A NEW DESIGN TOOL FOR DISTRIBUTION SUBSTATION EARTHING SAFETY

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ABSTRACT

This paper describes a tool developed for the assessment of earthing requirements at small ground mounted 'distribution substations'. These substations (typically 11kV:400V) are routinely installed in large numbers by Distribution Network Operators (DNOs) or Independent Connection Providers (ICPs) in the UK.

INTRODUCTION

Traditionally, the earthing associated with small distribution substations has been installed without detailed consideration. Older designs relied heavily on interconnection with nearby lead sheathed cables (or similar) to act as an earth electrode and to limit touch potentials in and around the substation. Often only a simple 'nominal' earth electrode was installed, and this approach was broadly compliant with UK regulations until they were revised in 2002 [1].

This approach may not always be sufficient to ensure safety for modern systems with polymeric (insulated sheath) cables, which are far more reliant on a dedicated and substantial earthing system at each substation. In recognition of this fact, European and UK standards [2,3] now require that touch and step potentials are calculated to confirm that a dangerous voltage will not appear on equipment under earth-fault conditions.

Given the high volumes of distribution substations that are installed every month, the suggestion that each installation is given a bespoke earthing design is unpopular. Designers need to source various items of network data, and (due to inter-relation between some of the parameters), producing a design can be an iterative and slow process. To address these concerns, UK Power Networks[1] commissioned Edif ERA to assist with the development of a design tool. The resultant 'Substation Earthing Design Tool' simplifies the design process and enables the designer to quickly arrive at a safe design. It also provides a mechanism to assess third party designs.

The tool includes fault current distribution calculations for underground cables building on work included in one of our previous CIRED papers [4]. Overhead (pole-mounted) substations are not considered here.

1 The Distribution Network Operator (DNO) responsible for distribution to London and South East England

THE EARTHING DESIGN PROCESS

The design of an earthing system for a small 'distribution' substation is, in essence, no different to that of any larger substation, and in fact can be more onerous due to close proximity to other systems/services, and direct connection (via cable sheaths) to consumer's premises.

The designer must ensure that:

1) The voltage rise (termed 'Earth Potential Rise' or EPR) appearing on substation metalwork under fault conditions must not exceed certain limits.
2) The voltage difference between any two points in and around the substation shall not exceed safe limits, in terms of 'touch voltage' or 'step voltages' which themselves are a function of fault clearance time.
3) The earthing system must be of sufficiently low resistance to allow earth-fault protection to operate reliably.
4) A dangerous voltage must not be exported or 'transferred' from the substation into other services, consumer installations, or anywhere where it may prove problematic.
5) The earthing system (and other systems) will not suffer damage due to the passage of fault current.

In order to accurately consider these effects, the designer needs various items of data relating to the network characteristics, including:

1) Earth fault level or 'source impedance' at the point of connection or upstream 'primary' substation. Ideally this will be in the form of positive and zero sequence impedance data.
2) Circuit data (cable / line types, cross sectional area, and lengths) between the primary substation and the new distribution substation. This data set needs to include the sheath types and cross sectional areas, and an indication of whether they are single core or three core cables with/without armour.
3) Characteristics of the primary substation, including its own earth electrode resistance values, and (if cable connected to the new substation) its EPR for all HV and EHV earth-faults. (E.g. any design for a substation supplied by cable from a 132/11kV

