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Issues That Can Arise With The Ground Grids Of Substations Constructed On Step-Like Terrain

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***Abstract*— Electrical power transmission from one location to another is facilitated by the construction of long transmission lines and substations. Substations are an essential part of the power transmission system, in which control and switching functions are carried out for a seamless flow of power. The reliable grounding system plays a critical role in the safety of personnel and operation of substation equipment during faulty conditions. At the utility end, substations with different voltage levels are essential. However, due to urbanization, utilities are experiencing a scarcity of uniform-levelled land for substation construction.**

As a result, many utilities in southern India have resorted to the construction of substations in step-like soil surface with 2-3 m height differences between different equipment bays. The ground grids of different bays in such constructions are at different relative heights, which is quite different from that of normal substations constructed in uniformly levelled land. Therefore, it is important to carefully scrutinize the performance of the ground grids of such special constructions. Soil resistivity normally decreases with depth, but there are certain cases where it can increase considerably with depth. As expected, the former would not pose any increase in the net grounding resistance, but the latter can. To quantitatively assess the situation, using the usual two-layer soil stratifications, evaluation of the grounding resistance along with the step potential is carried out in this work. It is then shown that the grounding resistance evaluated from the formulae for a levelled soil surface can significantly underestimate the grounding resistance evaluated for a substation grounding with a step-like soil surface.

Keywords—grounding, ground resistance, numerical method, soil, step-like land, substations, step potential

I. INTRODUCTION :

Electric power transmission utilities find air-insulated substations to be an economical choice for transmitting power. A large land area of nearly 400 m × 250 m and 200 m ×150 m is required for the construction of substations of 400 kV and 220 kV classes, respectively. Due to urbanization and the increased cost of land, it is difficult to obtain such a large amount of levelled land for the construction of substations indicated above. The utilities in South India are constructing 10-15% of substations in the uneven or tapered land made available with tailor-made arrangements accommodating equipment bays at a height difference of 2-3 m from one level to another. The total land area will not be fully levelled because levelling the whole area may not be technically feasible, as cutting and filling of the area may result in loosening of its original strength and may not be suitable for moving and installing heavy equipment such as transformers. Moreover, the levelling of large land areas is not only technically viable, but also economically it increases the cost of substation construction [1]. This aspect of techno-economic consideration which favours the construction of substations in step-like soil surfaces with tailor-made designs of different equipment bays at relative heights of 2–3 m, has been analyzed [1].

In such substations, ground grids of different equipment bays, in contrast to substations normally constructed in levelled land, will be at different relative heights of 2 to 3 m with stone retaining walls at the end of each bay. The ground grid conductors of the different equipment bays were interconnected to form a single ground grid. This calls for careful scrutiny of the performance of such ground grids, as there is a difference in height between the bays and a stone retaining wall at the end of each step. For normal constructions, in which the whole substation would be over a uniform soil surface, the method for the design and quantification of the performance of grounding grids have been well documented in the relevant international standards [2]. However, in the literature, such ground grids in steps such as land terrain are scarcely dealt with, except for isolated work. An example of such a substation constructed in a step-like terrain having a level difference of nearly 3 m from one level to another level of the equipment bay is shown in Fig.1:

Fig. 1 A 220 kV substation in Mysore, Karnataka, India with different bay at different heights (Courtesy: KPTCL, Karnataka, India).

Reliable grounding is very important to ensure the safety of the personnel working in the substation and for the proper operation of the protective relays and breakers. Therefore, the grounding grid needs to be analyzed carefully to avoid any step and touch voltage limit violations for non-conventional constructions, such as substations constructed over step-like soil surfaces.
It is well documented that, the soil resistivity varies with soil depth. Generally, the lower layers of soil have greater moisture content and lower resistivity; however, if the lower layer contains hard and rocky layers, it may result in increased resistivity with depth. This study aims to analyze the role of the bottom layer resistivity of two-layer model on the performance of a ground grid constructed on bays which are at different heights. The soil resistivity decreases with the depth of the soil having moisture content [2], and in such a scenario, the construction of a substation with step-like land terrain in such a soil may not pose a problem. However, when the soil resistivity increases with soil depth, there is no guarantee that the effective resistance estimated for a step-like land surface will be the same as that estimated for a levelled land surface, and the estimation made based on the uniform levelled land surface will not be accurate. This study aimed to investigate the same for two-layer soil stratification.

