Development of a Mobile Design Template for Substation Earthing System

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***Abstract*—Electrical engineers often find the process of designing the earthing system of substations to be tedious, arduous and time consuming. Mobile apps development and usage has been on the rise of late due to the high availability of smart phones and Internet of Things. In terms of electrical earthing system design, there are very few applications available which are neither helpful nor informative. Hence, this paper outlines the development of a mobile application which is able to assist and ease electrical engineers' design process. Functionality and validity of the app has been verified by comparing calculations obtained manually and by the app. Hence, this app can be used for the design and verification of an earthing system.**

Keywords—earthing system; substation; Javascript; mobile apps

I. INTRODUCTION

Earthing system is an electrical network that is connected to the earth to provide safe return path for fault current as well as to operationalise the protective devices to protect the safety of equipment and human [1]. Substation is an essential part of the power system to ensure power delivery to the consumers. Hence, substation earthing system is crucial to ensure not only reliable power distribution but also the safety of workers and equipment. The IEEE 80 standard has been one of the most comprehensive advocate of the design of a sound earthing system for substations [2]. However, practicing electrical engineer involved in the design of a substation earthing system often find the design process to be arduous and tedious. Once designed, several rounds of verification usually take place to ensure the calculation is done without error.

There are several commercial software such as CDEGS, ETAP and AutoGrid Pro which offer help for engineers to design the substations earthing system. Unfortunately, the aforementioned software tends to require significant subscription charges which could be burdensome to small or even medium-scale consulting firms. In addition, such software usually requires additional training to meaningfully apply them to design a substation earthing system. As the result, many practicing engineers still prefer to fall back on the manual design methodology as per IEEE 80 standard.

The field of mobile application development has been growing on an exponential scale in the past decade. More than 5 million mobile applications have been developed and made available today. Despite the staggering figure, the number of mobile applications developed for engineering application remains to be relatively insignificant compared to healthcare, learning, gaming and lifestyle domain. It cannot be denied that mobile apps can be an extremely convenient tool due to the high portability of smartphones.

A quick survey in the major apps store reveals limited number of apps developed to assist the design of electrical earthing systems. Table I summarises few of the aforementioned apps:

TABLE I. COMPARISON OF AVAILABLE APPS

Application name	**Electrical earthing**	**Electrical engineering practical**	**Electrical calculation**
Description	Describe earthing product installation in general..	Explains how electrical system works in general without any calculation.	The free version of the app calculates some basic value on electrical system such as voltage drop, current, active power, reactive power, etc. whereas the calculations of earthing system requires an amount of money to active the app.

With this motivation in mind, this paper shall outline the processes involved in developing a mobile app which has the capability to verify the design of a substation earthing system. It is desirable for the apps to have these characteristics:

- Perform calculation of all the needed values in a simple manner
- Simple User-Interface.
- Embedded user guide which briefly explains each parameter in a clear manner to the user
- Indicates whether the current earthing system design is safe or not after the calculation is complete.

Fig.1 depicts the fundamental working principle of a desirable app for the aforementioned purpose.

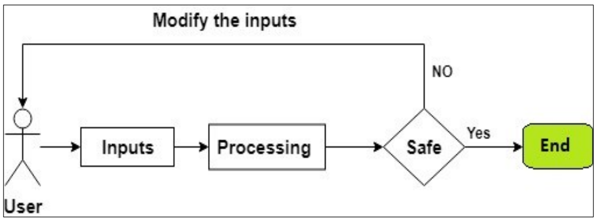

Fig. 1. Working flow of the desirable app

II. METHODOLOGY

Fig. 2 illustrates the overall design philosophy of a substation earthing system according to IEEE 80 [2]. The desirable app shall be able to perform the logic and calculations according to the flow in Fig. 2 before eventually providing a conclusion on whether the current design meets the safety criteria or otherwise.

