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A Simple Design Method of Unequal Spacing Arrangement for Substation Grounding Grid

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ABSTRACT To balance the potential distribution on the surface of a substation, an equal spacing arrangement of the grounding grid conductors is not an economical solution. The implementable solution is an unequal placement of its constituent elements. The design methodologies of such a configuration are complex and require computer-assisted numerical analysis. This paper proposes and validates a very simple method, based on an arithmetic progression, of arranging the conductors of the grounding grid that guarantees the reduction of touch and step voltages, ensures the efficiency of the material used and has no limitations on its applicability for atypical substation surfaces (too large or too small), respectively for few or many parallel conductors. To certify the method, the proposed algorithm is analyzed, through the CYMGRD Substation Grounding Program, and compared to the technologies currently applied, for the substation grounding grid presented as an example in the IEEE Guide for Safety in AC Substation Grounding 80™ - 2013 standard.

INDEX TERMS Electrical safety, grounding, substation.

I. INTRODUCTION

The optimized design of a grounding system related to a substation involves the fulfillment of the requirements regarding: the ground resistance, R_g, touch voltage, E_t, and step voltage, E_s, under the conditions of a minimum of material and labor involved.

The simplest and only one that benefits from validated analytical relationships that allow the determination of the variables mentioned above, is that of a grounding grid with equal spacing arrangement (GG-E). Unfortunately, it does not meet simultaneous the expected technical and economic requirements. Thus, there is an uneven variation of the potential on the surface of the station with maximums reached in the four corners. Even by adding vertical electrodes, the 12 steps design procedure recommended by [1] leads to a configuration with which the imposed touch voltage is satisfied in an uneconomical way.

Equalizing the ground potential distribution could be achieved with a grounding grid with unequal spacing arrangement (GG-U) of the parallel conductors that create the grid in both directions of the substation area. For such systems, the well-known Sverak [2] or alternately Schwartz's equations [3] (based on Sunde [4], Rudenberg [5] works and improved by Kercel [6]) for ground resistance give acceptable results, approx. 10-15% bigger than real ones, depending on the substation area and number of conductors [1]. This is due to the relatively low dependence of the resistance on the distribution of the conductors, for the usual distances between them. On the other hand, the relations used to calculate the maximum step and mesh voltages [1] have no applicability for other configuration except the equal spacing one. In such circumstances, all methodologies for determining unequal distances between conductors that minimize the values of touch and step voltages are dependent on computer-assisted numerical analysis. Based on these, several calculation strategies have been developed. Of these, the most used are [7]–[10]:

- Chen's arrangement [11], [12],
- Exponential distribution developed by Zeng [12]–[14].

A. CHEN'S GG-U

According to [11], [12], based on S_{ik}, the percentage of the length L_{ik} of the i^{th} conductor, counted along the direction of length (L_1) or width (L_2), see Fig. 1:

$$L_{ik} = \frac{S_{ik}}{100}L \tag{1}$$

$$i = 1 \div n_1 \quad \text{and } k = 1 \div (n_1 - 1) \tag{2}$$

$$\text{or } i = 1 \div n_2 \quad \text{and } k = 1 \div (n_2 - 1) \tag{3}$$

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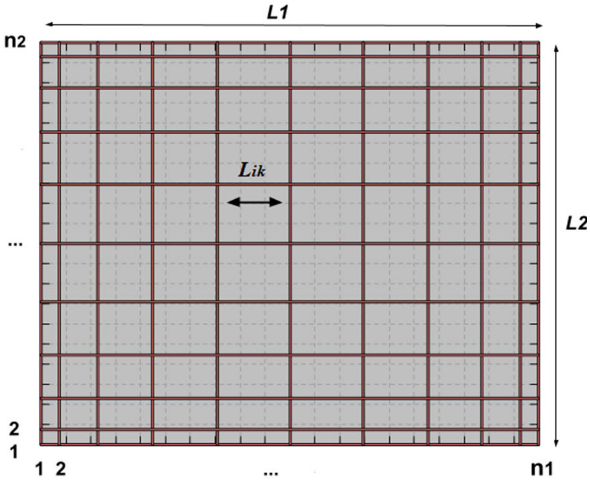

FIGURE 1. Chen's GG-U.

with:

$$S_{ik} = b_1 \cdot e^{-i \cdot b_2} + b_3 \tag{4}$$

The coefficients b_1, b_2, and b_3 are computed as follow, for different values of k.