II. PRESENT WORK:

The present work aims to analyze the substation grounding grid with two distinct cases of higher resistivity in the top and bottom layers. It should be noted that due to the difficulties in finding an extent of 100, 000 to 160,000 m2 (400 kV substation) levelled land in urban and semi-urban areas, the transmission utilities in southern India have resorted to constructing substation bays at different levels of land in a step-like formation. Therefore, it is essential to analyze the performance of such grounding grids for earthing resistance as well as step and touch potentials.

The electrical resistivity of soil varies with depth, and generally, if not all, the resistivity increases with depth. It is worth noting here that the depth under consideration is not beyond few tens of meters, as the influence diminishes with the distance to the grounding grid. This is solely due to the spatial spread of the current on Earth. For ease of analysis and representation, a two-layer soil stratification is generally considered [2].

The goal of this work is to ascertain the impact of step-like construction on the performance of the grounding grid for different ratios of layer resistivity. The representation of a ground electrode based on an equivalent two-layer Earth model is always considered in the design of a safe grounding system. The IEEE provides methods for determining the equivalent resistivities of the upper and lower layers of soil and the height of the upper layer for such a model. The different ratios of the top layer to the bottom layer and vice versa and varying depths of the top layers were also considered for analysis.

III. BRIEF ON METHODOLOGY:

In the present work, the surface current simulation method (SCSM) [3] is used, in which the buried conductors and interfaces are handled independently. Galerkin's method of weighted residues was employed for buried conductors. This approach is equivalent to the variational form and ensures good accuracy even for a simple basis function. In general, the pulse function (i.e. uniform current dissipation over the length of the segment) approximation is employed. With the pulse function approximation for the current dissipated by the segment, the self-potential of any dissipating segment is determined by [3]:

$$V_s = \frac{I}{4\pi\sigma L L'}\int_L \int_{L'} \frac{dl\, dl'}{\sqrt{a^2+(l-l')^2}} \tag{1}$$

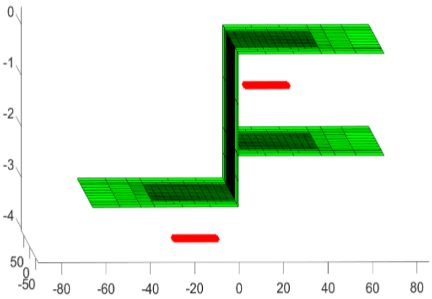
where a is the equivalent radius of the conductor; l and l' are the lengths measured on the segment (assumed to be straight); limits L and L' indicate that the integration is over the segment; L is the length of the segment; and I is the current dissipated by the segment. The equivalent radius is equal to the actual radius of cylindrical conductors and the geometric mean radius of the cross-section for non-cylindrical conductors. Similarly, the mutual (Galerkin average) potential was evaluated by [3].

$$V_{12} = \frac{I_1}{4\pi\sigma L_1 L_2}\int_{L_1}\int_{L_2}\frac{dl_1\, dl_2}{|\vec{R}_1(l_1)-\vec{R}_2(l_2)|} \tag{2}$$

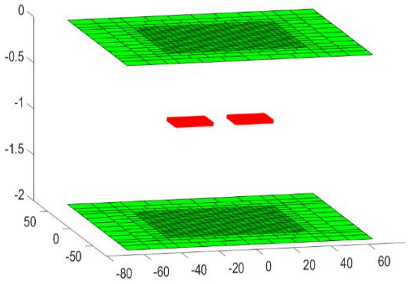
where dl1 and dl2 are the elemental lengths of segments 1 and 2, respectively; L1 and L2 indicate integration over the segments; term in the denominator of the integrand represents the distance between the elemental lengths in terms of the magnitude of the difference in their position vectors; and I1 is the current dissipated by the first (source) segment, as described in [3].

