

Field measurements and modelling of high frequency transients during disconnect switch operations in EHV Substations. Assessment of their effects on Current Transformers

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SUMMARY

The article describes the complete procedure carried out in order to determine the cause of high levels of gases detected in chromatographic determinations performed in Current Transformers (CT) oil. These analyses of gases are normally included in routine maintenance work. The obtained results could evidence some possible damage in the machine insulation.

According to the electrical stresses that Current Transformers are typically subjected to, it was presumed that the cause of the possible damaged could be the high-frequency transients that take place during air disconnect switch operations.

Therefore, with the aim of determining the presence of such electrical stress, field measurements were performed. A specially designed measuring system was utilized to accomplish this goal.

Taking into account the difficulties normally encountered when measuring currents flowing through Current Transformers to ground, especially in terms of accuracy, it was decided to perform voltage measurements. Then, by determining the real frequency response of the CT in the range of interest, it was possible to achieve such currents by computer simulations.

In order to achieve accurate results in the simulations, it was necessary to develop an appropriate electrical model of this type of transformers in the analyzed frequency range. Once the model was carefully adjusted, computer simulations were performed. As a result, both shape and magnitude of such currents were also achieved.

Finally, one of the Current Transformers with high levels of gases was taken out of service. Then, it was completely disassembled so as to confirm the suspected damage in the insulation. The results yielded in the inspection of the insulation are commented at the end of this work.

KEYWORDS

Electrical stress – Current Transformer – High-frequency transient – HV equipment – Insulation – Measurement – Model – Simulation.

1. INTRODUCTION

A Transmission Company of Argentina detected different anomalies in several EHV Current Transformers. The main anomaly consisted in the observation of high oil level probably due to the presence of different gases.

In order to determine the presence of gases a sample of oil was taken and then chromatographically analysed. By the tests performed to the sample of oil it was detected a severe increment in the amount of several gases: hydrogen, methane and carbon dioxide, among them. In Fig. 1 the results of the chromatographic analyses are shown. It has also been included the Total Dissolved Combustible Gases (TDCG).

