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Earthing Design of 11kV and 33kV Rural Substations in the UK

August 2017

Introduction

- This presentation is intended to give a simple overview of the basics of earthing and its applications to rural 11kV and 33kV substations in the UK.
- The presentation is split into three sections:
  - Earthing Basics and The UK
  - Earthing Theory
  - Examples and Application To Rural Substations
- Thanks for listening – and don’t be afraid to ask questions!

Common Assumptions Can be Dangerous!

- Earthing at 33kV and 11kV substations is simple.
- If normal DNO practice is followed the design will be ok.
- Soil resistivity values can be assumed or don’t matter.
- The Neutral Earthing Resistors on the 11kV and 33kV limit fault levels - so secondary substations will not be classed as hot.
- Fences should always be independently earthed.
- Areas outside the substation do not need to be considered.
- There is no risk of transferred potential.
- HV and LV earths can be combined if the grid impedance is less than 1 Ohm.
- If the earth grid impedance is less than 10 Ohm then the design will be ok.

Earthing Basics and The UK

Earthing Overview

- Earthing is not a ‘black art’ – but it is not simple either!
- Small rural 11kV and 33kV substations can often be problematic to earth safely.
- Problems can arise as the sites are fed entirely, or in part, by overhead line – this provides no return path for the fault current – which is instead injected into the ground.
- When sites are cable fed, problems can still arise if the soil resistivity is poor.
- An effective and functional earthing system is a legal requirement:
  - Electricity at Work Regulations (1989),
  - Electrical Safety, Quality and Continuity Regulations (2002).
- It is easy to get earthing wrong and not realise the problem until too late.

Earthing Overview - Continued

- Some sites are higher risk than others: Livestock, Caravan Sites, Open Air Pools, Areas easily accessible to the public, etc..
- There are lots of standards in the UK, and they can be confusing and conflicting:
  - ENA TS 41-24, ENA S34, BS EN 50522, BS 7671, BS 7354, BS EN 60479, IEEE-80 and IEEE-665,
  - In practice, ENA 41-24 is the defining standard for DNOs within the UK,
  - BS EN 50522 has good guidelines, but it has not been adopted by the DNOs yet.
- The only practical way to carry out earthing studies is to use computer simulation software. CDEGS is the industry standard software.
- Rural substations are not that difficult to design – so it is not expensive!

Hot and Cold Sites

- In the UK we have the concept of ‘Hot’ and ‘Cold’ sites. This refers to the maximum allowable Earth potential Rise (EPR):
  - An EPR above 430V for sites protected with IDMT relays is considered hot,
  - An EPR above 650V for sites protected with differential relays is considered hot,
  - Sites with an EPR below 430/650V are considered cold.
- Hot sites required detailed analysis with software such as CDEGS to prove that the touch and step voltages are safe to operators and the public.
- Cold sites do not require any special design principles and the touch and step voltages are deemed to be safe by inference.
- In Hot sites the HV and LV earths must be separated.

Earthing Design – Simple Overview

- Earthing design is a complex, iterative, process:

    1. Define the initial conditions (fault level, metallic return paths),
    2. Define the local soil conditions,
    3. Calculate the earth grid impedance,
    4. Calculate the Earth Potential Rise (EPR),
    5. If the EPR >430/650V site is 'hot' and a detailed analysis of touch and step voltages is required if the site is cold no further design is necessary,
    6. For 'hot' sites the configuration of the earthing system must be adjusted, to ensure that the touch and step voltages are acceptable – this often requires the need for surface layers like stone chippings, or even tarmac. Several iterations are necessary to get a cost-effective design.
    7. Consideration also needs to be given to fences, and other services like BT and pipelines.

