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Investigating the Electromagnetic Transient State of Shielding Failure in 1000 KV Transmission Line Caused by Lightning Strike, considering Impulse Corona, Soil Ionization of High-Frequency Grounding System and Frequency Dependent of Transmission Line

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Abstract-Lightening voltage is considered as one of the most important and fundamental keys in analyzing the shielding failure of ultra-high voltage transmission lines and power systems. Lightning strike has been surveyed and analyzed by the existence and non-existence of a corona phenomenon on overhead transmission line using EMTP-RV software and it was specified that the results of impulse corona caused a reduction of the voltage amplitude level of the conductor. In order to analyze the attenuation of the voltage signal in a part of the simulation. Since an increase in ground potential is a function of lightening waving current behavior and transient characteristic of the grounding system, the accomplished attenuation influenced by grounding system has been limited and partial in contrast to corona system, but the limited effect includes the significant impact on improving the isolation level of the high voltage transmission line.

Keywords- Electromagnetic Transient State, Shielding Failure, Lightning Strike

I. INTRODUCTION

When the voltage of a special value is increased, it creates corona voltage and the air around the conductor is ionized and an electrical charge is stored. This is the corona phenomenon which is spread in the transmission line and increases the capacitance of transmission line. The characteristics of the phenomenon are shown by a q-v curve. Some of the presented models are in the form of equivalent circuit and others are in the form of a linear approximation of q-v curve. All of them are dependent on the line temporary voltage. In this method, experimental results show that corona influences the voltage wave slope [1]. The wave form and the produced ultra-voltage amplitude in the transmission line are of utmost importance since the lightning strike enjoys the electrical equipment insulation in the power network and selecting strike protection. Corona strike and frequency dependency are factors which cause attenuation and distortion of airlines ultra-voltage. Impulse corona is one of the available skin effects which causes that the line radial parameters depend on strike frequencies and create changes in other parameters. Considering optimal designing of strike protection and insulation and economic aspects in transient characteristics from the strike, transmission lines include high necessity by analyzing two subjects of impulse corona and frequency dependency [2]. Numerical computations are a common method to research on electromagnetic transient characteristics of lightning impulses in a transmission line. Therefore, it is so essential to have proper knowledge of lightning transient process and to analyze the effects of impulse corona exactly in the transmission line for system protection and optimum designing the insulation coordination level for equipment related to the transmission line. In this survey, when the lightning strike hits the transmission line, the transmission line is divided into parts of frequency dependent wave-lengths of lightning wave. This section represents the fixed resistance and inductance and variable capacitance which reflects the electrical charge mechanism and variable conductance and presents corona power losses [3]. The shape of lightning waves includes a variety and parameters of various ranges during transmission line. Hence, it is so essential to study the Q-V characteristics and lightning strikes changes. The results of the charge-voltage curve represent that by increasing the frequency, energy losses under positive strikes are more than energy losses under negative strikes, and also by increasing the time constant, sub-rings after the peak are also increased. In this research, lightning ultra-voltage was attenuated under oscillatory strikes and double exponential strikes were evaluated and it was shown that these two methods are so similar to each other and their difference is after the peak. In oscillatory strikes, charge-voltage curve was shown in the ring and in double exponential strikes, the curve moves down smoothly [4]. The electric analysis was accomplished on polymer level by positive impulse corona in the air. In this method, it was considered as output (circuit current) and input (electrical fields and electrical charge space density) in the computer simulation analysis. In this study, dynamic and electric charge distribution and electrical fields have been analyzed and compared with two electric loading models from Corona (radiative and explosive). The results in this method represented that electric charge subsidence is seen continuously in radioactive corona and the charged point radius is increased gradually on a smooth level. In explosive corona, a series of ion are released from solid gas and generally, the charged radius in explosive corona is less than radioactive corona [5]. The lightning due to amplitude and high current slope causes an intense increase of ground potential in place of discharge or striking on the earth. The increase of ground potential can bring too heavy life and financial dangers. The increased value of ground potential is a function of lightening wave-oriented current behavior and also transient characteristics of the grounding system. The lightening grounding system includes three main parts: metal conductors (intermediate conductors) which lead lightening current to the ground electrode, metal electrodes buried in the soil and the ground around the electrodes [6-8]. In this article, impulse corona is not the only studied matter at the time of lightning strike to the transmission line, but it has been considered as a designing high-frequency grounding system and the effects of soil ionization on the function of UHV transmission line available signals in order to improve the ionization level and increase of prediction care in reducing the voltage amplitude.

