# FAILURE ANALYSIS OF CVT FROM SUBSTATIONS EL TABLAZO AND CUATRICENTENARIO UP 400 KV

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**Abstract--This paper shows some of the analysis made to determine the causes of the tripouts of 400 kV transmission lines El Tablazo – Cuatricentenario by a possible lightning and the following failures of Capacitive Voltage Transformers (CVT) after the lines energizing from El Tablazo and Cuatricentenario substations. The paper deals with three topics, correlation in time and space location for the lightning's detected by CVG EDELCA Atmospheric Discharges Detection System (SDDAE) for the days of the lines tripouts, followings by ATP simulations to get the CVT overvoltages for the lightning correlating and the overvoltages by lines energizing. The simulation results gave as conclusion that the CVT failure was not for lightning activity or line energizing after the tripout.**

**Keywords: Line-Tripout, back-flashover, lightning, energizing, CVT, ATP.**

## I. INTRODUCTION

On the days 15th and 26th of September 2003, the 400 kV transmission lines El Tablazo – Cuatricentenario was tripouts by a possible lightning. Then, CVT´s failures occurred at substations El Tablazo and Cuatricentenario after the lines energizing.

This paper deals with the correlations in time and space location between the SDDAE and lines tripouts, followings the ATP simulations to evaluate the CVT´s overvoltages for the lightning correlating for those two (2) days and the calculus of the overvoltages by lines energizing to determine the reasons of CVT failures.

## II. STUDY SYSTEM DESCRIPTION

The system show in Fig. 1, are located at the west side of Venezuela country, specifically at Maracaibo Lake border at the Zulia state. The system includes the substations El Tablazo and Cuatricentenario and the transmission lines # 1 & 2 up 400 kV. The transmission lines has a 33.3 kms long, subdivide in 14.13 kms land sections between El Tablazo substation and Punta Palma, following by a crossing lake of 8.75 kms and the remaining land section of 10.42 kms between Peonías and Cuatricentenario substation, located at the East and West coast of the lake respectively.

These lines as show in Fig. 1 & 2, are used a double line circuit tower with 45 & 60 m height for land sections and single line circuit tower of 135 m height to cross the Maracaibo Lake, with shielding angle of 20º & 0º to land and lake sections, given by the lightning shielding design.

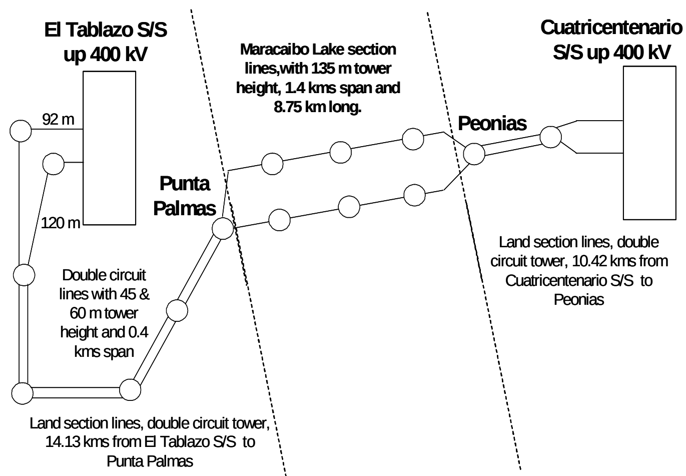


Fig. 1. Single line diagram for transmission lines # 1 & 2 El Tablazo – Cuatricentenario up 400 kV.

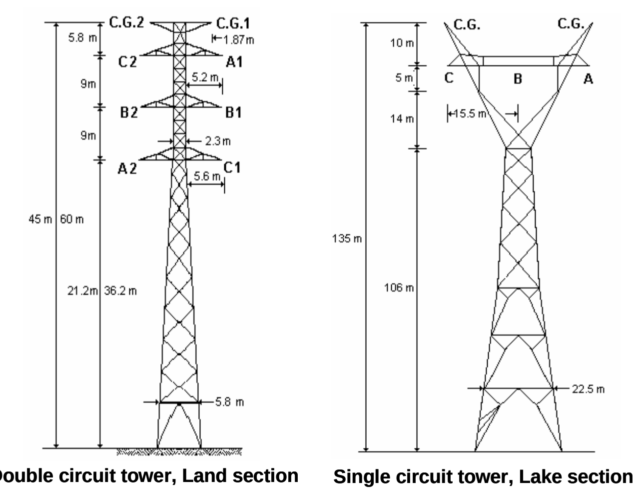


Fig. 2. Types of towers used for lines # 1 & 2 El Tablazo – Cuatricentenario up 400 kV.

