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Frequency Response of Grounding System of Wind Turbine Generators

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Abstract: This paper examines the frequency response of several grounding systems of wind turbine generators, as they are currently used in wind parks in Greece. Several cases were studied depending on the grounding system and the soil structure. For every given frequency of the fault current the following magnitude have been calculated: the complex grounding resistance, the step and the touch voltages on the ground surface. Also, the effect of the point from which the fault current is diffused in the grounding system of several connected wind turbine generators has been examined. Furthermore, cases for the grounding system, which was energized each time from a different wind turbine, have been separately studied.

The effect of the soil structure on the response of a grounding system has been also investigated. Cases of uniform soil model and two-layer soil model with different specific resistivity values for the first and second soil layers, in combination with altering the thickness of the first layer, have been studied. Moreover, the frequency response of a grounding system in each of the above cases has been examined. The soil structure has been computed using soil resistivity measurements and specialized genetic algorithm software, which has been developed in our lab.

INTRODUCTION

The wind farms in Greece are built on mountaintops. Consequently soil resistivity has high values. This forced us to determine the soil structure (one layer, two layers or multi layer) and calculate the soil parameters with high accuracy, as these are the most important argument to design a safe grounding system. The grounding system has to be safe (reduction of the resistance and of the touch and step voltages) and inexpensive (low cost of material and installation) [1]. In addition, the limitations due to the soil structure and the use of the construction have to be taken into consideration. Therefore, the connection of all wind turbines' grounding systems and the exploitation of areas with low soil resistivity were necessary. It must be mentioned that in every wind farm a limited number of different grounding systems is necessary for practical installation reasons.

In this paper the program CDEGS has been used, in order to study the behavior of the grounding systems in wind farm when short-circuit occurs. The influence of frequency, injection point, kind of the grounding system, soil and number of the wind turbines has been investigated. The design of the grounding system is based on the IEEE Std 80 - 2000 [1]. The soil resistivity and the topography of the area are the fundamental factors for the design. For the calculation of the soil structure a special methodology has been developed [2]. Furthermore the short-circuit current has to be estimated [3, 4]. The grounding system, which will be designed, has to be safe; if this is not possible several ways can be followed as: addition of sand/gravel on the surface of the soil (if it offers reduction), reduction of the mesh (more cooper), or reduction of the fault clearing time.

Based on the process of many measurements [2, 5-9] it is concluded that earth has usually multi-layer structure. As a result, a methodology for the calculation of earth structure parameters (resistivity and depth of each earth layer) is considered essential. In the present bibliography there are available methodologies for the calculation of these parameters for two-layer [2, 5-7] and three-layer earth structures [2, 8, 9], using soil resistivity measurements.

Various methods for the design of the grounding systems in wind farms have been published [10, 11]. In addition, high frequency and transient conditions influence on the grounding system design has been investigated in [12].

TWO-LAYER STRUCTURE

The calculation of the parameters of a two-layer structure of the earth is an optimization problem. For the computation of the three parameters (soil resistivity of both layers, thickness of the upper layer; the depth of the lower layer is considered to be infinite) the minimization of the function F_g is necessary:

$$F_g = \sum_{i=1}^{M} \frac{\left|\rho_{\alpha i}^{m} - \rho_{\alpha i}^{c}\right|}{\rho_{\alpha i}^{m}} \tag{1}$$

where $\rho_{\alpha i}^{m}$ is the *i-th* measurement of the soil resistivity, when the distance between two sequential probes is α_i, while $\rho_{\alpha i}^{c}$ is the computed value of the soil resistivity for the same distance. The soil resistivity is calculated using equations (2-4) [5]:

$$\rho_\alpha^c = \rho_1 \cdot \left(1 + 4 \cdot \sum_n k^n \cdot \left(\frac{1}{\sqrt{A}} - \frac{1}{\sqrt{A+3}}\right)\right) \tag{2}$$

where $n = 1 \ldots \infty$, k is the reflection coefficient, and

$$A = 1 + \left(\frac{2 \cdot n \cdot h_1}{\alpha}\right)^2 \tag{3}$$

$$\mathrm{k} = \frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} \tag{4}$$