II. EQUIVALENT CIRCUIT OF CORONA PHENOMENON

Accomplished studies represent that the conductivity amount in space around corona under lightening ultra-voltage can be ignored. Corona equivalent circuit of the high voltage transmission line has been shown in figure (1). C22, C23, and C24 are considered coupling capacitance between phases in corona model in figure (1). In the presented model, C14, C17, and C26 show capacitance between line and corona model and C15, C18 and C21 show capacitance between corona model and the ground. In the simulation, L and R have been assumed secretly. DC5, DC6, and DC7 are considered corona initial voltages. Before transmission line voltage reaches to corona initial line voltage, diode is off and does not lead, but when transmission line voltage is more than initial line voltage, diode is on and leads. In the simulation, each 100 meters of corona is added to the high voltage transmission line.

Before transmission line voltage reaches to corona initial voltage, diode does not lead and is off; this is the (q-v) corona characteristic in the linear part of the curve, and when line voltage reaches the same value of corona initial voltage, diode leads. Corona capacitance value is obtained by the following formula.

$$C_{cor} = 2kc(1-\frac{E_0}{U}) \tag{1}$$

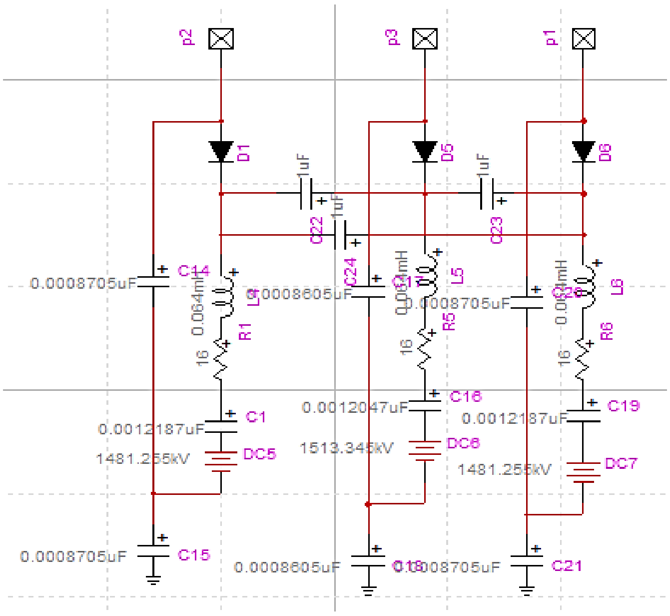

Figure 1. Corona equivalent circuit in three phases of transmission line

Which U is transmission line voltage and E_0 is corona initial voltage and kc is corona fixed losses. Corona initial voltage value has been shown in bundle conductors as follows:

$$E_{do} = nrE_c \ln(\frac{2h}{r_{ea}})[1+\frac{r(n-1)}{A}]^{-1} \tag{2}$$

n is the number of bundled conductors and E_C is initial corona field which 30mδ and δ is air relative density coefficient and m is roughness coefficient on conductor level. A is bundle space and r_{eq} is bundle conductor equivalent radius. Corona initial voltage for double airlines is as follows:

$$E_{bo} = \frac{3000m(1+\frac{0.03}{\sqrt{r_b}})2r_b}{1+\frac{2r_b}{D}} \ln\frac{2r_b}{\sqrt{r_b D}} \tag{3}$$

In which r_b is air conductor radius and D is considered as the distance between air conductors [9]. In table (1), corona computation parameters have been represented. In this corona model, L= 0.0644mH and R= 16Ω.

TABLE I. CORONA COMPUTATION PARAMETERS IN TRANSMISSION LINE

Line type	*Corona initial voltage* (KV)	*Geometric capacitance* (Pf/m)	*Corona capacitance* (Pf/m)
Edge phase conductor	1481.2551	17.4102	12.1862
Middle phase conductor	1513.3453	17.2103	12.0461
Guard wire	276.3341	6.7268	4.9284

III. HIGH-FREQUENCY OF GROUNDING SYSTEM MODEL BY CONSIDERING SOIL IONIZATION

In general, analysis methods of high-frequency grounding system model and its dynamic behavior at discharging lightening current are categorized into three classes: circuit theory method, transmission line theory method and electromagnetic field theory method. Circuit theory method has been used in the article. A simple method has been presented according to figure (2) for the modeling grounding system in high-frequencies.

