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Transient performance of interconnected wind turbine grounding systems

***Abstract**. We analyze the transient grounding characteristics of interconnected wind turbine grounding systems, for fast rising current pulses. By increasing the number of wind turbines, influences on harmonic impedance and transient potential are examined for different soil characteristics and different locations of excitation. Simulations are performed using simple model of grounding system that neglects the foundation reinforcement. The influence of such simplification for isolated wind turbines is analyzed in previous papers. Here we extend the previous analysis for interconnected wind turbines and we look at the possibilities for optimization of the transient analysis of extended grounding systems in wind farms.*

***Streszczenie.** Przeanalizowano w pracy charakterystyki stanów przejściowych uziemień turbin wiatrowych dla szybkiego narastania impulsów prądowych. Przy wzroście liczby turbin wiatrowych zbadano wpływu na impedancje harmoniczną oraz stan przejściowy dla różnych charakterystyk gleby i różnych lokalizacji wzbudzenia. Przeprowadzono symulacje przy użycie prostego modelu uziemienia, który zaniedbuje wzmocnienie fundamentów. Wpływ takiego uproszczenia dla pojedynczych turbin przebadany został w e wcześniejszych publikacjach. W tym artykule rozszerzono poprzednia analizę na połączone turbiny oraz skierowano uwagę na możliwości optymalizacji analizy stanów przejściowych rozbudowanych systemów uziemienia na farmach wiatrowych. (**Wyznaczenie stanu przejściowego w systemie uziemienia elektrowni wiatrowej**).*

Keywords: grounding system, lightning, transient analysis, wind turbine.
Słowa kluczowe: systemy uziemienia, wyładowania atmosferyczne, analiza stanu przejściowego, turbina wiatrowa.

Introduction

Recently a number of papers have been devoted to the transient performance of isolated wind turbine grounding systems [1-4]. In practice, wind turbines are often spread across large areas, electrically interconnected by buried medium voltage cables. Metallic armour of such cables and bare wires are bonded to the wind turbine grounding electrodes, forming an extended grounding system. Such connection should provide significant reduction of the overall grounding resistance [5]. Due to the specific construction at exposed locations, wind turbines often suffer direct lightning strikes that may provoke damage or malfunction on the equipment. Therefore the high frequency performance of interconnected grounding systems is of great practical interest.

In this paper we analyze the transient performance of extended grounding system in wind farm. We consider typical grounding systems of wind turbines with spread footing foundations, interconnected with bare wires buried at depth of 0.5 m. Mutual separation between wind turbines will be varied between 75 m and 300 m to analyze the influence of the length of the buried bare conductor that is in direct contact with earth (only in case of three wind turbines in row, in other cases mutual separation is 300 m). Details of the grounding system geometry are given in Fig. 1. By increasing the number of wind turbines, influences on the harmonic impedance and on the transient potential will be examined for different types of soil and for lightning current pulses related to the first and subsequent return strokes.

Wind turbine arrangement is illustrated in Fig. 2. Two cases of lightning strike, one in the middle and at the end of the row are analyzed separately. Simulations are performed using simplified model of wind turbine grounding system that neglects the foundation reinforcement mesh.

Recent papers have shown that simplified models for isolated wind turbine grounding system lead to significant overestimation of the transient potential and harmonic impedance in the high frequency range [6-7]. Here we extend the previous analysis for interconnected grounding systems. We compare the influence on the harmonic impedance and transient potential for simplified model of the adjacent grounding system and for model that integrates the foundation reinforcement (see Fig. 1).

Rigorous electromagnetic model is used for the computations [8–9], based on a mathematical method developed from the antenna theory and solved by the method of moments. This model is implemented into the Tragsys computer software [10].

