Session 2: Case Study

# Why There is No Such Thing as a Standard Earthing Design!

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## INTRODUCTION

Earthing studies are complex and frequently misunderstood by many design engineers and developers, particularly at 11 kV, where it is often assumed that the risk is low. A common assumption used by many developers is that a standard design for an 11 kV substation is suitable for most applications. This paper outlines why 11 kV substations in rural locations can be surprisingly difficult, and must always be assessed formally as there can be a significant touch and step voltage risk to operators and members of the public.

A case study is presented of a small 11kV substation installed in a housing estate, partially fed via overhead line, with slightly below average soil resistivity and a typical phase-earth fault level. It is subsequently shown, that the substation was classified as Hot / High Earth Potential Rise (EPR), and the zone of influence extended into a large portion of the site and the nearby houses, requiring a significant amount of design work, risk mitigation and planning.

## Background

Earthing is a complex area and many design engineers still view it as a 'black art'. This is a little dramatic, but it is also true that earthing is not easy either and it is very easy to get wrong. The ENA TS 41-24 [1] and S34 [2] standards, and the associated BS EN 50522 [3] standards, on the subject are very comprehensive, but they are not readily accessible or easy to follow for those that are unfamiliar with earthing design.

One of the fundamental problems with earthing design is that there are many variables and 'degrees of freedom' in the problem. This means that there is rarely a typical case, and using standard designs is often not appropriate, except when a Global Earthing System (GES) can be proven. Typically, each site has several variables that are specific to each installation

1. Earth Fault Current
2. Soil Resistivity
3. Earth Grid Impedance
4. Fault Current Return Paths
5. Protection Clearance Time
6. Surrounding Area / Context

## Simple Test Substation

Consider a typical earth grid layout for a standard GRP based 11kV substation, as indicated in Figure 1 below. This has been modelled in CDEGS SESCAD as a simple perimeter loop around the substation, using 70mm$^2$ conductor, with a 16mm, 3.6m rod driven into each corner and 50m length of 70mm$^2$ radial conductor installed in the incoming HV cable trench.

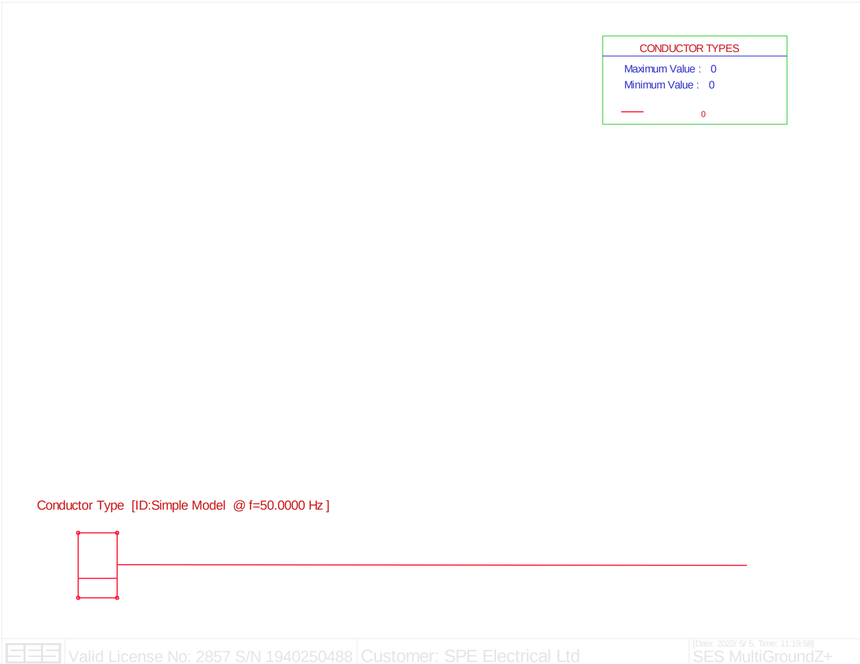


**Figure 1: Typical 11kV Substation Earthing Layout**

If the soil resistivity is varied, a simple relationship can be determined between the soil resistivity and the overall earth grid impedance, as indicated in Table 1 below. Where it can be seen, that as expected the earth grid resistance reduces as the soil resistivity increases in an approximately linear fashion, and that the presence of the horizontal radial conductor reduces the overall earth grid impedance by over 50%.

What is often surprising to many, is the amount of earth conductor needed to get a low impedance value. For a typical 1kA earth fault current, every one of the scenarios would result in a Hot / High EPR substation, if they were fed via overhead line. In most cases the EPR would be above 3kV, leading to significant design problems!

