Extensive analysis of ground systems and their effects on wind turbines.

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Abstract
This paper provides an extensive analysis of ground systems and their effects on wind turbines. A typical arrangement of wind turbine ground system based on Grounding rings electrode is analyzed in this paper. The Grounding rings electrode are metal rings that make contact with the process liquid. The important issue of the effect of additional vertical and horizontal electrodes, respectively, has been addressed. The effect of the grounding wire placed in the cable fortress on the transient behavior is investigated in more detail. The mathematical formula in the field of frequencies is based on the theory of thin wire antennas and Pocklington's set of integro differential equations which is commonly mathematic formulas usage in this issue. In this analysis, the corresponding transient response is obtained using inverse Fourier transform (IFT). In the following, you will see that Pocklington's set of integro-differential equations is solved using the Galerkin-Bubnov indirect boundary element method (GB-IBEM) which using isoparametric elements.

Keywords: *wind turbine – ground systems – renewable energy – wind energy*

1. Introduction

Grounding systems, such as buried vertical or horizontal ring electrodes and large grounding grids are important and sophisticated for safety of stuff and for the protection of electrical equipment in industrial and power plants. The principal task of such grounding systems is to avoid or reduce the values of transient step and touch voltages which determine and demonstrate the health hazard. The secondary critical purpose of grounding systems is to make common reference voltage for all connected electrical and electronic systems. Relatively recently, the development and installation of integral lightning protection system for wind turbines (WT) is of particular interest [1-8]. Namely, wind turbines are often struck by lightning due to their special shape, complex construction and the fact that they are usually placed in isolated locations like savannah where it has more lighting strike probable, mainly at higher altitudes. Available relevant statistics indicates that between 4% and 10% of wind power in Europe suffers damages due to lightning strikes each year [7]. This situation is even worse in southern parts of Europe, like Croatia, Italy and Slovenia, due to the increased number of thunder storms and usually relatively low soil conductivity and static electricity in soil. Despite the fact that the methodology for WT lightning protection has been already proposed in [1], a number of issues concerning transient behavior of grounding system, in the case of lightning strike, are not quite clarified. Namely, the grounding methodology described in IEC 61400-24:2011 [3] is completely subjected to the IEC 62305-3:2007 [11], which handles lightning protection for general structures including houses and buildings. The foundation and grounding system of a WT are generally much smaller compared to the grounding systems of the buildings that have the same size. Furthermore, the lightning protection level for a WT is much higher than that of a normal building having an equivalent foundation to a turbine. Therefore, low-impedance grounding system is a major prerequisite for an effective protection of WT from lightning strikes. Namely, proper grounding for the protection of the WT should be designed in a way to reach the grounding resistance of preferably less than 10 U (for an isolated wind turbine, without the contribution of the residue grounding system of wind farm) [3]. This task is very difficult to fulfill in the case of the high specific resistance of the earth. In the other hand, setting the optimal mathematical model in terms of accuracy and efficiency is of great importance of this issue. This means that smaller grounding systems of a wind turbine may not have sufficient capacity for lightning protection compared to the conventional equipment. Also, the standards for grounding systems [11] are based on the steady state or low frequency analysis. Therefore, all practical aspects of grounding systems design are mostly relied on the steady state analysis. However, such analysis does not account for a transient behavior of grounding system in the case of lightning strike. Importance of the transient analysis lies in the fact that the appearance of high impulse currents leads to an dramatically increase of the grounding system potential related to zero ground during the transient state, which cause great danger to creatures like humans and installations or equipment. One of the most important parameters arising from the transient analysis is the transient impedance of the grounding system. Generally, grounding systems can be modeled in three ways that includes: the simple electric circuit methods [12,13], the transmission line model (TLM) [14-16] or the antenna (full-wave) model (AM) [17-22]. While the circuit approximations can be considered to be

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oversimplified, the TLM models have advantage of simplicity and relatively low computational cost. Hence, though valid for long horizontal conductors, simplified TL approach is not convenient for the vertical and interconnected conductors. In general, the TLM based solutions are limited to a certain upper frequency, depending on the electrical properties of the ground and configuration of particular grounding system [21]. On the other hand, the rigorous electromagnetic models based on antenna theory are regarded as the most accurate ones. The AM approach is based on solution of the Pocklington integro-differential equation for the half space problems. In the last decade several researchers have raised important questions about WT grounding. One of the earliest works on the subject [22-25] is related to usage of commercial software packages EMPT and CEDGS for WT grounding analysis. Good examples of further investigations include the use of MoM (moment method) [26, 27], the FDTD (finite difference time domain) [28], the FEM (finite element method) [29], EMPT [30] and CEDGS [31, 32]. Recently published work [27] deals with the similar subject, but it is limited to a simpler grounding system arrangement (one ring electrode with or without couple additional rods), while this paper deals with much more realistic and complicated WT grounding system arrangement. Contrary to the previous works [22-32] the presented contribution is based on the antenna model presented in [21]. The model is based on the set of integro differential equations of Pocklington type, with grounder interface effects being taken into account trough exact Sommerfeld integral formulation. Contrary to the usual approach featuring the Moment Method [19,20] (also implemented in CEDGS), the current distribution along the grounding system is obtained by solving the set of the Pocklington integro differential equations in the frequency domain via the Galerkin-Bubnov indirect Boundary Element Method (GB-IBEM) [33] featuring the linear isoparametric elements. Finally, the corresponding transient response is obtained by the means of the Inverse Fast Fourier Transform (IFFT) algorithm. In the presented work the transient impedance of a typical WT grounding system placed in a low conductivity soil is analyzed. Since the standard [11] provides a very few information about installation and influence of additional electrodes attached to the original grounding system special attention is given to the influence of additional vertical and horizontal electrodes, respectively. The influence of grounding wire placed in a cable trench on the transient behavior is also studied in detail. Finally, the results for Transient Ground Potential Rise (TGPR) are presented together with the transient behavior of the step voltage.

