THE EFFECTS OF INCREASED FAULT CURRENT ON THE EXISTING SUBSTATION GROUNDING SYSTEM – a Case Study

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Abstract - The aim of this research is to investigate the effect of increased fault current on an existing substation grounding system. Increased load demands because of the new customers connecting on the existing network or reconfigured network, power flows on the transmission and distribution assets will increase, which will in turn trigger the increase in fault current levels, both three-phase and phase-to-ground, throughout the power system. The protection that ground grids provide against step- and touch potentials is only good up to the expected level and duration of ground fault currents, as originally communicated in the design phase. A case study is presented in this research project to investigate the effects of increased fault current on the existing Ruighoek distribution substation grid. This paper presents how increased fault current on the existing substation grounding system impact the safe limits as per IEEE Std. 80-2000, and what improvements are possible.

Keywords – Grounding System, Ground Potential Rise, Touch Potential, Step Potential, Fault Current.

I. INTRODUCTION

Eskom has power distribution improvement and expansion plans to reinforce its power distribution system to accommodate load growth in the future. The plans consist of construction of Ngwedi MTS, distribution substations, sub-transmission lines and installation of new equipment (e.g transformers, circuit breakers) [2]. This expansion plan will increase the effective short-circuit current at the Ruighoek substation. Substation earthing plays a vital role in the safety of the environment when a phase-to-ground fault occurs in or close to the substation. This impact on the safety of staff inside the substation, as well as the safety of staff of substations and the factories of customers connected to the faulting substation [1].

The two layer soil structure is used as a good approximation of the real earth structure. The ground grid design for Ruighoek substation is examined with the main objective to assess its grounding system condition in terms of GPR, step- and touch potential. These three parameters are analysed to ensure that they satisfy the safety criteria defined in the IEEE Std. 80-2000, with two scenarios classified by fault levels: 1.050kA for the existing configuration, 11.46kA for expansion plan or future configuration [7, 8].

II. COMPONENTS OF GROUNDING SYSTEM

A substation grounding system is an underground, regular mesh conductor network that serves the purpose of providing the path of least resistance to the traversing current so that, in the case of a fault, it is distributed in all directions in the underlying earth. If efficient, the resulting ground potential due to a fault and the ensuing step- and touch potential will be low enough to guarantee the safety of personnel working on the substation, as well as to the safety of the installed equipment [3]. The safety of a person depends on preventing the critical amount of shock energy, the safety criteria are very important values. It is the first thing to calculate a specific safety level, then the maximum touch and step potential are calculated to compare with the safety criteria to define it safe or unsafe [12, 13].

A. Ground Potential Rise (GPR)

The ground potential rise is the product of the ground resistance R_g, which is a function of the number of grid conductors, its area, its depth and the resistivity of the surrounding soil multiplied by the current I_G entering the grid during a fault [10, 15].

B. Step Potential

Step voltage is the difference in surface potential experienced by a person bridging a distance of 1m with the feet without coming into contact with any grounded object [7].

C. Touch Potential

Touch potential is defined as the voltage difference between ground potential rise and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure [4, 14].

D. Earth Resistivity

The measurements of soil resistivity constitute the basis of the grounding study and are therefore of primary importance. The Wenner four-pin method, as shown in (figure 1), is used to determine the soil model (top, bottom soil layer resistivities and soil top layer thickness) in the vicinity of the substation, taking into account possible factors that will influence the accuracy of the results [7,16].

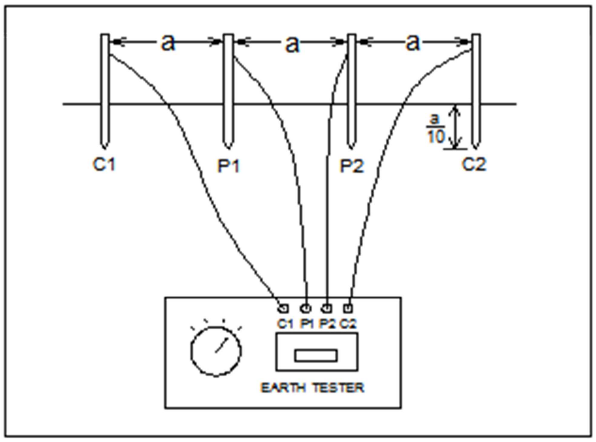

Figure 1: Wenner arrangement [12]

E. Earth Grid Resistance

The earth electrodes resistance (also commonly referred to as the grid resistance) is measured to verify the resistance between the earth electrode and true earth. The fall of potential method, as shown in (figure 2), is used to measure the resistance of the existing earth grid.