- *$7 \leq k \leq 14$:*

$$\begin{cases} b_1 = -1.8066 + 2.6681 \cdot \lg k - 1.0719 \cdot \lg^2 k \\ b_2 = -0.7649 + 2.6992 \cdot \lg k - 1.6188 \cdot \lg^2 k \\ b_3 = +1.8520 - 2.8568 \cdot \lg k + 1.1948 \cdot \lg^2 k \end{cases} \tag{5}$$

- *$14 < k \leq 25$:*

$$\begin{cases} b_1 = -0.00064 - \dfrac{2.50923}{k+1} \\ b_2 = -0.03083 + \dfrac{3.17003}{k+1} \\ b_3 = +0.00967 + \dfrac{2.21653}{k+1} \end{cases} \tag{6}$$

- *$25 < k \leq 40$:*

$$\begin{cases} b_1 = -0.0006 - \dfrac{2.50923}{k+1} \\ b_2 = -0.03083 + \dfrac{3.17003}{k+1} \\ b_3 = +0.00969 + \dfrac{2.2105}{k+1} \end{cases} \tag{7}$$

Even if Chen generated empirical formulas for the grounding resistance, the maximum touch and step voltages [11], [12], a numerical analysis is recommended for the GG-U determined with (1) - (7).

Shortcomings of the Chen algorithm are related to the limitation for the number of parallel grid conductors, n_1 and n_2: bigger than 7, smaller than 42, but also to the significant number of empirical coefficients and the complexity of the relations involved.

B. EXPONENTIAL GG-U

The spacing between two adjacent parallel conductors of the grid, d, is [12]–[14]:

$$d_k = d_{\max} \cdot C^k \tag{8}$$

where k is the segment number counted from the central mesh, d_{max} is the spacing of the central mesh:

$$d_{\max} = \frac{L \cdot (1-C)}{1 + C - 2 \cdot C^{\frac{n}{2}}}, \quad \text{if } n \text{ is even} \tag{9}$$

$$d_{\max} = \frac{L \cdot (1-C)}{2 \cdot \left(1 - C^{\frac{n-1}{2}}\right)}, \quad \text{if } n \text{ is odd} \tag{10}$$

C is the compression ratio, a constant ≤ 1, L is the length in one or in the other direction of the rectangular surface of the substation, and n is the number of parallel conductors along one direction, Fig. 2.

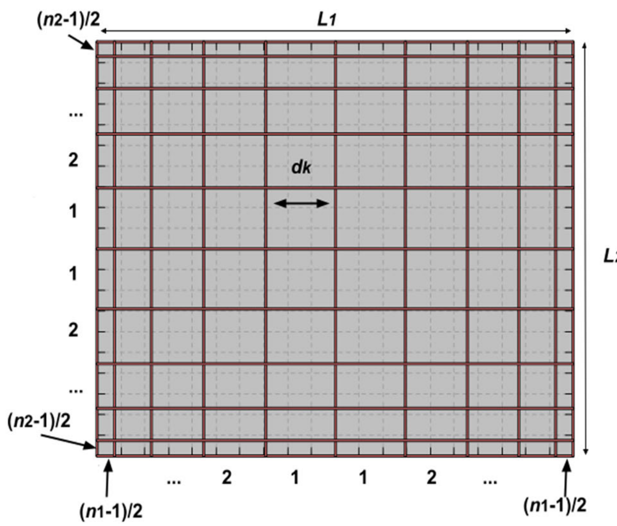

FIGURE 2. An exponential GG-U.

For a given configuration (substation area, soil proprieties, number of grounding grid conductors, the presence of the vertical rods), the optimum compression ratio (OCR) must be determined through tentative numerical analyses.

In [12]–[14] are presented many results and is developed an empirical expression to calculate the OCR for a double layer soil, no vertical electrodes added and for different side lengths of the grounding grid, L:

$$OCR = a_0 + a_1 \cdot e^{0.0001 \cdot h} + a_2 \cdot e^{b \cdot h} \tag{11}$$

The coefficients a_0, a_1, a_2 and b are computed based on formulas (12-14).

$$b = -0.3503 - 9.6311 \cdot e^{-0.03666 \cdot L} \tag{12}$$

$$\begin{cases} a_0 = a_{01} + a_{02} \cdot K + a_{03} \cdot K^2 \\ a_1 = a_{11} + a_{12} \cdot K + a_{13} \cdot K^2 \\ a_2 = a_{21} + a_{22} \cdot K \end{cases} \tag{13}$$

where h is the thickness of the upper layer of the soil with a resistivity ρ_1 and K is the reflective coefficient (ρ_2 being the resistivity of the bottom layer):

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{14}$$

The coefficients of the fitting relation (13) are shown in Table 1.

TABLE 1. Coefficients used in relation (13).

Coefficient	L			
	≤100 m	101 m ÷175m	176 m ÷250m	>250m
a_{01}	0.44	0.38	-0.51	0.32
a_{02}	-77.43	-50.65	-33.18	-15.44
a_{03}	15.63	13.88	18.49	13.42
a_{11}	0.033	0.19	1.15	0.38
a_{12}	76.9	50.21	32.82	15.16
a_{13}	-15.56	-13.83	-18.44	-13.38
a_{21}	-0.067	-0.037	-0.029	-0.022
a_{22}	0.5	0.41	0.34	0.26

II. PROPOSED DESIGN METHOD OF UNEQUAL SPACING ARRANGEMENT FOR SUBSTATION GROUNDING GRID

To avoid the use of complicated empirical relations, with many coefficients difficult to manage, the authors propose a simple method based on an arithmetic progression. As will be demonstrated in the following chapters, not only the simplicity of the method is what recommends it but also its behavior in relation to the touch and step voltages. Moreover, it will be observed that minimizing the potentials in problematic areas (e.g., station corners) by adding vertical electrodes is much more efficiently solved.