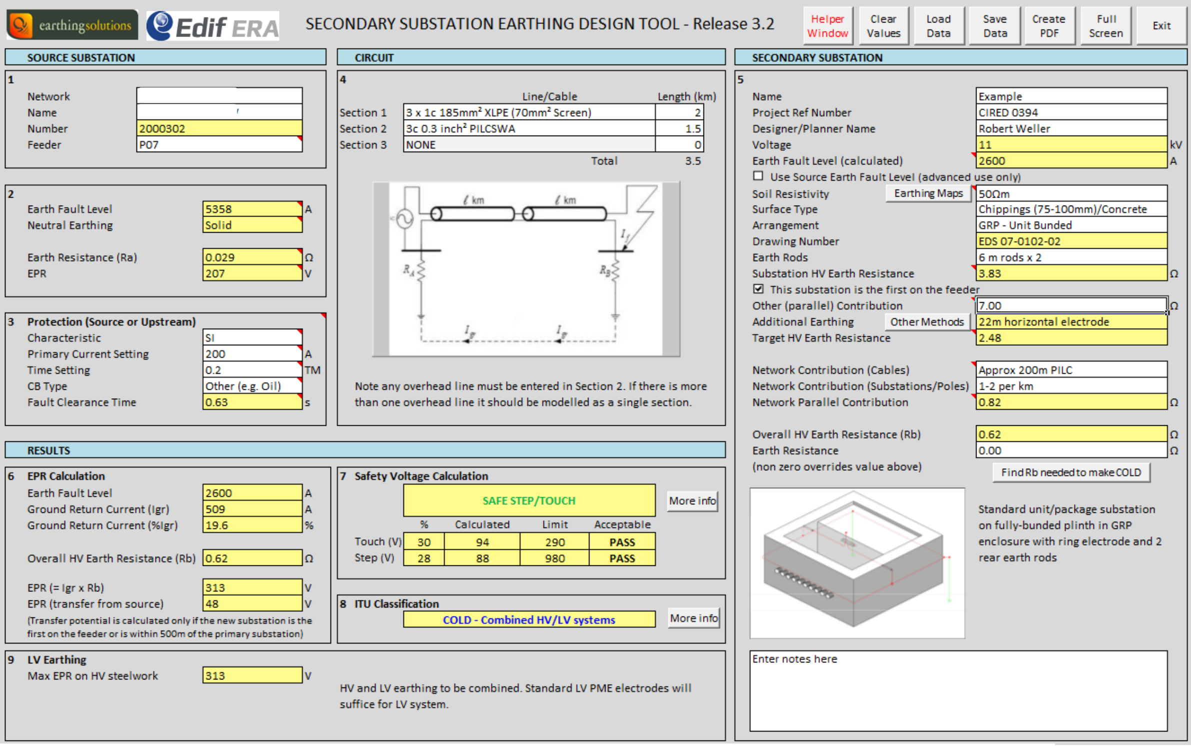

Figure 1 – The layout of the tool front page, as presented to the user.

substation must consider both 132kV and 11kV faults at that substation).

4) Protection settings at the primary substation, or along the feeder, to enable earth fault clearance time to be calculated at the new substation.
5) The soil type(s) present at the new substation's location, and the proposed electrode layout. The designer must estimate or specify the resistance of the new distribution substation's earthing system. To do so, he/she will need to apply the appropriate value for soil resistivity (Ωm) to relevant calculations.
6) Cable types, and nearby substations, that will be interconnected to the new substation.
7) Alternative running arrangements that may alter the supply or 'sheath return' contributions.
8) The designer also needs to consider the resultant voltage gradients that will occur in or around the site under fault conditions, and will need to apply formulae or detailed modelling to estimate touch and step voltages.

Thus it can be seen that data gathering, and calculations can be onerous, even for a relatively routine substation installation. The tool overcomes these obstacles by presenting the user with the majority of the necessary information, whilst at the same time performing calculations to establish if a proposed design is acceptable.

THE EARTHING DESIGN TOOL

Overview:

The tool presented to the user is built on a Microsoft Excel platform (front-end), with coded (visual basic) routines performing the majority of the calculations. Work is underway to further develop the tool so that its routines can be used from various 'front end' applications including Microsoft Access and web-browsers.

Practical use of the tool

The presentation of the tool is shown in Figure 1. The user is required to populate the white cells, whereas all remaining cells (coloured yellow) provide output, or display data that are stored within the tool. The tool layout is arranged, with 'source information' to the left of the page, circuit information in the middle, and the proposed new substation arrangements to the right.