The theoretical performance of these lines by lightning that will produce a shielding failure [1]-[2] or backflashover is summarizing in Table I and Fig. 3. These results mean to be as follow:

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### *A. Land Section of the Lines*

A shielding failure will happen and the stroke hit directly the conductor phase for lightning with peak current of 10 to 24 kA. For towers with 20Ω footing resistance and height of 60 & 45 m, lightning with peak current of 104 to 116 kA will cause a backflashover. As consequence the line tripouts will occur.

### *B. Lake Section of the Lines*

A shielding failure will be produced by lightning with peak current of 16 to 51 kA. For these tall towers with 135 m height and low footing resistance due the bottom by Maracaibo Lake, lightning with peak current of 92 kA will cause backflashover. As consequence the line tripouts will occur.

TABLE I
LIGHTNING FOR SHIELDING FAILURES IN TRANSMISSION LINES # 1 & 2 EL TABLAZO - CUATRICENTENARIO UP 400 KV

| Section | Land | Lake |
|---|---|---|
| Line leght (kms) | 24.55 | 8.75 |
| Shielding angle (α°) Theoretical / Design | 18 / 20 | 0 / 0 |
| Unshielding length (m) Theoretical / Design | 4.21 / 4.85 | 0 / 0 |
| Current for shielding failures (kA peak) I min / I max | 10.4 / 23.6 | 15.7 / 50.7 |

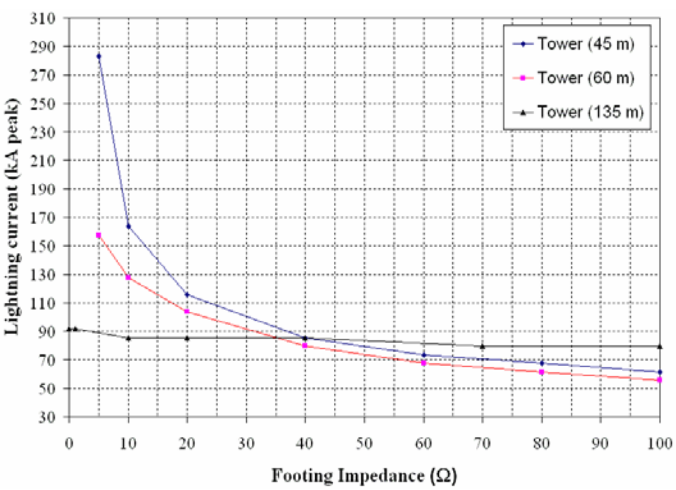



Fig. 3. Lightning current to produce backflashover in land and lake sections of lines # 1 & 2 El Tablazo-Cuatricentenario up 400 kV.

## III. 400 KV LINES TRIPOUT DESCRIPTION

The day 09/15/03, the line # 1 El Tablazo - Cuatricentenario up 400 kV tripout at 18:25:47 hours by a phase "C" fault located at 16.2 kms from Cuatricentenario substation and probably due by a lightning. Then at 18:28:00 hours, with line # 1 out of service, the line # 2 tripout for a phase "A" fault at 9.31 kms from Cuatricentenario substation, apparently by the same reason. At 18:58:38 hours, after the lines inspections, the line # 2 was energized from El Tablazo substation, occur an explosion of the phase "A" CVT. A few days later, at 04:59:19 hours of the day 09/26/03, the line # 1 tripout by a phase "C" fault at 12 kms from Cuatricentenario substation, by unknowed reason. At the same time with this fault, the non selective trip of line # 2 open the Cuatricentenario substation ended by an erratic distance relay operation from El Tablazo substation. Then at 05:35:26 hours with line # 2 in service, the line # 1 was energized from Cuatricentenario substation, afterward happened an explosion of phase "C" CVT and the non selective trip of line # 2 for unknowed reasons as mentioned before.

As consequence of these events (lightning and lines energizing) and like a part of the program of research for the failure of these equipments, the following approaches, simulations models and results analysis were done.

