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Lightning Overvoltages in a Single-Wire Earth Return Line at a Rural Branch in the State of Acre.

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***Abstract*—This study aims to analyze overvoltages produced by direct lightning strikes on a medium voltage SWER line, including those transferred to transformers low-side terminals. The power distribution system modeled on ATPDraw is an excerpt from a real rural network, located at the State of Acre. The transient behavior of the voltages at different points of the distribution line is analyzed considering current magnitude of lightning, discharge impact point, soil resistivity influence and surge-transferred to transformer secondary.**

Keywords—Overvoltages; Lightning; Transients; SWER; ATPDraw

I. Introduction

Overvoltages caused by direct or indirect incidence of lightning strikes on power transmission/distribution overhead lines are one of the major causes of power system outages [1]. Due to their broad extension and lower value of withstand voltage insulation level, power distribution networks are most affected by disturbances caused as a result of lightning discharge occurrence, in particular lines with a 15 kV rated voltage or less [2].

A special type of distribution lines is even more susceptible to the aforementioned phenomena. Single-wire earth return (SWER) lines are an efficient and cost-effective alternative for the energy supply of low-demand consumers located in remote regions far from traditional three-phase electrical power network [3]. These power distribution networks are widely used in developing countries or those with large rural areas such as Australia, Canada, South Africa and Brazil [4].

SWER line consists of a single-phase medium voltage network, derived from the conventional three-phase power distribution system. This can be done either directly or using an isolation transformer. The main feature of this network is the use of earth as return path, avoiding installation of appropriate wire to perform this function. Among the drawbacks, one can mention the voltage regulation, ohmic losses and unbalance effect on the origin three-phase feeder [5].

Regarding the performance of SWER lines against lightning, according to [6], these lines are sensitive to lightning-produced overvoltages once have no guard wire and few surge arresters located at transformers primaries. The soil effect on the distribution lines must also be taken into account, since [7] mentions the variation of line parameters as a function of soil resistivity and climate seasons in the Amazon region.

This work analyzes a set of overvoltages produced by direct lightning strikes on a medium voltage SWER line, including those transferred to transformers low-side terminals. In order to do it, responses obtained will be related to discharge point of incidence, current magnitude and soil resistivity. The article is organized as follows: Section 2 presents the base case description and its particularities; Section 3 shows each system component modeled on ATPDraw (Alternative Transients Program); Section 4 exposes and discusses simulation results. Conclusions are presented in section 5.

II. Rural Branch Description

The power distribution system studied is an excerpt from a real rural network, named Romão's Branch, located approximately 8 miles away from Rio Branco city center, State of Acre. Figure 1 shows a map of the rural branch.

The single-phase power grid has a total length of 3.15 kilometers, composed of one 4 AWG ACSR conductor. The total length is subdivided into a 2.64 kilometers length backbone and small branches of different lengths, varying from 140 to 220 meters.

Thirty-seven I-section 10m/150daN utility concrete poles support the power grid. Each pole is grounded by a 2.4 meters copper weld rod and has a 15kV pin-type insulator with critical flashover overvoltage (CFO) of 110 kV at its top.

There are five single-phase transformers in the power system, performing the conversion from medium to low voltage, 7.96kV and 220-127V, respectively. The system has four 15kVA transformers and one 30kVA transformer. For the sake of convenience, the low voltage side of all transformers is assumed to have no-load. This assumption amplifies the response of surge-transferred overvoltages at transformers secondaries.

Fig. 1. Location map of Romão's rural branch [8].

A diagram containing the distances between poles, and the positioning of the transformers is shown in Figure 2. Single-phase distribution transformers T1, T2, T3 and T4 are rated at 15kVA, and T5 has a rating of 30kVA.

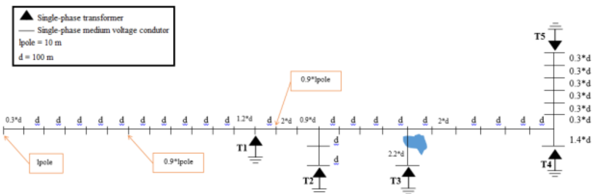

Fig. 2. Romão's branch distribution line diagram.

