This contains examples and formulae etc which are currently being transferred from 41-24 to S34, or otherwise in limbo…

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Assessment of 'Touch' Potential and Electrode Conductor Length (Text)

Commented [DC1]: Include in S34

When developing formulae for calculating the value of 'touch' potentials, it is normal practice to refer these calculations to the potential of the natural ground surface of the site. From the safety aspect these calculated values are then compared with the appropriate safe value given in Section 4.3 which takes account of any footwear or ground covering (chippings) resistance. It is important, therefore, to appreciate that the permissible safe value of 'touch' potential, as calculated in this section, will differ depending on the ground covering, fault clearance time and other factors prevailing at the site. Allowance is made for this in Figure 2.

The developed formulae (listed in EREC S.34) are not rigorous but are based on the recognised concept of integrating the voltage gradient, given by the product of soil resistivity and current density through the soil, over a distance of one metre. Experience has shown that the maximum values of 'touch' potential normally occur at the external edges of an earth electrode. For a grid electrode this potential is increased by the greater current density transferring from the electrode conductors to ground around the periphery of the grid as compared with that transferring in the more central parts. These aspects have been taken into account in the formulae firstly for 'touch' potential and secondly for the length of electrode conductor required to ensure a given 'touch' potential is not exceeded.

Small Area Outdoor or Indoor Substations (Design Example)

Commented [DC2]: Include example similar in S34

In this example two types of substation are considered:

Ex 1a

[Formerly Fig 7]

This is a 500kVA 11kV combined substation unit (CSU) teed from two 11kV, 3-core, 240mm^2, insulated sheath/armour cables each 1km long, with one cable connected to the 11kV source and the other feeding an open 11kV ring. A cladding enclosure surrounds the CSU and a concrete raft covers the internal area of approximately 2.5 metres square. The declared soil resistivity is 50 ohm m and the maximum calculated fault current is 2,700 amps for an earth fault at the transformer on the 11kV side. For many of the older buried LV cable installations the electrode earthing of the sheath/armour of these cables has been utilised to enhance the substation earthing, thus reducing its resistance. In this example, polymeric LV cables are assumed to be employed which offer no effective contribution to earthing.

The first preliminary design assumes an earth electrode comprising four rod electrodes 3 metres long, 20mm diameter, joined together and bonded to the CSU in two places.

Using the approximate assessment procedure from Section 9.1:

the resistance of the earth electrode is deducible from Engineering Recommendation S34 Table 1 as follows:

$$R = \frac{R'}{N}(1 + k\alpha)$$

$$R' = \frac{\rho}{2\pi l}\left(\log_e \frac{8l}{d} - 1\right)$$

$$= \frac{50}{2\pi \times 3}\left(\log_e \frac{8 \times 3}{0.02} - 1\right) = 16.15 \text{ ohms}$$

N = 4

k = 2.6

$$\alpha = \frac{r_h}{a} \qquad r_h = \frac{\rho}{2\pi R'} = \frac{50}{2\pi \times 16.15} = 0.494$$

and a = 2.5

$$\alpha = \frac{0.494}{2.5} = 0.198$$

$$R = \frac{16.15}{4}\left(\frac{1 + 2.6 \times 0.198}{}\right) = \underline{6.12\ \text{ohms}}$$

Assessment of the rise of earth potential based simply on the product of this resistance and the declared fault current is clearly inaccurate since the fault current alone would be reduced by the substation resistance. Thus a more rigorous evaluation, taking into account also the current returning in the 11kV source cable sheath, is necessary.

Assuming the source resistance to be approximately 1.0 ohm, the ground return current associated with the source 11kV cable is, from Engineering Recommendation S34,

Figure 7 ≈ 0.035 x 2700 = 94.5 amps.

The rise of earth potential = 0.94 x 6.12 = 578 volts

This is in excess of the limit for combined HV/LV earthing.

The second preliminary design assumes an earth electrode comprising a bare stranded earth conductor buried with each 11kV cable for a distance of 40 metres and connected to the CSU equipment.

The resistance of each earth conductor from Engineering Recommendation S34, Figure 4 is:

Rh = 4.0 ohms; thus for two cables R = 2.0 ohms

The ground return current associated with this value of resistance, together with a 1.0 ohm source, is from Engineering Recommendation S34, Figure 7 =: 0.075 x 2700 = 202 amps.

The rise of earth potential = 202 x 2.0 = 404 volts

This is within the limit of 430 volts and thus the LV neutral can be connected to the local earth electrode.

Ex 1b

[Also formerly fig 7]

This is an 11kV 250kVA distribution substation with two 11kV cables with non-insulated sheaths/armours each 500 metres long and three LV distribution cables with non-insulated sheaths/armours each 200 metres long. The main earth grid/earth electrode assessment depends primarily on information ascertained for the preliminary design arrangement. The configuration of the main earth grid is typically a length of buried conductor laid so as to form an earth mat under the operator's feet.

The preliminary design arrangement of electrode as indicated by an examination of the equipment layout etc, is a single 10 metre length of buried conductor connected to an earth plate 915 x 915mm, the mean depth of this plate being 1 metre.

Using the approximate assessment procedure from Section 9.1:

(1) determine local average soil resistivity - 50 ohm metres by measurement;

(2) estimate resistance using formulae given in Engineering Recommendation S34, Table 1.

