Transient Characteristics of Wind Turbine Grounding

Frequency Dependent and Soil Ionization Effects

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Abstract—**The goal of the analysis in this paper is twofold. First, we analyze the influence of different grounding electrode arrangements on the transient ground potential rise in case of direct lightning strokes. Particularly, we analyze the influence of the integration of the metallic foundation reinforcement with the grounding system. In addition we analyze the influence of long (30 m) vertical electrodes and additional ring electrode. Next, we analyze soil ionization effects. We compute the distribution of the electric field in the earth in time domain (for typical lightning current pulses) looking for the volume within which the magnitude of the electric field is above the critical strength (300 kV/m). Then we look for the possibility to apply a simple formula to account for the soil ionization effects. The parameters in the analysis are varied for low and highly resistive earth and for lightning current pulses related to the first and subsequent return strokes. We apply a rigorous electromagnetic model for frequency dependent analysis and an approximate model to account for soil ionization effects. Both models have been previously validated by comparison with experiments.**

Keywords-wind turbine; grounding; lightning; modeling

I. INTRODUCTION

Wind turbines are tall structures, often constructed at high and exposed locations in order to obtain good wind conditions. As such, they often suffer direct lightning strikes that may cause serious damages to the electric equipment and threaten the safety of the people near and inside the structure.

The grounding system is important component of the lightning protection system (LPS). Its basic function is to provide low impedance path for the fault and lightning discharge currents to ground, without causing dangerous levels of touch and step voltages for the people, and to provide low potential difference between different points of the system. The performance and design of grounding systems at LF are well established and described in the international standards [1], but there is lack of details in the related standards dealing with the transient phenomena during lightning discharges [2]–[5].

In general, wind turbine grounding systems must have LF grounding resistance below 10 Ω, as required by the IEC standard [2]. However when lightning current pulses are injected into the grounding system, the transient ground potential rise might have large peak values [6] leading to higher values of grounding impedance. This frequency dependent effect is emphasized in better conductive soil, for larger grounding systems and fast rising lightning current pulses (typical for subsequent strokes). Such inductive behavior might practically impair the grounding performance in comparison to the LF performance.

On the other hand, when lightning currents with high peak values are injected in the grounding system, the electric field near the electrodes may exceed the electric strength of the soil thus causing soil breakdown and spark discharges. The process of soil ionization might significantly increase the conductivity of the soil around the electrodes that could practically improve the grounding system performance. This effect is typical in less conductive soil, for smaller grounding electrodes and for lightning current pulses with high magnitudes (typical for first return-strokes) [7].

Wind turbine grounding systems are commonly comprised of ring conductors electrically bonded with horizontal and vertical grounding electrodes [2]. Furthermore, according to [2] “the metal reinforcement in a foundation shall always be considered a part of the LPS”. The performance of the basic grounding system has been recently investigated in several papers, for example [8]–[11]; however, in most cases the metal reinforcement in the foundation was ignored.

In this paper we first analyze the influence of the integration of the metallic reinforcement in the foundation with the grounding system. In addition we analyze the influence of long vertical electrodes (four 30-m long rods) and additional outer ring electrode. We compare the potential at the feed point in respect to neutral ground in frequency and time domains for low and high resistive earth and for fast and slow front lightning current pulses. Here we neglect the soil ionization effects since the basic interest is in the frequency dependent phenomena, such as: inductive behavior that may impair the grounding performance in the first moments of the lightning stroke. Presented analysis is complemented in the companion paper [12] where step and touch voltages are analyzed for the same cases.

Next we analyze the soil ionization effects simultaneously with the frequency dependent effects. We compute electric field distributions in the soil around the grounding electrodes and look at the volume within which the magnitude of the electric field is above the critical strength. The goal of the analysis is to estimate possible improvement of the grounding performance due to the soil ionization effects. We also look at

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the possibility to apply simple formula recommended by CIGRE and IEEE Working Groups [13], [14].