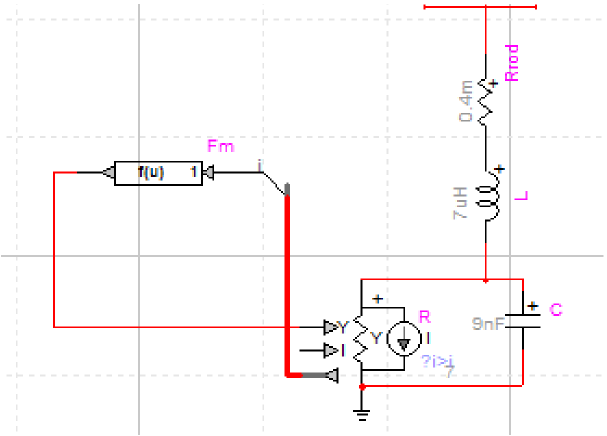

Figure 2. Grounding system circuit model by considering soil ionization

In this circuit, the value of R_n is specified according to the relations (4) and (5) and relation (6) and relation (7) have been suggested to compute a vertical electrode capacitance and for a horizontal electrode, respectively. In which ε(F/m) is soil penetrability coefficient. As the depth of horizontal electrode increases, the value of inductance (L) is decreased a little, too. Therefore, the value of inductance is almost equal for horizontal electrodes in various depths. Relation (8) has been suggested in order to compute the inductance value of a vertical electrode and relation (9) for a horizontal electrode. μ(H/m) soil penetrability coefficient is usually considered equal to the vacuum penetrability coefficient. In this method, it is supposed that longitudinal-current has been distributed smoothly in the electrode. In this article, the bar diamond is considered 16mm and copper bar length 2m and also the burial depth 0/5m. The base mast resistance is considered as a set of the circuit. It is a suitable selection model because the wave spread speed in the soil 150 m/μs and the base mast resistance includes real geometry dimensions. The base mast resistance has been expressed in equation (10). It must be noted that the high-frequency grounding system used in this article has been buried vertically [10].

$$R(\Omega) = \frac{\rho}{2\pi l}\left(\ln\left(\frac{4l}{a}\right) - 1\right) \tag{4}$$

$$R(\Omega) = \frac{\rho}{2\pi l}\left(\ln\left(\frac{2l^2}{ah}\right) - 1\right) \tag{5}$$

$$C(F) = \frac{2\pi\varepsilon l}{\ln\left(\frac{4l}{a}\right) - 1} \tag{6}$$

$$C(F) = \frac{2\pi\varepsilon l}{\ln\left(\frac{2l^2}{ah}\right) - 1} \tag{7}$$

$$L(H) = \frac{\mu l}{2\pi}\left(\ln\frac{4l}{a} - 1\right) \tag{8}$$

$$L(H) = \frac{\mu l}{2\pi}\left(\ln\frac{2l}{\sqrt{2ah}} - 1\right) \tag{9}$$

$$Rrod(i) = \frac{R_{st}}{\sqrt{1 + {}^{i}/_{Ig}}} \tag{10}$$

$$I_g = \rho_g \frac{E_g}{2\pi R_{st}^2} \tag{11}$$

IV. DESIGNED MODEL COMPONENTS

In this survey, when lightning strike hits the transmission line, the transmission line is divided into parts of lightning wave frequency dependent wave-lengths. The simulation has been considered 1600 m a transmission line, 5 towers having 400m span and 1000kv power supply with 1.5km away from the power supply. Transmission line various frequency parameters have much relation with a magnetic transient process from lightning strike. Therefore, it has been used as FD-LINE model in the simulation. In the following, power system design components like a ultra-high voltage transmission line, high voltage mast, electric discharge model, lightning current model have been explained. This part represents fixed resistance and inductance and variable capacitance which reflects the electric charge mechanism and variable conductance and presents corona power losses.

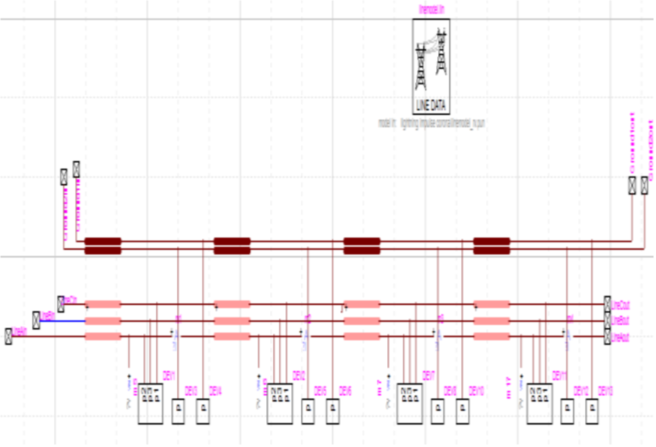

Figure 3. Computing model for transmission line by corona phenomenon

The transmission line characteristics include three conductors, two bundles, and bundle space is 400mm and conductors' radius is 30mm. The air relative density coefficient is (δ =1) and the roughness coefficient on the conductor is (m=0/82). Guard wires have also been considered with the 16mm radius. The height of the curve is 17m in transmission line and 15m in guard wires [11, 12].