From column 3 for buried plate:

$$R_p = \frac{\rho}{8r}\left(1 + \frac{r}{2.5h + r}\right)$$

where ρ = soil resistivity (ohm metres)

h = depth to centre of plate (metres)

r = $\left(\frac{A}{\pi}\right)^{1/2}$ (metres)

A = area of plate (metres^2)

$$r = \left(\frac{0.92 \times 0.92}{\pi}\right)^{1/2} = 0.52\text{metres}$$

$$R_p = \frac{50}{8 \times 0.52}\left(1 + \frac{0.52}{2.5 \times 1.0 + 0.52}\right) = 14.1\text{ohms}$$

From Engineering Recommendation S34, Figure 4 for cable sheaths:

11kV cables, earthing resistance = 0.4 ohms each

LV cables, earthing resistance = 0.9 ohms each

From Figure 4 for buried conductor:

10 metres of conductor, earthing resistance = 15 ohms

Total resistance of substation:

$$R_e = \left(\frac{1}{14.1} + \frac{2}{0.4} + \frac{3}{0.9} + \frac{1}{15}\right)^{-1} = 0.12 \text{ ohms}$$

1) determine the total earth current delivered to the substation for an HV earth fault. This is assessed to be 2,700 amperes;

2) determine the rise of earth potential, i.e. 2,700 x 0.12 = 324 volts.

This is below the limit of 430 volts.

There is no need to consider the alleviating factor of current returning via the cable sheaths.

In the finalised design it is required to use a buried conductor of 31.5 x 4mm (from Table 2 4 3 second rating for copper conductor based on a maximum three phase-fault current of 13.2kA).

From Figure 1 the surface current rating for this conductor is 44 amps/metre giving 44 x 10 = 440 amps for the 10 metre length. From Table 3 the current rating of the plate is 1038 amperes. Using the approximate assessment procedure the current distribution to earth through the four electrode elements will be:

$$\frac{324}{14.1} \approx 23 \text{ amperes through the plate}$$

$$\frac{324}{15} \approx 22 \text{ amperes through the buried conductor}$$

$$\frac{324}{0.4} \approx 810 \text{ amperes through each 11kV cable sheath}$$

$$\frac{324}{0.9} \approx 360 \text{ amperes through each LV cable sheath}$$

All these currents are well within the respective electrode surface current ratings. Since the total rise of earth potential does not exceed the limit there are no transfer, touch or step potentials to consider. The finalised design of the earthing system can be prepared.

Application of General Criteria

Examples 1(a) and 1(b) show how calculations are performed to assess rise of earth potential. In many cases it is useful to have available a few simple criteria to enable substation earths at distribution substations to be designed so as to minimise danger without the necessity to perform calculations. Application of these criteria will be appropriate in cases where it has been shown such criteria produce a satisfactory earth mat, for example, substations in urban areas connected to metallic-sheathed cables with no plastic oversheath.

The criteria are as follows:

Substation Metalwork (High Voltage) Earth

The metalwork associated with the high voltage system including the transformer tank shall be connected to an earth electrode or system of electrodes, the value of which should be such that the high voltage protection will operate in the event of a breakdown between either the HV windings of the transformer or the HV line and the supporting metalwork at the transformer position. This does not apply to a high voltage system earthed through a continuously rated arc suppression coil equipped with earth fault alarm facilities.

Substation Neutral Conductor (Low Voltage) Earth

An earth electrode or system of electrodes shall always be installed at or near the substation for the purpose of earthing the LV neutral. The function of this earth connection includes protection in the event of an HV/LV interwinding fault. It is recommended that the value should never exceed 40 ohms.

If required for testing purposes, disconnection facilities in the form of substantial bolted links may be provided in the neutral earth lead at the substation.

Combination of HV and LV Earths

Commented [DC3]: No change needed

[This text removed from 41-24, and replaced with similar clauses. Group to consider whether this needs to be retained / added to S.34]

Where the EPR exceeds 466 V (or 233 V for single point earthed LV systems), the HV metalwork earth and LV earth must be kept separate. The LV neutral should be earthed to a separate earth electrode or electrode system at or near the substation with a resistance to earth not normally exceeding 40 ohms and being outside the appropriate voltage contour.

Several arrangements of HV metalwork and LV earthing arise in practice. Typical methods of bonding and segregating are shown diagrammatically in Figures 1(c) to 1(g). **[Diagrams to be re-done??]**

The minimum separation of the electrodes shall normally be as described in Section **Error! Reference source not found.**.

POLE TYPE SUBSTATIONS (HV/LV)

Pole Type Substation Feeding Overhead Line (Figure 7 1(c))

Segregation of the neutral earth will normally be necessary. This can most conveniently be effected by installing the neutral earth electrode at the first LV pole, a span length away from the transformer pole. If, however, this is not practicable, the neutral should be connected by means of an insulated wire laid underground to a suitable earth electrode outside the resistance area of the HV metalwork earth in an arrangement similar to that shown in Figure 1(d). The insulation in this case should be related to the high voltage supply.

Pole Type Substation Feeding Underground Cable (Figure 7 1(d))

[If the HV EPR exceeds 466 V segregation is required.]

Where segregation of the neutral earth is necessary, this will normally be achieved by connecting the HV metalwork and LV neutral to their respective earth electrodes by means of insulated wire, in accordance with Figure 1(d). Alternatively the neutral may be earthed at a suitable joint located as close as practicable to the substation but outside the resistance area of the HV metalwork earth.

Ground Mounted Substations (HV/LV)

Where the general ground mounted substation supplies a LV underground distribution system containing cables with uninsulated armouring or lead sheathing, the overall earth resistance will be relatively low. In general, the resistance should be calculated or measured using the methods employed in Engineering Recommendation S34 and an estimate of EPR made.

The results of the tests will indicate the action to be taken to separate the earth electrodes.

EPR < 466 V (Figure 7 1(e))

HV and LV metalwork, cable sheaths and LV neutral should all be bonded together in accordance with Figure 3. Modern LV feeder pillars and fused cabinets usually have a combined neutral/earth bar and therefore will not be two separate bars as shown in Figures 3 and 4.