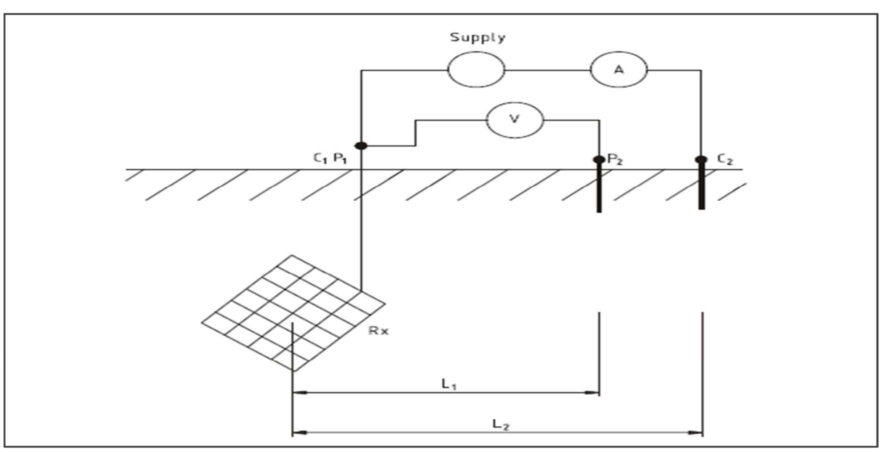

Figure 2: Fall of potential method for measuring earth resistance [7, 13].

III. CALCULATING PROCEDURE [x]

A. Earth Resistivity

The resistivity ρ in terms of the length units in which a and b are measured is given by the following equation:

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \qquad (1)$$

Where

ρ : soil resistivity (Ω.m)

R : measured resistance (Ω)

a : distance between adjacent electrodes (m)

b : depth of the electrodes (m)

If b<<a, the above equation (1) can be simplified to

$$\rho = 2\pi a R \qquad (2)$$

For small probe spacing, the current tends to flow near the surface, but for large spacing, more of the current penetrates deeper soils. It is therefore reasonable to assume that the resistivity measure for a probe of spacing a represents the apparent soil resistivity of depth a [7, 14].

B. Earth Grid Resistance

One of the first steps in determining the size and layout of the grounding system is the estimation of the total resistance to remote earth. Resistance primarily depends on the area of the grounding system. In the early stages of the design, the area to be occupied is usually known. As an approximation, the minimum value of the substation grounding resistance in uniform soil can be estimated as shown in equation (3) [7, 13]:

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \tag{3}$$

Where

R_g : substation ground resistance (Ω)

ρ : soil resistivity (Ω.m)

A : area occupied by the ground grid (m^2)

Laurent and Niemann proposed a method of calculating the substation ground resistance by adding a second term. This equation gives an upper limit of the substation ground resistance [7]. This proposed equation is:

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \tag{4}$$

Where

L_T : total burial length of conductors (m)

The total burial length is the combination of the horizontal and vertical conductors in the grid as well as the ground rods. L_T can be calculated as:

$$L_T = L_C + L_R \tag{5}$$

Where

L_C : total length of grid conductor (m)

L_R : total length of ground rods (m)

A better approximation was determined to include the grid depth

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{6}$$

Where

h : depth of the grid (m)

This equations shows that the larger the area and the greater the total length of the grounding conductor used would result in a lower ground grid resistance [3, 5].

C. Ground Potential Rise

Ground potential rise is determined by the following equation:

$$GPR = I_G \cdot R_g \tag{7}$$

Where

R_g : substation ground resistance (Ω)

I_G : maximum grid current (A)

D. Step and Touch Voltage

Step voltage is defined by equation (8)

$$E_{step} = (1000 + 6 \cdot C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_S}} \tag{8}$$

Similarly touch voltage criteria can be obtained from equation (9):

$$E_{touch} = (1000 + 1.5 \cdot C_s \cdot \rho_s)\frac{0.157}{\sqrt{t_s}} \tag{9}$$

Where

C_s : surface layer derating factor
ρ_s : resistivity of surface layer material (Ω.m)
t_s : is the duration of shock current (s)

If no protective surface layer is used in the substation, $C_s = 1$ and $\rho_s = \rho$.

E. Step and Touch Potential

The maximum touch voltage within a mesh of a ground grid is determined by equation (10).

