International Journal of Applied Engineering Research ISSN 0973-4562 Volume 18, Number 2 (2023) pp. 103-109

Electromagnetic Transient Determination in Sub-transmission Lines. A Case Study of the Azogues Electric Company

J. Morales and E. Orduña
Professor, Instituto de Energía Eléctrica, Universidad Nacional de San Juan, San Juan, Argentina
Grupo de Investigación de Energías GIE, Universidad Politécnica Salesiana

D. Quezada
Empresa Eléctrica de Azogues, Azogues, Ecuador

F. Quizhpi
Carrera de Ingeniería Eléctrica, Universidad Politécnica Salesiana, Cuenca, Ecuador
Grupo de Investigación de Energías, GIE

J. P. Cevallos
Constructora Eléctrica CEVARM CIA. LTDA, Loja, Ecuador

Abstract
Azogues Electric Company is a public utility company that distributes and commercializes electricity. Part of its infrastructure corresponds to a 69 kV sub-transmission line, which for unknown reasons, presented an electromagnetic transient that affected both the potential transformer of the Azogues 1 electrical substation and the power supply. In this context, to analyze and verify which internal or external phenomenon produced this drawback, single-phase short-circuits, switching operations, and direct, indirect, and induced lightning strokes have been simulated and analyzed along the sub-transmission line using the Alternative Transients Program software. Results showed that an induced lightning stroke of approximately 3 kA, which hits the ground at a distance of 50 meters from the sub-transmission line and a distance of 20 km from the substation can produce an oscillogram similar to the one recorded at the Azogues 1 electrical substation facilities.

Keywords: Electromagnetic transient, sub-transmission, lightning strokes.

I. Introduction

Azogues Electric Company (AEC) is a public utility for the distribution and commercialization of electrical energy located in the province of Cañar-Ecuador, which has a concession area of 1187 km^2. AEC supplies electricity to the Azogues, Déleg, and Biblian cantons as well as the Unión Cementera Nacional – Guapan Factory. In addition, the Azogues 1 Electrical Substation (E/SA1) is part of the jurisdiction of the AEC, which consists of a 69 kV sub-transmission line (STL). That STL starts from the Cuenca Electrical Substation corresponding to the Interconnected National System (INS), and with a route of 26.828 km, it reaches the electrical substation of 15-20 MVA corresponding to the Guapán cement factory. At a distance of 24.802 km is diverted by SF6 gas-insulated equipment to the E/SA1 (10-12.5 MVA, 69/22 kV). The current primary distribution system consists of four feeders denoted 121, 122, 123, and 124, respectively (see Section III) [1].

Besides that, as part of the implementation of the Supervisory Control and Data Acquisition (SCADA) project acquired for the Electric Distribution Companies in Ecuador, the point-to-point testing stage is carried out. These tests consist of verifying the correct communication of the different equipment such as Intelligent Electronic Devices (IEDs), Remote Terminal Unit (RTU), field teams, among others. The development of the tests was carried out normally, carrying out the tests of the ABB type REF-630 relays for the distribution feeders 122, 123, 124, and 125 (reserve), respectively.

Before carrying out the tests of the 121 feeder, erroneous values were observed in the voltage measurements both in the SCADA and in the IEDs. In this context, the staff of the AEC proceeded to verify the wiring from the IED to the Potential Transformer (PT) module, where it was possible to see that two fuses installed at the Low Voltage (LV) side corresponding to the phases A and B were blown. After suspending the tests, it was heard a noise in the PT, disconnecting the 22kV bar of the E/SA1. In this context, the PT corresponding to the E/SA1 was considerably affected as it is shown in Fig. 1. Similar to the previous case, other events occurred at the PT location as shown in Fig. 2, where the oscillogram of the possible electromagnetic transient produced along the STL was recorded.