EPR > 466 V (Figure 7 1(f))

If the EPR exceeds safe transfer voltage the HV metalwork earth must be segregated from the LV neutral earth.

This may be achieved by keeping the HV and LV cables well apart and in cases where the separating distance is less than the distance in Section **Error! Reference source not found.**, by wrapping any non-insulated sheathed HV cables with non-hygroscopic insulating tape [or other measures to achieve a suitable withstand voltage].

Where LV cables with non-insulated sheaths are used between the transformer and feeder pillar or fuseboard, it is necessary to provide insulation for the sheaths and armouring by the use of an insulating gland or similar means, at the transformer LV cable box. The metallic shell of the feeder pillar must also be segregated from all non-insulated sheathed cables.

All LV cables with non-insulated sheaths should also be wrapped with non-hygroscopic insulation tape where they are within [segregation distance] of the foundation plinths of any equipment connected to the HV earth electrode.

In the case of a fuse cabinet bolted directly to the transformer (Figure 1(g)), the cabinet itself will inevitably be connected to the HV metalwork earth. The neutral busbar, earth bar if any, and the sheath and armouring of the LV distribution cables will be insulated from the HV metalwork earth and will be connected to the neutral earth electrode by PVC insulated cable. This electrode must be installed at a distance of at least 3 metres from any other metalwork or cable associated with the HV system. However, the distance will depend on the length of electrode used to prevent overlapping. Alternatively, the neutral may be earthed at a suitable joint located as close as practicable to the substation but outside the resistance area of the HV metalwork earth.

Medium Area Outdoor Substation (Ex 2)

Commented [DC4]: Already covered in S34

[Formerly Fig 8]

33kV 20kA distribution substation with two 33kV lines of unearthed construction. The 24MVA 33/11kV CER transformers have directly earthed 11kV neutrals and the 11kV cables are PVC sheathed. The main earth grid/earth electrode assessment depends primarily on information ascertained for the preliminary design arrangement. The configuration of the main earth grid is typically a rectangular loop laid so as to keep the length of connections to equipment to a minimum or alternatively a single bar may be found more suitable.

The preliminary design arrangement of electrode as indicated by an examination of the equipment layout etc., is a single loop of buried conductor (25 x 4mm) in the form of a rectangle some 60 metres x 50 metres. The size and layout of the site is such that the fence can be independently earthed.

Using the approximate assessment procedure from Section 9.1:

(1) determine local average soil resistivity - 20 ohm metres by measurement;

(2) estimate resistance using formula given in Engineering Recommendation S34, Table 1.

From column 5 for buried grid:

$$R = \frac{P}{4r} + \frac{P}{L}$$

where ρ = soil resistivity (ohm metres)

L= length of buried conductors (metres)

A = area of grid (metres^2)

$$r = \left(\frac{A}{\pi}\right)^{\frac{1}{2}} (\text{metres})$$

$$R = \frac{20}{4 \times (955)^{\frac{1}{2}}} + \frac{20}{220} = 0.253$$

(3) determine the maximum value of earth fault current passing through the substation earth electrode system for an earth fault in the substation on the 33kV system which is resistance earthed at source or the value of current returning to the substation for an earth fault on the 11kV system external to the substation, whichever is the greater. This is assessed to be 2550 amperes for an earth-fault on the 33kV system;

(4) estimate the rise of earth potential, i.e. 2550 x 0.253 = 645 volts.

This rise of earth potential is significantly in excess of the 430 volt limit and further consideration of options is required.

For a 33kV earth-fault in the substation the fault resistance will be very low and thus the fault clearance time will also be very low (a small fraction of a second) if busbar protection is fitted. For typically low fault clearance times the above value of 645 volts is well below the permissible limits of touch and step potential derived from Figure 2. Consideration now centres on whether BT services are brought into the substation or whether they lie within the 430 volt contour as defined in Engineering Recommendation S34. If no such services are involved then there may be no necessity to spend more money on earthing. On the other hand, if costs for protecting services are to be incurred then the cost of improving the earth electrode system to remove the need for protection must be weighed against the cost of protection.

If improvement to the earth electrode system is desired then, for this preliminary earth electrode arrangement, the installation of rods around the periphery of the main electrode loop is likely to prove the most cost effective solution. For a first approximation a calculation will be made using 22 rods each 6 metres long, driven around the main electrode loop at 10 metre intervals.

From Engineering Recommendation S34 Table 1, Column 7

$$R = \frac{R_1 R_2 - R_{12}^2}{R_1 + R_2 - 2R_{12}}$$

R_1 = resistance of main electrode loop

= 0.253 ohms

R_2 = resistance of rod group (Column 6)

$$R_2 = \frac{R'}{N}(1 + k\alpha)$$

$$R' = \frac{20}{2\pi \times 6}\left(\log_e\left(\frac{8 \times 6}{0.02}\right) - 1\right) = 3.6 \text{ ohms}$$

N = 22

Column 1 $r_h = \frac{20}{2\pi \times 3.6} = 0.0884 \text{ metres}$

$$\alpha = \frac{0.884}{10} = 0.0884$$

k (Figure 18) = 6.6

$R_2 = \frac{3.6}{22}(1 + 6.6 \times 0.0884) = 0.259$ ohms

$$R_{12} = 0.253 - \frac{20}{\pi \times 220}\left(\log_e\left(\frac{6}{0.008}\right) - 1\right) = 0.09 \text{ ohms}$$

$$R = \frac{0.253 \times 0.259 - 0.09^2}{0.253 + 0.259 - 2 \times 0.09} = 0.0173 \text{ ohms}$$

The rise of earth potential is now 0.173 x 2550 = 441 volts

Although this result is still marginally in excess of the 430 volt limit experience has shown that calculations frequently give a pessimistic result when compared with measurement. It is therefore recommended that as rod installation progresses measurement of the total electrode resistance be made at intervals until a value of say 0.17 ohms is achieved.