To arrive at a suitable design, the user need only select the type of substation ('Standard Arrangement') from a drop-down list, and provide basic information relating to its connection to the existing network. The information that he/she must provide includes:

1) Source (primary) substation name and outgoing feeder name/number (if known);
2) Circuit lengths and types to the new substation;
3) Geographic area / soil type
4) Details of additional electrode (if any) or nearby network contribution

Input parameters can be saved to a 'study file' for future use.

Output from the tool can be saved, or printed as standard 'forms' for the use for installation or auditing purposes, as described in the next section.

Some aspects of an earthing design can be iterative, for example the interdependence between substation resistance, fault level, protection clearance time and 'safety limits' can mean that the user needs to make two or three successive guesses at a design to arrive at the optimal arrangement. To minimize this, one feature of the tool is a 'Find R_B' function; this uses an iterative algorithm to successively 'guess' at, and converge on the target resistance (the resistance of the new substation's electrode system) required to achieve an acceptable design. The user can then alter the electrode layout/options to achieve this resistance.

Tool Detail

Ground return current

The tool applies the design requirements in EN 50522 [2], and (UK Specific) requirements including ENA TS 41-24 [3].

Bespoke calculations within the tool calculate the split of current between the soil and the 'sheath return'; these calculations serve the purpose of 'nomograms' or 'C-factors' that are described in various earthing standards [5,6], and allow accurate calculations for all of UKPN's cable types. The calculations build on our earlier detailed modelling of all cable types, and use data relating to each cable's self and mutual impedances, including all combinations of mutual coupling between each core and each sheath/screen for faulted and unfaulted phases, including the effect of additional armour, if present.

In practice, if there is any overhead line present, almost all fault current returns through the distribution substation's electrode system, whereas, by contrast, this proportion can fall to 20% or less if a modern 'triplex' cable is used for the entire route length.

The equivalent circuit for an earth fault at a cable fed substation is given in Figure 2. The source (primary substation) is shown to the left, with its electrode resistance of R_A ohms. The new distribution substation has an electrode resistance of R_B. The cable is of length 'l'. The total 'earth fault' current at the new substation is I_f amps, and the component flowing through soil (and through the distribution substation's earth electrode) is I_{gr}.

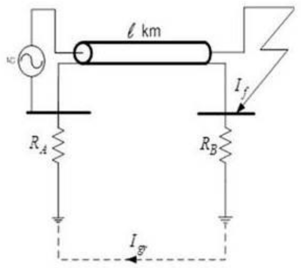

Figure 2 – Equivalent earth fault current circuit for a simple cable network

Cable data

The user specifies the length and type of cable or overhead line between the primary substation and the new distribution substation. For ease of use, the circuit 'make-up' is limited to three sections (the user can 'lump' the cable sections into polymeric, lead/metallic sheathed, and overhead line), although the tool has the capability of working with 100 sections. A proposed future development to the tool is to populate the cable entries automatically from UKPN's relevant circuit databases.

Network Data

Relevant (network specific) data sets are contained within the tool, which minimizes the need for the designer to look elsewhere. The tool contains information relating to the source (primary) substation including its source impedance characteristics, as well as its earth resistance (R_A) and EPR. The tool lists the outgoing feeders so that the user can select the appropriate connection point, and the protection settings for the feeder are displayed.

Substation data

UKPN has approximately 16 'standard' substation layouts for new build distribution substations. Each has its own electrode layout, usually consisting of a perimeter 'ring' electrode buried in soil (copper tape or stranded conductor), and two or four vertical rod electrodes driven into the ground. A typical electrode arrangement for a small ground-mounted transformer (and the concrete base) is shown in Figure 3.

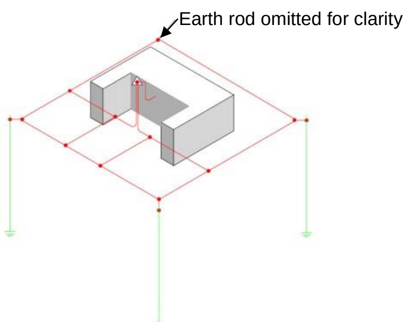

Figure 3 – Earthing arrangement for a small substation

Each arrangement has been modelled in CDEGS computer software [7] to establish the likely worst case step and touch voltages as a percentage of EPR. These percentages are stored in the tool. The user need not consider these values further, it is sufficient merely for him/her to specify the standard type (from a drop-down list), and the tool applies the relevant factors to calculations.

