

Comparison of Field Measurements with Simulations of Transients in an Arc Furnace.

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1. Abstract

Coordination studies on the protection systems of an arc furnace were required. The protection scheme consists of ZnO surge arresters and RC suppressors. Field measurements on switching transients were performed in order to get information for building and validation of an ATP model of the system.

The model was build for simulating switching operations that are not easy to be tested in the real system or difficult to record, such as multiple re-ignitions of the arc in the circuit breaker.

MODELS was used to build the control logic that simulates the multiple re-ignitions of the arc.

In this paper are presented the results of the simulations with the digital model, and their comparisons with the transients recorded during field measurements. Transients of opening (with and without load), and closing of the circuit breaker were recorded and simulated.

Key words: SF6 Circuit Breakers, Arc furnaces, Transients overvoltages, Re-ignitions, EMTP/ATP, MODELS.

2. Introduction.

The plant of SIDERAR SAIC, located at San Nicolás (Argentina), operates a 35 MVA arc furnace, connected to a 33kV feeder through a SF6 circuit breaker. A simple one-line scheme is shown in Figure 1.

The production cycle during the day requires more or less forty closing and opening operations of the SF6 circuit breaker. The breaking in each cycle is done with the electrodes raised up, that is without load on the transformer. Exceptionally, the breaking operation may occur with the electrodes inside the bath, caused by wrong operation of overcurrent protections.

The switching of small inductive currents is a potential source of overvoltages, caused by the ‘chopping current’ phenomena, and/or by possible occurrence of multiple re-ignitions of the arc in the circuit breaker [1]. When the overvoltage due to the current chopping is large, the occurrence of the re-ignition of the circuit breaker arc is frequent. In the case of an arc furnace the problem is enhanced because the frequent switching operations.

The current chopping may cause low frequency overvoltage, which must be compared with the power frequency withstand level of the transformer.

The re-ignitions cause overvoltages of very high frequency, stressing not only the insulation to ground, but also the inter-turns insulation of the transformer. These overvoltages should be compared with the impulse withstand level of the transformer.

To protect the transformer against these phenomenal, RC suppressors are installed at the terminals (principal), and ZnO surge arresters, in candelabrum connection, as backup protection.

To test the good behavior of the protection system, and to determine the maximum solicitations caused by the operation of the arc furnace, a study was performed with simulation using an ATP model of the network.

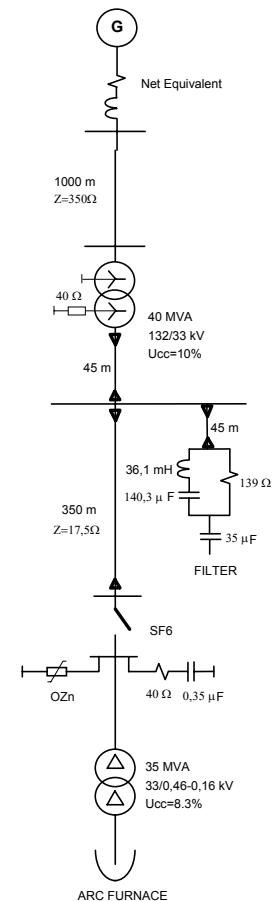


Figure 1. The network configuration.

3. Methodology.

To order to get information for building the digital model of the system, field measurements were realized recording the transients caused by the switching maneuvers [2].

Using that information, the digital model was build on EMTP/ATP code, used with the authorization of the Comité Argentino de Usuarios del EMTP/ATP (CAUE), under license without charge given by the Canadian-American User Group.

To validate the model, the maneuvers recorded during the field test were simulated, and compared with the measurements, adjusting the parameters adjust of the models when required.

With the validated model, simulations of different transients were done, looking the maximum stress in the system.

4. Field Measurements.

Field measurements were recorded from thirteen switching operations: ten opening and three closing operations of the arc furnace circuit breaker.