The permissible 3 second current rating of a 25 x 4mm conductor is, from Table 2A, 12kA. This is well in excess of the declared earth fault value of 2550 amps and will thus be an adequate conductor.

The 3 second electrode surface current rating can be assessed by assuming that the division of current between the 25 x 4mm buried conductor and the rods is in inverse ratio to their resistance.

The maximum permissible current rating for the buried conductor (Figure 1) = 56 amps/metre and for the rods (Table 3) = 50 amps/metre.

The actual current ratings are respectively:

conductor $= \frac{2550 \times 0.259}{(0.253 + 0.259)} \times \frac{1}{220} = 5.86$ amps/metre

rods $= \frac{2550 \times 0.259}{(0.253 + 0.259)} \times \frac{1}{132} = 9.55$ amps/metre

Both of the above values are well below the permissible ratings and thus the finalised design of the earthing system can be prepared.

Large Area Outdoor Substation (Ex 3)

Commented [DC5]: Review against Case Study 4

[Formerly Fig 9]

400/132kV substation located in a rural area. There are two 400kV (L6) and four 132kV (L4) double circuit overhead lines radiating from the substation which itself has a nominal perimeter dimension of 200 x 150 metres; the 132kV and 400kV systems are connected through auto-transformers.

The main earth grid/earth electrode assessment depends primarily on information ascertained for the preliminary design arrangement. The configuration of the main earth grid is typically a rectangular loop of conductor enclosing all the high voltage equipment and possibly one cross-connection for every substation bay or pair of bays. The considerations are as follows:

(i) soil resistivity tests suggest that a buried grid will provide the most economical way to obtain a low earth electrode resistance. For the purposes of this example additional peripheral earth rods will be installed;

(ii) to secure minimum resistance the loop of buried conductor should be taken as near to the perimeter fence as is practicable but still observing the 2 metre minimum clearance. For some substation layouts (usually very large area substations) this may involve separating it widely in places from the equipment which requires to be connected to it. In smaller substations the designer's problem may be to maintain the necessary 2 metre clearances from an independently earthed fence;

(iii) installing driven rod electrodes can, depending on subsoil conditions, be beneficial, convenient and relatively inexpensive. However, the earth electrode resistance is not significantly lowered by installing additional electrodes if the existing electrodes thereby become crowded. In general, putting additional electrodes inside the periphery of an existing electrode system is unrewarding.

The preliminary design arrangement of electrodes as indicated by an examination of the equipment layout etc, based on a combined interconnected earthing system for the 132kV and 400kV compound, consists of a buried 20 metre mesh grid 0.5 metres deep and made up from 50 x 4mm copper conductor with 3 metre long rods driven around the periphery at 20 metre intervals. The size and layout of the site is such that the fence can be independently earthed.

For this example approximate assessment procedures have shown to be inadequate and thus the refined assessment procedure from Section 9.2 is applied as follows:

(5) determine local average soil resistivity - 100 ohm metres by measurement.

(6) estimate resistance using formulae given in Engineering Recommendation S34 Table 1.

From Column 5 for buried grid = $R_1 \cong 0.28\Omega$

From Column 6 for group of rods in hollow square = $R_2 \cong 1.1\Omega$

From Column 7 for combined grid with rods = $R_g \cong 0.278\Omega$

It can be seen that the buried grid is by far the most effective earth electrode and that the additional rod electrode array provides negligible improvement indicating that the grid electrode has saturated the available ground area. The formulae assume homogeneous solid conditions whereas in practice this is virtually never the case;

(7) determine the value of earth fault current for an earth fault in the substation and deduct the appropriate value of earth fault current supplied by the local transformers (see Engineering Recommendation S34 Section 5) to provide the resulting value of earth fault current returning to remote neutrals. This value is assessed as 30,000 amperes of which 26,000 amperes is supplied from the 400kV system and 4,000 amperes from the 132kV system;

(8) make allowance for any fault current leaving the substation via overhead earthwires or cablesheaths due to induction, i.e. proportion of the above current contributions flowing to ground are from Engineering Recommendation S34 Table 2:

For the 400kV lines $I_{gr(400)} = 26{,}000 \times \frac{69.2\ \underline{/179°}}{100} = 17{,}992\ \underline{/179°}$ amperes

For the 132kV lines $I_{gr(132)} = 4{,}000 \times \frac{70.8\ \underline{/171°}}{100} = 2832\ \underline{/171°}$ amperes

Total current ground $I_e = 17{,}992\ \underline{/179°} + 2{,}832\ \underline{/171°} = 20{,}800\ \underline{/178°}$ amperes

(9) make allowance for the additional shunt resistance of tower footings connected by overhead earthwires, i.e.:

for each 400kV line with tower resistance of 5 ohms $Z_{ch} = 1.22\ \underline{/46°}$ ohms from Engineering Recommendation S34, Figure 5;

for each 132kV line with tower resistance of 10 ohms $Z_{ch} = 1.81\ \underline{/34°}$ ohms from Engineering Recommendation S34, Figure 5.

To a first approximation the combined impedance is:

$$Z_e = \left(\frac{1}{R_g} + \frac{1}{Z_{ch(400)}} + \frac{1}{Z_{ch(132)}} \right)^{-1}$$

$$= \left(\frac{1}{0.28\ \underline{/0°}} + \frac{1}{1.22\ \underline{/46°}} + \frac{1}{1.81\ \underline{/34°}} \right)^{-1}$$

= -$\underline{0.141}\ \underline{/19.9º}$ ohms

(10) calculate the rise of earth potential, i.e. 20,800 x 0.141 = 2.933 volts. This is above the limit of 650 volts.

