Optimized Design of Substation Grounding System Using Newly Developed IEEE Compliant Software

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Abstract — **Substations form important linkage between various parts of the interconnected power system. They can be considered as heart of entire power system because successful operation of any power system depends to a great extent upon proficient and satisfactory performance of substations. In such substations, electrical safety is one of the most basic and important requirements. Responsibility of keeping the substation safe is upon the grounding system installed within it. In any substation deliberately planned earthing system plays an important role since absence of reliable and effective grounding system can result in maloperation or non-operation of control and protective devices and may prove hazardous for persons working therein. Also operation and safety of the equipments installed in the substation may be threatened. Therefore grounding system design is a task that deserves significant care and responsiveness. This work is mainly concerned with development of standalone software which eases optimized design of grounding system as per guide lines given in IEEE standard. Windows standalone application has been developed using MATLAB as a programming platform and mathematical computing tool as well. Graphical User Interface Development Environment of MATLAB is sued for designing the software. It has been made standalone with the help of MATLAB runtime compiler. Once designed and compiled in MATLAB, the software is capable of being used on any system even where MATLAB itself is not installed. A sample problem of 400 kV EHV substation is solved with the help of this newly developed software. Results obtained here are validated by comparison with those obtained from Ground Grid System Module of ETAP Power Station.**

Index Terms — **Earthing, Substations, Safety, Software, Programming, MATLAB GUIDE**

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 and successful operation of substations. It is therefore essential to exercise at most care while designing and building a substation. Grounding system plays crucial role in the performance of a substation as it provides place for connecting system neutral points, equipment body and support structures to the earth. It also ensures safety of working personnel within the substation and enables earth fault detection and protection. It provides path for discharging the earth currents from neutrals of equipments, faults, surge arrestors, overhead shielding wires etc. It keeps step and touch potential within tolerable limits. Hence properly designed and installed grounding system ensures reliable performance of electrical substation, safety of persons working within or near substation and limits the ground potential rise GPR within

acceptable levels. 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 for any substation, primarily to ensure electrical safety of persons working within or near substations. Substation grounding system being an essential part of the overall electrical system, its design is also of very much importance [1, 2]

Design of grounding system is an area in which there has been extensive study and analysis for last five decades. Several methods for grounding system analysis and design have been proposed. Numbers of computer programs have been developed to calculate safety parameters of an earthing installation in order to obtain a reliable model of ground grid and predict the hazardous scenarios which could occur under certain situations. Most of these methods are based on professional experience, on semi – empirical works, on experimental data obtained from scale models and laboratory tests or intuitive idea [3-8].

This paper describes development and use of software Economical Substation Grounding System Designer (ESGSD) which implements theoretical concepts given in IEEE standard 80 – 2000 into programming environment. It is designed using MATLAB® as a mathematical computing tool as well as programming platform. Basically MATLAB is a numerical computing environment and fourth-generation programming language developed by Math Works. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and FORTRAN. Here GUI development facility of MATLAB is exploited to design user friendly and also technically well proven software. In order to validate its technical performance, design problem has been solved by ESGSD in uniform soil for simple performance analysis as well as optimal design of substation grounding system. Results obtained by it are compared with those given by Ground Grid Systems (GGS) module of ETAP – power station. Comparison table showing results obtained by both the software clearly prove that ESGSD gives fairly correct results for grounding system design and it is found to be trustworthy tool for design of grounding systems of HV / EHV substations as far as performance of grounding system is evaluated at power frequency.

II. THEORETICAL BACKGROUND FOR SUBSTATION GROUNDING SYSTEM DESIGN AS PER IEEE GUIDELINES

A. Safety criteria for grounding system design

A reliable grounding system should be able to maintain the actual mesh and step voltages within a substation well below the corresponding tolerable level. Before 1960s the design

criterion for substation earthing system was low earthing resistance alone. However during 1960s the new criterion for design and evaluation of substation earthing system was evolved which included following three conditions

Low step voltage, Low touch voltage and, Low earth resistance [9]

These tolerable safety criteria have been established based on fibrillation discharge limit of body current. In order to make grounding system safe, equivalent grounding system impedance should be low enough to assure that fault current dissipates mainly through grounding grid into earth. While designing grounding system, main consideration is to be given to the fact that under any circumstances actual mesh and step voltages must not exceed the tolerable values given by following equations.