The tool stores the calculated earth resistance values for each arrangement in a variety of soil types. The user is able to vary the depth of rod electrodes (up to 20m), or to add additional horizontal conductor or 'parallel contributions' to alter the overall earth resistance of the new substation. The overall resistance of the arrangement is automatically calculated. The product of the ground return current (I_{gr}) and resistance (R_B) gives the EPR that will appear on steelwork under earth fault conditions.

The resistance for the substation's electrode system in isolation must be below design limits set by the electricity company. It should also correspond to the value measured on installation, before connection of any cables. The network contribution, and 'overall resistance' is discussed below.

Network Contribution

When installing a new substation into an existing network, the nearby network will provide a contribution to the overall (connected) earth resistance of the new substation. In the case of large, lead sheathed cable networks connected or bonded to the substation HV earth, this contribution can be significant. A smaller, but nevertheless useful contribution may arise from polymeric cable networks where the nearby substation electrode systems are effectively connected together via insulated cables.

The user can select the amount of contributing lead sheathed cable, and distribution substation density (the number of substations within a 1km radius of the new site). The tool uses the selected soil type to calculate an approximate network contribution. This appears in parallel with the substation's electrodes system, giving an 'overall' resistance that will be achieved once the cable network is connected to the substation. It is this value that is used in EPR calculations.

Fault level

The tool takes into account the earth return path including R_B to provide an accurate calculation of earth fault level at the distribution substation. This is often more accurate than the figure provided by conventional modelling packages which tend to assume a 'zero ohm' fault. The fault-level at the distribution substation is recalculated each time a change is made to the electrode layout or to the supply arrangements.

Safety Voltages

Knowledge of the EPR is important, since excessive EPR can cause problems with insulation withstand or third party properties and services. It is important to note however that the EPR does not equate directly to 'safety voltages', i.e. the full EPR will not necessarily appear as a 'touch' voltage between a person's hands and feet, nor as a 'step' voltage between his/her feet. In a well designed system, the touch voltage may be below 25% of the EPR at all points in and around the substation.

If the substation is cable connected to the source, the 'transfer potential' (i.e. the voltage carried along the cable sheath from the primary substation) is calculated for faults at the source substation. In some cases this can be more onerous than the EPR arising from 'local' faults. The design must consider EPR resulting from 11kV faults at the new substation as well as faults at higher voltage levels. This is automatically considered in the tool whenever the primary substation EPR exceeds a set limit (presently 430(650) volts to align with UK standards [3]).

Once the EPR is known, the tool works out the 'touch' and 'step' potentials that will be present on the selected 'standard arrangement'. These are compared with permissible limits that are themselves dependent on protection clearance time (described below).

Protection operation

The protection clearance time is relevant to considerations of 'safety voltage', since higher voltages are permissible if the fault can be disconnected quickly. Permissible limits are also influenced to an extent by the ground covering (e.g. soil, chippings, concrete, etc.), since these provide some additional resistance between an individual and 'earth'; the relevant covering can be selected by the user.

Earth fault protection in the UK is typically implemented as 'instantaneous', or 'IDMT' (inverse definite minimum time). In general, the majority of faults will be disconnected within one second. The tool allows the user to enter specific relay settings (characteristic, current setting, and time setting/multiplier), so that the 'trip time' can be found. To assist the user, protection settings relevant to the selected feeder are displayed at the bottom of the tool's input screen; these values are derived from UKPN's protection settings database and are stored in the tool. The user can use these values to overwrite 'default' settings that appear automatically in the white cells of the tool. He/she can also use this function to explore whether protection settings can be modified to enhance safety.