In order for this value of rise of earth potential to be reduced to the limit of 650 volts, the substation's earth resistance would have to be lowered to $\left(\frac{650}{20{,}800}\right)$ = 0.03 ohms

The laying of further buried conductors within the proposed mesh would have only a small reducing effect due to saturation of the available ground area. For a major effect the additional conductor must be buried externally which is not possible in this case. Similarly, for the homogeneous soil conditions assumed, the putting down of more driven rods would also have only a limited effect. For a major effect they would have to be installed outside and well clear of the mesh, which again is not possible in this case.

In this case the value therefore has been accepted and the consequential effects must be evaluated.

In the finalised design it is required to use a conductor section of 50 x 4.0mm (from Table 2A, 1 second rating for copper conductor based on a maximum single phase fault current of 60kA) and a driven rod diameter of 16mm. The electrode current loading for this size of conductor below ground is 82.0 amperes per metre (from Figure 1) and for a l6mm diameter rod is 38.2 amperes per metre (from Table 3).

Using the above assessment the current distribution to earth through the combined grid with rods will be $\left(\frac{2933}{0.28}\right)$ = 10,475 amperes.

The highest current density to be dissipated by the grid and rod electrodes will occur around the peripheral edge of the grid. This can be determined by applying the k_d factor given in Section 9.3.1 as follows:

current density at edge of grid = average current density x k_d

$$= \frac{10475}{3450 + 108} \times \left(0.7 + 0.3\frac{(3450 + 108)}{(700 + 108)}\right)$$

= 5.95 amps/metre

This current loading is well within the permissible current loadings of either the grid conductor at 82 amperes/metre or rods at 38.2 amperes/metre.

Since the total rise of earth potential well exceeds the 'transferred' potential limit of 650 volts, an evaluation of the 'touch' potential is necessary.

(11) Estimate the 'touch' potential, using formulae given in Section 9.3.

The 'touch' potential, at the edge of the grid (Figure 3A) is given by:

$$E_{tgrid} = \frac{k_e.k_d.\rho.l}{L}$$

Where $k_e = \frac{1}{\pi}\left(\frac{1}{2}\log_e\left(\frac{0.5}{0.034}\right) + \frac{1}{(2\times0.5)} + \frac{1}{(0.5+20)} + \frac{1}{20}(1 - 0.5^{12-2})\right) = \underline{0.778}$

$$k_d = 0.7 + 0.3\left(\frac{3450+108}{700+108}\right) = \underline{2.02}$$

$$E_{t(grid)} = \frac{0.778 \times 2.02 \times 100 \times 10475}{(3450 + 108)} = 463 \text{ volts}$$

The ‘touch’ potential at the separately earthed fence (Figure 3A) is given by:

$E_{t(fence)} = \frac{k_f . k_d . \rho . I}{L}$ where $k_f = 0.26\ k_e = \underline{0.202}$

and $k_d = \underline{2.02}$

$$E_{t(fence)} = \frac{0.202 \times 2.02 \times 100 \times 10475}{(3450 + 108)} = \underline{120 \text{ volts}}$$

The 400kV and 132kV systems are designated 'high-reliability' systems having fault clearance times not exceeding 0.2 seconds. From Figure 2 the minimum safe 'touch' potential for t = 0.2 seconds is 1,750 volts which is well in excess of the above calculated values. Thus the earth electrode satisfies all the touch and step potential safety requirements and the final design of the earthing system can be prepared. It is noted that the rise of earth potential is 2,933 volts and therefore precautions are required to protect staff and equipment from transferred potentials.

The Use of Design Assessment to Achieve Acceptable 'Touch' Potentials (Ex 4A and Ex 4B)

Commented [DC6]: Not to be put in S34 – already covered

[Formerly Fig 10]

The following is a practical, although non-typical, example which demonstrates some of the procedures and processes of evaluation.

Consider a small area 400kV substation (Figure Ex 4A) with an evaluated single-phase earth-fault current to ground of 20,000 amperes. The outside dimensions of the earth mat are 80 metres x 80 metres and this contains 16 meshes made up from 50mm x 4mm copper conductor buried 0.5 metres deep.

Soil resistivity = 100 ohm metre

From Section 9.3

'touch' potential at the edge of the grid (Figure 3A) is given by:

$$E_{t(grid)} = \frac{k_e . k_d . \rho . I}{L}$$

where $k_e = \frac{1}{\pi}\left(\frac{1}{2}\log_e\left(\frac{0.5}{0.034}\right) + \frac{1}{(2\times0.5)} + \frac{1}{(0.5+20)} + \frac{1}{20}(1-0.5^3)\right) = \underline{0.776}$

$$k_d = 0.7 + 0.3\left(\frac{800}{320}\right) = \underline{1.45}$$

$$E_{t(grid)} = \frac{0.776 \times 1.45 \times 100 \times 20{,}000}{800} = \underline{2{,}813 \text{volts}}$$

‘touch’ potential at the separately earthed fence (Figure 3A) is given by:

$E_{t(fence)} = \frac{k_f . k_d . \rho . I}{L}$ where $k_f = 0.26$ $k_e = \underline{0.202}$

and k_d = $\underline{1.45}$

$$E_{t(fence)} = \frac{0.202 \times 1.45 \times 100 \times 20{,}000}{800} = \underline{732 \text{volts}}$$

The 400kV system is designated a 'high-reliability' system having a fault clearance time not exceeding 0.2 seconds. From Figure 2 the safe 'touch' potential for t = 0.2 seconds is 1030 volts and although the 'touch' potential at the fence (732V) is well below this value the grid 'touch' potential (2183V) exceeds this value and also exceeds the higher value of 1400 volts allowed when surface chippings are applied. Thus the earth mat of Figure Ex 4A does not satisfy all the criteria.

