ANALYSIS OF LIGHTNING STRIKES ON THE TRANSMISSION LINE BY CONSIDERING THE FREQUENCY-DEPENDENT MODEL

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Abstract. This research offers new functions for unveiling the appropriate time-domain model of ground systems that can be implemented in EMTP-RV type software. This exploration helps to consider the precise and frequency-dependent behavior of the ground system in the transient and non-transient analysis of power systems with the least error. The proposed solution is divided into several steps: First, the use of the instantaneous electromagnetic method to orbit the Maxwell equations, which leads to the extraction of the impedance matrix of the earth system in the desired frequency range. In the next step, the logical approximation of the impedance matrix of the earth system is performed using the fitting method (VF). The VF method used fits several poles for all the elements of the proposed impedance matrix. Finally, due to the advanced and transient software, it analyzes power systems based on the acceptance matrix. By changing the appropriate variables, the appropriate model of the multi-port ground system in the time domain that can be implemented in the transient state software is presented as the equations of state space. In this paper, the proposed modeling is simulated and operated on a typical 132 kV transmission line. Ground systems have been compared with lesser-known methods such as modeling based on acceptance matrices and conventional modes using simple linear resistors.
Keywords: *electromagnetic transient mode, vector fitting, multi-port grounding system, impedance modeling*

Introduction

Investigating the behavior of power equipment against lightning transitions requires a model of equipment that is valid over a wide frequency range. The maximum amount of short circuit current that may occur at a particular point in the system is defined as the available or available short circuit current, assuming that no fault-dependent effect is applied to reduce the current. This current is directly related to the size and capacity of the system's power supply sources. The larger capacity of the power sources will usually result in a larger short circuit current. The main factors determining the amplitude and duration of short circuit current are the type of fault, the sources of current fault current, and the impedance between the source and the short circuit point. The need for such a model is due to the fact that transient phenomena include a wide range of frequencies depending on their waveform. Due to this, a frequency-dependent model of equipment should be available for accurate transient state studies (IEEE Official Portal, 2020; Mahdiraji, 2020a). One of the influential factors in the behavior of transmission lines against lightning currents is the impedance of tower footing because the amplitude of the back flashover in the lines depends on the impedance of the tower footing, so the correct implementation and accurate study of the grounding system behavior It can help protect lines and power grids more effectively against lightning strike.

In studying the behavior of the grounding system, the two factors of soil ionization and the dependence on the frequency of soil electromagnetic parameters complicate the analysis, but because ignoring these two phenomena leads to conservative answers, usually from it is ignored. However, taking them into account can lead to increased accuracy and thus reduce land network implementation costs. Time-domain electromagnetic analyzers are popular because of their ability to implement complex networks and model nonlinear phenomena such as corona and devices such as arresters. In various simulations, these analysts perform calculations with high accuracy and sufficient speed, and new devices are added to them day by day. However, the grounding system has not yet been accurately modeled in these tools, such as the grounding system in time domain transient software such as ATP-EMTP (Mahdiraji and Ramezani, 2015a), PSCAD/EMTDC (Mahdiraji et al., 2018), and EMTP-RV (Datsios et al., 2019) is modeled as a simple linear or nonlinear resistor. However, this conventional modeling for the grounding system, especially when calculating the over voltages caused by lightning strikes on the lines, leads to inaccurate results at high frequencies. So far, many studies have been performed on the performance of the power system to improve its protection in flow-dependent (Amouzad Mahdiraji, 2020; Amouzad Mahdiraji and Shariatmadar, 2019; Araujo et al., 2015).

Recently, the authorities (Mahdiraji and Amiri, 2021; Alemi and Sheshyekani, 2015; Sheshyekani et al., 2014; Sheshyekani and Tabei, 2014) by modeling the grounding system in the frequency domain and using methods to implement it in the time domain have been able to obtain the admission matrix of the grounding system for modeling in the time domain. In these papers, the Moment method is used to model the grounding system in the frequency domain, which basically obtains the impedance matrix of the grounding system in the desired frequency range. But since transient software is programmed based on the admin matrix; in these papers, the ground system admittance matrix is calculated by inverting the impedance matrix obtained from the moment method. Finally, the state-space model is based on the admittance matrix, which can be implemented in transient state software. But the problem is that the impedance matrix in multi-port ground systems at low frequencies has the same components and therefore is not invertible at these frequencies; As a result, in the methods introduced in (Mahdiraji and Amiri, 2021; Alemi and Sheshyekani, 2015; Sheshyekani et al., 2014; Sheshyekani and Tabei, 2014), at low frequencies, approximations have been used to inverse the impedance matrix. With the development of networks, the possibility of network errors also increases.

When an error occurs, large currents flow in the system and cause high thermal and dynamic stresses to the power system equipment such as lines, cables, transformers, and power switches and can cause serious damage to them. An error in a system occurs when the system voltage level reaches its maximum value, so the current flow along the power switch has no power other than DC. Mechanical power switches will usually cut off short circuit current over several cycles. Passing large amounts of fault current through network equipment in just a few cycles can cause serious damage to this equipment. As the short circuit level in the system increases, the short circuit currents may increase and even exceed the nominal values of the equipment. In this case, the need to change equipment is essential, which in turn will increase investment in network development. It is impossible to eliminate faults in the power system, but it is possible to reduce the harmful effects of the fault on the system by reducing the current during the fault. To have continuous operation and reliability of power systems, it is necessary to limit the fault currents in the system to a lower value, and there are several methods to reduce the short circuit level.

In this paper, first, the impedance matrix of the ground system in the frequency domain is obtained using the moment method in the required frequency range. Then, with the modifications made on the vector fitting (VF) method, the approximation directly to the expressive functions of the impedance matrix of the ground system has been done. Finally, by changing the appropriate variables, a state-space model based on the ground system admission matrix, which can be implemented in EMTP-RV software, is obtained. Using the method presented in this paper, due to the lack of need to calculate the admittance matrix of the ground system, without any approximation, the ground system modeled in the frequency domain is prepared for the analysis of time-domain transitions. In this paper, to investigate the behavior of lightning, the ground system of the tower is modeled in three ways: (1) static model; (2) wide-band model assuming constant electrical parameters of soil; and (3) wide-band model assuming electrical parameters dependent on soil frequency.

Materials and Methods

Modeling the grounding system

One of the methods used for accurate modeling of high-frequency ground systems is TLM modeling. This method is used to solve Maxwell equations in the propagation of electromagnetic waves and is in fact a differential numerical method that is used in both time and frequency domains. The advantage of this method is that in addition to considering the frequency dependence of soil parameters and the inductive behavior of electrodes during lightning strikes, it also considers soil ionization, because as seen in the analysis, the phenomenon of soil ionization causes an Increase in the radius of the electrode in the area where the soil ionizes. With the development of power systems, the need for annual inspection and review of fault levels in all important power posts has increased and it has become necessary to check the cut-off capacity and type of operation of power switches so that new switches with higher cut-off power can be installed in the network or equipment. Be added to existing networks, such as fault current limiters. In this regard, the methods of limiting the error flow, which is some industrialized countries, semi-industrial samples of which are also made at high-pressure levels, can be divided into two main categories: active and inactive.

Since the short circuit level in the network depends on the equivalent tonnage impedance from the fault location, so in the passive method this impedance is increased in normal operation and also in the event of a fault, and load distribution analysis, transient stability, and reliability of the network should be Check that the network does not deviate from the standard state. These limiters make voltage regulation and power quality worse under normal conditions. But in the active method, this impedance is only increased when an error occurs, and with normal tricks, the increased impedance goes out of the way to reduce the current only in the error mode. Although the active limiter reduces the amplitude of the fault current, but they also affect other parts of the network and have economic and technical limitations such as cooling and high material costs and can affect system reliability, power quality, network stability, and useful life. Other equipment is also effective. Among the solutions of the passive method are the use of high series impedance transformers, the use of series reactors, network structure restructuring, network separation using HVDC, and bus breakage.

For the active method, the author mentions the use of superconducting devices, semiconductor current limiters, high voltage fuses, and impedance limiters with parallel switches. In passive methods, network losses increase under normal operating conditions, and load distribution and transient stability analyzes should be considered so that the network does not deviate from the standard state. Also, solutions such as network separation or bus breakage may affect the reliability of the network, which can be done if the necessary indicators are available. Most active methods have not yet been widely used in industry due to their high cost, complexity (having a variety of elements that reduce equipment reliability), voltage and current limitations, and the creation of transient states in the network. Increasing the potential of grounding systems, transformers, or lightning protection equipment is one of the most important sources of overvoltage in facilities (*Figure 1*).