Figure 1: TP connection socket [1]

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 18, Number 2 (2023) pp. 103-109

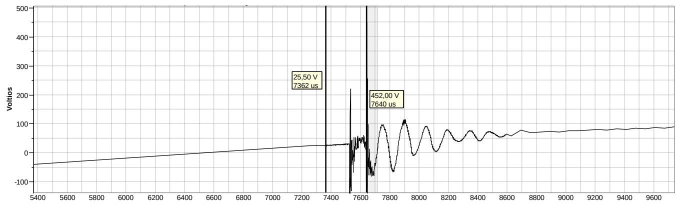

Figure 2: Oscillogram of the event recorded at the PT location [1]

Based on the aforementioned, and to carry out preventive actions both for the safety of the TP, the E/SA1, and the STL, it is necessary to determine and analyze what phenomenon, whether internal or external, could have caused said electromagnetic transient. Therefore, in this paper, several case studies corresponding to single-phase short-circuits, switching operations and direct, indirect, and induced lightning strokes have been analyzed along the STL denoted in this paper as E/S Cuenca - E/SA1.

II. Theoretical Bases

Different electromagnetic transients may be present on EPSs, which can produce different overvoltages [2-3]. These phenomena can be classified as follows:

A. Overvoltage Classification

Based on the IEC 60071-1 standard, surges can be classified according to their shape, frequency, and front and tail of the surge. Overvoltages can be both internal and external. As regards internal overvoltages, these can be caused by changes in the operating conditions of the EPS.

Based on IEEE standard 100-2000, temporary overvoltage is defined as an oscillatory phase-ground or phase-phase overvoltage that occurs at a given location for a relatively long duration (seconds or even minutes) and that is undamped or weakly muffled. This type of transient is usually caused by ground short circuits, switching operations, unexpected disconnections, or non-linearities such as resonance effect, and harmonics, among others.

The magnitude of temporary overvoltages is characteristically low compared to other types of overvoltages. The magnitude is usually only a few percent of 50% above the normal operating voltage except for some cases such as ferroresonance which can be as high as 300-400% of the normal operating voltage.

As regards the slow front overvoltages, when closing or opening a Power Switch (PS), connecting or disconnecting a compensation bank (capacitive or inductive), at the time of reconnection caused by a fault, among others, slow front overvoltages can occur. In addition, the normalized waveforms for these surges can be compared with a shock wave of 250/2 500 μs where the duration of the front time will be between 250 ± 50 μs and the tail time of 2 500 ± 1 500 μs, respectively.

Finally, fast front overvoltages originate from LSs. This may be due to direct LSs (lightning hits on the phases), indirect LSs (lightning hits on transmission towers), and induced LSs (lightning hits on the ground).

III. ELECTRICAL POWER SYSTEM SIMULATED

The EPS shown in Fig. 3 is simulated by using the Alternative Transients Program (ATP) software [4], widely used in the simulation of electromagnetic transients. ATP allows both the use of previously available models and the generation of new models with the use of simulation tools and languages available such as TACS and/or MODELS.

For the analysis of the different overvoltages, the SEP is formed by the equivalent source of 60Hz corresponding to the E/S Cuenca, two transformers, and a sub-transmission line, which in turn make up a radial system. Regarding the different elements simulated in this work, they are modeled by using international references [5-8]:

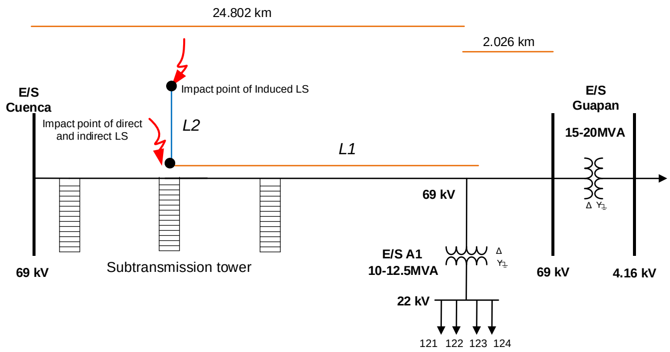

Figure 3: Single line diagram of the AEC Subtransmission system

A. Equivalent source

The system is composed of a 69 kV equivalent source, which is simulated in the ATP using the AC3PH model.

B. Transformers

Regarding the model used in the ATP, the BCTRAN model is used. For the simulation of this type of transformer, an equivalent non-linear model of the core must be connected externally from the information collected in the BCTRAN routine in the form of a saturation curve as is shown in Fig. 4.

