A COMPARISON OF GROUND GRID MESH DESIGN AND OPTIMIZATION FOR 500KV SUBSTATION USING IEEE 80-2000 AND FINITE ELEMENT METHODS

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Abstract: *An Air Insulated substation is chosen for the analysis located in Pakistan. The protective scheme installed in any substation should be fully active to ensure its proper and accurate operation in case of any fault. Ground Grid mesh used under substation ground consist of horizontal conductors connected with vertical rods. The function of mesh is to dissipate extremely high current generated in any scenario related to fault. In this regard, firstly 500KV substation is chosen for analysis of protection scheme with focus especially on Ground Grid mesh. The analysis of mesh is carried out using both IEEE 80-2000 and Finite Element Methods for the evaluation of important ground grid mesh parameters. A Software is used for analysis i.e. ETAP -12 having more enhanced features than previous versions. The problems regarding existing functioning ground grid mesh are brought to light in one case study. In second Case study, the remedies for the rectification of mesh are provided. In third, case study a new ground mesh is designed for the existing substation considering new methodologies and latest analysis techniques. In fourth case study, a new ground mesh for Ultra High Voltage Substation is designed for 750KV substation. Finally, a inter comparison is done between mesh designed using IEEE 80-2000 and FEM methods to effectively establish the efficiency and effectiveness of each method by each Case study. A recommendation is given regarding the best method to be used for the future designing of ground grid mesh of all AIS substations.*

Key Terms: *Electrical Transient Analysis Program, National Transmission and Dispatch Centre, Potential Ground Rise, Ground grid System*

1. Introduction

The appropriate explanation of grounding described as link created intentionally or unintentionally along live apparatus /part which itself connects to electrode laid at suitable depth below substation ground and it functions as earthing electrode.

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The scheme used for HV systems grounding is solidly grounded structure [1, 2].The value of resistance among ground earth and neutral of system is retained at low level as it is difficult to attain zero value. The current due to ground fault peaks at a high level which is damaging. The problems like stress due to high fault currents do not arise often.

The insulation related problems are the major concern in high voltage systems but in system grounded properly by employing solid grounded scheme, upon line and ground fault occurrence voltage does not rise massively across healthy phases. The fault current value for 500KV system is 40-45KA and for 750KV system value is between 60-70KA.

The protective scheme design is an important aspect in design and construction of substation. The voltage gradients are created across ground mesh and points linked to earth as reference [3]. The difference in potential is kept within the limits provided by IEEE and it is continuously monitored for the equipment proper functionality and people safety working in surrounding.

The vital factors required for ground grid mesh evaluation are GPR,Voltage StepV_s,Voltage StepV_t, Resistance of Ground Rg , Voltage MeshV_m,ESP & Potential Absolute. There are various methods available for designing of ground mesh for substation. IEEE 80-2000 and FEM methods are adopted for mesh designing in research conducted as these are more reliable ones. The collection of data is carried out for 500 KV substation by making use of new available IEEE 81 methods. The mesh modeling is carried out and analysis is performed by each methods mentioned above. The GGS module in ETAP-12 data is used for ground grid mesh modeling.

The inter-comparison of FEM & IEEE 80-2000 results is done of various case studies developed on existing ground grid mesh to establish the effectiveness in terms of cost& efficiency of each method. The recommendations are made regarding the methods upon which the future designing of ground grid mesh for substations may be based upon.

1.1 IEEE 81 ^{2013} Methods

IEEE has provided latest set of methods for measurement of various potentials, resistivity and ground resistance [3,4].These methods are called IEEE 81 methods launched in 2013.The main aim for the development of these methods was to eradicate the deficiencies in various measurement techniques used for collection of practical data from the site where ground grid mesh is about to be constructed or from area where ground grid mesh is already laid and functioning. The remedial actions were related to false measuring techniques, errors related to the equipment and human errors readings slip-ups.

These all things were taken into account by a committee formed to address these problems. The recommendations were forwarded by the committee to the council and upon those proposals IEEE 81 methods were adopted.

IEEE 81-1983 methods were previously utilized used for soil resistivity and resistance before making use of IEEE 81 standard. All measurements are taken by making use of IEEE 81 methods in current project & afterwards further modeling is done based on available data.

1.2 Resistivity of Soil Measurement

The ground mesh design is difficult practice comprising numerous stages. The data collection of area substation is to be created is an important part. A comprehensive test is carried out during data collection phase for information like layers in number, soil type, resistivity of soil and soil stratification whether soil is horizontally or vertically stratified [2, 3].