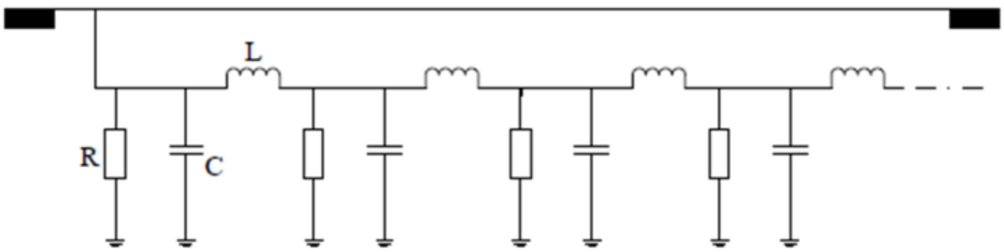

Figure 1. *Theoretical modeling of the circuit of a grounding electrode.*

Modeling using moment method (MoM)

Due to the necessity of network development, it is necessary to reduce the short circuit current to an acceptable level. If fault current limiters are not used, the power switches must be made in such a way that they can cut off large currents caused by faults, which is a difficult task and requires a lot of money. Although high disconnect switches are currently being manufactured, due to the time required for fault detection by the relay and the operation of the switch, short circuit currents cannot be prevented in the first few cycles of equipment faults. This time lasts more than 2-time cycles in the power frequency. Therefore, due to the high current stresses until the operation of the power switches, some of the problems and damages to the equipment remain and the insulation of the network equipment is difficult. For this reason, the issue of adjusting the increase in short circuit level has been one of the most important research topics in the world for a long time. The mechanism of all fault current limiting methods is based on the introduction of large impedance at the time of the fault and differs only in the way it operates and how the impedance enters the circuit and exits it from the electrical system. One way to control and reduce the short circuit level in large networks that have bus bars by connecting a large number of transmission lines or power plant feeders is to break one bus bar and turn it into two bus bars. In this method, after breaking the bus and turning it into two bars, two new buses can be normally connected by a key but with high cut-off speed (Thyristor) so that the network load distribution remains normal in the normal state. In this method, using the thin wire approximation method, the electric field integral equation (EFIE2) is formulated to calculate the currents flowing through different parts of the grounding conductor as follows (Datsios et al., 2014):

$$t.E^{i} = \frac{j\omega\mu}{4\pi}\int_{i} I_i(r')G(r,r')dl \qquad \text{Eq. (1)}$$

Where, t is the unit tangential vector along the wire (l), μ is the magnetic permeability, E^{i} is the electric field generated by the external source, $G(r,r')$ is a binary Green function for the electric field in the coordinates r caused by the current in the coordinates r'; $I_i(r')$is also the current along the wire. The EFIE equation is solved using the moment method (Mahdiraji and Ramezani, 2019) and the resulting current distribution across different parts of the conductor is obtained. In this method, the current distribution on the conductors is finite expanded:

$$I(l) = \sum_{n=1}^{N} I_n F_n(l) \qquad \text{Eq. (2)}$$

Where, N is the number of dipoles (each pair of adjacent parts in which the current flows forms a dipole), I_n the unknown current to be determined, l the length of each part, and F_n (l) the current distribution along the Bipolar is n-th. To calculate the unknown currents, the electric field propagated at the desired point must first be determined. To distribute the current in each part, it is assumed as follows:

$$I(z) = \frac{I_1 \sinh\gamma(z_2 - z) + I_2 \sinh\gamma(z - z_1)}{\sinh\gamma d} \qquad \text{Eq. (3)}$$

Where, $d = z_2 - z_1$ and z_1 and z_2 are the starting and ending points of the dipole, respectively. I_1 and I_2 are also endpoint streams. After performing the calculations, the various components of the electric field in the grounding system are obtained as follows:

$$E_\rho = \frac{\eta}{4\pi\rho\sinh\gamma d}\Big[\big(I_{1e}^{-\gamma R_1} - I_{2e}^{-\gamma R_2}\big)\sinh\gamma d + (I_1\cosh\gamma d - I_2)e^{-\gamma R_1}\cos\theta_1 + (I_2\cosh\gamma d - I_1)e^{-\gamma R_2}\cos\theta_2\Big]E_z$$

$$= \frac{\eta}{4\pi\rho\sinh\gamma d}\left[(I_1 - I_2\cosh\gamma d)\frac{e^{-\gamma R_2}}{R_2} + \left((I_2 - I_1\cosh\gamma d)\frac{e^{-\gamma R_1}}{R_1}\right)E_\varphi\right] = 0,\quad \eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Eq. (4)

Where, E_ρ, E_z and E_φ are the components of the electric field in the coordinates of the cylinders, η is the inherent impedance of the environment and $\gamma = -\omega^2\mu\varepsilon_1$. The total electric field at any given point is obtained from the sum of the different parts of the sinusoidal current sources (Alemi and Sheshyekani, 2015). After performing the calculations, the impedance matrix $z_{ij}(s)$ (which is equal to the ratio of the voltage at gate i to the current injected at gate j, assuming the other circuits are open), is obtained as follows:

$$z_{ij}(s) = \frac{V_i(s)}{I_j(s)} | I_k = 0 \ \ (k = 1,2,3, \dots, P, k \neq j) \qquad \text{Eq. (5)}$$

Where, P refers to the number of ports that located on the grounding system. Therefore, the impedance matrix of the grounding system is expressed as follows:

$$Z_g(s) = \begin{pmatrix} z_{11}(s) & \dots & z_{1P}(s) \\ \vdots & \ddots & \vdots \\ z_{P1}(s) & \dots & z_{PP}(s) \end{pmatrix} \qquad \text{Eq. (6)}$$

Where, z_{ii} and z_{ij}, represent the self-and-mutual impedances between gates i and j of the grounding system, respectively.

Communication with transient software

Internal overvoltages are caused by switching, which is not important in medium pressure networks when the line is energized, provided that the switch is suitable (in high-pressure networks, the most important overvoltage overvoltage is due to capacitance and long lines). These types of overvoltages are interesting and very destructive in their own right. When a phase conductor breaks or breaks in the network load path in such a way that the distance between the conductors at the cut-off point is small, then a load current is generated through an electric arc at the conductor breakpoint. The arc naturally shuts off at zero sinusoidal moments and the passing current is zeroed for 100 to 50 microseconds. After the current is cut off, the voltage across the conductor breaks to its steady-state after the end of the transient state of the circuit, which, depending on the type of inductor or capacitor circuit, may reach twice the mains voltage. From the moment the current is completely cut off until it reaches a steady-state (which has a steady-state), a transient return voltage is generated. This return voltage has two main effects, which is overvoltage surges and switches following the switching on-and-off of the switches, whereby the transient voltage appearing in the system results.

The resulting overvoltages in the network are determined by their amplitude coefficient and probability percentage. The amplitude coefficient shows the maximum amount of overvoltages relative to the amount of phase to the ground voltage under normal network operating conditions. First, the peak voltage can reach several times the mains voltage peak, which insulating equipment may not tolerate this voltage and lead to the phenomenon of spark return. Second, the rate of increase of the return voltage from the initial value, which is assumed to be zero, to its first transient peak is also an important factor in the return of the spark. The source of external overvoltages is outside the system, which is the most important type of external overvoltage is the direct impact of lightning on the line or other equipment. The nature of lightning is actually a current that creates an overvoltage due to the wave impedance of the line. The larger the amplitude of the lightning current, the greater the amount of overvoltage generated. A power switch is the most important control and protection equipment in the power system, the most difficult and important task of which is to detect successful disconnection and isolate short circuit faults. Switching sparks are always generated simultaneously with a high-pressure CB that cuts off a short circuit fault.

Vector fitting

When the current is in the distributed power system, the spark between the switch disappears when the switch is opened and the system current is cut off, the system is divided into two parts upstream of the switch and downstream of the switch. At this time, each part due to the internal resistance, inductor, and scattering capacitor caused by transmission lines and other equipment, forms an RLC circuit in which the natural frequency and damping of each side of the switch are different. This difference creates a high-frequency double-circuit voltage, called a transient reverse voltage. Each impedance matrix-vector of the grounding system is fitted as follows (Gustavsen and Semlyen, 1999):

$$z_{ij}(s) \approx \{z_{ij}(s)_{fit}\} = \sum_{m=1}^{M} \frac{R_{m,ij}}{s - a_m} + d_{ij} + se_{ij}$$
$$i = 1,2, \dots, P; \quad j = 1,2, \dots, P \qquad \text{Eq. (7)}$$

Where, a_m and R_m represent the poles and residues of the system, respectively; And *d* and *e* are also fixed values. In the VF method, to achieve the poles z(s), the following linear equation must first be solved using the least squares method:

$$\sigma(s).z(s) = p(s) \qquad \text{Eq. (8)}$$

$$\sigma(s) = \sum_{m=1}^{M} \frac{\tilde{R}_{m,ij}}{s - q_m} + 1 \qquad \text{Eq. (9)}$$

$$p(s) = \sum_{m=1}^{M} \frac{R_{m,ij}}{s - q_m} + d_{ij} + se_{ij} \qquad \text{Eq. (10)}$$

Where, σ (s) is a scalar and p (s) is generally a vector. q_m is also a set of primary poles. All poles and residues in Eq. (9) and Eq. (10) are real or conjugate pairs, while d and e are real values. It can be shown that the poles z (s) must be equal to the zeros σ (s) which can be calculated as eigenvalues of a matrix (Gustavsen and Semlyen, 1999):

$$\{a_m\} = eig(A - b.c^T) \qquad \text{Eq. (11)}$$

Where, A is a diagonal matrix containing the initial poles q_m, b is a columnar vector equal to one, and c^T is a row vector containing the residues $\tilde{R}_m$. Eq. (6) to Eq. (9) can be solved by iteration by replacing the previous poles q_m with the new poles a_m. The pole displacement process usually converges after 2 to 3 repetitions. After determining the poles, the residues of Eq. (7) are calculated by solving the problem of the least-squares corresponding to the determined poles. The output of the state space of the fitting method is basically strict (D = 0, E = 0). While in the proposed method of the paper, because there is a need to invert the D matrix, the D matrix should be 0. Given that the VF method can output as a whole (D ≠ 0, E ≠ 0), so by selecting the mode that the output of this method is a whole, our desired output (Matrix D ≠ 0) is obtained.