## IV. APPROACHES AND USED MODELS

This section will describe the approaches and some models used for the different studies carry out.

### *A. The Line up 400 kV*

For the studies of lines energizing and lightning phenomena respectively, were used a line model for not balanced distributed parameters (R, L and C) calculated a frequency of 60 Hz & 500 kHz [3]-[4]-[5]. The span length and towers height will be depending at the line section (land or lake) under study.

### *B. The Lightning*

A double ramp type source of current was used to simulate a lightning. This source reaches the peak magnitude in a few microseconds (time to crest) and after 50μs or tail time, fall to a 50% of the magnitude peak [1]. Table II, shows a summary for the source time to crest in function of lightning current magnitudes and insulators strings disruptive voltage [1]-[4]-[5].

TABLE II
TIME TO CREST OF LIGHTNING AND DISRUPTIVE VOLTAGE FOR INSULATORS STRINGS

| Lightning current (kA peak) | Time to crest (μs) | 400 kV insulators strings disruptive voltage for 2.7 & 4.5 m length (kV) |
|---|---|---|
| 10 – 30 | 0.5 | 4304 / 7173 |
| 50 – 100 | 1.2 | 2752 / 4587 |
| 100 – 200 | 2.0 | 2220 / 3700 |
| 200 – 300 | 2.8 | 1966 / 3276 |

### *C. The Insulators String up 400 kV*

These are a series-parallel combination of capacitances that represent the voltages distribution with regard to the tower and the leakage current along the insulator string. For the land section a polymeric string with 2.7 m effective length were used and for the lake, a porcelain string of 4.5 m. To simplify the representation, an equivalent capacitance was determined, giving a value of 11 pF to both strings [3]-[4].

The dielectric strength of these insulators strings were simulated by a voltage controlled switch [3] with disruptive voltages as indicated in Table II. This switch closes their contacts when the voltages difference between the tower and some circuit phase overcomes the disruptive voltage as a consequence of the lightning.

*D. The Tower up 400 kV*

The towers were represented by singles transmission lines, with impedances calculated from the tower sections geometry and connecting with the footing resistance. The propagation time in the tower, was calculated as the relationship between the height or the sections length and the 70% of the speed of the light for travel in a different medium to the vacuum [1]-[3]-[4].

*E. The Footing Resistance*

To cover all the footing resistances values among of 0.01 to 100Ω measuring along the line, a lumped resistance representation were used by each study's cases [1]-[2]-[3]-[4].

## V. Analysis Methodology for Lightning Phenomena

To get the target proposed, the following tasks were done:

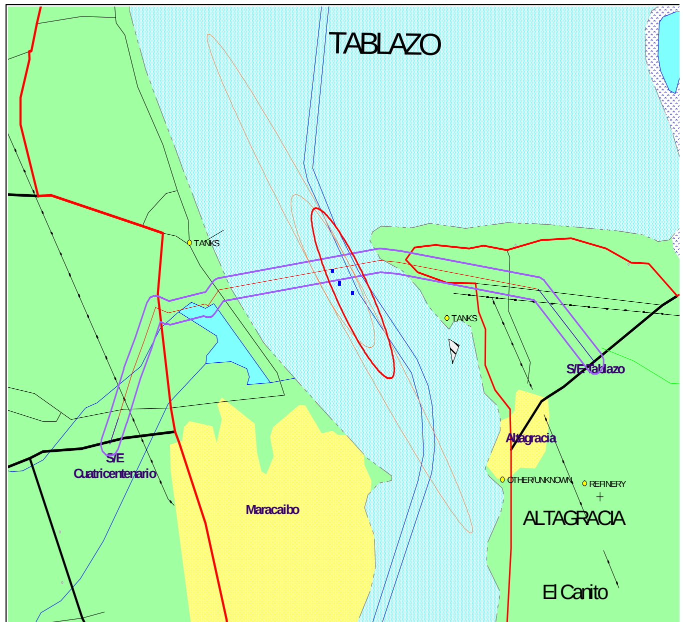
1. Correlation of the lines tripouts for those days through the revision of the lightning recorded data by the SDDAE, taking a time span of ±15s around the time of line tripout and a lightning incidence area of ±500m with a confidence level of 99%. Once the information was processed, the peak current, time and geographic location of lightning could be identified.
2. A comparison between the lightning peaks current obtained above with the values from Table I or Fig. 3 to select which magnitude will produce faults in the lines.
3. Simulation with ATP [6] to get the lightning overvoltages that can be reaching the substation and stress the CVT at the moment before the failures.