2. Problem description and formulation

The physical problem of interest is illustrated in Fig. 1. The arbitrary wind turbine grounding system is buried below ground and is subjected to a transient current generated by the lighting strike at a certain point. It should be noted that the influence of WT itself (tower, blades etc.) is neglected. Most of the wind turbines manufactures specifies grounding standards for the tower grounding. One of the typical wind turbine grounding system arrangement is shown in Fig. 2. The tower grounding system basically consists of a square of galvanized steel flanges (Fe/Zn 30 _ 3.5 mm e gray line in Fig. 2) at the 2 m depth, two copper ring wires (Cu 70 mm2 e black line in Fig. 2) at different levels (smaller one of 3.25mradius at 5 cm depth and the larger with 6.8 m radius buried at 55 cm depth) and additional four copper wires connecting rhombus with the tower. All this parts of the grounding system are connected by aluminothermy welding. The grounding system is placed in a homogenous soil of relatively high specific resistance of r = 1200 U/m, which is a realistic scenario for the wind farms located on the Croatian coast. The relative dielectric constant is assumed to be ε_r = 9.

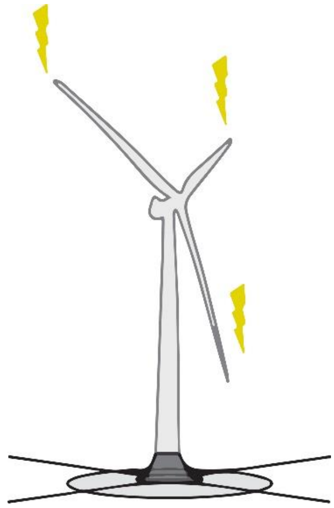

Fig. 1. Wind turbine subjected to a lightning strike.

2.1. Set of Pocklington integro-differential equations for arbitrarily shaped wires

The currents along the grounding grid configuration are governed by the set of coupled Pocklington integro differential equations for the wires of arbitrary shape. This set of Pocklington equations is derived from Maxwell equations and by satisfying certain continuity conditions for the tangential field components of the electric field at the electrode surface [17-21]. The outline of the derivation of this integral equation is given in [21]. For the sake of completeness the formulation is briefly repeated here. Thus, the set of Pocklington equations is given by [21]:

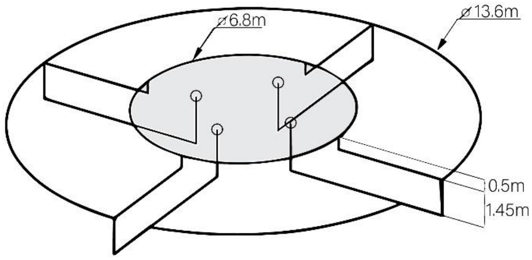

Fig. 2. Typical wind turbine grounding system arrangement.

$$E_{sm}^{exc}(S)=C.\sum_{n=1}^{Nw}\left[\begin{array}{c}\int_{C_n'}^{0}\ln(\acute{S}).\hat{S}_m.\hat{S}_n'.[K_1^2+\nabla\nabla]g_{0n}(S_m,S_n)d\acute{s} \\ +R.\int_{C_n'}^{0} l(\acute{S}_n).\hat{S}_m.\hat{S}_n^{*}.[K_1^2+\nabla\nabla]g_{in}(S_m,S_n^{*})d\acute{s} \\ \int_{C_n'}^{0}\ln(\acute{S}).\hat{S}_m.G_s(S_m,\acute{S}_n)d\acute{s}\end{array}\right]$$

$$m=1,2,\ldots N_W; \quad C=-\frac{1}{j4\pi\omega\varepsilon_{efec}} \quad R=\frac{K_0^2-K_1^2}{K_0^2+K_1^2} \qquad (1)$$

Where *I(S')* is the induced current along the wire, $E_{sm}^{exc}(S)$ is the excitation function, $g_0(S,S')$ denotes the lossy medium Green function, while $g_i(S,S')$ arises from the image theory. These functions are given by:

$$g_0(S,S')=\frac{e^{-jK_1R_1}}{R_0} \qquad g_1(S,S^*)=\frac{e^{-jK_1R_1}}{R_1} \qquad (2)$$

And R_0 and R_1 are the distances from the source point and its image to the observation point, respectively.

Furthermore, k_0 and k_1 are propagation constants of air and lossy ground, respectively:

$$K_0^2=\omega^2\mu_0\varepsilon_0$$

$$K_0^2=\omega^2\mu_0\varepsilon_{efec}=K_0^2=\omega^2\mu_0\left(\varepsilon_0\varepsilon_r-j\frac{\sigma}{\omega}\right) \qquad (3)$$

Where ε_r and σ are relative permittivity and conductivity of the ground, respectively, and ω is operating frequency. The third term $G_s(S,S')$ contains the Sommerfeld integrals and is constructed from the vector components for horizontal and vertical dipoles [21,34]:

$$G_s(S,S')=(\hat{X},\hat{S'}).(G_\rho^H.\rho+G_\emptyset^H.\emptyset+G_Z^H.Z)$$
$$+(\hat{Z},\hat{S'}).(G_\rho^V.\rho+G_Z^V.Z) \qquad (4)$$

The vector components are given in [21]. In the case of the grounding system excited by the current source the left hand side of the equation (1) vanishes a corresponding Pocklington equation simplifies to the homogenous one. Consequently, the excitation is incorporated into the formulation through the boundary conditions.