The distance between two adjacent parallel conductors of the GG-U is determined as follows:

- if the number of parallel conductors along one direction, n, is odd, i.e., there is a central conductor in the grid, Fig. 3:

$$d_k = d_{\min} + (k-1) \cdot d_{\min} = d_{\min} \cdot k \tag{15}$$

with k being the segment number counted from the outer side of the grid, $1 \leq k \leq (n-1)/2$ and d_{min}, the spacing of the furthest mesh from the center, computed as:

$$d_{\min} = \frac{4 \cdot L}{n^2 - 1} \tag{16}$$

- if the n is even, i.e., there is a central mesh in the grid whose spacing is the $n/2^{\text{th}}$, Fig. 3:

$$d_k = d_{\min} + (k-1) \cdot d_{\min} = d_{\min} \cdot k \tag{17}$$

for $1 \leq k \leq (n-1)/2$ and

$$d_{\frac{n}{2}} = d_{\min} \cdot \frac{n}{2} \tag{18}$$

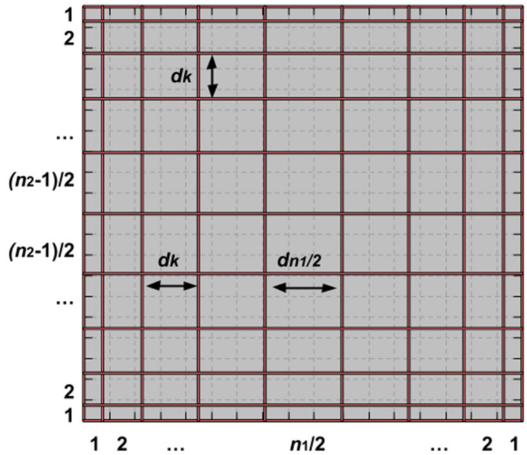

FIGURE 3. The proposed GG-U with an even number of parallel conductors in one direction and an odd number in the other direction.

with d_{min} resulting from the relationship:

$$d_{\min} = \frac{4 \cdot L}{n^2 + n - 1} \tag{19}$$

Although the method is applicable to an even or odd number of parallel grid electrodes, we recommend, for maximum simplicity, the use of an odd number of electrodes, i.e., a distribution with central conductors in both directions, equations (15-16).

III. VALIDATION FOR GG-Us WITHOUT VERTICAL RODS

For validation, the example "B. 1. Square grid without ground rods," presented in [1] was chosen. From the design data and the analytical calculated parameters, accessible in full in [1], we reproduce only those that are relevant to the purpose of the work:

- homogenous soil resistivity, $\rho = 400\ \Omega \cdot \text{m}$,
- 0.102 m thickness crushed-rock surfacing with a resistivity (in wet condition) $\rho_s = 2500\ \Omega \cdot \text{m}$,
- depth of grid burial 0.5 m,
- 70 m × 70 m grounding grid with no ground rods,
- number of parallel conductors of the grid in both directions $n_1 = n_2 = 11$,
- tolerable step and touch voltages: 2686.6 V, and respectively 838.2 V,
- 30% copper-clad steel grid wire of 10 mm diameter.

The following arrangements have been tested: GG-E, Chen's GG-U, Exponential GG-U, and Proposed GG-U.

All tests were made using CYMGRD Substation Grounding Program.

A. GROUNDING GRID WITH EQUAL SPACING ARRANGEMENT

The distance between two adjacent parallel conductors of the grid is 7 m, Fig. 4.

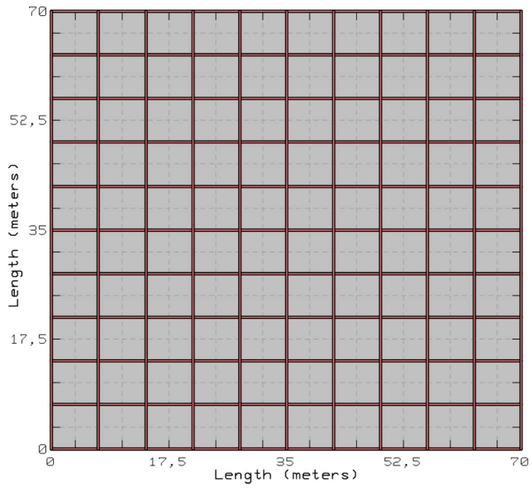

FIGURE 4. The GG-E.

Using relations from [1], the next results are computed: grid resistance $R_g = 2.78\ \Omega$, ground potential rise $GPR = 5304$ V, mesh voltage, $E_m = 1002.1$ V.