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_M} \tag{10}$$

Where

ρ : resistivity of the earth (Ω.m)

L_M : effective burial length (m)

K_m : geometrical spacing factor

K_i : irregularity factor

The step potential is determine from equation (11).

$$E_s = \frac{\rho \cdot K_S \cdot K_i \cdot I_G}{L_S} \tag{11}$$

Where

E_s is the step potential (V)

K_s is the step factor defined for n parallel conductors

L_s is the effective length for step potential (m)

Steps for design are shown in (figure 3) [7].

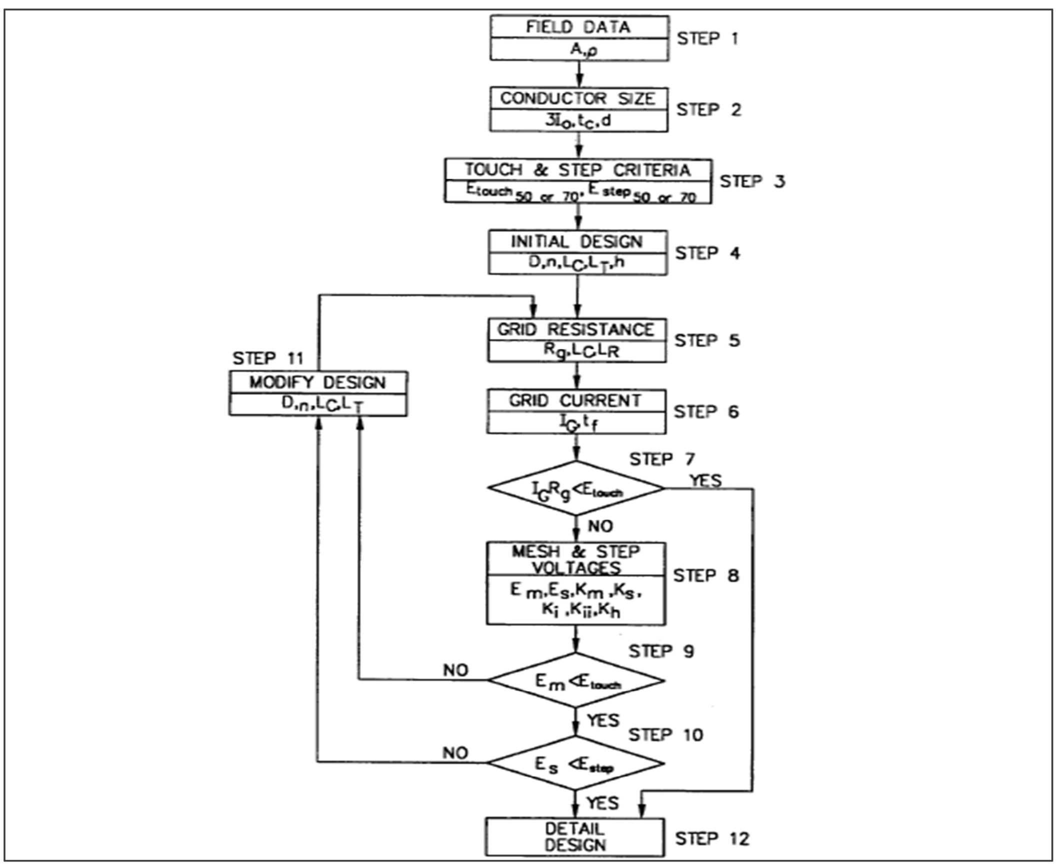

Figure 3: Design procedure block diagram [7].

IV. CASE STUDY

Ruighoek substation has a grounding grid of 65 x 49m and 5.74 x 3.4 square meshes of horizontal grid solid round copper conductors buried about 1m below ground level, as shown in (figure 4). The grid extends over the whole area occupied by the substation. All metalwork in this substation (steel structures, gutters, fences, etc.) are bonded to the earth grid so that a direct low-resistance path to ground is provided for short-circuit currents. Ruighoek substation has yard stone of between 25-38mm in size, and wet resistivity of 3000 ohm metre over the whole area occupied by the substation, and this serves to increase the resistance in the accidental circuit (through the person) to limit the current to safe levels.