MULTI-LAYER STRUCTURE

The calculation of the parameters of a N-layer soil structure is an optimization problem with ($2N$-1) variables. It is necessary to minimize equation (1), where ρ_{ai}^m is the *i-th* measurement of the soil resistivity when the distance between two sequential probes is α, ρ_{ai}^c is the computed value of the soil resistivity for the same distance. The soil resistivity is calculated using equations [2, 13]:

$$\rho_\alpha^c = \rho_1 \cdot \left(1 + 2 \cdot F_N(\alpha) - F_N(2 \cdot \alpha)\right) \tag{5}$$

where

$$F_N(x) = 2 \cdot x \cdot \int_0^\infty \frac{K_{N1} \cdot e^{-2 \cdot \lambda \cdot h_1}}{1 - K_{N1} \cdot e^{-2 \cdot \lambda \cdot h_1}} J_o(\lambda \cdot x) \cdot \partial\lambda \tag{6}$$

For $1<i<N-1$ the coefficient of reflection k_i for two sequential layers is given by the formula:

$$k_i = \frac{\rho_{i+1} - \rho_i}{\rho_{i+1} + \rho_i} \tag{7}$$

In addition, for $N>2$ and $1<S<N-2$ the factor K_{NS} is given by the formula:

$$K_{NS} = \frac{k_S + K_{NS+1} \cdot e^{-2 \cdot \lambda \cdot h_{S+1}}}{1 + k_S \cdot K_{NS+1} \cdot e^{-2 \cdot \lambda \cdot h_{S+1}}} \tag{8}$$

and

$$K_{NN-1} = k_{N-1} \tag{9}$$

GENETIC ALGORITHM

In our methodology, the parameters of a two or a multi-layer structure of the earth are calculated using a GA. This GA has been developed using the software package Matlab and produces excellent results in this problem [2]. The flow chart of the developed GA is shown in Fig. 1.

The procedure of the GA starts with a randomly generated population of P_s=30 chromosomes. It generates 30 random values for each layer resistivity ($0<\rho_i<20000$, $1\le i\le N$) and 30 random values for each layer thickness ($0<h_i<20$, $1\le i\le N-1$). Each parameter is converted to a 20-bit binary number. Each chromosome has ($2N$-1) variables so ($40N$-20) bits are required for the chromosome. Each pair of parents with crossover generates N_c=4 children. The crossover begins as each chromosome of any parent is divided into N_p=6 parts, the pair of parents interchange their genetic material. After crossover there is a probability of P_m=5% probability for mutation. The termination criterion is fulfilled if either the mean value of F_g in the P_s-members population is no longer improved or the number of iterations is greater than the maximum prescribed number of iterations N_{max}.