To measure the voltage, two capacitive divider were available, so only the voltages in two points of the network could be recorded at the same time. The highest sample frequency was $0.5\mu\text{s}$, in order to record the highest frequency phenomena's, taking into account possible re-ignitions of the arc in the circuit breaker.

For measuring the current in the circuit breaker, the current transformer existent in the installation were used, connecting the recording equipment to the secondary of the current protections relays of the transformer.

Measurements were done in normal behavior of the furnace. Only for the recording of transients during the breaking of the load current, the operators were asked to alter the normal operation, opening the circuit breaker with the electrodes inside the bath.

5. Model of the system.

The main difficulty to building the model of the system was the lack of certain important characteristics of some elements of the network: the behavior of the arc and the recovery dielectric strength between contacts of the circuit breaker are not know; neither are known the characteristic of the magnetic circuit of the transformer and the necessary information for building a valid model for high frequency transients.

That situation obliges to use simple models, and to do a sensitivity analysis of the transients with respect to the parameters of the network. A description of the model used follows.

5.1.1 Circuit Breaker

As the parameters that describe the behavior of the arc in the circuit breaker are not known, we did not use a model in witch it is simulated. We used a simple switch model (type 13), which is controlled by means of a logic imposed in MODELS, simulating the multiple re-ignitions of the arc in it.

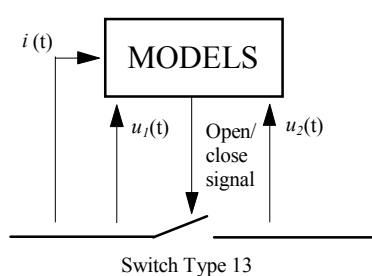


Figure 2. Signals between MODELS and ATP

This model takes into account the following qualities:

- The recovery dielectric strength characteristic between contacts when opening.
- The ability of the circuit breaker to chop the current before its natural zero (“Chopping Current”).
- The highest slope of the current, when passing through zero, that the switch is able to interrupt.

This model is considered suitable for this study, considering that the principal interest is to verify the effectiveness of the protection against of eventual re-ignitions of the arc in the circuit breaker, and not to test the existence or not of them.

The control logic implemented in MODELS, that allows simulations of multiple re-ignitions (scheme in Figure 2), is the following:

- After mechanic separation of the contacts of the circuit breaker, it is considered that the dielectric strength between them grows up linearly, with a definite slope. This straight rise defines the transient recovery voltage withstand between contacts for each instant after the current interruption.
- The voltage between contacts in each instant, $u_1(t)-u_2(t)$ in Figure 2, is compared with the voltage withstand (defined by the above mentioned straight rise) and in case it is surpassed, a closing signal is given to the switch, so a re-ignition of the arc is simulated.
- If the re-ignition occur, then two conditions should be fulfilled for the switch to interrupt the current again: a) the slope of the current through zero must be bellow of a definite value, and b) the instantaneous value must be smaller than that which the circuit breaker can chop (“Chopping current”). Only in the case were both conditions are met, an opening signal for the switch is produced.

The preceding logic is repeated for each time step, and in this manner is possible to simulate the multiple re-ignitions phenomena.

5.1.2 Furnace transformer

We represented the transformer with the simple model TRANSFORMER of the ATP. The data for the model are obtained initially from the test reports, they are:

KV rating = 33/0,46 kV	Load losses = 283 kW
MVA rating = 35 MVA	No-Load losses = 40 kW
$U_{cc} = 8.3 \%$	Magnetizing current = 3.4 A
Connection = Δ/Δ	

We included in the magnetizing branch of the model a resistance which takes into account the core losses. Since the connection of the transformer is delta, the value of the resistance is $33^2\text{kV}/40\text{kW}=80\text{k}\Omega$. Other data of the magnetic circuit, such as the saturation curve, are unknown. Both resistance and no-lineal characteristics of the magnetizing circuit are parameters to be adjusted through comparisons between field measurements and simulations results.

