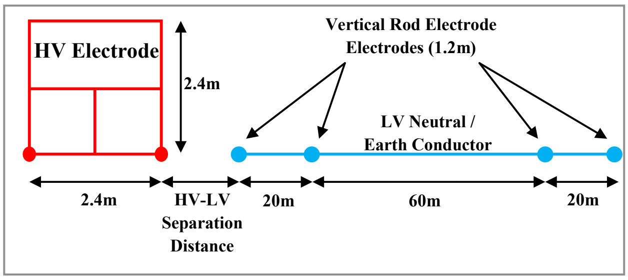

Figure 1. Case Study Arrangement (Top View)

The HV Electrode is a standard design typically used in the UK [4] and is buried at 0.6m below the surface (copper tape or stranded conductor), with a few vertical earth rods. A 70mm^2 copper neutral earth conductor has been assumed and a uniform soil of 100Ωm resistivity. With this size neutral/earth, the LV service cable has a self impedance that is negligible compared to the electrode resistances.

Methodology

Three calculation methods are compared: the existing UK standard approach [2]; the proposed new method and detailed computer simulation [3]. For each method the transfer potential is calculated over a range of HV to LV electrode separation distances (1m, 3m, 9m, 12m and 18m) which are typical of those used by electricity distribution companies throughout the world. Equation 2 is used for the existing and new methods.

Previous work on how to best represent the HV electrode in standard calculations revealed that the hemispherical approximation (Equation 1) provides the lowest values and hence a conservative and satisfactory transfer potential. This is because this formula is based on the assumption that an electrode with a low resistance occupies a large area and hence extends surface potentials around it for a considerable distance. The values obtained using Equation 1 and detailed simulation software are shown in Table 1 and are in good agreement for this particular HV electrode.

Table 1. HV Electrode Resistances Calculated Using Different Methods.

Calculation Method	Calculated HV Electrode Resistance
Equation 1	11.8Ω
Detailed Simulation [3]	12.0Ω

Results

In Figure 2, the calculated transfer potential, obtained using the three different methods, are compared.

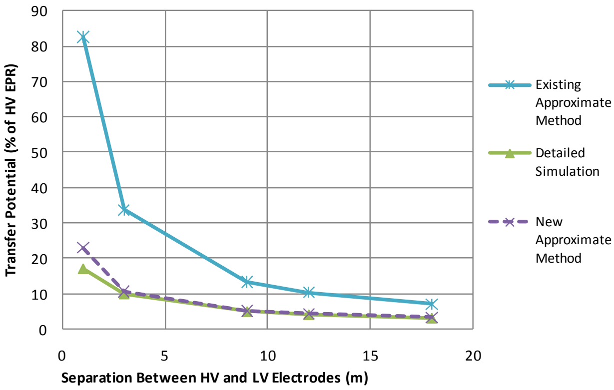

Figure 2. Comparison of Calculated Transfer Potential Using Different Methods

The results in Figure 2 show good agreement between the new method and detailed simulation and of course both show a much lower transfer potential than the existing method. For larger separations (>3m), there is very close agreement with detailed simulation as surface potentials around the simulated square HV electrode approximate more closely the circular equipotential contours assumed by the hemispherical formula. .

The largest 'error' occurs for small separation distance of 1m. It is in this area that the standard formula has not adequately represented the shape of the contours emanating from the electrode. Here, the existing method overestimates the transfer potential by a factor of almost 8, compared to just over 2 using the new method.

Calculating the Effect of a Low Resistance LV Electrode at the Extremity of a Distributed Earthing Network

Up to now the case study has considered that all four individual LV rod electrodes have the same earth resistance (R_{LV}). We now consider a case where the rod located furthest away from the HV electrode has a resistance five times lower than the other three $\left(\frac{R_{LV}}{5}\right)$.

Figure 3 shows the results obtained for the new method and detailed simulation over the same range of HV to LV electrode separation distances as in previous sections.

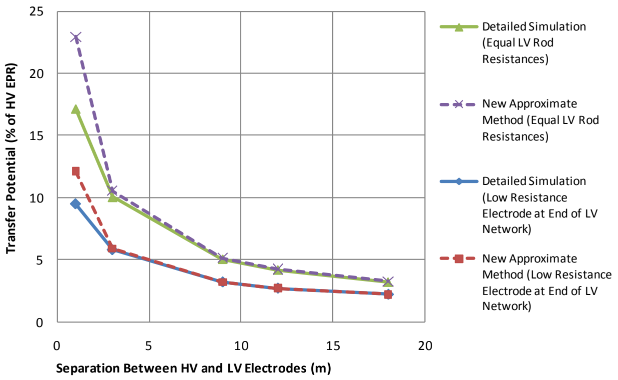

Figure 3. Calculated Transfer Potential Using Different Methods for Reduced LV Rod Resistance.

The new method provides results which are in good agreement with detailed simulations, but are still conservative. The existing approximate method would not include the effect of the low resistance electrode at all and would provide the same results as in Figure 2, i.e. a very large overestimation of the transfer potential. The much lower transfer potential achieved using the new and detailed simulation methods demonstrates the effect that including low resistance electrodes remote from the HV installation has and this is an important design lesson. From the detailed simulation results in Figure 3 the effect of the low resistance electrode can be seen to reduce the calculated transfer potential by between 45% and 30% over the range of separation distances considered.