2.2. Numerical solution

The set of Pocklington integro-differential equations (1) is numerically handled by means of the Galerkin Bubnov variant of Indirect Boundary Element Method (GB-IBEM) [21]. The unknown current $I_n^e(\zeta)$ along the *n-th* wire segment is expressed by the sum of a finite number of linearly independent basis functions f_{ni}, with unknown complex coefficients I_{ni}:

$$I_n^e(s')=\sum_{i=1}^{n}I_{ni}f_{ni}(S')=\{f\}_n^T\{I\}_n \qquad (5)$$

Using the isoparametric elements yields:

$$I_n^e(\zeta)=\sum_{i=1}^{n}I_{ni}f_{ni}(\zeta)=\{f\}_n^T\{I\}_n \qquad (6)$$

Where n is the number of local nodes on the element.
A linear approximation over a boundary element along n-the wire is used in this work and the corresponding shape functions are given by:

$$f_1=\frac{1-\zeta}{2}, f_2=\frac{1+\zeta}{2} \qquad (7)$$

As this choice was proved to be optimal in modeling various wire structures [33]. Applying the weighted residual approach featuring the Galerkin-Bubnov procedure the set of Pocklington equations is transformed into a system of algebraic equations. Performing a certain mathematical manipulations, the following matrix equation is obtained [21]:

$$\sum_{n=1}^{N_W}\sum_{i=1}^{N_n}[Z]_{ji}^{e}\{I_n\}_i=0 \quad m=1,2,\ldots,N_W; \quad j=1,2,\ldots,N_m \quad (8)$$

Where N_W is the total number of wires, N_m is number of elements on the *m-th* antenna and N_n is number of elements on the *n-th* antenna.
$[Z]_{ji}^{e}$ Is the mutual impedance matrix for the *j-th* observation boundary element on the m-th antenna and *i-th* source boundary element on the *n-th* antenna. Implementing isoparametric elements yields following expression for mutual impedance matrix:

$$\begin{aligned}[Z]_{ji}^{e} &= -\int_{-1}^{1}\int_{-1}^{1}\{D\}_j\{D'\}_i^T g_{0_{nm}}(S_m,S'_n)\frac{ds_n}{d\zeta}d\zeta'\frac{ds_m}{d\zeta}d\zeta \\ &+ k_1^2.\ \hat{s}_m.\ s'_n\int_{-1}^{1}\int_{-1}^{1}\{f\}_j\{f'\}_i^T g_{0_{nm}}(S_m,S'_n)\frac{ds_n}{d\zeta}d\zeta'\frac{ds_m}{d\zeta}d\zeta \\ &- R.\int_{-1}^{1}\int_{-1}^{1}\{D\}_j\{D'\}_i^T g_{0_{nm}}(S_m,S^*_n)\frac{ds_n}{d\zeta}d\zeta'\frac{ds_m}{d\zeta}d\zeta \\ &+ R.k_1^2.\ \hat{s}_m.\hat{s}_n^*\int_{-1}^{1}\int_{-1}^{1}\{f\}_j\{f'\}_i^T g_{i_{nm}}(S_m,S_n^*)\frac{ds_n}{d\zeta}d\zeta'\frac{ds_m}{d\zeta}d\zeta \\ &- \hat{S}_m.\int_{-1}^{1}\int_{-1}^{1}\{f\}_j\{f'\}_i^T G_{s_{nm}}(S_m,S'_n)\frac{ds_n}{d\zeta}d\zeta'\frac{ds_m}{d\zeta}d\zeta \qquad (9)\end{aligned}$$

Matrices {*f*} and {*f '*} contain the shape functions while {*D*} and {*D'*} contain their directional derivatives. The excitation function in the form of the current source I_g is taken into account as a forced boundary condition at the certain node *i* of the grounding system:

$$I_g=I_i \qquad (10)$$

At the conductor free ends, the total current vanishes, i.e. is forced to be zero.

The treatment of wire junctions is related to the Kirchhoff's current law in its integral and differential form, respectively, related to continuity of currents and charges at the junction [21,35].

2.3. The evaluation of the input impedance spectrum

The input impedance is defined by the ratio:

$$Z_{in} = \frac{V_g}{I_g} \tag{11}$$

Where V_g and I_g are the values of the voltage and the current at the driving point. Once calculating the current distribution, a feeding point voltage is obtained by integrating the electric field from infinity (remote ground that has zero voltage) to the feeding point on the electrode surface:

$$V_g = -\int_{\infty}^{r} E\ D\ l \tag{12}$$

In all calculations the integration path was vertical (i.e. over z axis) because it was found that it provides the best and fastest convergence.

The frequency dependent input impedance is then obtained and multiplied with current spectrum to obtain the frequency response of grounding system. Finally, transient response is calculated by means of the IFFT.

integration of electric field, defined by (13), is also used to assess the surface potential and ground potential rise (GPR), but then the integration path goes from infinity (remote ground) to the point on the ground surface.

3. Numerical results

In all computational examples the lightning current is expressed by the double exponential function:

$$I(t) = I_0\,(e^{-\alpha t} - e^{-\beta t}) \tag{13}$$

With parameters: I_0 = 1.1043 A, $\alpha = 0.07924{\cdot}106\ s^{-1}$, $\beta = 4.0011{\cdot}106\ s^{-1}$ (so called 1/10 μs impulse).