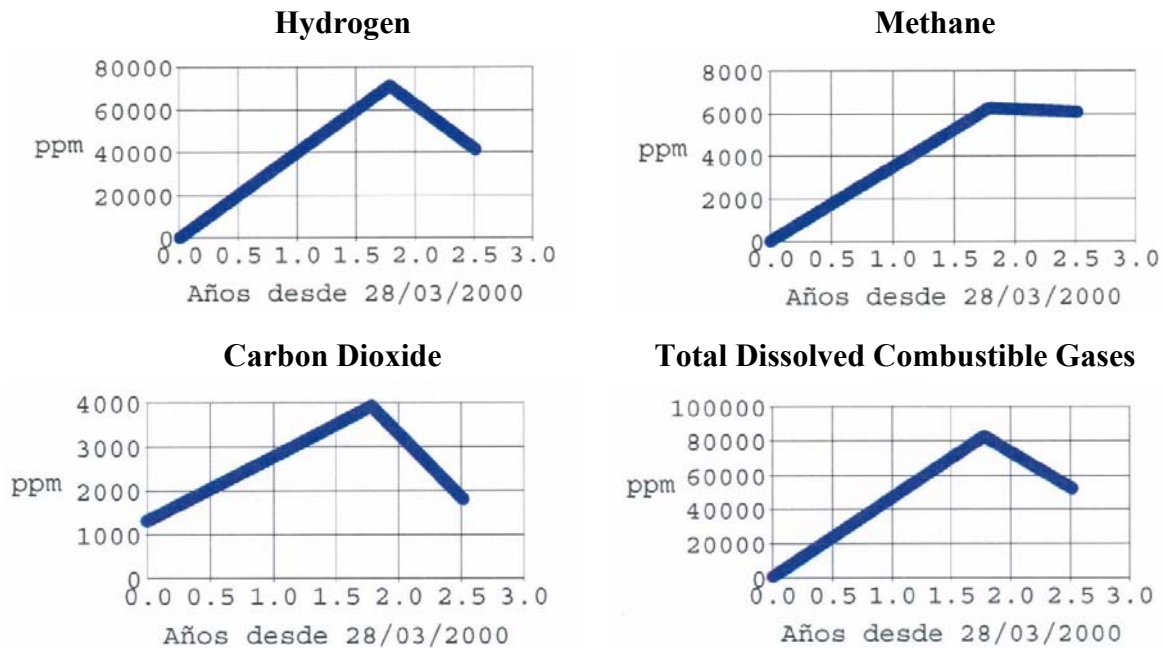


Figure 1. Results of gases analyses performed in oil.

The charts indicate the levels of gases in **parts per million [ppm]** as a function of time. In all the cases the amount of gases increased dramatically between the analyses carried out in March of 2000 and the next ones performed after the CT was taken out of service, in January of 2002. After that, personnel of the Company continued taking samples of oil and performing the same corresponding analyses. For this reason, the trends decrease once the peak has been reached.

Naturally, such an increment in the amount of gases in the oil evidenced a possible damaged in the CT insulation. Because of this reason, several CTs were taken out of service.

Since it was necessary to confirm whether the insulation was damaged, one of the CTs taken out of service was carefully disassembled in its totality.

Additionally, it was also essential to determine the reasons for this premature damage. It was immediately thought that a possible cause of this could be the electrical stress that CTs suffer during air disconnect switch operations. It consists of high-frequency transients that arise in CTs while the arc is present in the disconnect switch. They take place in both opening and closing operations. Photograph in Fig. 2 shows the very moment in which the arc is present.

With the purpose of determining the existence of such high-frequency transients, field measurements in several Transformer Stations were carried out.



Figure 2. Arc present in the air disconnect switch during an operation.

2. HIGH-FREQUENCY TRANSIENT MEASUREMENTS

2.1. Measuring System Description

A specially designed measuring system was utilized to carry out field transient measurements. This system basically consists of an electric field (E) sensor, an E/V transducer, and finally a transmitter and a receiver connected by a fiber optic link. The signal arriving at the receiver can be easily observed with either an oscilloscope or a spectrum analyzer. Its bandwidth is from 5 Hz to 10 MHz. In Fig. 3, some photographs of the system are shown.