The soil resistivity is calculated by using methods given as:

A.Schlumberger
B.Three Point Driven Rod
C.four Point
D.wenner

The resistivity calculation can be made by any one of above method but Driven Rod/3 point is consistent method adopted for soil resistivity calculation shown in figure 1.
In this method, the depth 'Lr' of the driven-rod located in the soil to be tested is varied. The other two rods, known as reference rods are driven to a shallow depth in a straight line. The location of the voltage rod is varied between the test rod and the current rod. Alternately, the voltage rod may be placed on the side opposite the current rod. The apparent resistivity is given in equation 1.

$$\rho_a = \frac{2\pi L_r R}{\ln\left(\frac{8L_r}{d}\right) - 1} \qquad \text{………. eq 1}$$

Where Lr = Rod Length in meters, d =RodDia in meters

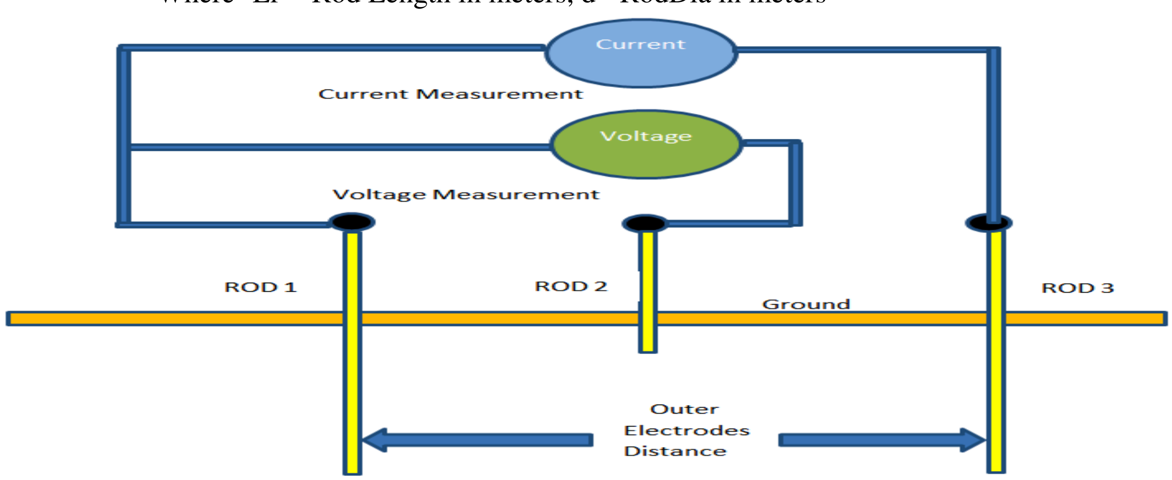

Figure 1 Three Point Driven Rod-Method

1.3 IEEE 80-2000 Methods

The 80-2000 methods for calculation of Ground Resistance provided below:

I. Newman-Laurent
II. Shevrak

1.3.1 Newman-Laurent Methods

The soil resistance varies directly with resistivity change. The main objectiveis to approximate a depth defined "h" at which resistance is minimum [3, 4].
The method estimates ground resistance by making use of eq2.

$$\mathrm{Rg} = \rho \frac{1}{4} . \frac{\sqrt{\pi}}{\mathrm{Ag}} + \rho \frac{1}{\mathrm{Ls}} \text{ .... eq 2}$$

L_a = Conductors length meters,N_r = Vertical rods used
L_s can be calculated by equation3

$$\mathrm{Ls} = \mathrm{La} + \mathrm{Nr.\ H} \text{ .... eq3}$$

1.3.2 Sevrak Methods

It is an advance version of Newman- Laurent method incorporating some changes. It is latest version of Newman Method. The adjustment in ground resistance value for surface of soil is carried out for accuracy and improvement of resistance. The deepness of grid has substantial effect on ground resistance calculation. The grid depth effect on resistance was incorporated in existing data. eq 4 provides the formula after necessary modifications.

$$\mathrm{Rg} = \rho . [\frac{1}{La} + \frac{1}{\sqrt{20A}} . \left[1 + \frac{1}{1 + \frac{h\sqrt{20}}{Ag}} \right]] \text{......eq 4}$$

L_a = Conductors Length (m),A_g = Ground grid area

1.4 Finite Element Methods

The Finite Element method is one of the more reliable methods of finding ground grid mesh resistance. The resistance found is fairly close to the actual value, compared to one calculated using conventional measurement methods.

In previous FEM methods, which are outdated now includes analysis of current by making use of potential grid set. After the determination of current, the ground resistance was calculated by dividing the known voltage with the calculated value of current. The drawback of this method was to select model considering that distance of earth to be considered was starting from the grounding grid. The main advantage of this method is selecting the size of the model such as distance of earth under consideration is starting from the grounding grid. Since analysis of each potential in the soil for a selected point is considered from grounding grid to the point [5].

The new FEM methods are available developed by researches with shortcomings in previous methods removed. FEM methods are developed by researchers such as main disadvantage of old FEM method are overcome. In new FEM methods, modeling starts from beginning. In the first step, they assume that grounding resistance is such a parameter which does not depend on potential or current in the grid except frequency cases other from frequencies [6,7] (50Hz or 60Hz frequency of power). The second assumption is to consider the whole region as flat surface which is infinite.

The formulas for calculations of Resistances are given below as:

$$\mathrm{R} = \mathrm{R1} + \mathrm{R2} \text{ ....eq4}$$

Where R is the combined resistance sum of resistances of two portions of the flat surfaces

R2 is calculated from formula given in equation 5.

$$R2 = \frac{p}{2\pi . d1} \quad \text{.............eq5}$$

The R1 is found calculated with eq6.

$$R1 = \frac{\text{Power Disssipated}}{\text{voltage x volatge}} \text{......eq6}$$

The potential called actual voltage is found with eq 7.

$$V_{avg} = I_{fault} . R \text{ ....eq7}$$

The boundary voltage is found with eq 8.

$$V_{avg} = I_f . R2 \text{ ....eq8}$$

2. Practical Data Collected

The practical Air Insulated 500KV substation is chosen for the analysis of protection scheme. Ground Grid Mesh of substation will be evaluated to highlight the various essential parameters that are related to developed potentials around the mesh and ground mesh resistance.