*A. Lightning Analysis for days 15th and 26th, September 2003*

The SDDAE record for the day 09/15/03 as show in Fig. 4, gave three (3) lightning who was happened at 18:25:47 hours and were located in the lines lake section at 16 & 17 kms of El Tablazo and Cuatricentenario substations. The lightning peak current was 49.5, 41.5 & 35.4 kA with a time of 107, 412 & 598 ms after the line tripout. As result of this evidence and the comparison with the lightning magnitude of Table I, was assumed like a responsible for the line # 1 tripout a direct stroke of 49.5 kA that took place at 16 kms from El Tablazo substation.

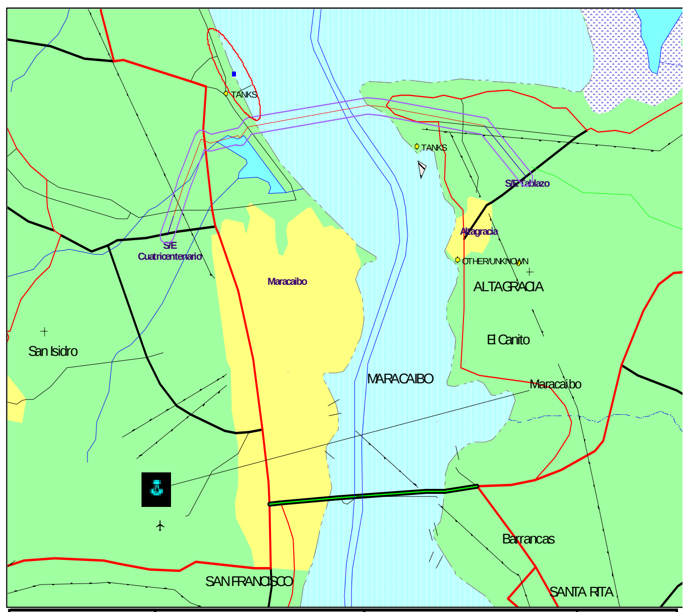
For the trip of line # 2 at 18:28:00 hours as show in Fig. 5, the SDDAE recorded a lightning of 107 kA located in the line lake section at 10 & 23 kms from Cuatricentenario and El Tablazo substations. As result of this finding and the comparison with the lightning magnitude of Fig. 3, was assumed like the cause for the line # 2 tripout, a backflashover by a stroke of 107 kA and took place at 23 kms from El Tablazo substation.

Also, during the time that both lines were out of services were registered only a lightning of 32 kA that took place at the lake section at 18 kms from El Tablazo substation.




| ASSET_NAME | EVENT_TIME | LTG_TIME | LTG_KA |
|---|---|---|---|
| Tab-Cua | 09/15/2003 18:25:47.000 | 09/15/2003 18:25:47.107 | -49,49 |
| Tab-Cua | 09/15/2003 18:25:47.000 | 09/15/2003 18:25:47.412 | -41,46 |
| Tab-Cua | 09/15/2003 18:25:47.000 | 09/15/2003 18:25:47.598 | -35,35 |

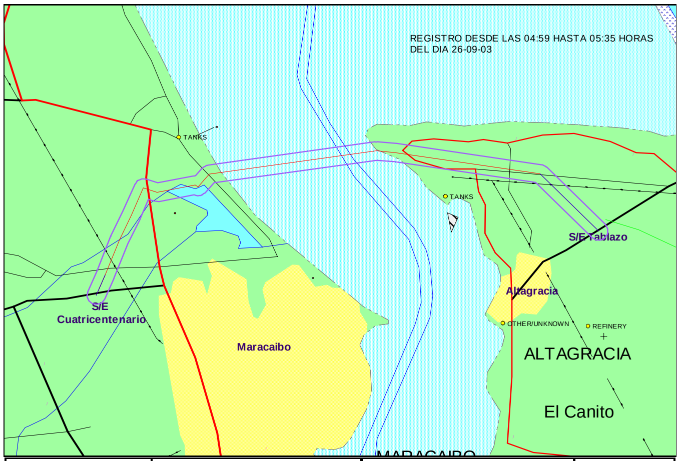
Fig. 4. Lightning recorded by SDDAE for day 09/15/03 at 18:25:47 hours.




| ASSET_NAME | EVENT_TIME | LTG_TIME | LTG_KA |
|---|---|---|---|
| Tab-Cua | 09/15/2003 18:28:00.000 | 09/15/2003 18:28:00.000 | -107,152 |

Fig. 5. Lightning recorded by SDDAE for day 09/15/03 at 18:28:00 hours.