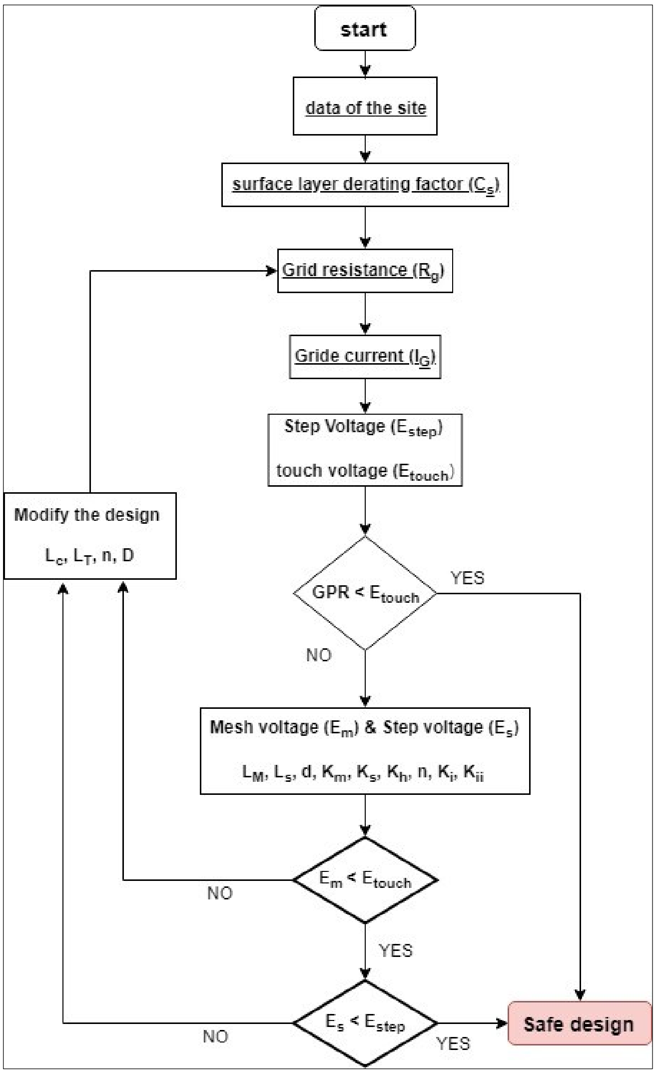

Fig. 2. Substation earthiig system design flow [2]

Before starting to design an earthing grid, it is paramount to ensure that the soil resistivity data is obtained via measurement method as recommended in IEEE 81 [3]. Due consideration has to be given to possible environmental factor which may affect the soil resistivity value [4].

A thin layer of high resistivity material such as gravel, is usually placed above the ground grid to increase the contact resistance between the ground and the human feet in the substation area. The thickness of the surface layer should be between 0.08m and 0.15m to help to protect person against dangerous step and touch voltages [2]. The surface layer derating factor is calculated by:

$$C_s = 1 - \frac{0.09\,(1 - \frac{\rho}{\rho_S})}{2\,h_s + 0.09} \quad (1)$$

where

C_s Surface layer derating factor.

ρ Soil Resistivity (Ω.m)

ρ_s Resistivity of surface layer material (Ω.m).

h_s Thickness of surface layer (m).

Minimizing the ground potential grid (GPR) can be done by the design of a good earthing grid with low resistance [1]. Grid resistance goes side by side with the earthing grid design and it can be calculated by [2]:

$$R_g = \rho\,[\frac{1}{L_T} + \frac{1}{\sqrt{20\,A}}\,(1 + \frac{1}{1+h\,\sqrt{20\,/\,A}})] \quad (2)$$

where

R_g grid resistance (Ω)

L_T total buried length of conductors (m)

A area of grid (m^2)

h depth of grid (m).

ρ Soil Resistivity (Ωm)

The worst scenario where the earth fault current would flow through the earthing grid back to earth is known as maximum grid current and can be calculated by [2]:

$$I_G = I_g \times D_f \quad (3)$$

where

I_G grid current (A)

I_g symmetrical earth fault current (A).

D_f decrement factor.

The decrement factor used in conjugation with the symmetric ground fault current parameter is given by [2]:

$$D_f = \sqrt{1 + \frac{T_A}{t_f} + (1 - e^{\frac{-2\,t_f}{T_A}})} \quad (4)$$

where

D_f decrement factor

T_A dc time offset constant

t_f Fault duration (s)

The dc time offset constant is given by [2]:

$$T_A = \frac{X}{R} \times \frac{1}{2\pi f} \quad (5)$$

where

X/R ratio of fault location

f system frequency (Hz)