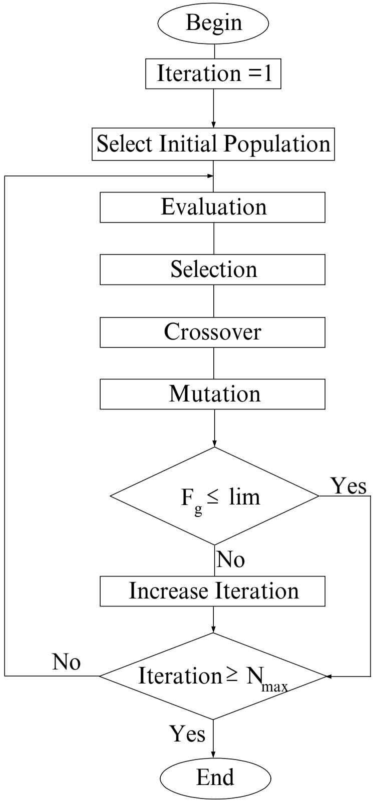

Fig. 1. The flow chart of our Genetic algorithm

SIMULATION RESULTS

In this paper various grounding systems of wind turbines with similar values of resistance but different values of touch and step voltages are investigated. The behavior of a grounding system is studied for various cases of soil. The investigated grounding systems, which are presented in Fig. 2, are buried in 90cm depth. The dimensions of the big (outer) rectangle of the grounding grid are 35m x 25m. The outside cycle has diameter 12m and it is buried in 2.5m. The inside cycle has diameter 3m and it is buried in 0.90m. The length of each vertical rod is 3m.

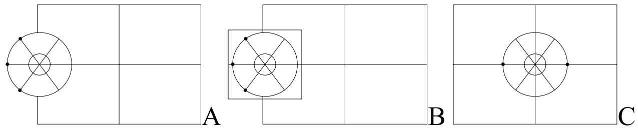

Fig. 2. The investigated grounding systems.

The effect of the soil structure on the response of a grounding system has been studied. In case of a homogeneous soil the resistance R of each grounding systems is given by equation (10).

$$R = K_{1L} \cdot \rho \tag{10}$$

where
ρ is the soil resistivity and K_{IL} is the coefficient for one layer structure. The values of K_{IL} are 15.7388(km)$^{-1}$, 15.2243(km)$^{-1}$ and 16.5167(km)$^{-1}$ for grid A, B and C of Fig. 2, respectively.

The case of the two-layer soil model with various resistivity values for the first and second layer and with alterations of the thickness of the first layer has been examined. The dependence of the resistance upon the depth of the first layer (for some cases of soil resistivity of both layers) is presented in Fig. 3.

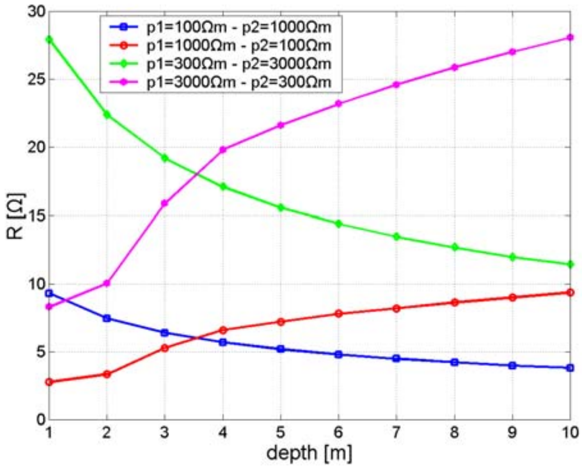

Fig. 3. Grounding systems resistance vs. depth (Grid A)

Moreover, the frequency response of a grounding system has been studied, taking into consideration the influence of the frequency in the grounding system of five interconnected wind turbine (WT) generators (Fig. 4).

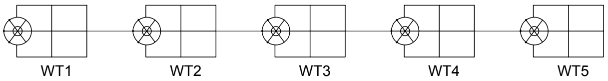

Fig. 4. Grounding system of five interconnected wind turbine generators.

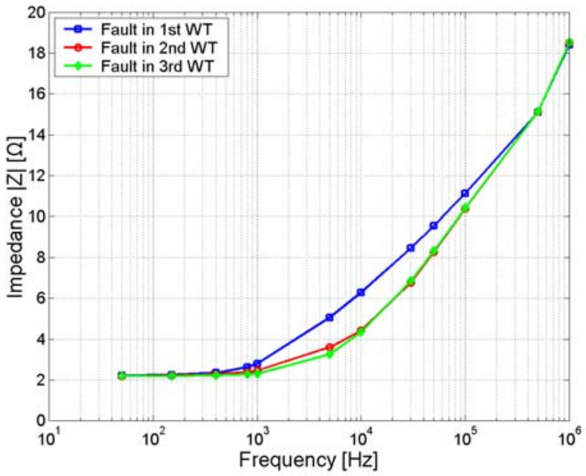

Fig. 5. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 100\Omega m$, $\rho_2 = 1000\Omega m$).