Table 1. Ruighoek Substation Parameters

Description	**(88kV System)**	**(132kV System)**	**Unit**
High Voltage	88	132	kV
Medium Voltage	22	22	kV
Transformers	10 and 20	20	MVA
HV(3- Phase fault current)	1.94	13.96	kA
HV(1- Phase fault current)	1.05	11.46	kA
MV(3- Phase fault current)	4.46	9.33	kA
MV(1- Phase fault current)	720	720	A
Switchyard operator	50	50	kg
Resistivity of the crushed rock laye	3000	3000	Ω.m
Grid buried depth	1	1	m
Fault clearing time	0.5	0.5	s

Ruighoek substation will be converted from 88/22kV, 1x20MVA and 1x10MVA to 132/22kV 2x20MVA and 8x22kV overhead lines. It will be supplied through loop in, loop out 132kV Kingbird overhead lines, replacing a single 88kV Hare overhead line. The substation parameters are shown in (table 1) and are used to analyse the existing grounding system. Customers are fed from overhead medium voltage (MV) lines and the customers' earth electrodes are decoupled from utility substation earth electrode, because there is simply not any direct galvanic connection. MV lines do not have shield wires, and even if there were shield wires, the design of the MV-LV transformer installation is specifically done to prevent the transfer of fault GPR to customers [6, 12].

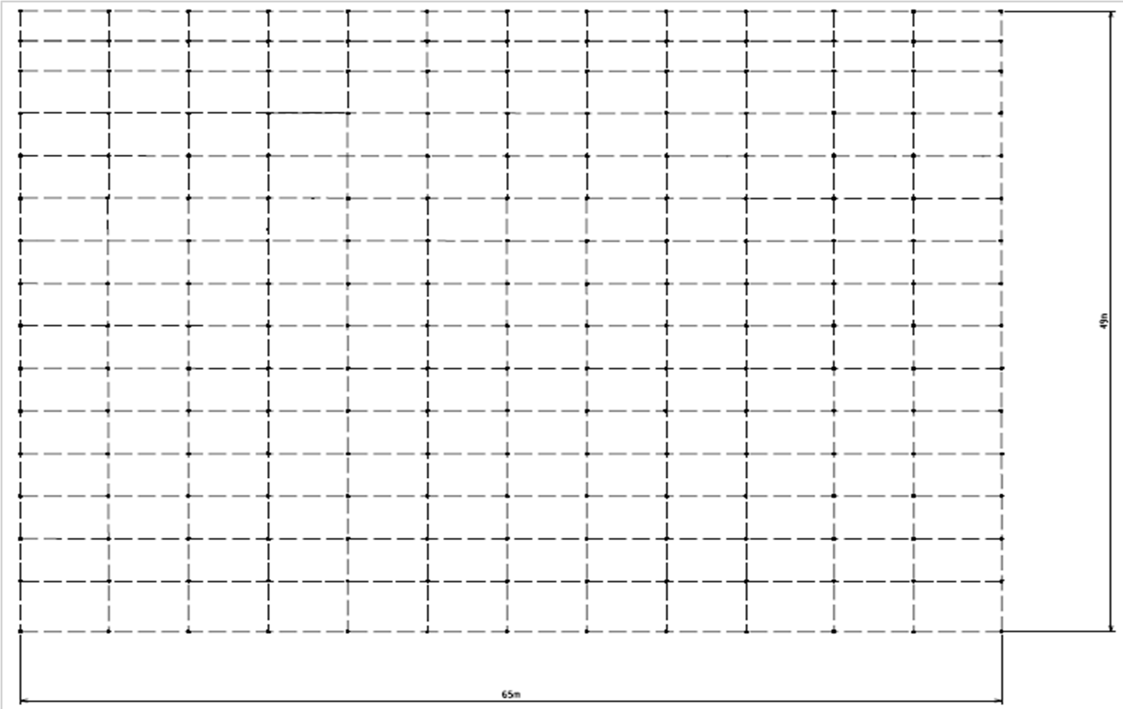

Figure 4: Existing Ruighoek substation earth mat configuration [2].

A. Grounding system design analysis with current fault currents

Ruighoek substation is examined with the main objective to assess its grounding system performance in terms of GPR, step- and touch potential. These three parameters are analysed to ensure that they satisfy the safety criteria defined in the IEEE Std. 80-2000, with two scenarios classified by fault levels: 1.050kA for the existing configuration, 11.46kA for expansion plan or future configuration.

Table 2: Existing ground grid results

Safe touch potential limit	**Mesh potential (actual)**	**Safe step potential limit**	**Step potential (actual)**	**Ground potential rise limit**	**Ground potential rise (actual)**
871.5V	155.03V	2994.1V	68.03V	5000V	948.6V

The existing grounding system is able to support the 1.050kA short-circuit current. The GPR, step- and touch potential criteria are satisfied, as shown in (table 2).