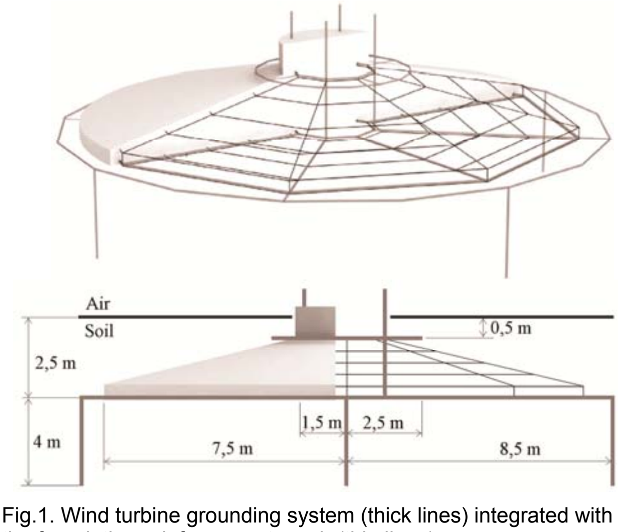

Fig.1. Wind turbine grounding system (thick lines) integrated with the foundation reinforcement mesh (thin lines)

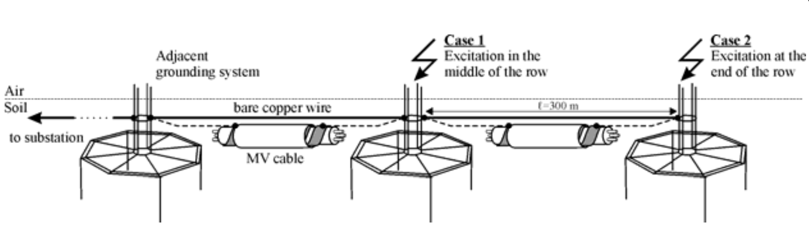

Fig.2. Illustration of wind turbines arrangement

Frequency domain analysis

Harmonic impedance is important quantity in transient analysis of grounding systems. It does not depend on the excitation, but solely on geometry and electromagnetic characteristics of the grounding system and surrounding medium. It is equal to the grounding resistance R in the low frequency range and it has larger or smaller values than R in the high frequency range, whether the inductive or capacitive characteristics of the system are dominant.

Current with variable frequency from 100 Hz to 10 MHz is injected in the vertical conductors above earth, in one grounding system of the row (see Fig.2). Analysis are performed for low resistive earth, with ρ = 100 Ωm, and highly resistive earth, with ρ = 1000 Ωm, for excitation in the middle and at the end of the row. We analyze the influence of the buried bare bonding wires and the influence of the adjacent grounding systems. The foundation reinforcement mesh is omitted due to computational efficiency and its influence will be analyzed later.

From Fig. 3 and Fig. 4, it is evident that the buried horizontal bare wires have major influence on the reduction of the harmonic impedance in the low frequency range, while the influence of the adjacent grounding systems is considerably lower. The interconnection of several wind turbines improves the grounding performance for slow varying excitations with low frequency contents, such as fault currents or slow rising current pulses (typical for first lightning strokes) in case of highly resistive earth. However due to the great mutual separations, the adjacent grounding systems do not provide improvement in case of fast rising lightning current pulses (typical for subsequent return strokes). At high frequencies, currents dissipate only locally, near the affected wind turbine grounding system.

Time domain analysis in case of lightning strike

Time domain analysis are important for proper design of protective equipment. We analyze the transient potential (in respect to distant neutral earth) at current feed points, for low resistive earth with ρ = 100 Ωm and for highly resistive earth with ρ = 1000 Ωm. Two standardized lightning current waveforms related to the first and subsequent return strokes are considered. They are reproduced by means of a usual double exponential function:

$$i_{DE}(t) = \frac{I_m}{k}\left(e^{-t\cdot\tau_1} - e^{-t\cdot\tau_2}\right) \qquad (1)$$

where I_m is the peak value of the current pulse. Values of the coefficients k, τ_1 and τ_2 for the current pulses are given in Table 1.

Table 1. Parameters of first and subsequent lightning current pulse

T1/T2 [μs]	I_m [kA]	k	τ_1 [μs]	τ_2 [μs]
10/350	200	0.951	0.00211	0.2485
0.25/100	50	0.995	0.00699	10.87

Fig.5 illustrates the transient potential at current feed points, for lightning current pulse related to the subsequent return stoke, injected in grounding system at the end of the row. Wind turbine interconnection has no influence on the transient potential in the initial surge period, during the current pulse rise, while the horizontal buried bare conductors significantly reduce the transient potential during the pulse decay. The adjacent grounding systems contribute to further reduction only in case of highly resistive earth, after a period of the decay time to half-peak. In case of low resistivity earth the adjacent grounding systems and the horizontal conductors longer than 200 m do not provide improvement of the transient performance.