Fig.3 shows the transient response of the basic grounding system. Dashed line represents a ten times higher input current waveform for the comparison reasons.

It can be seen that the maximal value of voltage is about 37 V and it is reached slightly after current peak value. Transient impedance continuously increases from zero to maximal value of 40 U which is equivalent to the steady state condition.

Given that the value of transient impedance is relatively high, i.e. four times higher than required by the standards in the steady state, this grounding system does not satisfy required safety standards.

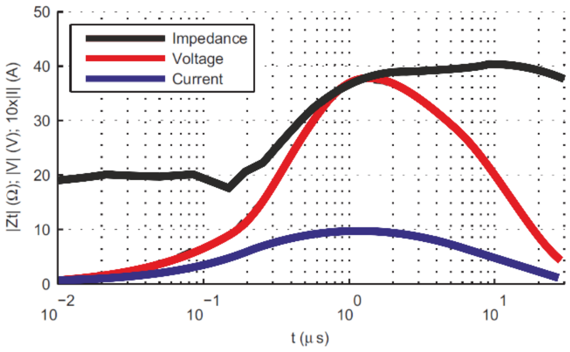

Fig. 3. Transient behavior of basic grounding system.

In order to improve the transient behavior, the original grounding system can be enhanced by adding horizontal and/or vertical electrodes.

3.1. Influence of additional horizontal electrodes

To investigate the influence of additional horizontal electrodes, the wind turbine grounding system has been upgraded with four 5 m or 15 m long horizontal electrodes (like shown in Fig. 4) placed at 2 m depth.

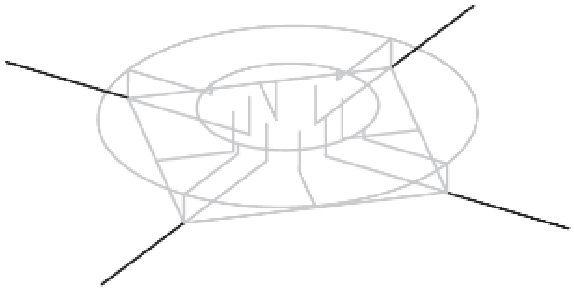

Fig. 4. Additional horizontal electrodes on wind turbine grounding system.

Figs. 5 and 6 show transient voltage induced at the feeding point and the transient impedance, respectively, for different lengths of additional horizontal electrodes.

A significant reduction in the value of the maximal induced voltage and consequently the transient impedance can be seen with the increase of the horizontal electrodes length.

Compared to the configuration without horizontal electrodes (blue line in Figs. 5 and 6), additional four 5 m horizontal electrodes reduce maximal transient voltage by 13% while four 15 m electrodes reduce it by 40%. A similar behavior can be noticed for transient impedance in Fig. 6.

It is worth emphasizing that no difference in transient behavior until 0.15 μs occurs, which shows that additional horizontal electrodes do not affect very early time behavior.

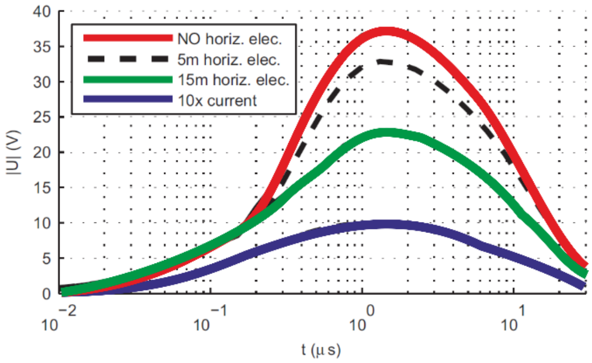

Fig. 5. Induced feeding point transient voltage for different lengths of additional horizontal electrodes.

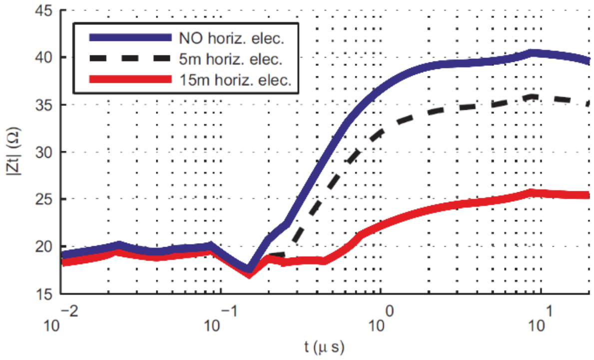

Fig. 6. Transient impedance for different lengths of additional horizontal electrodes.

3.2. Influence of vertical electrodes

In order to investigate the influence of vertical electrodes on proposed wind turbine grounding system in detail vertical electrodes of various length (3 m, 5.5 m and 15 m) were examined. Placement of the vertical electrodes is shown on Fig. 7. Results given in Figs. 8 and 9 show the influence of additional vertical electrodes of various lengths on transient behavior of the wind turbine grounding system. It is clear that additional, relatively short, vertical electrodes do not significantly decrease the value of the transient impedance with respect to the case without vertical electrodes (5% with four 3 m electrodes, and 12% with four 5.5 m electrodes). On the other hand, in the case of long vertical electrodes such influence is significant (around 40% with respect to the case without vertical electrodes).

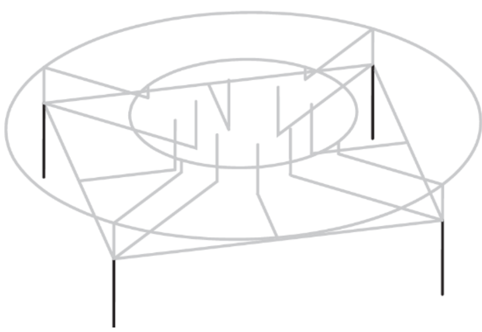

Fig. 7. Additional vertical electrodes on wind turbine grounding system.