$$E_{step\_50} = \left(1000 + 6 \cdot \rho_S \cdot C_S\right) \cdot \frac{0.116}{\sqrt{t_S}} \ldots\ldots\ldots..(1)$$

$$E_{step\_70} = \left(1000 + 6 \cdot \rho_S \cdot C_S\right) \cdot \frac{0.157}{\sqrt{t_S}} \ldots\ldots\ldots..(2)$$

$$E_{touch\_50} = \left(1000 + 1.5 \cdot \rho_S \cdot C_S\right) \cdot \frac{0.116}{\sqrt{t_S}} \ldots\ldots\ldots..(3)$$

$$E_{touch\_70} = \left(1000 + 1.5 \cdot \rho_S \cdot C_S\right) \cdot \frac{0.157}{\sqrt{t_S}} \ldots\ldots\ldots..(4)$$

Where

E_{step_50} and E_{step_70} are tolerable step voltages for person weighing 50 Kg and 70 Kg respectively

E_{touch_50} and E_{touch_70} are tolerable touch voltages for person weighing 50 Kg and 70 Kg respectively

For grounding system to be safe actual voltages present on substation earth must be less than the values given by above equations which describe the maximum value of voltages that can be tolerated by human being in case of step voltage accidental scenario and touch voltage accidental scenario respectively.

B. *Design objectives*

A practical grounding system is designed to fulfill following two design objectives

- To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.
- To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.
  Following figure 1 shows flowchart describing IEEE methodology for grounding system design
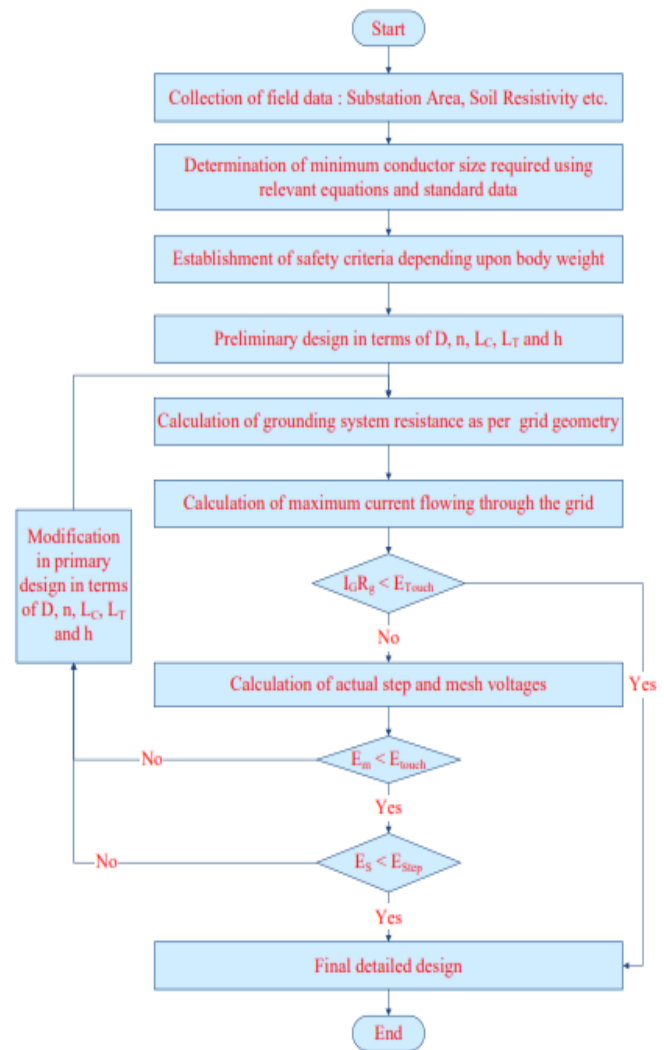 Detailed guidelines for designing the grounding system and relevant equations can be found from [9].

Fig. 1. *Flowchart showing step by step methodology of grounding system design as per IEEE standard guidelines*

Based on these guidelines software ESGSD has been developed to design grounding system in optimized way.