V. UHV TRANSMISSION LINE TOWER MODEL

The wave form and the produced ultra-voltage amplitude in the transmission line due to lightning strike include special importance to coordinate the electrical equipment insulation in the power network and selecting strike protection. The presented model in this method includes four parts: wire-protective layer, upper, lower and middle phases. Each part includes transmission line losses which have been mysterious with parallel RL circuit that shows transient waves attenuation. The tower multi-waves impedance model components in ultra-high voltage alternating current transmission line with an attenuation constant ($\gamma = 0.7$) and damping coefficient ($\emptyset = 1$) are as following according to reference {13, 14}.

R_1=40.7 Ω, R_2=38 Ω, R_3=53.5 Ω,

L_1=16.9 µH, L_2=15.8 µH, L_3=22.2 µH

Zt_1=220 Ω, Zt_2=220 Ω, Zt_3=150 Ω

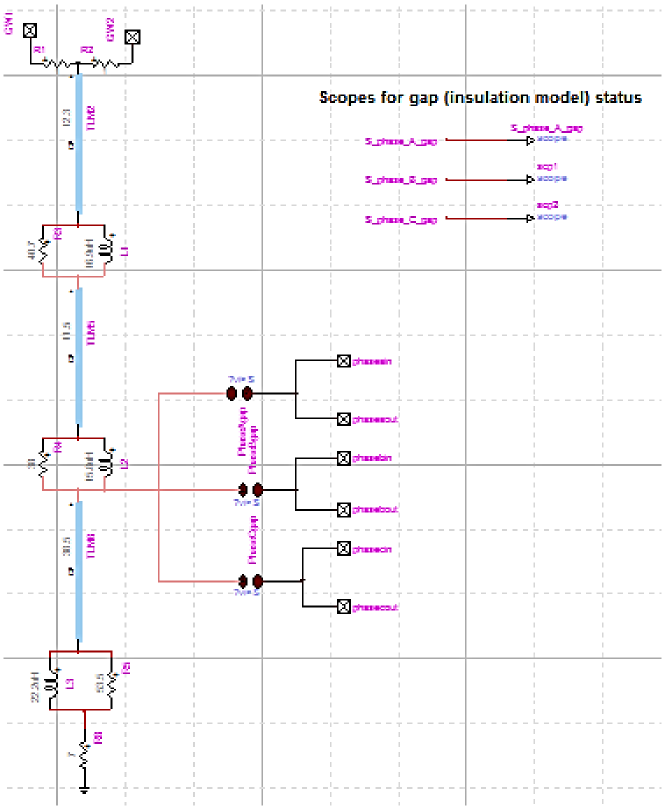

Figure 4. Multi-waves impedance model of power transmission system

VI. LIGHTENING CURRENT MODEL

There is more possibility of lightning strike to the transmission line by frequent lightning strikes and soil high resistance in some areas. In this proposed method, due to the skin effect of conductors and lightening alternating magnetic field, the resistance and inductance of the transmission line will be changed with current frequency. In this situation, the transmission line by presenting a series of characteristics in various frequencies tries to influence directly the magnetic transient process. It has been used double exponential function 50/2.5 µs in the lightening current simulation. The modeled lightning current source has been considered as 200KA.