C. Sub-transmission lines

The line characteristics of both phase and guard wire were implemented in the ATP using the Jmarti line model [6], which allows for defining the arrangement of the phase and guard conductors, the number of phases, the heights, the distances, the resistance, the diameter of the conductors, the length of the line, among other characteristics.

D. Sub-transmission towers

One of the models widely used and accepted worldwide is the conical one that provides a constant impedance for the Sub-transmission tower. The impulse impedance for vertical discharges is given by the following equation:

$$Z_t = 60 \ln(\sqrt{2}\frac{\sqrt{r^2+h^2}}{r}) \quad (1)$$

Where:
h is the height of the tower
r the radius at the base of the tower

E. Footing Tower Resistance

In the analysis of electromagnetic transients, the Footing Tower Resistance (FTR) value influences the peak value of the overvoltage that can appear on the tower (in the specific case of the value of overvoltage on the insulator string). It is because the reflection from the base of the tower can reach the top of the tower much faster than reflections from adjacent towers.

The final resistance value, considering this ionization, is represented as follows:

$$R_i = \frac{R_0}{\sqrt{1+\frac{I_R}{I_g}}} \quad (2)$$

Where:

R_o represents the resistance at the foot of the tower measured at low current and low frequency (Ω).

R_i represents the apparent grounding resistance at the moment of discharge (Ω).

I_g represents the limiting current to initiate a sufficient ionization of the ground (A).

I_R =represents the atmospheric discharge current through the tower foot resistance (kA).

The non-linearity characteristics of the FTR were implemented in the ATP using the line resistance model $R_{(i)}$ type 99, which allows defining of different resistance values depending on the current value.

F. Insulator string

Because ATP does not have an element that considers the characteristic equation of the insulators, a USER MODEL that considers said equation was developed using the MODELS programming language. A more detailed description of those user models can be reviewed in [7].

G. Surge arrester

The most accepted and used model for simulations corresponds to the CIGRE model. For its implementation in the ATP, the MOV model type 92 (current-dependent exponential model).

IV. Study cases

To carry out an adequate analysis of overvoltages to which the 22 kV side of the E/SA1 can be exposed, it is necessary to adequately consider the factors that influence the magnitudes and waveforms of said overvoltages. In this context, the next case studies are carried out:

A. Case studies corresponding to single-phase short-circuits

Different single-phase short-circuits are simulated along the 69 kV STL, considering a variation of the parameters as is presented in Table 1. Based on Table 1, extensive case studies are performed for different combinations of Fault Resistance (FR), faulted phase, and Fault Distance (FD).

Table 1: Parameters for single-phase fault simulations

Fault Resistance (Ω)	Failed phase	Fault Distance (km)
20-80-100	R–S–T	1-5-10-15-20

For example, a case study corresponding to a single-phase short-circuit (FR=20 Ω, failed phase=R, FD=5km from the bar of the E/S Cuenca) in the 22 kV bus of the E/SA1 is shown in Fig. 4. By considering the parameters and variables of Table 1, several case studies are also shown from Fig. 5 to Fig. 7, respectively.

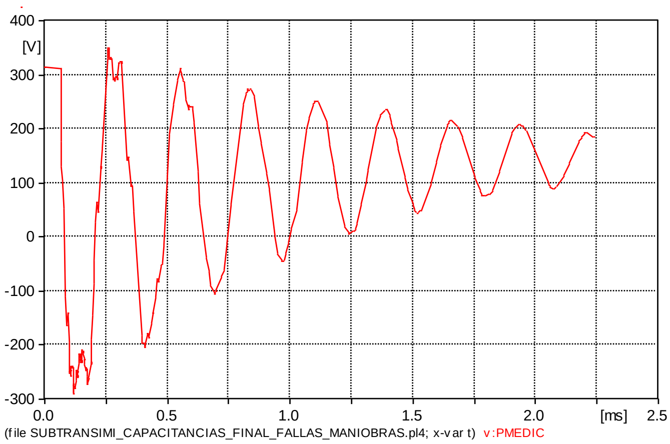

Figure 4: Single-phase fault with FR=20 Ω, Failed phase=R, FD=5 km.