III. DEVELOPMENT OF IEEE COMPLIANT SOFTWARE ECONOMICAL SUBSTATION GROUNDING SYSTEM DESIGNER

A. *Basics of MATLAB GUIDE and ESGSD*

MATLAB GUI Development Environment (GUIDE) allows creation of GUI so that the code written in script files becomes more user-friendly. With the help of MATLAB GUIDE standalone applications can be developed for professional use or for educational or training purpose. Here software named 'Economical Substation Grounding System Designer' (ESGSD) has been developed using MATLAB GUIDE. It implements theoretical concepts given in [9] in the software form. ESGSD is preliminary developed in order to assist the engineers in the design of substation grounding system. More details about the detailed procedure for grounding system design as per IEEE standard guide lines can be found from [2, 9]. This is for the first time that such stand alone application for grounding system design is developed using MATLAB GUIDE. This investigates applicability of MATLAB for the purpose of GUI development that helps programmers familiar with MATLAB coding in terms of application deployment. ESGSD is found to be quite useful for electrical engineers for

gaining basic knowledge about grounding system design. Also this can be used for educational purpose for students of electrical engineering studying subjects of power system design.

Figure 2 shows main page of the software ESGSD that allows access to all other input and output modules. Main details related to substation grounding system design such as shape of ground grid, voltage rating of the substation etc. are to be entered in this page. This page allows access to all other input - output modules. By accessing various other input pages like grid layout, soil model and system data, further details about grounding system design can be entered. Also simple analysis or optimization of the proposed grounding system can be performed by respective options. Report for the designed grounding system can also be generated from here which will be Microsoft word document.

By using the software developed here, performance of grounding system can be analyzed for human safety. In addition of analyzing grounding system as per IEEE guide lines, ESGSD can apply optimization to the grounding system design process by considering various factors. ESGSD is designed to work for uniform soil as well as for two layered soils for simply analyzing performance of grounding system or to get optimal design.

B. Algorithm for working of ESGSD

Equations given in [9] and other derived from relevant literature [3 – 8] are converted into MATLAB code and implemented as per algorithm shown in Figure 3 which describes flow chart for working of ESGSD.

As a first step input details are taken from user through input modules viz. grid layout, soil model and system data. Now performance of the system can be analyzed or optimal design can be obtained from the software as per user need by selecting appropriate decision variables in main page. Optimized design can be obtained by considering various options e.g. optimization for minimum cost, optimization for maximum safety etc.

C. ESGSD as windows standalone application

GUI developed with the help of MATLAB runs well in MATLAB environment however if not deployed as standalone application it may fail when appropriate version of MATLAB is not available.
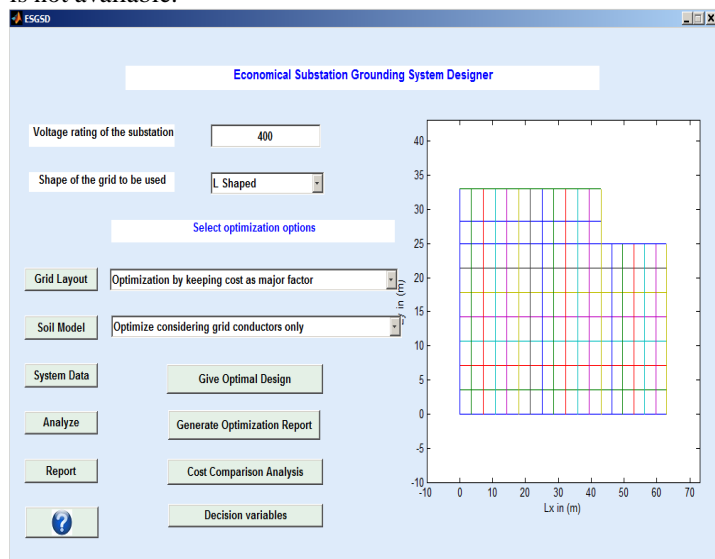