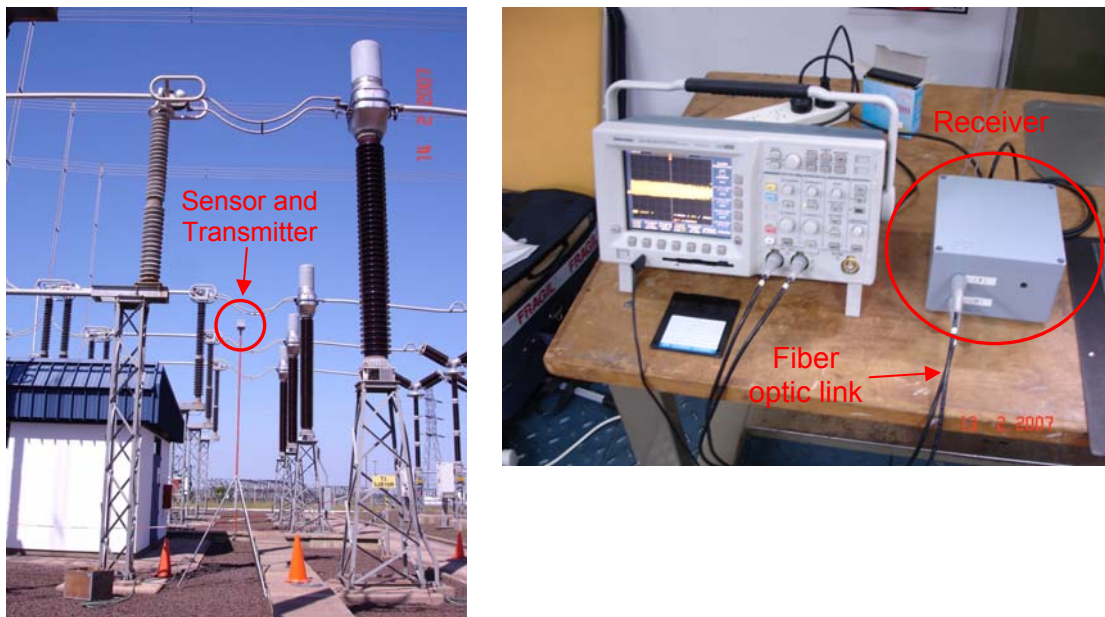


Figure 3. Photographs of the measuring system.

The main advantage of this measuring system lies in the fact that measurements can be performed without affecting the normal operation of the substation since it has no physical contact with the installation. Added to this, due to the fiber optic link, measurements are not affected by the electromagnetic noise present in the substation.

By the use of this measuring system it is possible to obtain waveforms of voltage transients.

2.2. Waveforms captured in field measurements

As it was mentioned in the Introduction, in order to determine the presence of high-frequency transients, field measurements in several EHV Transformer Stations were made. Thus, some of the oscillograms captured by the measuring system in a particular EHV Transformer Station will be shown as follows.

The voltage records were taken upstream one of the Current Transformers existing in two fields of the Station – called Field 1 and Field 2 in the present paper. The sensors were located below the connection bar of the transformers. In this way, the line-to-ground voltage was recorded.

In Fig. 4 two oscillograms belonging to a closing operation in Field 1 are depicted. The first one was captured at the beginning of the arc, whereas the second was obtained 790 ms after the arc began.

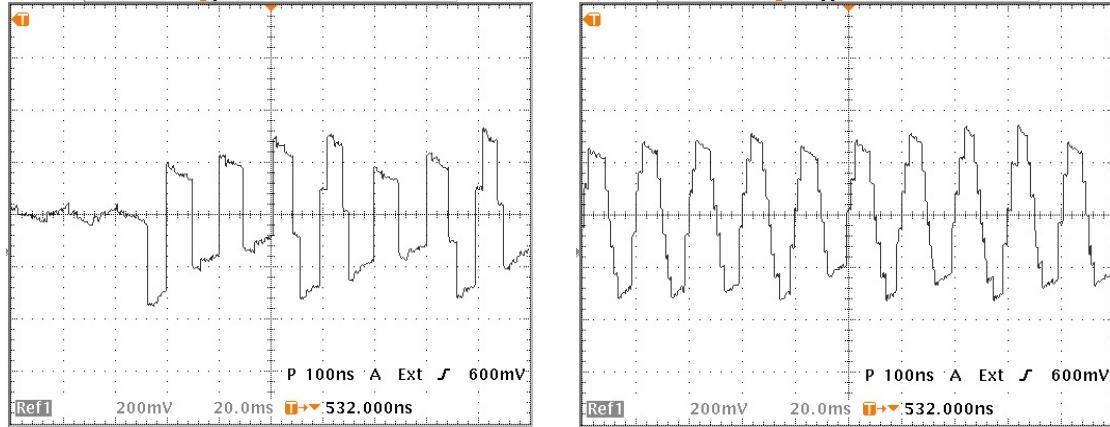


Figure 4. Oscillograms during closing operation. At the beginning and close to the end of the arc.

As it can be observed in both graphs the perturbation due to the arc in the disconnect switch does exist and appears on the CT. At the beginning of the arc voltage steps of great amplitude, which only occur twice, one positive and another negative, during each period of the power-frequency are present. On the other hand, close to the end of the arc, as its length is reduced, the steps are of smaller amplitude than at the beginning, but their amount is greater during each period of the power-frequency.