B. Grounding system design with increased faults currents

The new rms symmetrical ground fault current is 11.46kA, the number of lines that will be connected to Ruighoek substation are Ngwedi – Ruighoek 132kV Kingbird line with two shield wires and Sun City – Ruighoek 132kV Kingbird line with single shield wire respectively. Both lines will be build parallel to each other. These overhead ground wires will be connected to the substation ground, and a substantial portion of the ground fault current will be diverted away from the substation ground grid [7, 9].

I. Ground potential rise analysis

The grid current decreases because of the split factor, but the GPR is still above the safe limit. This means that ground potential rise in case of ground faults may cause dangerous voltages between telecommunication and local ground. The GPR, as well as distribution of the earth surface potential during the current flow in the grounding system, are important parameters for the protection against electric shock. Since Ruighoek substation does not have telecommunication circuits, metal pipes, metallic fences and low voltage neutral wire directly coupled to the adjacent substation earth electrodes, the aggravated GPR due to an increase in faults current, is thus not considered.

II. Mesh potential analysis

The calculated mesh potential exceeds the touch potential tolerable value of 871.5V by 63%. This implies that substation ground grid is unsafe, a person standing while at the same time having his hands in contact with a grounded structure will experience unsafe touch potential of 63% more than the allowable touch potential. The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energised. In this case the magnitude and duration of the current conducted through a human body can cause ventricular fibrillation of the heart, since the tolerable value of touch potential is exceed.

III. Step potential analysis

The calculated step potential is less than the tolerable step potential value of 2994.1V. This implies that the substation ground grid has safe step potential. This means that a person can bridge a distance of 1m with his feet in Ruighoek substation without contacting any other grounded object and without being exposed to dangerous step potential. It clear that there is no safety concerns regarding step voltages in and around this substation. The grounding system safety analysis is based on the step and touch voltage criterion. The maximum driving voltage of any accidental circuit (step or touch voltage) should not exceed the maximum permissible limits.

Table 3: Results from case study

Particular	**Unit**	**Result**
Grid resistance	Ω	1.02
Max. grid current (before)	kA	0.93
Max. grid current (after)	kA	8.34
Tolerable GPR	Volts	5000
Actual GPR (case 1)	Volts	948.6
Actual GPR (case 2)	Volts	8510
Tolerable step voltage	Volts	2994.1
Tolerable touch voltage	**Volts**	**871.5**
Actual step voltage (case 1)	Volts	68.03
Actual step voltage (case 2)	Volts	610.1
Actual step voltage (case 3)	Volts	522V
Actual touch voltage (case 1)	**Volts**	**155.03**
Actual touch voltage (case 2)	**Volts**	**1390.27**
Actual touch voltage (case 3)	**Volts**	**860.7**
Safety (case 1)	**-**	**Safe**
Safety (case 2)	-	Unsafe
Safety (case 3)	**-**	**safe**

Table 3, shows a case study results, where **case 1** represents the results of the existing grounding system before increase in fault current, **case 2** represents the results of the existing grounding system with increase in fault current and **case 3** representing an improved grounding system with increased in fault current .

It can be seen that safety characteristics of a substation grounding system are satisfied in **case 1** and **3**.The number of conductors parallel to the length and to the width of the earth grid determines the size of the grid meshes. The size of the grid meshes has a strong impact on the step and touch potentials that will arise under fault conditions. Adding conductors and thereby reducing the size of the meshes results in a reduction of step and touch potentials. By employing closer spacing of grid conductors, dangerous potentials within the substation are eliminated.