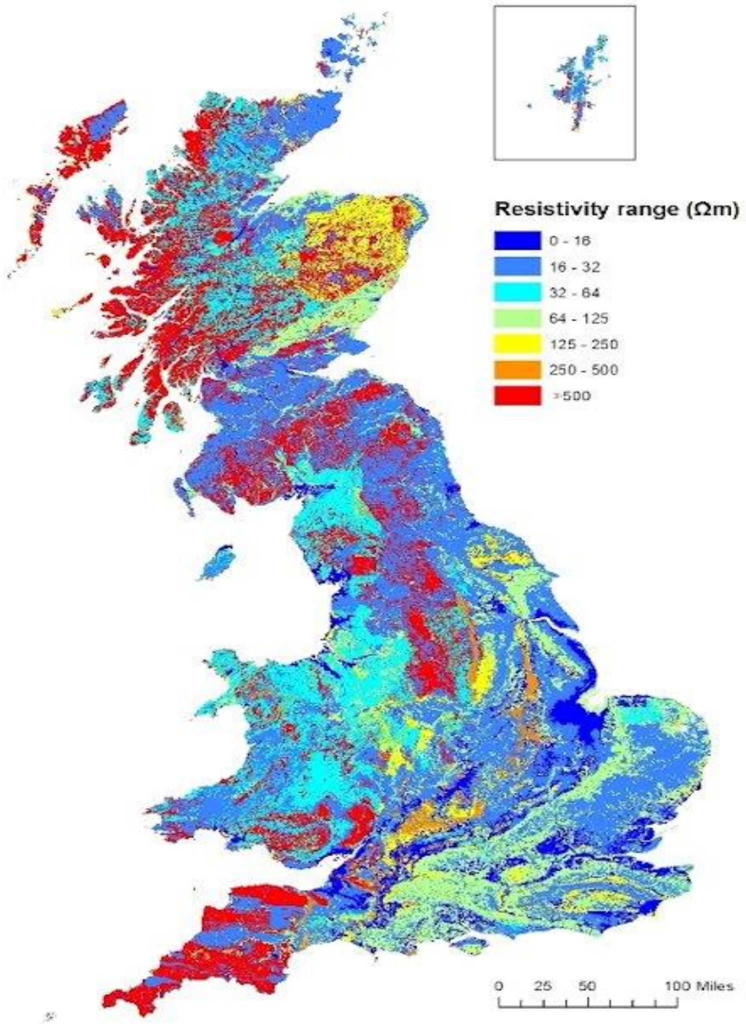
Earthing Theory

Earthing Theory Overview

- Earthing design is a complex area and covers lots of different sub-areas, all of which are important:
  - Soil Resistivity,
  - Earth Grid Impedance,
  - Fault Current Distribution,
  - Earth Potential Rise,
  - Touch and Step Voltages,
  - Tolerable Touch and Step Voltage Limits.

