A Proposed Method for Calculating Earth Electrode Length for a Wind Turbine Generator Grounding System

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Abstract—A safe and reliable grounding system plays a critical role in the design of an effective lightning protection system of a wind turbine generator. An accurate design of grounding electrodes is required to achieve the necessary low impedance of a wind turbine generator earthing system. IEC 61400-24 provides guidelines for selecting the minimum length of an earth electrode, however, this standard cannot be utilized for all types of electrode shapes and buried depths. Moreover, it is important to address the frequency dependency of soil resistivity for the selection of electrode length. This paper proposes a novel method enhancing the frequency dependency of soil resistivity for the selection of electrode length. This paper proposes a novel method enhancing the frequency dependency of soil resistivity for the selection of electrode length. The minimum length of the earth electrode to achieve a resistance of less than 10 Ω is determined predominantly by the soil resistivity of the WTG site [7]. Hence the soil resistivity measurement and the interpretation of soil structure is critical in selecting the earth electrode length. The soil resistivity also varies with frequency [8]. Thus, it is important to understand the effect of the frequency dependent soil parameters on the WTG earthing system.

This research proposes a novel method to calculate the minimum length of an earth electrode for a WTG grounding system by considering the electrode dimensions and bury depth. This methodology can also be used to calculate the electrode length for a required resistance value. A thorough analysis of the influence of frequency dependent soil resistivity on required minimum electrode length is also performed as part of this research. Finally, this paper provides recommendations for design of wind turbine earthing electrodes in designing a grounding system.

Index Terms—Wind turbine generator, lightning, earth electrode length.

I. INTRODUCTION

Wind turbine Generators (WTGs) are tall structures in their surroundings and are installed at locations with high thunderstorm activity and high soil resistivity to capture more energy from the wind [1]. Hence, there is a high probability of lightning strikes on the WTGs, which can result in severe damage to the electrical equipment inside the WTGs [2]. Hence the need for developing effective lightning protection methods for wind turbines.

Amongst various components of a wind turbine lightning protection system, the grounding (earthing) system plays a pivotal role [3]. A low impedance value of grounding system ensures lightning discharge currents dissipate into the earth by keeping ground potential rise to a minimum value. Hence, a safe and reliable grounding system design must be ensured to protect the WTGs from lightning strikes. WTG grounding systems commonly serve two purposes: power system fault protection and lightning protection [4]. However, the grounding system behaviour is different for lightning discharge currents due to the high-frequency components [5]. At higher frequencies, the inductive component of the impedance is a dominant factor compared to the resistance. Hence, protection of WTGs from lightning strikes takes priority over power system faults when designing the WTG grounding systems.

The design of a wind farm grounding system begins with the design of an individual WTG grounding systems [6]. IEC 61400-24 [7] recommends a grounding resistance value of less than 10 Ω for an isolated WTG from rest of the wind farm [6]. In addition, the standard recommends using a type B earthing arrangement, which consists of ring earth electrodes surrounding the WTG foundation in combination with additional radial or vertical earth electrodes [7].

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This research proposes a novel method to calculate the minimum length of an earth electrode for a WTG grounding system by considering the electrode dimensions and bury depth. This methodology can also be used to calculate the electrode length for a required resistance value. A thorough analysis of the influence of frequency dependent soil resistivity on required minimum electrode length is also performed as part of this research. Finally, this paper provides recommendations for design of wind turbine earthing electrodes in designing a grounding system.

II. WIND TURBINE EARTHING SYSTEM

The lightning protection requirement takes a priority over the power system fault protection in the design of the wind turbine earthing system [6]. The lightning protection system requirement in relevance to the international standard IEC 61400-24 is designed to prevent the earthing system from exceeding the resistance value of 10 Ω measured at a frequency different from power frequency and its lower harmonics. To achieve the low resistance, an earthing system with a minimum electrode length recommended by the standard. The minimum length of electrode can be selected from Fig. 1 based on the lightning protection level and the respective soil resistivity value.
The earthing system of a wind turbine comprises a steel foundation structure, tower base, staircase and the designed earthing system. A three-dimensional perspective view of the wind turbine earthing system consisting of foundation and ring electrode is depicted in Fig. 2. Additional radial or vertical electrodes may be connected according to the required minimum electrode length. Finally, it is essential to ensure proper bonding of all the metallic components to avoid hazardous potential differences between different structures and the earthing system.

III. FREQUENCY DEPENDENT SOIL PARAMETERS

The grounding grid impedance and the potential gradients within a WTG earthing system are dependent on the soil resistivity [9]. In practice, soil resistivity varies with temperature, moisture, mineral content and compactness [10] as well as frequency. It is extremely important to consider this frequency dependency while designing the earthing system owing to the high frequency components of the lightning discharge currents.