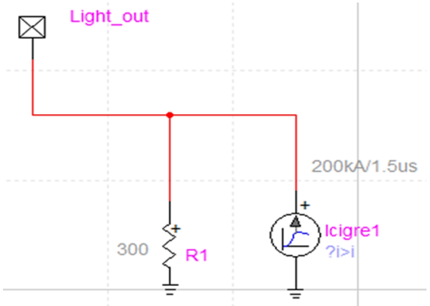

Figure 5. Lightening direct strike model to UHV transmission line

VII. SHIELDING FAILURE DIAGRAM ANALYSIS

The method has been presented in diagram block figure (6). Lightning is one of the most important factors of creating electromagnetic transient in power transmission line. Hence, the relationship between shielding failure, 200KV lightning strike, corona phenomenon and high and low-frequency grounding systems with the existence and non-existence of soil ionization have been evaluated. When voltage is increased from a special value, corona voltage is created and the air around the conductor is ionized and electric charge is stored. It is the corona phenomenon which spreads in the transmission line and leads to an increase in the transmission line capacitance. On the other side, occurring impulse corona has concentrated on the axial flows in the line. After spreading lightning pulse and specifying non-linear capacitance between corona and conductor and the capacitance between ground and conductor, the final inductive voltage is measured. The results of the stage represent transient signal attenuation on transmission lines. Then, two high and low-frequency grounding systems have been used for the dynamic improvement of the proposed model. When the current inducted to ground bar is more than soil Ionization current eve, we observe that the soil around the conductor of grounding system is changed and influences positively on computed signals from corona phenomenon. The output of flowchart will be the voltage attenuation and amplitude reduction and Shielding Failure improvement. The advantage of the proposed method in the article is BIL level improvement and achieving a true comprehension of the real wave process.

VIII. SHIELDING FAILURE ANALYSIS OF UHV TRANSMISSION LINE

The behavior of corona phenomenon under lightening conditions in high and low-frequency grounding systems by considering soil ionization in the simulation has been surveyed. A corona model with the high-frequency grounding system has been modeled using EMTP-RV software in UHV alternating current transmission line model and the effect of grounding system soil resistance change and pals from corona in inductive voltage signals in power system transmission line from lightning strike has been shown in the transmission line. It was demonstrated that corona phenomenon causes attenuation and damp the voltage signal and also increase the wave forehead time. It has also been shown that high-frequency grounding system by considering soil ionization includes more credit than low-frequency grounding system. The most important positive effect of corona phenomenon and soil ionization are considered in the shielding failure of UHV alternating current transmission line due to damp and attenuation of transient waves. Analyzing high voltage transmission line with 200KA lightning strike of 1600m long and 5 high voltage masts has also been considered. The analysis has been performed in intervals of 100m, 300m, 700m, 1100 and 1300 m from lightning strike point.

IX. POWER SYSTEM TRANSMISSION LINE INDUCTIVE VOLTAGE BY SOIL IONIZATION IN THE ABSENCE OF CORONA PHENOMENON

In the first step of analyzing the voltage of ultra-high voltage transmission line, soil ionization was performed in transient simulation in the absence of corona phenomenon. Figure (7) shows an inductive voltage of a high voltage transmission line in the low-frequency grounding system and by considering soil ionization in the absence of corona phenomenon. Figure (8) represents the inductive voltage of a high voltage transmission line in the high-frequency grounding system in the absence of corona phenomenon by considering soil ionization. For instance, in figure (7) the voltage of ultra-high voltage transmission line in 100m away from strike point is 2.502MV and in figure (8) the transmission line voltage is about 2.593MV.