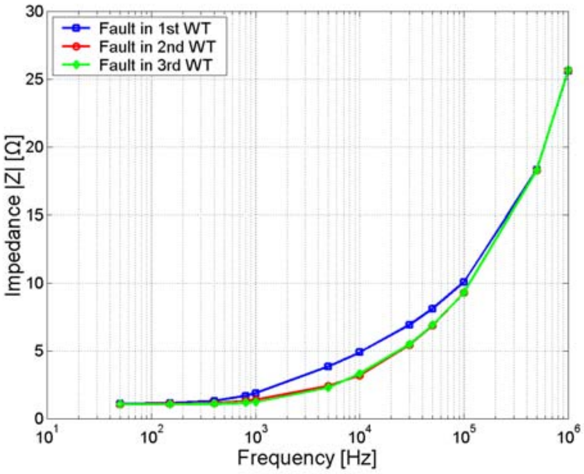

Fig. 6. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 1000\Omega m$, $\rho_2 = 100\Omega m$).

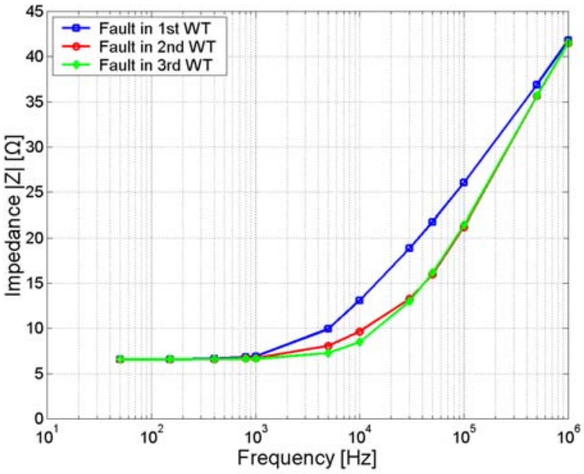

Fig. 7. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 300\Omega m$, $\rho_2 = 3000\Omega m$).

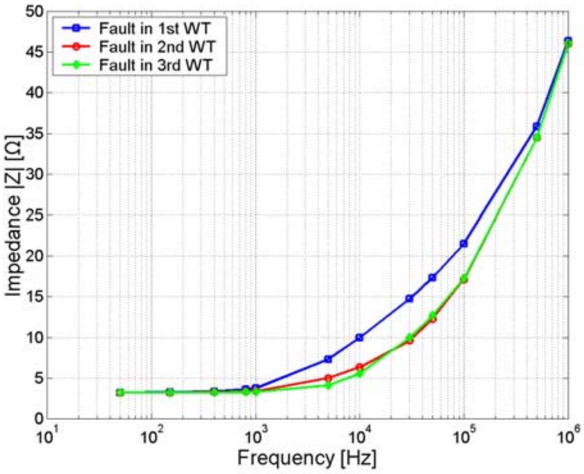

Fig. 8. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 3000\Omega m$, $\rho_2 = 300\Omega m$).

Furthermore, the cases of the grounding system, which were energized each time from a different generator, have been separately examined. The grounding impedance of the system of five connected wind turbines, which are grounded with the grounding system A of Fig. 2, buried in various two-layer soils with depth of first layer 3m is shown in Figs. 5-8.

In Figs. 5-8 it is obvious that the impedance values, when the fault current is injected in a central wind turbine, are lower than in the case when the fault current is injected in a terminal wind turbine.

Figs. 9-12 illustrate the grounding impedance of the system of five connected wind turbines (grid A) in the case of the grounding system, which is energized each time from one terminal wind turbines. The thickness of the first layer of the soil varies.