The Air Insulated 500KV substation is shown in figure 2.

Figure 2 Air insulated Substation

The ground grid mesh modeling incorporating horizontal conductors and vertical rods is shown in figure3 and the practical data of grid is provided in Appendix-A.

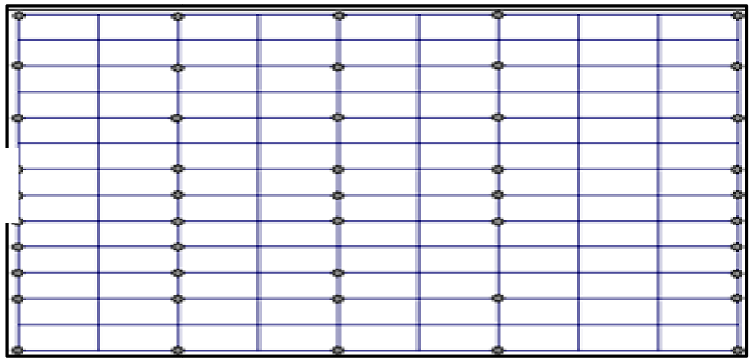

Figure 3 Ground Mesh designed in ETAP

3. Case Studies Comparison using IEEE80-2000 & FEM Methods

A strategy is adopted regarding Case Studies comparison in which the ground grid mesh is compared using IEEE 80-2000 & FEM methods. With the help of results & material consumption for the establishment of mesh using each methodology, the efficiency &effectiveness of each method is established [8,9].

Case Study-I IEEE & FEM Comparison

The Case study-I is based on the amendments made in existing functioning ground mesh to limit the potentials and temperature rise within the safe limits. The input parameters are provided in table I.

TABLE I. GROUND MESH INPUT DATA CASE –I

Parameters		IEEE 80-2000 Methods	FEM Methods
Length Grid	x-direction	144	144
	y-direction	100	100
Number of Conductor	x-direction	20	25
	y-direction	16	20
ConductorsType		Soft DrawnCopper Annealed	Soft DrawnCopper Annealed
Conductor Depth		0.3	0.3
Conductors Size		185	185
Number of Rod		54	57
Number of Rod		Steel RodCopper Clad	Steel RodCopper Clad
Rod Diameter		1.52	1.56
Length of Rod		2	2

The results of IEEE 80-2000 & FEM methods are given in table II with all potentials meeting the limits.

TABLE II. CASE-I COMPARISON RESULTS

Case Study	Methods	Step Voltage	Touch Voltage	GPR	Ground Resistance
Case Study-I	IEEE80-2000	1311.1	1556.7	10139.7	0.392
	FEM Methods	1380.1	1248.1	9287.5	0.37

The graphs for Step, Touch& Absolute Potential are given in figure 4, 5 & 6.