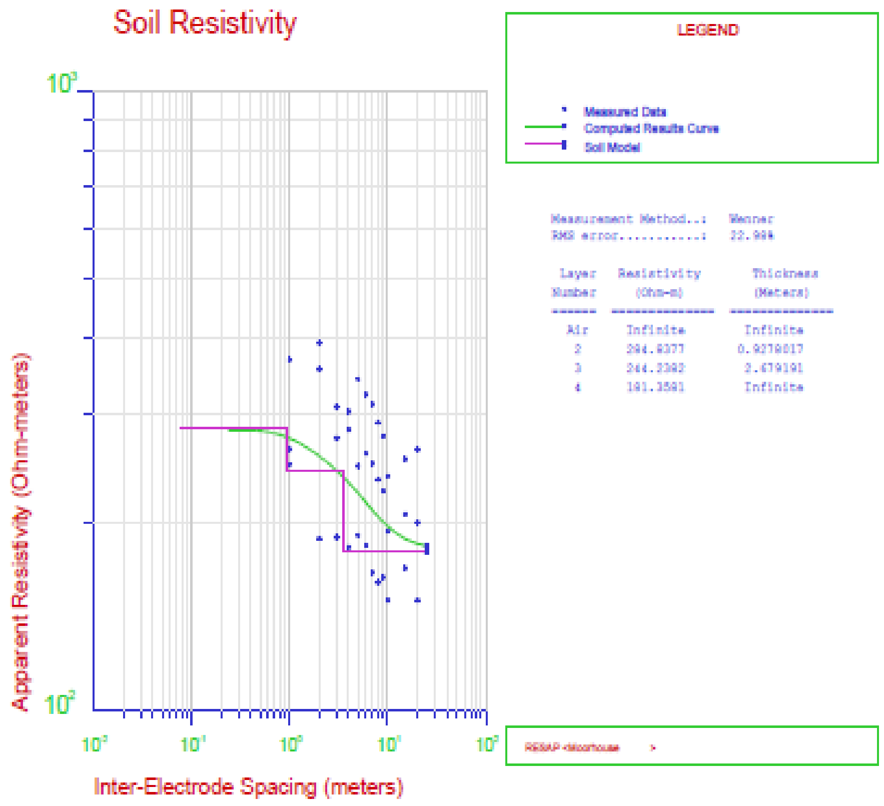
Soil Resistivity - Overview

- The soils ability to conduct electricity (resistivity) is of key importance as it key factor in defining the impedance of the earth grid.
- Soil resistivity survey is always recommended as the UK soil is very varied and can range from very good to very poor.
- There can be considerable changes in only a few hundred meters.
- Most DNOs have a wide range of conditions in their area.
- Because of this variation – standard designs are not always suitable.