III. SYSTEM MODELLING

The modeling of each component of the SWER line is presented in this section. The ATPDraw software was used to represent system elements, being appropriate to simulate electrical transients.

A. *Network Equivalent*

The network equivalent is modeled in ATPDraw using Thevenin theorem, consisting in a 7.96kV AC single-phase voltage source in series with an RLC branch. The equivalent parameters were obtained from the local utility. At derivation point, the matched line has the following values: positive sequence resistance is 5.52Ω and positive sequence reactance is 7.95Ω.

B. *Pole Model*

The poles were modeled following the method described in [9] and represented by a surge impedance, which is calculated from the geometric dimensions of the pole. Using (1), we can obtain the pole resistance value:

$$R_{pole} = 60 \,.\, \ln \left(2(\sqrt{2}).H_c \,/\, r_c \right) - 60 \qquad (1)$$

Where:

R_{pole} = Pole resistance in Ω;

H_c = Average pole height in meters;

r_c = Cross-section radius at pole bottom in meters.

Applying rc = 0.1335 meters, extracted from utility pole dimensions datasheet [9], and Hc = 8.4 meters, obtained from a 10-meter high pole by subtracting the depth of burial, we found a resistance value of 250.89 Ω.

Figure 3 shows an illustrative diagram of usual SWER line utility poles and its model implemented on ATPDraw.

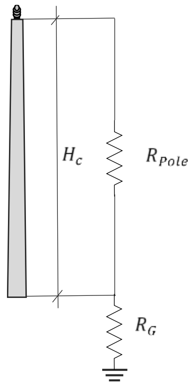

Fig. 3. Pole model for SWER distribution network.

Each pole is grounded through a copperweld ground rod. In this study, we will assume rod resistance as R_G = 10Ω [10].

C. *Insulator Model*

As described previously, the single-phase line conductor is attached to pole top through a 15kV pin-type insulator. This type of isolator is fixed directly to the pole, without crosses or any other additional structure.

Figure 4 presents insulator model implemented on ATPDraw. It is composed by a capacitor in parallel with a voltage-controlled switch, representing Critical flashover overvoltage (CFO). According to [10], a 15kV insulator is typically modeled by a 60 pF capacitance. Critical flashover overvoltage is assumed as 110 kV.

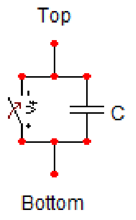

Fig. 4. 15kV pin-type insulator model in ATP-Draw.

D. Grounding Resistance

Figure 5 presents the grounding resistance model implemented on ATPDraw. Based on HEM (Hybrid Electromagnetic Model) [11], this model is composed by an inductor, that represents the wire connection between the transformer neutral and the grounding rod, and a parallel configuration formed by a resistance and a capacitor, representing frequency and other non-linear effects. Applying equations (2) and (3), we can achieve adequate values for different types of soil.

$$R = 0.119\rho_s \tag{2}$$

$$C = 0.0743\varepsilon_r \tag{3}$$

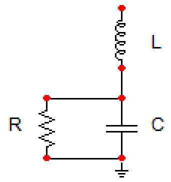

Fig. 5. Grounding resistance model in ATPDraw.

To properly represent the clayey soil in the study region, the Brazilian National Standards Organization (ABNT) 7117 recommend values of ρ_s = 500 Ω.m and ε_r = 20 [12].

E. Transmission Line Model

Spans between poles were modeled using the LCC (Line Constants) component of ATPDraw. JMarti line model [13] was used to represent the transmission line in the simulation. As mentioned earlier, the single-phase line is composed by one 4AWG ACSR conductor. The technical data sheet of the cable, including the resistance and the internal and external diameters, can be seen in [14]. The Figure 6 shows the transmission line model in ATP.

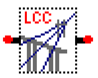

Fig. 6. Transmission line model in ATP.

The height of the transmission line in relation to the ground is adopted as 8.4 meters at the pole locations and 8.2 at the mid-spans.

F. Transformer Model

In order to represent high frequency surges, such as those caused by the incidence of an atmospheric discharge, the model of the transformer used in this work is presented in Figure 7.