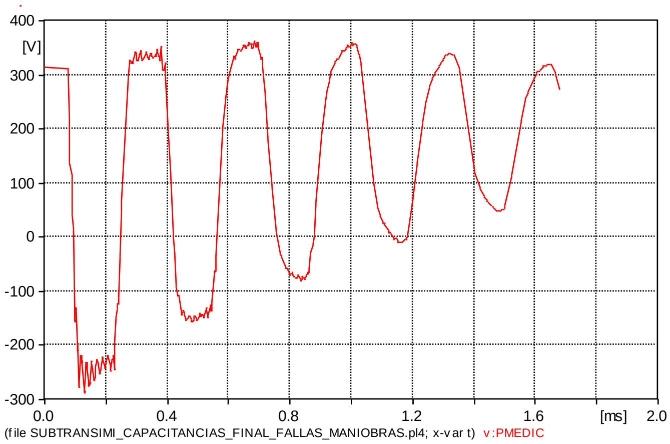

Figure 5: Single-phase fault with FR=20 Ω, Failed phase=R, FD=1 km.

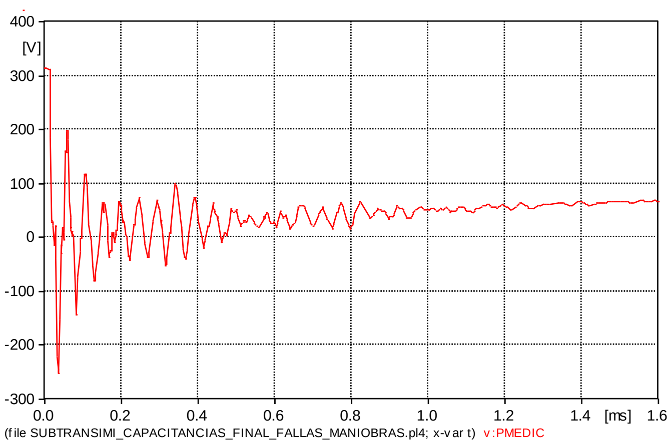

Figure 6: Single-phase fault with FR=20 Ω, Failed phase=R, FD=20 km.

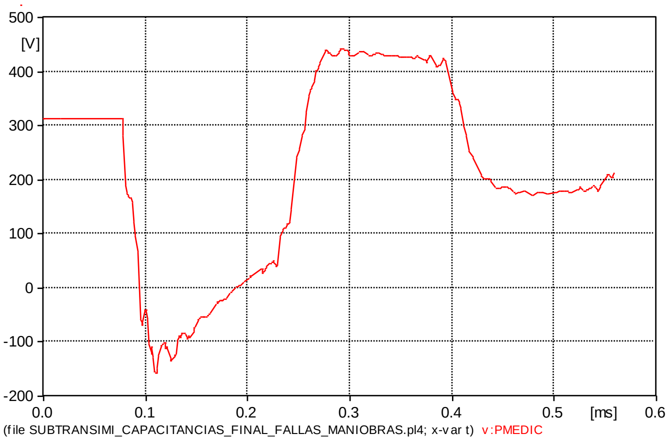

Figure 7: Single-phase fault with FR=80 Ω, Failed phase=R, FD=1 km.

B. **Case studies corresponding to switching operations**

As regards the case studies of switching operations, both energization and de-energization are carried out considering the variables presented in Table 2.

Table 2: Parameters for the simulation of switching operations

Energization type	Power breaker closing time
Single-phase energization	Between 0 and 16ms, with steps of 2ms
Three-phase energization	Between 0 and 16ms, with steps of 2ms
Single-phase de-energizing	Between 0 and 16ms, with steps of 2ms
Three-phase de-energizing	Between 0 and 16ms, with steps of 2ms

By varying the PB closing time of phase A, phase B, and phase C, and with single-pole or three-pole closure, the voltage waveforms are determined. In addition, angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° are assigned to the different phases according to the switching operation simulated.

Fig. 8 shows the waveform corresponding to a tripolar closure at a time of 8.33 ms. Similar to the previous case studies, several examples are shown from Fig. 9 to Fig. 10.