Inactive actions

The type of error and the effective coefficient of the earth system are the factors influencing the transient return voltage waveform and its characteristic values. The probability of an unearthed three-phase fault is very low; the IEEE standard recommends a three-phase fault for transient reverse voltage studies. Also, in errors that occur at close distances to the terminal, due to the presence of traveling waves in the form of high-frequency toothed waveforms, usually in the first moments after the spark is extinguished, the rate of transient return voltage increases. Regarding the necessity of this work, it can be said that by applying the method of limiting the fault current with the changes that it causes in the transient impedances of the network, there is a possibility of exceeding the slope and peak voltage return values from its nominal values. Because it is possible that despite applying the error flow restriction method, the error flow has reached an acceptable level for the keys, but due to the lack of the following two relationships, the author face the problem of key explosion and the cost of limiting the error flow is practically useless.

In high voltage power grids with power switch protection, there are always problems due to the impact of TRV. Power switch error current occurs when the power system current exceeds the power switch rate. TRV is an almost random orbital parameter that will affect the braking capacity of the power switch. In addition, TRV affects the inductance and capacitance of the system and the fault current level of the studied system, the TRV as well as the grounded system. The rate of return voltage rise is fast for any medium with medium arc insulation mode, due to the current flow inside the power switch, which has a high rate of rising in the first few microseconds and may recreate a flow rate commensurate with the heat. This condition is created by the power switch, which is related to insulation failure. The eigenvalues of the real part of the impedance matrix must be positive at all frequencies (Gustavsen, 2008).

$$\mathrm{eig}(\mathrm{Re}\{z(j\omega)\}) > 0 \qquad \forall\omega \qquad \text{Eq. (12)}$$

In one of the passive operation methods, assuming Re(z)=X, the real part of the impedance matrix can be written as follows (Mahdiraji, 2020b):

$$X_{i,j}(s) = d + \mathrm{Re}\left\{\sum_{m=1}^{n} \frac{R_m}{s - a_m}\right\} = d + p(s) \qquad \text{Eq. (13)}$$

The total matrix contains the real components of the impedance matrix equal to:

$$X(s) = D + P(s) \qquad \text{Eq. (14)}$$

Assuming that the matrix X is diagonal and for any desired frequency s:

$$T\Lambda T^{-1} = D + P \qquad \text{Eq. (15)}$$

Where, the matrix Λ contains the positive eigenvalues Λ_{pos} and the negative Λ_{neg}. Therefore, Eq. (15) can be rewritten as follows (Mahdiraji, 2020b):

$$T(\Lambda_{pos} + \Lambda_{neg})T^{-1} = D + P \quad \text{Eq. (16)}$$

$$X_{corr} = T\Lambda_{pos}T^{-1} = D - T\Lambda_{neg}T^{-1} + P \quad \text{Eq. (17)}$$

Therefore, by substituting zero for negative eigenvalues and adding modifications to matrix D, the real part of the impedance matrix (matrix X) can be modified. This process is repeated at all frequencies until the desired passive criterion is reached.

Development of the mode space model

The transient return voltage that appears at both ends of the power switch is affected by various factors such as fault current. Transient reverse voltage under the influence of various system parameters, the most important of which are presented in the list below. When the fault on the transmission line is a short distance from the power switch, the transient return voltage on the line on the side of the power switch decreases. Transient reverse voltage is characterized by very rapid voltage rise teeth, which can damage the power switch. As can be seen in the analysis, depending on the location of the error, it is possible for exponential or triangular waveforms to form in a specific network. A network may also be exposed to TRV. If the network is exposed to exponential and triangular TRVs, it is necessary to consider both conditions and then the final TRV cover of the network is obtained by combining triangular and exponential curves. If the network is subject to oscillating TRV, it is sufficient to draw the same oscillation curve. The pole-residue model of the impedance matrix (5) can be expressed as follows

$$Z_g(s) = D + C(sI - A)^{-1}B + sE \quad \text{Eq. (18)}$$

According to the polarization-residual model, the display of state space for an input P model, n output, and M polarization-residue model can be expressed as follows (Gustavsen and De Silva, 2013):

$$C_m = R_m, \qquad A_m = \frac{1}{a_m} I, B_m = I$$
$$A \in R^{Q\times Q}, B \in R^{Q\times P}, C \in R^{n\times Q}, D \in R^{n\times P}, E \in R^{n\times P} \quad \text{Eq. (19)}$$

Where, P is the number of system ports and Q is the total number of state variables, which is equal to the product of the total number of poles in the total number of ports (Q = M × P). However, the state space equation of the impedance matrix Zg (s) in the time domain will be equal to:

$$\begin{pmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \\ \dot{\tilde{x}}_3 \end{pmatrix} = \begin{bmatrix} A_r & 0 & 0 \\ 0 & Re(A_c) & Im(A_c) \\ 0 & -Im(A_c) & Re(A_c) \end{bmatrix} . \begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{pmatrix} + \begin{bmatrix} B_r \\ 2Re(B_c) \\ 2Im(B_c) \end{bmatrix} . i \quad \text{Eq. (20)}$$

$$v = [C_r \quad Re(C_c) \quad Im(C_c)] . \begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{pmatrix} + D.i. \quad \text{Eq. (21)}$$

The above state space equation can be rewritten as follows:

$$\dot{x}(t) = A_{old}.x(t) + B_{old}.i(t)$$
$$v(t) = C_{old}.x(t) + D_{old}.i(t) \qquad \text{Eq. (22)}$$

For this purpose, by using the following variables, the equations of state space based on the admin matrix of the grounding system can be obtained so that it can be implemented in transient analyzer software. First, the input is obtained in terms of output:

$$y = Cx + Du \Rightarrow Du = y - cX \Rightarrow u = D^{-1}(y - Cx) \Rightarrow$$
$$u = -D^{-1}Cx + D^{-1}y \qquad \text{Eq. (23)}$$
$$\dot{x} = Ax + Bu \Rightarrow \dot{x} = Ax + B(D^{-1}y - D^{-1}Cx)$$
$$\Rightarrow \dot{x} = (A - BD^{-1}C)x + BD^{-1}y \qquad \text{Eq. (24)}$$

As a result, the new state-space matrices based on the admittance matrix will be as follows:

$$\dot{x}(t) = A_{new}.x(t) + B_{new}.v(t)$$
$$i(t) = C_{new}.x(t) + D_{new}.v(t) \qquad \text{Eq. (25)}$$

Where in:

$$A_{new} = A - BD^{-1}C, \qquad B_{new} = BD^{-1}$$
$$C_{new} = -D^{-1}C, \qquad D_{new} = D^{-1}$$

Error type and ground system effect coefficient are the factors influencing the transient recovery voltage waveform and its characteristic values. The highest amplitude of the voltage across the opening is the first contact of the switch, this type of error is the basis for obtaining the allowable operating range of the switch. The ground-to-ground phase error is also considered the RRRV standard, as this is usually the worst-case scenario of RRRV. Since the three-phase ground fault on the switch output terminal has the highest transient recovery voltage amplitude during the opening of the first switch contact and usually causes the most severe condition, this type of error is the basis for obtaining the allowable switch operating range in terms of the recovery voltage range. It is considered transient and is known as the key terminal error. Also, the phase-to-ground error at a distance of about 500 meters to a few kilometers of the line due to the high oscillation frequency of the line voltage has the highest transient voltage slope and therefore is considered as a transient voltage slope criterion to obtain the allowable operating range of the switch. This is known as short line error (SLF) or kilometer error.
These equations can be directly implemented in EMTP-RV software using state-space blocks (Sheshyekani et al., 2014) (*Figure 2*).