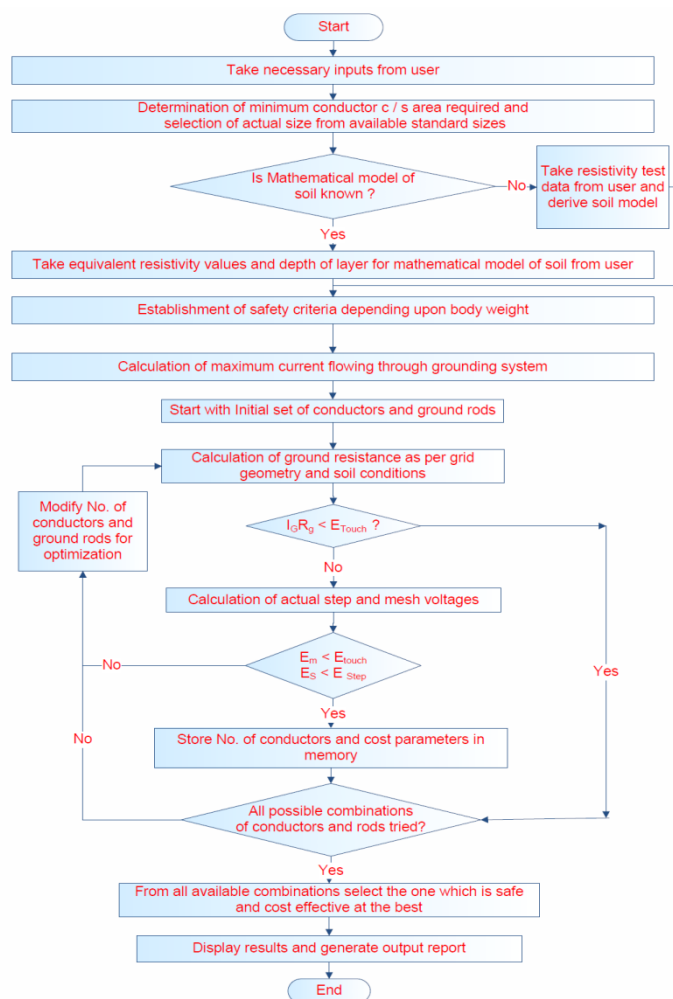Fig. 2. *Main Page of the software ESGSD*

Fig. 3. *Flowchart showing algorithm of the software ESGSD*

MATLAB compiler addon facilitates standalone application deployment easily which can be used by person with little knowledge of software engineering. However in order to develop such applications using MATLAB certain things are very much important. Main consideration while deploying any GUI as standalone application using MATLAB is that all data transfer between various GUIs should be implicit i.e. data transfer mechanism should be such that it facilitates smooth data transfer between all the GUIs which are packed in a project file to generate executable application.

Certain instances are observed when an application runs properly in presence of MATLAB but fails when deployed as standalone application which has to work with MATLAB run time compiler. Here all such possibilities are avoided by following data sharing mechanism.

- Data to be shared within GUI or among GUIs is set as application data with the help of *'setappdata'*
- Handle of the GUI from which data is to be taken is passed to the GUI to which the data is to be sent
- Application data is retrieved using appropriate graphic handle and *'getappdata'*
- Occasionally important data is passed to the called function where the data is retrieved from that function's *'varargin'* in opening function of the called GUI. After calculations the results can be passed back to the calling

function with the help of 'varargout' option available in output function of the GUI.

Because of this mechanism the application becomes standalone in a true sense i.e., it works satisfactorily even when MATLAB is not available.

IV. OPTIMIZATION OF GROUNDING SYSTEM DESIGN

ESGSD allows two options for any grounding system

- Simple performance analysis of grounding system by taking data related to grid geometry, system parameters and soil parameters.

- Optimal design of grounding system consisting of ground grids having any of the five basic grid shapes namely square, rectangular, triangular, L shape and T shape in uniform as well as two layered soil by taking the same data as for first option.

After analyzing effects of various parameters on grounding system performance following are identified as the most dominating and controllable parameters that affect grounding system performance [10].

- Spacing between adjacent conductors in ground grid (D),

- Depth of burial of earthing grid (h),

- Number of vertically buried grounding rods (N_r)

- Area covered by grounding grid (A),

Detailed description of effects of these parameters on grounding system performance can be found from [1, 2 and 10]. At least two if not all must be the decision variables while deciding optimization problem for the grounding system design. Optimization is applied in order to make design safe as well as cost effective such that the technical performance of grounding system in terms of human safety and equipment safety is never compromised and additionally cost benefits are incurred after meeting all the fundamental requirements of electrical safety performance.

Linear cost objective function is defined for grounding system optimization problem and is subjected to linear safety and geometrical constraints. Decision variables are D (or N_x and N_y), h, N_r and L_r .This can be treated as mixed integer programming problem because, here decision variables h and L_r may assume non integer values.