a)

b)

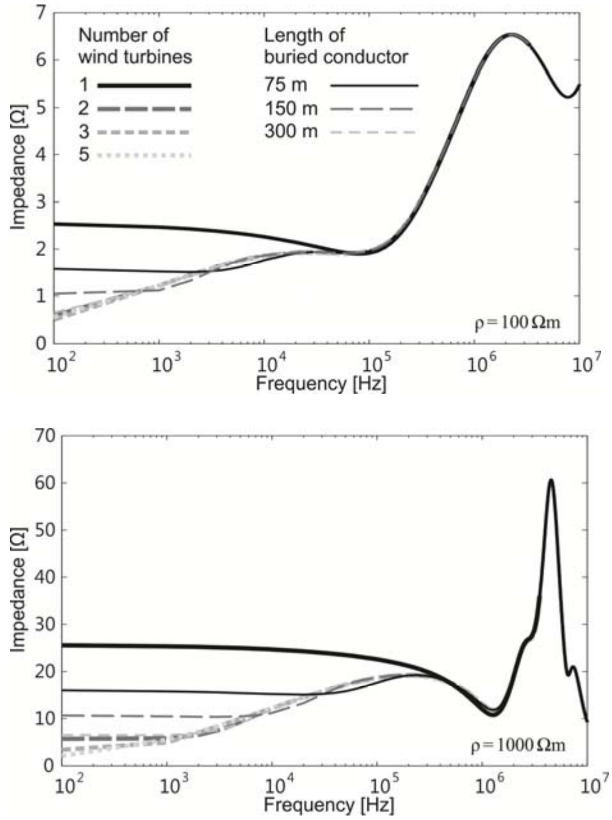

Fig.3. Harmonic impedance of interconnected wind turbines, for excitation at the end of the row: a) ρ=100 Ωm; b) ρ=1000 Ωm.

a)

b)

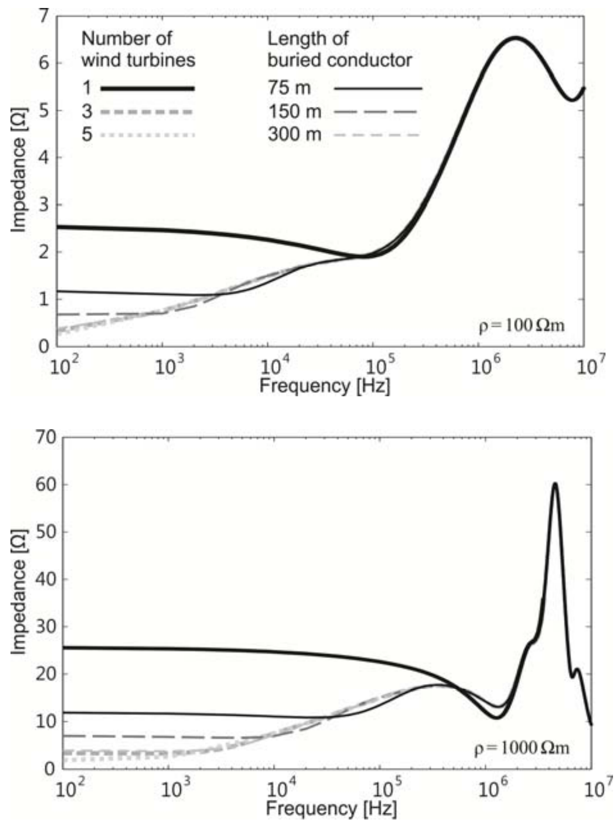

Fig.4. Harmonic impedance of interconnected wind turbines, for excitation at the middle of the row: a) ρ=100 Ωm; b) ρ=1000 Ωm.