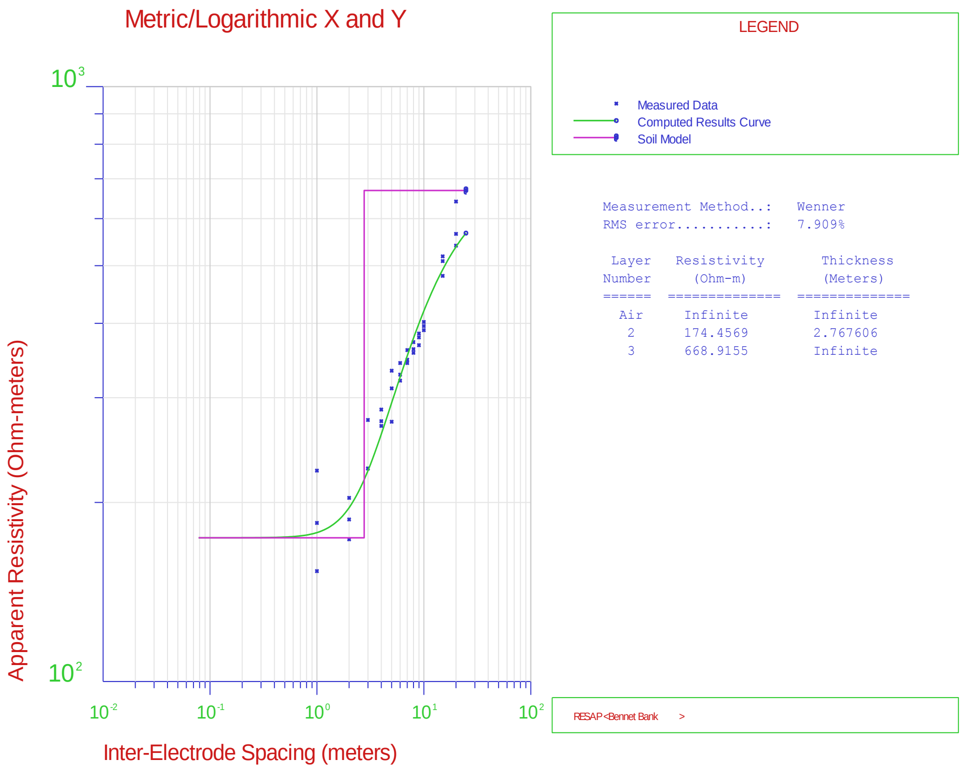
Soil Resistivity - Measurements

- Resistivity measurements should be carried out using a Wenner 4-pin method.
- It is not always possible to measure at the site and sometime it is necessary to use a nearby field or verge.
- Considering how the measurements are taken is important:
  - The probe spacing’s can be a little subjective.
  - BS EN 50522 recommends 1m, 1.5m, 2m, 3m, 4.5m, 6m, 9m, 13.5m, 18m and 27m.
  - BS EN 50522 also recommends 36m, 54m, 80m and 100m spacing’s – but very wide probe spacing isn’t always practical.
  - Take at least 2-3 different readings, along different traverses and average the values.
  - Other nearby earthing systems, buried cables and water courses can throw readings off.



Soil Resistivity – Design Implications

- The soil model is of key interest to the earthing designer:
  - The higher the average soil resistivity values - the harder it will be to get a low earth grid value.
  - Looking at the soil model indicates what type and length of earthing rods should be used.
- On the previous slide you can see that the soil resistivity is average but gets better with depth – so using deep rods of 3.6m length is best.
- On this slide you can see the soil resistivity is average down to 2.4m and then gets very high – indicating a rock layer – so using shallower rods of 1.8m would make most sense.



Earth Grid Impedance

- An accurate understanding of the earth grid impedance is critical to correctly assess the earthing system. The earth grid impedance is a function of:
  - Site soil resistivity,
  - The amount of earthing electrode in contact with the soil.
- A large grid in poor / sandy /rocky soil can be less effective, than a much smaller grid installed in damp loamy soil - a site's location is therefore a critical factor!
- How the earth electrode is positioned in the soil – its depth and proximity to other electrodes influence how effective it is.
- Hand calculations are very difficult and in practice it is necessary to use simulation software.

Fault Current Distribution

- Earth fault current must flow back to the star-point (or earthing transformer) of the source substation. It can do this in two main ways:
    - Through metallic paths such as dedicated earth conductors, overhead ground wires or cable sheaths.
    - Through the general mass of the ground.
- It is only current that flows through the general mass of the ground that gives rise to an Earth Potential Rise (EPR).