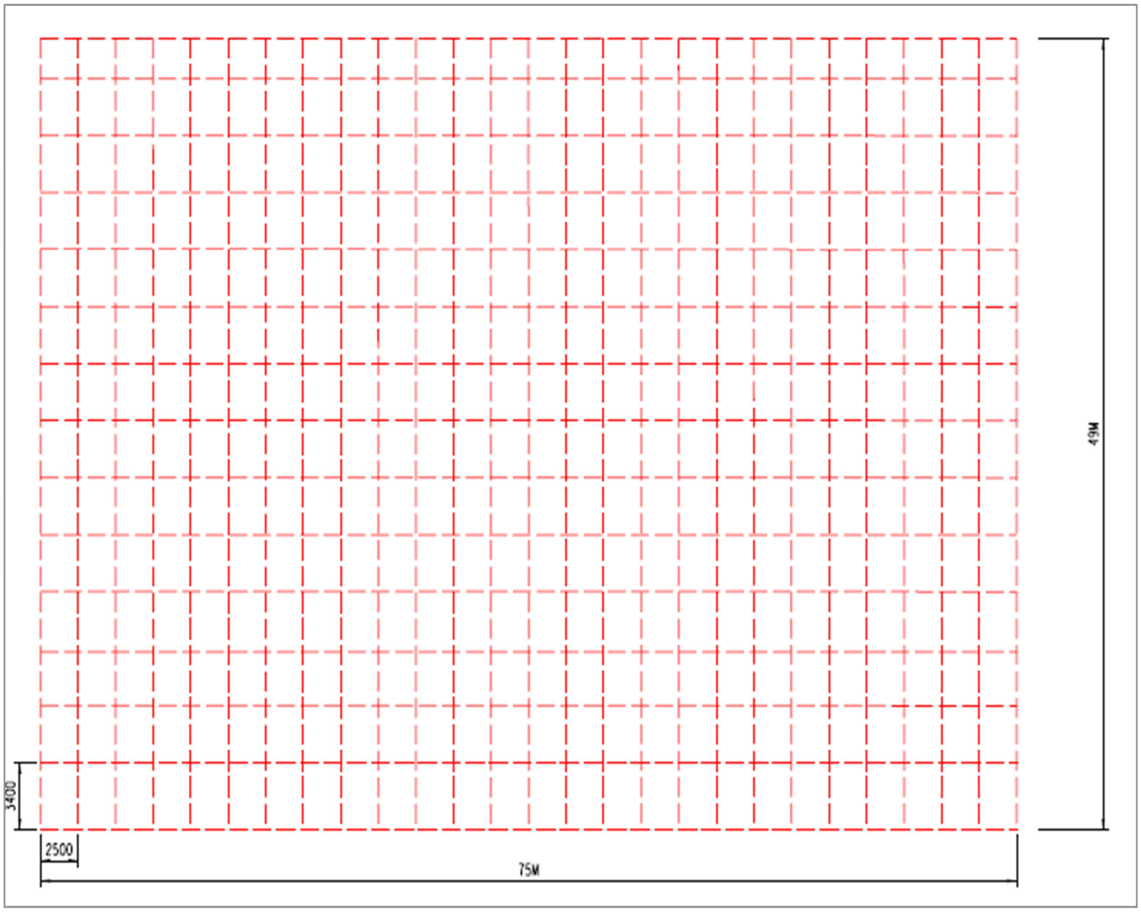

Figure 5. An Improved Ruighoek substation earth mat configuration

The grid area increased from A = 65m x 49m = 3185m^2 to A = 75m x 49m = 3675m^2, the substation is extended in X – direction by 10m, with minimum horizontal spacing of 2.5m. Area occupied by the grounding grid has major effect on step- and touch potential. Thus, the step- and touch potential decreases significantly with increased grid area.

V. CONCLUSION

The effects of increased fault currents on an existing substation grounding system have been studied. It was found that ground potential rise and touch potential were aggravated by the increased fault currents. In order to effectively prevent hazardous situations in substations upon increased ground faults on the existing grounding system, a safety-based design of the grid should be implemented. In addition, it is of paramount importance to be aware of the present ground-fault current levels at the customer’s plant, as they should not exceed the safety limit, due to increased power flows on the existing utility transmission and distribution assets.

The ground grid design for Ruighoek substation is examined with the main objective of assessing its grounding system condition in terms of GPR, step- and touch potential. These three parameters are analysed to ensure that they satisfy the safety criteria defined in the IEEE Std. 80-2000, with two scenarios classified by fault levels: 1.050kA for the existing configuration, 11.46kA for expansion plan or future configuration. The existing grounding system is able to support the 1.050kA short-circuit current, and the GPR and step- and touch potential criteria are satisfied. The grounding system of the future configuration does not satisfy all safety criteria, except the step potential that is within the safe limit. This case study showed that, the ground potential rise and touch potential are aggravated by the increased fault currents. Since customers earth electrodes are decoupled from Ruighoek substation earth electrode, the effect of unsafe GPR due to an increase in fault currents is not considered.

Improvement measures have been proposed and showed that step- and touch potentials can be improved by increasing the area occupied by the grid, as well as decreasing the horizontal spacing of parallel conductors. This means that step- and touch potential is inversely proportional to the area occupied by the grid and directly proportional to the horizontal spacing of parallel conductors. An improved grounding system is able to support 11.46kA short-circuit current.

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