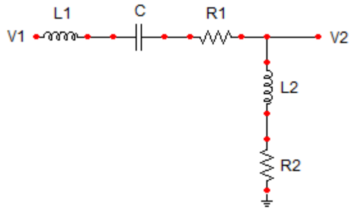

Fig. 7. Transformer Model (RLC) in ATP-Draw.

This model is described in [9], being suitable only for operation with the secondary of transformer on no-load condition. In this circuit, lumped parameters R1, R2, L1 and L2 represent the copper losses and dispersive flux at the primary and secondary sides, respectively. The capacitance C represents the parasitic capacitance of the transformer, which takes in account high frequency phenomena, due to proximity effect of primary and secondary windings.

Table 1 shows the values used in the model [8].

TABLE I. PARAMETERS FOR EQUIVALENT CIRCUIT

Power (kVA)	***R_1 (Ω)***	***R_2 (Ω)***	***L_1 (μH)***	***L_2 (μH)***	***C (pF)***
15	70	90	246	54	320
30	83	42	157	29	344

G. Lightning Discharge Model

The circuit made in ATPDraw to represent the atmospheric discharge is shown in Figure 8. It is composed of two components, a Heidler type current source and a resistor. The current source represents the waveform of the discharge current and its magnitude, which in the simulations carried out have values of 1.2μsx50μs and 5kA and 10kA, respectively.

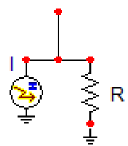

Fig. 8. Lightning Discharge Model in ATP-Draw

With a view to represent the ionization channel, a resistance of 400 Ω in parallel with the current source was incorporated into the model.

H. Surge Arrester Model

These devices have the function of protecting the networks which are installed against the surges. Zinc Oxide (ZnO) is used in the network under analysis. The CIGRE model was used for modeling. The Figure 9 shows the surge arrester model. [10]

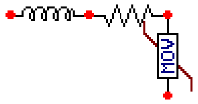

Fig. 9. Lightning rod Model in ATP-Draw

I. System Model

The Figure 10 shows the system modeling in ATP-Draw.

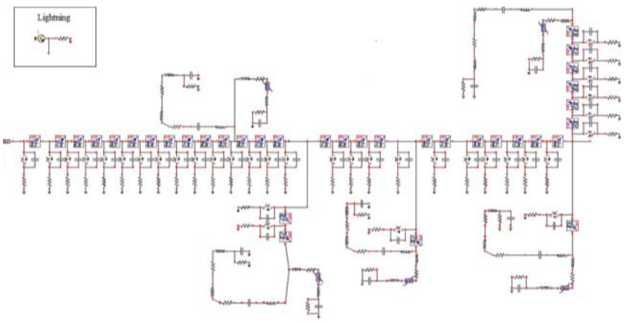

Fig. 10. Modelling of the distribution line SWER in ATP-Draw.

IV. RESULTS AND DISCUSSION

The graphs obtained from performed simulations are shown in this section. The transient behavior of the voltages at different points of the distribution line is analyzed considering current magnitude of lightning, discharge impact point, soil resistivity influence and surge-transferred to transformer secondary.

A. Voltages at the medium-voltage line, considering ground as perfect condutor surface and varying lightning current magnitude.

Figures 11 and 12 show voltages behavior at the beginning, middle and end of power distribution line, due to the occurrence of a lightning discharge over T1 transformer primary. In both simulations, soil was modeled as a perfect conductive surface, i.e., approximately zero resistivity.

In the simulation performed in Figure 11, the atmospheric discharge has a current of 5kA. We can note that the overvoltages have higher values at the dropping point of the discharge and a strong attenuation at line ends, due to the perfect nature of soil resistivity.

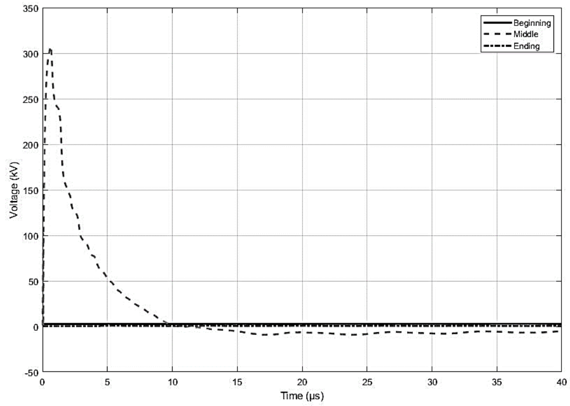

Fig. 11. Voltage at different points of distribution line, considering 5kA lightning strike at T1 and perfect ground.