IV. ANALYSIS FOR BOTTOM LAYER WITH LOWER RESISTIVITY:

A ground grid of typical dimension of 80 x 40 m in which a step formation depth of 3m is formed between one level and another with ground grid buried at depth of 0.9m at both levels and interconnected at the land jump is considered. Similar dimensions of the ground grid in a uniform soil surface were considered for the analysis. Here, discretization is considered with the ground grid spaced at 2m distance from each other for both cases. The grid and discretized interfaces for both the step-like land surface and the uniform land surface are shown in Fig.2 (a) and (b).



(a) Step-like terrain



(b) Normal/uniform surface

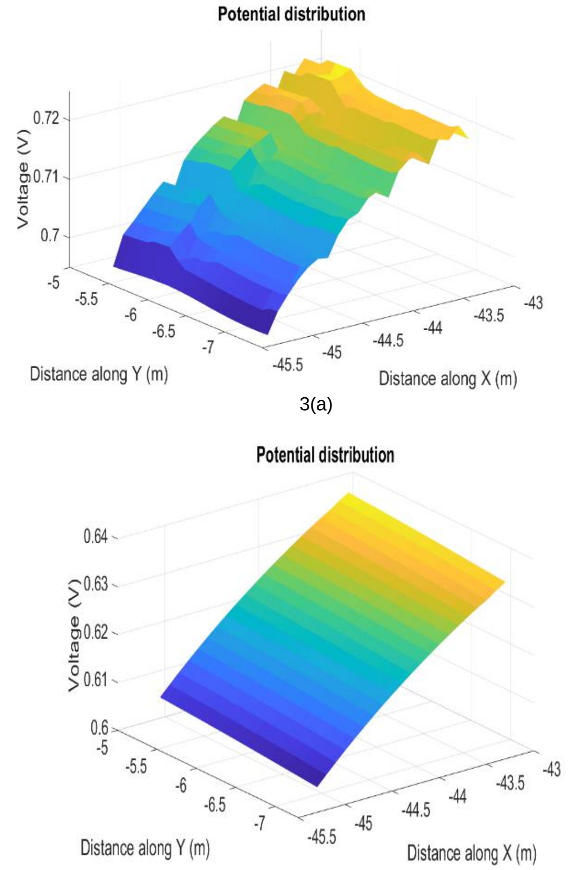
Fig.2 (a) and (b) Ground grid and discretization for step-like terrain and uniform land surface

In the above arrangements of ground grids in step-like land surface and uniform levelled land surface, the second layer resistivity is varied, and the result of the ratio of resistivity from the second layer to that of the first layer and the variation in resistance are tabulated in table1.

Table 1. The comparison of the ground grid resistance between step-like terrain and uniform land surface for bottom layer of lower resistivity

Sl No	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step-like land terrain in Ω	Resistance in uniform land in Ω
1	300	250	1.73	1.76
2	300	200	1.41	1.45
3	300	150	1.08	1.14
4	300	100	0.74	0.82
5	300	50	0.4	0.49
6	300	25	0.21	0.32