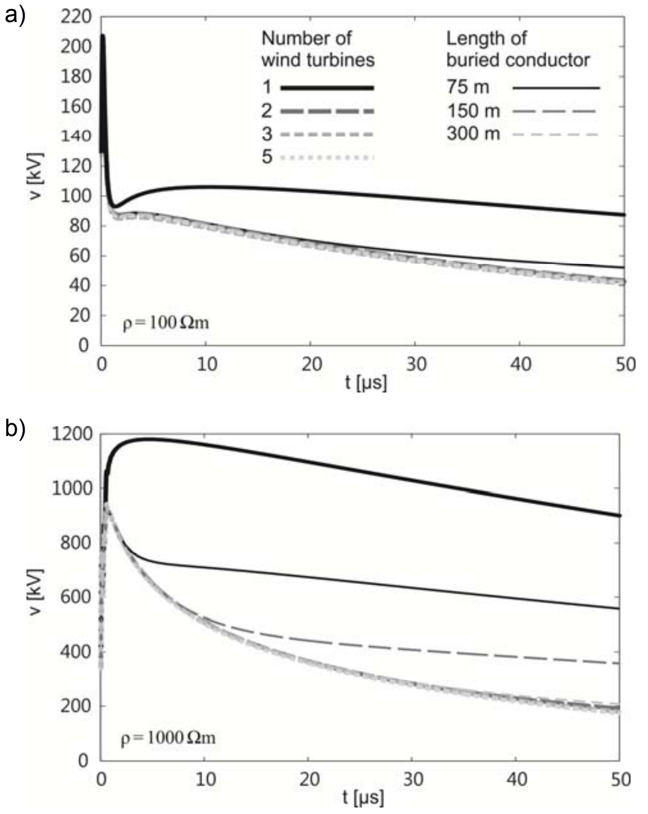

Fig.5. Transient potential in respect to distant neutral earth for current pulse related to subsequent return stroke in low and highly resistive earth: a) ρ=100 Ωm; b) ρ=1000 Ωm.

Fig.6 illustrates the transient potential at current feed points, for lightning current pulse related to the first stoke, injected in grounding system at the end of the row. Transient response in case of slow rising current pulse is primarily governed by the low frequency behaviour of the harmonic impedance. In case of low resistive earth, the adjacent grounding systems provide small reduction of the transient potential during the entire transient period, while the main contribution comes from the buried bare bonding wires. In case of highly resistive earth, adjacent grounding systems provide significant reduction of the transient potential, after a period of the decay time to half-peak.

It is worth noting that for excitations in the middle of the row, harmonic impedance has lower values in the low frequency range (relative to the earth resistivity) than for excitations at the end of the row. Consequently, transient potentials are expected to be considerably reduced for first lightning stroke, and during the pulse decay for subsequent return strokes.

Influence of the grounding system models in transient analysis of extended grounding systems in wind farms

Previous analysis have been performed using simplified model of grounding system that neglects the influence of the foundation reinforcement mesh, (see Fig. 1, with thin lines). Such model leads to significant overestimation of the transient potential, since the foundation reinforcement mesh provides additional paths of the lightning current and reduces the inductive behaviour of the harmonic impedance in the high frequency range. To analyze the influence of the grounding system models, we compare three cases. First the excited and the adjacent grounding systems are modelled by simple geometry that includes only the basic