**Table 1: Typical Earth Grid Resistance vs Soil Resistivity**

| Case | Soil Resistivity Ωm | HV Earth Grid Resistance (Substation only) | HV Earth Grid Resistance (Substation + 50m radial) |
|---|---|---|---|
| Good Soil Conditions | 50 | 3.5 | 1.5 |
| Average Soil Conditions | 100 | 7.1 | 3.0 |
| Below Average Conditions | 200 | 14.2 | 6.0 |
| Poor Soil Conditions | 400 | 28.4 | 12.0 |

## Case Study – Rural Substation for a New Housing Estate

For analysis purposes, a fictious Case Study is developed (based on an amalgamation of several real projects), where a small 11kV substation that is to be used to supply a new housing estate development is assessed. The initial design proposed has located the substation in the middle of a housing development, to help optimize the LV cabling and distribution system and reduce the system losses. This is a very typical scenario and one that is encountered frequently throughout the UK.

The initial substation design consists of a simple substation located in the edge of a residential estate as shown below in Figure 2, and it is assumed for simplicity that the substation is located on a simple homogenous soil, with a resistivity of 200 Ohm-m.

The DNO supply to the site is taken from a nearby 11kV cable to the Southwest of the site, with the 11kV cable looped in and out of a new Ring Main Unit (RMU) inside the substation. The total distance to the tee-in is approximately 150m, and the developer has planned to install 50m of radial 70mm$^2$ cable in the incoming HV trench and has planned to install a standard earthing configuration as shown in Figure 1.

Next, let us assume that the local DNO network is partially supplied from an overhead line, and therefore there is no metallic return path and any 11kV fault current must return to the DNO primary substation through the earth grid. Let us also assume that the DNO network is fairly modern and all of the existing DNO cables are XLPE or EPR and cannot be treated as a horizontal earth electrode. We will also assume that the DNO has advised that their fault level is 1kA and their protection clearance time for HV faults can be up to 1s.

**Figure 2: Site Layout**

A preliminary model of the system has been created in CDEGS, based on the 'standard' design shown in Figure 1; but which has been modified slightly to account for the incoming HV cable route. The preliminary CDEGS model is then shown in Figure 3.