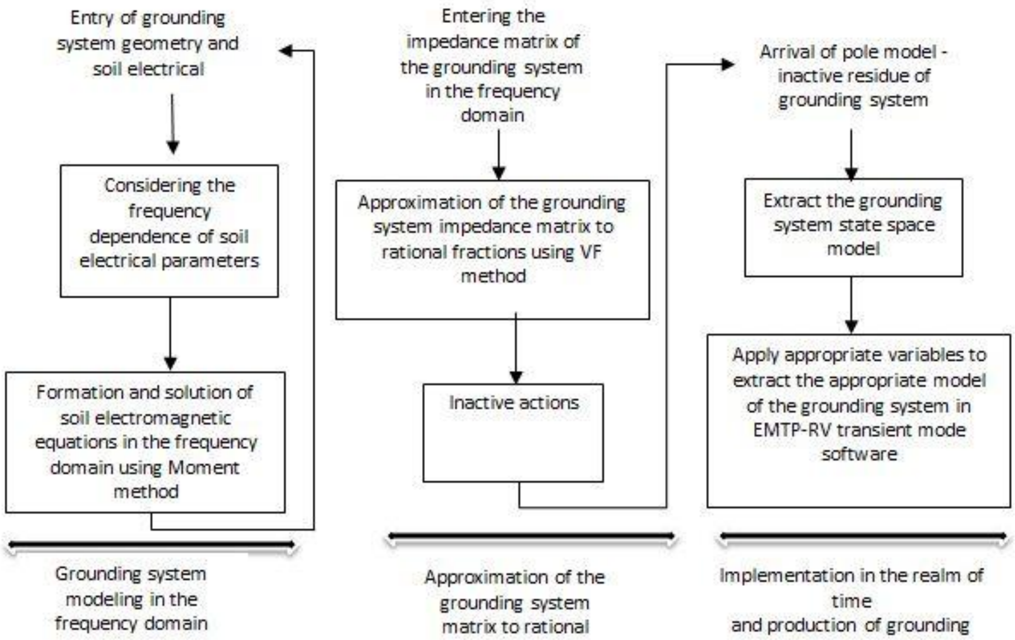

Figure 2. *Flowchart of the proposed model.*

Modeling transmission line components

Transmission tower

The selection of the appropriate power switch is of particular importance due to the essential role of this equipment in the protection of electricity networks. In the process of a power outage, CB is considered as an ideal switch. The success of the fault current cut-off operation depends on the TRV index. Improper switching causes problems for the power grid, the most important of which is short circuit current, because if the switch is not able to cut off the short circuit current, the possibility of error and serious damage to other equipment located in the substation and there is a network. Therefore, the correct choice of power switches can increase the reliability of the entire network. In this chapter, the author show that in many cases the initial key selection based on static parameters is not able to meet the TRV limits. In such cases, it is necessary to provide solutions to lead to the adaptation of the key and network conditions for this parameter. These include using a more capable switch, using a parallel capacitor, and using a current limiter.

To select the keys to power, it is necessary to consider international standards as a reference that is accepted by experts. The selection of the appropriate switch based on IEC and IEEE standards is as follows: first, the initial selection is made based on static parameters (voltage, short circuit current, and constant current) and then the selected switch performance is based on dynamic parameters (capacitive current and TRV) will be evaluated. Also according to the standard, the ability to cut the same key is different based on some indicators such as TRV in different networks. To analyze the grounding system, the towers of a 132 KV line are simulated in EMTP-RV as shown in *Figure 3*. Each tower base is modeled with the following wave impedance (Hara and Yamamoto, 1996).

$$Z_{T,n} = \sum_{i=0}^{n} 60.\left(1n\frac{2\sqrt{2}h_i}{r_{ei}} - 2\right)$$
$$r_{ei} = 2^{\frac{1}{8}}\left(r_{Ti}^{\frac{1}{3}}.r_{B}^{\frac{2}{3}}\right)^{\frac{1}{4}}.\left(R_{Ti}^{\frac{1}{3}}.R_{B}^{\frac{2}{3}}\right)^{\frac{3}{4}} \quad \text{Eq. (26)}$$

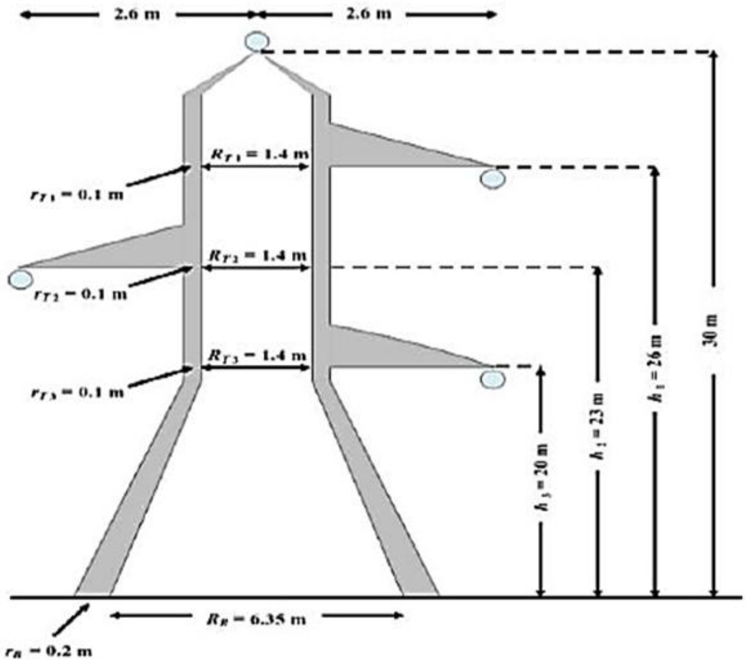

Figure 3. *Geometry of the transmission tower under study.*
Source: Alemi and Sheshyekani (2015).

Characteristics of electrical discharge of insulator string

To select the appropriate key based on the TRV index, the network TRV curve must first be obtained at the key installation location. Then compare this curve with the key TRV capability curve. If the TRV capability curve of the environment key is on the network TRV curve, the selected key is acceptable in terms of the TRV parameter, otherwise, solutions should be used to adapt the key and network conditions. The most important feature of TRV due to short line error is its high initial slope. Each switch must be able to interrupt the SLF error as specified in the standard. This capability means adding two new points in the key capability curve; Thus, four-parameter curves become six-parameter and two-parameter curves become four-parameter. By combining these three parts, the final TRV capability curve can be obtained. After determining the TRV curves of the switch and the network, both curves must be plotted on one device. If the key capability curve is on the TRV curve of the peripheral network, the key will not have a problem with the TRV parameter, otherwise, the network and key conditions must be adapted using some solutions. In this paper, the equivalent region criterion or integral method is used to model the insulator and investigate the effect of overvoltages caused by non-standard lightning strikes, which is characterized by the discharge of the insulator string as follows (Datsios et al., 2014):

$$DE = \int_{t_0}^{t} (V(t) - V_0)^{K} dt \qquad \text{Eq. (27)}$$

Where, (kV) V_0 is the minimum voltage required for failure and t_0 (μs) is the starting time of failure or the moment when the instantaneous voltage V(t) exceeds V_0. $DE(kv^{k}.\mu s)$ is the degradation effect constant and *k* is a constant coefficient for applying the effects of frontal time and overvoltage size. In this method, as soon as the DE value exceeds the DE* value, the discharge occurs in the insulator string. The values of DE* and V_0 for the 132 kV transmission line are $DE^{*} = 0.524kV.\mu s$ and V_0 = 650kV.

Impedance of the tower footing

Due to the frequency dependence of soil electrical parameters, the grounding system in this paper is modeled in three ways: (1) static model (conventional): which uses a simple resistor equivalent to the dc resistor of the grounding system for modeling; and (2) wide-band model with frequency-dependent parameters (FD4 Wide-Band): assuming the frequency dependence of soil electrical parameters, which is defined as follows (Mahdiraji and Ramezani, 2015b):

$$\rho_0 = 125.(p/10)^{-0.54}(\Omega m), \varepsilon_\infty = 5$$

$$\rho(f) = (\rho_0{}^{-1} +$$

$$2\pi\varepsilon_0 \sum_{n=1}^{14} \frac{a_n((p/10)^{1.28}.10^{n-1})\left(\frac{f}{(p/10)^{1.28}.10^{n-1}}\right)^2}{2})$$

$$1 + \left(\frac{f}{(p/10)^{1.28}.10^{n-1}}\right)^2$$

$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{n=1}^{14} \frac{a_n}{1 + \left(\frac{f}{(p/10)^{1.28}.10^{n-1}}\right)^2}$$

Results and Discussion

In this method, the impedance of the rig foot is considered as an equivalent DC resistance and is obtained by measuring and calculating the field with the help of a suitable algorithm. In this method, it should be considered that the radius of the conductor is much smaller than its length, buried depth, and lateral conductor distance, and it is possible to model the conductors as a current source, so each conductor is divided into sections. That the linear current density is constant in each section but varies concerning each other, and based on this a linear equation system is obtained. And its solution results in the distribution of current in the earth system, and through this, the author can calculate the current density in linear conductors, increase the potential in the earth system and the potential of any point on the earth's surface, and finally the resistance of the earth system. In recent years, the use of current-limiting series reactors to limit short-circuits current in transmission lines has expanded.

