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Comparison of Circuit Models for the Simulation of Soil Ionization

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***Abstract*—The main characteristic of the transient behaviour of a grounding system is the decrease of the soil resistivity and consequently of the grounding impedance, due to soil ionization phenomena that take place, when the density of the injected current exceeds a critical value. In this paper two circuit models proposed by researchers have been implemented using the ATP/EMTP programme in order to simulate the transient response of a grounding system taking soil ionization into account. The simulation results are compared to measurements received by imposing impulse voltages on soil samples. The accuracy of each model is evaluated according to the level of proximity to the oscillogramms and conclusions are drawn about the effectiveness of each modeling approach.**

Keywords-transient response; soil ionization; equivalent circuit; simulation

I. IONIZATION CIRCUIT MODELS

Measurements with high impulse voltages applied by Nor et al. [1] on soil samples yielded current waveforms with two peak values. This led to the formation of an equivalent circuit that consists of two parallel branches representing the pre-ionization and post-ionization stages respectively, as shown in Fig. 1 [1]. The pre-ionization resistance R_1 expresses the conduction behaviour related to the thermal effects and their interaction with the properties and structure of the soil. The post-ionization resistance R_2 accounts for the final state of conduction after the ionization procedure has reached its full extent of expansion and is therefore always lower than the pre-ionization resistance R_1. The resistance values R_1 and R_2 are calculated using the two peak currents and their corresponding instantaneous voltages as in equations (1) and (2). The inductance element L introduces the required time delay for the expansion of the ionization zone.

$$R_1 = \frac{V_{Ipeak1}}{I_{peak1}} \quad (1)$$

$$R_2 = \frac{V_{Ipeak2}}{I_{peak2}} \quad (2)$$

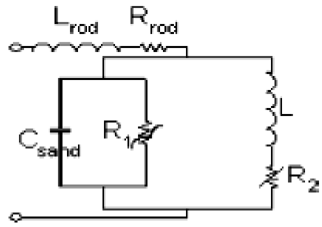

Figure 1. The ionization circuit proposed by Nor et al. [1]

Based on experimental I-V curves Kalat, Loboda et al. proposed the dynamic sand surge conduction model depicted in Fig. 2 [2]. The soil conductance for small current values is taken into account by the linear elements g_{LDC} and g_{LAC}. The looped shape of the curve is interpreted by a non-linear conductance g_N which is described by the steady state characteristic (3) and the differential equation (4).

$$i_{No} = Au^a \quad (3)$$

$$\frac{di_N}{dt} = \frac{1}{T}[i_{No}(u) - i_N] \quad (4)$$

The model is completed by the following equations:

$$ug_{LDC} + i_C + i_N = i(t) \quad (5)$$

$$Ri_C + 1/C\int i_C dt = u \quad (6)$$

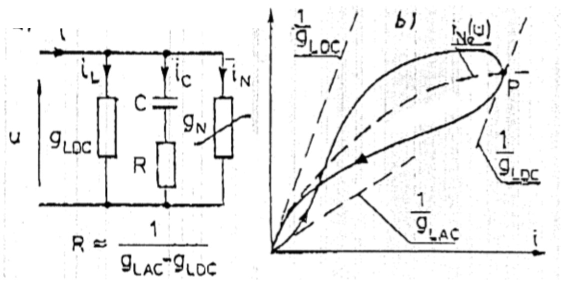

Figure 2. The surge conduction model proposed by Kalat, Loboda et al. for sand soil sample [2]

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II. EXPERIMENTAL SET UP

Along with the simulations, series of measurements were carried out by applying on soil samples 1.2/50μsec positive impulse voltages produced by the impulse voltage generator presented in Fig. 3 [3]. The impulse voltage generator is supplied by a variac and a transformer with ratio 220V/200kV. The fluctuation of the 230V, 50Hz AC network supply is minimized to ±0.1% by means of a voltage stabilizer. A low pass filter and an insulating transformer shield the power supply from noise and disturbances.

