INTEGRATED GROUNDING SYSTEM OF WIND-FARMS FOR LIGHTNING AND FAULT PROTECTION

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ABSTRACT:

Wind turbines (W/T) and Wind farms (W/F) require a grounding system for the protection of human life and the installed equipment, in case of short-ciruits or lightning strikes. In particular, there is an increased probability of lightning striking a W/T, because good wind potential normally exists in places of high altitude. An effective grounding system means that the resistance of W/T and W/F grounding systems remains low. The objective of this paper is to present a methodology and a practical study case concerning the optimal design of individual W/T and W/F grounding systems. In this design the minimization of the grounding resistance and the satisfaction of the safety criteria (step and touch voltage) are of major concern [1].

1. INTRODUCTION

Grounding systems should be designed in order to prevent excessive overvoltages and potential gradients that may cause damage to equipment or threaten human life [2]. Fault or lightning currents to any W/T in a W/F installation, may damage equipment directly or indirectly as transferred potentials may exceed allowed values at W/Ts in the neighborhood of the fault.

W/Fs in Greece are usually situated in mountainous (and usually rocky) areas where the wind potential is high. In these areas the soil resistivity in most of the cases has high values. For this reason difficulties arise when designing grounding systems of W/Ts in terms of reduction of touch and step potentials and minimization of grounding system resistance.

The area that the grounding system of a W/F occupies is often limited by topographical factors. For this reason practical problems arise, as the area which is practically available is smaller than the one required for correct dimensioning of the grounding arrangement. Grounding systems installation costs also increase in highly resistive soil. (due to increased excavations and the need of special equipment).

In the examined case W/T grounding systems are interconnected. In the paper the effect of "effective length" of interconnection conductors is analyzed and investigated. Its effect on lightning surge analysis is very important as it weakens the effect of adding more material in order to reduce grounding resistance [3].

For the purposes of this paper, the software package CYMGRD [4] is used. CYMGRD is suitable for grounding system analysis, (calculation of grounding resistance and touch and step potential values). Analysis using CYMGRD is based on finite element method, and division of the grounding system into elementary segments. Particular methods followed in order to reduce maximum voltages observed are presented. Alternative grounding system design techniques are also presented and discussed. Various methods to minimize touch and step voltages are examined regarding their effectiveness.

2. THEORETICAL BACKGROUND

2.1. Description of the problem

Design of grounding systems has to satisfy safety requirements for the people that work at the W/F, and also to ensure minimization of the materials and installation costs. Theoretical issues related to effective design of W/F grounding systems are analytically presented in this paragraph.

2.1.1. Soil resistivity. Soil resistivity is the most important factor to be considered when designing W/F grounding systems. It depends mainly on the constitution of soil. It takes higher values for drier and rocky soils, while it is lower in humid or marshy soils with simultaneous presence of electrolytes. It is preferable to measure the resistivity of the soil during the summer season in order to obtain the highest possible value which corresponds to the worst case in terms of fault current dispersion into the soil.

Realistic soil models involve more than one layer for properly representing the conductivity profile of the stratified ground. A widely accepted model is the two layer model, and this is the model this program arrives at, by interpreting field measurements of soil resistivity.

TABLE 1 – Example set of soil resistivity mesurements

Electrode distance a(m)	Soil resistivity (Om)
2.5	2127.65
5	3411.8
10	4637
20	8865.6
40	12600
80	16800.6

Reduced gradient optimization techniques are employed to obtain an equivalent two layer model that best fits the measurement data (see Table 1). Soil resistivities and depth of the resulted two layers model are shown in Table 2.

TABLE 2 – Example two layer soil model

Depth of upper layer (m)	Soil Resistivity of the Upper Layer (Om)	Soil Resistivity of the Lower Layer (Om)	% Error
4.26	1967.48	21729.28	6.6

In fig. 1, soil resistivity measurements are graphically compared to the calculated values obtained from the two layer soil model shown in Table 2.

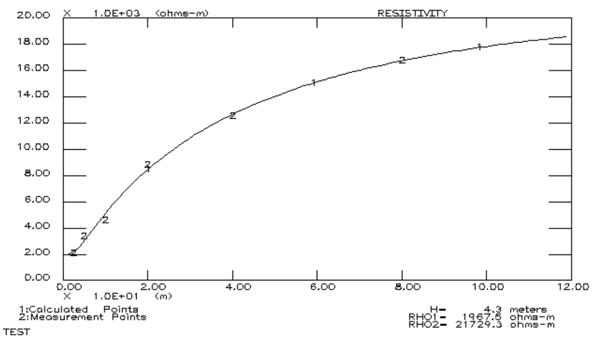

Figure 1: Example soil resistivity measurements vs. calculations for a two layer soil model.