The reactance and resistance parameter in the fault location ratio is given by:

$$R = \frac{100\,(Tx\ load\ loss - Tx\ no\ load\ loss)}{Tx\ rating \times 1000} \quad (6)$$

$$X = \sqrt{Tx_{impedance}{}^2 + R^2} \quad (7)$$

where

T_X transformer

Next, the safe touch and step voltages for human being weighing 50kg and 70kg can be calculated as follows [2]:

$$E_{touch,50kg} = (1000 + 1.5C_s\rho_s)\frac{0.116}{\sqrt{t_s}} \quad (8)$$

$$E_{step,50kg} = (1000 + 6C_s\,\rho_s)\frac{0.116}{\sqrt{t_s}} \quad (9)$$

$$E_{touch,70kg} = (1000 + 1.5C_s\,\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (10)$$

$$E_{step,70kg} = (1000 + 6C_s\,\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (11)$$

where

C_s surface layer derating factor

t_s maximum fault clearing time

ρ_s soil resistivity (Ωm)

Then, the ground potential rise, GPR can be calculated by:

$$GPR = I_G \times R_g \quad (12)$$

The next step is crucial as it will determine whether the current earthing grid design is safe or otherwise. The design is deemed as safe if GPR does not surpass touch voltage limit. Conversely, the design is deemed as unsafe if GPR value exceeds the touch voltage limit. In such case, further calculation of mesh voltage E_m and step voltage E_s is required as follows [2]:

$$E_m = \frac{\rho_s\ K_m\ K_i\ I_G}{L_m} \quad (13)$$

where

ρ_s soil resistivity (Ωm)

K_m geometric spacing factor

K_i irregularity factor

L_m effective buried length of the grid

$$K_m = \frac{1}{2\pi}\left(ln\left[\frac{D^2}{16h \times d} + \frac{(D+2h)^2}{8D \times d} - \frac{h}{4d}\right] + \frac{K_{ii}}{K_h} ln\left[\frac{8}{\pi(2n-1)}\right]\right)$$

where

D spacing between parallel grid conductors (m)

h depth of buried grid conductors (m)

d diameter of grid conductor (m)

k_h weighting factor for burial depth = $\sqrt{1+h}$

K_{ii} weighting factor for earth electrodes /rods on the corner mesh

$K_{ii} = 1$ for grid with electrodes along the corner

$K_{ii} = \frac{1}{2n^{\frac{2}{n}}}$ for grid with no electrodes on the corners

n geometrical factor

$$n = n_a \times n_b \times n_c \times n_d$$

where

$$n_a = \frac{2L_c}{L_p}$$

- $n_b = 1$ for square grid otherwise

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}}$$

- $n_c = 1$ for square and rectangular grid, otherwise

$$n_c = \left[\frac{L_x L_y}{A}\right]^{\frac{0.7A}{L_x L_y}}$$

- $n_d = 1$ for square, rectangular or L-shape, otherwise

$$n_d = \frac{D_m}{\sqrt{L_x{}^2 + L_y{}^2}}$$

where

L_c total length of horizontal grid conductors (m)

L_p grid perimeter (m)

A total area of grid (m^2)

L_x and L_y maximum length of grid in x and y directions (m)

D_m maximum distance between any two points on the grid (m)

$K_i = 0.644 + 0.148\,n$

For grid without earthing electrodes:

$$L_M = L_c + L_R$$

For grid with earthing electrodes on the corners:

$$L_M = L_c + \left[1.5 + 1.22\left(\frac{L_r}{\sqrt{L_x{}^2 + L_y{}^2}}\right)\right] L_R$$

where

L_c total length of horizontal grid conductors (m)

L_R total length of earthing electrodes (m)

L_r length of each earthing electrodes (m)

L_x and L_y maximum length of the grid in x and y directions (m)

The step voltage can be calculated as follows [2]:

$$E_s = \frac{\rho_s \; K_s \; K_i \; I_G}{L_s} \qquad (14)$$

where

ρ_s soil resistivity (Ωm)

I_G maximum grid current (A)

K_s geometrical spacing factor

K_i irregularity factor

L_s effective buried length of the grid

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right]$$

where

D spacing between parallel grid conductors (m)

h depth of buried grid conductors (m)

n geometrical factor

$$L_s = 0.75L_c + 0.85L_R$$

where

L_c total length of horizontal grid conductors (m)

L_R total length of earthing electrodes (m)

After mesh and step voltages have been found, their values will be compared with maximum allowable mesh and step voltages. If ($E_m > E_{touch}$) and ($E_s > E_{step}$) then the current design of earthing grid system needs to be modified possibly by increasing the grd area, reducing the grid spacing, burying additional ground conductor grid outside the vicinity or by increasing the thickness of surface materials. Otherwise, the current design is deemed as safe.