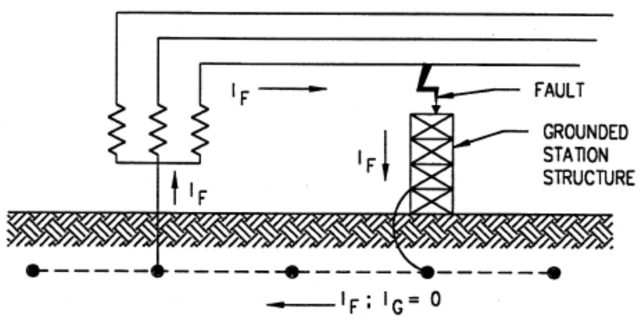


Figure 28—Fault within local substation; local neutral grounded

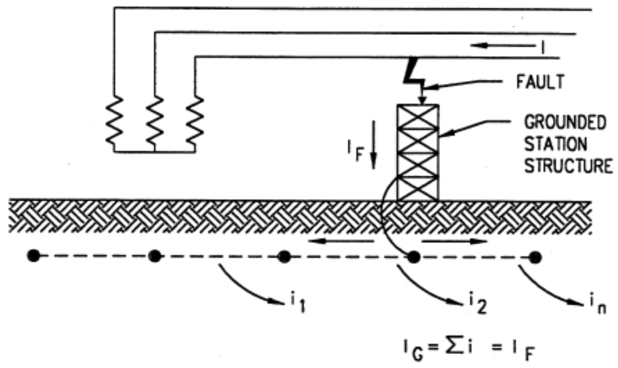


Figure 29—Fault within local substation; neutral grounded at remote location

Fault Current Distribution – Continued

- Presence of a metallic return path means that the fault current will divide between the metallic path and the general mass of ground – this is known as the split or scaling factor.
  - A cable fed substation will have a split factor somewhere between 5% and 40% depending on the cable sheaths and earthing configuration
  - Where a substation is fed via overhead line and has no metallic return path, all the earth fault current with flow through the mass of earth and the split factor will be 100%.
- Be careful though - if a long cable circuit has a small overhead section the metallic path will be broken and a split factor of 100% must still be used.
- Overhead lines can be provided with earth conductors to help reduce the problem - this is common at 132/275/400kV where the earth fault currents are much higher.

Earth Potential Rise (EPR) Calculations

- So what exactly is an Earth Potential Rise? It is the voltage (potential) the ground around a substation rises to during an earth fault.
- The EPR is caused only by the current injected into the ground by the earthing grid. Current flowing back through metallic cable sheaths and earth wires don't contribute.
- EPR is given by the simple equation:
  - $EPR = I_E * Z_E * S_f$
  - Where: I_E = Earth Fault Current; Z_E = Earth Grid Impedance & S_f = Split Factor
- The maximum value of an EPR is the RMS phase-neutral value of the source.
- Hot sites must have the HV and LV earths separated.

Touch and Step Voltages

- Touch Voltages are shocks that can occur by touching a metallic object – they are usually limited to inside the substation, unless there is a risk of transferred potential.
- Step voltages are shocks that can occur to anyone in or near the substation – the public and livestock are particularly vulnerable to these shocks.
- In both cases it is a potential gradient / difference that causes the shock.