The impact of a surface layer of gravel (of resistivity $?_s$ and of thickness h_s) in increasing the step and touch potential limits is also considered. However when the upper layer of the soil has a resistivity above 2000O, a surface layer does not improve surface voltage profiles

2.1.2. Grounding system design criteria. Selection of the grounding systems configuration is based on the following criteria:

- Minimization of grounding resistance of the grounding system of each individual W/T and the whole W/F. A resistance of 10O or less for the individual W/T grounding system is stated in the appropriate British Standard [2] as being suitable for lightning protection purposes. A similar value can be found in other international standards and/or recommendations. According to the same standard, in cases where it is not possible to reduce the grounding resistance below 10 ohms threshold, additional length of grounding strips and/or vertical rods should be added to the grounding system. This length is determined from the lightning protection level of the structure, and is calculated using IEC [5] formulas. The major design criteria are:
- Satisfaction of safety criteria regarding touch and step voltages.
- Minimization of material cost.
- Easy installation of the grounding system.

In any case the most important criteria are those who refer to safety against developed Touch and Step voltages at the surface of the soil above the W/F grounding system. In general, even if all the other criteria cannot be fully satisfied, when touch and step voltages do not exceed the maximum allowable values, the grounding system configuration design can be considered acceptable.

2.1.3. Effective length – Effective area of the grounding system. In case of a lightning strikes one of the wind turbines, the ground potential rise near the injection point, as well as touch and step voltages will be affected by that part of the grounding system that is within a distance shorter or equal to the "effective length" [3], [6]. According to the most recent international standard on lightning protection of wind turbines [3], this cannot exceed, in any case, 60m. The W/T grounding systems selected extend in an area of 60m radius around the W/T.

2.1.4. Worst case short circuit fault current. According to ANSI/IEEE Std. 80, the worst fault type for a given grounding system is the one resulting in the highest value of the maximum grid current I_G = 3Io. In a given location, a single line to ground fault will be the worst type if $Z_0 Z_1 > Z_2^2$ at the point of fault and a line to line to ground fault will be the worst type if $Z_0 Z_1 < Z_2^2$ In the usual case where Z_2 is assumed equal to Z_1 the above comparison reduce to $Z_0 > Z_1$ and $Z_0 < Z_1$, respectively. In Greece, Wind Farms are usually connected to the grid via Overhead Distribution

Lines of type ACSR-95 (of single or double circuit), where the condition $Z_o>Z_1$ holds (see Table 3). Therefore, the single line to ground fault will be the one resulting in the highest value of the maximum grid current injected to the Winf Farm grounding system.

TABLE 3 - Sequence impedances of ACSR-95 Overhead Distribution Line

R1= R2	0,215 O/km
X1=X2	0,334 O/km
RO	0,363 O/km
XO	1,556 O/km

3. SHORT DESCRIPTION OF THE ANALYSIS TOOLS

Calculations within this study have been made using the specialized software CYMGRD by CYME International [4]. CYMGRD bases its calculations on the ANSI/IEEE Std.80/1986[1] which is the base for carrying out this study.

4. METHODOLOGY

The methodology for design of the W/F grounding installation is described as follows:

Step 1: Calculation of soil models from sets of soil resistivity measurements
Step 2: Calculation of single phase short circuit at the W/F busbars.
Step 3: Calculation of maximum allowable touch and step voltages
Step 4: Design of single WT grounding system. The grounding of a single wind turbine is normally achieved by placing a ring electrode around the foundation and bonding it through the foundation to the turbine tower. The foundation reinforcement bar is also connected directly or via the turbine tower to the ring electrode and will be effective in acting as an ground electrode since the surrounding concrete can be considered to have a resistivity equal to that of the surrounding soil [7]. However, it is normally ignored to provide a worst case analysis of the grounding system. More particularly, the basic components of the W/T grounding arrangements considered in this paper are shown in fig 2. In the cases examined in this paper the foundation grounding system comprises 2 rings, a ring with the radius of the tower base and an outer ring with diameter that of the erection base. Six horizontal conductors are placed radically from the center to the perimeter of the outer ring where 3m vertical rods are additionally installed.

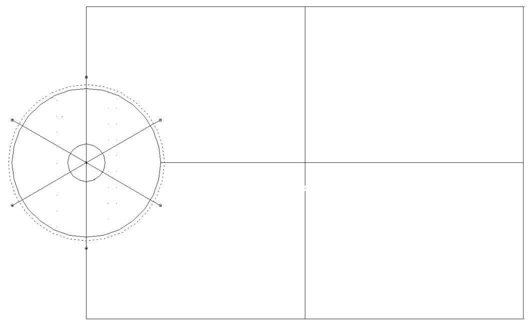

Figure 2: Top view of the default W/T grounding system arrangement

Step 5:
Step 5.1.: Calculation of the total grounding resistance of W/F grounding system which comprises the interconnected W/T grounding systems.
Step 5.2.: Calculation of the allocated short circuit current to individual W/Ts grounding systems.
Step 5.3.: Calculation of developed touch and step voltages at the surface of the soil where a person can be exposed to danger.
Step 6: Check whether touch and step voltages obtain acceptable values.