Where a low resistance LV electrode exists close to a HV electrode the opposite effect will be observed, i.e. the overall transfer potential will increase. It is for this reason that this type of arrangement should be avoided in practice.

To implement the new calculation method it is necessary to calculate (or measure) each of the individual LV electrode resistances. Formulae are available for this [2] but approximations can be made. Because the relative LV rod resistance is effectively a weighting factor in calculating the overall transfer potential it is only the ratio of resistances between the different rods which is required. For example, in an area of reasonably consistent soil resistivity this could be estimated by comparison of relative rod depths or horizontal electrode lengths.

Discussion of Limitations

The previous sections have indicated results for a simple case study arrangement which are generally in good agreement with detailed simulation software. Further calculations have identified limitations some of which are discussed below.

Soil Model

The new calculation method is based on the assumption of uniform soil conditions. Whilst this is consistent with the present approach included in most international standards it is recognised that it is a situation which rarely exists in practice. Initial studies suggest that the proposed method is conservative for uniform soils and where there is a lower resistivity deeper layer. Where there is a high resistivity layer beneath the surface, e.g. underlying rock, then additional safety factors would need to be introduced as the transfer potential would be underestimated by standard calculations.

LV Electrodes Near to HV Electrodes

From Figure 2 and 3, it is evident that the new approximate method is least accurate for small separation distances. This is because the surface potentials close to the HV electrode are least consistent with the circular shape assumed by the approximate formulae. Although significant error can be introduced for separation distances below 3m, electrodes closer than this will rarely be used in practice. If they are used, then detailed computer modelling is probably needed to get results of the required accuracy.

Extended HV Electrodes

An extended HV electrode (such as a substation connected to a large underground cable network with bare sheaths / armouring in contact with the soil) will have the effect of increasing transfer potential (as a percentage of the HV EPR). Whilst this would initially indicate an underestimation by the new method, the actual transfer potential would be expected to reduce because of the much lower HV electrode resistance and EPR, i.e. in a 'Global Earthing System'.

IMPLICATIONS TO LV EARTHING SYSTEM DESIGN

The work has important implications for future LV system earth electrode design, particularly close to a HV installation with a high EPR. Significant reductions can be made to the LV transfer potential by biasing electrode installation to areas remote from the HV Electrode where the surface potentials are lower. For example, up to a 45% reduction was achieved for the simple case study considered.

LV earthing design practices should be reviewed and the new calculation method described in this report developed to assist designers in applying the new approach. For new installations this would be considered at the planning stage where LV electrodes close to the distribution substation would be designed to have the highest resistances (approaching the minimum requirement to allow adequate protection to operate, e.g. 20Ω). At the end of each main LV feeder, where practicable, a larger electrode would be installed, designed to achieve a lower resistance, e.g. 10Ω or 5Ω.

The approach could also be used retrospectively at an existing substation where there was an unacceptably high transfer potential onto the LV system. The existing LV network would be examined and locations identified for installing additional LV electrodes in areas remote from the HV substation.

There will inevitably be abnormal situations where detailed simulation and measurements will still be necessary, but it is envisaged that the new approximate method outlined in this paper will provide useful guidance for the majority of standard installations.

FUTURE WORK

The next stage of this research will be to investigate the effect of more factors on the transfer potential. These will include electrode burial depth, electrode routing, extended HV electrode systems and non-uniform soil resistivity conditions. The intention will be to use these results to further test the new calculation method proposed in this paper, quantify its limitations and introduce correction factors where necessary. The method will also be applied to horizontal LV electrodes which are often installed in practice instead of vertical rods. Studies are required to determine the optimum number of vertical electrodes required to provide a reasonable representation of a complex LV network including a mixture of vertical and horizontal electrodes.

The method may then be automated with a user-friendly interface such that it can be used by electricity company planners as a design tool.

In conjunction with the above theoretical evaluation, actual measurements are planned at real 11kV distribution substations in the UK where the location and size/resistance of all the electrodes are known. This will allow a direct comparison between real and predicted results and allow further verification of the technique.

The above work is planned or in progress and it is anticipated that the authors will be able to update conference delegates with the key findings at CIRED 2011.

Acknowledgments

The Energy Networks Association in the UK and their sponsoring member companies for their financial support of the project and desire to make the findings known.

Jonathan Williams of Earthing Solutions for his assistance in carrying out the detailed simulations.

REFERENCES

[1] T.Charlton, M.Davies, D.Baudin, 2007, "Transfer Potentials from MV to LV Installations During an Earth Fault", *Proceedings of the 19th International Conference on Electricity Distribution (CIRED)*, Session 2, paper No. 0805.

[2] ‘A Guide for Assessing the Rise of Earth Potential at Substation Sites’, Energy Networks Association, Engineering Recommendation, S.34, May 1986.

[3] Current Distribution, Electromagnetic Interference and Grounding Analysis Software (CDEGS), MALZ Module, Version 13.4.28, Safe Engineering Services, Canada, 2009.

[4] Earthing Construction Manual, Section 3, Secondary Distribution Network Earthing Construction, UK Power Networks, Version 1, 20/2/09.