Finally, the SDDAE record for the day 09/26/03 at 04:59:19 hours as show in Fig. 6, did not registered any lightning activity during a time of nine (9) minutes before and after the trip of line # 1. The line was energized at 05:35:26 hours when an explosion happened in phase "C" CVT. The analysis of this information rejects the hypothesis that the trip of transmission line was due by lightning.




| ASSET_NAME | EVENT_TIME | LTG_TIME | LTG_KA |
|---|---|---|---|
| Tab-Cua | 09/26/2003 04:59:19.000 | 09/26/2003 05:35:26.000 | 0 |

Fig. 6. Lightning recorded by SDDAE for day 09/26/03 at 04:59:19 hours.

*B. ATP Simulation for Lightning's on Day 09/15/03.*

This point shows the lightning overvoltages simulation made with ATP that reaches the CVT and the results analysis.

1. Direct stroke of 49.5 kA in line # 1 at 18:25:47 hours

   As show in Fig. 7, a peak overvoltage of 5850 kV was developed by the phase of the line hit by the stroke. This overvoltage travels in both ways of the line, and was attenuated at 10.8% (630 kV) after cover the distance of 16.2 kms to El Tablazo substation. At Cuatricentenario substation arrived approximately the same overvoltage, due the strike point is around the half of the line length between these substations. The magnitude of these overvoltages represent not risk of failure for the equipments at the terminal substation because the magnitude is just 44.2% of their basic impulse level peak by lightning (BIL = 1425 kV).

   The simulation of 32 kA direct stroke at 18 kms from El Tablazo substation with both lines out of service, show a 675 kV overvoltage at the CVT place and it can be applied as the same comments before.

   As conclusion, direct stroke in Maracaibo lake section of these lines will not produce a CVT failure at El Tablazo and Cuatricentenario up 400 kV substations. The overvoltages developed by these direct strokes are attenuated by the lines losses and the traveled distance as the simulations showed.

2. Backflashover by stroke of 107 kA in line # 2 at 18:28:00 hours

   In Fig. 8 is shown a peak overvoltage of 5630 kV developed by the phase of the line as consequence of the backflashover due the stroke. This overvoltage travels in both ways of the line and is attenuated a 4.96% (279 kV) and 7.6% (428 kV) after cover a distance of 22.8 and 10 kms to El Tablazo and Cuatricentenario substation. In this case, the overvoltages arrive to El Tablazo and Cuatricentenario substations as result of the backflashover and have a magnitude of 19.6 & 30% of the BIL (1425 kV peak) of the equipments by the terminal substation. These overvoltages were considered without risk that will produce an equipment failure.

   As conclusion, backflashover in Maracaibo lake section of these lines will not provoke a CVT failure at El Tablazo and Cuatricentenario substation. The overvoltages developed by these backflashover are attenuated by the losses lines as the simulations showed.