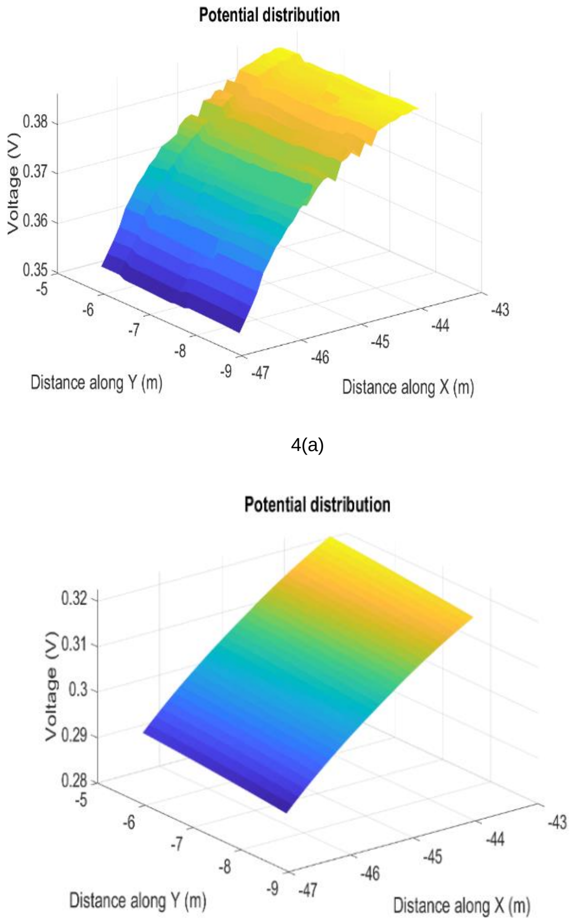
In these cases, the thickness of the top layer was kept at 2m and did not vary. It is evident from Table 1 that the stepped formation of the ground grid does not pose a huge variation in grounding resistance; however, the value of resistance with respect to step-like land is not exactly equal to that of a uniform soil surface, but varies slightly from each other. The potential distributions for the two cases were also plotted to analyze the extent of the difference between the ground grid of step-like land and uniform-level land. The potential distribution for the cases at the edge of the ground grid in steps such as land terrain and uniform soil surface for the resistivity of the top and bottom layers at 300 Ωm and 150 Ωm, respectively, are shown in the plots in Fig.3 (a) and (b).



3(b)

Fig.3 (a) and (b) Potential distribution at a corner of the ground grid for step-like terrain and uniform land surface (resistivity of top and bottom layer is kept at 300 Ωm and 150 Ωm respectively)

Similarly, for more clarity on understanding the potential distribution for the cases at the edge of the ground grid in step-like land terrain and uniform soil surface with a resistivity of top kept at 300 Ωm and varying the bottom layer at a lower value to 50 Ωm, to determine the extent of difference it can cause are shown in the plots in Fig.4 (a) and (b).



4(a)

4(b)

Fig.4 (a) and (b) Potential distribution at a corner of the ground grid for step-like terrain and uniform land surface (resistivity of top and bottom layer is kept at 300 Ωm and 50 Ωm respectively)

From the above figure, it can be seen that the extent of difference for both cases is not significant and shows that, apart from a small difference in resistance, it may have a small variation in potential difference but not very significant enough to cause any concern on step or touch potential in the substation yard.

Further, for the sake of completeness of analysis with various parameters, the depth of the top layer is varied while the ratio of the top to bottom layer resistivity is kept constant, and the computed results are tabulated as shown in Tables 2 (a) and (b) below.

Table 2 (a) & (b). The comparison of the ground grid resistance between step-like terrain and uniform land surface for bottom layer of lower resistivity with depth of top layer varied

Table 2 (a)

Top layer depth	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step- like land terrain in Ω	Resistance in uniform land terrain in Ω
2	100	1000	5.16	4.20
4	100	1000	4.04	3.26
5	100	1000	3.58	2.96
6	100	1000	3.24	2.71

Table 2 (b)

Top layer depth	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step- like land terrain in Ω	Resistance in uniform land terrain in Ω
2	100	1000	5.16	4.20
2	200	2000	10.32	8.40
2	300	3000	15.47	12.60
2	400	4000	20.63	16.80

From the above tables, it can be seen that the difference in the value of resistance obtained for step-like land surface and uniform land surface varies slightly but not significantly as and when the depth of the top layer is varied. However, when the depth of the top layer is kept constant and the top and bottom layer resistivities vary proportionately, the value of resistance obtained shows a proportionate increase, and the difference between step-like land terrain and that of uniform surface land is higher at higher values of resistivity.