A voltage divider with ratio 421:1 and a differential probe with attenuation ratio 100:1 connected to the output of the impulse voltage generator are used for the measurement of the produced voltage. The current injected to the soil sample is measured with a Pearson current monitor with 0.002A/V sensitivity. The voltage and current signals are recorded with a two-channel 500MHz digital oscilloscope, which is placed in a Faraday cage with 50dB attenuation for signals up to 1GHz.

The soil samples are placed in a metallic cylinder with 19cm depth, 25cm diameter and wooden bases. The impulse voltage is applied on a vertical copper electrode with 5mm diameter that penetrates longitudinally the soil sample.

The soil samples are subjected to special preparation in order to analyze their contents and achieve a desired moisture percentage. At first, stones and foreign material are removed from the samples through sieving and, then, the soil is dried in an oven at 105°C for 2 days. The moisture content is specified by adding the necessary amount of de-ionized water (% by weight). The resistance (R_o) at a low impulse voltage was measured in order to calculate the resistivity of the used samples based on the relationship [4], [5], [6]:

$$R_0 = \frac{\rho \ln\left(\frac{r_{out}}{r_{in}}\right)}{2\pi\ell} \Rightarrow \rho = \frac{2\pi\ell}{\ln\left(\frac{r_{out}}{r_{in}}\right)} \cdot R_0 \qquad (7)$$

Where: ℓ =19cm is the height of the cylinder

r_{out} =12.5cm is the inner radius of the outer electrode (cylinder)

r_{in} =2.5mm is the radius of the inner electrode

The following values of soil relative permittivity ε_r are adopted taking into account the soil resistivity and the water percentage as shown in Table I.

TABLE I. PROPERTIES OF THE SOIL SAMPLES

Soil Sample	Per weight water content (%)	Low impulse resistance R_o (Ω)	Soil resistivity ρ (Ωm)	ε_r
A	5	3113	950	12
B	10	2884	880	15

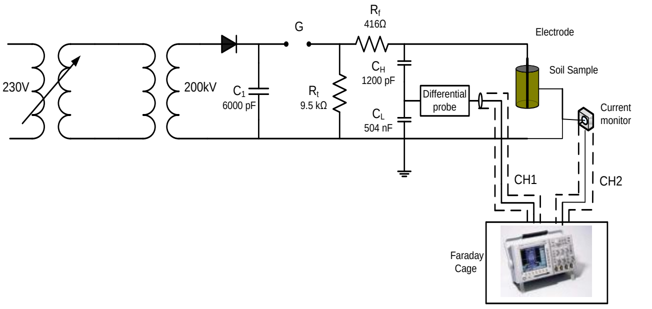

Figure 3. Experimental setup [3]

III. SIMULATION PROCEDURE AND RESULTS

The measurements, conducted under a 59kV charging voltage of the surge generator, where chosen as a basis for the simulations, because the acquired oscillogramms of the two samples differ, displaying nevertheless the soil ionization procedure, either directly (sample A: 2 current peaks) or through the experimental voltage - current characteristic (sample B: looped shape of the curve). Thus, comparison of the models under a common basis is enabled, not only for different soil properties but also for different types of surge response.

The grounding resistance models are evaluated using the ATP/EMTP software. According to the schematic diagram of Fig. 4, the surge generator is designed with the following components: AC generator 50Hz, 59kV RMS (corresponding output of the variac: 68.75V), C_1=6000pF, R_t=9.5kΩ, R_f=416Ω, C_H=1200pF, C_L=504nF. The proper charging of the generator is achieved with a switch SW1 (initial state: closed), that opens at Top_{SW1}, and a resistance R_d connected in series to an ideal diode D. The switch SW2 represents the spark gap of the impulse generator (initial state: open) that closes at Tcl_{SW2}.

