Optimal Design and Development of Software for Design of Substation Grounding System

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Abstract—**Role of substation is crucial in overall functionality of power system. In any substation, grounding system deserves considerable attention as far as performance and design are considered. Design of an effective grounding system is of very much importance because it deals with personnel safety and also operation and protection of equipments. Main purpose of this work is development of software *'Optimal Ground Grid Designer'* which gives safe and optimum design of substation grounding system. This software has been designed using MATLAB as a mathematical tool. Methodology adopted for designing the grounding grid is as per IEEE standard 80 – 2000. Moreover this program also allows two layered soil modeling which is not given in IEEE guide. This program allows simple analysis of grounding system performance for given data and is able to recommend optimal design of the grounding system in the given conditions and safety constraints. A Design problem of grounding system design of 400 kV ASOJ (Gujarat) substation has been solved using this software. Results obtained here are also compared with those obtained by using '*Ground Grid Systems'* module of ETAP. A close agreement is observed between the results obtained by both softwares. Hence the software developed herein effectively gives optimal design of substation grounding system in terms of cost effectiveness as well as safety for various grid geometries.**

Index Terms— **Electrical safety, Ground grid, Mesh voltage, Ground Potential Rise, Step voltage.**

I. Introduction

On its way from generating station to the end consumers, through extensive transmission and distribution network, electrical power passes through number of different kind of substations. Thus substations can be called as heart of the entire power system because integrity of operation of complete power system depends to a considerable extent on reliable operation of substations. In any safe and reliable substation a well designed grounding system plays a crucial role. Absence of safe and effective grounding system can result in mal-operation or non-operation of control and protective devices thereby disturbing operation of complete power system. Hence great care should be taken while designing grounding system of any substation, primarily to ensure electrical safety of persons working within or near substations.

Main two functions of any grounding system are

To provide a path for electrical current to earth without exceeding operating limits of equipments

To provide safe environment for protecting personnel in the vicinity of grounded facilities from the danger of electrical shock particularly under fault conditions. [1]

Grounding system comprises of all of the interconnected grounding facilities in the substation area including ground grid, overhead ground wires, neutral conductors underground cables etc. ground grid being the main component. Ground grid consists of horizontal interconnected conductors often supplemented by vertical ground rods. Being major component of overall grounding system, design of grounding grid should be such that total grounding system is safe and at the same time it is cost – effective [1].

This paper describes effects of various parameters on the performance of grounding system and decides the most effective parameters to be considered while making the design safe and cost-effective. A program, based on IEEE standard 80 – 2000 '*IEEE Guide for safety in AC substation grounding*', is developed using MATLAB GUI. It implements theoretical concepts described in IEEE guide into computer software form. This program gives optimum design of substation grounding grid for various grid geometries in uniform soils as well as in two layered soil.

II. Safety Criteria for Grounding System Design

A good grounding system should be able to maintain the actual mesh and step voltages within a substation well below tolerable touch and step voltages respectively. These tolerable safety criteria have been established based on *fibrillation discharge limit* of body current. To attain this safety the equivalent electrical resistance of the grounding system must be low enough to assure that fault currents dissipate mainly through the grounding grid into the earth. Main performance parameters of the grounding system are Grid resistance, Step voltage, Touch voltage and GPR.

While designing any substation grounding system the main thing to be taken care of is that *under any circumstances actual step and touch voltages must not exceed those described as tolerable values* [1]. Tolerable step and touch voltages for person weighing 50 and 70 Kg as described in IEEE guide are as follows

$$E_{step50} = (000 + \rho C_s)\cdot\frac{0.116}{\sqrt{t_s}} \ldots\ldots(1)$$

$$E_{step70} = (000 + \rho C_s)\cdot\frac{0.154}{\sqrt{t_s}} \ldots\ldots(2)$$

$$E_{touch50} = (000 + .5\rho C_s)\cdot\frac{0.116}{\sqrt{t_s}} \ldots\ldots(3)$$

$$E_{touch70} = (000 + .5\rho C_s)\cdot\frac{0.154}{\sqrt{t_s}} \ldots\ldots(4)$$

Where

ρ_s = Surface layer resistivity in ($\Omega\cdot$)

C_s = Surface layer derating factor

t_s = shock duration in (Sec.)