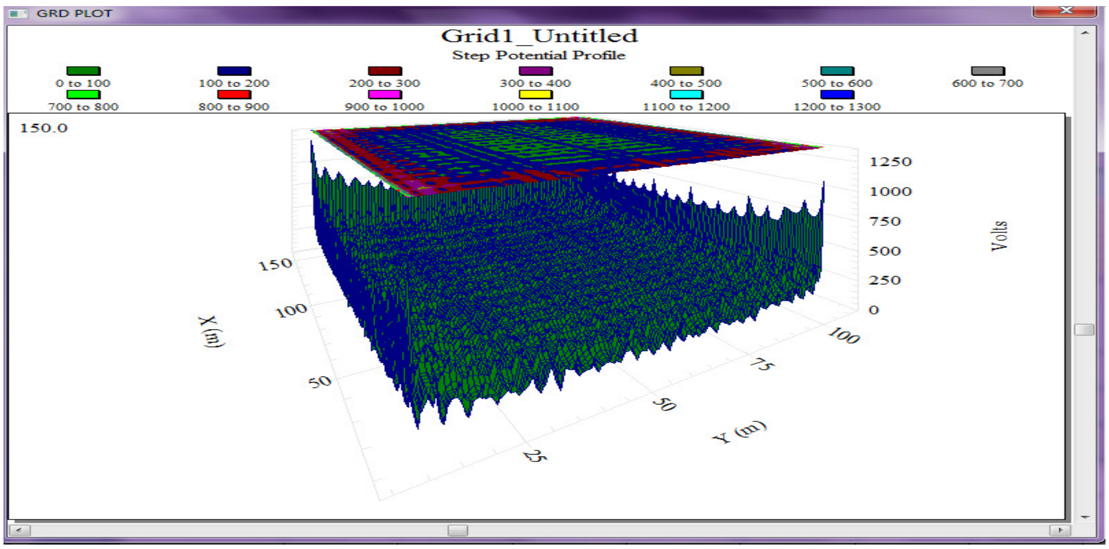

Figure 4 Step Potential

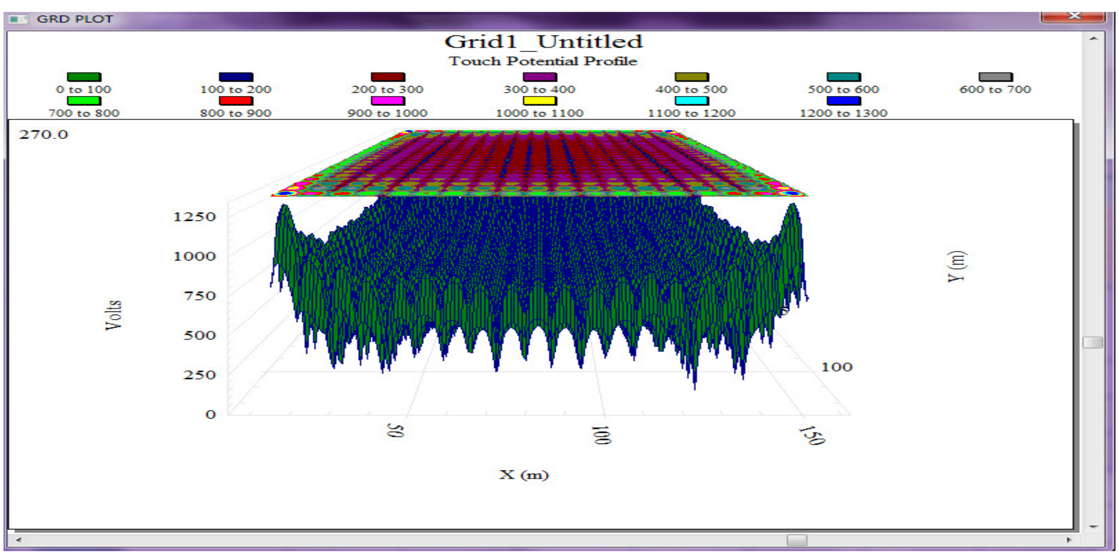

Figure 5 Touch Potential

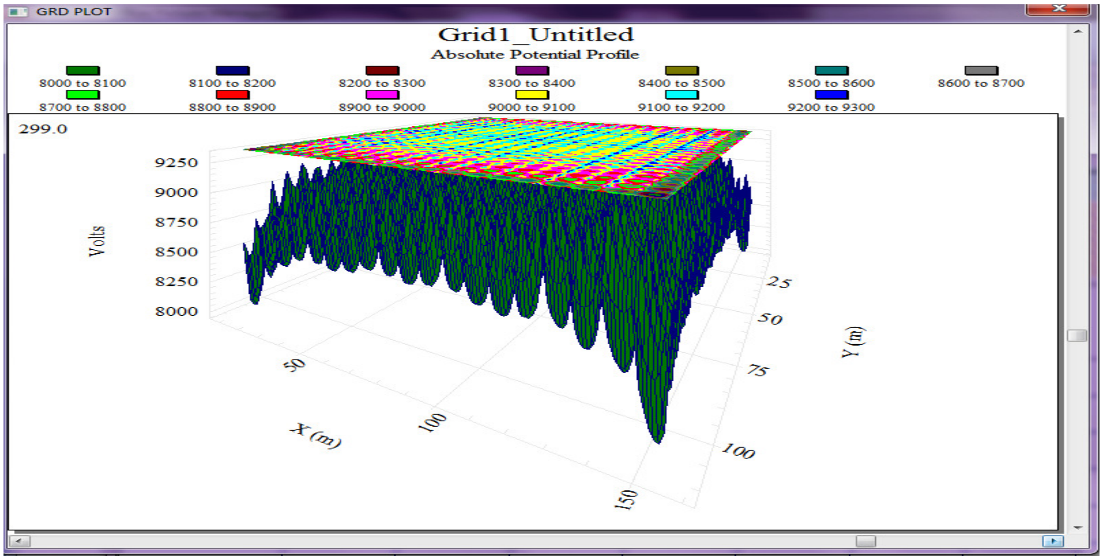

Figure 6 Absolute Potential

Case Study-II IEEE & FEM Comparison

The Case study-II is based on planned enhancement in substation level of fault from existing value of 40KA to 45 KA. The enhancement is due to replacement of old transformer with new large capacity power transformer.[10] The effect is taken into account in case study with analysis made with both methodologies and necessary amendments are suggested based on each method. The input parameters are provided in table III.

TABLE III. GROUND MESH INPUT DATA CASE -II

Parameters		**IEEE 80-2000 Methods**	**FEM Methods**
Grid Size Length	X-Direction	144	144
	y-direction	100	100
Number of Conductor	x-direction	22	29
	Y-Direction	19	26
Conductors Type		Soft Drawn Copper Annealed	Soft DrawnCopper Annealed
Conductors Depth		0.3	0.3
Conductors Size		185	185
Number of Rod		65	60
Number of Rod		SteelRodCopper Clad	Steel RodCopper Clad
Rod Diameter		1.61	1.63
Length of Rod		2	2.1

The results of IEEE 80-2000 & FEM methods are given in table IV.