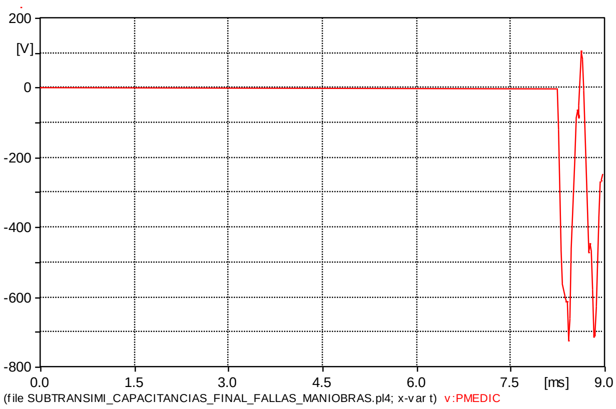

Figure 8: Three-phase closure at a time of 8.33 ms.

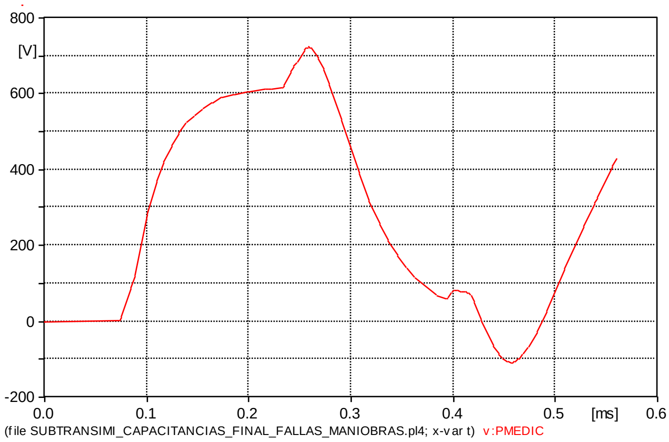

Figure 9: Three-phase closure at a time of 0 ms.

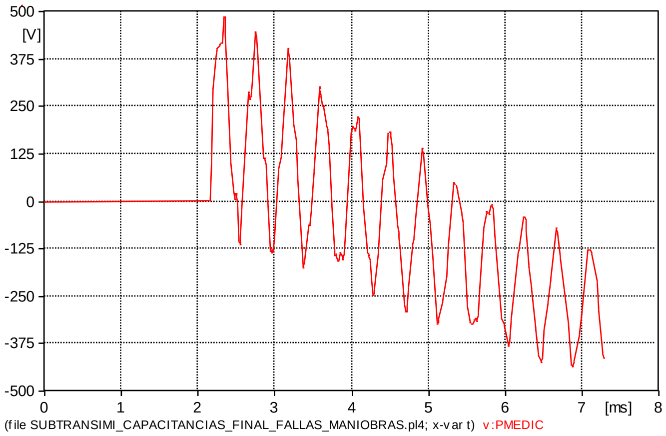

Figure 10: Triphasic closure in a time of 2.08 ms.

C. **Case studies corresponding to lightning strokes**

As regards overvoltages produced by LSs, it is necessary to indicate that the STL must be designed with perfect shielding, which has a very low probability of occurrence. Therefore, the atmospheric discharges that directly hit the phase conductors would have a very small probability compared to the discharges that would impact the sub-transmission towers or the guard wire. However, to carry out an adequate analysis of the different overvoltages produced by LSs, in this paper, both the direct, indirect, and induced LSs are simulated and analyzed. Table 3 presents the variables considered for the cases of direct LSs (LSs on the phase conductors), indirect LSs (LSs on the towers or guard wire), and induced LSs (LSs on the ground).

Based on the previous said, in Fig. 11, the oscillogram produced by a lightning current of 20 kA, 1.2/50 µs, Point of Impact (PI) along the STL 20km from S/E Cuenca, is shown. Similar case studies are simulated, which are shown from Fig. 12 to Fig. 15. For example, Fig. 15 shows the surge produced by a lightning current of 40 kA, 1.2/ 50 µs, which hits 20km from the E/S Cuenca.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 18, Number 2 (2023) pp. 103-109

Table 3: Parameters for the simulations of atmospheric discharges

Lightning type	**Lightning current (kA)**	**Polarity**	**Point of impact along the sub-transmission line (km)**	**Point of impact on the ground (m)**	**Grounding (Ω)**
Straight	3-10-15-20	Negative	5-10-15-20	Does not apply	Does not apply
Indirect	21-40-80-120-160-200	Negative	5-10-15-20	Does not apply	10
Induced	3-10-15-20	Negative	5-10-15-20	50-100	Does not apply