The CYMGRD analyses goes to a 2.65 Ω grid resistance, $GPR = 5103.1$ V, a maximum touch voltage of 1011.3 V and a maximum step voltage of 161.18 V, Fig. 5. As expected, the periphery of the grid causes the tolerable voltage value to be exceeded.

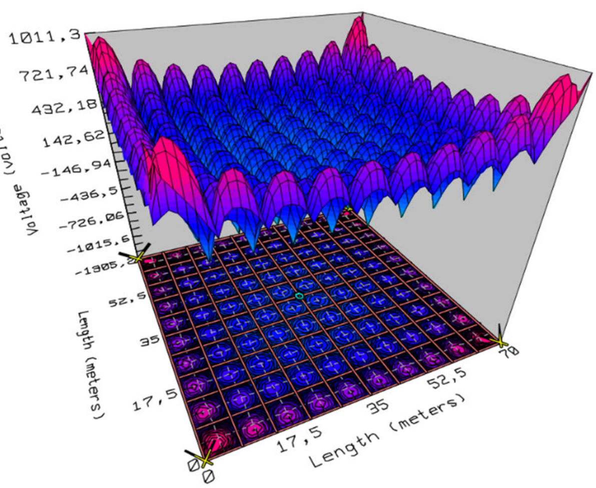

FIGURE 5. Touch voltage distribution for the GG-E.

B. CHEN'S GG-U

Using (1) – (5) the successive grid mesh widths, starting from the outer conductor, are: 2.557 m, 5.464 m, 7.584 m, 9.131 m, 10.259 m, Fig. 1.

Numerical analysis leads to the next results: $R_g = 2.62\ \Omega$, $GPR = 5046.16$ V, $E_t = 922.419$ V, $E_s = 192.56$ V. It can be observed that a reduction to 91.2% of the GG-E maximum touch voltage is achievable and these values are present only in the corners of the grid, Fig. 6.

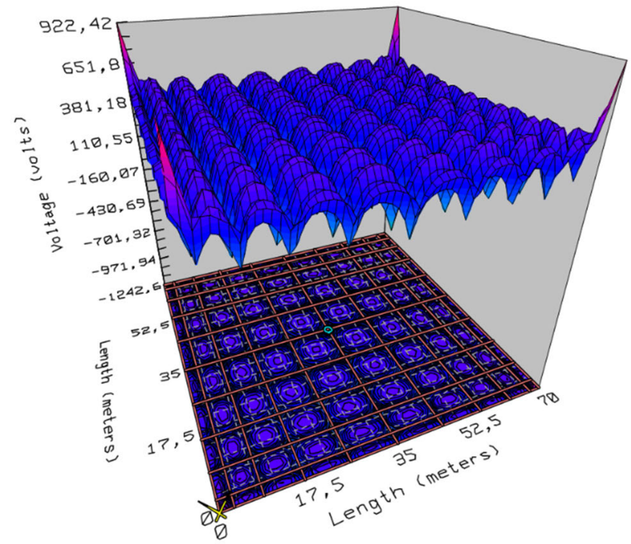

FIGURE 6. Touch voltage distribution for Chen's GG-U.

C. EXPONENTIAL GG-U

According to the relations (8) and (10), the mesh widths are presented in the Table 2.

TABLE 2. The mesh widths of the exponential GG-U for different compression ratio.

C	*Mesh width (m)*				
	d1	*d2*	*d3*	*d4*	*d5*
1	7	7	7	7	7
0.9	5.607555	6.23061707	6.922908	7.69212	8.5468
0.8	4.264636	5.3307948	6.663494	8.329367	10.41171
0.7	3.030363	4.32909018	6.184415	8.834878	12.62125
0.6	1.967384	3.27897293	5.464955	9.108258	15.18043
0.5	1.129032	2.25806451	4.516129	9.032258	18.06452
0.4	0.543162	1.35790494	3.394762	8.486906	21.21726
0.3	0.198933	0.66311136	2.210371	7.367904	24.55968

The aspects of the Exponential GG-Us and the distribution of the touch voltages on the substation surface, for different compression ratio C, are shown in Fig. 7 – 8, respectively in Fig. 9 – 10.

Applying (11), the optimum compression ratio results: OCR = 0.48, value confirmed by numerical analysis with CYMGRD.

Table 3 lists the main results of the Exponential GG-U simulations, and Fig. 11 shows the variations of the touch voltage on the diagonal of the station for $0.3 \leq C \leq 0.9$.