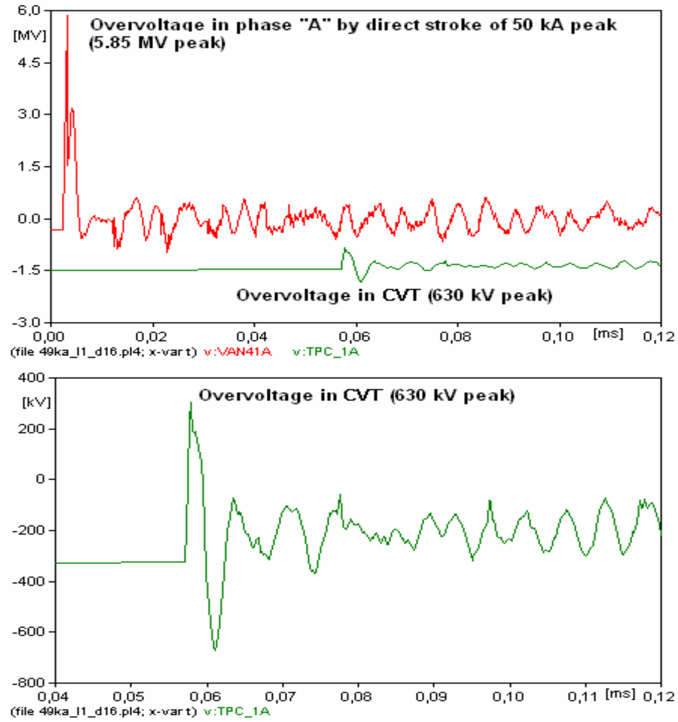



Fig. 7. Line # 1 direct stroke of 49.5 kA at 18:25:47 hours. Upper is a phase "A" and CVT overvoltages and lower is an enlargement for CVT overvoltage.

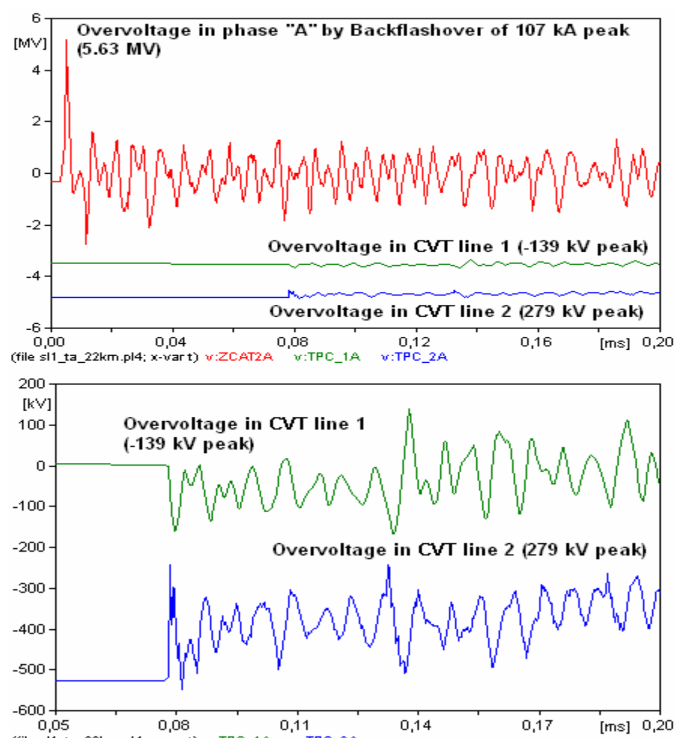



Fig. 8. Line # 2 Backflashover by 107 kA at 18:28:00 hours. Upper is a phase "A" and CVT overvoltages and lower is an enlargement for CVT overvoltage.

## VI. Analysis Methodology for Lines Energizing

The insulation at the end line CVT from lines #1 & 2 El Tablazo - Cuatricentenario up 400 kV, can be stressed by the overvoltages produced by the energizing. At this section, the lines energizing overvoltages are quantifying to evaluate the possible influence in the CVT failures at El Tablazo and Cuatricentenario substations.

### *A. Simulation Methodology*

To get the target, the lines circuit breakers were modelled without pre-insertion resistors. Then, two hundred (200) simulations of lines energizing under study were done, with closing time of circuit breakers given by ATP [6] in random way and using a normal distributions in the close time with a standard deviation (δ) of 1.2 ms. The random time for the moment when the circuit breakers are close to energize the line, was a uniform distributions over the period for a 60 Hz voltage wave. The overvoltages were statistically processed to get the standard deviation (δ) and the overvoltages with minimum (Vmin), maximum (Vmax) and fifty percent of probability (V50%) to be happen. Using these values the overvoltage with 2% of probability to be exceeded was calculated to finally quantifying their possible influence in the CVT failures.

### *B. Energizing Analysis of Lines up 400 kV*

The Table III is a summary for the statistical processed overvoltages getting by ATP simulation when El Tablazo – Cuatricentenario line up 400 kV, were energized with or without the other line in service, as shown in Fig. 9.