For the simulation of the model proposed by Nor et al. the following parameters have been added to the circuit: The initiation of the ionization is implemented by the switch SW3 (initial state: open) that closes at Tcl_{SW3} = Tcl_{SW2}+Tion, where Tion is defined from the oscillogramms as the beginning of the ionization. The model parameters R_1 and R_2 are evaluated according to equations (1) and (2) from the impulse characteristics V_{Ipeak1}, V_{Ipeak2}, I_{peak1} and I_{peak2}. The inductance of the rod L_{rod}=0.191μH is calculated from equation (8) [7]:

$$L_{rod} = 2\ell \cdot \ln\left(\frac{4\ell}{d}\right) \cdot 10^{-7} H \qquad (8)$$

where: ℓ =19cm is the length of the rod

d =5mm is the diameter of the rod

The above procedure is applied to the oscillogramms of soil sample A, based on the recorded impulse characteristics (Figs. 5 and 6).

A further attempt is to adjust the Nor et al. circuit to the oscillogramms of soil sample B (Figs. 8 and 9), where the current waveform presents only one peak. According to this modelling approach, the implementation of the current peak in the circuit requires an equivalent total resistance:

$$R = \frac{V_{\mathrm{Im}ax}}{I_{\max}} \quad (13)$$

Ignoring the contribution of L to the magnitude of the current, it can be considered that during the ionization the above resistance is the parallel connection of the pre- and post-ionization resistances R_1 and R_2. Thus, an approximation of R_1 and R_2 is given by equation (14):

$$R \cong R_1 // R_2 \Rightarrow R_1 = R_2 = 2 \cdot \frac{V_{\mathrm{Im}ax}}{I_{\max}} \quad (14)$$

The Nor et al. simulation of soil sample B is approached in two ways regarding the initiation of the ionization (T_{clSW3}); the ionization branch is either exactly synchronized to the spark gap of the surge generator i.e. Tcl_{SW3} = Tcl_{SW2} (Case I) or added to the circuit with a small time delay i.e. Tcl_{SW3} = Tcl_{SW2}+Tion (Case II).

The basic component of the Kalat, Loboda et al. model [2] is a MODEL element, named "lobodasand", written in the MODELS language, which incorporates the algorithm for sandy soil conduction. This MODEL component uses as an input the rod voltage in order to calculate according to equations (3)…(6) the rod current and to produce consequently as an output the transient resistance. The transient response is implemented by a "controllable resistance" TACS element, connected to the output of the "lobodasand" MODEL [8]. The steady state resistance R_o is used as the initial value R(0), required by the TACS element.

The parameters of the "lobodasand" MODEL are defined in the following way; for an arbitrarily chosen value of the exponent α, the parameter A of the linear equation (3) is calculated:

$$\mathrm{A} = \frac{I_{\max}}{(V_{I_{\max}})^{a}} \quad (9)$$

where I_{max} and V_{Imax} are defined from the oscillogramms for the specific soil sample. The linear conductances of the model are defined according to equations (10) and (11):

$$g_{LDC} = \frac{I_{\max}}{V_{I_{\max}}} \quad (10)$$

$$g_{LAC} = \frac{1}{R_0} + g_{LDC} \quad (11)$$

The following relationship is adopted for the evaluation of the soil capacitance [4]:

$$C = \frac{2\pi\varepsilon \cdot \ell}{\ln\left(\frac{r_{out}}{r_{in}}\right)} F \quad (12)$$

where: ε is the soil permittivity

The oscillogramms of soil sample B allow direct application of the Kalat, Loboda et al. model (Figs. 13 and 14). On the contrary, the simulation of soil sample A with this model requires some initial assumptions, due to the presence of two peaks in the recorded current waveform. Therefore, two simulation scenarios have been implemented, by choosing a different V_{Imax} value (Figs. 11 and 12). In the first scenario the instantaneous voltage at the second current peak is attributed to the V_{Imax} value (Case I: V_{Imax}=V_{Ipeak2}), whereas in the second scenario V_{Imax} is synchronized to the first current peak (Case II: V_{Imax}=V_{Ipeak1}). In both simulation cases the maximum current is defined as the second current peak (I_{max}=I_{peak2}).