5.1.3 Cables.

The arc furnace and the primary transformer are connected through three underground cables of $3 \times 1 \times 120\text{mm}^2$ each, 0.35 km length. These cables are represented as an equivalent line with distributed parameters. The capacitance of each phase of the cable is $0.19\mu\text{F}/\text{km}$. The dependency of the parameters with the frequency is not taken into account.

5.1.4 Other elements.

With respect to the protection elements of the transformer, only the RC suppressors were included in the model, because from the field records there were not evidences of operation of the surge arresters.

The feeding network was represented with an equivalent impedance, so that at the 132kV bus of the energy supply company the short circuit power is 1500 MVA. From there to the incoming point of the plant, there is a line of 1 km length, simulated with distributed parameters and connected to the main transformer of the plant. At the secondary side of this transformer, were included the 3th order filters.

6. Field records and comparisons with simulations.

The field record were first converted to ASCII format, and then to PL4 format, using the GENPL4 utility, from Prof. Kizilcay. In this way, plotting and comparing the measurements against the results of simulations was possible with the TPLOT. It was used the command JOIN of the TPLOT to put together different files, and the command MATH to process the voltage records at the two sides of the circuit breaker, to get the transient recovery voltage between contacts.

6.1 Breaking the magnetizing current.

The field measurements of the current provides information on the behavior of the magnetic circuit. From the record shown in Figure 3, it is evident that the effects of saturation are present at the nominal voltage, and therefore they cannot be ignored.

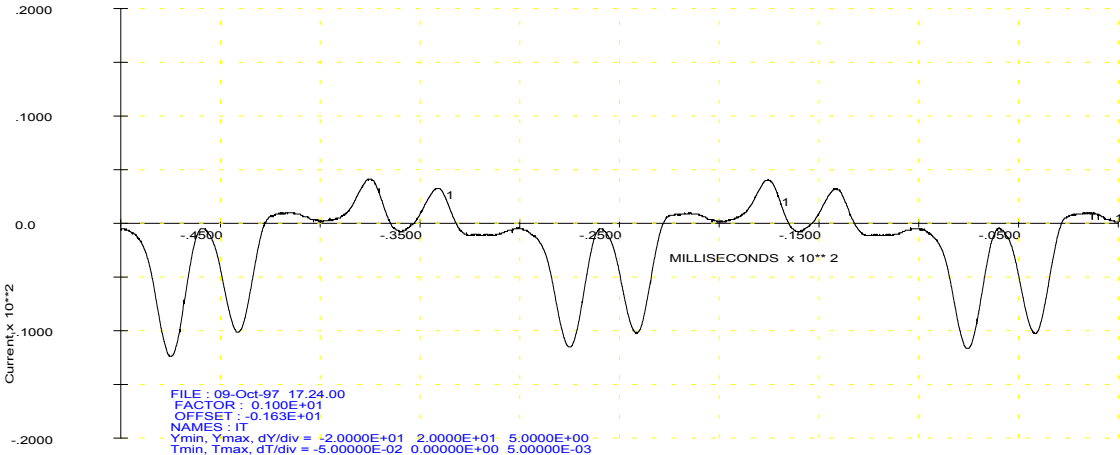


Figure 3. Circuit breaker current (measured).

It can also be observed that the waveform of the current is not symmetrical. This is due to the residual flux in the magnetic circuit of the transformer, at the moment of switching-off.

In the model, this phenomena was not included, because of the difficulty to do it. It takes into account, however, the saturation of the magnetic circuit, which is represented by means of two straight lines, defined by the following points:

I_{rms} [A]	V_{rms} [V]
0.98	29700
3.00	33000

These points were obtained by trial and error. The waveform of the current was adjusted so that the sum of the absolute values of negative and positive peaks, are equal in the simulation that in the measurement record.