TABLE IV. CASE-II COMPARISON RESULTS

Case Study	Methods	StepVoltage	Touch Voltage	GPR	Ground Resistance
Case Study-II	IEEE80-2000	1747.3	1307.3	11332.8	0.39
	FEM Methods	1538.9	1323.6	10677.1	0.367

The graphs for Step, Touch and Absolute Potential are given in figure 7,8 & 9.

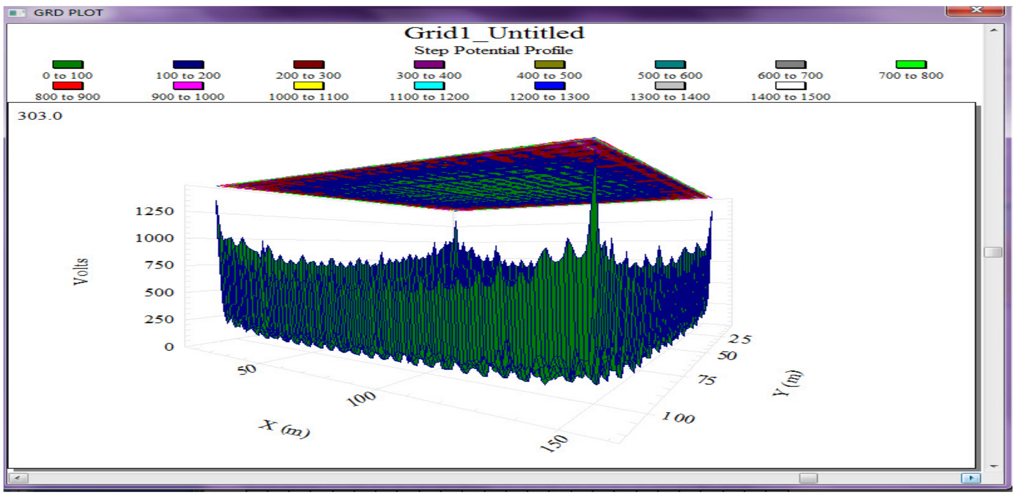

Figure 7 Step Potential

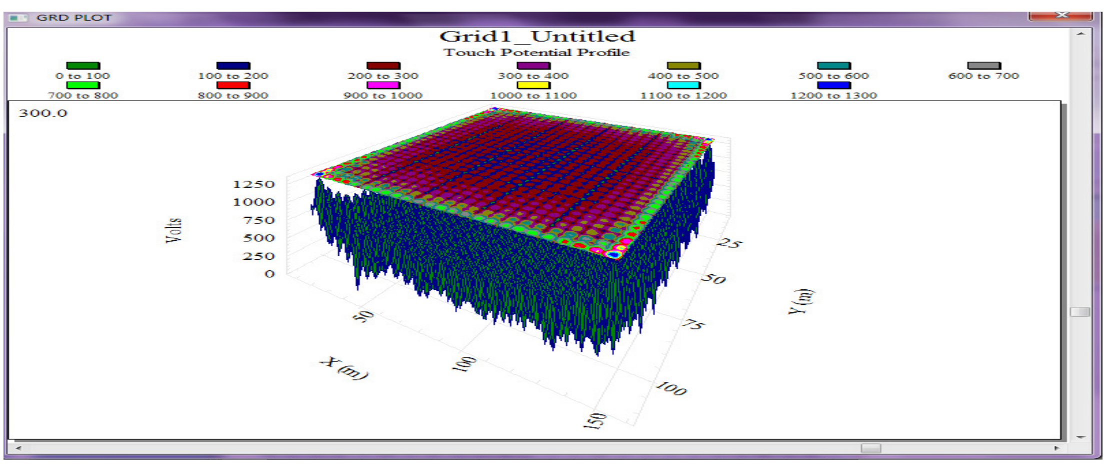

Figure 8 Touch Potential

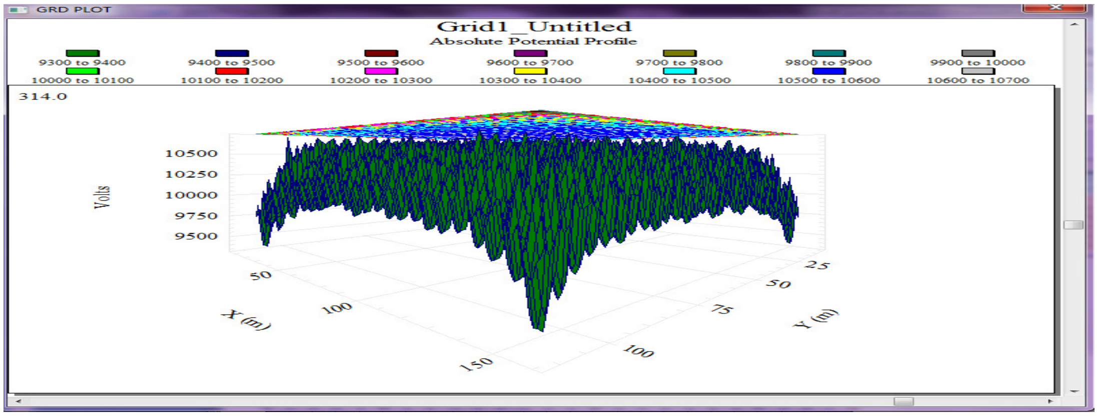

Figure 9 Absolute Potential

Case Study-III IEEE & FEM Comparison

The Case study-III is based on re-designing of whole substation grounding scheme using latest optimization techniques based on IEEE 80-2000 & FEM methods as latest advancement in technology has led to improvement in overall ground mesh designing [11,12].The input parameters are provided in table V.