The values of the circuit parameters for both soil samples and for the various simulation cases are presented in Table II, for the Nor et al. model and in Table III, for the Kalat, Loboda et al. model.

TABLE II. CIRCUIT PARAMETERS FOR THE SIMULATIONS WITH THE NOR ET AL. MODEL

Soil Sample		Impulse Characteristics	Nor et al. Model					
			R_1 [Ω]	**R_2 [Ω]**	**L [mH]**	**C [pF]**	**T_{ion} [μs]**	**R_d [Ω]**
A		V_{Ipeak1}=49kV V_{Ipeak2}=32kV I_{peak1}=40A I_{peak2}=54A	1225	593	1.4	-	1.88	100
B	Case I (T_{ion}=0μs)	V_{Imax}=51.53kV I_{max}=37.4A	2756	2756	1.4	40.53	0	100
	Case II (T_{ion}=0.1μs)		2756	2756	0.02	40.53	0.1	100

TABLE III. CIRCUIT PARAMETERS FOR THE SIMULATIONS WITH THE KALAT, LOBODA ET AL. MODEL

Soil Sample		Impulse Characteristics	Kalat, Loboda et al. Model						
			α	**A[A/kV]**	**g_{LDC} [mS]**	**g_{LAC} [mS]**	**C [pF]**	**T [s]**	**R_d [Ω]**
A	Case I (V_{Imax}=V_{Ipeak2})	V_{Ipeak1}=49kV V_{Ipeak2}=32kV I_{peak1}=40A I_{peak2}=54A	3	1.648	1.69	2.01	32.42	0.001	140k
	Case II (V_{Imax}=V_{Ipeak1})		2.5	3.213	1.10	1.42	32.42	4.5E-6	100
B		V_{Imax}=51.53kV I_{max}=37.4A	3	0.273	0.73	1.07	40.53	0.008	100

The equivalent circuit models that have been implemented with the ATP-Draw programme of the ATP/EMTP software are shown in Figs. 4, 7 and 10. The recorded and simulated waveforms of the rod voltage (V_{ROD}) and of the injected current (I) are displayed in Figs. 5, 6, 8, 9 and 11…14.

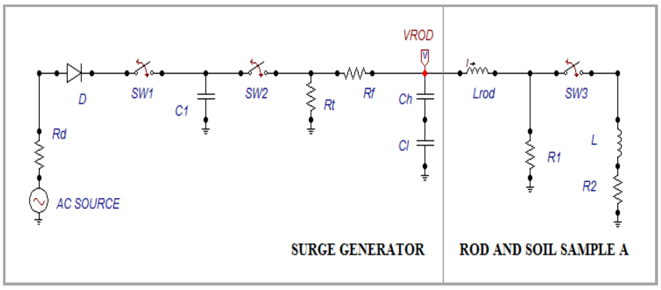

Figure 4. The circuit for soil sample A (according to the model by Nor et al.) designed with the ATP-Draw programme

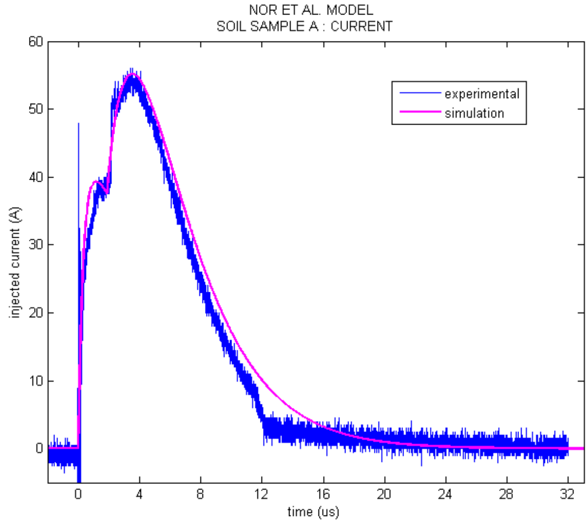

Figure 5. Computed and recorded traces of the injected current (I) for a 59kV charging voltage for soil sample A