The waveform of the current obtained with this model is shown in Figure 4 (in full line). Obviously, there is no asymmetry with respect to the abscissa axis. It can be considered that this would be the current for the circuit breaker if no residual flux exist in the core of the transformer.

The current waveform is important for the determination of the instantaneous value of the current in each phase at the moment of switch-off, which is representative of the magnetic energy available to be converted into electrostatic energy when current chopping occurs. The Figure 4 shows furthermore that the transformer magnetizing current is bigger than in the circuit breaker and do not necessary pass through zero simultaneously. The difference is the current through the RC suppressors, which cannot be ignored in this case. It is important to realize that even without chopping of the current in the circuit breaker, there is energy stored in the magnetic circuit to be converted into electrostatic energy.

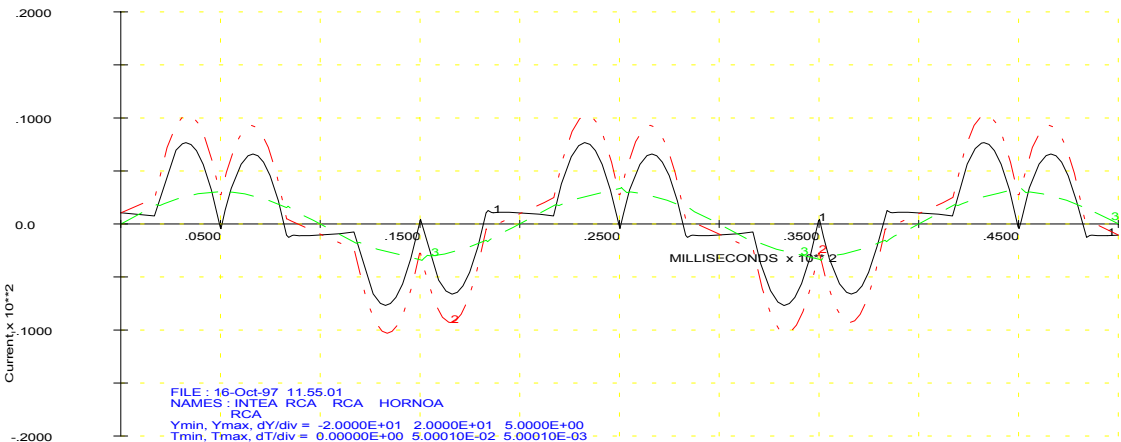


Figure 4. Simulated results: 1-circuit breaker current, 2-magnetizing current, 3-current in the RC suppressor.

The residual flux cause that the current peak is bigger in the real circuit breaker than in the model, so that if the circuit breaker can chop a current of, say, 10 A, then this cannot be simulated with the model. However, it was verified from the field records that the current chopping was no greater than 5 A.

It was also ascertained that the three phases of the circuit breaker open simultaneously. However, since in the model the asymmetry of the current was not represented, the distribution of the magnetic energy among the phases will not be equal that in the real circuit.

But, we are looking for voltages, and then the question is: what happens with them when the asymmetric behavior of the current is not represent?

Figure 5 shows the voltage to ground, measured and simulated, at the terminals of the transformer. It is observed that the frequency of the measured oscillations is close to the power frequency, strongly damped, and deformed due to the no lineal characteristic of the magnetic circuit and the effects of the residual flux. This was observed in all field records.