Cost objective function to be minimized is

$$f\left(N_X, N_Y, N_r, L_r, h\right) =$$

$$N_r \cdot (L_r \cdot C_{ri} + C_r) + L_c (C_i + C_C) + k_1 \cdot h ....(5)$$

The objective function is to be minimized subjected to geometrical and safety constraints as shown below

$$E_{m\_act} \le X \cdot E_{m\_tol} ....(6)$$

$$E_{s\_act} \le X \cdot E_{s\_tol} ....(7)$$

$$C_1 D_1 \le C_2 D_2 \le C_2 ....(8)$$

$$2.5 \le D \le 22.5 ....(9)$$

Where

N_r = No. of vertically buried grounding rods

L_r = Length of each ground rod (m)

C_{ri} = Installation cost of ground rods (Rs. / m)

C_r = Material cost for ground rods (Rs. / rod)

L_C = Total length of conductors in ground grid (m)

C_i = Installation cost for grid conductors (Rs. / m)

C_C = Material cost of conductors (Rs. / m)

E_{m_act} = Actual mesh voltage (Volts)

E_{m_tol} = Tolerable mesh voltage (Volts)

E_{S_act} = Actual step voltage (Volts)

E_{S_tol} = Tolerable step voltage (Volts)

D_1 = Spacing between conductors in X direction (m)

D_2 = Spacing between conductors in Y direction (m)

D = Average separation between any two consecutive conductors in the ground grid (m)

X = Specified percentage of the tolerable value.

These safety criteria state that actual mesh and step voltages must be less than X percent of the corresponding tolerable values, X is dependent on user requirement. Spacing between the conductors in horizontal grid should be uniform and almost equal in both directions and spacing between two adjacent conductors should be between 2.5 m to 22.5 m. By satisfying geometrical constraints the design assures that equations given in [9] are applicable to the present grounding system with a fair degree of accuracy and by satisfying safety constraints electrical safety of persons working in the substation site is ensured. Minimization of cost objective function gives economical and yet safe i.e. cost effective design of grounding system. Thus design given by solving above optimization problem is optimal because it reveals minimal cost among all the designs giving similar performance.

V. VALIDATION OF TECHNICAL PERFORMANCE OF ESGSD (TESTING OF THE SOFTWARE)

Before accepting any newly developed software one important stage is its testing. In order to check performance of any software and declare it as reliable one the results obtained by it need to be verified against some standard or widely used expert software. The same thing is also true for ' ESGSD' software developed herein. For the purpose of checking the validity of the results given by ESGSD, a sample design problem is solved by ESGSD and 'Ground Grid Systems' module of ETAP intelligent power system analysis software package [11]. Results obtained by both the software are compared for simple performance analysis and also for optimal design as can be seen from following subsection.

ESGSD is capable of analyzing the ground grid of five various shapes namely square, rectangular, L shaped, T shaped and triangular grids. Here sample problem of rectangular grid in uniform soil is taken. Other results can be found from [2].

TABLE I. INPUT DATA REQUIRED FOR GROUNDING SYSTEM DESIGN

Input data	Value
Grid shape	Rectangular
Depth of burial of grid (h)	0.6 m
Length in X direction (L_x)	80 m
Length in Y direction (L_Y)	41 m
Spacing between conductors (D)	4 m
No. of ground rods (N_r)	50
Length of ground rod (L_r)	3 m
Ambient temperature (T_a)	50 ^{o}C
Cost of grid conductors ($C_c + C_i$)	2100 Rs/m
Cost of ground rods ($C_r + C_{ri}$)	2100 Rs /m
Fault current split factor (S_f)	0.6
Shock Duration (t_s)	0.5 sec
Fault duration (t_f)	1 sec
Current projection factor	1.25

Surface layer resistivity (ρ_s)	1500 $\Omega \cdot m$
Surface layer thickness (h_s)	0.2 m
Soil resistivity (ρ)	50 $\Omega \cdot m$
Fault current (I_f)	15kA
Material for grid conductors	Galvanized steel
Material for ground rods	Galvanized steel

TABLE II.   RESULTS FOR RECTANGULAR SHAPED GROUNDING SYSTEM LOCATED IN UNIFORM SOIL

Particular	Results obtained form	
	ESGSD	ETAP
Resistance (R_g) Ω	0.408	0.41
GPR (Volts)	4598.9	4598.9
(E_{s_tol}) (Volts)	1378.34	1378.3
(E_{m_tol}) (Volts)	467.62	467.6
(E_{s_act}) (Volts)	459.1	459.1
(E_{m_act}) (Volts)	362.6	362.6
(E_{s_act}) / (E_{s_tol}) %	33.3	33.3
(E_{m_act}) / (E_{m_tol}) %	77.54	77.54

In the table – II following notations are used
(E_{s_tol}) = Tolerable step voltage
(E_{m_tol}) = Tolerable mesh voltage
(E_{s_act}) = Actual step voltage
(E_{m_act}) = Actual mesh voltage
As seen from the table, there is close agreement between the results given by both the software. Also proposed grounding system is safe. This validates performance of newly developed software ESGSD as compared with ETAP – GGS. Various other possibilities comprising of various grid shapes and soil models are also evaluated that can be found from [2].