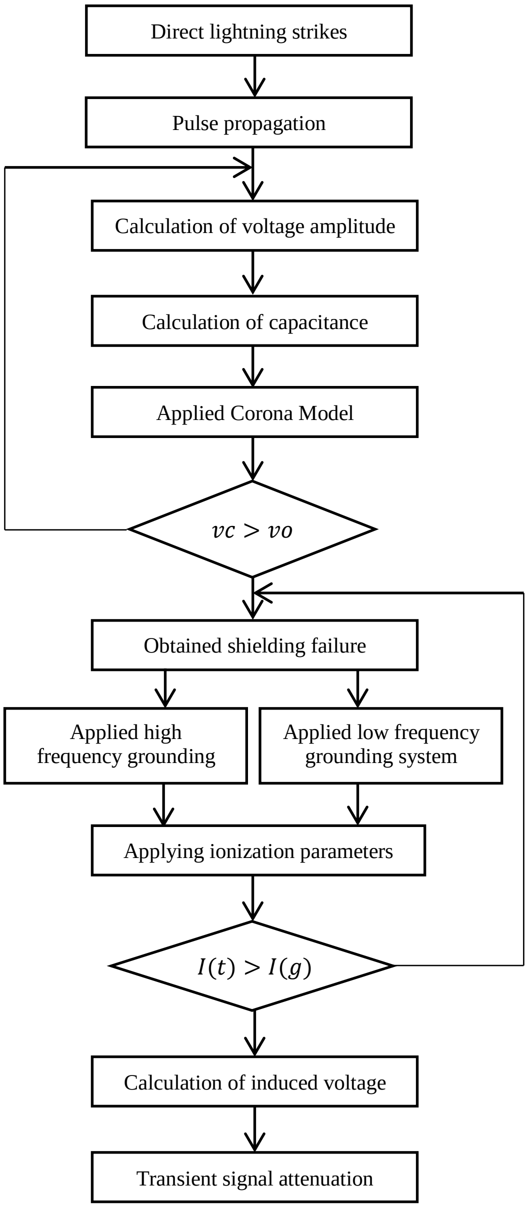

Figure 6. Shielding failure flowchart of UHV transmission line by calculating corona and grounding system soil ionization

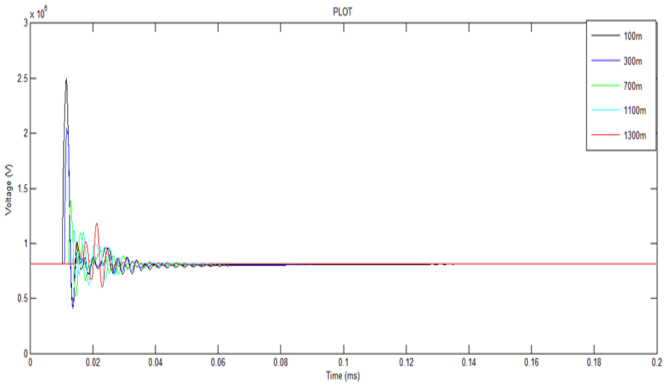

Figure 7. The voltage of ultra-high voltage transmission line in the low-frequency grounding system by considering soil ionization in the absence of corona phenomenon

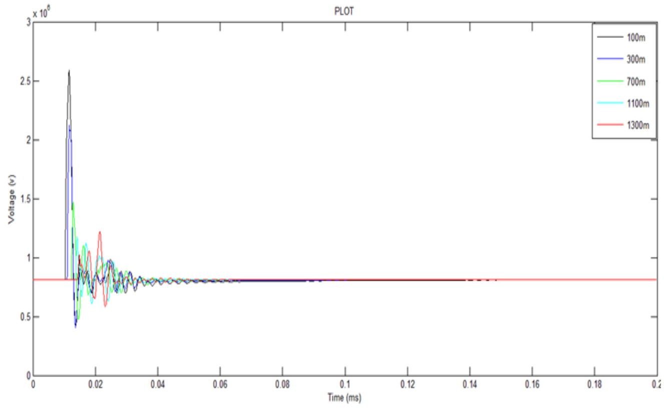

Figure 8. The voltage of ultra-high voltage transmission line in the high-frequency grounding system by considering ionization in the absence of corona

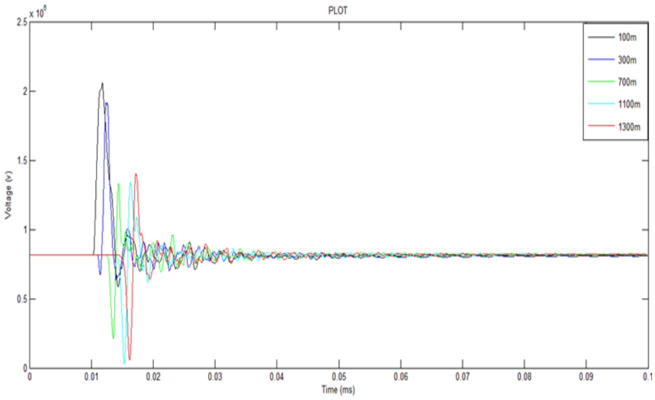

Figure 9. The voltage of ultra-high voltage transmission line in low-frequency grounding system in the presence of corona and soil ionization

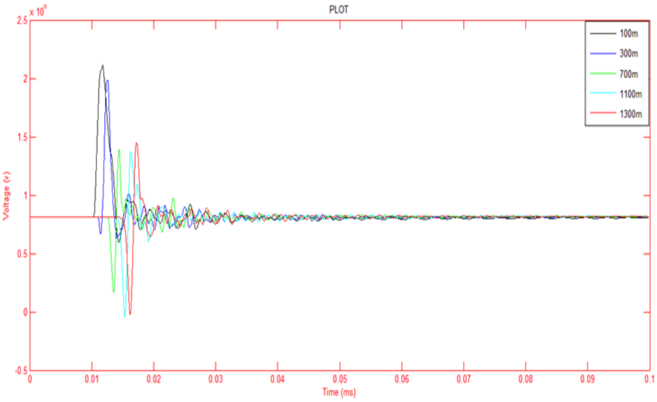

Figure 10. The voltage of ultra-high voltage transmission line in high-frequency grounding system in the presence of corona and soil ionization