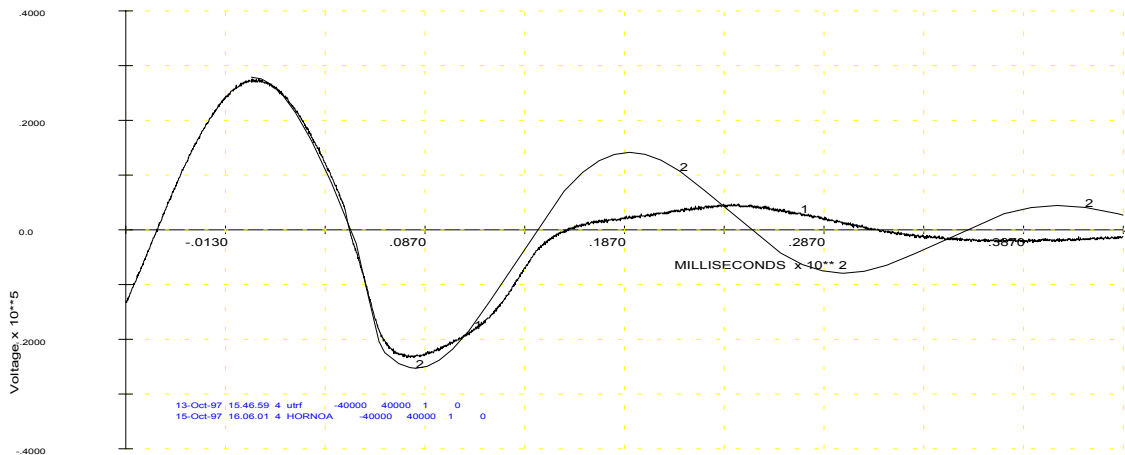


Figure 5. Measured (1) and simulated (2) phase to ground voltage at transformer terminal.

This behavior is due to the RC suppressors, which together with the low level of current chopping of the circuit breaker contribute to maintain the voltage stresses below the nominal voltage of the system. Hence, there are no significant overvoltages due to chopping current phenomena. It is observed that the oscillations obtained by simulation are well damped and the first cycle is close to the recorded, but is more oscillatory and not deformed.

Since voltage was measured at both sides of the circuit breaker, it is possible to get the transient recovery voltage (TRV) between contacts of the switch through digital processing of the records. The results are shown in Figure 6, in which the waveform of the TRV obtained by simulation has been superposed.

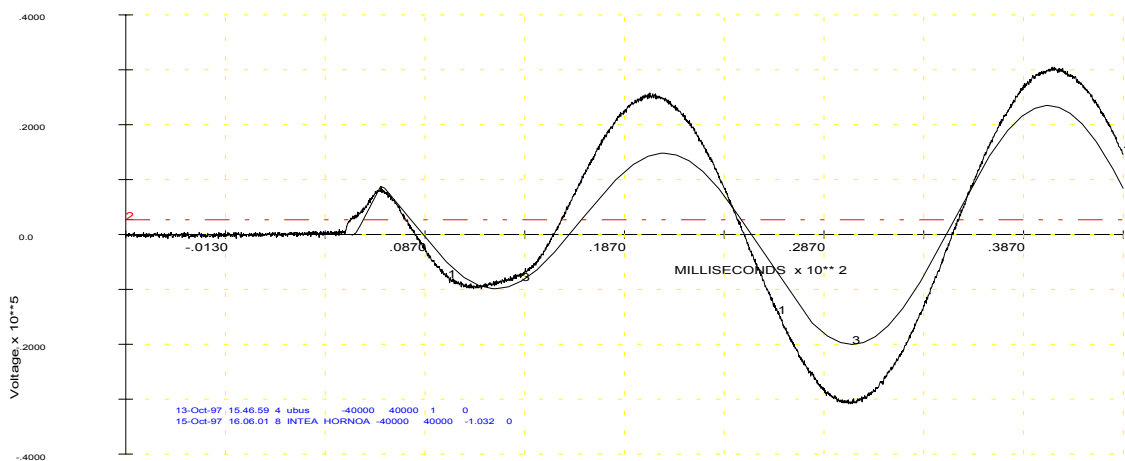


Figure 6. Comparison between measured (1), and simulated (3) transient recovery voltage.

It is observed that due the low frequency of the oscillation, the recovery voltage between circuit breaker contacts obtained by the model is optimistic, and the phase to ground voltage in the model is more oscillatory that in the real circuit.

