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Transient analysis of grounding systems for wind turbines

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ABSTRACT

The paper deals with transient analysis of grounding systems wind turbines. A typical wind turbine grounding system arrangement based on ring electrode is analyzed. Special attention is focused to the influence of additional vertical and horizontal electrodes, respectively. Influence of grounding wire placed in cable trench on the transient behavior is studied in detail. The mathematical formulation in the frequency domain is based on the thin wire antenna theory and the related set of Pocklington integro-differential equations. The corresponding transient response is obtained by means of the Inverse Fourier Transform (IFT). The set of Pocklington integro-differential equations is solved by the Galerkin-Bubnov Indirect Boundary Element Method (GB-IBEM) featuring the use of isoparametric elements. A number of illustrative computational examples are presented in the paper.

1. Introduction

Grounding systems, such as buried vertical or horizontal electrodes and large grounding grids are important for safety of personnel and for the protection of electrical equipment in industrial and power plants.

The principal task of such grounding systems is to avoid the values of transient step and touch voltages which determine the health hazard. The secondary purpose of grounding systems is to provide 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 [1–10]. 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, mainly at higher altitudes. Available relevant statistics indicates that between 4% and 8% of wind power in Europe suffers damages due to lightning strikes each year [6]. This situation is even worse in the southern parts of Europe, like Croatia, due to the increased number of thunder storms and usually relatively low soil conductivities. 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 61400-24:2010 [1] is completely subjected to the IEC 62305-3:2006 [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 of the same height. 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 Ω (for an isolated WT, without the contribution of the residue grounding system of wind farm) [1]. This task is very difficult to fulfill in the case of the high specific resistance of the soil. Hence, setting the optimal mathematical model in terms of accuracy and efficiency is of great importance. This means that smaller grounding systems of a WT 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 increase of the grounding system potential related to zero ground during the

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transient state, which represents great danger to humans, installations and 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 using the simple electric circuit methods [12,13], the transmission line model (TLM) [14–16] or the antenna (full-wave) model (AM) [17–21]. While the circuit approximations can be considered to be oversimplified, the TLM models have advantage of simplicity and relatively low computational cost. On the other hand, 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 ground–air 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.

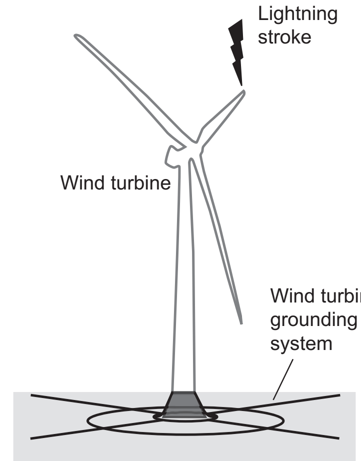

Fig. 1. Wind turbine subjected to a lightning strike.

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 $\times$ 3.5 mm – gray line in Fig. 2) at the 2 m depth, two copper ring wires (Cu 70 mm^2 – black line in Fig. 2) at different levels (smaller one of 3.25 m radius 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 $\rho = 1200$ Ω/m, which is a realistic scenario for the wind farms located on the Croatian coast. The relative dielectric constant is assumed to be $\varepsilon_r = 9$.

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]:

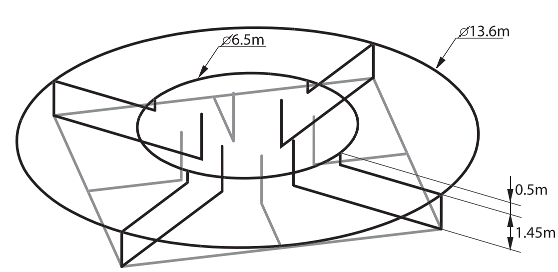

Fig. 2. Typical wind turbine grounding system arrangement.