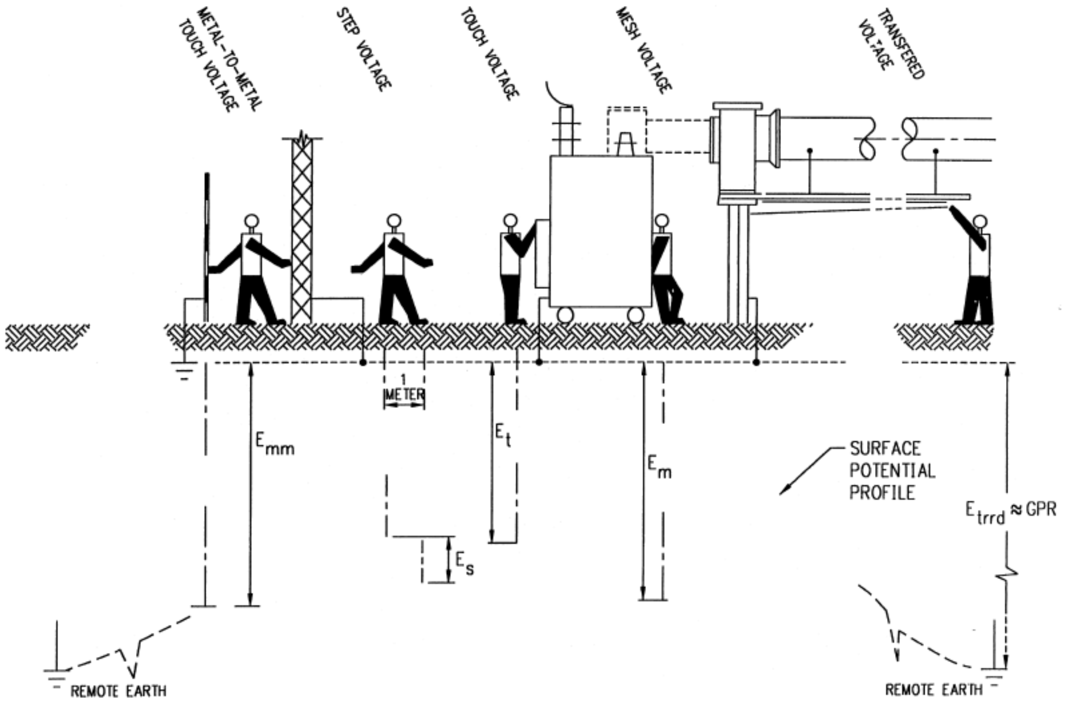


Figure 12—Basic shock situations

Touch and Step Voltages - Continued

- Once the actual touch and step voltages have been calculated it is necessary to determine the tolerable touch and step voltage limits.
- Tolerable limits of touch and step depend on several factors:
  - Shock duration – protection clearing time (usually 0.2s for differential or 1s or 3s for IDMT)
  - Protective footwear and hand-wear.
  - The type of ground they are standing on.
- An adult engineer in rubber boots and with work gloves on standing on stone chipping could withstand a high voltage of several hundred volts, while a small child in bare feet playing near a substation fence could be vulnerable to a shock of 50V or more.
- Putting a surface layer of gravel, or tarmac down helps form a protective barrier.

Touch and Step Voltages - Continued

- There are substantial differences between ENA 41-24 and BS EN 50522 – particularly in relation to step voltages:

Standard	Soil Condition	Maximum Touch Voltage		Maximum Step Voltage	
		1s Protection	3s Protection	1s Protection	3s Protection
ENA 41-24	Bare (1)	150	120	450	360
ENA 41-24	Chippings (2)	200	160	650	520
ENA 41-24	Tarmac (3)	900	720	3450	2760
BS EN 50222	Bare (4)	233	162	17571	11727
BS EN 50222	Chippings (5)	298	205	24083	16074

Notes:

(1) ENA 41-24 is based on 4k Ohm per shoe, 1k Ohm body resistance and no additional ground resistance.

(2) ENA 41-24 is based on 4k Ohm per shoe, 1k Ohm body resistance and 2k Ohm resistance of 150mm gravel.

(3) These values are extrapolated based on (1), but assuming 30K Ohm per shoe based on 100mm tarmac.

(4) BS EN50522 value is based on 4k Ohm per shoe, 1k Ohm body resistance and no additional ground resistance.

(5) BS EN50522 value is based on 4k Ohm per shoe, 1k Ohm body resistance and 2k Ohm resistance of 150mm gravel.

High Risk Areas

- Some areas and situations are considered high risk and need careful management:
  - Substations with a high EPR where the step voltage could extend well beyond the substation boundary.
  - Animals and livestock in close proximity – as these are much more vulnerable to step voltages.
  - Children's playparks, camp sites and swimming areas – as people may be barefoot and more vulnerable to step voltages.
  - Transferred potential due to telephone cables, railways, pipework etc. – this can move the risk to a distant location this is not controlled.
  - Areas where explosive gasses and liquids may be present – this is a specialist area with self evident risks!
  - Copper Theft!

Substation Fences

- Fences are a very important consideration in earthing!
- Standard practice is to earth fences independently from the main earth grid – this is done because of the potential touch shock to the public and/or livestock.
- Where a fence is bonded into the earth grid additional measures are required as it creates a touch voltage hazard. Typically installation of an earth conductor on the outside of the fence perimeter. This helps control the step and voltage gradient profiles at the fence line.
- Independently earthed fences should be at least 2m away from the main earth grid, otherwise voltages can be induced on the fence during a fault.

Earthing Theory - Summary

- The DNO should provide the fault data and confirm if there is a metallic return path.
- Accurate soil resistivity data is the cornerstone of any earthing design.
- Sites fed via overhead lines, or with overhead line sections, pose a much higher risk and will usually be ‘hot’.
- The Earth Potential Rise (430/650V) defines if a site is cold or hot.
- Hot sites need detailed assessment for touch and step voltages.
- Step voltage risks can extend well beyond the substation boundary.
- Touch voltages are usually more dangerous – but usually limited to the substation.
- Some areas can be high risk.
- Fences need special consideration – if they are bonded into the earth grid.