X. POWER SYSTEM TRANSMISSION LINE INDUCTIVE VOLTAGE IN THE PRESENCE OF SOIL IONIZATION AND CORONA PHENOMENON

In the second step of analyzing the inductive voltage of ultra-high voltage transmission line, both soil ionization and corona phenomenon have been used in the electromagnetic transient simulation. Figure (9) shows an inductive voltage of ultra-high voltage transmission line in the low-frequency grounding system and in the presence of corona and soil ionization. Figure (10) shows an inductive voltage of ultra-high voltage transmission line in the high-frequency grounding system in the presence of corona phenomenon and soil ionization. For example, in figure (9), the inductive voltage in 100m away from the lightning strike point is 2.075MV and in figure (10), the inductive voltage in 100m away from the lightning strike point is 2.124MV.

XI. POWER SYSTEM TRANSMISSION LINE INDUCTIVE VOLTAGE IN THE ABSENCE OF SOIL IONIZATION AND CORONA PHENOMENON

In the third step of analyzing the inductive voltage of power transmission line, soil ionization corona phenomenon has not been considered in the simulation. Figure (11) shows an inductive voltage of ultra-high voltage transmission line in the low-frequency grounding system in the absence of corona and soil ionization. Figure (12) shows an inductive voltage of ultra-high voltage transmission line in the high-frequency grounding system in the absence of corona phenomenon and soil ionization. As an instance, in figure (11), the inductive voltage in the high voltage transmission line in 100m away from the lightning strike point is 2.607MV and in figure (12), the inductive voltage is 2.641MV.

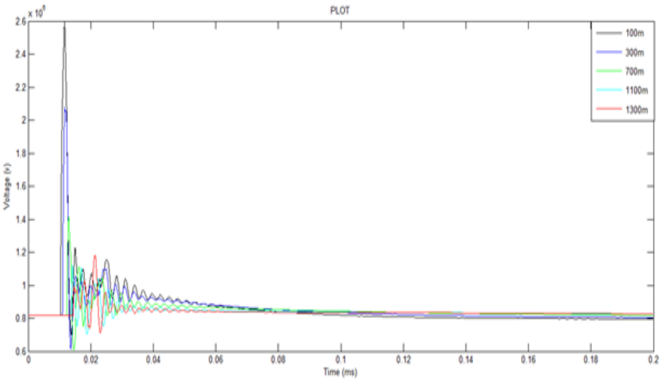

Figure 11. The voltage of ultra-high voltage transmission line in low-frequency grounding system in the absence of corona and soil ionization

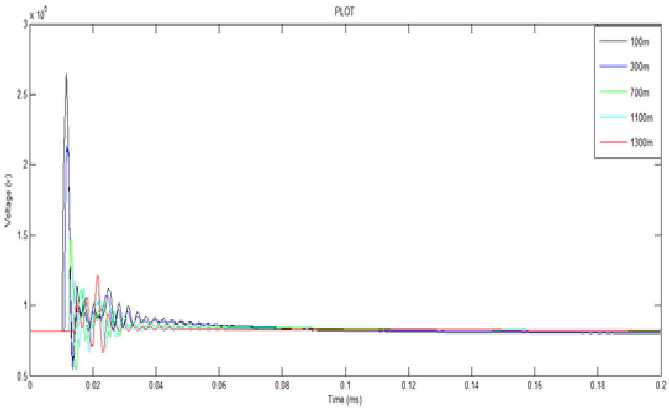

Figure 12. The voltage of ultra-high voltage transmission line in high-frequency grounding system in the absence of corona phenomenon and soil ionization

XII. POWER SYSTEM TRANSMISSION LINE INDUCTIVE VOLTAGE IN THE PRESENCE OF CORONA PHENOMENON AND IN THE ABSENCE OF SOIL IONIZATION

In the last step of analyzing the inductive voltage of power transmission line, the simulation was performed in the presence of corona phenomenon and in the absence of soil ionization. Figure (13) shows an inductive voltage of ultra-high voltage transmission line in the low-frequency grounding system in the presence of Corona phenomenon and in the absence of soil ionization. Figure (14) shows an inductive voltage of alternating current ultra-high voltage transmission line in the high-frequency grounding system in the presence of corona phenomenon and in the absence of soil ionization. As an instance, in figure (13), the inductive voltage in 100m away from the strike point is 2.134MV and in figure (14), the inductive voltage is 2.163MV.

