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A circuit model of vertical conductor using Semlyen's line model based on transient response calculated by FDTD

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ABSTRACT

A circuit analysis method for analyzing a fast transient of a vertical conductor is proposed in this paper. The characteristic of the vertical conductor is previously calculated by a field analysis method, and is introduced into the circuit analysis method as a frequency dependent line model. In this paper, the vertical conductor is expressed by Semlyen's line model installed in Electromagnetic Transients Program (EMTP). The line parameters are derived by z-transformation method from discretized data obtained by Finite-Difference Time-Domain (FDTD) calculation. One of the application fields of the proposed model is a wind turbine tower. The proposed method enables an efficient surge simulation of the wind generation system with a high speed and high accuracy including a variety of internal circuits by the circuit analysis method. The incoming surge, which is determined by the tower characteristic, is introduced by the field analysis. The combined method is a practical approach to an accurate simulation for a surge simulation including vertical structures whose characteristic cannot be directly dealt with by the circuit analysis method. A calculated result obtained by a circuit analysis using Semlyen's line model derived by the proposed method shows a good agreement with a measured result using a reduced tower model. The proposed method accurately introduces transient characteristics of a tower into a circuit analysis method.

1. Introduction

Wind power generation system is one of sustainable systems and has been spread throughout the world. The wind turbine tower is often struck by lightning due to its location and height [1,2]. If a wind power generation system is failed by a lightning strike, its operational efficiency is considerably reduced. The lightning protections of the wind turbine tower have been studied by many researchers [3–6].

The transient characteristic of the tower is theoretically unclear because the characteristic of the traveling wave propagating along the vertical structure is complicate. Although the experiment using an actual tower is a straightforward approach to clarify the characteristic, it is very difficult from economical and technical viewpoints. The investigation has to be relied upon numerical simulations. Circuit analysis using Electromagnetic Transients Program (EMTP) and electromagnetic field analysis based on Finite-Difference Time-Domain (FDTD) method are major for the lightning surge simulation [7–9]. Although the circuit analysis is an effective method to deal with variety of power system apparatuses, it cannot directly express the vertical conductor such as wind turbine tower, because there is no generalized circuit model expressing its wave propagating characteristics and influence of the electromagnetic radiation. On the other hand, a circuit with a number of the apparatuses cannot be represented by the field analysis method. For an accurate numerical simulation of the wind generation system, the two methods should be combined. Because an introduction of the circuit analysis technique into the field analysis is not realistic from a viewpoint of the present computational circumstances, the field analysis technique has to be introduced into the circuit analysis method.

In this paper, a numerical model of a vertical conductor for a circuit analysis is developed based on a result obtained by the FDTD method [10]. The vertical conductor is expressed by Semlyen's line model, which can take into account the traveling wave propagating along the conductor with frequency dependent effect [11]. The modeling method is divided into three steps. In the first step, transient responses of a voltage and a current at the top of the conductor are calculated by the FDTD method. From the results, the characteristic admittance and wave deformation are extracted. In the second step, these characteristics are approximated by rational functions in z-domain. The final step is conversions of the

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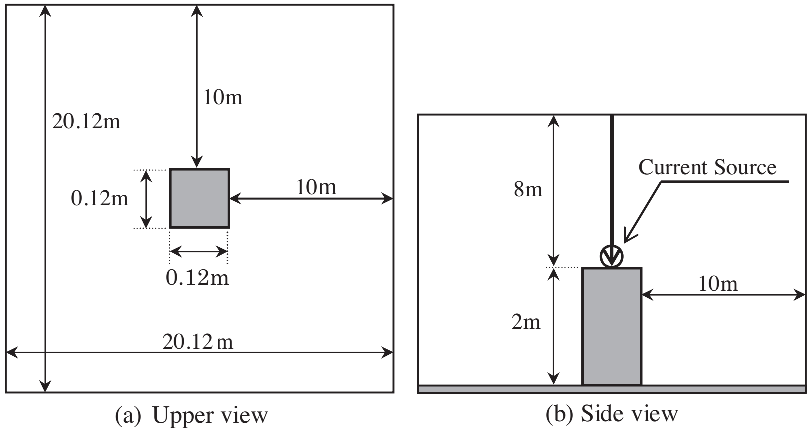

Fig. 1. Model for FDTD simulation to obtain tower top voltage and current.

coefficients of the rational functions to the parameters for Semlyen's line model in the EMTP. Simulation results using Semlyen's line model derived by the proposed method are compared with the measured results using a reduced model. The accuracy of the circuit model obtained by the proposed method is discussed.