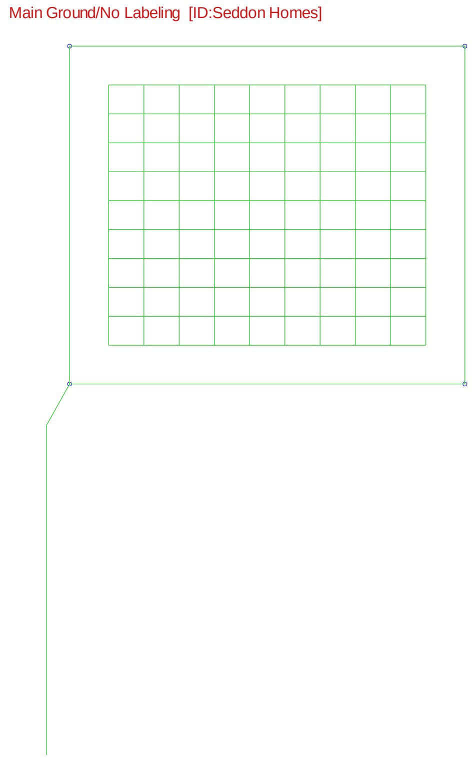
Examples and Applications for Rural Substations

Rural Substation Earthing Considerations

- Rural secondary substations have many issues that can make them difficult:
  - They are usually overhead line fed - so there are no metallic return paths to the source,
  - They can be in remote locations, and soil resistivity can often be poor,
  - Substations are physically small so only have a limited area in which to install an earth grid,
  - Livestock are very susceptible to step voltages – step voltages as low as 50V can be fatal,
  - Step potential zones can extend significantly beyond the substation and into surrounding fields & farmland.
- A few examples of ‘standard’ earthing design can demonstrate the problems

Example Problems – Typical 11kV Substation

- The diagram shows a layout of a typical compact 11kV GRP substation.
- Outer ring of 70mm2 conductor and 4 rods of standard depth, 10m tail in the HV trench plus a layout for the concrete rebar.
- The substation is in a GRP enclosure, so touch risks are only a problem inside.
- Step voltages around the substation could be a problem.
- Limited space available to add more conductor.



Example 1 – Overhead Line Vs. Cable

- Previous substation fed via OHL:
  - No metallic return paths
  - Earth fault level (I_E) of 1500A
  - Fault clearance time of 1s
  - Earth grid impedance (Z_E) of 2 Ohms
  - EPR = $I_E * Z_E * S_F$
  - **EPR = 3000V !!!**
- **The site is hot and could present a significant hazard to personnel and livestock!**

- Previous substation fed via Cable:
  - Metallic return path – scaling factor of 20%
  - Earth fault level (I_E) of 1500A
  - Fault clearance time of 1s
  - Earth grid impedance (Z_E) of 2 Ohms
  - EPR = $I_E * Z_E * S_F$
  - EPR = 300V
- The site is cold and requires no special measures.