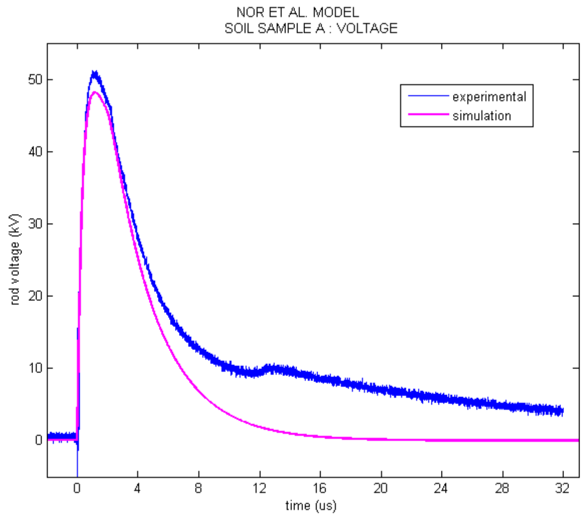

Figure 6. Computed and recorded traces of the rod voltage (V_{ROD}) for a 59kV charging voltage for soil sample A

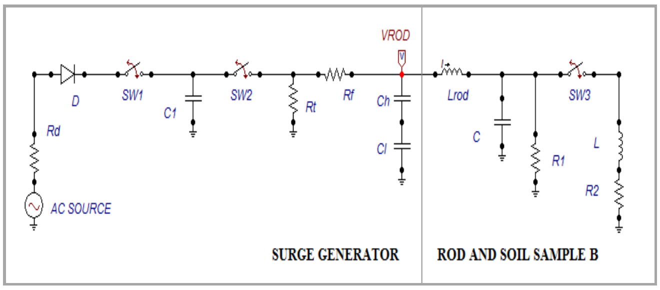

Figure 7. The circuit for soil sample B (according to the model by Nor et al.) designed with the ATP-Draw programme

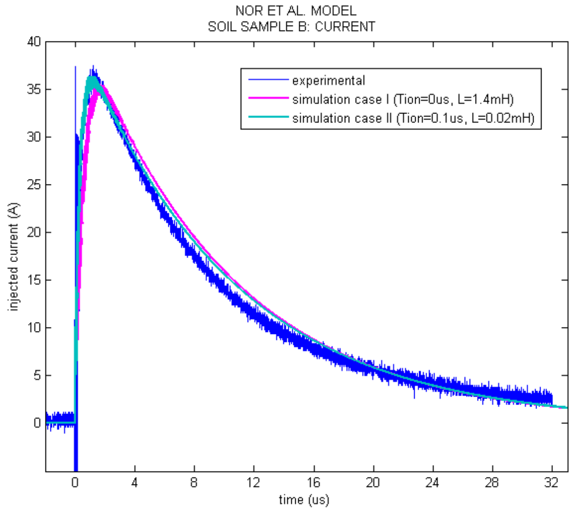

Figure 8. Computed and recorded traces of the injected current (I) for a 59kV charging voltage for soil sample B

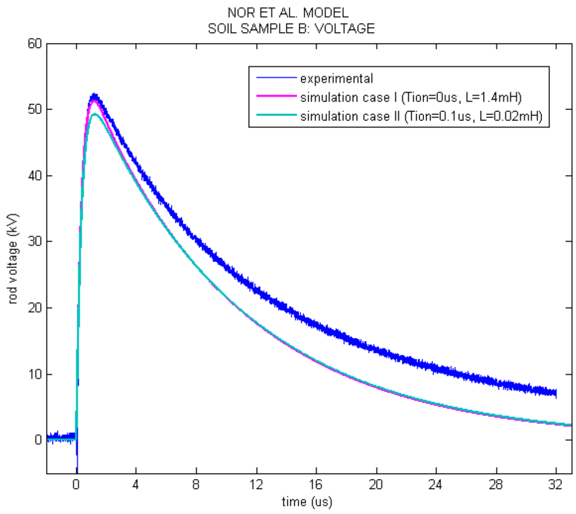

Figure 9. Computed and recorded traces of the rod voltage (V_{ROD}) for a 59kV charging voltage for soil sample B