The proposed model can be applicable to a transient analysis not only of a wind turbine tower but also a transmission tower. The model contributes an accurate transient analysis of a power system including a power system apparatuses and vertical conductors.

2. Derivation method of tower model

In this chapter, the derivation procedure of Semlyen's line model from the result of the FDTD analysis is described. A scaled vertical conductor whose length is 2 m is used for the FDTD analysis. The simulation result using the proposed model is compared with the experimental results in Section 3.2.

2.1. FDTD analysis

The circuit analysis model of the wind turbine tower proposed in this paper is derived based on the information of a tower top voltage and an injected current into the tower. These data are given by an electromagnetic field analysis or by an experimental observation. In this paper, a result by the FDTD analysis is used for derivation of the circuit model of tower.

Fig. 1 shows the FDTD analysis model which is a reduced model of a 2.5 MW class wind turbine tower with its reduction ratio of 1/30. Because orthogonal coordinate system is employed in the FDTD program used in this paper, the cylinder cannot be accurately expressed. Generally, in the FDTD analysis employing an orthogonal coordinate system, the cylinder is represented approximately by cubic cells [12]. The tower model is represented by a square pole whose height is 2 m and side length is 0.12 m in the analytical space of the FDTD simulation. The side area of the FDTD tower model is equal to the reduced cylindrical tower model that is used for the experiment.

The analytical space is 20 m × 20 m × 10 m (=$x \times y \times z$) and it is divided with cubic cells with a side length of 0.04 m. The tower and earth surface are expressed by perfect conductors. The minimum distance between the tower model and the boundary surface is 8 m. Although the second order Liao's absorbed boundary condition is applied to the surface, a small amount of reflection is unavoidable. Therefore, the result of the FDTD analysis up to 50 ns, which is the arrival time of the reflected wave from the boundary surface, is used for the modeling.

The waveforms of the voltage and current at the tower top calculated by FDTD method are illustrated in Fig. 2. If a step current is injected into the tower, the voltage response before arriving the reflected wave from the tower bottom directly express the characteristic impedance (admittance) of the tower. The steep current, however, reduces the numerical stability of the field analysis. The time constant of the current rise is 1 ns, which is sufficiently shorter than the propagation time of the traveling wave along the tower. Because tower length is 2 m, the reflected wave coming back from the bottom is observed at twice of the traveling time ($2\tau \approx 13$ ns). The characteristic admittance and wave deformation are calculated based on these waveforms.

2.2. Characteristic admittance

The characteristic admittance is obtained as a ratio between the tower top voltage and the current before the arrival of the reflected wave from the tower bottom ($0 \le t < 2\tau$) [13].

z-Transform is adopted as a time to frequency transformation in this paper, instead of a numerical Laplace transformation. Although *z*-transform has close relation to Laplace transform, it has an advantage that no calculation in a complex region is required.

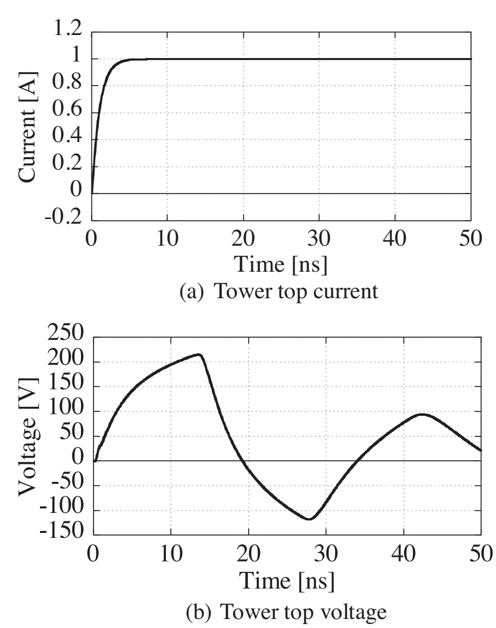

Fig. 2. Calculated results by FDTD analysis.