In Fig. 5 two oscillograms obtained during an opening operation are shown. The comments are analogous to those made in the previous case, but now the voltage steps of great amplitude take place at the end of the arc, while those of smaller amplitude appear at the beginning.

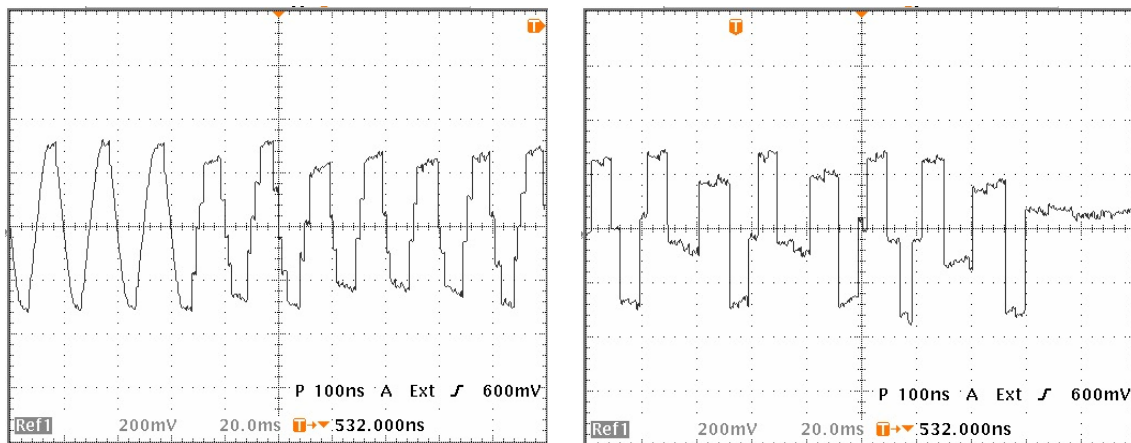


Figure 5. Oscillograms during opening operation. At the beginning and at the end of the arc.

These four records were done using a time scale of 20 ms per division. Nevertheless, new oscillograms with different time scale were captured. First, with the aim of knowing the front time of the voltage steps, faster records (1 μ s per division) were taken. Then, slower records (0.4 ms per division) were also obtained so as to know the time length of the arc during both operations.

In order to summarize the totality of the results obtained in the Transformer Station Table I shows the maximum voltage step found throughout all the operations carried out in both fields.

Table I. Maximum Voltage Step in Each Operation

FIELD	Maximum Voltage Step ΔU_{\max} [kV]	
	Closing Operation	Opening Operation
1	590 ; 530 ; 500 ; 470 ; 440 ; 420 ; 410	560 ; 530 ; 480 ; 400
2	520 ; 450	620 ; 600

In addition, Table II shows the range within front times lay for both kinds of operations.

Table II. Front Times Recorded

FIELD	Front Times [ns]	
	Closing Operation	Opening Operation
1	From 500 to 600	From 550 to 560
2	780	810

Finally, in Table III the durations of the arcs are given considering both the average value and their standard deviation.

Table III. Time Lengths of Arcs

FIELD	Time duration [ms]	
	Average Value Closing / Opening	Standard Deviation Closing / Opening
1	1235 / 1780	26 / 131
2	345 / 720	25 / 40

3. COMPUTER SIMULATIONS

3.1. Purpose of simulations

All the records performed involved only voltage measurements. However, in order to assess the actual solicitations that Current transformers are exposed to it is worth knowing the current flowing through transformers to ground as well.

Since such currents were not measured – the sensor included in the measuring system performs an E/V conversion – they were obtained by computer simulations.

In order to achieve successful results in computer simulations it is necessary to obtain an accurate model of the Current Transformer. For this reason, a detailed study of the CT frequency response in the range of interest was carried out. This included the measurement of its actual response *in situ*.