TABLE III
STATISTICAL PROCESSED RESULT OF THE ENERGIZING OVERVOLTAGES FOR LINES # 1 & 2 EL TABLAZO - CUATRICENTENARIO UP 400 KV

| Scheme | # 1 | # 2 |
|---|---|---|
| Substations | Tablazo / Cuatric. | Tablazo / Cuatric. |
| Vmin (pu) | 1.17 / 1.2 | 1.1 / 1.3 |
| Vmax (pu) | 2.27 / 2.67 | 1.59 / 2.57 |
| V50% (pu) | 1.72 / 1.93 | 1.93 / 1.94 |
| δ (pu) | 0.22 / 0.29 | 0.1 / 0.28 |
| V2% (pu) | 2.18 / 2.53 | 1.55 / 2.51 |

Note: 1 pu = 327 kV peak

As indicated in Table III, the higher overvoltage was obtained from the energizing of line # 1 with line # 2 out of service (Scheme 1). This peak overvoltage maximum was 2.67 pu (871.6 kV) and is reduced to 2.57 pu (841.8 kV) when line # 2 is in service (Scheme 2). For example, in Fig. 10 is shown the overvoltage wave for Cuatricentenario end of the line when line # 1 is energizing from El Tablazo substation.

The CVT from lines El Tablazo – Cuatricentenario up 400 kV have a basic switching level peak (BSL) of 1050 kV. The above BSL mean a margin of 17% higher than the maximum overvoltages by lines energizing (871.6 kV). This margin is higher than 15% recommended by the IEC-71[7] standard for systems with a voltage above 300 kV and protected by surge arrester and is appropriated for the insulation coordination by switching overvoltages of these lines.

These figures allow as conclusion that is not necessary to use pre-insertion resistor by the circuit breakers of the lines.

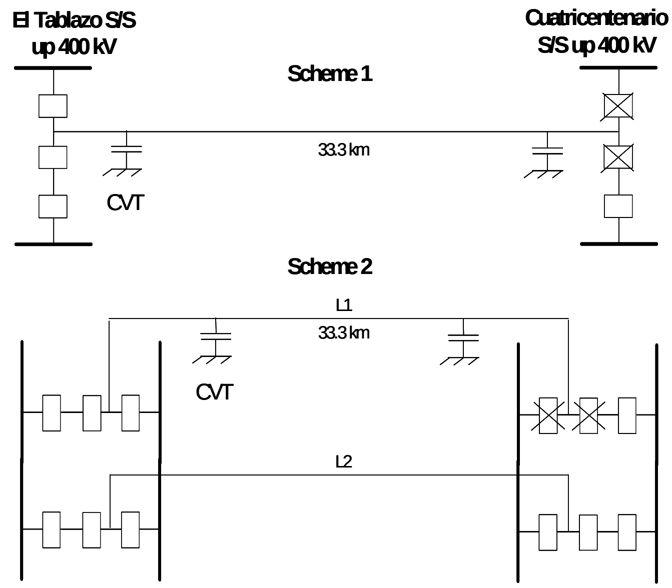


Fig. 9. Scheme 1 & 2 to energizing the 400 kV lines

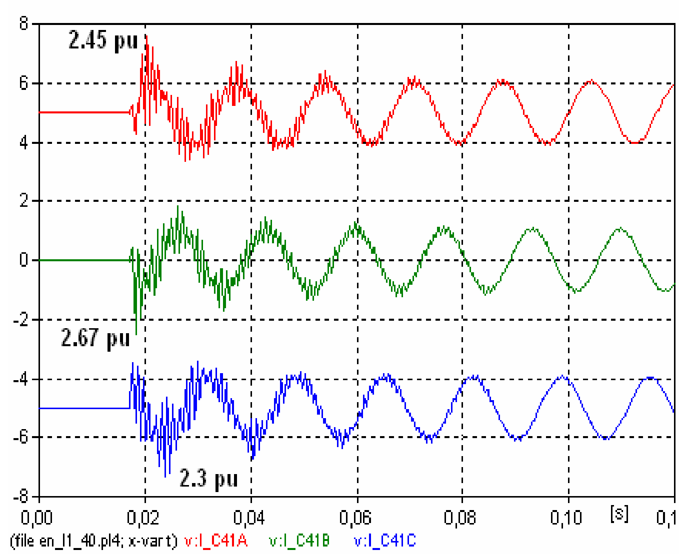


Fig. 10. Overvoltages in Cuatricentenario end by line energizing from El Tablazo up 400 kV substations.