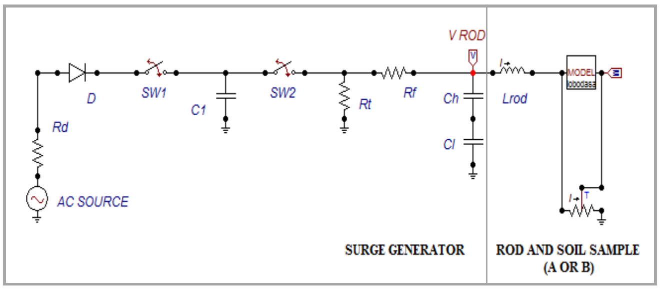

Figure 10. The circuit for soil samples A and B (according to the model by Kalat, Loboda et al.) designed with the ATP-Draw programme

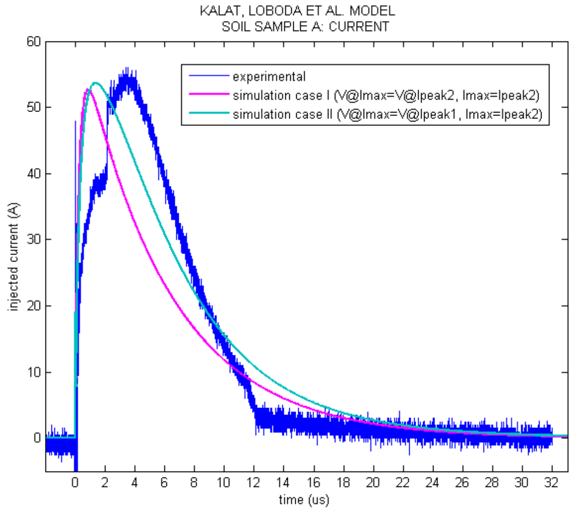

Figure 11. Computed and recorded traces of the injected current (I) for a 59kV charging voltage for soil sample A

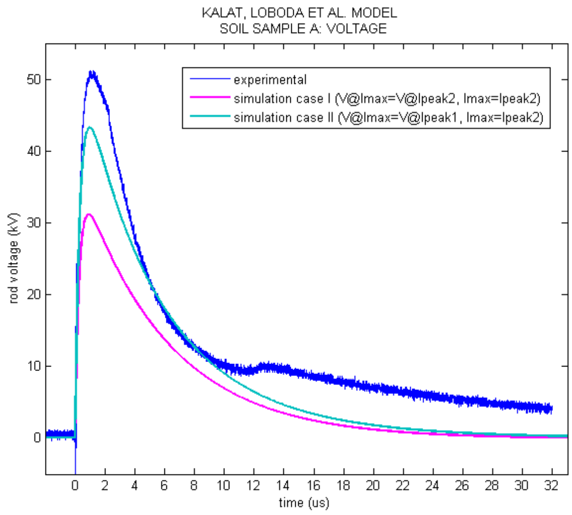

Figure 12. Computed and recorded traces of the rod voltage (V_{ROD}) for a 59kV charging voltage for soil sample A

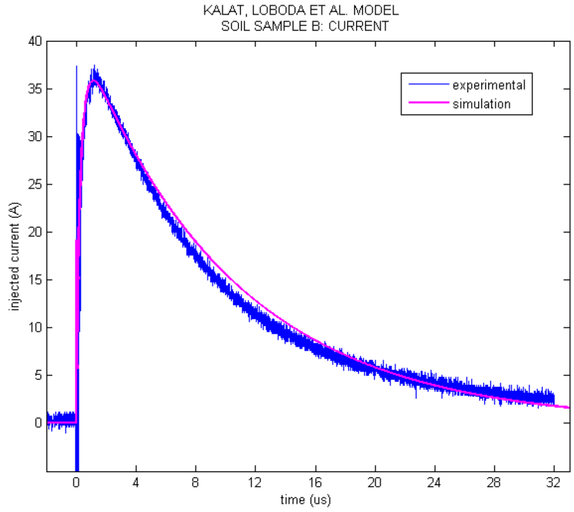

Figure 13. Computed and recorded traces of the injected current (I) for a 59kV charging voltage for soil sample B