- If yes, end of calculations.
- If no, and if it is possible to add more grounding conductors to the W/T grounding systems, go to step 4 and reinforce grounding system or extend its dimensions in the area between the WTs.
- If no, and there can be no further reinforcement of grounding arrangements, then go to step 7.

Step 7: Reduction of the fault clearing time in case all the above measures fail to satisfy safety criteria for acceptable touch and step voltages. Check again if touch and step voltages obtain acceptable values.

- If yes, end of calculations.
- If no, then go to step 8.

Step 8: Use of surface layer of gravel above the W/T grounding systems that are buried at relatively low resistivity soil. Use of protective fence in crucial areas (where unacceptable touch and step voltages arise).

4.1. Improvement of grounding system performance.

4.1.1.Reinforcement of the individual WT grounding system. In order to reduce the grounding resistance of each individual WT, there should be used additional horizontal strips or electrodes and grounding rods.

Grounding rods can be effectively used to reduce the grounding resistance of the individual W/T grounding configuration only if the lower layer of the soil has low resistivity values. Also inclined grounding rods can be effective when the lower layer soil is sufficiently conducting. Inclined grounding rods placed at the edges of the grounding system, also improve step voltages which become maximum at these points.

Maximum contribution of horizontal grounding strips and electrodes to reduction of grounding resistance is achieved only when they are buried at the surrounding area and connected to WT grounding. This is achieved because the overall area occupied by the grounding system is increased.

4.1.2.Improvement of the overall W/F grounding system performance. Improvement of the overall W/F grounding system should be realized, by reinforcing the grounding systems of wind turbines where there is a relatively conductive soil.

3. APPLICATION EXAMPLE

3.1. W/F installed in low soil resistivity area (Site A)

3.1.1.Short Description of the W/F. The W/F under consideration is located in Peloponnese penninsula in the Greek mainland. It consists of two (2) branches with eighteen (18) and with nineteen (19) W/T, which are connected to the grounding system of control building. Each wind turbine is equipped with a 850 kW generator.

3.2.2.Soil resistivity. The measurements of soil resistivity have been conducted by the High Voltage Laboratory of NTUA. Based on the soil resistivity measurements, the soil resistivities of the equivalent two layer model have been obtained applying the Wenner methodology. In Table 4 the soil stratification based on four (4) measurement sets is shown. Four (4) soil models result from the mean values of related measurements and they are representative in the present study because they are taken at prospective locations for installation of W/Ts with high and low soil resistivities.

TABLE 4 – Two layer soil models

Soil	h_1 [m]	P_1 [Om]	P_2 [Om]
Soil W/T A	5.41	345.13	575.22
Soil W/T B	10.98	237.48	395.80
Soil W/T C	4.74	68.43	114.05
Soil W/T D	23.58	134.72	224.53

3.2.3. Calculation of maximum allowable touch and step voltages. The maximum allowed step and touch voltages considering 1.0s and 0.5s fault clearing times at each one of the W/F installation locations are calculated next. In Table 5 the maximum allowed touch and step voltages at the prospective locations for W/T installation shown in table 5 are given, considering a person of 50 kg weight.

TABLE 5 – Maximum allowable Touch and Step voltages

	Maximum Allowable TOUCH VOLTAGE		Maximum Allowable STEP VOLTAGE	
	Fault Clearing Time (sec)		Fault Clearing Time (sec)	
	0.500	**1.000**	**0.500**	**1.000**
W/T A Soil	305.67	216.14	730.53	516.56
W/T B Soil	261.44	184.87	553.63	391.48
W/T C Soil	192.11	135.84	276.31	195.38
W/T D Soil	219.3	155.07	385.05	272.27

3.2.4.Single W/T grounding system. Using CYMGRD alternative grounding systems of W/Ts configurations are calculated and compared. Grounding systems will consist of the following:

- Vertical grounding rods made of electrolytic copper E-Cu (250μm), with diameter F17mm and length 3m in a hole of diameter D. The space inside the hole is filled with soil improvement material (e.g. bentonite).
- Horizontal interconnection strip 40 x 4 mm made of copper (Cu) at depth 0.9m
- Inner ring of diameter 5m encased in foundation base at depth 1m (horizontal strip 40x4mm)
- Outer ring of diameter 15m placed at depth 2.5m (horizontal strip 40x4mm)

The grounding system configurations shown in figs 3 and 4 are selected to be installed at the W/T locations. The main effort at this part of the study was to minimise the grounding resistance of individual W/T grounding systems in order to satisfy safety criteria against touch and step voltages.