Results presented in Figs.10 and 11 show that additional vertical electrodes decrease transient impedance in later time frame by 1%, 4% and 20% for four 3 m, 5 m and 15 m vertical electrodes, respectively. Comparing these results to the results obtained for grounding system without four 15 m horizontal electrodes, the effect of additional vertical electrodes is appreciably reduced. Figs. 12 and 13 show the transient behavior of the grounding system with added four 15m horizontal or vertical electrodes. Comparing those two cases no significant difference can be found. This should be bear in mind because placing horizontal electrodes is much cheaper than placing vertical ones, particularly in a rocky terrain. This means that the main factor determining the overall grounding system performance is the length of the electrodes.

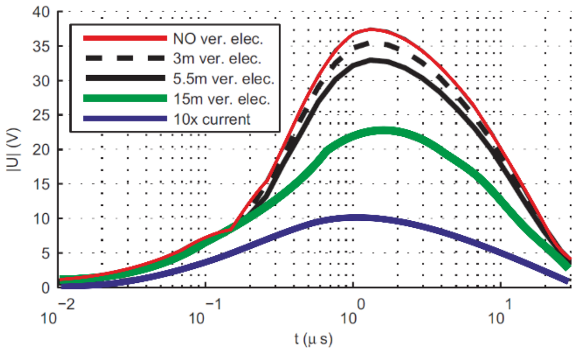

Fig. 8. Induced feeding point transient voltage for different lengths of additional vertical electrodes.

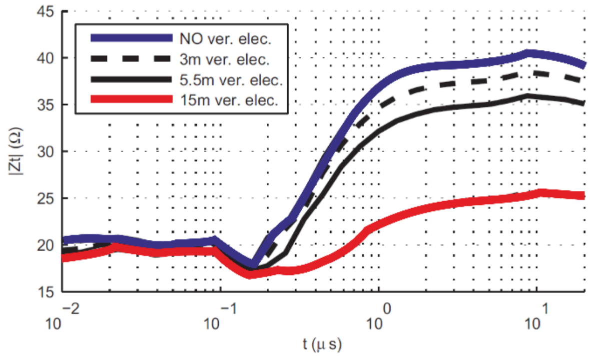

Fig. 9. Transient impedance for different lengths of additional vertical electrodes.

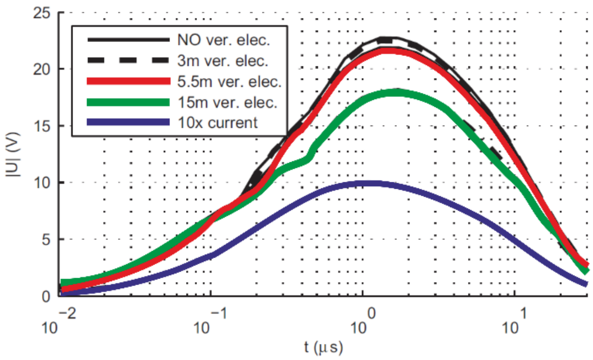

Fig. 10. Induced feeding point transient voltage for different lengths of additional vertical electrodes.

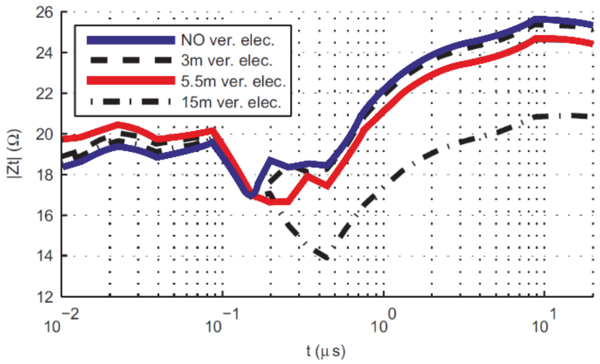

Fig. 11. Transient impedance for different lengths of additional vertical electrodes.

Installation of the vertical electrodes will give more benefit only in case when there is better conductive earth layer under the main grounding system. However, it is rarely the case in the rocky terrain.

3.3. Influence of grounding wire in cable trench

In further analysis the impact of the grounding wire in cable trench is taken into account on the behavior of grounding system in impulse mode. Results are compared (Figs. 14 and 15) for three different configurations:

- Grounding system with additional four 15 m horizontal electrodes without grounding wire in cable trench (config 1);
- Grounding system without additional horizontal electrodes with 200 m grounding wire in cable trench (config 2);
- Grounding system with additional three 15 m horizontal electrodes with 200 m grounding wire in cable trench (config 3);

All configurations do not contain any vertical electrode. The grounding wire in cable is modeled as a horizontal electrode of 200 m. From the obtained numerical results it clearly follows that the adding of grounding wire in cable trench reduces grounding impedance in steady state, which is consistent with the previous theoretical and practical experience. On the other hand, it is evident that in the case of configuration without additional horizontal electrodes there has been a significant increase of maximal induced voltage and related transient impedance. Consequently, the added long grounding wire in cable trench influences only the steady state behavior, while in the transient regime only first few tens of meters of the wire (depending on the specific resistance of ground) contributes to the decrease of transient impedance. The optimal configuration, as expected, is therefore the configuration with both horizontal electrodes and grounding wire in cable trench, which has the optimal characteristic overall.

It should be noted that the actual length of the grounding wire in cable trench in realistic situations significantly exceeds 200 m.