Using these reactors near high voltage (CB) switches can cause a transient return voltage change of the power switches when the rated current is cut off or shorted due to changes in the characteristic impedance of the network at the location of the power switches. Installation of these devices, in addition to the disadvantages of voltage drop, change of power flow in the network in normal mode, reduce the transient stability margin (if used in power substations) will reduce the TRV range of the two ends of the switch (which is desirable) but in, On the other hand, the RRRV can also increase the two ends of the switch to such an extent that it exceeds the allowable limit of the switch, which will lead to re-ignition. This condition may produce even higher TRVs when the second (third, etc.) arch is suffocated. The power switches may overheat and explode with these repetitive re-ignitions, and the system equipment may be damaged by high currents or voltages (or both). Therefore, the RRRV of the circuit is more problematic than the maximum of the TRV circuit, which is why it is more important (Heidler et al., 1999).

$$i(t) = \frac{I_P \ k^n}{\eta \ 1 + k^n} e^{-t/\tau_2}$$ Eq. (28)

I_P is the current peak, η the current peak correction factor, n is the current slope factor, and $k = t/\tau_1$. τ_1 and τ_2 are time constants that determine frontal and flow sequence times, respectively. To investigate lightning over-voltages, the initial shock and subsequent shocks are considered. The statistical distribution of lightning strike parameters is considered as a normal logarithmic distribution function whose mean values of the parameters for the initial and subsequent lightning strikes are as shown in *Table 1*. The transmission line was modeled using the J. Marti frequency-dependent model, the specifications of which are given in *Table 2*.

***Table 1**. Statistical parameters of initial and subsequent lightning strikes with negative polarity.*

Parameters	Subsequent strike	Initial strike
Ip (kA)	11.8	31.1
σLn I (kA)	0.5296	0.48
tf (μs)	0.43	4.83
Sm (kA/μs)	39.9	24.3
th (μs)	32	75

***Table 2**. Transmission line conductor specification.*

Category	Type	Resistance (**Ω**/km)	Diameter (cm)
Phase conductors	CURLEW	0.045	3.556
Guard wire	94S	0.642	1.36

An overhead transmission line is a type of transmission line that uses a power transmission tower (power tower) and a power pole to keep cables above ground level. Since air is used as insulation for cables in such lines, this method of transmission is one of the least expensive and most common methods of power transmission. The masts and beams used to hold the cables can be made of wood, steel, concrete, aluminum, and in some cases plastic. The cables used in airlines are mostly made of aluminum (which, of course, is reinforced with a strip of steel inside). Of course, copper cables are used in some medium and low voltage transmission lines and the connection to the consumer.

The structure of an overhead line can take many different forms depending on the type of line. This structure can simply be a series of wooden beams with one or more crossbars to hold the cables.

At high voltages, the cable holder is usually a metal mast made of a neat network of smaller parts. In remote and special areas where it is not possible to carry the towers from the ground, aluminum beams are used and they are transported to the site by helicopter. Each method is used according to the characteristics of the environment and the line as well as the weight of the cables. In a large transmission project, different types of beams and masts may be used. In the areas of changing the angle of the line and the areas at the end of the line, different methods must be used to hold the beams and masts, and in these areas, completely different beams are used. Special towers should also be used in the areas of the line crossing of an important road or river. To model the grounding system in the time domain, the proposed method of the paper has been implemented for different grounding models according to *Figure 4* and the results of the simulation have been analyzed. Grounding system analysis has been performed for 3 different soil resistivity ρ = 100, 500, 1000Ωmρ. In all cases it is assumed that the electrical conductivity is εr=20. The magnitude of the frequency components of the square grounding network impedance matrix is shown in *Figures 5* to *Figure 7*.

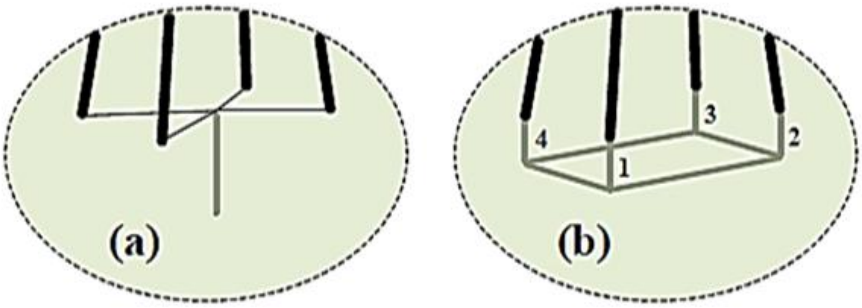

Figure 4. *Grounding system: (a) single-port vertical electrode with a length of 15 meters and a radius of 12.5 mm; and (b) a four-gate square system with 6 x 6 m^2 and a radius of 12.5 mm.*

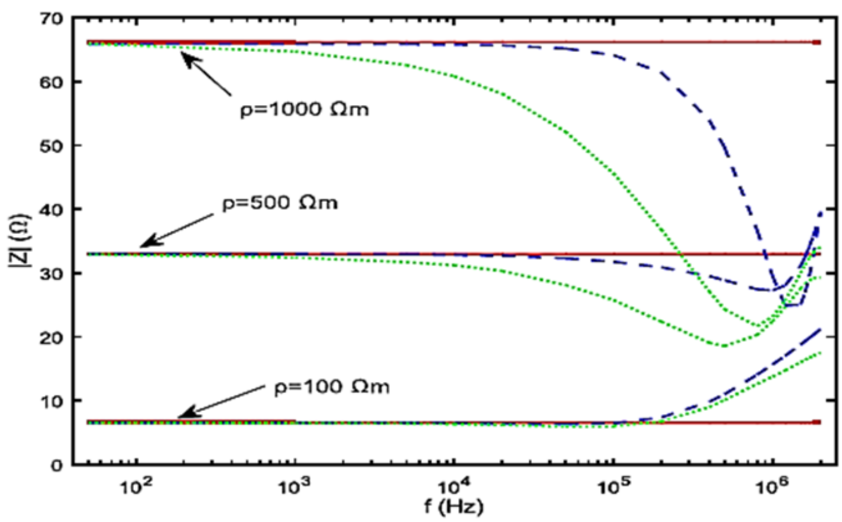

Figure 5. *Self impedance (Z_{11}) for a square grid includes continuous red line (simple resistance equivalent to dc resistance); blue line (wide-band model); and green dotted line (FD wide-band model).*

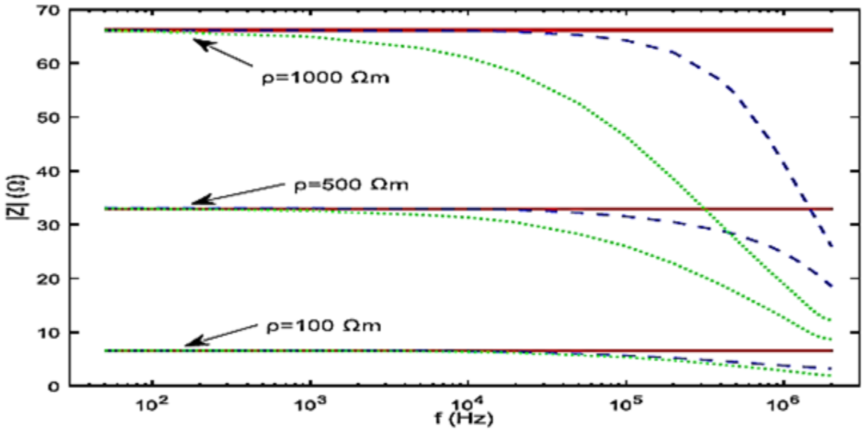

Figure 6. *Mutual impedance (Z_{12}) for square grid includes continuous red line (simple resistance equivalent to dc resistance); blue line (wide-band model); and green dotted line (FD wide-band model).*