Soil type

The resistance that a given earthing arrangement will achieve in practice is influenced to a large extent by the surrounding soil type.
For large substation designs, it is normal to commission a

'soil resistivity' survey to determine the layers of soil, and the depth and resistivity of each layer. It is not usual practice to commission such a survey prior to the design of small substations, as the cost and work involved is usually considered disproportionate to the overall job. Nevertheless, it is necessary for the designer to make some estimate of the soil type present at the new substation.
To assist the user, the tool provides a link to a mapping system that UKPN has developed with the aid of the British Geological Survey (BGS). The system provides an indication of soil resistivity (Ωm) in different geographic areas; the user need only specify an address or map reference.

Pass/Fail criteria

Safety

The permissible step/touch voltages are calculated and presented to the user. The actual 'touch' and 'step' potentials are compared to the permissible limits and the design is given a 'PASS/FAIL' as appropriate. A substation design that fails must be revisited by the designer, at which stage he/she may opt to reduce EPR by adding additional electrode. Alternatively, he/she may explore the effect of other changes, such as changes to surface covering (e.g. by use of concrete or asphalt to increase permissible limits), or protection modifications to achieve faster clearance time, or the removal of an overhead line section, etc.

Transfer Potential - Hot/Cold limits

In addition to the safety limits for touch/step potential, the user is also informed if the site EPR is 'HOT' or 'COLD' according to the present definition of 650V for fast acting protection (<0.2 seconds) or 430V (slower clearance times); these limits are important as additional requirements need to be satisfied to ensure that dangerous potentials are not transferred to the LV network or telecommunication systems. It is the network operator's preference to achieve a COLD site where possible.
The tool will indicate if the substation EPR is sufficiently low that the LV and HV networks can be combined. If it is necessary to separate the HV and LV systems, the electrode requirements to achieve a standard LV earth (e.g. 20Ω) are presented to the user.

The tool is capable of applying different limits to those above, and a version is under development which will allow the user to work with 'F factors' as defined in BS EN 50522 [2], since these may supersede or obviate the need for applying historical 'HOT' or 'COLD' limits [3].
An upper limit for EPR may be specified by the network operator (typically 2-3kV). The user is warned if the EPR is greater than this limit.

Output from the tool

The most significant output from the tool is the 'target resistance' that must be achieved at the new substation. This is the resistance of the electrode system measured in isolation, i.e. before connection of the substation to the cable network. Where additional electrode is specified (beyond the usual rods associated with a standard arrangement), or where a separate LV electrode system is required, the tool provides an indication of how a given resistance will be achieved in a given soil type (e.g. single rod, multiple rods, or horizontal electrode).

The data items that have been entered are recorded in a printable form that the designer can save as part of the overall project file. In this way there is a record of network data, and assumptions (if any) made as part of the design process. Variations of these forms exist (intended for different purposes), for example a 'Construction Form' records details which are relevant to those installing or commissioning the substation, such as 'Standard Arrangement type', depth and number of rods required, additional electrode (if any), and the size of earthing conductor/bonding required (this being dependent on fault level).

CONCLUSIONS

The developed tool provides a relatively easy way for a designer to arrive at an efficient and safe earthing system design using a consistent approach based on international standard procedures. The majority of the data required for the design are provided by the tool, minimizing the need for the designer to search or collate data from various sources.
This new approach produces a design that is optimal in terms of electrode material, whilst demonstrating compliance with statutory requirements relating to electrical safety.

REFERENCES

[1] Electricity, Safety, Quality and Continuity Regulations, 2002

[2] EN 50522: *Earthing of power installations exceeding 1 kV a.c*

[3] Energy Networks Association (ENA) Technical Specification 41-24:1992, *Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations*.

[4] A.M.Davies et al, 2011, "Impact of Cable Sheath Sizing, Material and Connections on the Safety of Electrical Power Installations", *Proceedings CIRED conference* 2011, Paper 0548

[5] Energy Networks Association (ENA) Engineering Recommendation S.34:1986, *A Guide for Assessing the Rise of Earth Potential at Substation Sites.*

[6] BS 7354: *Design of high-voltage open-terminal stations*, 1990

[7] Current Distribution, Electromagnetic Interference and Grounding Analysis Software (CDEGS), Safe Engineering Services, Canada, 1996.