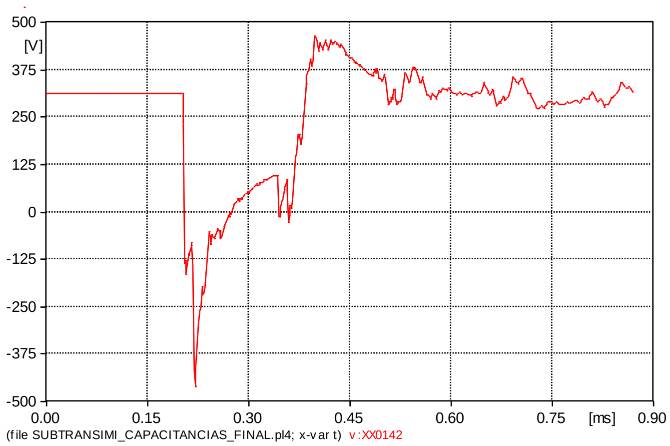

Figure 11: Overvoltage on the 22 kV side produced by a direct LS of 20 kA, 1.2/50 µs, PI at 20 km.

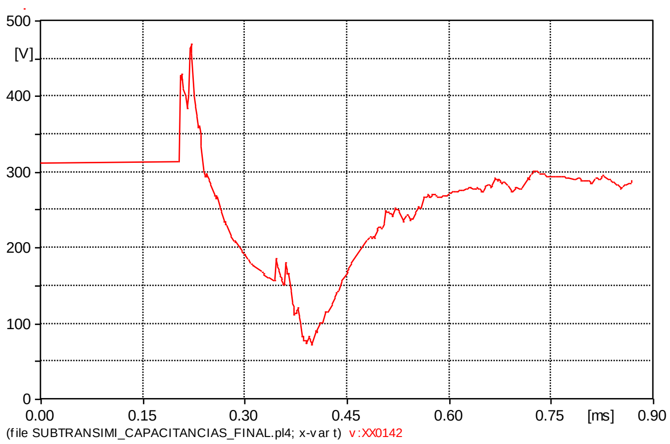

Figure 12: Overvoltage on the 22 kV side produced by a direct LS of 15 kA, 1.2/50 µs, PI at 20km.

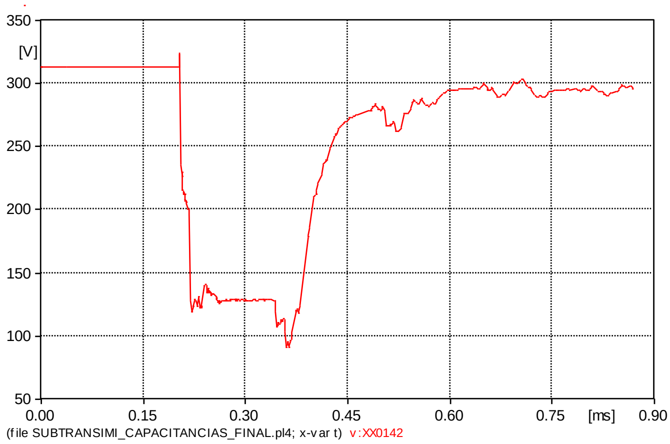

Figure 13: Overvoltage on the 22 kV side produced by an indirect LS of 200 kA, 1.2/50 µs, PI at 20 km.

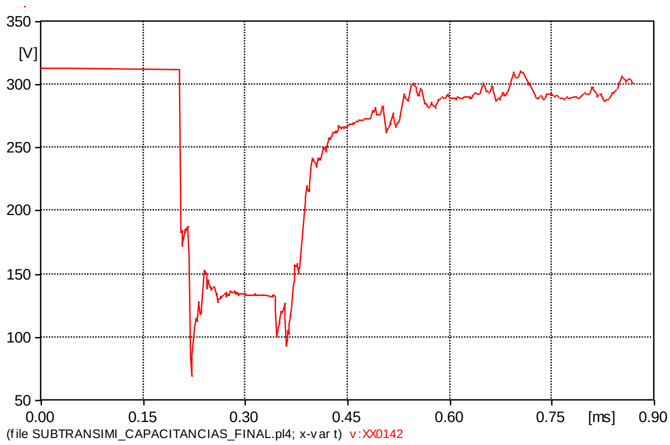

Figure 14: Overvoltage on the 22 kV side produced by an indirect LS of 50 kA, 1.2/50 µs, PI at 20.4 km.