III. MAJOR FACTORS AFFECTING GROUNDING SYSTEM PERFORMANCE

1) Description of parameters [2 – 4]

Following parameters have been found to have substantial effect on ground grid design and performance.

Maximum grid current, Fault duration, Shock duration, Soil resistivity, Surface layer resistivity, Thickness of surface layer, Area occupied by the grid conductors, Depth of burial of grid, Spacing between grid conductors, Number and location of vertical ground rods [2].

Of these parameters Area of grounding system (A), Conductor spacing (D), Depth of grid (h) and No. of Vertical ground rods (N_r) have dominating effect on the grid performance among the others.

Following graphs show effects of above mentioned major parameters on actual step and mesh voltages.

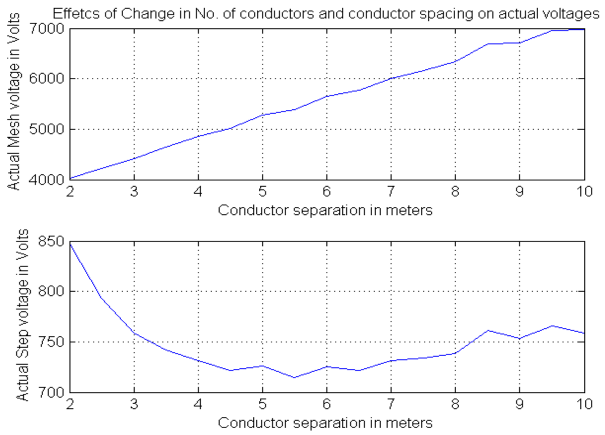

Fig.1. Variation of actual step and mesh voltages with change in conductor spacing

2) General observations

As seen from the graphs following general observations can be made.

Spacing between the adjacent conductors and No. of conductors are certainly dependent on each other for fixed area of grid. The more conductors are installed, the smaller the distance between the conductors. With reduced separation and increased No. of conductors, Mesh voltage (E_m) decreases but at the same time Step voltage (E_S) increases. However effect of reduction in E_m is more than that of increase in E_S. So designer has to carefully decide no. of conductors and separation between them to keep both voltages below tolerable limits. Also physically, there is a limit on how close conductors can be installed and should be a design consideration [2].

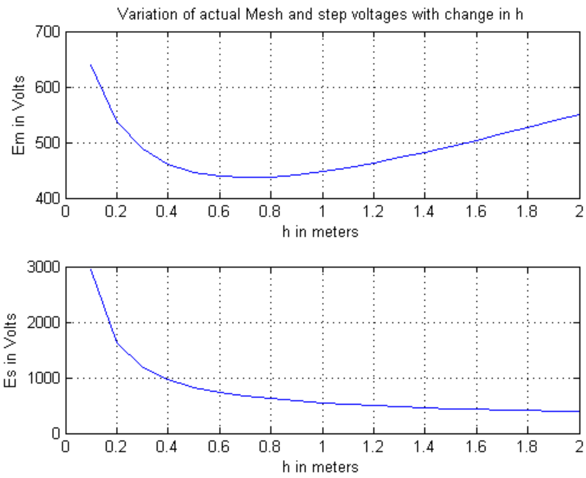

Fig.2. Variation of actual step and mesh voltages with change in grid depth

Depth of burial of grid does not have great effect on mesh voltage but has drastic effect on step voltage. With increased depth of grid step voltage decreases significantly because as current flows up toward surface most of the voltage is dropped in the soil itself and at the surface of earth less step voltage is experienced. Also GPR reduces with increased depth of burial until and unless lower layer earth has higher resistivity than upper layer. This is because with higher resistivity layers in the lower portion more current tends to flow toward lower resistivity earth surface thereby increasing potential at the earth surface [3].