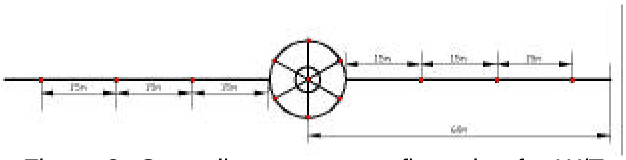

Figure 3: Grounding system configuration for W/Ts A, B

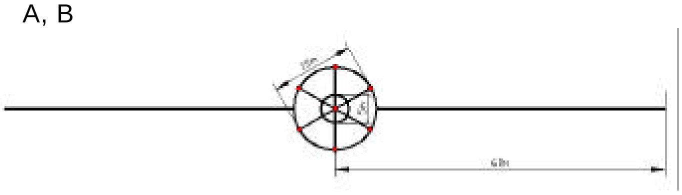

Figure 4: Grounding system configuration for W/Ts C, D

Grounding resistance of each of the selected single W/T's grounding system as well as of the substation is shown in Table 6.

It is noted that the grounding resistance of individual W/T grounding systems does not exceed 10O. Consequently lightning protection is achieved in all cases, and at the same time, the more economic solution in terms of materials and installation costs, has been chosen.

3.2.5. Total Grounding Resistance of W/F Grounding System. The total grounding resistance of W/F grounding system in case of a short circuit is approximately equal to the parallel synthesis of grounding resistances of individual W/Ts and the S/S grounding systems. This is acceptable because W/Ts are situated at distances that allow neglecting interactions between the individual grounding systems. Grounding system resistances have been calculated and the results are shown in Table 6. The total grounding resistance is given by:

$$R_{W/F} = \frac{1}{\sum \frac{1}{R_{W/T}} + \frac{1}{R_{S/S}}} = 0.1653\Omega$$

3.2.6. Ground Potential Rise when a short circuit occurs. Ground potential rise at the grounding system of the W/F when the short circuit current is considered to be equal to 1500? is:

$$V_{W/F} = 1500A \cdot 0.1653\Omega = 247.928V$$

3.2.7. Allocation of short circuit current to individual WTs grounding systems. Short circuit current is allocated inversely proportional to the resistances of individual grounding systems, in such a way that the ground potential rise at the surface of the earth is everywhere in site A equal to 247.93V. Short circuit currents dispersed into the soil through individual grounding systems are shown in table 6.

TABLE 6 – Resistance of individual grounding systems and short circuit current allocation

Soil	W/T or S/S	Grounding Resistance (O)	Short Circuit Current (?)
Soil W/T A	W/T A	9.9994	24.7943
Soil W/T B	W/T B	9.7653	25.3887
Soil W/T C	W/T C	1.9937	124.3558
Soil W/T D	W/T D	3.6543	67.8456
Soil S/S	S/S	8.0399	30.8372

3.2.8. Meeting the Criteria of Safety against Touch and Step Voltage. The proposed W/T grounding system meets the criteria of safety regarding touch and step voltages under the most unfavourable short circuit conditions. The worst conditions in terms of danger caused by touch and step voltages occur when the fault clearing time is 1s, there is no surface layer of gravel and the person is considered to weight 50kg. Calculation is done along lines (1) to (4) as shown in fig. 5 that refers to the grounding systems of each W/T.

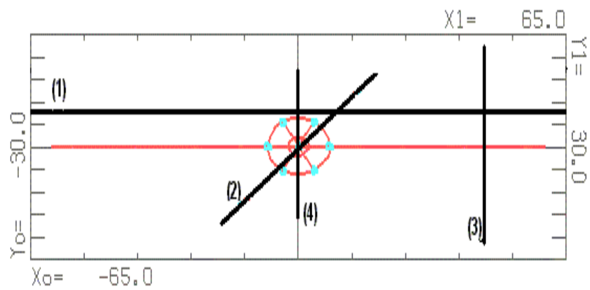

Figure 5: Straight line (2) above the grounding system of W/T along which calculation and check for dangerous Touch and Step Voltages is done.

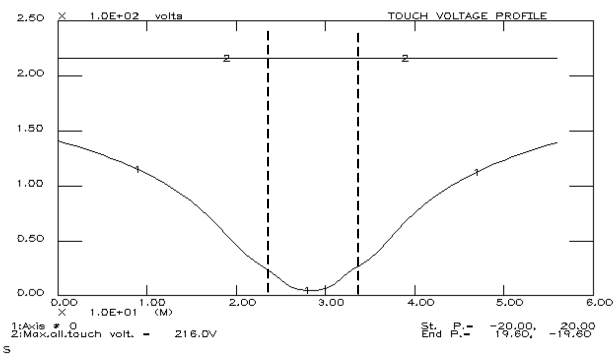

Figure 6: Touch voltage profile along line (2) at the surface of the soil above W/T B (limit calculated for fault clearing time equal to 1s)

Choice of the straight lines (1) to (4) is made in order to calculate the dangerous step and touch voltages at those points above the grounding system where they obtain their maximum value. It should be noted that along the straight lines where a person is possible to be subject to dangerous touch and step voltages, a zone 10m wide around the W/T tower is checked for violation of safety limits.