To improve this situation the following options or combinations of them may be available:

(i) increase the mesh density in the existing grid;

(ii) drive ground rods around the periphery of the existing grid;

(iii) expand the area occupied by the grid by bonding-in an additional buried peripheral conductor one metre beyond the substation fence. For this option it will then be necessary to also bond the fence to the grid thus over-riding the normal practice of independently earthing the fence;

(iv) expand the ground area of the substation and the grid if it is desired to retain an independently earthed perimeter fence.

If for option (i) the grid density is doubled, i.e. the mesh size is halved to 10 metres, the new 'touch' potentials

(Figure 3A) would be:

new $k_e = \frac{1}{\pi}\left(\frac{1}{2}\log_e\left(\frac{0.5}{0.034}\right) + \frac{1}{(2\times 0.5)} + \frac{1}{(0.5+10)} + \frac{1}{10}(1-0.5^7)\right) = \underline{0.808}$

new $k_d = 0.7 + 0.3\left(\frac{1120}{320}\right) = \underline{1.75}$

$$E_t = \frac{0.808 \times 1.75 \times 100 \times 20{,}000}{1120} = \underline{2{,}525 \text{volts}}$$

$$E_{t(fence)} = \frac{0.26 \times 0.808 \times 1.75 \times 100 \times 20{,}000}{1120} = \underline{656 \text{ volts}}$$

This has resulted in a relatively small decrease in the 'touch' potentials, approximately 10%, but has not yet achieved the aim and is expensive.

If, for option (ii), soil resistivity surveys indicate the presence of low resistivity soil at reachable depths by rods driven around the periphery of the grid then, due to their ability to distribute the fault current deep into the soil, a significant reduction in all the potentials can often be achieved. Evaluations of the ground voltage profile for these conditions is highly complex and is considered impractical for presentation in this document. In such circumstances a trial and measurement procedure is recommended.

If the soil resistivity remains sensibly constant with depth and 16 rods each 5 metres long are installed around the periphery of the grid, the touch potentials at the grid and fence reduce to 2550 volts and 664 volts respectively. This still does not meet the safety criteria but by using 10 metre rods or doubling up the number of 5 metre rods results in acceptable values of 2235 volts and 582 volts respectively if surface chippings within the substation are also used. For small grid areas, such as in this example, a significant reduction of potential may be practical with moderate length rods, but for large grid areas rod lengths required can become impractical.

Where it is impractical to drive long rods or it is desired to make a greater reduction in the grid touch potential, option (iii) will give the following result. See Figure Ex 4B.

The new parameters for this arrangement (Figure 3C) are:

$$k_{fe} = \frac{1}{\pi}\left(\frac{1}{2}\log_e\left(\frac{0.5}{0.034}\right) - \frac{1}{4}\log_e(3^2 + 0.5^2)^2 + \frac{1}{4}\log_e(3^4 + 3^2)\right) = \underline{0.432}$$

L = 1204 metres

Lp = 344 metres

$$k_d = 0.7 + 0.3\left(\frac{1204}{344}\right) = \underline{1.75}$$

$$E_{t(fence)} = \frac{0.432 \times 1.75 \times 100 \times 20{,}000}{1204} = \underline{1{,}256 \text{volts}}$$

This value of fence 'touch' potential is much higher than the original isolated fence value of 779 volts or of the option (i) value of 637 volts or option (ii) values of 664 volts and 582 volts but it is well below the declared safe value of 1,750 volts and therefore is acceptable.

It is instructive to observe the resulting change in resistance and hence overall rise of station earth potential due to the addition of the peripheral grading conductor.

From Engineering Recommendation S34 the resistance of the original grid electrode is given by:

$$R = \left(\frac{\rho}{4r} + \frac{\rho}{L}\right) \quad \text{where } r = \left(\frac{\text{Area of grid}}{\pi}\right)^{1/2}$$

(i) For the original 80 x 80 grid:

L = 800 metres

$$r = \left(\frac{80 \times 80}{\pi}\right)^{1/2} = 45.1 \text{metres}$$

$$R = \frac{100}{4 \times 45.1} + \frac{100}{800} = \underline{0.679} \text{ohms}$$

total rise of earth potential = 20,000 x 0.679 = <u>13,580 volts</u>

(ii) or the expanded 86 x 86 metres grid:

= 1204 metres

$$r = \left(\frac{86 \times 86}{\pi}\right)^{1/2} = 48.5 \text{metres}$$

$$R = \frac{100}{4 \times 48.5} + \frac{100}{1204} = \underline{0.599 \text{ohms}}$$

total rise of earth potential = 20,000 x 0.599 = <u>11,980 volts</u>

Thus, although the provision of the peripheral grading conductor has reduced the maximum touch potential considerably (2991 down to 1346 - by approximately 55%), the rise of station earth potential has been reduced by approximately 12% only. For such unusually high values of station rise of earth potential some further reduction in these potentials would likely be sought. In this event rod electrodes located around the periphery of the grid electrode would provide a significant reduction.

Substation with Seperately Earthed Fence

[Agreed to move all examples with formulae to S34. Formerly Fig 3]

Perhaps include here a diagram showing potential contours?