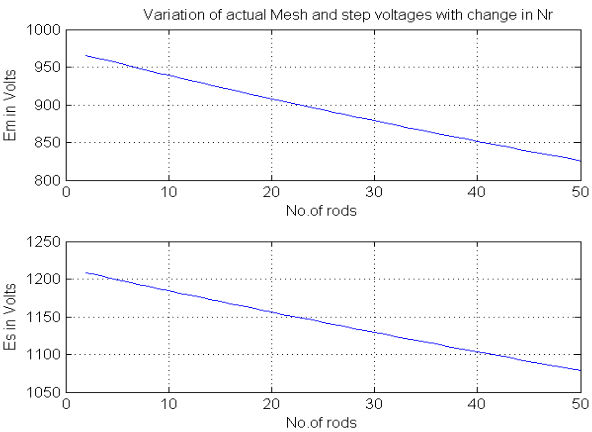

Fig.3. Variation of actual step and mesh voltages by changing No. of ground rods

Vertical ground rods discharge the grid current in the soil at sufficient depth. Thus they effectively reduce grid resistance and GPR. Also with more number of ground rods, total length of conductors buried in the earth increases thereby decreasing step and mesh voltages. In actual practice ground rods are considered to be an effective means of reducing grid resistance and also actual mesh and step voltages whenever design modifications are necessary. For same total length of conductor to be installed vertical rods are more cost – effective than horizontal grid conductors because they penetrate into lower resistivity layer of soil in the deep earth [4].

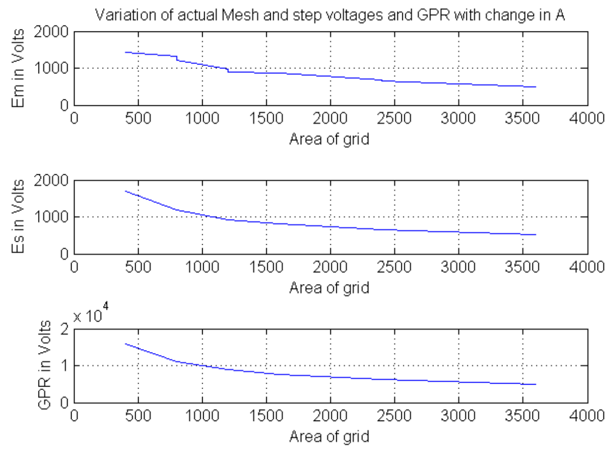

Fig.4. Variation of actual mesh and step voltages and GPR with change in area of grounding system

Area occupied by the grounding grid has major effect on GPR, step voltage as well as on mesh voltage. With increased area all the three types of potentials reduce significantly. Area contributes to reduction in grid resistance and thus GPR directly as is apparent from the relevant equations given in [1], also with increased area the length of buried conductors increases and thus actual step and touch voltages reduce.

All these parameters need to be considered while designing a safe and cost – effective grounding system.

IV. Optimal Ground Grid Designer

1) Salient features of the program

- Software named **"Optimal Ground Grid Designer"** has been developed using MATLAB GUI which utilizes theoretical concepts given in *IEEE standard 80 – 2000, 'IEEE Guide for Safety in AC substation Grounding'* for designing grounding system for any substation.
- This program is able to design grounding system for any substation as per methodology of IEEE guide. Additionally this program also allows modeling of soil as two layered soil which is not given in [1]. Two layer modeling of soil is nicely given in [5 - 6].
- In addition of being able to calculate various parameters of the grounding system for analyzing its performance, this software is also able to suggest the most appropriate safe, effective and optimal design of grounding system for the selected grid shape and given necessary data regarding soil and system parameters.
- Graphical user interface developed with the help of MATLAB GUI makes it quite user friendly and easy to work with.
- This program calculates required conductor size and automatically chooses the most appropriate standard conductor size available in the market manual entry is also possible.
- A list of commonly used conductor materials is provided and program automatically takes the standard values of material constants for the selected conductor material.
- This software is able to give ground grid design for all the basic shapes of grid as given in [1] and also triangular shaped grid.
- It gives well formatted output in Microsoft Word file.
- Results obtained here are found to be quite matching with those obtained from 'Ground Grid Systems' module of ETAP – a professional software used for solving problems related to power system by many utilities.

2) Program description

Following snap shots show various input pages of "Optimal Ground Grid designer". Result pages are shown in next section along with description of a design problem and its solution. User can easily navigate within the software and work with it easily. Any novice user can also use this software without having to go for thorough technical literature study before using it. Only thing needed is that basic methodology for designing grounding system and related terminology need to be known.