## VII. Conclusions

The conclusions can be summarizing as next:

- The tripout on the day 09/15/03 at 18:25:47 hours of line # 1 El Tablazo - Cuatricentenario up 400 kV, was assumed like a direct stroke of 49.5 kA according the SDDAE registered data and the theoretical current value to produce a shielding failure in Maracaibo lake section of the line. However, the peak overvoltage developed by the phase (5850 kV) hitting by the stroke is attenuated at 10.8% (630 kV) after travel 16.8 kms to El Tablazo or Cuatricentenario substation. These figures reject the possibilities of dielectric stress in CVT from El Tablazo and Cuatricentenario up 400 kV, because the overvoltages just represent 44.2% of the basic impulse level by lightning (BIL = 1425 kV peak) of the equipments.

- The tripout on the day 09/15/03 at 18:28:00 hours of line # 2, was assumed like a backflashover by a stroke of 107 kA that took place in the west coast of Maracaibo lake, according the SDDAE registered data and theoretical current value calculus. However, the peak overvoltage developed by the phase (5630 kV) is attenuated at 4.96% (279 kV) and 7.6% (428 kV), after cover a distance of 22.8 and 10 kms to El Tablazo and Cuatricentenario substation. These overvoltages only represent a 19.6 & 30% of the basic impulse level by lightning (BIL = 1425 kV peak) of the equipments by the terminal substation El Tablazo and Cuatricentenario. These figures reject the possible dielectric stress in the lines CVT as responsible of the failures.
- The SDDAE record for the day 09/26/03 at 04:59:19 hours, did not registered any lightning activity during a time of nine (9) minutes before and after the trip of line # 1. The line was energized at 05:35:26 hours when an explosion happened in phase "C" CVT. The analysis of this information rejects the hypothesis that the trip of transmission line # 1 was due by lightning and atmospheric overvoltages were the responsible of CVT failure in Cuatricentenario substation.
- The peak overvoltage maximum by lines energizing was 2.67 pu (871.6 kV) that is 17% less than the basic switching level (BSL=1050 kV peak) of the terminal CVT equipment from lines El Tablazo – Cuatricentenario up 400 kV. This margin is higher than 15% recommended by the IEC-71[7] standard for systems with a voltage above 300 kV and protected by surge arrester and is appropriated for the insulation coordination by switching overvoltages of these lines.
- The conclusions by simulations results for the CVT failure at El Tablazo and Cuatricentenario up 400 kV substations on the days 15th and 26th of September 2003, were not provoked by any atmospheric overvoltages neither by energizing lines overvoltages for those days.
- As finally remark, now will are starting together with the manufacture a review program that maybe include some dissection of similar CVT place at the system and the analysis of the CVT insulation measuring for the data collected by each time the line trip after lightning occurrence. At the moment, not correlation between lightning and some insulation change were found.

## VIII. Bibliographic References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## IX. Biographies

**Alessandro Villa R.**, (M´99) was born in Venezuela. He received the E.E. and M.Sc. degrees by Metropolitana University (UNIMET) and Simon Bolivar University (USB) in 1987 and 1993 respectively. Since 1987 he works by the Research and Transient Analysis Department from Electrical System Engineering Division of CVG EDELCA Company, where he has been involved in power system transients analyses for studies design of insulation coordination for 115 until 765 kV substations, field test on 765 and 400 kV systems, studies of new transmission technologies (SVC, HVDC, FACTS and Line Arresters), transient analysis performance of Venezuela – Brazil Interconnection and EMTP/ATP simulations in this fields. Since 1994 is the Chief of the Transient Analysis Section of the Research and Transient Analysis Department and teaches power system transient's analysis using ATP program for post graduated students of the electrical school by Central University of Venezuela (UCV) from 1996.

**Zulay Romero C.**, was born in Venezuela. She received the E.E. degree by Central University of Venezuela (UCV) in 1987. Since 1988, she has been involved with the operation and planning studies for CADAFE Company power systems. Also since 1998 she works with the Research and Transient Analysis Department from Electrical System Engineering Division of CVG EDELCA Company, where she was studying the induction phenomena in lines that share the same corridor and now joint the power quality and harmonics study group for field measurements on CVG EDELCA system.