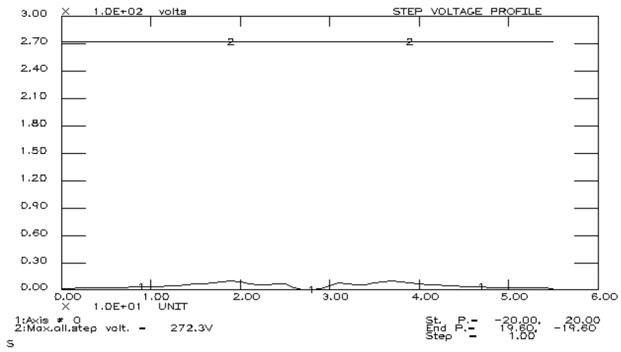

Figure 7: Step voltage profile along line (2) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 1s)

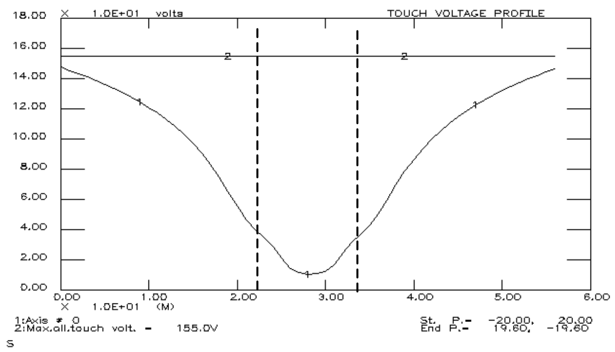

Figure 8: Touch voltage profile along line (2) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 1s)

3.1.9.Summary of the results. Summarizing the results shown in the previous sections, the following conclusions can be drawn:

1. Touch and Step Voltages are under the maximum allowable value in all cases.
2. The W/F grounding system protects effectively against lightning because the individual W/T systems have resistance to earth less than 10O, and at the same time the step and touch voltages when a short circuit occurs, will be much under the allowable limits.

3.2. W/F installed in high soil resistivity area (Site B)

The W/F under consideration is located in a mountainous area in Peloponnese peninsula. Soil resistivity values are extremely high.

3.2.1.Short Description of the W/F. The W/F located in site B consists of three (3) branches with five (5), four (4), and one (1) W/T, which are connected to the grounding system of control room and Substation S/S 2. Each wind turbine is equipped with a 850 kW, generator.

3.2.2.Soil resistivity. The measurements of soil resistivity have been conducted by the High Voltage Laboratory of NTUA. Based on the soil resistivity measurements, the soil resistivities of the equivalent two layer model have been obtained applying the Wenner methodology. In Table 7 the soil stratification in eleven (11) measurement locations is shown. The two layer soil models result from the mean values of related measurements and they are considered representative in the present study because they are taken at the prospective locations for installation of W/Ts.

TABLE 7 –Two layer soil models

Soil	h_1 [m]	P_1 [Om]	P_2 [Om]
Soil W/T A	4.26	1967.48	21729.28
Soil W/T B	2.50	792.58	13818.20
Soil W/T C	3.25	1813.18	13975.48
Soil W/T D	3.06	1728.28	19331.23
Soil W/T E	3.82	1552.76	16138.48
Soil W/T F	6.12	2653.91	11744.29
Soil W/T G	2.50	1087.18	20530.78
Soil W/T H	7.17	2614.42	15168.05
Soil W/T I	2.50	1760.62	13879.10
Soil W/T J	2.50	1940.29	25872.49
Soil S/S	6.20	1919.88	12879.28

3.2.3.Calculation of maximum allowable touch and step voltages. The maximum allowed step and touch voltages considering various fault clearing times at each one of the W/F installation locations are calculated. In table 8 the maximum allowed touch and step voltages at the prospective locations for W/T installation are shown, considering weight of a person equal to 50 kg.