Fig – 5 shows the *Introduction* page of software giving general information and taking most basic information from user. This program works for all the four grid geometries as described in IEEE guide and also triangular shaped grid.

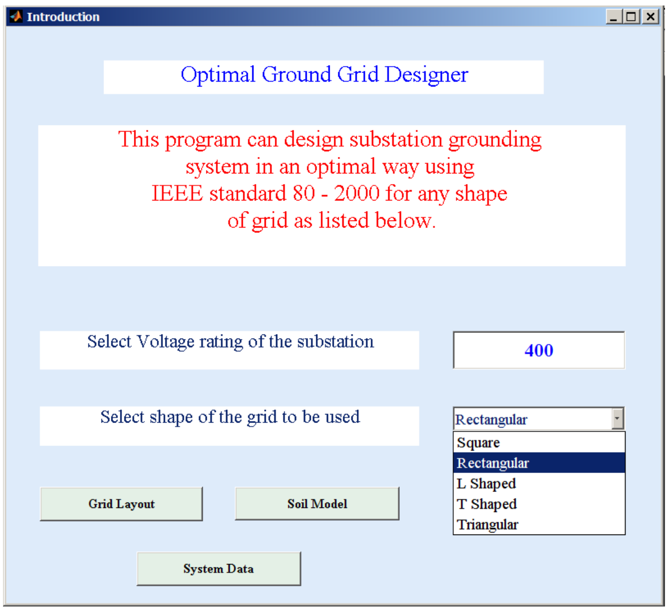

Fig.5. Introduction page of "Optimal Ground Grid Designer"

Next fig - 6 shows input page *Grid Layout* that asks for parameters related to general grid design like length of grid in both directions, number of conductors, depth of grid, conductor material for horizontal conductors and vertical ground rods etc. Standard material constants for selected conductor type are also shown which are decided by program itself implicitly based on values given in standards. In case of L and T shaped grids Lx long, Lx short, Ly long and Ly short values are to be taken but for all other cases Lx short and Ly short are not needed hence they are shown dark in the following figure. Based on information regarding conductor type and material constants from this page and fault current and fault duration from system data page, ampacity of conductor is decided and after taking into account corrosion allowance and future growth, conductor size is calculated. The software chooses nearest standard conductor size available in market from preloaded database.

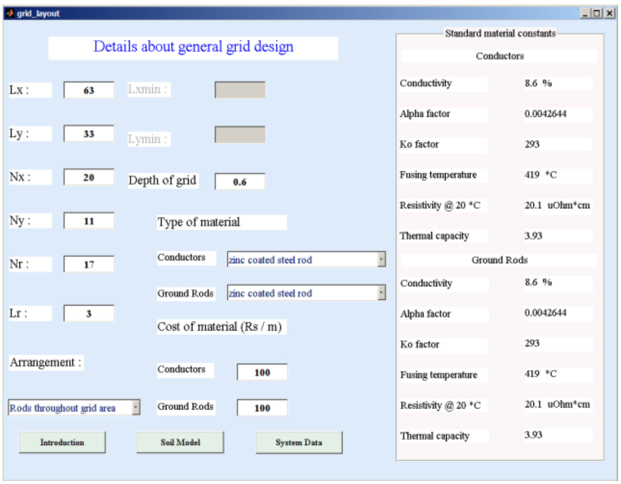

Fig.6 Input page *grid layout* that asks for data about general grid layout for proposed substation to be designed

Fig - 7 is *soil modeling* page that takes input data required for deriving mathematical model of soil at substation site in order to design grounding grid in uniform or two layered soil. Surface layer resistivity, thickness of surface layer, soil resistivity, and type of soil model decide resistance of grounding grid and actual voltages within substation. Uniform soil is not frequently encountered in actual practice. Two layer model of soil is generally satisfactory for normally encountered soils at actual substation sites, if not one has to go with multi layer soil modeling. However IEEE guide is valid for uniform soil assumptions only.