TABLE V. GROUND MESH INPUT DATA CASE-III

Parameters		IEEE 80-2000 Methods	FEM Methods
Length Grid	x- direction	120	120
	y-direction	83	83
Conductor Number	x-direction	22	26
	y-direction	12	22
ConductorsType		Soft DrawnCopper Annealed	Soft DrawnCopper Annealed
Depth of Conductors		0.7	0.5
Size of Conductors		185	240
Number of Rod		42	50
Number of Rod		Copper Clad SteelRod	Copper Clad Steel Rod
Rod Diameter		1.6	1.56
Length of Rod		2	2.5

The results of IEEE 80-2000 & FEM methods are given in tableVI.

TABLE VI.CASE-II COMPARISON RESULTS

Case Study	Methods	StepVoltage	Touch Voltage	GPR	Ground Resistance
Case Study-III	IEEE80-2000	981.5	1295.8	12053.8	0.466
	FEM Methods	1218.7	1329.8	10367.2	0.438

The graphs for Step and Absolute Potential are given in figure 10,11, & 12.

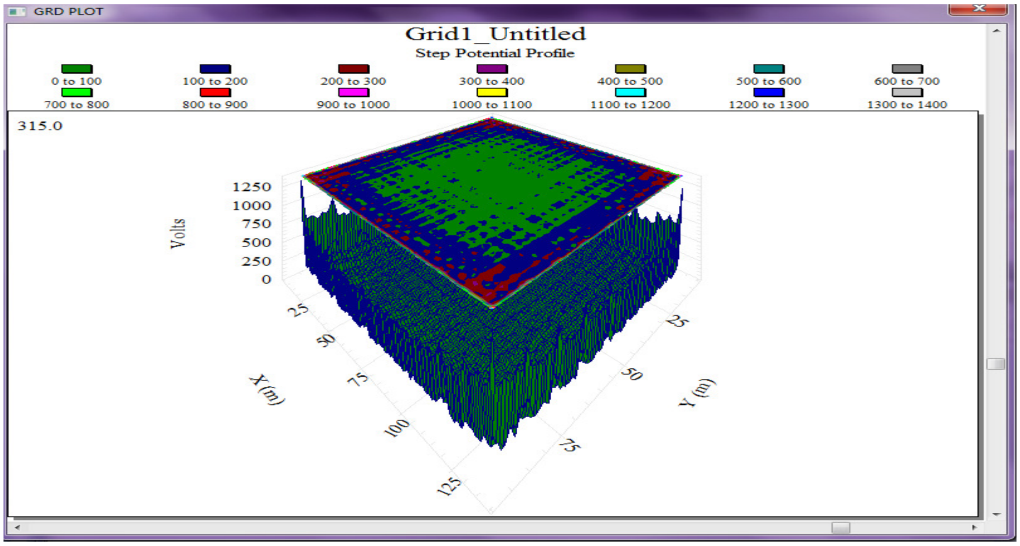

Figure 10 Step Potential

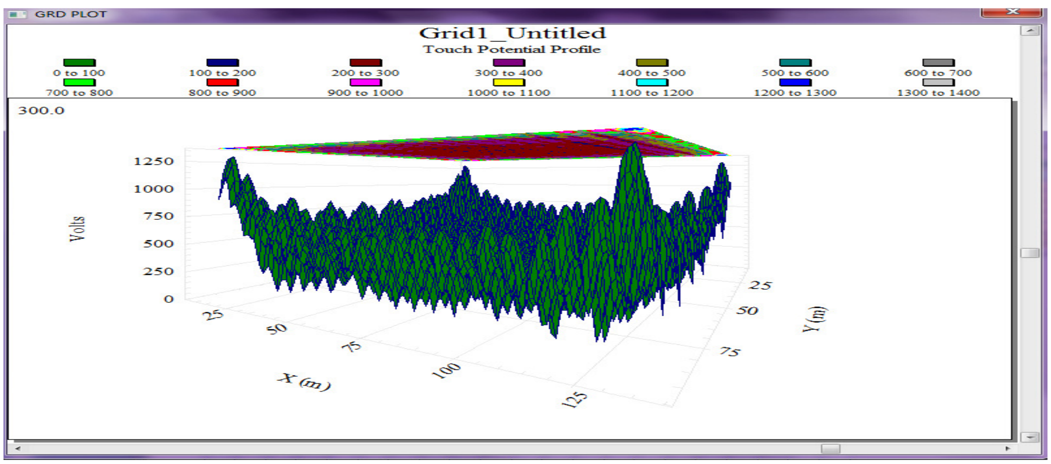

Figure 11 Touch Potential

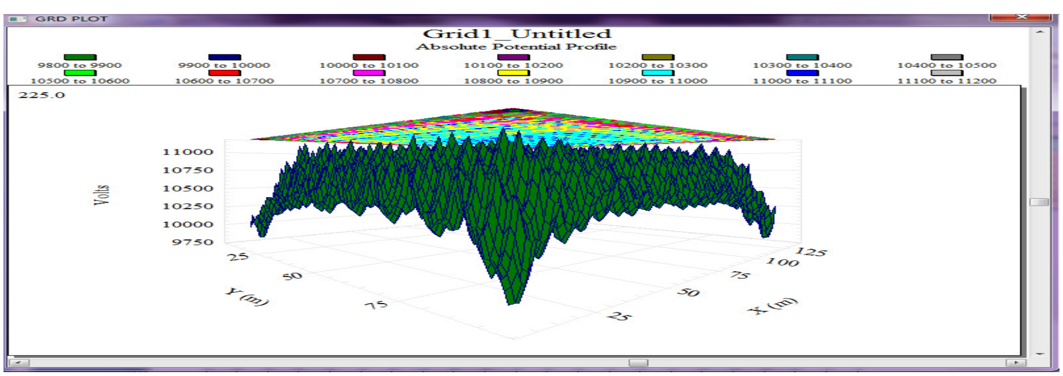

Figure 12 Absolute Potential

Case Study-IV IEEE & FEM Comparison

The Case study-III is based on new 750 KV mesh of substation to be included in system in future. The soil characteristics obtained for 500KV substation will be used for further designing of 750KV substation. The designing will be based on IEEE 80-2000 & FEM methods incorporating optimization techniques.

The input parameters are provided in table VII.

TABLE VII. GROUND MESH INPUT DATA CASE-IV

Parameters		IEEE 80-2000 Methods	FEM Methods
Length Grid	x-direction	150	150
	y-direction	70	120
Conductor Number	x-direction	30	31
	y-direction	22	37
Conductor Type		Soft DrawnCopper Annealed	Steel RodCopper Clad
Conductors Depth		0.8	0.8
Conductors size		240	240
Number of Rod		42	100
Number of Rod		steelRodCopper Clad	SteelRodCopper Clad
Rod Diameter		2.1	1.6
Length of Rod		2.5	2.3

Results of IEEE 80-2000 & FEM methods are given in table IV.

TABLE VIII.CASE-IV COMPARISON RESULTS

Case Study	Methods	StepVoltage	Touch Voltage	GPR	Ground Resistance Rg
Case Study-4	IEEE80-2000	1090.9	1319.1	14899.9	0.33
	FEM Methods	1150.3	1525.5	11843.1	0.318