It has been reported that the use of constant soil parameters resulted in over 60% ground potential rise compared to frequency dependent soil parameters [11]. However, the frequency dependency of soil parameters has not been considered for designing the earthing system due to the lack of accurate formulations to represent the frequency dependency of soil parameters. Alipio et al. [11] proposed the frequency dependent soil parameter formula shown in (1).

\[
\rho = \rho_0 \left\{ 1 + \left[ 1.2 \times 10^{-6} \cdot \rho_0^{0.73} \right] \cdot \left[ (f - 100)^{0.65} \right] \right\}^{-1} \tag{1}
\]

where \( \rho_0 \) is the soil resistivity at 100 Hz and \( \rho \) is the soil resistivity at frequency \( f \). Equation (1) is valid from 100 Hz to 4 MHz.

IV. PROPOSED METHOD

The required low resistance of a WTG earthing system can be achieved by an accurate design of length, dimension and the buried depth of earthing electrodes [7]. The conventional earthing system recommended by the IEC 61400-24 is designed initially for buildings having longer foundations where longer ring electrodes are possible [12]. However, WTGs typically have foundations with shorter mean radius and might need additional electrodes for higher values of soil resistivity.

The mean radius of the ring earth electrode \( (r_e) \) must be higher than the minimum length of the electrode \( l_1 \) based on Fig. 1. However, if the required length of the electrode is greater than the radius of the ring electrode, additional horizontal and vertical electrodes are connected, as expressed in (2) and (3).

\[
l_e = l_1 - r_e \tag{2}
\]

\[
l_v = \frac{(l_1 - r_e)}{2} \tag{3}
\]

where, \( l_1 \) is the minimum length of earth electrode, \( l_e \) the length of radial electrode, \( l_v \) the length of vertical electrode, and \( r_e \) the mean radius of ring earth electrode.

In the conventional approach based on the standard IEC 61400-24, the length of the earth electrode is dependent only on the soil resistivity. However, the current dissipation in an earthing system is dependent on the dimensions and the buried depth of an earth electrode. Hence, the electrode dimensions and its buried depth are critical to a WTG earthing system.

The resistance of a ring electrode can be calculated by (4), proposed by Sunde [13]. However, the calculation of resistance using this formula doesn’t consider the WTG foundation structure.

\[
R = \frac{\rho}{2\pi^2r} \ln \frac{8r}{\sqrt{2ad}} \tag{4}
\]

where, \( \alpha \) is the radius of cross section of the ring, \( d \) is the buried depth of the ring, \( r \) is the mean radius of the ring earth electrode, \( R \) is the equivalent earth resistance of the ring electrode, and \( \rho \) is the soil resistivity.

Yasuda et al. [3] proposed a modified formula for calculating the WTG earthing resistance, given by (5):

\[
R' = \frac{\rho}{\alpha 2\pi^2r_e} \ln \frac{\beta 8r_e}{\sqrt{2ad}} \tag{5}
\]

where, \( \alpha \) is the radius of cross section of the ring, \( d \) is the burying depth of the ring, \( r_e \) is the mean radius of the ring earth electrode, \( R' \) is the equivalent earth resistance of WTG, \( \rho \) is the soil resistivity, and \( \alpha \) and \( \beta \) are constants.

Our method is based on the WTG earthing equivalent resistance formula given by (5). The mean radius of the ring
The WTG grounding electrode lengths which are calculated according to the standard IEC 61400-24 for frequency independent and dependent soil resistivity are depicted in Fig. 3. For the soil resistivity values of up to 500 $\Omega$m an electrode length of 5 m is recommended by the standard. Based on our studies, it is noted that the soil resistivity reduces to 60 $\Omega$m and 150 $\Omega$m at 4 MHz for 100 $\Omega$m and 500 $\Omega$m at 100 Hz, and hence an electrode length of 5 m is valid for the soil resistivities under 500 $\Omega$m. However, for soil resistivity of 3000 $\Omega$m at 100 Hz an electrode length of 80 m is required, whereas at 4 MHz the soil resistivity is about 200 $\Omega$m, thus, an effective electrode length of 5 m is found to be sufficient. A similar pattern is observed for the other soil resistivity values ranging from 100 $\Omega$m to 3000 $\Omega$m. The soil resistivity value drops below 500 $\Omega$m at 4 MHz for all the resistivity values from 100 $\Omega$m to 3000 $\Omega$m, hence, an effective length of 5 m is sufficient at higher frequencies. For an earth resistivity of 10000 $\Omega$m at 100 Hz an electrode length of 290 m is required, however, the effective electrode length of 5 m is sufficient at 4 MHz as the soil resistivity drops to 487 $\Omega$m.