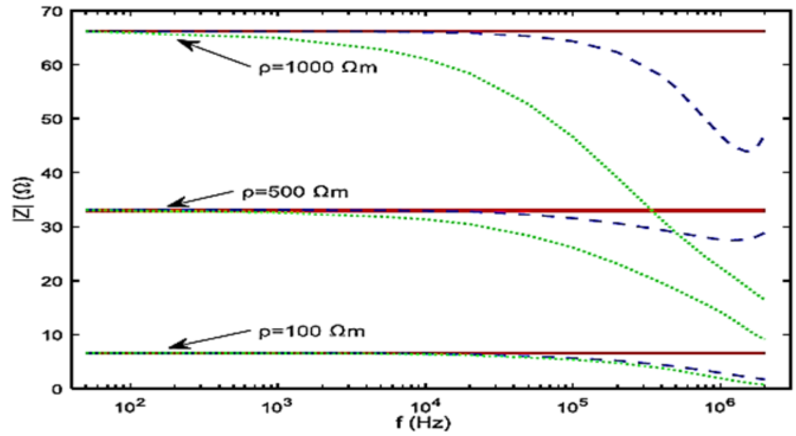

Figure 7. *Mutual impedance (Z_{13}) for square grid includes continuous red line (simple resistance equivalent to dc resistance); blue line (wide-band model); and green dotted line (FD wide-band model).*

For short circuit current, a three-phase short circuit to symmetrical ground is considered, which almost the worst-case scenario, and the author assume that CB can eliminate other errors. The intensity of a CB is generally determined by the amount of short-circuit current and the transient return voltage. In this case, the three-phase circuit can be simplified to a single-phase circuit. The impedance size obtained from the conventional methods (Mahdiraji and Amiri, 2021; Alemi and Sheshyekani, 2015; Sheshyekani et al., 2014; Sheshyekani and Tabei, 2014) for the quadratic system in the case of frequency-dependent modeling of the electrical parameters of the soil with ρ = 1000Ωm is shown in *Figure 8*. The results show that the size of the different components of the impedance matrix is equal to each other at a frequency of about 100 kHz; therefore, at these frequencies, the determinants of the impedance matrix are zero and are not invertible. For this reason, in the previous conventional methods, it is necessary to inverse the impedance matrix and achieves the approximate matrix of the earth system admittance matrix. The overvoltage of the insulator string due to the initial lightning strikes and subsequent to the guard wire is shown in *Figure 9*. In this case, no electrical discharge has occurred in the insulator string. Here, the grounding system is a horizontal electrode that is modeled in three static forms, CP Wide-Band and FD Wide-Band, based on the impedance matrix (the method proposed in this paper).

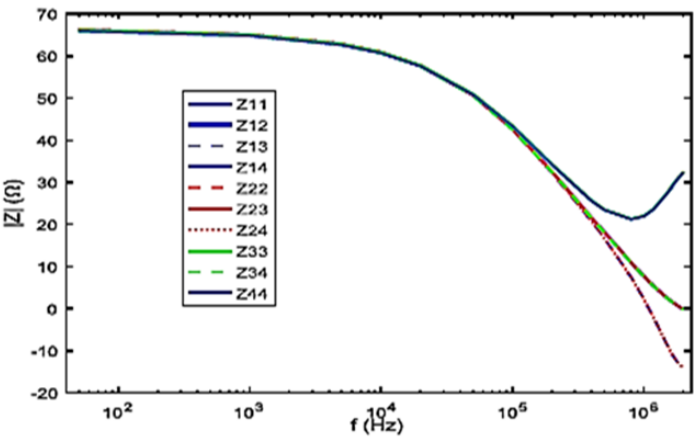

Figure 8. *Self and mutual impedances for square grounding system, in FD wide-band mode and resistivity ρ = 1000Ωm.*

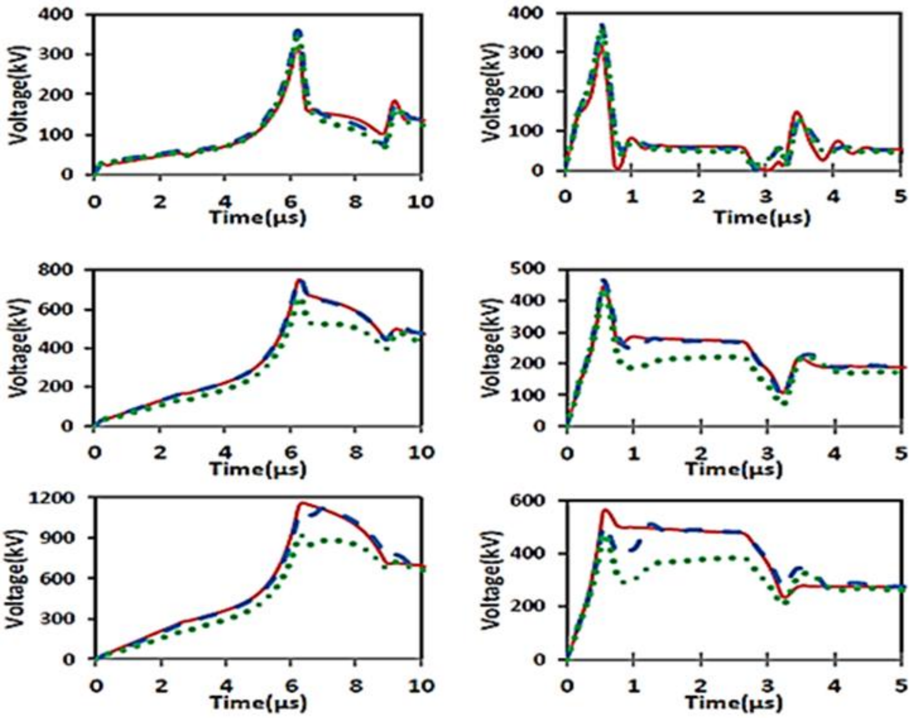

Figure 9. *Insulator string overvoltage for vertical ground electrode. ρ = 100Ωm (a), ρ = 1000Ωm (b), ρ = 500Ωm (c) Left Column: Primary Impact, Right Column: Subsequent Impact, Continuous Red Line: Simple Resistance Equivalent to dc Resistance, Blue Dashed Line: CP Wide-Band Model, Green Dotted Line: FD Wide-Band Model.*

To compare the proposed method based on the impedance matrix with the previous methods based on the admittance matrix, the insulator string overvoltage for both modeling methods for the grounding system with vertical electrode is shown in *Figure*

10. It can be seen that for the vertical electrode (single-port grounding system) the values of over voltages are the same in both modeling methods, because the inverse of the impedance matrix of the single-port grounding system is done without any approximation and as a result the matrix the state space results obtained from both types of modeling behave similarly. *Figure 11* shows the overvoltage of the insulator string due to a lightning strike to the guard system for modeling a square grounding system based on the impedance matrix. *Figure 11* shows that similarly, with increasing soil resistivity, insulator string overvoltages, and the difference between the calculated overvoltages in wide-band modeling and static model increase, which is similar to the method. Alemi and Sheshyekani (2015) research is increased by considering the frequency dependence of soil electrical parameters. To show the difference between the results of modeling with the proposed method and the reference method (Alemi and Sheshyekani, 2015), the insulator string overvoltage resulting from the modeling of the grounding system in the time domain based on impedance and admittance matrices (Alemi and Sheshyekani, 2015) in the square grounding network It is shown in *Figures 12* and *Figure 13*.

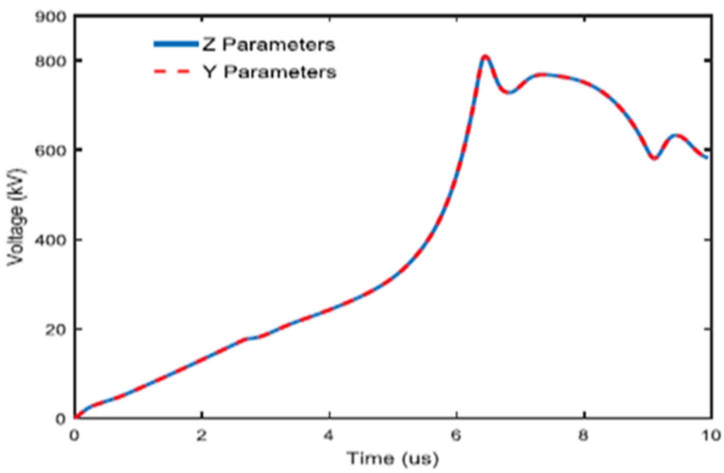

Figure 10. *Insulator string overvoltage for vertical ground electrode, for initial lightning (27kA, 3.83μs/75μs) and resistivity ρ = 1000 Ωm in FD Wide-Band modeling mode.*