The graphs for Step, Touch and Absolute Potential are given in figure 13, 14 &15

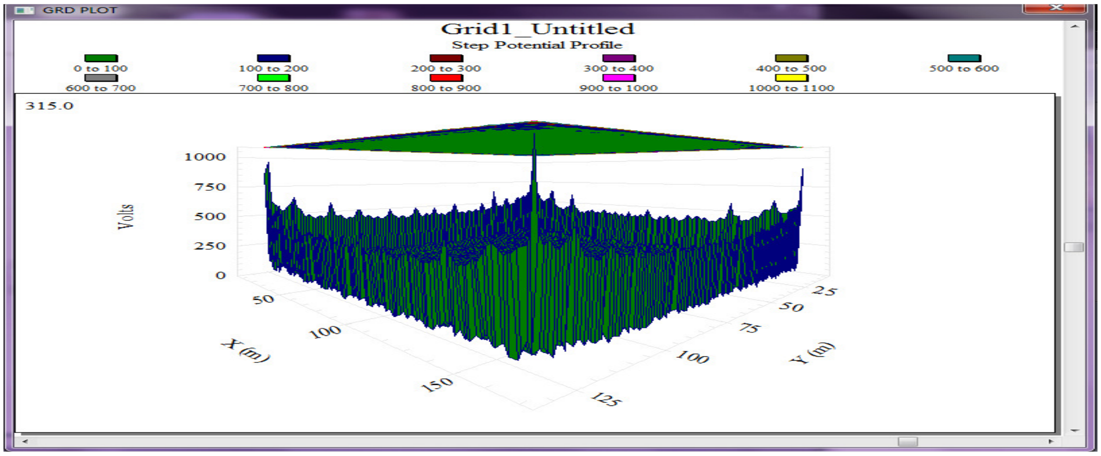

Figure 13 Step Potential

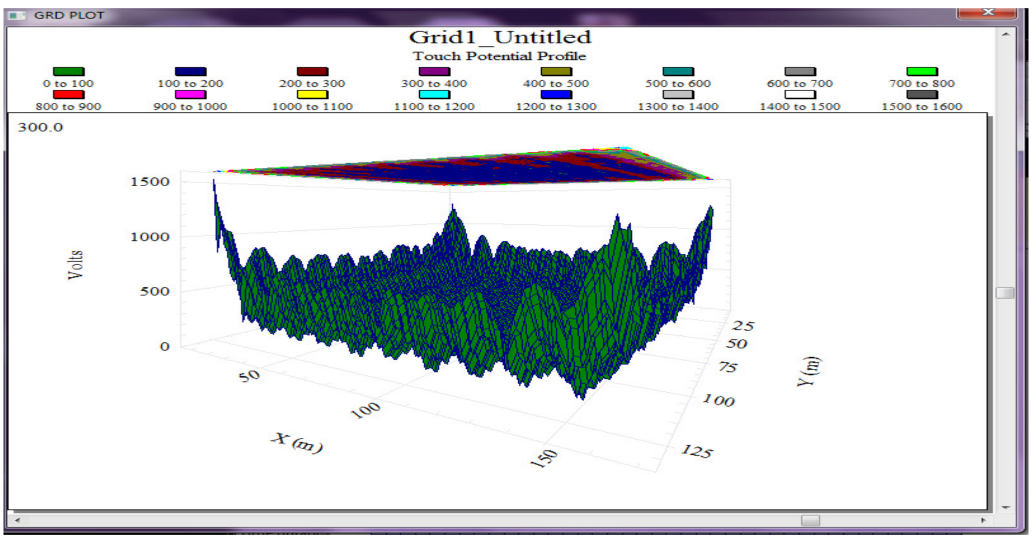

Figure 14 Touch Potential

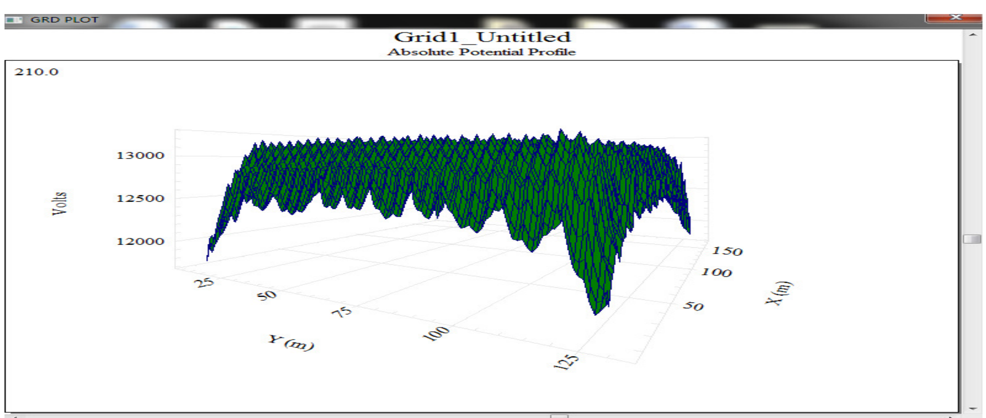

Figure 15 Absolute Potential

4. Recommended Analysis Methodology

The case studies results show that ground mesh structure cost for solution provided by IEEE 80-2000 methods is less than one designed using FEM methods.

The reason behind the increase cost by FEM is incorporation of number of conductors and rods used for mesh structure. The horizontally laid conductor's surface area is significantly more in mesh designed by FEM. The vertical rod diameter also exceeds the diameter of rods used in 80-2000 methods [12, 13, 14].The lower soil layer effect is also included in mesh designed by FEM methods. The proper grounding requirement increases by further lower layer inclusion in design eventually resulting in increase in material consumption for keeping parameters within limits.

5. Conclusions

The analysis of mesh was performed with both FEM and 80-2000 methods and also a new ground grid mesh for UHV (750KV Substation) was designed. Latest version of ETAP-12 was used for the verification of results. It can be concluded form obtained results that cost of mesh by FEM remains greater from mesh designed with 80-2000.

First time structure cost will be more for mesh designed by making use of FEM methods but the mesh designed will be more durable, long life and withstand the excessive fault currents more efficiently. The main complications in mesh often come after eight to ten years. The issues are met more in80-2000 designed mesh. The under designing is the major issue in problematic ground meshes.