V. ANALYSIS OF BOTTOM LAYER WITH HIGH RESISTIVITY:

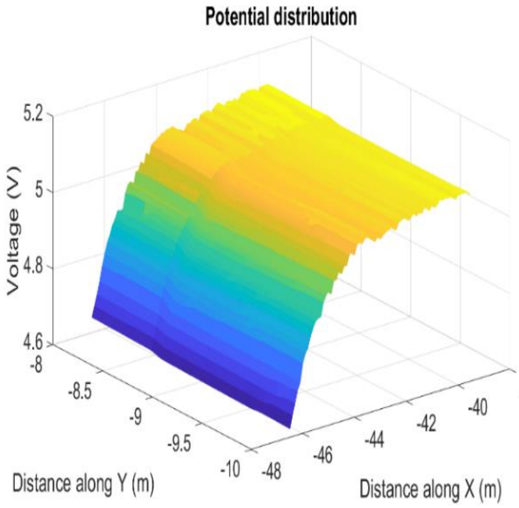
A similar exercise for a grid size of 80 × 40 m with a step of 3 m and ground grid constructed at a depth of 0.9 m was considered for analysis by varying the top layer resistivity while maintaining the bottom layer resistivity at a fixed higher value. The values obtained is tabulated for various values of resistivity at the top layer and the resistance values for ground grids in step-like land surface and uniform soil surface, respectively, in Table 3.

Table 3. The comparison of the ground grid resistance between step-like terrain and uniform land surface for bottom layer of higher resistivity.

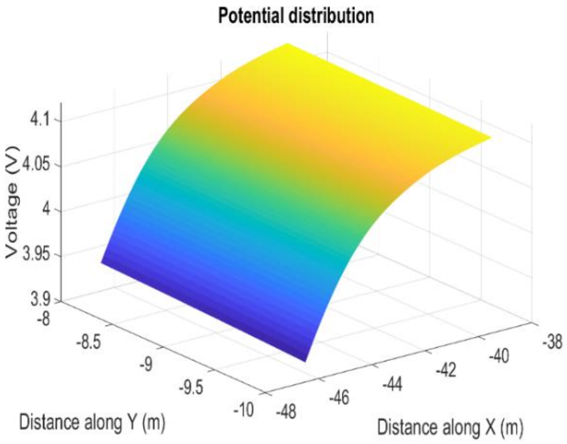
Sl No	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step-like land terrain in Ω	Resistance in uniform land terrain in Ω
1	20	1000	3.78	2.31
2	25	1000	4.37	2.74
3	50	1000	6.36	4.37
4	100	1000	8.33	6.31
5	150	1000	9.36	7.49
6	200	1000	10.01	8.31
7	250	1000	10.48	8.94
8	300	1000	10.84	9.45
9	350	1000	11.13	9.87
10	400	1000	11.37	10.24
11	450	1000	11.57	10.56
12	500	1000	11.75	10.85

In this case, the thickness of the top layer was kept at 2m and did not vary, as the effect of varying the depth did not result in a significant variation of the computed resistance values, as shown in the earlier section. However, it is evident from the above table that the ground grid resistance value obtained for the ground grid constructed in step-like land is much higher than obtained for the ground grid of uniform land terrain. This difference in the resistance value may have an impact on the potential distribution and potential gradients and may not be the same as that obtained for the uniform soil surface case.

The potential distribution plots for both cases of step-like land terrain and uniform land surface are plotted in Fig. 5(a) & (b).



5(a)



5(b)

Fig.5 (a) and (b) Potential distribution at the corner of the ground grid with step-like terrain and uniform land surface (resistivity of top and bottom layer is kept at 300 Ωm and 1000 Ωm, respectively)

From the above potential distribution plots at the edge of the ground grid, a comparable difference is observed between the case of the ground grid with step-like land and uniform land potential distribution. The difference in potential distribution from step like land and uniform land is to an extent of around 27% which is comparably high and may pose threat to the working person around that area.