It is not necessary to take into account the rest of grounding wire in cable trench as it would not affect transient behavior of wind turbine grounding system at all.

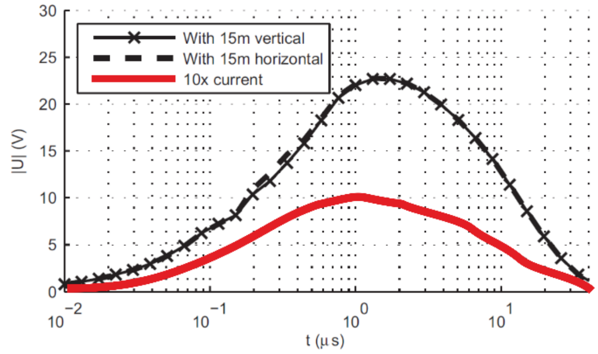

Fig. 12. Comparison of the induced feeding point transient voltage in the case of adding 15 m horizontal or vertical electrodes.

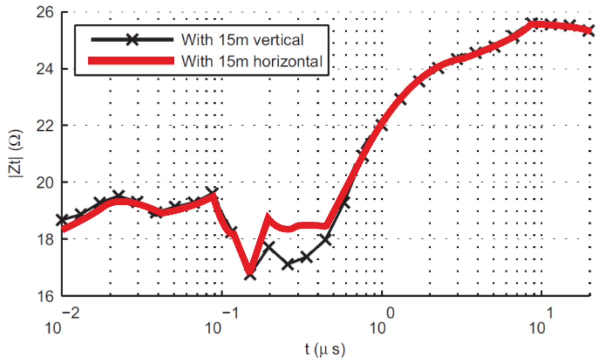

Fig. 13. Comparison of transient in the case of adding 15 m horizontal or vertical electrodes.

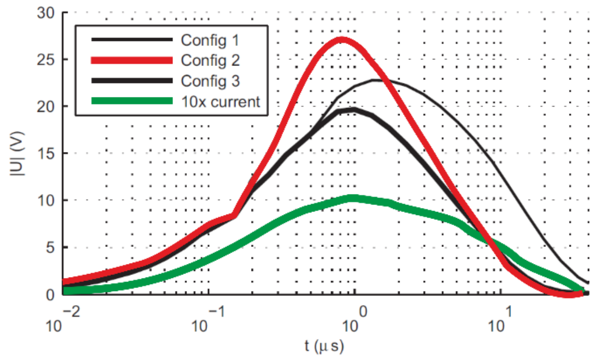

Fig. 14. Influence of grounding wire in cable trench on the

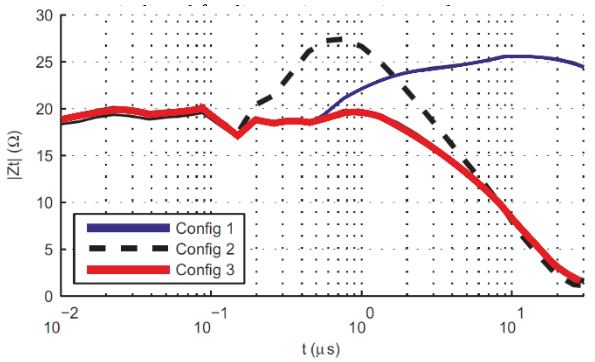

Fig. 15. Influence of the grounding wire in cable trench on the transient impedance.

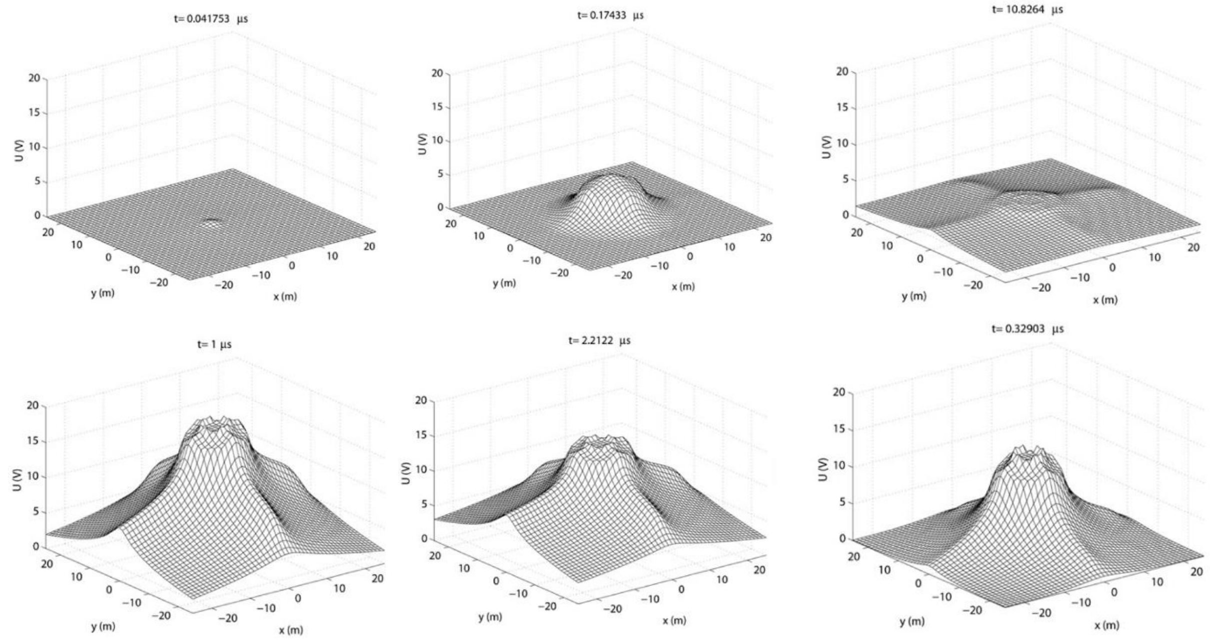

Fig. 16. Transient GPR above the grounding system.