For normal buried grid depths (typically 0.5 metres):

$$E_{t(grid)} = \frac{k_e.k_d.\rho.I}{L} \text{(volts)}$$ Orw here Col 1 $$L = \frac{k_e.k_d.\rho.I}{E_{touch}} \text{(metres)}$$

(i) External Touch Potential at the Edge of the Electrode (Figure 3A)

k_e is a factor which allows for the effect of a uniformly distributed electrode current over the grid and is given by:

$$k_e = \frac{1}{\pi}\left(\frac{1}{2}\log_e\frac{h}{d} + \frac{1}{2h} + \frac{1}{(0.5+D)} + \frac{1}{D}(1-0.5^{n-2})\right)$$

h = grid depth (metres)

d = equivalent diameter of conductor

$$= \frac{\text{circumference of conductor}}{\pi} \text{(metres)}$$

D = average spacing between parallel grid conductors (metres)

where n_A = number of parallel grid conductors in one direction

where n_B = number of parallel grid conductors in the other direction

k_d is a factor which modifies ke to allow for the non-uniform distribution of electrode current and is given by:

$$k_d = \left(0.7 + 0.3\frac{L}{L_p}\right)$$

where L = total length of buried electrode conductor including rods if connected (metres)

L_p = perimeter length if buried electrode conductor including rods if connected (metres)

ρ = soil resistivity (ohm metres)

I = total current passing to ground through electrode (amperes)

E_{touch} = resulting ‘touch’ potential or, when assessing length L, the safe ‘touch’ potential from Figure 2

Commented [DC7]: Already covered in S34

(ii) External 'Touch' Potential at the Fence (Figure 3A).

The ground current density is significantly diminished at the fence to that at the edge of the grid electrode. As a result, a new factor, k_f, based on a two metre separation between fence and grid electrode, is applied in place of k_e in the above formulae.

Hence:

$$E_{t(fence)} = \frac{k_f . k_d . \rho . I}{L} \text{(volts)} \quad \text{or} \quad L = \frac{k_f . k_d . \rho . I}{E_{touch}} \text{(metres)}$$

where $k_f = 0.26k_e$

Substation with Integrally Earthed Fence

Commented [DC8]: Not to be included in S34, formula already in Appendix

[Discuss whether example (overview) should remain in 41-24. ALL CALCULATIONS TO MOVE TO S34]

There are two situations to be considered here. The first assumes that the fence is situated at the edge of the substation electrode whilst the second allows for a further peripheral electrode conductor buried half a metre below the surface at a distance of one metre beyond the fence and regularly bonded to it at intervals as recommended in Section 11.2.2:

(i) External Touch Potential at Fence with No External Peripheral Electrode (Figure 3B)

$E_{t\,(fence)}$ is the same as $E_{t\,(grid)}$ in (i) above.

(ii) External Touch Potential at Fence with External Buried Peripheral Conductor 1 Metre away from Fence (Figure 3C).

$$n = (n_A \times n_B)^{1/2}$$

$$E_{t(fence)} = \frac{k_{fe}.k_d.\rho.I}{L}(\text{volts}) \text{ or } L = \frac{k_{fe}.k_d.\rho.I}{E_{touch}}(\text{metres})$$

where $k_{fe} = \left(\frac{1}{2}\log_e\frac{h}{d} - \frac{1}{4}\log_e(S^2+0.5^2)^2 + \frac{1}{4}\log_e(S^4+S^2)\right)$

h and d as given under Section 9.3.1

S = distance between the outermost buried grid conductor and the next nearest parallel conductor (metres).

Electrode resistance tables

Commented [DC9]: Not needed in S34

Table 1 – Electrode Resistance Values for 2.4 m Rods

Soil Resistivity (ohm m)	No. of 2.4m Rods in Parallel, Spaced 3.6m Apart									
	1	2	3	4	5	6	7	8	9	10
	Earth Electrode Resistance (ohms)									
10	4	2.3	1.6	1.3	1.0	0.90	0.79	0.70	0.63	0.58
20	8	5	3	3	2	1.8	1.57	1.4	1.27	1.16
30	12	7	5	4	3	3	2	2	1.9	1.7
40	16	9	6	5	4	4	3	3	3	2
50	21	11	8	6	5	4	4	4	3	3
60	25	14	10	8	6	5	5	4	4	3
70	29	16	11	9	7	6	6	5	4	4
80	33	18	13	10	8	7	6	6	5	5
90	37	21	15	11	9	8	7	6	6	5
100	41	23	16	13	10	9	8	7	6	6
125	51	28	20	16	13	10	10	9	8	7
150	62	34	24	19	16	13	12	11	10	9
200	82	46	32	25	21	18	16	14	13	12
250	103	57	40	32	26	22	20	18	16	15
300	124	68	49	38	31	27	24	21	19	17
500	206	114	81	63	52	45	39	35	32	29
1000	412	228	162	127	105	90	79	70	63	58
2000	823	456	323	253	210	180	157	140	127	116

Table 2 - Electrode Resistance Values for 1.2m Rods

Soil Resistivity (ohm m)	No. of 1.2m Rods in Parallel, Spaced 1.8m Apart									
	1	2	3	4	5	6	7	8	9	10
	Earth Electrode Resistance (ohms)									
10	7	4	3	2	1.9	1.64	1.44	1.29	1.17	1.07
20	15	8	6	5	4	3	3	3	2	2
30	22	12	9	7	6	5	4	4	4	3
40	29	16	12	9	8	7	6	5	5	4
50	37	20	15	12	10	8	7	6	6	5
60	44	25	18	14	11	10	9	8	7	6
70	51	29	20	16	13	11	10	9	8	7
80	59	33	23	18	15	13	12	10	9	9
90	66	37	26	21	17	15	13	12	11	10
100	73	41	29	23	19	16	14	13	12	11
125	91	51	37	29	24	21	18	16	15	13
150	110	61	44	35	29	25	22	19	18	16
200	146	82	59	46	38	33	29	26	23	21
250	183	102	73	58	48	41	36	32	29	27
300	219	123	88	69	57	49	43	39	35	32
500	366	205	146	115	96	82	72	64	58	53
1000	732	410	293	230	191	164	144	129	117	107
2000	1463	820	586	461	382	328	289	258	233	214

Comments received

Comments received which group decided are more relevant to S34:

WPD 33: Single layer or uniform models may be incorrect with regard to touch voltage assessment and Hot Zone contour assessment.