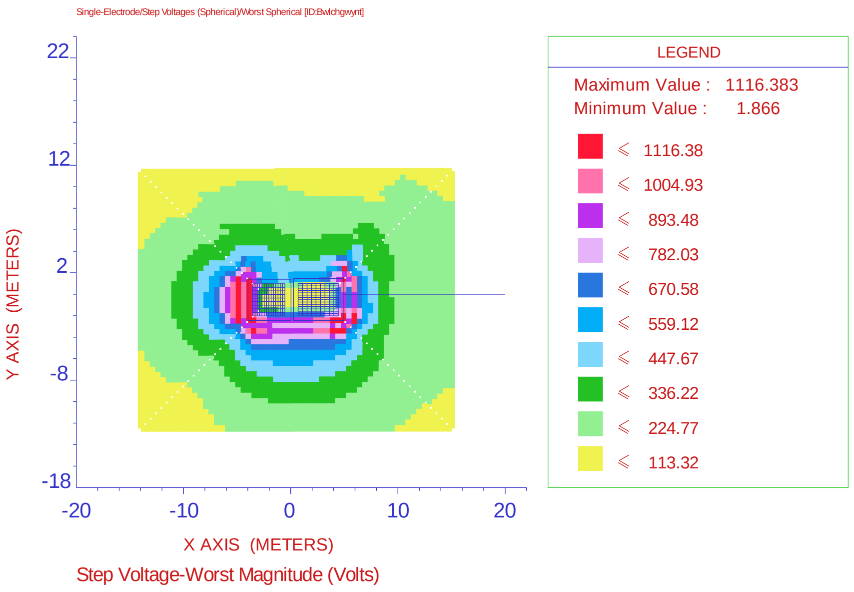
Example 2 – Good and Poor Soil Resistivity

- Previous substation – Good Soil:
  - Metallic return path – scaling factor of 20%
  - Earth fault level (I_E) of 1500A
  - Fault clearance time of 1s
  - Earth grid impedance (Z_E) of 1 Ohms
  - EPR = I_E * Z_E * S_F
  - EPR = 300V
- The site is cold and requires no special measures.

- Previous substation – Poor Soil:
  - Metallic return path – scaling factor of 20%
  - Earth fault level (I_E) of 1500A
  - Fault clearance time of 1s
  - Earth grid impedance (Z_E) of 5 Ohms
  - EPR = I_E * Z_E * S_F
  - **EPR = 1500V!!**
- **The site is hot and could present a significant hazard to personnel and livestock!**

Example – Step Profile of 11kV Rural Substation

- The step profile opposite is very high and can present a real risk.
- If the earth grid impedance cannot be lowered, then it will be necessary to provide a tarmac surface layer immediately around the substation.
- The step voltage falls off to an acceptable value (to humans) in a few meters. But it remains a risk to animals (i.e. >50V) for a much greater distance.



Mitigation Measures

- When faced with a difficult earthing design, the standard approach is to add more conductor and earth rods - this isn't always beneficial as costs can be expensive and rods in proximity to each other have reduced effectiveness.
- Installing a length of bare conductor in the HV trench is usually very helpful.
- There is no fundamental problem with a hot site, provided the risk is controlled.
- Alternative methods to reduce the EPR and touch/step voltages include:
  - Use of protective surface layer,
  - Satellite earthing grid,
  - Mesh plates to control touch voltages,
  - Ground enhancing materials (Bentonite, Marconite etc.),
  - Exclusion Zones around high risk areas.

Livestock Considerations

- Livestock are very susceptible to step voltages:
  - No protective footwear (!!!),
  - Longer step length,
  - Often in wet and muddy fields (i.e. low surface layer resistivity).
- A standard earthing design approach is not sufficient.
- A Step voltage gradient as low as 50V is enough to kill a horse.
- Accidental death of livestock can lead to costs and negative publicity.
- BS EN 60479-4 provides details on fibrillation current for animals.

Summary

- Correct earthing design is a legal responsibility.
- Small rural substations fed via overhead lines will almost always have a high EPR and be classified as ‘Hot’ as can cable fed substations in poor soil conditions.
- Relying on DNO standard designs for a hot site is not appropriate, even for simple 11kV and 33kV substations.
- The zone of influence from a hot rural substation can pose a real risk to personnel and livestock.
- Livestock are very sensitive – a step voltage of 50V can be enough to kill.
- Soil resistivity surveys are always recommended.
- A good earthing design does not just simply add more conductor and rods.

What Next?

- All questions welcome!
- Do you have upcoming projects or existing sites where you think you may have a problem?
- Please contact us to discuss your issue.
  - www.sp-eng.co.uk
  - info@sp-eng.co.uk
- How can SPE help you with your design?