The proposed method is applied to calculate the electrode lengths for two resistance values and different electrode parameters where the variation in electrode lengths are significant in some cases compared to the traditional method. Fig. 4 shows the calculated electrode lengths for achieving a resistance of 10 $\Omega$ when an electrode is assumed to be buried at a depth of 0.5 m below the earth surface. As depicted in Fig. 4(a), an electrode length of 1.8 m is required for soil resistivity of 100 $\Omega$m at 100 Hz. As the soil resistivity reduces with an increase in frequency, an electrode length of 0.95 m is found to be sufficient at 4 MHz. For soil resistivity of 500 $\Omega$m, an electrode length of 11.8 m is required to achieve a resistance value of 10 $\Omega$ at 100 Hz, as illustrated in Fig. 4(b), in contrast to a 5 m electrode length used in the conventional method. Also, at 4 MHz, an active electrode length of 5 m is required for the earth resistivity of 500 $\Omega$m. For soil resistivity of 3000 $\Omega$m, an electrode length of 87.5 m is required at 100 Hz and 7 m at 4 MHz compared to a length of 80 m for all frequencies using the conventional method.

In the next scenario, the electrode burying depth is changed to 2 m from the surface of the earth for calculating electrode lengths, as depicted in Fig. 5. It can be seen that the required electrode lengths have reduced for all soil resistivity values when burying the electrodes deeper into the earth. The required
Fig. 3. Frequency dependent WTG earth electrode length according to IEC 61400-24.

Electrode length is reduced from 87.5 m to 81.2 m at 100 Hz when the electrode depth is changed from 0.5 m to 2 m. This is due to a more uniform electrical field distribution that exists around the electrodes.

In the next case, the electrode lengths are evaluated for achieving a resistance of 5 \( \Omega \). As illustrated in Fig. 6, at a frequency of 100 Hz, an electrode length of 4.1 m is required for 100 \( \Omega \) m, and an electrode length of 26 m is required at 500 \( \Omega \) m against lengths of 1.8 m and 11.8 m for 10 \( \Omega \). For earth resistivity of 3000 \( \Omega \) m, an electrode length of 187.5 m is needed at 100 Hz and 16 m at 4 MHz.

In the final case, the electrode lengths are calculated to achieve a resistance of 5 \( \Omega \) with an electrode buried depth of 2 m. Although at lower soil resistivity values the reduction in electrode length is smaller, about 2 m for 500 \( \Omega \) m compared to a burying a depth of 0.5 m, a reduction of approximately 13 m is observed at higher soil resistivity value of 3000 \( \Omega \) m, as depicted in Fig 9.

With the frequency independent soil resistivity, the effective length of the electrode is constant at all frequencies. However,
the resistivity changes with change in frequencies. It can be observed from results of this research that the earth resistivity of 3000 $\Omega \cdot m$ at 100 Hz drops to 329 $\Omega \cdot m$ at 4 MHz. Hence, the effective length of an electrode required at a higher frequency is shorter than that required at lower frequencies.

According to IEC 61400-24, electrode lengths greater than 80 m have very little influence on the WTG impedance value at high frequencies. On the contrary, the standard recommends to achieve resistance less than 10 $\Omega$ at a frequency different from the lower order harmonics of the power frequency. Hence, in order to achieve a low resistance at low frequencies for higher soil resistivity WTG sites, longer length of electrodes can be applied. This is evident from Table II, an electrode length of 187 m is recommended to achieve a resistance 5 $\Omega$ for 3000 $\Omega \cdot m$ earth resistivity.

The method proposed in this research is effective in calculating the electrode length for varying electrode dimensions and buried depths. It is also useful for calculating the electrode lengths for required minimum resistance values.

This analysis also highlights that the required electrode
lengths can be longer than 80 m as the effective length required at the higher frequencies are lower compared to low frequencies. Hence, with longer electrodes, the required low resistance can be achieved at lower frequencies. Moreover, the effective length of the electrodes at high frequencies for high soil resistivity WTG sites is much less compared to low frequencies. For achieving a 10 Ω resistance, an effective electrode length required at higher frequencies is less than 10 m and hence can be achieved by a ring electrode alone. However, to achieve the minimum resistance at lower frequencies, longer electrodes may be required and it can be achieved by horizontal or vertical electrodes for a single wind turbine. In a wind farm this can be achieved by connecting other wind turbines using an earth conductor, as the wind turbines are generally placed with a spacing of five rotor diameters.

VI. CONCLUSION

This research proposes a method to calculate the ring electrode length for a WTG earthing system. The proposed method is effective and can be used to calculate the electrode length by considering the electrode dimensions, buried depth and frequency dependent soil resistivity. This research indicates that the required electrode length reduces by burying an electrode deeper into the ground, creating a uniform electric field distribution around the electrodes. Furthermore, the calculated electrode lengths at lower frequencies can be longer than 80 m for high soil resistivity sites as an effective length required at high frequencies reduces to significantly shorter lengths.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Victoria University of Wellington for this work through the VUW Research Trust.

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