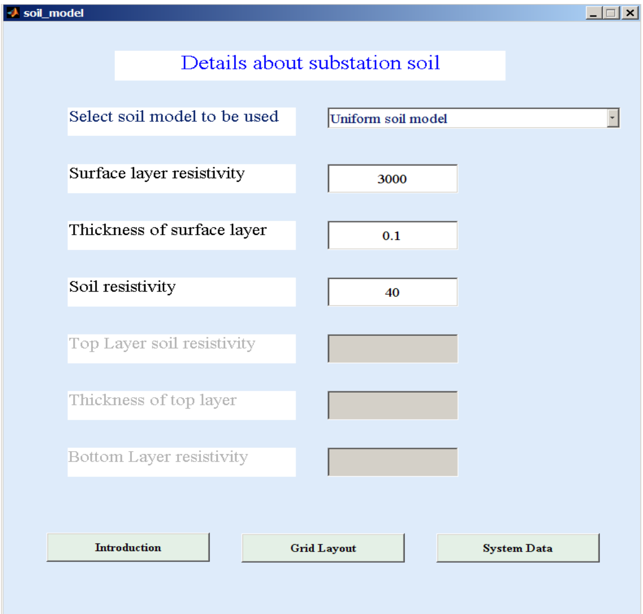

Fig.7 *Soil modeling* page taking inputs regarding soil data

Fig – 8 is *System data* page that takes inputs of general system related data, ambient conditions and fault current related data. These data are necessary to establish safety criteria and designing grounding system such that it does not violate the safety criteria.

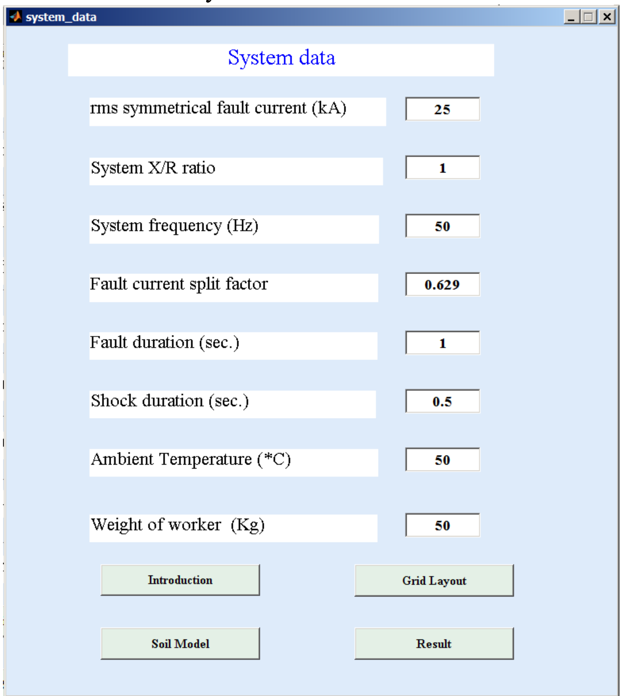

Fig.8 *System data* page that asks user to input necessary system data for ground grid design

After entering all the required parametric values for grounding system design this program asks for type of analysis to be done i.e. simple performance analysis or optimal design of grid considering changes in horizontal conductors only as shown in fig - 9.

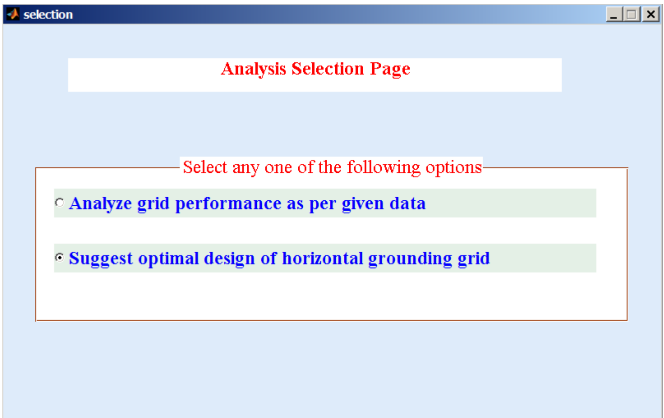

Fig.9 *Selection* page asking for analysis method to be adopted

After selecting analysis method, results are displayed on separate page and also complete report is provided in the form of Microsoft Word document.

Here follows description of a design problem of actual substation grounding system design as given in [7].