3.2.4.Single W/T grounding system. Using CYMGRD alternative grounding systems of W/Ts configurations are calculated and compared. Grounding systems will consist of the following:

- Vertical grounding rods made of electrolytic copper E-Cu (250µm), with diameter F17mm and length 3m in a hole of diameter D. The space inside the hole is filled with bentonite.
- Horizontal interconnection strip 40 x 4 mm made of copper (Cu) at depth 0.9m
- Inner ring of diameter 3m placed at depth 1m (horizontal strip 40x4mm)
- Outer ring of diameter 12m placed at depth 2.5m (horizontal strip 40x4mm)

TABLE 8– Maximum allowable Touch and Step volages

	Maximum Allowable TOUCH VOLTAGE		**Maximum Allowable STEP VOLTAGE**	
	Fault Clearing Time (sec)		**Fault Clearing Time (sec)**	
	0.500	1.000	0.500	1.000
W/T A Soil	648.19	458.34	2100.63	1485.37
W/T B Soil	359.08	253.91	944.18	667.64
W/T C Soil	610.22	431.49	1948.75	1377.97
W/T D Soil	589.33	416.72	1865.18	1318.88
W/T E Soil	546.14	386.18	1692.42	1196.72
W/T F Soil	817.10	577.78	2776.27	1963.12
W/T G Soil	431.57	305.17	1234.15	872.68
W/T H Soil	807.39	570.91	2737.40	1935.64
W/T I Soil	597.29	422.35	1897.01	1341.39
W/T J Soil	641.50	453.61	2073.86	1466.44
S/S Soil	636.48	450.06	2053.77	1452.24

The grounding system configurations shown in figs 9 to 13 are selected to be installed at the corresponding W/T locations where the soil conditions are the most unfavourable. Grounding systems design is done in such a way that the cable trench and the flat area around the wind turbine tower are exploited in order to minimize the costs of installation. Furthermore, when additional reinforcement was needed, horizontal strip was buried at or near the road that runs between wind turbines in order to increase the area of grounding system. The main effort was to minimize grounding system resistance in order to achieve safety against touch and step potentials.

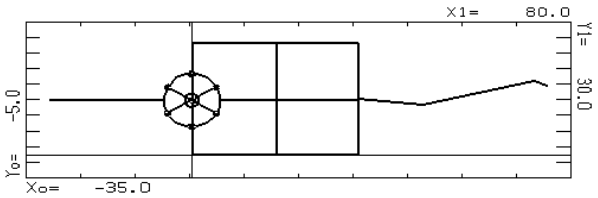

Figure 9: Grounding system configuration for W/T A

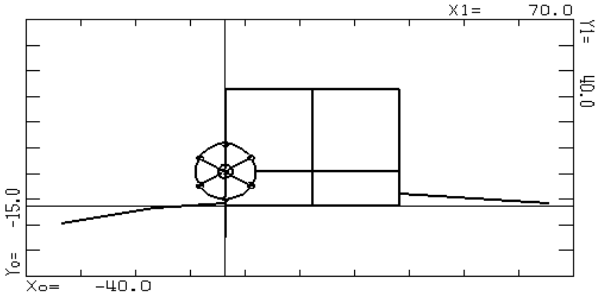

Figure 10: Grounding system configuration for W/T C

Grounding resistance of each of the selected single W/T's grounding system as well as of the substation is shown in the following table 9. .It is generally observed that grounding resistance of individual W/Ts systems exceeds 10O in all cases. In that case, application of IEC standard leads to additional use of horizontal and vertical electrodes of certain length. Proposed grounding electrodes lengths according to IEC for the highest protection level, are in all cases less than the radius of the arrangements suggested in the present study, because the W/T grounding systems are interconnected. Consequently, satisfactory lightning protection is achieved.