As can be seen from the results shown in Fig. 9 – 11, the maximum values of the touch voltage appear in the corners of the grid, for $C \geq 0.5$, as in the case of the GG-E and Chen's GG-U configurations, and in the central meshes for $C < 0.5$. The grid resistance varies between 2.68 Ω for $C = 0.3$ and

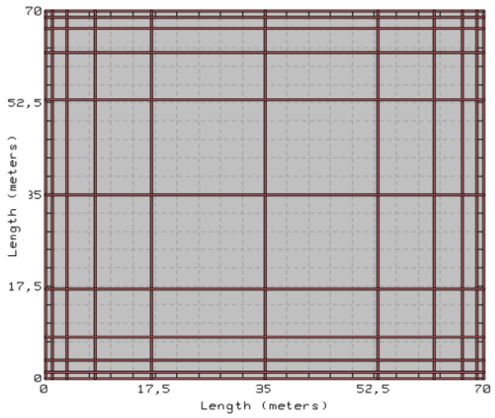

FIGURE 7. The exponential GG-U with $C = 0.5$.

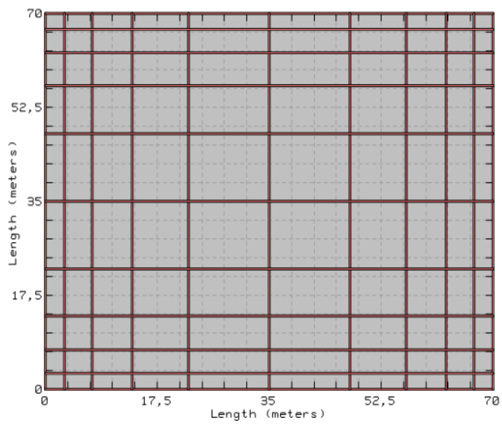

FIGURE 8. The exponential GG-U with $C = 0.7$.

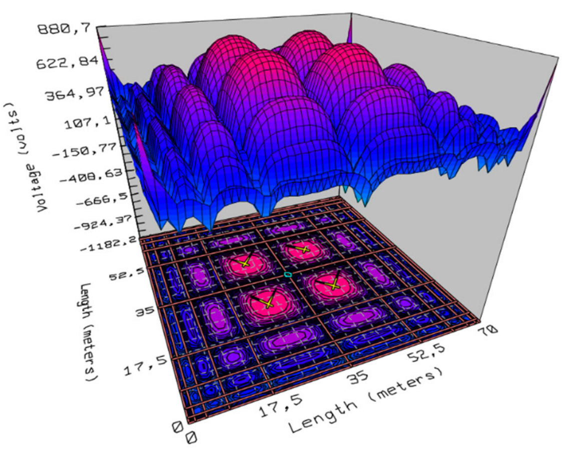

FIGURE 9. Touch voltage distribution for the exponential GG-U, $C = 0.5$.

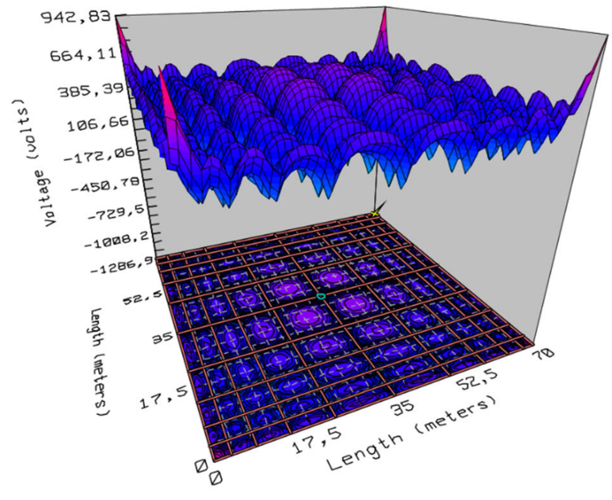

FIGURE 10. Touch voltage distribution for the exponential GG-U, $C = 0.7$.

TABLE 3. The main parameters for the exponential GG-U for different compression ratio.

C	*Rg (Ω)*	*GPR (V)*	*Max.* E_t *(V)*	*Max.* E_s *(V)*
0.3	2.68111	5159.13	1205.45	350.02
0.4	2.64382	5087.42	1029.87	331.48
0.5	2.62543	5052.04	881.203	267.97
0.6	2.62012	5041.82	904.555	208.29
0.7	2.62361	5048.55	942.831	181.41
0.8	2.63184	5064.39	975.041	168.71
0.9	2.64278	5085.43	1003.1	162.8

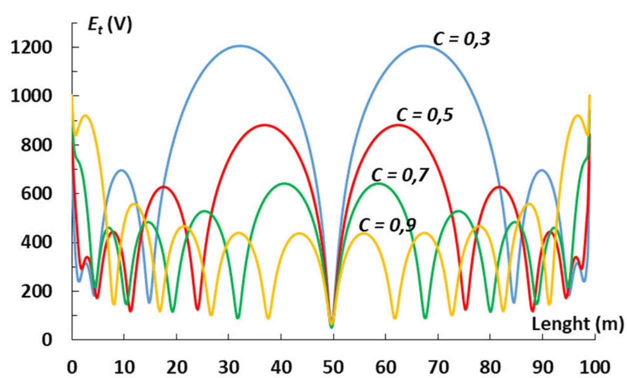

FIGURE 11. Touch voltages on the diagonal of the substation for the exponential GG-U for different compression ratio.