Once the electrical model was properly adjusted, this was excited by a voltage generator with the shape of the oscillograms recorded in the Transformer Stations so as to determine the required current.

3.2. Frequency Response Determination

The frequency response of a Current Transformer of the same brand and model as those installed in Field 1 was obtained by field measurements. By the use of a spectrum analyzer which includes a built-in tracking generator it was obtained the impedance of both CTs as a function of frequency between 10 kHz and 5 MHz.

In Fig. 6 both voltage and current measured spectrums are depicted. These responses also include contribution of the measuring circuit (coaxial cables, etc.).

As it can be seen, the resonant frequency lies in 1.127 MHz. In addition, the total equivalent series resistance is 7.46 Ω .

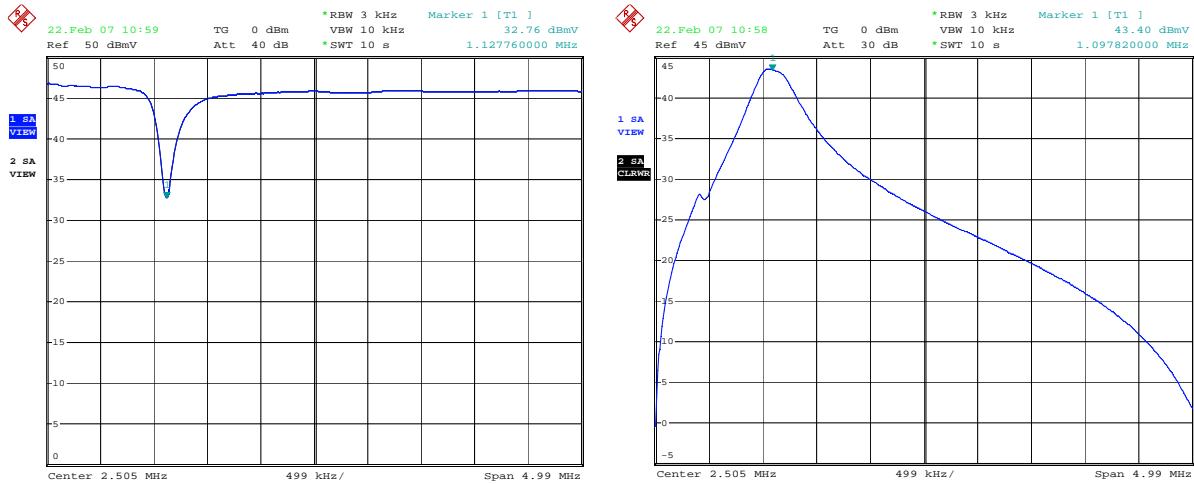


Figure 6. Spectrums of voltage and current of a CT between 10 kHz and 5 MHz.

The next challenge was to achieve the reproduction of both responses in the model proposed in the simulation program. This model has to include not only the components related to the Current Transformer itself but also those belonging to the measuring circuit.

3.3. Computer Modelling of Current Transformers

The CT can be modelled as a series impedance including a capacitance (C_t), an inductance (L_s) and a resistance (R_s). At this point, the values of these three components are unknown.

Added to this, since CTs are over the ground level by means of a support, it is also necessary to include the inductance representing the influence of this support (L_{base}). Its magnitude can be estimated theoretically from the geometry.

As regards the magnitude of the components belonging to the measuring circuit, since the signal connection used during the measurements is of known geometry, it is also possible to estimate their value theoretically.

Then, the complete circuit was drawn in the simulation program. The values of C_t , L_s and R_s were determined by trial and error, i.e. they were adjusted many times until the simulated responses matched the measured ones. As a result, it was achieved that $C_t=1$ nF, $L_s=4,4$ μ H and $R_s=6,5$ Ω .

In Fig. 7 the responses obtained by simulations are depicted (voltage in red and current in blue). Thus, it has been proved that the model achieved for the CT and the measuring circuit works successfully.