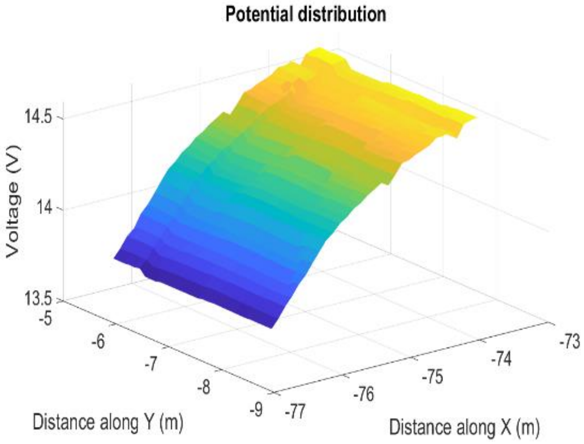
VI. ANALYSIS OF BOTTOM LAYER WITH EXTREME HIGH RESISTIVITY:

Some extreme cases of high resistivity in the bottom layers were also considered, and it was found that the difference in resistance values obtained for the ground grid with step-like land terrain was still greater than the resistance obtained for the uniform soil surface. This requires careful examination of the effect of potential distribution in the ground grid and its effect on personal working as well as on the equipment in the substation with regard to touch and step potential. The different values of resistivity in the bottom layer and the resistance values obtained are listed in Table 4.

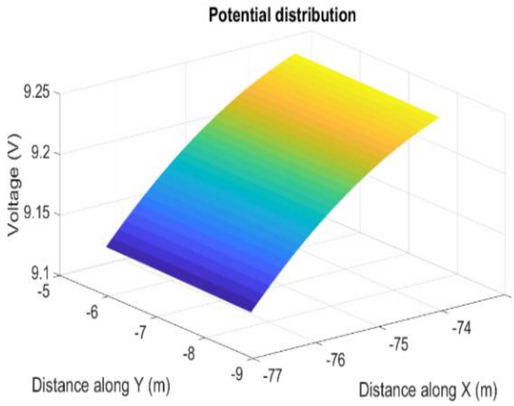
Table 4: Ratio of resistivity of top layer to bottom layer and the variation of resistance between land with step-like terrain and uniform land surface for some extreme cases with very high lower layer resistivity.

Sl No	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step- like terrain in Ω	Resistance in uniform land terrain in Ω
1	100	1500	7.07	5.51
2	100	2000	8.66	6.5
3	100	2500	10.02	7.3
4	100	3000	11.21	7.96
5	100	3500	12.26	8.52
6	100	4000	13.18	9
7	100	5000	14.76	9.78
8	100	10000	19.49	11.87

From the above table, it is evident that the obtained value of resistance for the ground grid with step-like land would be considerably different compared to the ground grid of uniform-level land. This calls for a careful consideration of such cases to ensure that the potential difference does not exceed the safe value. The potential plots for the ground grid with step-like land and uniform-levelled land are shown in Fig. 6(a) and (b).



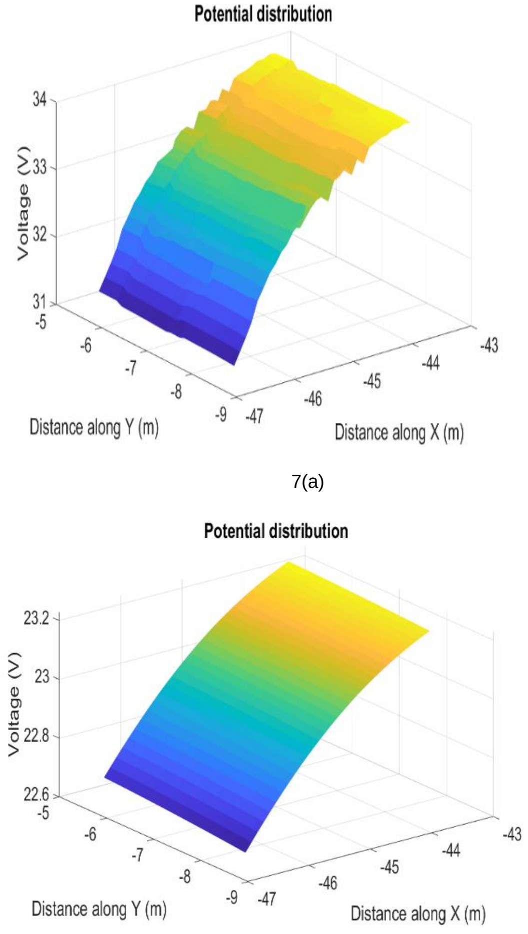
6(a)