2.62 Ω for $C = 0.3$. The maximum touch voltage reaches a minimum of 881.2 V for $C = 0.5$.

D. PROPOSED GG-U

From (15) and (16) the distances between two adjacent parallel conductors of the GG-U are: 2.34 m for the outer mesh and then successively 4.67 m, 7 m, 9.34 m and 11.67 m, Fig. 3.

The numerical analyze, using CYMGRD, produces the following results: $R_g = 2.62\ \Omega$, $GPR = 5042.66$ V, Max. $E_t = 918.838$ V, Max. $E_s = 196.99$ V.

In Fig. 12 it can be seen the touch voltage distribution on the substation surface.

It is noteworthy the uniform distribution of the touch voltage and the existence of maximums only in the area of the grounding grid corners.

TABLE 4. The main parameters for the analyzed configurations.

GG type	Rg (Ω)	GPR (V)	Max. E_t (V)	Max. E_s (V)
GG - E	2.65201	5103.08	1011.301	161.18
Chen's GG-U	2.62237	5046.16	922.419	192.56
Exponential GG-U, $C = 0.5$	2.62543	5052.04	881.203	267.97
Exponential GG-U, $C = 0.7$	2.62361	5048.55	942.831	181.41
Proposed GG-U	2.62055	5042.66	918.838	196.99

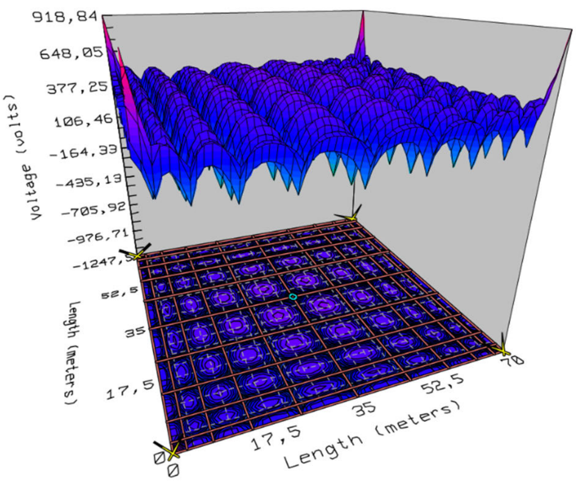

FIGURE 12. Touch voltage distribution for the proposed GG-U.

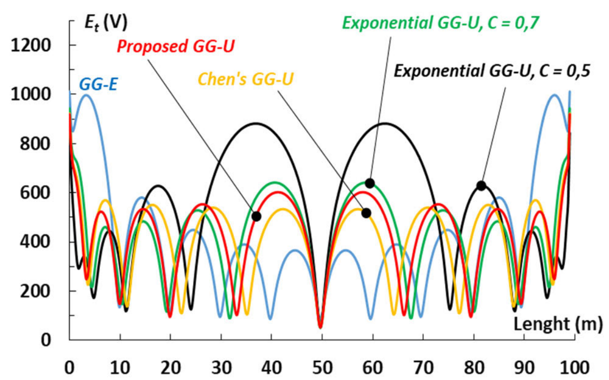

FIGURE 13. Touch voltages on the diagonal of the substation for analyzed grounding grids.

To synthesize, the main parameters are listed in Table 4 and the distributions of the touch voltage on the diagonal of the substation were grouped in a single graph for the analyzed configurations, Fig. 13, with the mention that among the Exponential GG-Us were retained only those corresponding to the optimum compression ratio and $C = 0.7$ (the reason for this last selection will be depicted forthwith.

From Table 4 we can conclude that the Proposed GG-U leads to a maximum touch voltage of 918.838 V (90% from the one corresponding to the GG-E), which is slightly bigger then Exponential GG-U with $C = 0.5$, i.e. 881.203 V, but, if we are looking at Fig. 6, 9, 10, 12 and 13 we notice that the voltage distribution on the substation surface is quite uniform, excepting the exponential GG-U, C = 0.5. For this last configuration the maximum voltages appear in the central meshes of the grid, for the others, the maximum touch voltages are present only in the corners of the substation. Tolerable touch voltage, having a value of 838.2 V [1] is exceeded for all grounding grids. Lowering the danger of electrocution imposed the use of vertical grounding rods. In the next chapter only the following configurations will be retained for analysis: GG-E, as reference, Chen's GG-U, Exponential GG-U, $C = 0.7$ and Proposed GG-U, all configuration having added vertical electrodes in the four corners of the grid.