III. APPLICATION DEVELOPMENT

The application has been developed by using the SCRUM model of app development. SCRUM model is an iterative process, whereby the development of the application is split into multiple stages. Agile SCRUM process helps the companies and developers in enhancing the quality of the products by being more adaptive to changes, requiring less time to create best estimates, thus allowing developers to more control over the project scheduling [5]. Fig. 3 shows how the flow of how an app is typically being developed.

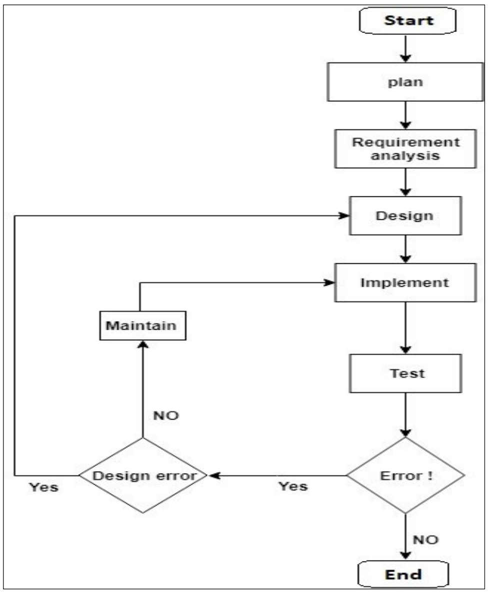

Fig. 3. Flow of application development

Planning requires identification of the objective of the mobile application, target users as well as the features of the app. Requirement analysis is to determine the users' expectations for the mobile application. These requirements have been detailed out in Section II of this paper. At the design stage, care has to be given to ensure that the design of each screen of the application is as detailed as possible to ease users' experience. Inclusion of short description for each input, placement of each screen button, navigation between screens and display of result have to be considered.

IV. RESULTS AND DISCUSSIONS

Fig. 4 shows the home screen of the application. The current version of the application includes a user guide that briefly explains every parameter used in the calculation.

Fig. 4. Home screen of the app

Fig. 5 shows the first screen of the application. User has to input several parameters such as soil resistivity, grid dimensions and has to select the type of surface layer.

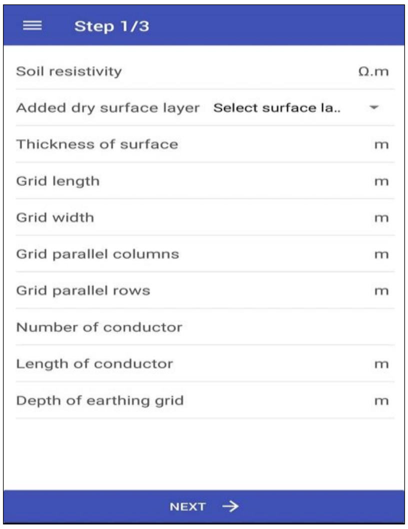

Fig. 5. First screen of the app

Fig. 6 illustrates the second screen of the app where the design engineer has to specify parameter such as system frequency, maximum fault duration and transformer rating.

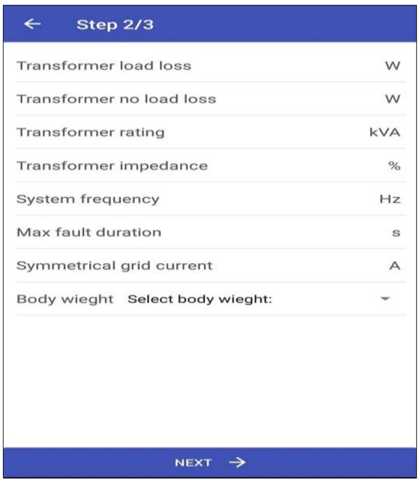

Fig. 6. Second screen of the app

The third screen as shown in Fig. 7 requires the user to select the shape of the grid which is currently limited to either square or rectangular. If the safety criteria is not satisfied, a warning message will be displayed at the bottom of the screen.