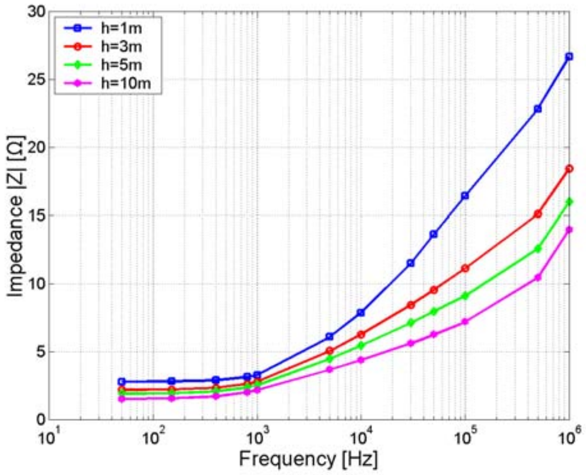

Fig. 9. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 100\Omega m$, $\rho_2 = 1000\Omega m$).

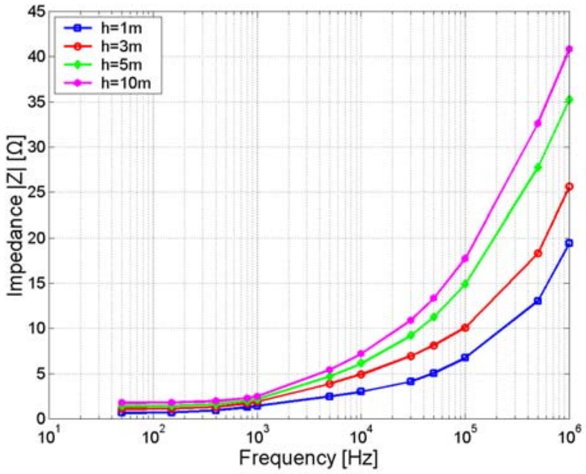

Fig. 10. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 1000\Omega m$, $\rho_2 = 100\Omega m$).

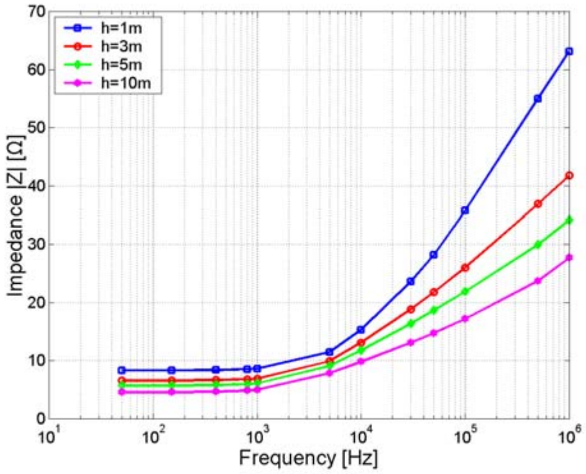

Fig. 11. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 300\Omega m$, $\rho_2 = 3000\Omega m$).

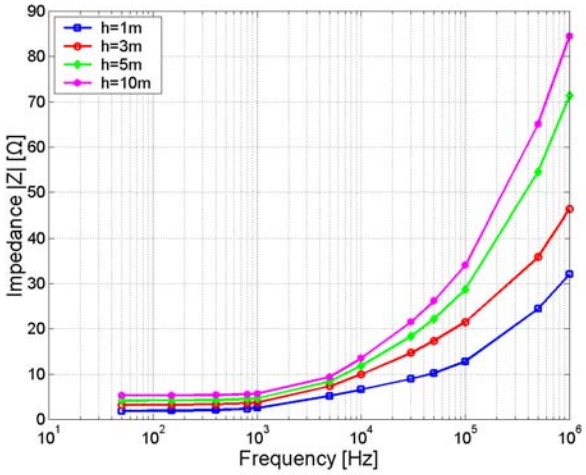

Fig. 12. Grounding impedance of five connected wind turbines vs. frequency ($\rho_1 = 3000\Omega m$, $\rho_2 = 300\Omega m$).