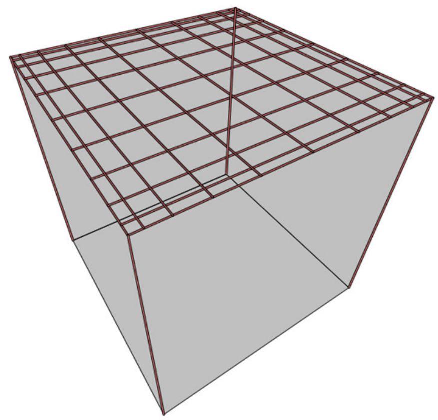

FIGURE 14. The proposed GG-U with vertical rods in the four corners.

TABLE 5. The ground resistance for the analyzed configurations.

GG type	Rg (Ω) for vertical rods length of			
	1 m	2.5 m	5 m	10 m
GG - E	2.6474	2.63773	2.61842	2.57204
Chen's GG-U	2.61859	2.61054	2.59359	2.55069
Exponential GG-U, $C = 0.7$	2.61971	2.61153	2.59453	2.55168
Proposed GG-U	2.61681	2.60886	2.59207	2.54946

IV. VALIDATION FOR GG-Us WITH VERTICAL RODS

Vertical electrodes will be attached to the substation grounding grid detailed in chapter III as shown in Fig. 14 for the Proposed GG-U.

The vertical electrodes, placed in the four corners of the substation grounding grid, are successive: 1 m, 2.5 m, 5 m and 10 m length.

In Tables 5-8, the values of the ground resistance, ground potential rise, maximum touch and step voltages are compared for all analyzed configurations.

Adding vertical electrodes in the corners of the substation grounding grid goes to reduce all the essential parameters that must be fulfilled in the design process. In terms of the maximum touch voltage, it is lowered in grounding grid systems with unequal spacing arrangement below the allowed value. The lowest values are obtained for the Proposed GG-U.

TABLE 6. The GPR for the analyzed configurations.

GG type	*The GPR* for vertical rods length of			
	1 m	2.5 m	5 m	10 m
GG - E	5094.31	5075.71	5038.57	4949.33
Chen's GG-U	5038.9	5023.41	4990.8	4908.26
Exponential GG-U, $C = 0.7$	5041.04	5025.3	4992.6	4910.17
Proposed GG-U	5035.47	5020.17	4936.53	4905.89

TABLE 7. The maximum touch voltage for the analyzed configurations.

GG type	*Max.* E_t *(V)* for vertical rods length of			
	1 m	2.5 m	5 m	10 m
GG - E	973.347	930.993	873.31	800.504
Chen's GG-U	766.956	686.167	630.575	574.094
Exponential GG-U, $C = 0.7$	784.044	701.845	645.306	610.461
Proposed GG-U	763.956	684.17	629.227	573.653

TABLE 8. The maximum step voltage for the analyzed configurations.

GG type	*Max.* E_s *(V)* for vertical rods length of			
	1 m	2.5 m	5 m	10 m
GG - E	118.49	109.47	103.55	94.73
Chen's GG-U	152.15	143.1	135.95	152.2
Exponential GG-U, $C = 0.7$	140.41	131.76	125.28	115.45
Proposed GG-U	153.38	147.16	139.78	128.78

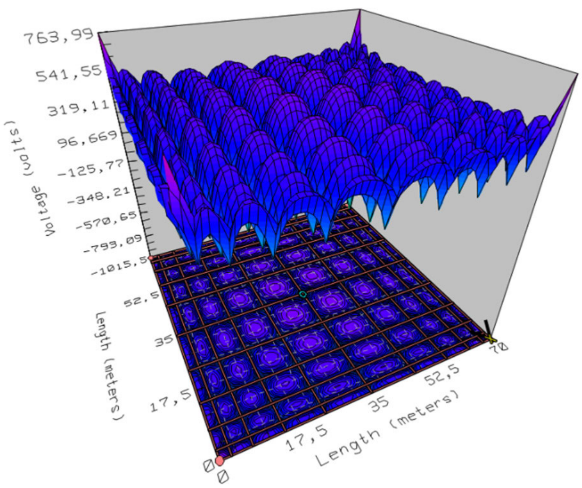

FIGURE 15. Touch voltage distribution for the proposed GG-U with 1 m length rods.

Instead, in GG-E, only the addition of 10 m long vertical rods ensures compliance with this requirement.

The touch voltage distributions on the substation surface, for the Proposed GG-U, with 1m respectively 10 m length rods in corners are shown in Fig. 15 and Fig. 16.

In Fig. 17 the touch voltages on the diagonal of the substation for analyzed grounding grids with 1 m length rods

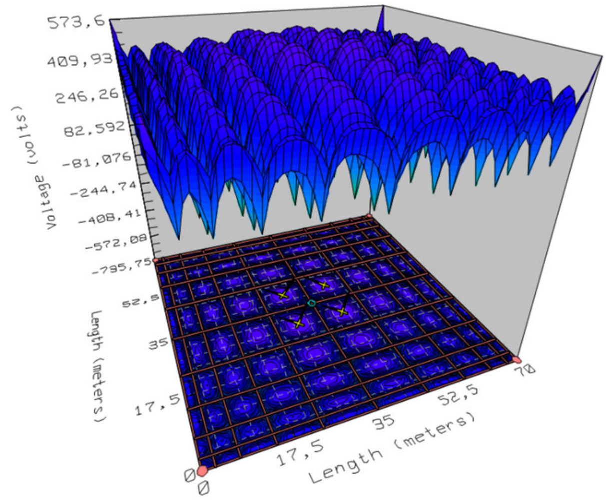

FIGURE 16. Touch voltage distribution for the proposed GG-U with 10 m length rods.