Keeping in view future requirements after passage of eight to ten years substations life, mesh degradation occurs and various potentials surpasses limits. It is essential that proper designing of system is carried out using right set of methods to accommodate new requirements and mesh degradation.FEM methods may be used for future designing of mesh.

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Appendix

The table of containing substation data is provided below:

Sr. No	Description of Parameter	Value
1.	Level of Voltage	500KV
2.	Maximum Fault Current	40KA
3.	Ground Grid Mesh Area	144 x 100 m^2
4.	Ground grid mesh Horizontal Distance	144m
5.	Ground grid mesh Vertical distance	100m
6.	Horizontally Installed Conductors	14
7.	Vertically installed Conductors	10
8.	Conductors Area	185mm^2
9.	Conductors Type	Copper annealed Soft Drawn
10.	Maximum Temperature of conductors	50 C◦
11.	Rods installed in vertical Direction	50
12.	Rod Diameter of Vertical Rods	1.2 centimeter
13.	Rod	steel Rod Copper clad
14.	Duration of fault	1 second
15.	Temperature Outside	-5- 50 ◦C
16.	Temperature of Rod	50 ◦C
17.	X/R_{ratio} Reactance over Resistance	50
18.	Person Weight	50 kg
19.	soil Type at surface	gravel
20.	Resistivity	9976 Ω.m

21.	Height	0.2 m
22.	Top Soil	Moist layer
23.	Resistivity	130 Ωhm. Meter
24.	Height	2 m
25.	Soil bottom layer Type	Semi Moist soil
26.	Soil bottom layer Resistivity	200 Ω.m
27.	Soil bottom layer Height	infinity
28.	Level of fault in relation to earth S_f	60
29.	Increase in fault level C_p	100