V. Design Problem Solved Using Optimal Ground Grid Designer

The design problem taken is of 400 kV ASOJ (Gujarat) proposed substation as described in [7]. Details of various parameters related to substation site, grid configuration and conductor are as follows.

TABLE I
INPUT DATA FOR SUBSTATION GROUNDING SYSTEM DESIGN

No.	Particular	Magnitude
1	Fault current	25 kA
2	Shock duration	0.5 Sec
3	Fault duration	1 Sec
4	Surface layer resistivity	3000 $\Omega \cdot m$
5	Surface layer thickness	0.1 m
6	Soil resistivity	40 $\Omega \cdot m$
7	Depth of burial of grid	0.6 m
8	Length of grid in X direction	63 m
9	Length of grid in Y direction	33 m
10	Conductor separation	3.3 m
11	No. of ground rods	17
12	Length of each ground rod	3 m
13	Ambient temperature	50 $^{\circ}C$
14	Cost of material	100 ₹/m
15	Conductor material	Zinc coated Steel rod

In ref. [7] authors have worked out for design of substation grounding system of ASOJ substation. They have proposed a safe grounding system considering rectangular shaped grid. However they have not tried for optimization.

In the present paper the same design problem of ASOJ substation is solved by using newly developed software 'Optimal Ground Grid Designer'.

Electrical Transient Analyzer Program (ETAP) power station is power system analysis software used by many power system engineers throughout the world. In ETAP there is a module named 'Ground Grid Systems' (GGS) for designing grounding system of substations as per methodology of IEEE 80 [8]. Hence ETAP 'Ground Grid Systems' module is used here to verify the results obtained with software developed herein.

TABLE II
COMPARISON OF RESULTS OF DESIGN PROBLEM OBTAINED IN THREE WAYS FOR ANALYZING GROUNDING SYSTEM PERFORMANCE

Particular	Unit	Solution method		
		1	2	3
Grid resistance	Ω	0.4099	0.41	0.41
Max. grid current	kA	15.750	15.750	15.734
GPR	Volts	6456.1	6456.2	6449
Tolerable step voltage	Volts	2212.7	2212.7	2212.8
Tolerable touch voltage	Volts	676.22	676.2	676.23
Actual step voltage	Volts	734.23	734.2	734.5
Actual touch voltage	Volts	439.62	439.6	438.5
Safety		Safe	Safe	Safe

Above table shows results of aforementioned design problem. The problem has been solved in three ways namely

1 – Using Optimal Ground Grid Designer
2 – Using ETAP Ground Grid Systems
3 – Suggested by authors in ref. [7]

Fig – 10 is *result page* of Optimal Ground Grid Designer which shows results in terms of Resistance, GPR, tolerable and actual step and mesh / touch voltages and safety comments.

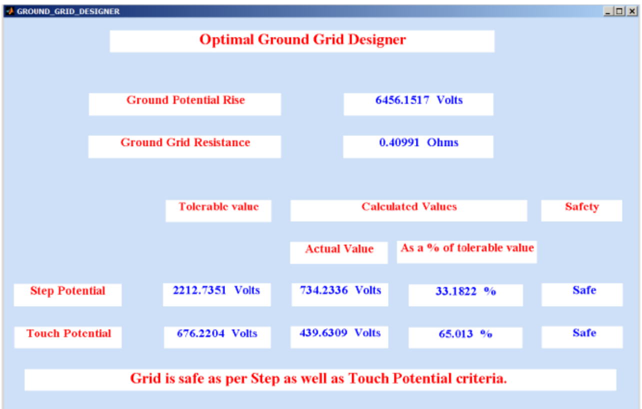

Fig.10 Output report page showing grid performance results obtained form Optimal Ground Grid Designer for general grid design without considering optimization.

Now same data is used and optimization process is applied in order to obtain optimal design of substation grounding system under given constraints of safety. Following figure shows result page of Optimal Ground Grid Designer for optimal design considering only horizontal grid conductors. The table that follows the figure shows comparison of results obtained by two softwares.