6(b)

Fig.6 (a) and (b) Potential distribution at the corner of the ground grid with step-like terrain and uniform land surface (resistivity of top and bottom layer is 100 Ωm and 10000 Ωm respectively)

From the above plots, it can be seen that the ground grid design for step-like land terrain will have a higher potential distribution than that of the ground grid designed for a uniform soil surface. Similarly, the plots for different ratios of top layer resistivity to that of bottom layer are tried, and one such example for 300 Ωm and 10000 Ωm is shown in Fig.7 (a) and (b) below:



7(a)

7(b)

Fig.7 (a) and (b) Potential distribution at the corner of the ground grid with step-like formation and uniform land surface (resistivity of top and bottom layer is 300 Ωm and 10000 Ωm respectively)

From the above plots, it can be seen that, the percentage difference in potential distribution from step like land to that of uniform land is to an extent of around 46% which is comparably high and may pose threat to the working person around that area.

VII. ANALYSIS OF BOTTOM LAYER WITH EXTREME HIGH RESISTIVITY WITH GRID SIZE OF 70 M X140 M:

With a higher ground grid size of 70 m x140 m which houses a typical 220 kV substation and found that the ground grid resistance value was consistently higher for step-like land surfaces compared to uniform soil surfaces. This shows that substations constructed on land with step-like land terrain need special consideration to deal with the increased resistance due to step formation. Table 4 shows the variation in the resistance value as and when the bottom layer resistivity is increased to a larger value.

Table 4: Ratio of resistivity of first layer to second layer and the variation of resistance between land with step-like terrain and uniform land surface for some extreme cases with very high lower layer resistivity for a bigger size of grid.

Sl No	Top layer resistivity in Ωm	Bottom layer resistivity in Ωm	Resistance in step- like land terrain in Ω	Resistance in uniform land terrain in Ω
1	300	2000	7	6.22
2	300	4000	12.53	10.37
3	300	5000	14.92	12.02
4	300	10000	24.29	17.82

It is pertinent to note here that, when such a scenario of huge resistivity at the bottom layer is encountered by the utilities, remedial measures such as chemical grounding or techno-economically viable designs are being taken to ensure that the step and touch potential in the area of operation within the substation are not compromised. However, in some extreme cases, the utilities are going in for satellite grounding of the substation under consideration to mitigate the problem of step and touch potential. In many cases, where the extent of land available for construction of the ground grid is limited and encounters a huge bottom layer resistivity, satellite grounding has been considered as a viable solution and is generally practiced. This is achieved by taking the substation ground connection through an overhead line to a remote location at a distance where the ground grid has an acceptable level of resistivity and is connected.

VIII. CONCLUSION:

Due to various constraints, the local utilities are opting for the construction of the substation bays on different steps. As a result, unlike the grounding grids of the conventional construction, the grounding grids of different steps would be at different distances from the interface or even different layers of soil altogether. Also, the usual soil resistivity measurements are carried out before trimming the surface into suitable steps. As expected, for the usual situation, wherein the bottom soil layer has lower resistivity, things are under control. However, the study results, clearly indicates that for cases with bottom soil layer is of much higher resistivity. From the above analysis, it can be deduced that substations constructed in step-like terrain with tailor-made design with grounding grids at different heights for different equipment bays will not show a similar performance to that of the grounding grids on a uniform land surface. In particular, when the lower or bottom layer resistivity is higher than that of the top layer, the potential distribution will not be the same as that of the grounding grid of the uniform soil surface and needs careful consideration to see that the step and touch potentials are within the limit. Hence, substations constructed on a step-like terrain which hosts equipment bays at different heights require special attention in cases where the lower layer resistivity is likely to be higher than that of the upper layer.

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