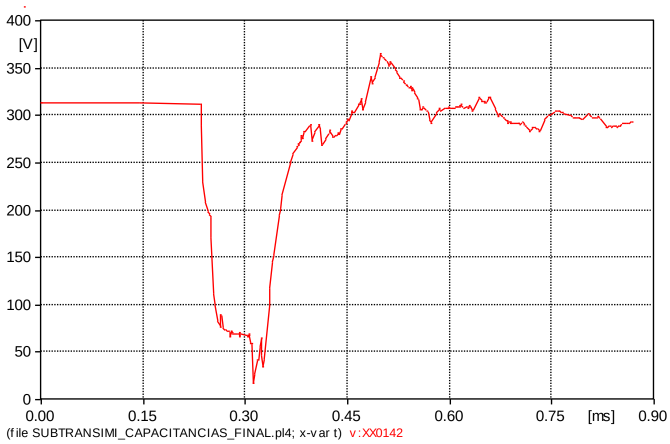

Figure 15: Overvoltage on the 22 kV side produced by an indirect LS of 40 kA, 1.2/50 µs, PI at 10 km.

Finally, as regards the case studies of atmospheric discharge that impact the ground, these are also simulated and analyzed according to the parameters presented in Table 3. For example, Fig. 16 shows the case study for an induced LS that impacts 10 km from the E/S Cuenca and hits the ground at a distance of 50 m from the external phase of the sub-transmission line (see Fig. 3).

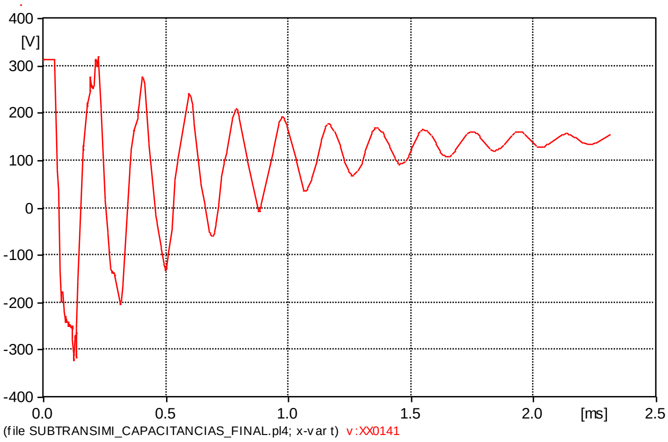

Figure 16: Overvoltage on the 22 kV side produced by an induced LS of 3 kA, 1.2/50 µs, which impacts at 10 km and a distance of 50 meters on the ground.

Another case study is shown in Fig. 17, which shows the oscillogram for an induced atmospheric discharge that hits 10 km from the E/S Cuenca and hits the ground at a distance of 100 m from the external phase of the sub-transmission line.

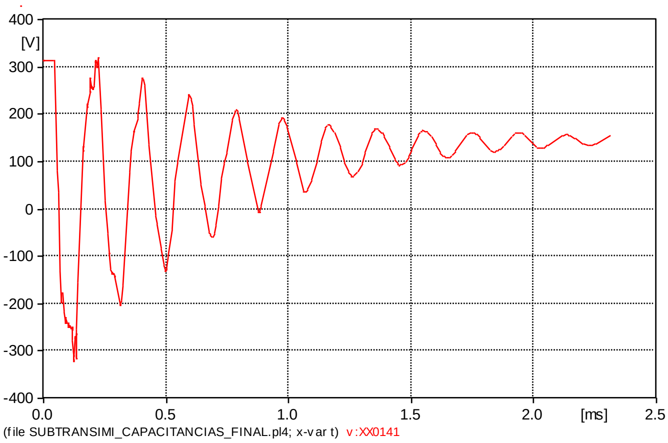

Figure 17: Overvoltage on the 22Kv side produced by an induced LS of 3 kA, 1.2/50 µs, which impacts at 10 km and a distance of 100 meters on the ground.