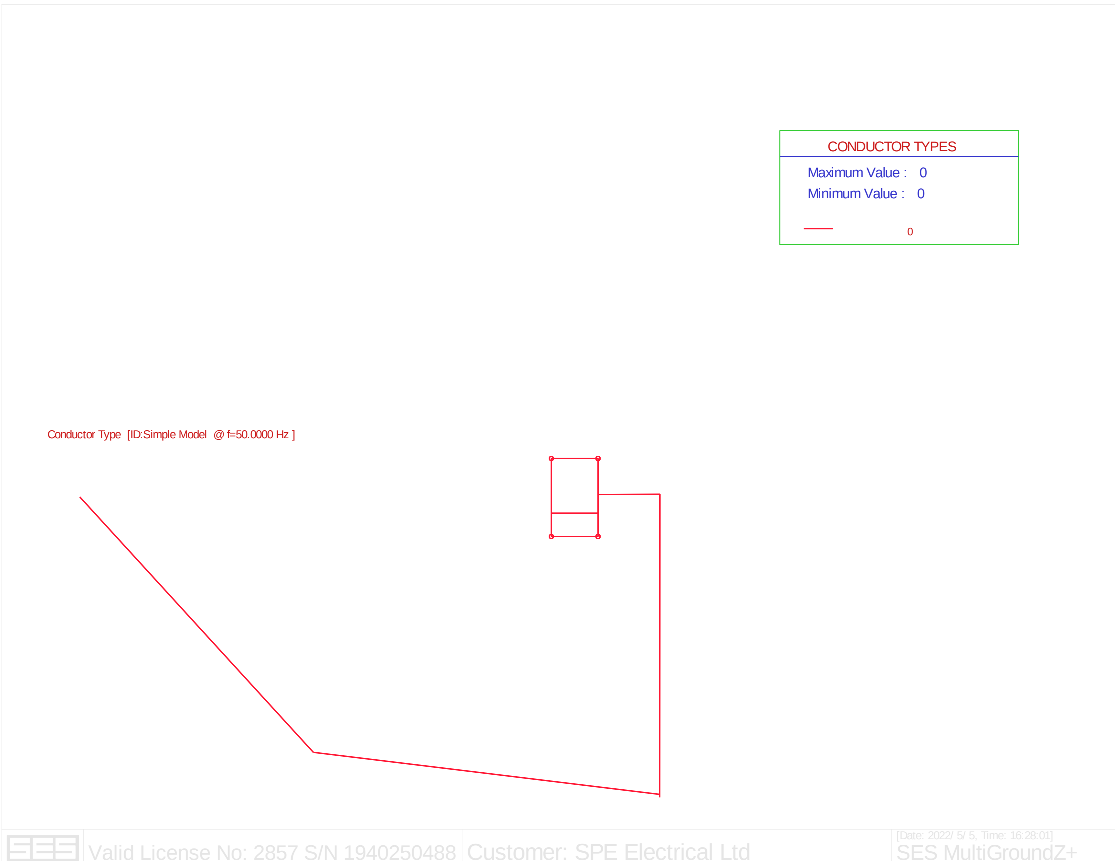


**Figure 3: Preliminary CDEGS Model**

Based on the initial preliminary CDEGS model shown in Figure 3 above, the substation EPR is calculated as 5.2 kV using the MALZ simulation module. This is a very high EPR and is clearly unacceptable. The first design step is obvious, which is to extend the radial earth conductor down the HV trench, all the way back to the Point of Connection. This increases the length to around 220m, and the new EPR is calculated as 2.59 kV. This is a significant improvement, but the site is still classed as High EPR, and the zone of influence of the HV earthing system has now been extended and encroaches on a large number of houses.

This represents both a problem and dilemma to the designer and the developer as the high EPR means that mitigation measures are necessary, but the EPR is just about low enough that it could be managed and contained. However, if the Hot Zone / High EPR contour is plotted around the substation, as shown in Figure 4, then some wider context issues start to emerge.

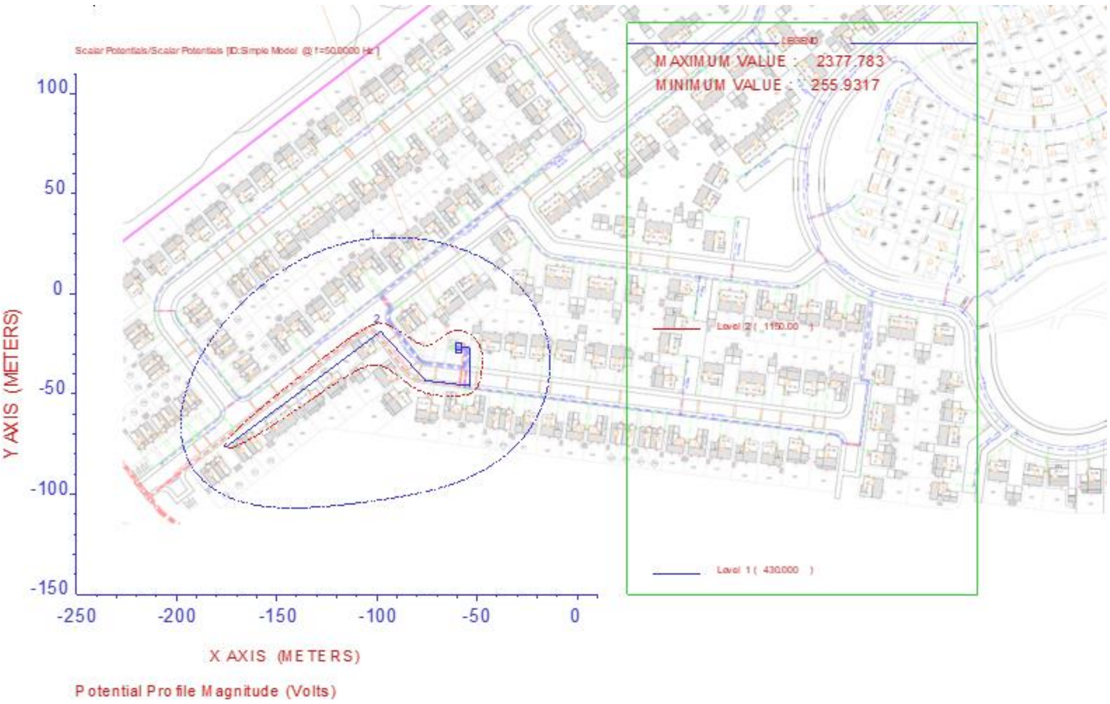


**Figure 4: Hot Zone Contour**

It can be seen that the 1150V+ contour extends around 10m away from the substation and the radial earth conductor and would encroach on a number of the houses. The 430V+ contour extends nearly 30m away from the substation and radial earth conductor and would cover most of the section of the site shown. However, several houses would fall outside of the 430V+ contour.