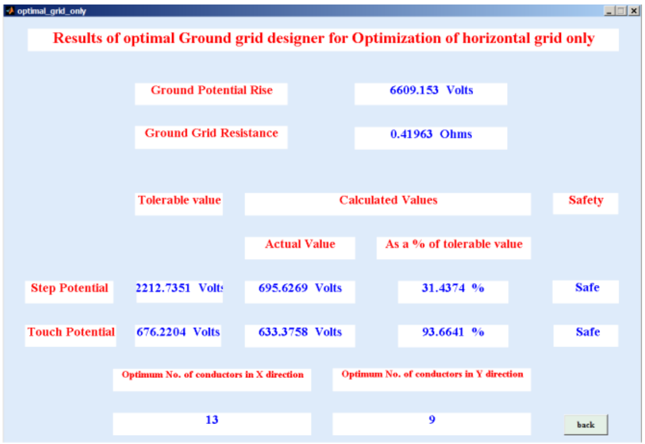

Fig. 11 Output report page showing grid performance results for Optimized grid design considering horizontal conductors only

TABLE III
COMPARISON OF RESULTS OBTAINED FOR GRID DESIGN CONSIDERING OPTIMIZATION OF *HORIZONTAL CONDUCTORS ONLY* BY TWO SOFTWARES

Particular	Unit	Solution method	
		1	2
Grid resistance	Ω	0.4196	0.4195
Max. grid current	kA	15.750	15.750
GPR	Volts	6609.1	6607.4
Tolerable step voltage	Volts	2212.7	2212.7
Tolerable touch voltage	Volts	676.22	676.2
Actual step voltage	Volts	695.63	698.9
Actual touch voltage	Volts	633.37	626.5
Optimum No. of conductors in X direction		9	8
Optimum No. of conductors in Y direction		13	15
No. of ground rods		17	17
Total conductor length (before)	m	1353	1353
Total conductor length (after)	m	996	999
Cost of grid (before)	₹	140400	140400
Cost of grid (after)	₹	104700	105000
Saving	₹	35700	35400

Now using the same data but by changing grid shape design problem is solved once again for triangular shape of grid. Following tables show comparison of results by two softwares before and after applying optimization. Also snap shots showing results generated by software developed here are shown in corresponding figures that follows the tables.

TABLE **IV**
COMPARISON OF RESULTS OBTAINED BY TWO SOFTWARES FOR TRIANGULAR SHAPED GRID BEFORE OPTIMIZATION

Particular	Unit	Solution method	
		1	2
Grid resistance	Ω	0.582	0.582
Max. grid current	kA	15.750	15.750
GPR	Volts	9167.9	9168
Tolerable step voltage	Volts	2212.7	2212.7
Tolerable touch voltage	Volts	676.22	676.2
Actual step voltage	Volts	1118.3	1118.4
Actual mesh voltage	Volts	696.77	696.8
Safety		Not Safe	Not Safe

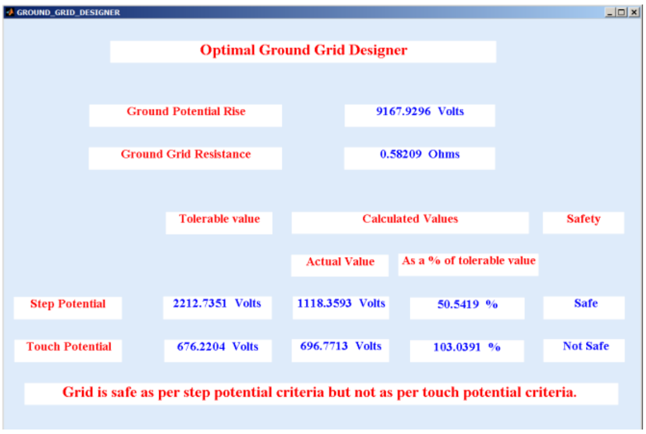

Fig. 12 Output report page showing grid performance for triangular shaped grid before optimization

TABLE **V**
COMPARISON OF RESULTS OBTAINED BY TWO SOFTWARES FOR DESIGN OF TRIANGULAR SHAPED GRID AFTER APPLYING OPTIMIZATION

