Electric Power Systems Research 139 (2016) 133–138

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Influence of grounding impedance model on lightning protection analysis of transmission system

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ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form 28 August 2015
Accepted 26 November 2015
Available online 4 January 2016

Keywords:
Grounding
Transient performance
Lightning protection
Transmission system

ABSTRACT

Lightning protection analysis is of vital importance for the transmission system, on which the grounding impedance model has a great effect. This paper concerns the influence of the grounding impedance model on lightning protection analysis. The transmission system is established in PSCAD/EMTP with consideration of three grounding impedance models as constant resistance, standard dynamic resistance and real-time dynamic resistance. The lightning withstand level is simulated and obtained under several typical conditions of soil resistivity and voltage levels. Moreover, the models are comparison and analyzed in the aspects of the dynamic resistance, as well as the ground potential rise and the insulator voltage. This makes a contribution for determining the suitable grounding impedance model applied in the lightning protection analysis, which is very meaningful both in theory and practice.

1. Introduction

The lightning is the main cause of failure in the transmission system. Direct striking on the shielding wires is a frequent phenomenon which leads to lightning overvoltage. Among the many factors influencing the protection effect, the grounding device plays an extremely important role, which is required to have "sufficiently low impedance and current-carrying capacity to prevent the buildup of voltages that may result in undue hazard to connected equipment and to persons" [1].

For evaluating the direct striking protection effect of the transmission system, researchers usually establish the simulation model of the transmission system including the tower, the insulator, the transmission line and the grounding device in the electromagnetic transient analysis programme such as PSCAD/EMTP [2]. Considering the importance of the grounding device to the protection effect, it is very essential to determine a suitable model of the grounding impedance for transient analysis, which the proposed paper precisely aims at.

1.1. Model of grounding impedance

Generally speaking, there are three models which are commonly applied to describe the transient performance of the grounding device:

1.1.1. Constant Resistance (CR) model

The constant resistance model is the most usual model applied in the lightning protection analysis. For this model, the impedance of the grounding system is represented by a lumped resistance [3], which is defined as:

$$R_{CR} = \frac{V_m}{I_m} \quad (1)$$

where V_m and I_m are the peak values of the impulse voltage and the impulse current, respectively.

There are many methods to obtain the value of the resistance, including the field tests and the calculation algorithms. Moreover, while the power frequency grounding impedance R_0 is obtained, impulse grounding resistance can be calculated as [4]:

$$R_{CR} = \alpha R_0 \quad (2)$$

where α represents the impulse coefficient.

As a matter of fact, the grounding impedance is not a constant while the lightning current is injected into the grounding device. Firstly, while the grounding conductor is excited by impulse currents, the soil around the grounding conductor will ionize [5,6], thus the grounding impedance will change over the value of the impulse current. Moreover, the frequency-dependence of the soil parameter and the conductor parameter [7,8] also results in a dynamic resistance.

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http://dx.doi.org/10.1016/j.epsr.2015.11.022
0378-7796/

1.1.2. Standard Dynamic Resistance (SDR) model

In order to consider the time-variation of the grounding resistance in consequence of soil ionization, CIGRE recommends a standard dynamic resistance model $R_{SDR}(t)$ as [9]:

$$R_{SDR}(t) = \frac{R_0}{\sqrt{1 + I(t)/I_g}} \quad (3)$$

$$I_g = \frac{E_0 \rho}{2\pi R_0^2} \quad (4)$$

where:

$R_{SDR}(t)$ Resistance of grounding device under impulse condition, Ω
R_0 Resistance of grounding device under power frequency condition, Ω
$I(t)$ Lightning current through the tower footing, kA
I_g Critical ionization current, kA
E_0 Soil ionization gradient, kV/m
ρ Soil resistivity, Ω·m

This model is time-varying, but is semi-empirical and gives up some accuracy. However, because of its simplicity, this formula is usually applied in lightning protection analysis of the transmission system.