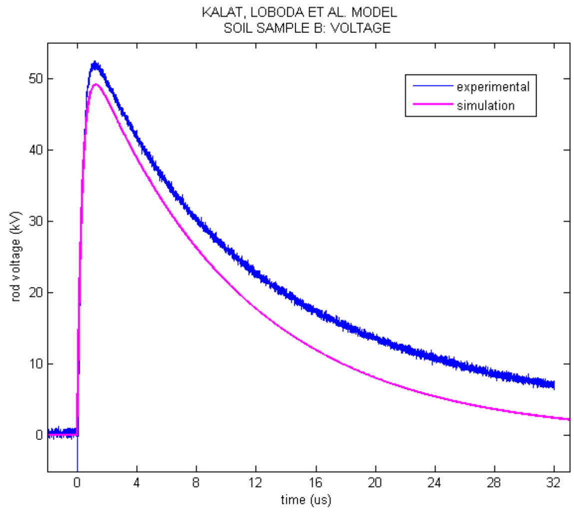

Figure 14. Computed and recorded traces of the rod voltage (V_{ROD}) for a 59kV charging voltage for soil sample B

IV. DISCUSSION AND CONCLUSIONS

In the present analysis, two circuit models have been implemented for the simulation of transient grounding response under soil ionization. Conclusions regarding their theoretical background and the advantages or disadvantages of their practical application emerge.

An initial comparison of the equivalent circuits shows that simulations with the circuit proposed by Nor et al. are very similar to the current oscillogramms - and to a smaller degree to the voltage oscillogramms - exactly because the circuit parameters are calculated according to the characteristics of each oscillogramm.

The components of this model have constant values, since the time variation of the grounding resistance is implemented with switches that add the ionization branch to the circuit. A disadvantage of the method is the fact that the closing and opening time of the ionization switch (T_{clSW3}, T_{opSW3}), that represent the beginning and the end of the ionization phase respectively, are not specified by the model, but are selected arbitrarily in order to approach the oscillogramms. The appearance of the second current peak is an indication for the selection of the T_{cl}.

Despite having included an R_{rod} component in their model, Nor et al. have omitted it from the implementation of their equivalent circuit in [1], a choice which has been adopted in the present simulations. On the contrary, the inductance of the rod is taken into account throughout the whole phenomenon as the component L_{rod} is placed before the ionization switch. The value of the inductance *L* is chosen with trial and error, in order to increase the proximity of the simulation results to the measurements.

Nor et al. consider the capacitive behaviour of the soil negligible in [1] - although it is known that in some soil types it has a significant contribution to the grounding response and although the presence of spikes in the waveforms verifies the effects of soil capacitance. Specifically, only after the addition of the soil capacitance C was the simulation of soil sample B with the present model satisfying.

The parameters of the equivalent circuit proposed by Kalat, Loboda et al. are defined from experimental voltage-current curves for this specific type of soil. A disadvantage of the model is the fact that the equivalent circuit varies according to the type of soil [2]. Therefore, a preliminary analysis of the soil sample is required in order to determine its components and decide which circuit should be used.

A time variable approach dependent on the instantaneous value of the current is adopted for the simulation of the ionization procedure, implemented as a branch with non-linear current-voltage characteristic. The values of the time constant T and the exponential factor α are those that provide simulation results closer to the measurements.