This presents a problem for the designer. The substation is classed as Hot / High EPR and the zone of influence spreads into the surrounding dwellings, with some falling in the 1150V+ contour, some in the 430V+ contour and some outside both contours. Some significant further design is therefore required to ensure that the site is safe. The area around the substation becomes a high EPR area, but also needs to supply dwellings in the local high EPR area at LV, as well as dwelling outside the high EPR.

A slightly interesting side issue to note, is that there is now a slight disconnect between the new(ish) ENA 41-24 standard and the ENA S36 [4] in relation to Hot Zones. In the previous version of ENA 41-24, the Hot zone threshold for slow protection systems was 430V, and ENA S36 [4] also defined 1150V as the potential zone, where specific mitigation methods are needed. The new edition of ENA 41-24 uses a slightly different method, and the Hot Zone limit is 2x the tolerable touch voltage, which depends on the protection clearance times, but for a 1s fault is now 466V, and the threshold for action is now generally taken as 1200V instead of 1150V. For the sake of convenience, we will continue with the older 430V / 1150V definitions for Hot Zone / High EPR.

A standard mitigation measure required in ENA 41-24 for High EPR sites, that supply external LV systems, is that the HV and LV earths should be separated. Normally, this can be accomplished easily in many cases, as there is sufficient physical space. In the Case Study, the substation location does not easily allow this, as the substation is located in the middle of an area with LV equipment. Specifically, the design needed to consider the following questions:

- Is it possible to make the site cold / low EPR economically?
- Is the substation location suitable?
- Can the EPR be reduced any further by adding in more radial conductor?
- Will adding more radial conductor make the problem worse by extending the High EPR zone?
- If the site is left as High EPR, will the step voltage contours pose a risk, as children who may be barefoot playing in nearby gardens?
- Where will the LV earth be located?
- How will the dwellings inside the 1150V+ and 430V+ contours be supplied and earthed?

At this stage, the design was forced to consider four main options:

1) Keep adding in additional earth conductor to the system to make the site Cold / Low EPR – this is expensive and difficult due to limited space.
2) Try and relocate the substation to an area away from the dwellings.
3) Accept the high EPR site and apply risk and control measures to manage the EPR.

Let us consider the potential solutions in turn.

The first solution is to keep adding in additional earth conductor and rods into the system, in the hope of achieving an earth grid resistance that is low enough that the site classification becomes Cold / Low EPR. With an average soil resistivity of 200-Ωm this is tricky but possible. There is no further space in the HV trench, but the HV earth conductor can potentially be installed in the LV cables trenches. This approach is expensive but potentially the best solution as it ensures the overall system EPR will be low and creates an inherently safe design.

The second solution is to move the substation away from the housing estate area and site it nearer the 11kV supply point. This solution actually increases the EPR, as there is less available space to install radial HV earth conductor without encroaching into the dwellings, but the problem is now sited away from the dwellings, and a high EPR can potentially be contained in specified risk area. The developer would typically have to consider increase LV cable lengths and when supplying the properties, and this may turn out to be more expensive than the first option.

The third solution is to accept the high EPR and then to take mitigation measures. If this approach is followed, the first aspect that must be checked is that the step potentials in the nearby gardens are within the allowable limits, if this is not achieved then the EPR must be reduced. It should be noted here that the step voltage limit for a 1s fault of bare feet on the ground is 2249V, compared with 17.5kV for someone wearing shoes, and is thus much greater. The LV star point of the transformer must be run to a location outside of the 430V+ contour using an insulated cable and a local earthing nest installed.  The houses within the High EPR zone must be supplied with TT earthing to ensure that unsafe touch potentials are not created inside the dwelling. Finally, the site should be recorded on the Hot zone register and other utility companies notified.

The final design approach adopted was (1), where additional earthing conductor was installed through the site in the LV utility cable trenches. The earthing system was extended by a significant amount through the site, as can be seen below in Figure 5. Whilst this approach resulted in some significant extra cost for the developer, the alternative options were considered less favorable. Moving the substation would have resulted in more costs elsewhere and would have resulted in less space available for trying to lower the EPR. Accepting a high EPR site would have been possible, but this would have led to various difficulties in installing the earthing systems and providing all the necessary isolations and risk mitigations. It would also have been hard to justify under the CDM principle of designing out risk.

The design solution was possible because we have assumed that the earthing study was engaged early on before the site had been developed. If the site had already been developed and the earthing study was engaged too late, then the only option would have been to consider a mixture of Option (2) and (3).