Figure 18 shows the case study for an induced atmospheric discharge that hits 20 km from the E/S Cuenca and hits the ground at a distance of 50 m from the external phase of the sub-transmission line.

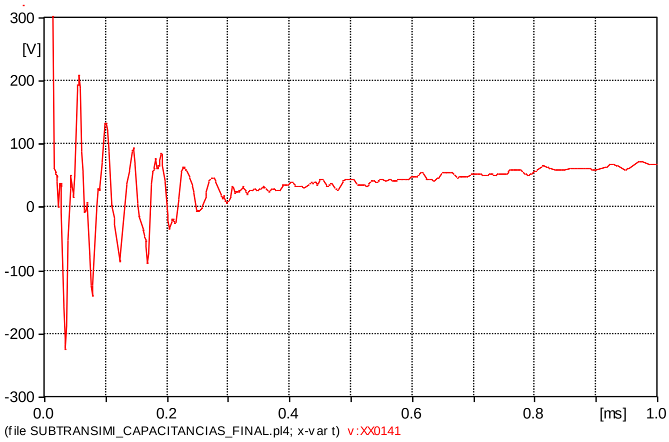

Figure 18: Overvoltage on the 22 kV side produced by an induced LS of 3 kA, 1.2/50 µs, which impacts at 20 km and a distance of 50 meters on the ground.

V. Analysis of results

Based on the study cases carried out previously, it can be determined that in the study case corresponding to single-phase short-circuits, the overvoltage waveforms registered in the 22 kV bus are notoriously different from the waveform registered in real-time in the said bar (See Figure 2).

In the case study corresponding to switching operations, the connection and disconnection of STLs also cause slight overvoltages similar to single-fault faults. However, the switching operations produce transient signals that are very different in comparison to the one registered in the 22 kV bus.

In the case study corresponding to atmospheric discharge, LSs between the range of 3kA to 20kA cause slight overvoltages. On the other hand, lightning currents greater than 20 kA cause a very pronounced overvoltage in the 22 kV bus, which tends to be very similar to the reference oscillogram. In this context and based on the large number of simulations carried out (72), it can be determined that the overvoltage produced by a 3kA lightning discharge, negative polarity, 20 km impact distance along STL, and 50 m point of impact on the ground, it is very similar in magnitude and shape to the reference waveform.

Acknowledgment

The authors gratefully acknowledge: the Instituto de Energía Eléctrica at Universidad Nacional de San Juan, and Azogues Electric Company for the assistance and financial support.

References

[1] Empresa Eléctrica Azogues, “Analysis of the Failure Occurred in the TP of S/E Azogues 1”, EEA Technical Direction.

[2] Andrew R. Hileman, Insulation Coordination for Power System, Taylor & Francis Group, New York, 1st ed., 1999.

[3] Juan A. Martinez-Velasco, Power System Transients Parameter Determinations, Taylor & Francis Group, Natick, 1st ed., 2010.

[4] ATP DRAW Version 3.5 for Windows 9x/NT/2000/XP Users' Manual; SINTEF Energy Research–Norwegian Univ. Sci. Technol.: Trondheim, Norway, 1999.

[5] N. Chiesa and HK Hoidalen, "Modeling of Nonlinear and Hysteretic Iron-Core Inductors in ATP", Department of Electric Power Engineering- NORGES TEKNISKNATURVITENSKAPELIGE UNIVERSITET, Tech Rep. 2008.

[6] JR Marti, "Accurate modeling of frequency-dependent transmission lines in electromagnetic transient simulations," IEEE Trans. Power App. Syst., vol. PAS-101, no. 1, p. 147–157, Jan. 1982.

[7] Fast Front Transients Task Force of the IEEE Modeling and Analysis of System Transients Working Group, "Modeling Guidelines for fast Front Transients", IEEE Transactions on Power Delivery, vol 11, No. 1, January 1996.

[8] Erasmo Echeverría, Thesis: Modeling and Analysis of the Transient Response of Non-Extensive Grounding, Lima, 2012.