3.4. Transient ground potential rise (TGPR) analysis

Finally the TGPR analysis has been carried out for the grounding system with three 15mhorizontal electrodes and 200mgrounding wire in cable trench. Fig. 16 shows the temporal and spatial distribution of the ground potential above the grounding system.

The spatial distributions are presented in compact 3D graphical form and temporal variations are presented as individual "snapshots" of the computer animation. Such presentation enables instant global insight in the distribution of voltages on large grids during the transient period. Presented results show large differences of the surface potential between points on the ground during the transient state. Higher values of the voltage occur above the main part of the grounding system near the injecting point. The voltage values then decrease along the rest of grounding system (above horizontal wires).

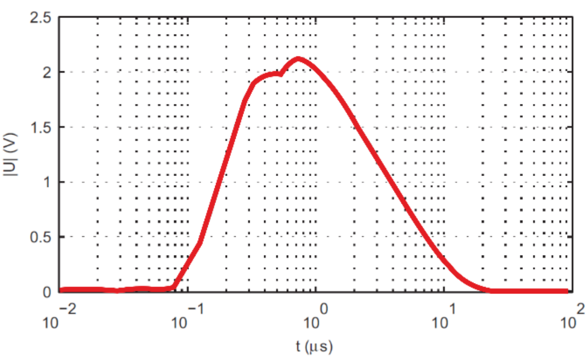

Fig. 17. Transient behavior of maximal step voltage.

This space-time distribution can be used for very accurate assessment of touch and step voltages. Due to geometry of the grounding system the maximum value of touch voltage was found to be around 0.32 V. On the other hand the step voltage has much higher value. Fig. 17 shows transient behavior of maximum step voltage. The maximum step voltage accurse just outside of the outer ring electrode (approximately at the point (5.5 m, 5.5 m)).

The maximum value of step voltage (around 2.1 V) occurs early around 0.7 µs from the beginning of the excitation, compared to time-to-maximum of 1 µs of current impulse.

It should be noted that the computed values are normalized to 1A peak value of the injected current impulse and will be proportionally larger for higher currents (i.e. 2.1 kV of maximal step voltage for the 1 kA current pulse). Also voltages will be larger in the case of low conducive soil.

4. Discussion and conclusion

Transient behavior of wind turbine grounding system has been analyzed using the thin wire antenna theory. The formulation based on wire antenna theory is related to the set of corresponding Pocklington integro-differential equation for curved wires. This set of equations is numerically treated via the Galerkin Bubnov scheme of the indirect Boundary Element Method. Finally, the corresponding transient response is obtained by means of the Inverse Fast Fourier Transform (IFFT) algorithm.

The analysis on the typical grounding arrangement of wind turbine grounding system has been analyzed. Influence of the horizontal and vertical electrodes of various lengths on transient behavior was examined in detail. The impact of the grounding wire in cable trench on the transient behavior of grounding system is also taken into account. It is shown that short vertical electrodes do not significantly reduces transient impedance values. In the case of long vertical electrodes the influence is significant but almost the same as achieved using horizontal electrodes of the same length. This is very important, especially when grounding is performed in rocky terrain, where drilling is very expensive. The analysis performed on grounding wire in cable trench showed that it did not contribute to the better behavior in very early stages of transient state. The significant influence is present in steady state only. To achieve the best transient response in overall the best configuration is the one with certain number of additional, long enough, horizontal electrodes and grounding wire in cable trench.

Finally the TGPR analysis found smaller values of touch voltages compared to the significant values of step voltages during the transient state of lightning impact.

The results presented in this paper can be, to a certain level, compared with the results obtained in [28] using FDTD. FDTD requires closed domain and consequently the discretization of the whole domain with the application of suitable absorbing boundary conditions at the far domain boundaries. The choice of the appropriate domain shape and size as well as adequate boundary conditions is then of a critical importance. On the other hand the integral formulation and implementation of the GB-IBEM requires only discretization of the wires. This makes GB-IBEM method very suitable for the analysis of the grounding system placed in homogenous half space. However, it is very hard to treat discontinuities, like concrete foundations, using GB-IBEM while with FDTD it is relatively easy.

Comparing results presented in this work with the results reported in [28] a very similar behavior of WT grounding system under transient conditions is found. Only one thing bounces. The results for very early time behavior of the transient impedance (less than few tens of µs) are much more realistic in this paper then in [28] where steep peaks of transient impedance values occur at about 0.1 µs. this makes the method implemented in this work more suitable for the analysis of very early time behavior. This ability to provide accurate results in the whole period of the transient is the main strength of the proposed method.

5. References

[1] Liu Y, Theethayi N, Thottappillil R. An engineering model for transient analysis of grounding system under lightning strikes: nonuniform transmission-line approach. IEEE Transactions on Power Delivery April 2005; 20(2):722e30.

[2] IEA. Recommended practices for wind turbine testing and evaluation. In:
Lightning protection for wind turbine installations, vol. 9; 1997.

[3] IEE Professional Group S1 (New concepts in the generation, distribution and use of electrical energy): half-day colloquium on “Lightning protection of wind turbines”, (1997, 11).

[4] Sorensen T, Sorensen JT, Nielsen H. Lightning damages to power generating wind turbines. In: Proceedings of 24th international conference on lightning protection (ICLP98); 1998. p. 176e9.