Particular	Unit	Solution method	
		1	2
Grid resistance	Ω	0.58	0.577
Max. grid current	kA	15.75	15.75
GPR	Volts	9139.2	9099.5
Tolerable step voltage	Volts	2212.7	2212.7
Tolerable touch voltage	Volts	676.22	676.2
Actual step voltage	Volts	662.4	611.4
Actual touch voltage	Volts	1129.6	1150
Optimum No. of conductors in X direction		20	23
Optimum No. of conductors in Y direction		12	12
Total length (Before)	m	824	824
Total length (After)	m	856	905
Original cost of grid	₹	82400	82400
Cost after optimization	₹	85600	90500
Safety before optimization		Not safe	Not safe
Safety after optimization		Safe	Safe

General observations

- Software developed herein successfully analyzes performance of any shape of substation grounding grid.
- The program also gives optimal design of grounding system which is safe and cost effective.
- Results obtained here are reasonably matching with those obtained with Ground Grid Systems of ETAP.

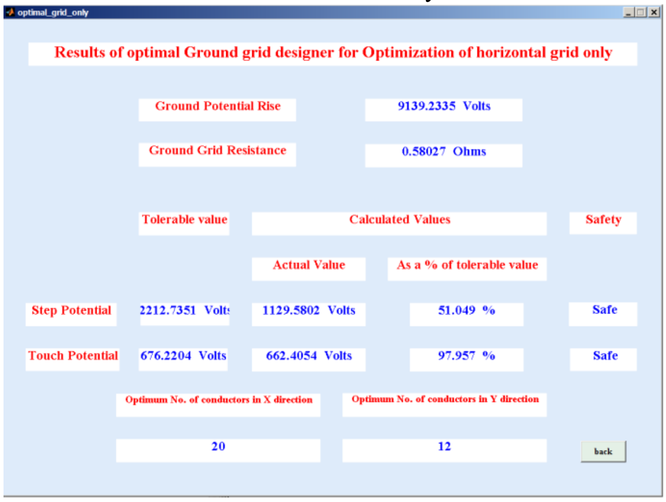

Fig. 13 Output report page showing grid performance and optimal design for triangular shaped grid after optimization

VI. CONCLUSION

In this paper effects of various parameters on the performance of ground grid are analyzed and most effective parameters are identified. Next by using newly developed software 'Optimal Ground Grid Designer', a design problem of grounding system design for 400 kV substation of ASOJ (Gujarat) has been solved. An attempt is made to solve the design problem so as to analyze performance of grounding system in general and also to achieve most appropriate and optimal design for the same for rectangular and triangular shapes of ground grid. This problem has been also solved by ETAP and the results by two softwares are compared. Comparison shows soundness of the program developed herein. This program analyzes grounding system performance satisfactorily and also suggests safe and cost – effective optimal design of grounding grid. Hence this software is found to be an effective solution in the field of substation grounding system design.

VII. REFERENCES

[1] Institute of Electrical and Electronics Engineers, *IEEE Guide for Safety in AC Substation Grounding*, IEEE standard 80 – 2000

[2] John D Mc Donald, *Electrical power substation engineering*, CRC Press, 2006

[3] A. Puttarach N.Chakpitak T. Kasirawat and C. Pongsriwat, *Ground layer depth and the effect of GPR*, IEEE PES Conference and Exposition Johannesburg, South Africa, 2007

[4] Ahdab Elmorshedy Rabah Amer Sherif Ghoneim, Holger Hirsch, *Surface potential calculation for grounding grids,* First International Power and Energy Conference, November 2006

[5] N.C. Chang and C.H. Lee, *Computation of Grounding Resistances and assessment of ground grid safety at 161/23.9 kV indoor type substation,* IEEE transactions on power delivery, Vol. 21, No. 3, pp. 1250 – 1260, 2006

[6] Y.L. Chow, M M A Salama and M M Elsherbiny, *Resistance Formulas of Grounding system in Two Layer Earth,* IEEE transactions on power delivery, Vol. 11, No. 3, pp. 1330 – 1336, 1996

[7] Pujara Ninad and Kapasi Husen, *Design of economical EHV substation,* B. Tech Major Project Report, Institute of technology Nirma University Ahmedabad, 2011

[8] ETAP user manual for ETAP power station 4.7.0

[9] Math works. Inc., *MATLAB online help manual* for MATLAB 7.6

[10] Stephen J. Chapman, *Essentials of MATLAB programming*, Fourth edition, Cengage Learning, Inc., 2006