From Figs. 9-12 it is obvious that when the resistivity of the upper layer of the soil has higher value than the resistivity of the lower layer ($\rho_1 > \rho_2$), the impedance of the grounding system is as higher as the upper layer is thicker. When occurs the opposite ($\rho_2 > \rho_1$), the impedance of the grounding system is as higher as the upper layer is thinner.

Figs. 13-18 show the touch voltage in the case of a system with five connected wind turbines, when the grounding system is energized each time from a terminal generator. The depth of the first layer of the soil is 3m. The minimum threshold of the touch voltage has been calculated for a fault clearing time 0.5s and for a human body weight of 50kg according to the IEEE Std 80 - 2000 [1]. It is obvious that the grid B of Fig. 2 results in lower touch voltage (Fig. 14 and 17) than grids A and C (as they are presented in Figs. 13 and 16 for grid A and in Figs. 15 and 18 for grid C).

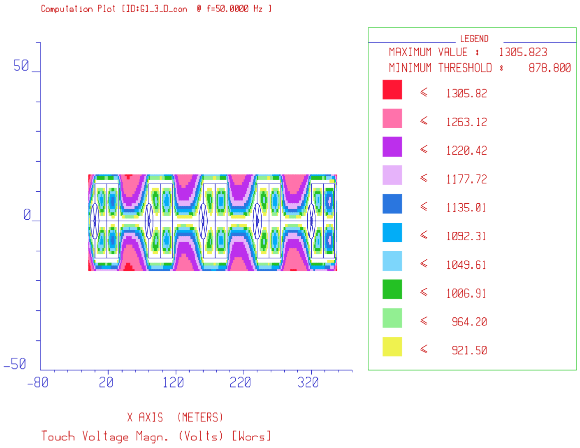

Fig. 13. Touch voltage in the case of grid A ($\rho_1 = 3000\Omega m$, $\rho_2 = 300\Omega m$).

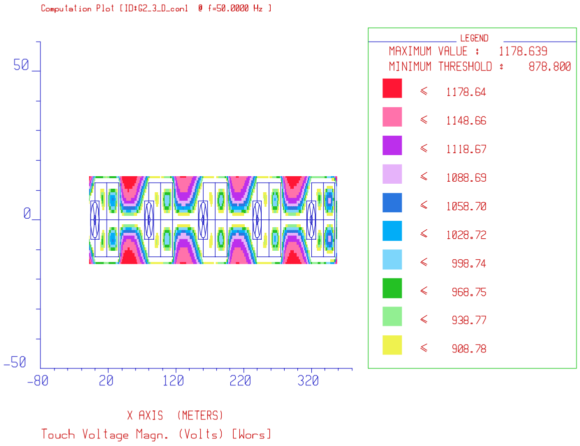

Fig. 14. Touch voltage in the case of grid B ($\rho_1 = 3000\Omega m$, $\rho_2 = 300\Omega m$).

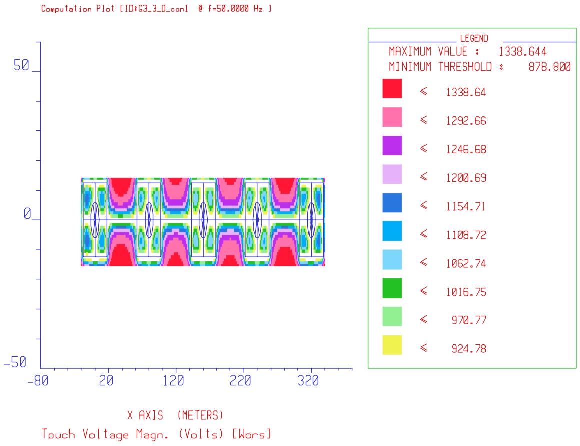

Fig. 15. Touch voltage in the case of grid C ($\rho_1 = 3000\Omega m$, $\rho_2 = 300\Omega m$).