[5] McNiff B. Wind turbine lightning protection project 1999e2001. NREL subcontractor report, SR-500e31115; 2002.

[6] Rachidi F, Rubinstein M, Montanya J, Bermudez JH, Rodriguez Sola R, Sola G,
Korovkin N. A review of current issues in lightning protection of newgeneration wind turbine blades. IEEE Transactions on Industrial Electronics 2008; 55(6):2489e96.

[7] Yoh Y, Toshiaki F, Toshiaki U. How does ring earth electrode effect to wind turbine? Universities power engineering conference, 2007. UPEC 4e6 Sept. 2007; 42nd International volume: 796e9.

[8] Sarajcev P, Sarajcev I, Goic R. Transient EMF induced in LV cables due to wind turbine direct lightning strike. Electric Power Systems Research 2010; 80(4):
489e94.

[9] Burke GJ, Miller EK. Modeling antennas near to and penetrating a lossy interface. IEEE Transactions on Antenna and Propagation October 1984;
32(10):1040e9. AP.

[10] Glushakow B. Effective lightning protection for windturbine generators. IEEE
Transactions on Energy Conversion March 2007; 22(1):214e22.

[11] IEC International Standard. Protection against lightning e part 3: physical damage to structures and life hazard. IEC 62305e62303. Geneva: International
Electro-technical Commission; 2006.

[12] Meliopoulos AP, Moharam MG. Transient analysis of grounding systems. IEEE
Transactions on Power Apparatus and Systems 1983; 102(2):389e99.

[13] Ramamoorty M, Narayanan MMB, Parameswaran S, Mukhedkar D. Transient performance of grounding grids. IEEE Transactions on Power Delivery 1989;
4(4):2053e9.

[14] Liu Y, Zitnik M, Thottappillil R. An improved transmission line model of grounding system. IEEE Transactions on Electromagnetic Capability 2001;
43(3):348e55.

[15] Lorentzou MI, Hatziargyriou ND, Papadias BC. Time domain analysis of grounding electrodes impulse response. IEEE Transactions on Power Delivery
2003; 2:517e24.

[16] King RWP, Wu TT. Analysis of crossed wires in a plane-wave field. IEEE
Transactions on Electromagnetic Compatibility 1975; 17(4):255e65.

[17] Poljak D, Doric V. Wire antenna model for transient analysis of simple grounding systems. Part I: the vertical grounding electrode. Progress in

Electromagnetics Research 2006; 64:149e66.
[18] Poljak D, Doric V. Wire antenna model for transient analysis of simple grounding systems. Part II: the horizontal grounding electrode. Progress in Electromagnetics Research 2006; 64:167e89.
[19] Grcev L, Dawalibi F, Grcev L, Dawalibi F. An electromagnetic model for transients in grounding systems. IEEE Transactions on Power Delivery November 1990; 5(4):1773e81.
[20] Cotton I, Jenkins N. The effects of lightning on structures and establishing the level of risk. No. 3. In: Proceedings of IEE half-day colloquium on lightning protection of wind turbines; 1997. [21] Cavka D, Harrat B, Poljak D, Nekhoul B, Kerroum K, Drissi KEK. Wire antenna versus modified transmission line approach to the transient analysis of grounding grid. Engineering Analysis with Boundary Elements 2011; 3: 1101e8.
[22] Hatziargvriou N, Lorentzou M, Cotton I, Jenkins N. Wind farm earthing. No. 6. In: Proceedings of IEE half-day colloquium on lightning protection of wind turbines; 1997.
[23]
[24] Cotton I, Jenkins N. Windfarm earthing. In: Proceedings of European wind energy conference (EWEC1999); 1999. p. 725e8.
[25] Lorentzou M, Hatziargyriou N, Papadias BC. Analysis of wind turbine grounding systems. In: Proceeding of 10th Mediterranean electrotechnical conference (MELECON2000); May 2000. p. 936e9. Cyprus.
[26] Lewke B, Krug F, Kindersberger J. Risk of lightning strike to wind turbines for maintenance personnel inside the hub. In: Proceedings of 28th international conference on lightning protection (ICLP2006); September 2006. No. XI-9, Kanazawa.
[27] Ukar O, Zamora I. Wind farm grounding system design for transient currents. Renewable Energy 2011; 36:2004e10. doi:10.1016/j.renene.2010.12.026.
[28] Yasuda Y, Fuji T, Ueda T. Transient analysis of ring earth electrode for wind turbine. In: Proceedings of European wind energy conference (EWEC2007); May 2007. No. BL3.212, Milan.
[29] Muto A, Suzuki J, Ueda T. Performance comparison of wind turbine blade receptor for lightning protection. In: Proceedings of 30th international conference on lightning protection (ICLP2010); September 2010. No. 9A-1263, Cagliari.
[30] Yasuda Y, Uno N, Kobayashi H, Funabashi T. Surge analysis on wind farm when winter lightning strikes. IEEE Transactions on Energy Conversion 2008; 23(1):257e62.
[31] Kontargyri VT, Gonos IF, Stathopulos IA. Frequency response of grounding systems for wind turbine generators. In: Proceedings of the 14th international symposium on high-voltage engineering (ISH 2005), Beijing; August 2005. No. B-13.
[32] Elmghairbi A, Haddad A, Griffiths H. Potential rise and safety voltages of wind turbine earthing systems under transient conditions. In: Proceedings of 20th international conference on electricity distribution (CIRED2009); June 2009. P.8e11.
[33] Poljak D. Advanced modeling in computational electromagnetic compatibility. New York: John Wiley & Sons; 2007.