VI. OPTIMIZATION OF SUBSTATION GROUNDING SYSTEM

Here actual design problem of the grounding system installed at ASOJ substation located in Gujarat India is considered. Data is taken form [13]. Following table III shows the input data required for grounding system design.

TABLE III.   INPUT DATA REQUIRED FOR GROUNDING SYSTEM DESIGN

Input data	Value
Grid shape	Rectangular
Depth of burial of grid (h)	0.6 m
Length in X direction (L_x)	63 m
Length in Y direction (L_Y)	33 m
Spacing between conductors (D)	3.3 m
No. of ground rods (N_r)	17
Length of ground rod (L_r)	3 m
Ambient temperature (T_a)	50 ^{o}C
Cost of grid conductors ($C_c + C_i$)	2000 Rs/m
Cost of ground rods ($C_r + C_{ri}$)	2000 Rs /m
Fault current split factor (S_f)	0.6
Shock Duration (t_s)	0.5 sec
Fault duration (t_f)	1 sec
Current projection factor	1.25
Surface layer resistivity (ρ_s)	3000 $\Omega \cdot m$
Surface layer thickness (h_s)	0.1 m
Soil resistivity (ρ)	40 $\Omega \cdot m$
Fault current (I_f)	25kA
Material for grid conductors	Galvanized steel
Material for ground rods	Galvanized steel

Upon analyzing the grounding system it is observed that the system is safe with safety margin of 68% and 34% in step and touch potential respectively. This shows that there is considerable potential of cost saving if we allow the actual voltages to nearly reach upto 80 – 85% of tolerable value. After optimizing the design of proposed grounding system result shown in table IV are obtained. Also figure 4 indicates the cost benefit obtained by application of optimization taking N_X, N_Y, N_r and L_r as decision variables. As seen from figure 4 saving of Rs. 6, 12,000/- is obtained which is almost 22% of cost of original proposed design. These results are also validated by comparing them with those obtained from GGS module of ETAP power station. Details can be obtained from [2].

TABLE IV.   RESULTS OF ASOJ SUBSTATION GROUNDING SYSTEM DESIGN

Particular	Results obtained	
	Before Optimization	After Optimization
Resistance (R_g) Ω	0.4099	0.417
(E_{s_tol}) (Volts)	2212.73	2212.73
(E_{m_tol}) (Volts)	676.22	676.22
(E_{s_act}) (Volts)	710.32	609.03
(E_{m_act}) (Volts)	452.39	573.32
(E_{s_act}) / (E_{s_tol}) %	32.1	27.52
(E_{m_act}) / (E_{m_tol}) %	66.9	84.78
N_X	20	14
N_Y	11	8
N_r	17	49
Cost of grid (Rs)	2736000	1932000
Cost of rods (Rs)	1,02,000	2,94,000
Total cost (Rs)	28,38,000	22,26,000
Saving (Rs)	-	6,12,000
Safety	Safe	Safe

Fig. 4. *Output of ESGSD software for simple performance analysis of given grounding system*

VII. CONCLUSION

Here Software for optimal design of grounding system is built up by using MATLAB. Standalone application named 'Economical Substation Grounding System Designer (ESGSD)' has been developed using MATLAB as

mathematical computing tool as well as programming platform. It has been packed and deployed as windows standalone application using MATLAB compiler addon, hence it is capable of working satisfactorily on its own. MATLAB GUIDE provides excellent environment for software development. By developing GUIs code becomes more user friendly. MATLAB runtime compiler addon helps in making the application standalone so that it can run on any system even where MATLAB is not installed. The only thing that is needed is installing MATLAB compiler which is available in the application itself. Here MATLAB is used for first time for such extensive application development which is quite useful for educational purpose as well apart from its conventional use for coding and simulations. ESGSD implements safe grounding system practices described in IEEE standard 80 2000. Additionally it allows modeling of soil as two layered structure. Also by selecting appropriate options for optimization, ESGSD gives optimized grounding system design which is safe and cost effective. ESGSD designed here gives quite reliable results for optimal design of grounding systems for any substation. These are also verified by GGS module of ETAP Power Station. From the sample problem of grounding system design taken here it is observed that In majority of cases, grounding systems are intentionally made overdesigned to take into account future growth and to cope up with any unexpected scenario in order to ensure safety of people. Hence in such cases by judiciously designing the grounding system, great amount of saving can be incurred

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