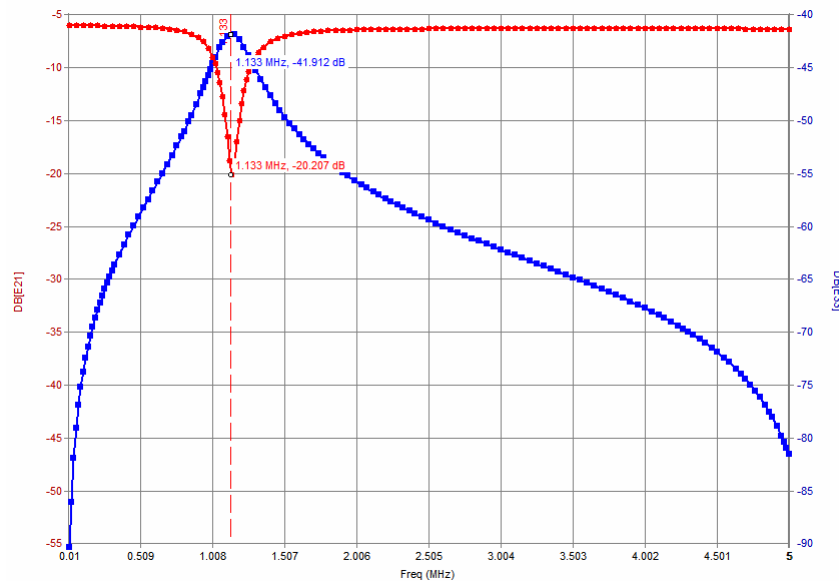


Figure 7. Responses achieved by simulation, tuning the values of the components.

3.4. Currents flowing through the CT

Once the complete model was properly adjusted, it was possible to run simulations so as to obtain both shape and magnitude of the current flowing through the Current Transformer to ground.

Therefore, the circuit was analyzed by applying a step voltage generator representative of the recorded transients, especially in terms of the measured front times. As from the simulations that are described as follows, the current transient produced by a voltage step is quickly attenuated (duration shorter than $10\text{ }\mu\text{s}$), it is valid to analyze the successive steps as if they were independent events since they appear with a difference of 2 ms to 20 ms between them.

Provided that each of the voltage steps corresponding to the real complete transient has different amplitudes, the simulations were carried out with reference amplitude of 100 kV. The reason of that was to enable later the conversion of the obtained results to proportional current values, according to the step amplitude of real recorded voltages.

The result of one of the simulations carried out appears in Fig. 8. As expected, the current resulted in a damped oscillation, whose oscillation frequency is 1.9 MHz. It is worth remarking that its amplitude is reduced to less than 10 % of its maximum value at $6\text{ }\mu\text{s}$ after the transient begins. In addition, the current peak reached a value of 280 A for each 100 kV of the step voltage amplitude.