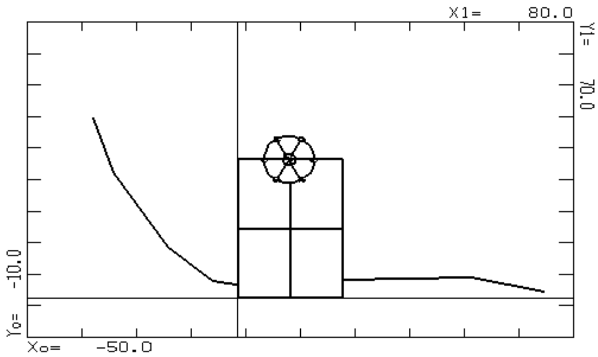

Figure 11: Grounding system configuration for W/T D

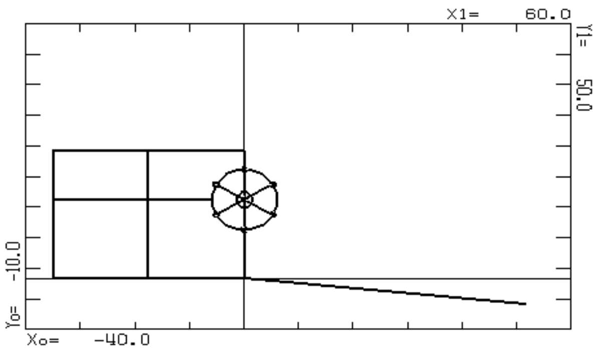

Figure 12: Grounding system configuration for W/T I

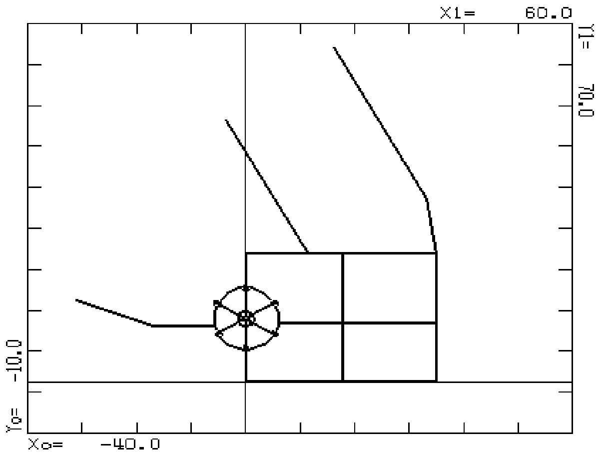

Figure 13: Grounding system configuration for W/T J

3.2.5.Total Grounding Resistance of W/F Grounding System. The grounding systems of W/Ts of the W/F will be connected in series forming groups of five (5), four (4) and one (1) W/T, as well as with the Grounding System of the S/S and the Control Building. The total grounding resistance of W/F grounding system in case of a short circuit is approximately equal to the parallel synthesis of grounding resistances of individual W/Ts and the S/S grounding systems. This is acceptable because W/Ts are situated at distances that allow neglecting interactions between their grounding systems independent. Grounding system resistances have been calculated and the results are shown in Table 9. Consequently the total grounding resistance of the windfarm is given by:

$$R_{W/F} = \frac{1}{\sum \frac{1}{R_{W/T}} + \frac{1}{R_{SS}}} = 7.069\Omega$$

3.2.6.Ground Potential Rise when a short circuit occurs

Ground potential rise at the grounding system of the W/F when the short circuit current is considered to be equal to 700? is:

$$V_{W/F} = 700A \cdot 7.069\Omega = 4948.32V$$

3.2.7.Allocation of short circuit current to individual WTs grounding systems. Short circuit current is allocated inversely proportional to the resistances of individual grounding systems, in such a way that the ground potential rise at the surface of the earth is everywhere in site B equal to 4948.32V. Short circuit currents dispersed into the soil through individual grounding systems are shown in table 9.

TABLE 9 – Resistance of inidvidual grounding systems and short circuit current allocation

Soil	W/T or S/S	Grounding Resistance (O)	Short Circuit Current (?)
Soil W/T A	**W/T A**	93.99	52.65
Soil W/T B	**W/T B**	54.27	91.18
Soil W/T C	**W/T C**	79.85	61.97
Soil W/T D	**W/T D**	84.81	58.35
Soil W/T E	**W/T E**	71.34	69.36
Soil W/T F	**W/T F**	71.70	69.01
Soil W/T G	**W/T G**	71.86	68.86
Soil W/T H	**W/T H**	76.96	64.30
Soil W/T I	**W/T I**	85.72	57.73
Soil W/T J	**W/T J**	121.12	40.85
Soil S/S	**S/S**	75.27	65.74

3.2.8.Meeting the Criteria of Safety against Touch and Step Voltage. The proposed W/T grounding system meets the criteria of safety regarding touch and step voltages under the most unfavourable short circuit conditions. The worst conditions in terms of danger caused by touch and step voltages occur when the fault clearing time is 1s, there is no surface layer of gravel and the person is considered to weight 50kg. Calculation is done along lines (1), (2) and (3) as shown in figs 14 and 15 that refer to the grounding systems of W/Ts B and H. WTs B and H grounding systems are chosen to be presented here as the one from which the highest current is dispersed into the soil and one where touch voltage is close to the limit for t_s=1s. Choice of the straight lines (1), (2) and (3) is made in order to calculate the dangerous step and touch voltages at those points above the grounding system where they obtain their maximum value. It should be noted that along the straight lines where a person is possible to be subject to dangerous touch and step voltages, a zone 10m wide around the W/T tower is checked for violation of safety limits.

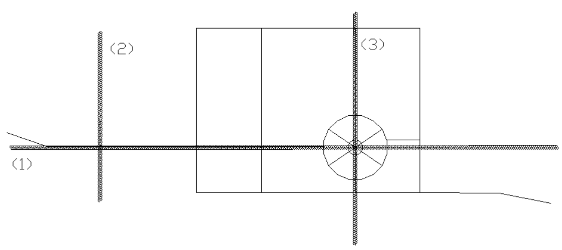

Figure 14: Straight lines above the grounding system of W/T B along which calculation and check for dangerous Touch and Step Voltages is done.

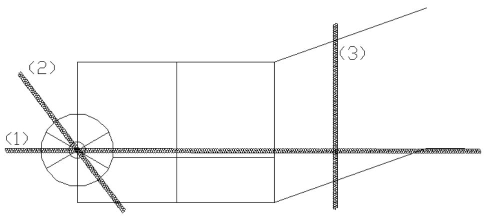

Figure 15: Straight lines above the grounding system of W/T H along which calculation and check for dangerous Touch and Step Voltages is done.