Unlike the previous model by Nor et al., here, the pre-ionization stage is formed based on the measurements for low values of current. It must be pointed out, that, while the model proposes a dynamic evaluation of soil capacitance C, the use of formula (6) for the calculation of C in the present analysis has yielded satisfactory results.

The inductive behaviour of the grounding system is totally ignored by the Kalat, Loboda et al. model. Nevertheless, the L_{rod} element was necessary for the simulations for both soil samples, because otherwise the resulting current spike in the wavefront was very high.

The suitability and effectiveness of each circuit model depends on the soil type and the shape of the recorded oscillogramms, as the comparison between the various experimental and their corresponding simulation results shows.

In the case of soil sample A, the simulation with the circuit by Nor et al. displays the greatest proximity to the oscillogramms. The performance of this model, concerning the peak values of the current, is very satisfying. The simulated voltage waveform displays a small deviation from the maximum value and from the tail of the experimental trace. Thus, the need for simulation of the de-ionization phase arises.

The model by Kalat, Loboda et al. is not suitable for soil sample A, as it cannot simulate the presence of two current peaks and the time delay between them. However, it reaches adequately both the maximum value of the current and the voltage value chosen as V_{Imax}. Simulation case II ($V_{Imax}=V_{Ipeak1}$, $I_{max}=I_{peak2}$) approaches better the voltage oscillogramm even in the wavetail and produces a current graph that resembles the part of the corresponding experimental after the beginning of the ionization.

In the case of soil sample B, the model by Kalat, Loboda et al. produces very satisfying simulation results, even in the current wavetail. Moreover, it reproduces the current spike in the wavefront

The proposed simplification of the Nor et al. model for a current waveform with only one peak approaches the oscillogramms of soil sample B with great accuracy. Simulation cases I and II show that the timing of the ionization initiation causes a small tradeoff of accuracy between voltage and current. Introduction of a very small ionization time (case II) leads to an exact current waveform and a small deviation in the V_{peak} value. On the contrary, the omission of the ionization time (case I) improves the accuracy of the voltage waveform, but, as expected, shifts slightly the current peak.

The ability of simulating the response of both soil types with the Nor et al. circuit leads us to the conclusion that this is a more general model, which can be applied and properly adjusted to all types of impulse responses and soil samples. For a further improvement of this model, especially regarding the voltage wavetail, the de-ionization phase needs to be simulated.

REFERENCES

[1] N. M. Nor, A. Haddad, H. Griffiths, "Characterization of Ionization Phenomena in Soils under Fast Impulses", IEEE Transactions on Power Delivery, Vol. 21, No. 1, January 2006, pp. 353-361.

[2] W. Kalat, M. Loboda, Z. Pochanke, "Implementation of the dynamic model of surge soil conduction for transient behaviour of grounding electrodes simulations using ATP version of EMTP", 22nd International Conference on Lightning Protection, Budapest 1994.

[3] F.E. Asimakopoulou, I.F. Gonos, I.A. Stathopulos, "I-V Curves for the Determination of the Ionization Voltage in Soil Samples", Proceedings of the 17th International Symposium on High-Voltage Engineering (ISH 2011), Hannover, Germany, August 22-26, 2011 (paper B-045).

[4] J.L.C. Lima "Avaliacao experimental sobre o efeito de ionizacao do solo devido a injecao de correntes impulsivas," Master Thesis, August 2008.

[5] I.F. Gonos, I.A. Stathopulos, "Soil Ionization under Lightning Impulse Voltages", IEE Proceedings Science, Measurement and Technology, Vol. 151, No. 5, pp. 343-346, Sept. 2004.

[6] F.E. Asimakopoulou, I.F. Gonos, I.A. Stathopulos., "Experimental Investigation on Soil Ionization", Proceedings of the 16th International Symposium on High-Voltage Engineering (ISH 2009), Cape Town, South Africa, August 24-28, 2009 (paper G9-328).

[7] M.Khalifa, "High Voltage Engineering", Marcel Decker Inc., New York, 1990.

[8] Alternative Transients Programme, Rulebook, 2001.