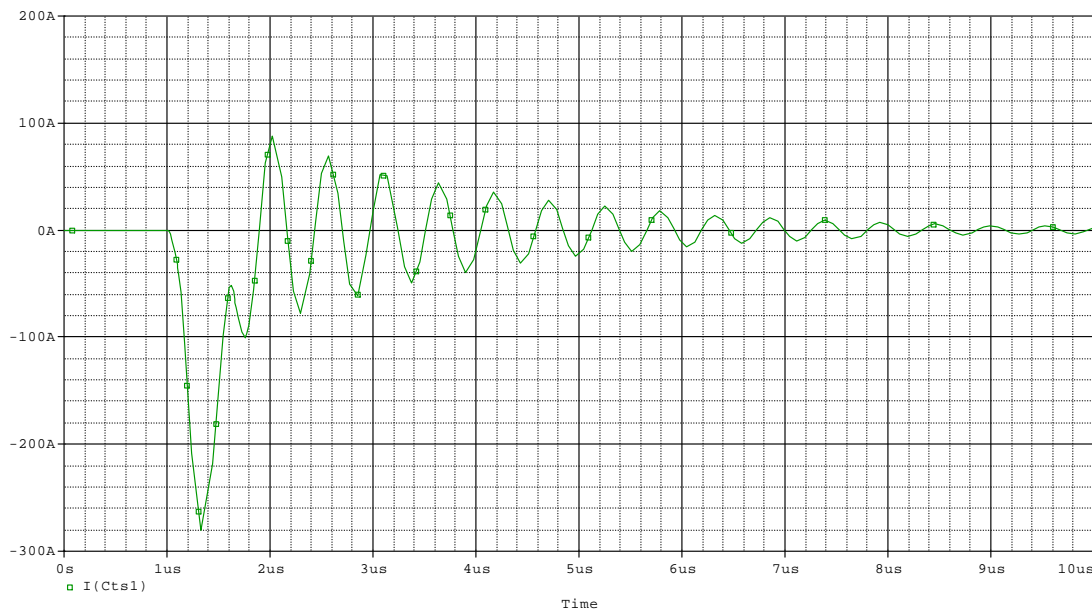


Figure 8. Current through CT to ground.

By using the conversion factor of 2.80 A/kV and the actual magnitudes of the different voltage steps recorded it was possible to determine the maximum and the average values of the peak currents that would be expected. These are 1206 A and 1060 A, respectively.

It is pointed out that such impulsive currents are applied to the real transformer as a train of impulses during each operation of the air disconnect switch.

4. CURRENT TRANSFORMER DISASSEMBLY

With the aim of detecting some damage in the insulation of the analyzed Current Transformers due to the solicitation above described, one of the machines taken out of service was completely disassembled.

The primary insulation of this type of Current Transformers basically consists of multiple layers of paper, which is impregnated with oil. They also include a number of equipotential layers in order to accomplish an adequate potential distribution inside the insulation.

The methodology employed to disassemble the CT was, as much as possible, just the opposite to that carried out during the manufacture of it.

Therefore, first the oil was completely removed. Then, the expansion bellows were also taken out and no anomaly was detected. The next step was to remove all the elements related to the primary of the CT. All the components were found in good state, as well.

Finally, it was the turn of the active part of the insulation. The procedure began by the high-voltage electrode, then the first equipotential layer (**S1**) and the three inner layers, reaching finally the last one (**S5**) corresponding to the earth electrode.

As soon as the disassembly of this part began it was possible to observe some damage in **S1** layer. The metallic had been noticeably affected by internal discharges. Once **S1** was removed, some severe damage was also observed in the oil-impregnated paper located between **S1** and **S2**.

In Fig. 9 photographs of the metallic layer and the paper are presented. Both pictures show clearly the damage caused by the electrical stress to which the isolation was subjected to.

Naturally, the level of the stress was high enough to “carbonize” the paper. Normally, discharges occur at the edge of the layers, but they can propagate rapidly in oil-impregnated paper.

After the destructive effects of the discharges were observed, the disassembly continued according to the originally planned schedule. As a result, in the **S2** layer as well as in the paper situated between **S2** and **S3** some damage was also detected, but not in the same level as in the previous case. Before reaching the layer **S3** the carbonization of the paper disappeared completely and no important anomaly was found until the end of the work.

Obviously, this damage in the insulation of the CT led to the production of the gases detected in the chromatographic determinations performed at the beginning of the study.



Figure 9. Metallic layer and paper affected by internal discharges.

This “puncture” on the insulation of the CT is thought to have been caused by the high-frequency transients that were dealt with in the previous sections. Discharges are presumably initiated at the edge of a layer with the first operations, but in the long term they can result in considerable propagation, extending through several layers of paper. If these anomalies are not detected at the correct time, they could lead the Current Transformer to complete breakdown.