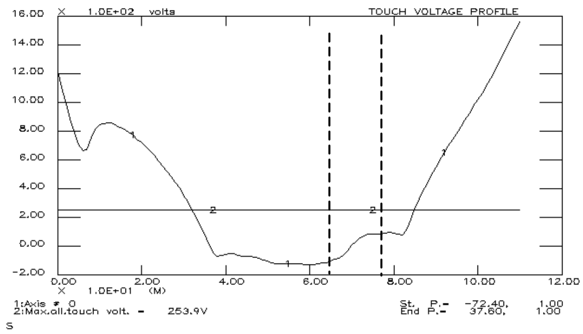

Figure 16: Touch voltage profile along line (1) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 1s)

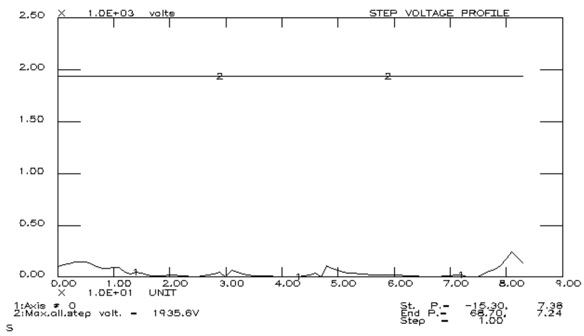

Figure 17: Step voltage profile along line (1) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 1s)

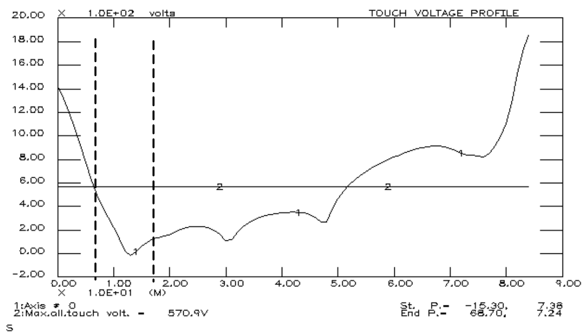

Figure 18: Touch voltage profile along line (1) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 1s)

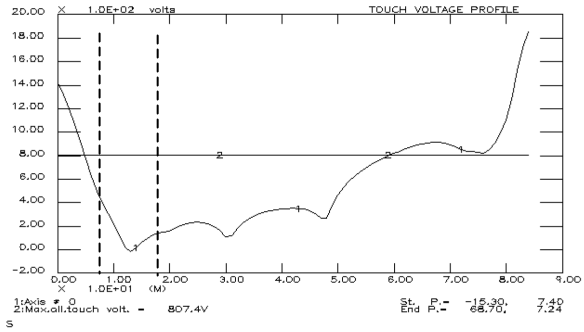

Figure 19: Touch voltage profile along line (1) at the surface of the soil above W/T H (limit calculated for fault clearing time equal to 0.5s)

It can be observed, that despite the fact that the highest current is dispersed into the soil through grounding of W/T B the most dangerous touch potentials appear at a zone close to the tower of W/T H. This is explained from the topology of the systems and happens because the tower of W/T B is above the grounding in the erection area while the tower of W/T H is at the edge.

3.2.9.Summary of the results

Summarizing the results shown in the previous sections, the following conclusions can be drawn:

- Step Voltages are in all cases and for the two fault clearing times under the maximum allowable value.
- Touch Voltages are of interest only at points where a person is likely to be in danger by the voltage difference between his feet (surface dynamic) and his hand touching a metal object that will be at potential during the short-circuit. Hence distances larger than 2m from the W/T tower are of no interest, since it is practically impossible ofr a person there to touch the tower.
- For fault clearing time equal to 1.0sec, dangerous Touch Voltages are developed in some W/Ts as for example at W/T H.
- For fault clearing time equal to 0.5sec, no dangerous Touch Voltages are observed in any point of the W/F.

5. CONCLUSIONS

Grounding systems should be designed in order to prevent excessive overvoltages and potential gradients that may cause damage to equipment or threaten human lfe. Fault or lightning currents to any W/T in a W/F installation, may damage equipment directly or indirectly as transferred potentials may exceed allowed values at W/Ts in the neighborhood of the fault

In this paper a methodology for the optimal design of individual W/T and W/F grounding systems, in order to minimise possible grounding resistance, in order to meet the safety criteria regarding touch and step voltages set by the IEEE standard is proposed.

Application examples of the methodology, considering two W/Fs one installed at a low and one at a high soil resistivity area are presented. Safety against lightning and short circuit is achieved in combination with the optimal costs of installation and materials.

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