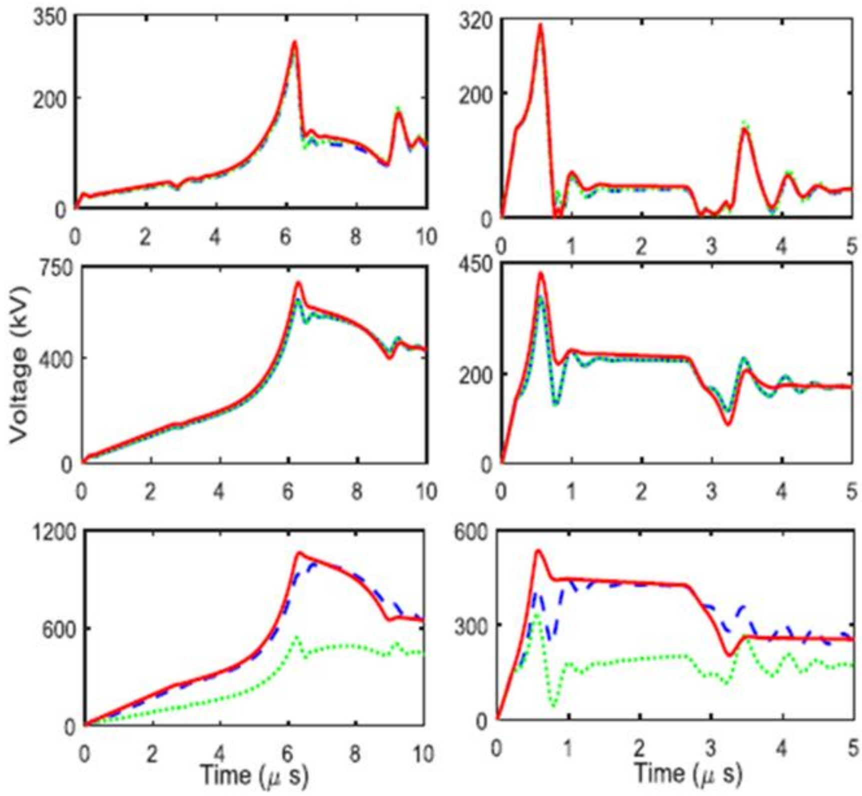

Figure 11. *Insulator string overvoltage for square earth network.* ρ *= 100* Ω*m (a),* ρ *= 500 .m (b),* ρ *= 1000* Ω*m (c) Left column: initial impact, right column: subsequent impact. It consists of red line (simple resistance equivalent to dc resistance); blue line (wide-band model); and green dotted line (FD wide-band model).*

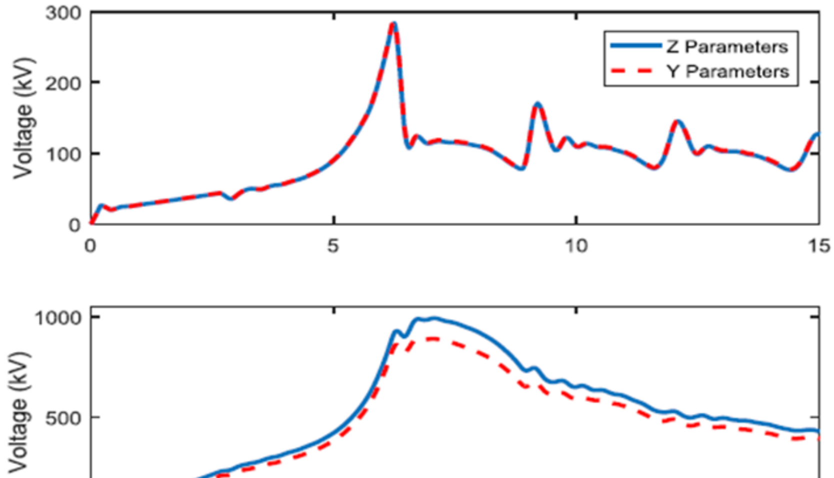

Figure 12. *Insulator string overvoltage for square grounding network. Primary lightning value (31.1kA, 3.83*μ*s/75*μ*s) and resistivity* ρ *= 100* Ω*m (a),* ρ *= 1000* Ω*m (b) in CP Wide-Band modeling mode.*

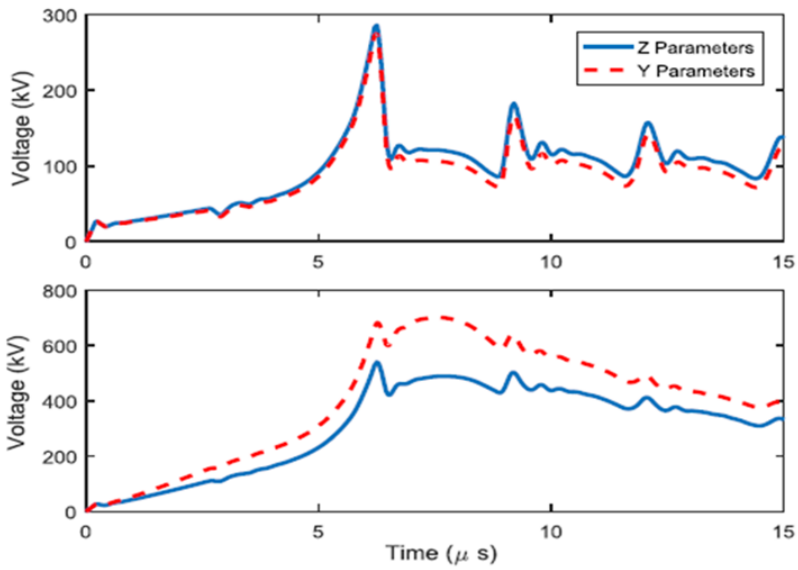

Figure 13. *Insulator string overvoltage for square grounding system. Primary lightning value (31.1kA, 3.83**μ**s/75**μ**s) and resistivity **ρ** = 100 **Ω**m (a), **ρ** = 1000 **Ω**m (b) in FD Wide-Band modeling mode.*

Another type of SFCL is the inductor type limiter, which is the most widely used and useful type of limiter in high voltage and very high voltage systems compared to the resistance type. This type of limiter is connected in series with the CB for operation on transmission lines and provides almost zero impedance in the normal power grid. Installing the limiter changes the line parameters, which in turn may create a more dangerous error condition for the CB than without the FCL. It can be seen that the difference of overvoltage obtained from the grounding model based on the impedance matrix (proposed method) with modeling based on the admittance matrix [11], in both types of modeling, wide band with fixed and dependent electrical parameters As the frequency increases, so do the resistors. This difference in maximum overvoltage stress in CP Wide-Band model and **ρ** = 100 **Ω**m is about 2kV (less than 1%) and in model **ρ** = 1000 **Ω**m is about 100kV (10%). In FD Wide-Band model and **ρ** = 100 **Ω**m the difference is about 12kV (5%) and in **ρ** = 1000 **Ω**m is about 100kV (15%). According to the results, it is clear that the calculated maximum overvoltage difference increases with the frequency dependence of the electrical parameters of the soil. *Figures 14*, *Figure 15* and *Figure 16* show the overvoltage of the insulator string in terms of changes in current magnitude, front line time and back wave time for different models of grounding system.

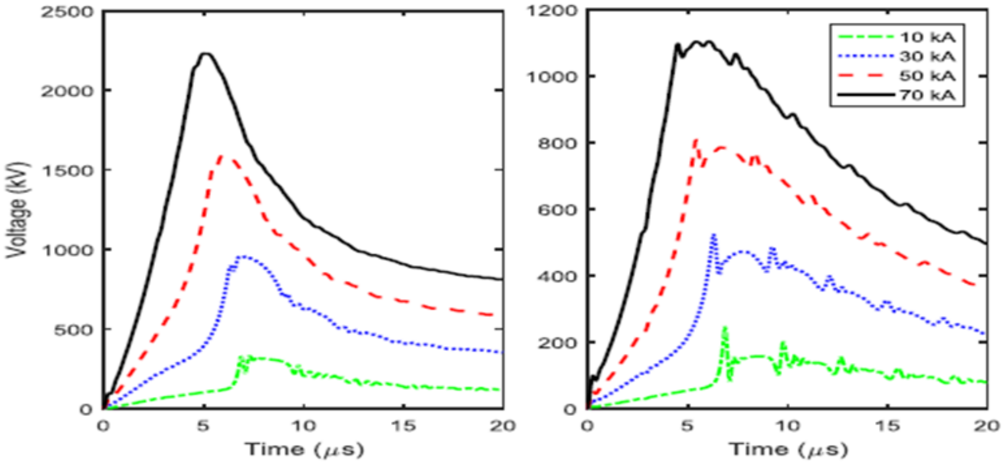

Figure 14. *Insulator string overvoltage for a square grounding system. Equivalence = 1000* ***Ω****m due to change of peak lightning current peak (1kA, 3.83****μ****s/75****μ****s) Left column: CP Wide-Band model, right column: FD Wide-Band model.*