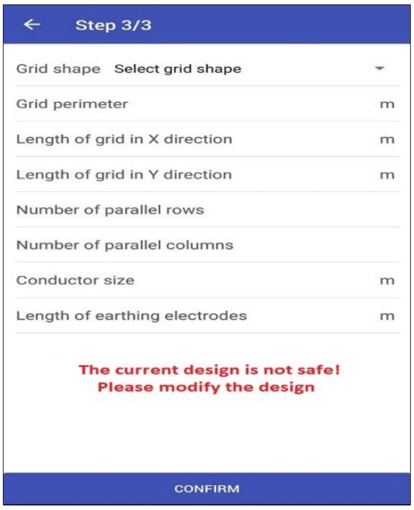

Fig. 7. Final screen of the app

Table II shows the comparison between manual calculation and apps calculation to verify the functionality of the apps.

TABLE II. VERIFICATION OF APPS

Input values	**Manual calculations**	**App calculations**
Pa = 400 Ω.m Ps = 5500 Ω-m (other) h_s = 0.102 m W =70 m L = 70 m C = 11 m R = 11 m No. = 0 m L = 0 m h = 0.5 m	Pa = 400 Ω.m Ps = 5500 Ω-m Cs = 0.71614 Rg = 2.77569 Ω	Pa = 400 Ω.m Ps = 5500 Ω-m Cs = 0.716 Rg = 2.776 Ω
Tx load loss = 12300W Tx no load loss = 2800 W Tx rating = 1600 kVA Tx impedance = 6 Frequency = 50 Hz Fault duration = 0.5 sec Fault current = 3180 A Body weight = 70 kg	R = 0.59375 Ω X = 5.97055 Ω X/R = 10.05566 Ω TA = 0.03201 Df = 1.031512 IG = 3280.207 A GPR = 9104.838 V E_{touch} 70 = 1533.828 V $E_{step\ 70}$ = 5469.218 V (GPR > E_{touch}) Continue	R = 0.594 Ω X = 5.971 Ω X/R = 10.056 Ω TA = 0.0320 Df = 1.0315 IG = 3280.207 A GPR = 9104.838 V E_{touch} 70 = 1533.830 V E_{step} 70 = 5469.226 V (GPR > E_{touch}) Continue
Grid shape = rectangular Lp = 280 m Length of grid in X=70 m Y=70 m n_r = 11 n_c = 11 d = 0.01 m Lr = 7.5 m	n = 11 D = 7 K_m = 0.7687 K_i = 2.3070 L_m = 1540 m E_m =1493.899 V K_s = 0.4061 L_s = 1155 m E_s = 1048.23 V $E_m < E_{touch\_70}$ $E_s < E_{step\_70}$ Your design is safe	E_m = 1493.899 E_s = 1048.234 $E_m < E_{touch\_70}$ $E_s < E_{step\_70}$ Your design is safe

It can be seen that the calculated values and the computed values are closely matched yielding similar conclusion that the current design is deemed as safe. Fig. 8 shows the output summary. Note that the user will only be able to reach the screen as shown in Fig. 8 if the design is safe.

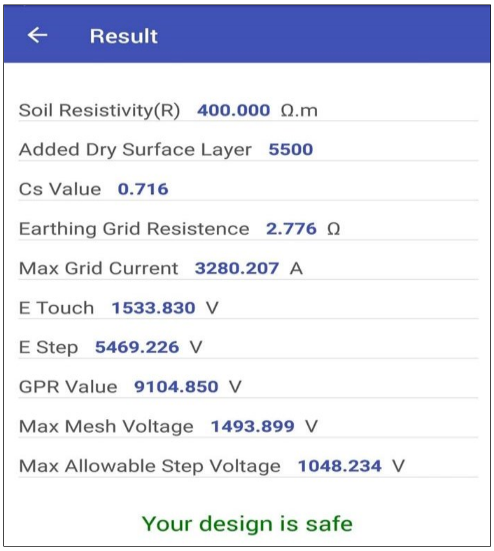

Fig. 8. Final screen of the app

After further testing with several other scenarios, it can be deduced that the app is perfectly working and giving satisfactory results for the following conditions:

When ($GPR < E_{touch}$)

When ($GPR > E_{touch}$)

When ($E_m > E_{touch}$)

When ($E_m < E_{touch}$)

V. Conclusion

This paper has outlined the process involved in developing a mobile application capable to verify the safety level of a substation earthing system design. With the availability of this app, the time required for the design of a substation earthing system to be verified can be significantly shortened without the need for tedious manual calculation. This mobile application is expected to be made available at the apps store by the end of this year.

Acknowledgment

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