Suggest: Multi-layer soil models and computer modelling may offer more effective / optimal**/accurate** designs than typical or 'homogeneous' soil models**. Note that safety voltages and voltage contours calculated using 'homogeneous' soil models may be inaccurate.** Except for… [REJECTED – refer this to S.34]

41-24 mentions: "*Limiting values of surface current rating calculated (from formula described in EREC S34 formula XXX*"

[**NOTE: currently S34 does not include these formulae or limits**]. Surface current density calculations and limits to be included in S34.)

Commented [DC10]: Already covered

Commented [DC11]: Include formula in S34 ex 41-24 scetion 8.3.2

Risk assessment (highlighted for removal from current draft of 41-24)

This is just a brief introduction and needs further development. The whole of this 584 *section will be placed in TS 41-24 eventually.* 585

It can be extremely expensive to control the risks of damage, shock or electrocution to levels 586 that are risk free. It is recognised in new standards that risks must be accepted in order to 587 provide electrical infrastructure to society. As set out in BS EN 50522, (BS EN 50522 : 2010 - 588 Earthing of power installations exceeding 1 kV a.c., 2010) risk assessment is one of the 589 acceptable tools for analysis of situations where the cost of removing an identified risk 590 appears to be disproportionately high. 591

When an earth fault creates a significant EPR within an installation, the following four 592 scenarios need to be considered: 593

Injury or shock to persons within the installation 594

At locations where a person is expected to be both working and in contact with earthed metal 595 (for example operating circuit breakers within a switchroom, a switching device in an outdoor 596 area or working on a power transformer), the earthing system must be designed to control 597 safety voltages such that they are below the acceptable threshold. The only unforeseeable 598 risks are associated with a defective earthing installation or failure of the protection 599 equipment. The design is expected to provide a high safety factor at such locations. For less 600 frequently occupied areas or intermittent tasks where the safety thresholds may be 601 exceeded, the risk should be managed by control measures (such as approved procedures, 602 permanent barriers and notices etc.) If these are still not initially deemed acceptable, the 603 decision on whether to carry out design improvements or accept the risk of an incident can be 604 aided by use of the risk assessment method described in BS EN 50522 A2. These examples 605 ENA Engineering Recommendation EREC S34 Draft Issue 2 2014 Page 25 are presently quite simplistic and would need further development for widespread application. 606

Injury or shock to persons and animals (if applicable) outside the installation 607

These can be introduced by metallic transfer (fence, pipe, cable) or via the soil. Where a 608 transferred potential can occur due to metallically conductive means, that eventuality should 609 be removed by the introduction of insulation or other protective measures (examples include 610 insulated sections introduced into external metal fences.) Where metal fences are bonded to 611 the substation earthing system, the touch and step potentials external to them must be 612 controlled by the design, such that they are within the acceptable limits. In other words, most 613 risks should be managed by design. An ideal application for risk assessment is coated type 614 fencing (such as expanded metal) where parts of the coating may degrade over time. Where 615 HV and LV earthing systems are combined, the EPR is transferred from the installation into 616 domestic, commercial or industrial properties and must be at a level such that there is no risk. 617 *(We consider some research is needed to determine the threshold voltage for this from a* 618 *safety perspective (at present it is 430V – an ITU equipment limit value)).* Issues include 619 identification of the realistic shock scenarios in a range of property types and the probability 620 of this occurring and risking electrocution at a range of voltage levels. Where HV and LV 621 systems are combined, the EPR (or part of it) will transfer to the LV system. 622

For potentials transferred via the soil, the risk is related to the EPR magnitude (together with 623 proximity of the person, animal or property to the installation), the likely presence of humans 624 or animals and the degree/time of exposure. If the substation has an elevated EPR, obvious 625 concerns are shock risk to humans who do not have appropriate footwear (beach-side or 626 camping site locations) and electrocution to animals (such as a horse – especially one that is 627 being trained/ridden at the time). 628

Some guidance is needed for areas within the 430V contour – i.e. are there elevated risks or 629 is it an irrelevant contour in relation to human safety. The situation here is related to safe 630 touch and step potentials, not equipment thresholds. For example – risk of shock in a house 631 (similar scenario to the HV/LV bonded issue at a distribution substation), risk of shock in a 632 field, risk of shock to a horse whilst being ridden in an adjacent field. 633

Damage to equipment within the installation

This is generally covered by design practice and the need to meet the requirements of documents such as EREC S36. For example, the use of isolation units of appropriate voltage withstand on communication and protection circuits. It would be useful to have an element of risk guidance in this area too – for example, if the isolation equipment is matched to normal operating conditions, what is the risk of this being exceeded?

Damage to equipment within properties outside the installation

Communication equipment issues covered by EREC S36. (S36-1 : Identification and Recording of Hot Sites - Joint Electricity / British Telecom Procedure, 2007)

Again – some of this is covered in EREC S36 – especially for telecommunication cables and equipment. What is less obvious is the quantified risk of damage to non-communication equipment or items that are not apparent from an initial survey. These may include metal gas pipes, railway signalling, equipment within farm outbuildings etc.