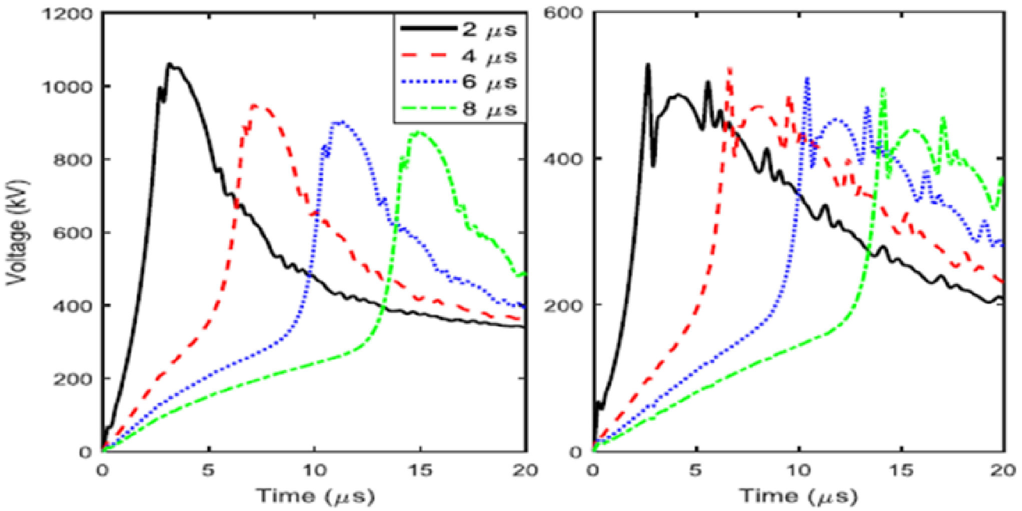

Figure 15. *Insulator string overvoltage for square grounding system. Equivalence = 1000* ***Ω****m due to the change of the frontal wavelength of the primary lightning current (30kA, Tf****μ****s/75****μ****s) Left column: CP Wide-Band model, right column: FD Wide-Band model.*

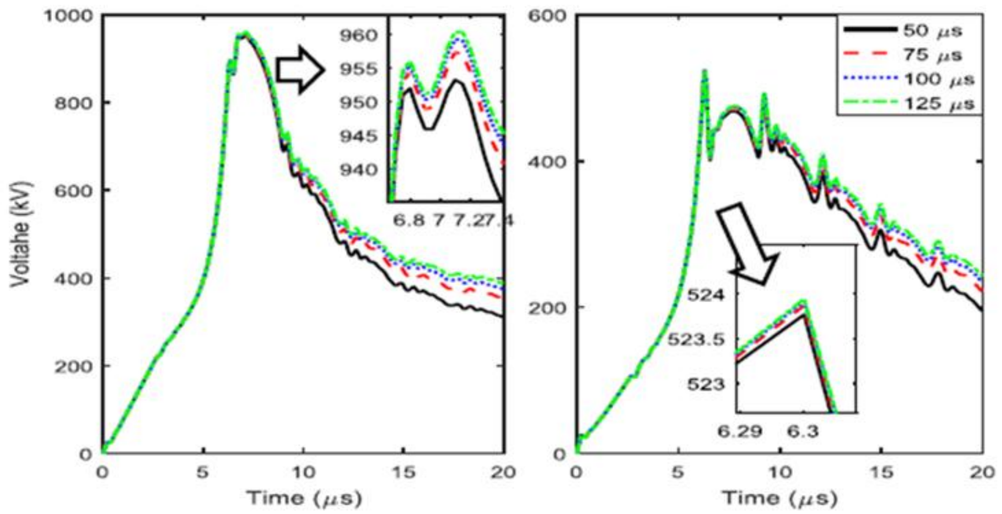

Figure 16. *Insulator string overvoltage for a square grounding system. Equivalence = 1000 Ωm due to time change behind the primary lightning current (30kA, 3.83µs/Thµs) Left column: CP Wide-Band model, right column: FD Wide-Band model.*

The effect of grounding system modeling on overvoltages caused by lightning strike to the guard wire is shown in *Figure 17*. According to the results, in the case of static modeling and CP Wide-Band ground system, reverse discharge occurs; however, if the FD Wide-Band model is used for the grounding system, a short circuit will not occur. As a result, the effect of grounding system modeling on the estimation of overvoltages and lightning performance of transmission lines is determined (*Table 3* and *Table 4*). In general, capacitive equipment may reasonably affect the speed of the transient process on the transmission line side, which may be affected by the dispersion capacitor, which will affect the CB contacts in the CB cut-off specification. Therefore, the study of the effect of an induced FCL on the RRRV of the power switch in a series connection must be combined with the inductive FCL scattering capacitor of the current limiter (Alemi and Sheshyekani, 2015).

Table 3*. Probability of back flashover for square grounding system (%).*

Resistivity (Ωm)	Grounding system model	Impedence matric based method (proposed method)			Method based on admittance matric (Alemi and Sheshyekani, 2015)		
		Total	Subsequent	Primary	Total	Subsequent	Primary
ρ= 100	ST	13.6	5.9	0.3	13.6	5.9	0.3
	CP	14.0	6.1	0.3	13.3	5.7	0.3
	FD	14.0	6.1	0.3	13.3	5.7	0.3
ρ= 500	ST	33.4	7.8	19.5	33.4	7.8	19.5
	CP	30.0	6.2	18.7	33.6	7.3	17.2
	FD	24.0	6.2	15.1	24.4	6.7	11.0
ρ= 1000	ST	68.8	11.5	58.7	68.8	11.5	58.7
	CP	62.3	8.2	54.0	54.1	10.1	46.6
	FD	46.6	7.1	35.5	46.4	8.6	33.8

***Table 4**. Back flashover rate (flashes/100km/year) of transmission line for all types of square grounding system modeling.*

Resistivity (Ωm)	Grounding system model	Impedance matric based method (proposed method)		Method based on admittance matric (Alemi and Sheshyekani, 2015)	
		Subsequent	Primary	Subsequent	Primary
ρ= 100	ST	4.08	0.09	4.08	0.09
	CP	4.20	0.09	4.99	0.09
	FD	4.20	0.09	3.99	0.09
ρ= 500	ST	10.0	5.8	10.0	5.8
	CP	9.0	5.6	9.1	5.1
	FD	8.1	4.5	7.3	3.3
ρ= 1000	ST	20.6	17.6	20.6	17.6
	CP	18.6	16.2	17.7	14.2
	FD	14.2	10.6	13.9	10.1

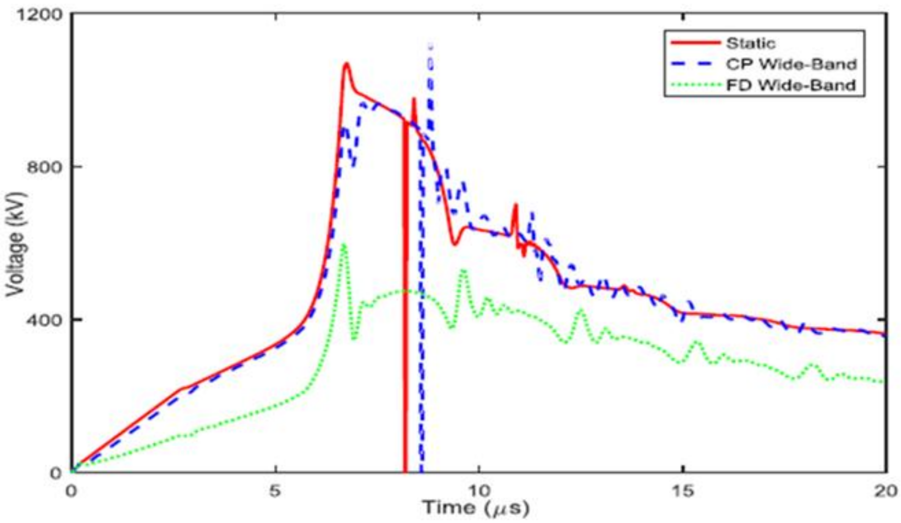

***Figure 17.** Insulator string overvoltage for a square grounding system. Lightning rate (30kA, 3.83**μ**s/75**μ**s) and resistivity **ρ** = 1000 **Ω**m.*

Conclusion

In the proposed method, a new analysis based on the impedance matrix of ground systems was used to model and simulate the ground system in the frequency domain. Proposed methods for ground system modeling use the ground system management matrix. In fact, in the methods of obtaining the acceptance matrix, the impedance matrix of the earth connection system must be inverted, but the disadvantage of this method is that inaccurate modeling of earth connection systems, these impedance matrices have the same values at lower frequencies and so they are not reversible, which is not a good thing. As a result, in previous studies, the acceptance matrix was approximated. While in this paper, by presenting a new method, the modeling of the time domain of the terrestrial system was performed directly based on the impedance matrix of the terrestrial system. As a result, in this method, the ground system has the ability to model in transient software in the time domain without any approximation. Also, with the help of the proposed method, ground connection systems are implemented and simulated directly in the time domain and can be used in the analysis of passages caused by lightning. In impedance matrix modeling, the frequency-dependent behavior of the earth system in the time domain was obtained without the need for inversion. As a result, this method never has the computational complexity of inverting high-order matrices. On the other hand, there is no need for low frequency approximations to invert, and as a result, this method is closer to the real wave than conventional methods.

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Conflict of interest

The authors confirm that there are no conflicts of interest involved with any parties in this research study.

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