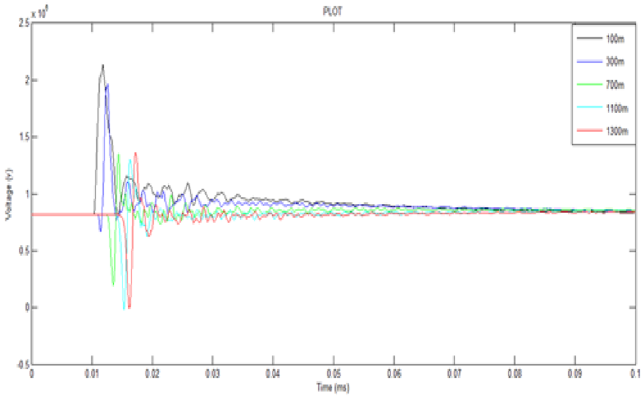

Figure 13. The voltage of ultra-high voltage transmission line in the low-frequency grounding system in the presence of corona and in the absence of soil ionization

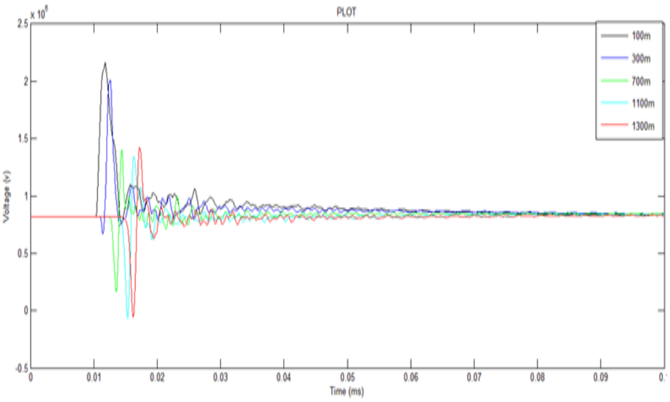

Figure 14. The voltage of ultra- high voltage transmission line in high-frequency grounding system in the presence of corona and in the absence of soil ionization

XIII. FINAL SIMULATION RESULTS TABLE

The results from analyzing the effect of corona phenomenon on transient waves from lightning strike 200KA in alternating current ultra-high voltage transmission line have been shown in tables (2) and (3). The final results represent the effect of corona with a frequency dependent transmission line in power system inductive voltage in 100m away from the lightning strike point. The results show that the lightning ultra-voltage is attenuated and distorted by various factors in the method and is spread in the transmission line. Corona phenomenon in both high and low-frequency grounding systems causes reduction of an inductive voltage amplitude of the power system transmission line.

TABLE II. SIMULATION ANALYSIS IN HIGH-FREQUENCY GROUNDING SYSTEM

	Without soil Ionization	With soil Ionization
Inductive voltage amplitude without Corona	2.641 MV	2.593 MV
Inductive voltage amplitude with Corona	2.163 MV	2.124 MV

TABLE III. SIMULATION ANALYSIS IN LOW-FREQUENCY GROUNDING SYSTEM

	Without soil Ionization	With soil Ionization
Inductive voltage amplitude without Corona	2.607 MV	2.502 MV
Inductive voltage amplitude with Corona	2.134 MV	2.075 MV

XIV. CONCLUSION

In this article, the effects of corona phenomenon in the electromagnetic transient from lightning strike 200KA in alternating current ultra-high voltage transmission line were considered 1000kv with 1600m long. The lightning ultra-voltage played a significant role in power system transmission lines shielding failure; therefore, corona phenomenon showed its positive role in weakening released waves from lightning strike in the accomplished simulation by EMRP-RV software in the article. The positive role of corona phenomenon on attenuation and reducing amplitude on voltage signals from lightning strike was completely clear which can promise cost reduction in power system utilizations. On the other side, the effects of high and low- frequency grounding systems were analyzed by considering soil ionization on the produced waves by lightning strike. It turned out that grounding system has a limited and little effect on attenuating and damping transient waves from lightning strike, but the little effect positively influences the improvement of the situation of BIL high voltage alternating current transmission line and discharge will not occur. Moreover, the amount of attenuation in low-frequency grounding system due to the effect of soil ionization on ground resistance was more than high-frequency grounding system.

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