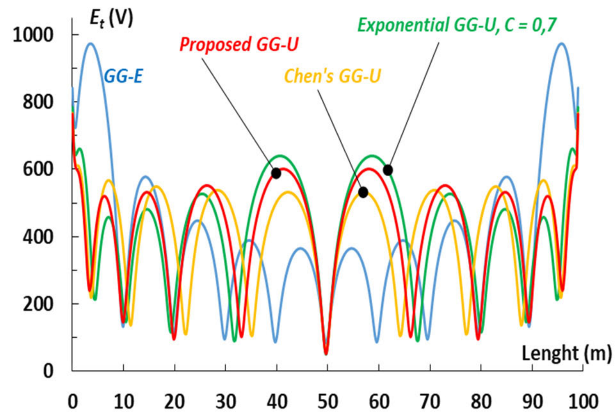

FIGURE 17. Touch voltages on the diagonal of the substation for analyzed grounding grids with 1 m length rods.

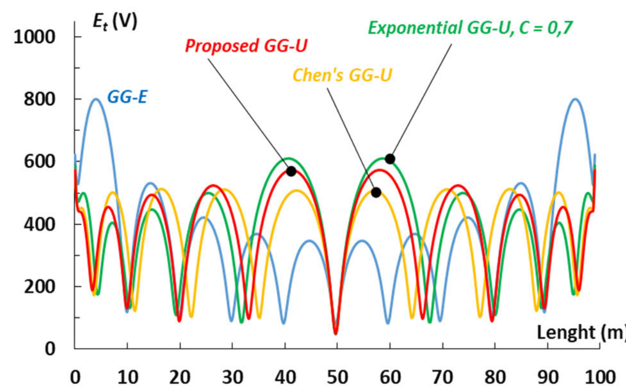

FIGURE 18. Touch voltages on the diagonal of the substation for analyzed grounding grids with 10 m length rods.

are represented comparatively. The same representations are displayed in Fig. 18 for 10 m length vertical electrodes in the four corners.

Analyzing all the results obtained from the simulations with CYMGRD, it is clear, that by adopting a GG-U

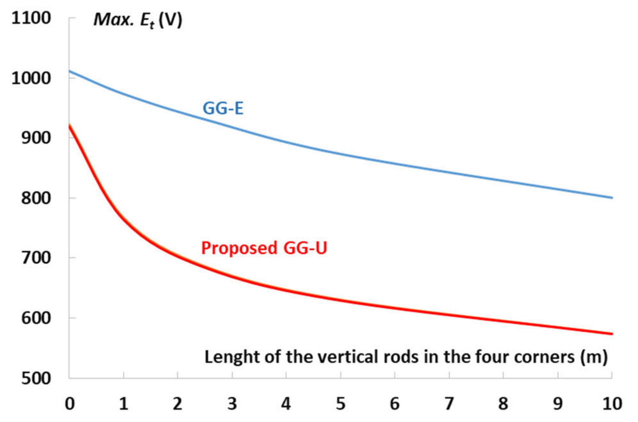

FIGURE 19. **Touch voltages on the diagonal of the substation for analyzed grounding grids with 10 m length rods.**

configuration, lower values of touch voltages are obtained than in the variant GG-E and, moreover, by adding only four vertical electrodes in the corners of the network the maximum values of these voltages are dramatically reduced.

V. CONCLUSION

As demonstrated, the proposed design method of unequal spacing arrangement for substation grounding grid provides the following benefits:

- very simple algorithm, based on an arithmetic progression (15-19), applicable regardless of the dimensions of the station, respectively of the number of parallel conductors of the grid. The maximum distance between two parallel adjacent conductors varies between the uniform arrangement distance and twice this value, guaranteeing close to uniform distribution of the potentials.
- significant reduction of the maximum touch and step voltages on the substation surface. In Fig. 19, the difference between the configurations: GG-E and Proposed GG-U, for the substation detailed in chapter III, can be noticed, i.e., we are talking about a reduction to 91% without any vertical electrodes up to 72% using 10 m length rods in the four corners.
- quite uniform distribution of the potentials on the substation surface.

Based on this research, the proposed design method of unequal spacing arrangement for substation grounding can be considered an optimized one because it ensures the fulfillment of both the technical and the economic.

The next step to be able to implement this method in standards, is to determine analytical relationships for the variables of interest (grounding resistance, maximum touch and step voltages), based on the results of numerical analyzes processed statistically and with the help of artificial intelligence.

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