Similarly, Figure 12 shows resulting voltages of a 10kA lightning discharge applied at T1 primary terminals. As in previous case, soil has been modeled as perfect ground.

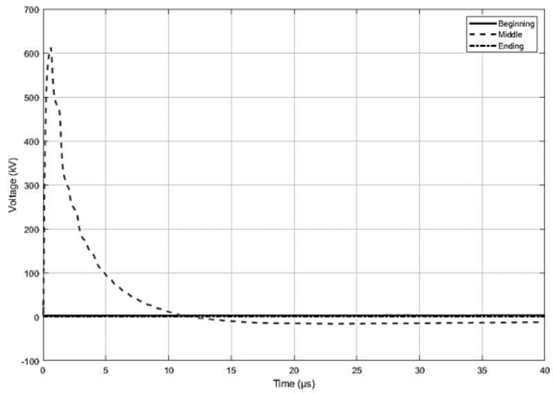

Fig. 12. Voltage at different points of distribution line, considering 10kA lightning strike at T1 and perfect ground.

B. Voltages at the medium-voltage line, considering ground as perfect condutor surface and varying lightning strike position.

In this simulation, the voltages waveforms in three different line positions are evaluated when a 5kA and 10 kA lightning discharges are applied at backbone end (between T4 and T5 transformers) of power distribution grid. Results are shown in Figures 13 and 14.

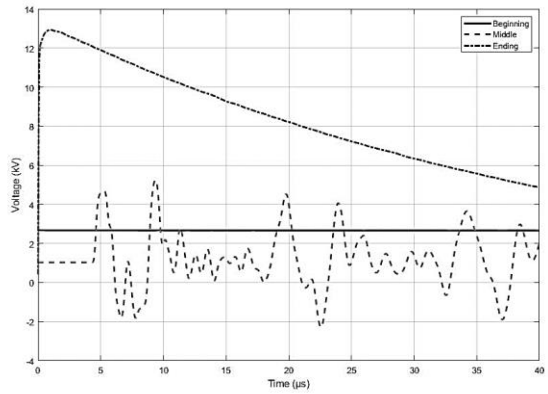

Fig. 13. Voltage at different points of distribution line, considering 5kA lightning strike at backbone end and perfect ground.

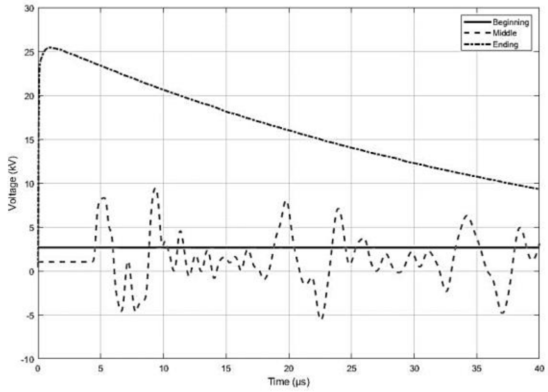

Fig. 14. Voltage at different points of distribution line, considering 10kA lightning strike at backbone end and perfect ground.

Comparing previous results with those exhibited in Figure 11 and 12, it may be noted that as close to the point of lightning strike, higher voltages values are experienced.

C. Voltages at the medium-voltage line, considering real soil resistivity and varying lightning current magnitude.

Figures 15 and 16 present the same simulation as performed in Figures 11 and 12, differentiated by adoption of a realistic value for soil resistance.

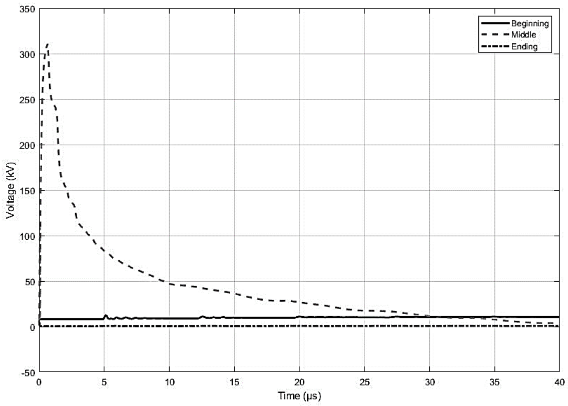

Fig. 15. Voltage at different points of distribution line, considering 5kA lightning strike at T1 and real soil resistivity.