In the schematic drawing of Fig. 10 it is represented the area where the main damage of the insulation was located.

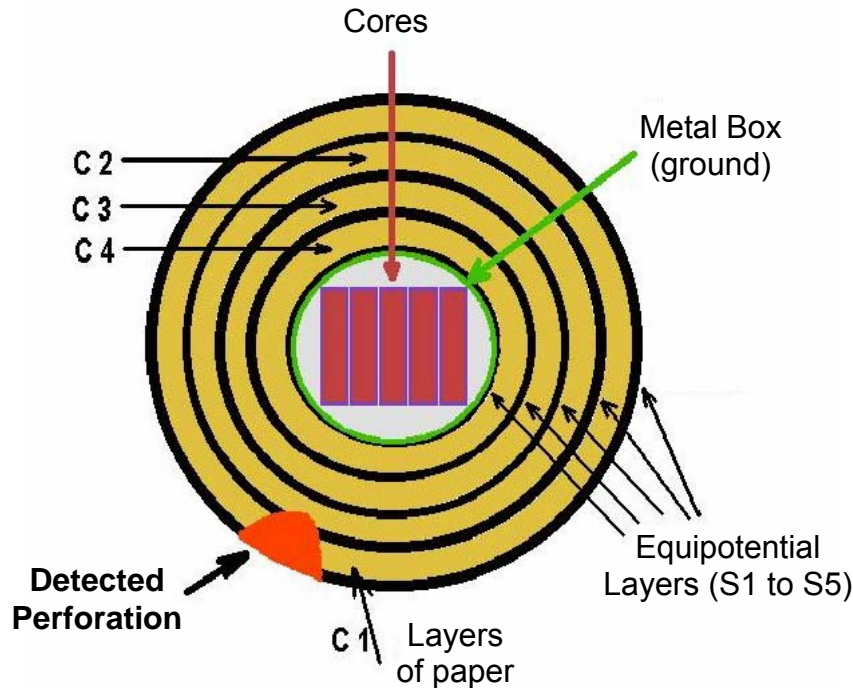


Figure 10. Schema showing the area affected by the perforation.

5. FINAL COMMENTS AND CONCLUSIONS

- By both field measurements and simulations it was possible to determine the presence of high-frequency perturbations caused by the normal operations of air disconnect switches.
- The amount of gases detected in chromatographic determinations indicated some possible damage in the insulation.
- The suspected damage was confirmed once one of the CTs was disassembly. It proves that analyses of gases are a reliable indicator of the insulation state.
- It is important to remark that the knowledge acquired from this research will be useful in the design of new Current Transformers under real electrical stresses.
- Personnel of Transmission Companies also should address the issue dealt with in this paper so as to prevent high-voltage equipment from being damaged.
- This work raises the question whether these sorts of electrical stresses are included in the type-tests described in the Standards concerning high-voltage testing. And, if so, are they properly represented?

BIBLIOGRAPHY

- [1] IEC 60044-1. Instrument transformers - Part 1: Current transformers, 2003.
- [2] IEC 62271-102. High-voltage switchgear and controlgear - Part 102: Alternating current disconnectors and earthing switches, 2003.
- [3] "Application of Fibre Optics to the Measurements of Corona Losses in UHV Experimental Lines". Third International Symposium on High Voltage Engineering. Milan, August 1979. L. Thione, G. Costa, E. Elli (CESI – Milano, ITALY). A. Manzini, A. Centemeri (ENEL CREL Milano, ITALY).
- [4] L. L. Alston. "Alston High-Voltage Technology". Oxford University Press, 1968.
- [5] M. D. del Pozo, D. Esteban, P. Issouribehere, A. Funes, A. Ledesma. "Mediciones de transitorios durante las maniobras de seccionadores en Estaciones Transformadoras de 500 kV". XIII ERIAC. Puerto Iguazú, Argentina, Mayo de 2009.