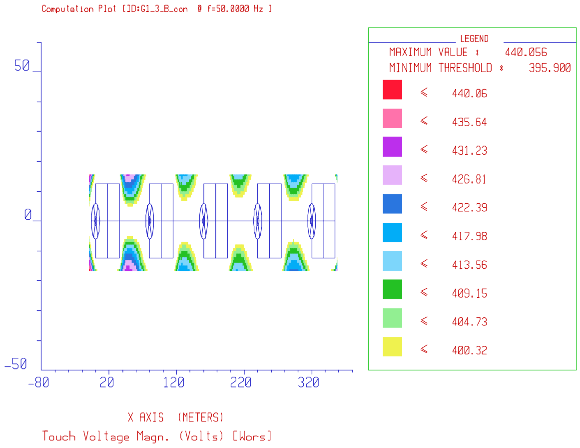

Fig. 16. Touch voltage in the case of grid A ($\rho_1 = 1000\Omega m$, $\rho_2 = 100\Omega m$).

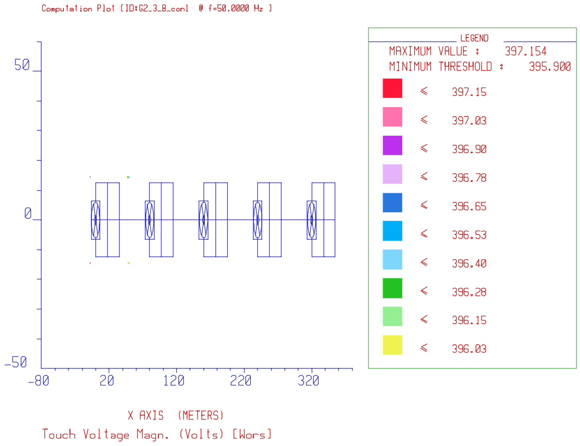

Fig. 17. Touch voltage in the case of grid B ($\rho_1 = 1000\Omega m$, $\rho_2 = 100\Omega m$).

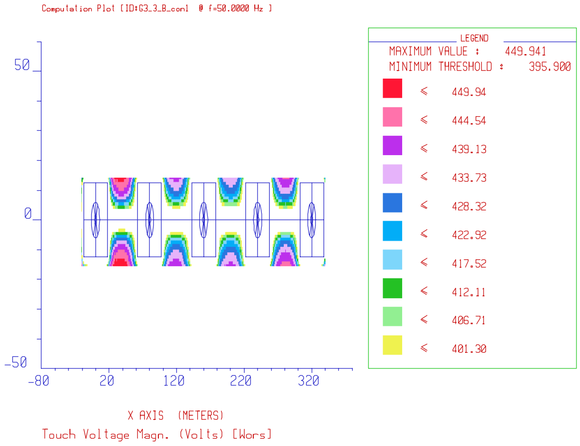

Fig. 18. Touch voltage in the case of grid C ($\rho_1 = 1000\Omega m$, $\rho_2 = 100\Omega m$).

CONCLUSIONS

The frequency depended behaviour of three typical grounding systems for wind turbines has been analysed in this paper. The investigated grounding systems are buried in a two-layer soil. The earth structure parameters have been calculated using a GA. A two-layer soil model with various resistivity values for the first and second layer and with alterations of the thickness of the first layer has been examined. The dependence of the resistance upon the depth of the first layer has been studied. It has been observed that the impedance of a grounding system is as lower as the soil resistivity of the first layer is lower, the thickness of the first layer is higher and the frequency of the injected current is lower. Also, the impedance is lower when the fault current is injected in a central wind turbine, than in the case when the fault current is injected in a terminal wind turbine. The touch voltage is depended upon the parameters of the soil structure, the shape and the dimensions of the grids. Finally, as greater is the density of the grounding system mesh close to the wind turbine, as lower is the touch voltage.

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