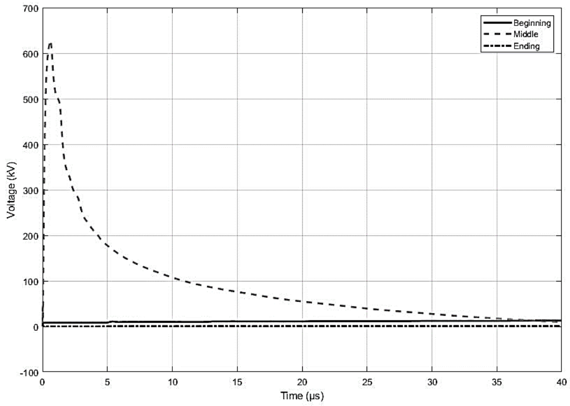

Fig. 16. Voltage at different points of distribution line, considering 10kA lightning strike at T1 and real soil resistivity.

The choice of a realistic soil resistivity resulted in a less attenuated voltage waveform than for the ideal case.

D. Overvoltages transferred to the low-voltage side of transformers

In this section, voltages transferred to the low-voltage side of transformers were analyzed. Figures 17 and 18 present the obtained results.

As expected, transformer T1 shows a more consisting overvoltages due to its proximity to lightning discharge.

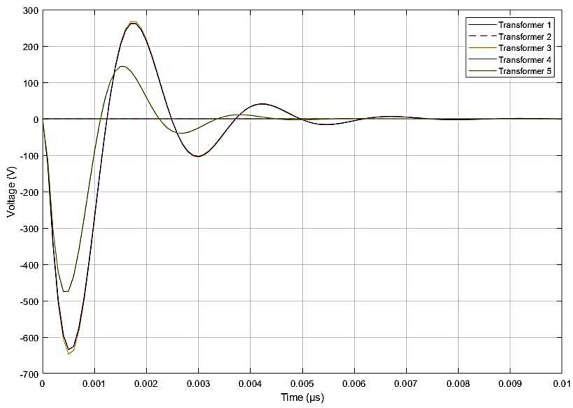

Fig. 17. Voltages at low-voltage side of transformers, considering 5kA lightning strike at T1 and real soil resistivity.

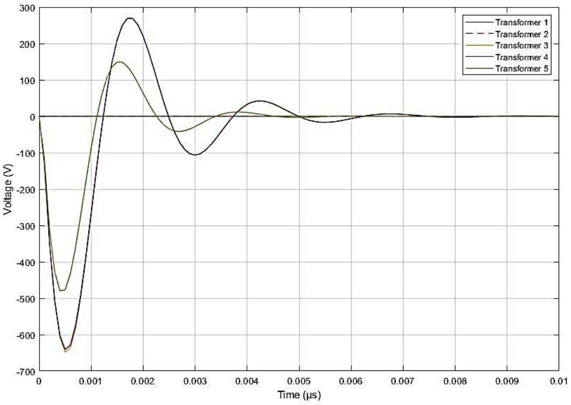

Fig. 18. Voltages at low-voltage side of transformers, considering 10kA lightning strike at T1 and real soil resistivity.

V. CONCLUSIONS

In this work it was constructed a model in the ATP-Draw of a SWER network located in the rural zone of the Rio Branco city in the State of Acre. Analyzes were performed regarding lightning surges along the line. It was sought to verify the impacts on the MV side, as well as on the LV side, the latter with potential to cause damages to the consumer units, as well as the influence of soil resistivity.

Among the results obtained and due to the construction characteristic of the network, it was verified its sensitivity to atmospheric impulses since the surge suppression devices in the network under study are located only in the point where there are transformers.

However, the importance of such protective equipment is emphasized. It was verified that depending on the point of the network in which the impulse occurs, these equipments attenuate the impact of over voltage considering it distance from the point of impact.

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