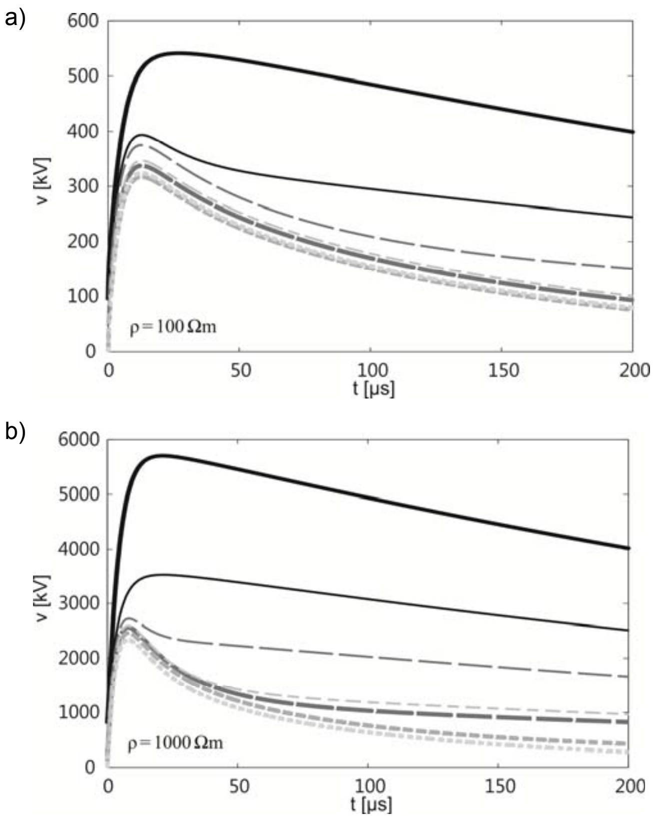

Fig.6. Transient potential in respect to distant neutral earth for current pulse related to first stroke in low and highly resistive earth: a) ρ=100 Ωm; b) ρ=1000 Ωm.

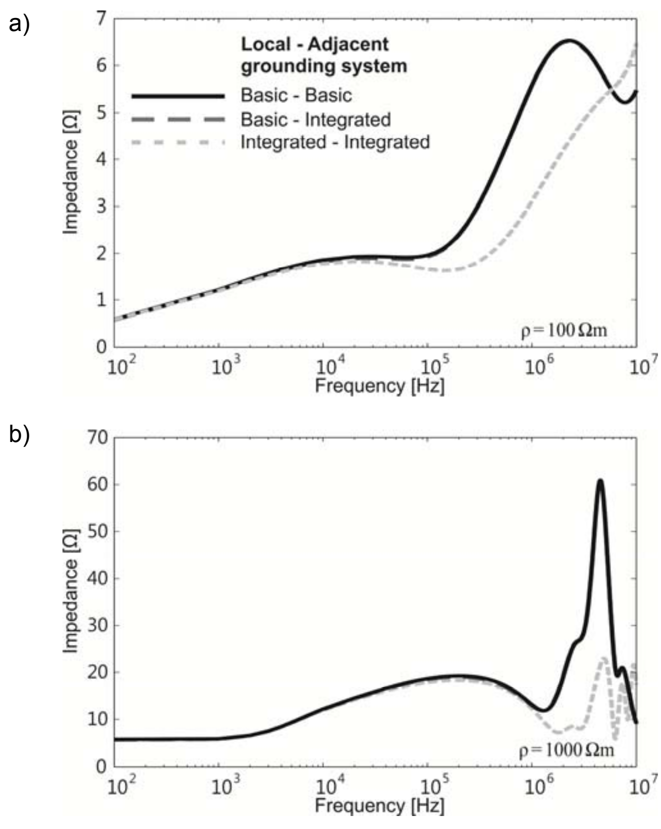

Fig.7. Influence of the model for local and adjacent grounding systems: a) ρ=100 Ωm; b) ρ=1000 Ωm

grounding electrodes. Next we use complex model for the adjacent grounding system, integrated with the foundation reinforcement. Finally we use complex integrated models for the two interconnected grounding systems.

Fig.7 shows that the complexity of the model for adjacent grounding system has no influence on the low frequency and high frequency performance of the grounding systems. The use of complex model that integrates the foundation reinforcement mesh has significance only for the local wind turbine grounding system, in case of transient analysis for fast rising current pulses. For low frequency analysis the use of simplified model for the local grounding system will not introduce significant errors.

Conclusion

When wind turbine grounding systems are interconnected by buried bare wires, these wires are most effective in the improvement of the transient performance.

Adjacent grounding systems provide negligible improvement of the transient performance in case of low resistive earth. For highly resistive earth, the adjacent grounding systems provide additional improvement of the transient performance, during the pulse decay period that is mostly governed by the low frequency behaviour of the extended grounding system.

The analysis for lightning strikes at the end of the cascade can be considered as worst case analysis for interconnected grounding systems. Lightning strikes to wind turbines in the middle of the row will produce lower transient potentials. This is due to the lower values of the harmonic impedance in the low frequency range for different types of soil (see Fig.4), than in case of excitation at the end of the row (see Fig.3).

The use of complex model of grounding system, integrated with the dense mesh of the foundation reinforcement has significance only for the local grounding system that is directly affected by the lightning current pulse. For low frequency analysis, simple model of grounding system can be used as well. The complexity of the adjacent grounding systems has negligible influence on the transient performance of the extended grounding system. This observation is important for optimization and reduction of the computational times during transient analysis of extended grounding systems

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