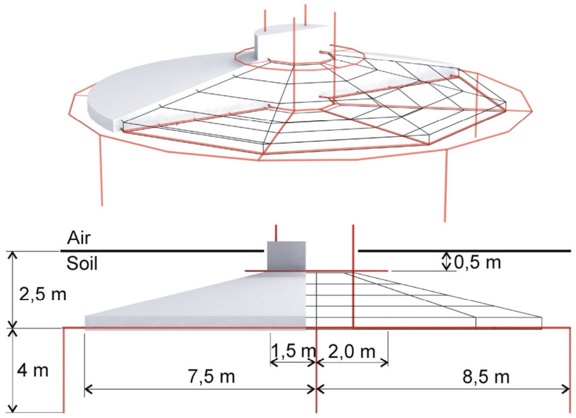

Figure 1. Wind turbine grounding system (red lines) integrated with the foundation reinforcement metal network (grey lines)

We apply the rigorous electromagnetic model [15]–[16] for the computations in this paper. The model is based on a mathematical method developed from the antenna theory and solved by the method of moments [17]. Computations are performed by Tragsys computer software [18], however, modifications were made for the time domain analysis of the electric field distributions. The computer model accuracy has been validated through comparisons with published experimental results by a number of independent research groups (for example, see [19] and [20]). Soil ionization effects were computed by the approximate method [20].

II. Geometry of the Analysed Grounding System

We consider a typical grounding system for 1.5 MW wind turbine. The foundation type is spread footing with octagonal shape, made of reinforced concrete with diameter of 15 m and depth of 2.5 m, Fig. 1.

The basic grounding system considered in this study consists of three ring electrodes embedded in the concrete foundation, additional two ring electrodes buried in soil and four vertical rods, Fig. 1. Two inner rings are embedded in the foundation with diameters of 3 m (similar to the tower base), one at 0.5 m depth and the other at 2.5 m depth. The outer ring embedded in the foundation is with diameter of 15 m. All rings are mutually connected. Additionally, one inner ring is buried in soil above foundation around the tower at 0.5 m depth and 4 m diameter, and one outer ring is buried in soil at the periphery of the foundation at 2.5 m depth with 17 m diameter. The latter is connected with four vertical rods with 4 m length. The Basic grounding system is given with red lines in Fig. 1.

Steel reinforcement in the foundation is represented by conductor network with grey lines in Fig. 1. The reinforcement bars are mutually connected with the grounding electrodes at every 1.5 m, to establish good electrical connection. For reasons of simplicity and computational efficiency we use sparse network that encompass the volume of the foundation, although the real foundation reinforcement consists of very dense network.

III. Computation Test Cases

To investigate the influence of different grounding arrangements we consider four cases:

- Basic grounding system with foundation reinforcement ignored;
- Grounding system integrated with foundation reinforcement;
- Integrated grounding system with additional outer ring electrode with 23 m diameter buried at 1 m depth (not shown in Fig. 1). It is at 4 m distance from the foundation periphery [2], [4], and is connected to the 17-m diameter ring at four points; and
- Integrated grounding system with four 30 m vertical rods (that replace the 4-m vertical rods in Fig. 1).

Two different earth conductivities are considered:

- $\rho = 100\,\Omega\mathrm{m}$
- $\rho = 1000\,\Omega\mathrm{m}$

Two lightning current waveforms related to the first and subsequent return strokes are considered.

- Current pulse related to the first stroke has peak value I_m = 30 kA, zero-to-peak time $T_1 = 5$ µs, and decay time to half-peak T_2 = 50 µs. Current peak value has been varied up to 200 kA in the analysis of the soil ionization effects.
- Pulse related to the subsequent stroke has I_m = 12 kA, $T_1 = 0.5$ µs and $T_2 = 50$ µs.

They are reproduced by means of a usual double exponential function:

$$i(t) = I_m \cdot k \cdot \left[\exp(-\alpha t) - \exp(-\beta t)\right] \quad (1)$$

where I_m is the peak value of the current pulse. Values of the coefficients k, α and β in (1) for the pulses used in the simulations are given in Table 1.

TABLE I. Lightning Current Pulse Parameters

	T_1/T_2 [µs]	I [kA]	k	α [s^{-1}]	β [s^{-1}]
First Stroke	5 / 50	30	1.00806	0.0140235	13.79696
Subsequent Stroke	0.5 / 50	12	1.10433	0.0158478	0.800219

IV. Harmonic Impedance

Harmonic impedance is useful quantity in transient analysis. It is equal to the grounding resistance R in the LF range (related to response to slow varying excitation) and its