The Case Study examined represents what appears to be a very simple scenario of a small low-cost secondary substation in an area of slightly below average soil resistivity, with a typical earth fault level. Many designers could be forgiven for thinking that such a site would be low risk and a standard design would be sufficient, but as the case study has shown, the resolution to make the design safe was far from simple.

It is also important to note that if the same substation had been located in an area with higher soil resistivity, or a part of the network with a higher fault level, then the design constraints and management of the risks become significantly more challenging.

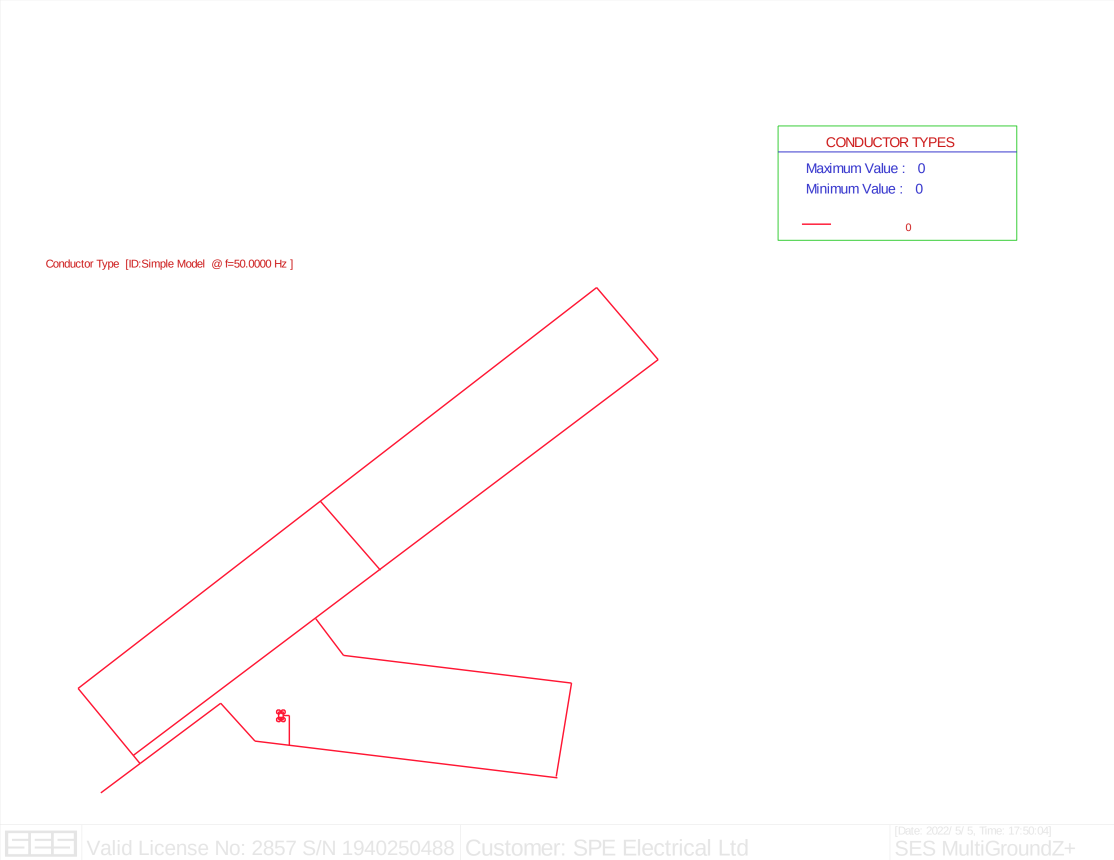


**Figure 5: Final Earthing Layout**

## Summary

It has been shown in this paper that small 11kV substations on a rural network, with average values of soil resistivity and fault level will frequently be classed as Hot / High EPR, due to the small size of the substation coupled with the limited geographic space to install an earth grid and the 100% split factor. These sites are often located near dwellings or industrial units and can potentially pose a significant risk that may not be fully appreciated if a standard design approach is adopted.

The case study showed the context of how the location of a small simple 11kV substation in a new housing estate, created a number of significant problems that could put dwellings and members of the public at risk, even though the initial data for the site may look very reasonable.

## References

[1] ENA TS 41-24 Guidelines for the design, installation, testing and maintenance of main earthing systems in substations
[2] ENA S34 A guide for assessing the rise of earth potential at electrical installations
[3] BS EN 50522 Earthing of power installations exceeding 1 kV a.c.
[4] ENA S36 Identification and recording of 'hot' sites - joint procedure for Electricity Industry and Communications Network Providers