1.1.3. Real Time Dynamic Resistance (RTDR) model

By electromagnetic simulation and field test, the impulse voltage $V(t)$ and the impulse current $I(t)$ can be obtained. On the basis, the real time dynamic resistance model $R_{RTDR}(t)$ can be calculated as:

$$R_{RTDR}(t) = \frac{V(t)}{I(t)} \quad (5)$$

The RTDR model represents the actual transient performance of the grounding device under lightning. However, it is not easy to be obtained. This leads to rare research performing thorough analysis on the influence of the grounding impedance model.

1.2. Approach for transient performance of grounding device

Besides the field test, there are several methods for calculating the transient performance of the grounding device. In short, they can be summarized as three kinds:

The first one is the circuit method such as the lumped circuit method [10–12] and the distributed circuit method (so-called transmission line methods, TLM) [13]. These circuit methods are convenient and efficient, but are not easy to be applied in the complex grounding device in the multi-layer medium [14].

The second one is the finite-element method (FEM) or the finite-difference time-domain (FDTD) method [15–20]. These methods base on the differential form of Maxwell's equations and obtain accurate solutions. However, they require discretization of the grounding space, which would be troublesome and complicated for a complex grounding system.

The third one is the hybrid electromagnetic method (HEM) [21–24], as well as the partial element equivalent circuit method (PEEC) [25,26]. Based on the integral forms of Maxwell's equations, these methods form an equivalent circuit to solve the electromagnetic problem. The derivation is closely related to the method of moment (MoM) [27–30]. Following the idea, a recently published paper [31] presented an approach to obtain the transient performance of the grounding system. It is a time-domain method so that it can be applied for joint simulation with the time-domain analysis software. Besides, it takes the mutual coupling, the frequency-dependence and the soil ionization into account.

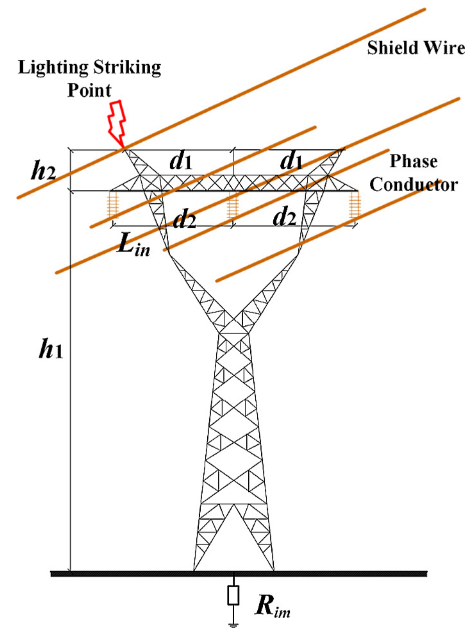

Fig. 1. The configuration of tower.

In the proposed paper, the influence of different grounding resistance models on the lightning protection analysis is concerned. The transmission system is modelled in PSCAD/EMTP including tower, insulator, transmission line and grounding device. As for grounding device, the method in Jinpeng et al. [31] is adapted for the transient performance and embedded into PSCAD/EMTP. The lightning withstand level is selected as the analysis indicator, and several typical situations with different voltage levels and different soil resistivity are considered.

2. Structures and parameters of transmission system

2.1. Tower

The transmission tower configuration in simulation is illustrated in Fig. 1. It consists of a single-circuit three-phase line and two shield wires with horizontal spacing of $2d_1$. The vertical spacing of the only cross arm to ground is labelled as h_1, and h_2 refers to the vertical distance of ground line and cross arm. The three-phase conductors are connected to the bottoms of insulator strings with L_{in} in length, and the spacing of the adjacent insulator is labelled as d_2. Besides, R_{im} represents the equivalent grounding resistance of the grounding device. In the simulation, three towers in every side of the struck tower were considered, and then the transmission lines and the shielding wires are replaced by infinite long wires beyond three towers.

Table 1 gives the typical tower design for 110, 220, 500 and 1000 kV transmission lines.

Table 1
The tower parameters for different voltage levels.

Voltage level (kV)	1000	500	220	110
h_1 (m)	63.0	45.0	24.14	20.0
h_2 (m)	5.0	5.5	3.26	3.0
d_1 (m)	28.8	12.0	5.5	4.9
d_2 (m)	26.8	13.9	7.0	6.5