Concerning the possibility of re-ignitions, it is observed in the Figure 6 (and also in the remaining records) that the slope of the TRV in the first cycles is less than 5 kV/ms. The slope of the dielectric recovery strength between contacts of circuit breaker is usually higher,

and therefore there is not risk of re-ignition of the arc during the opening of the magnetizing current of the transformer.

6.2 Breaking of the load current.

Because the equivalent impedance of the transformer with the load is much less than the magnetizing impedance, the oscillation of the transients are of greater frequency than those in the case of breaking the magnetizing current. Also, the characteristic impedance is much lower and, consequently, the overvoltage due to the chopping phenomena should be lower.

Figure 7 shows the measured phase to ground voltage at the transformer terminals in the phase that opens first, and Figure 8 shows the transient recovery voltage between contacts. In both figures the waveform obtained by simulation is superposed.

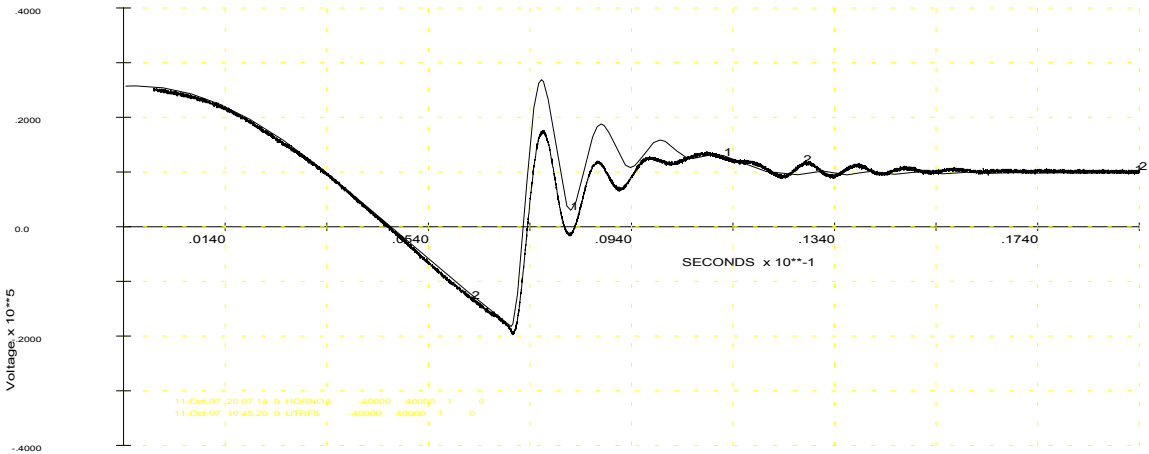


Figure 7. Phase to ground voltage, simulated and measured, when breaking the load current of the transformer.

The measured slope of the TRV recorded in the field measurements is approximately 85 kV/ms and the amplitude more of 40 kV, both magnitudes are much greater than when breaking the magnetizing current of the transformer.

To simulate the arc, it was included in the secondary of the transformer a symmetrical RL branch to ground, in order to obtain approximately the nominal current of the transformer. Due to the symmetry of the load, and the delta connection of the transformer, the oscillation of the voltage in the first phase to open it is about $0.5 \cos(\omega t)$ p.u., until the opening of the remaining two phases, which occurs 5ms later. This can be observed in the waveform simulated of Figure 7.

But the load is an arc in the arc furnace, and this is not symmetrical. Then, in the first phase to open, the oscillation of the recorded voltage is about a lower value than the above mentioned. In other words, the difference that can be seen between the curves shown in Figure 7 is due to the representation of the arc.

Even though it is possible to get the asymmetry of the load so that the field record coincides with the simulation shown in the figure, this would be valid only for this particular measurement, since the behavior of the arc is random.

But, since considering the load as symmetrical implies a situation more pessimistic for the voltages at the transformer terminals and for the transient recovery voltage between contacts, we accept this model as valid.

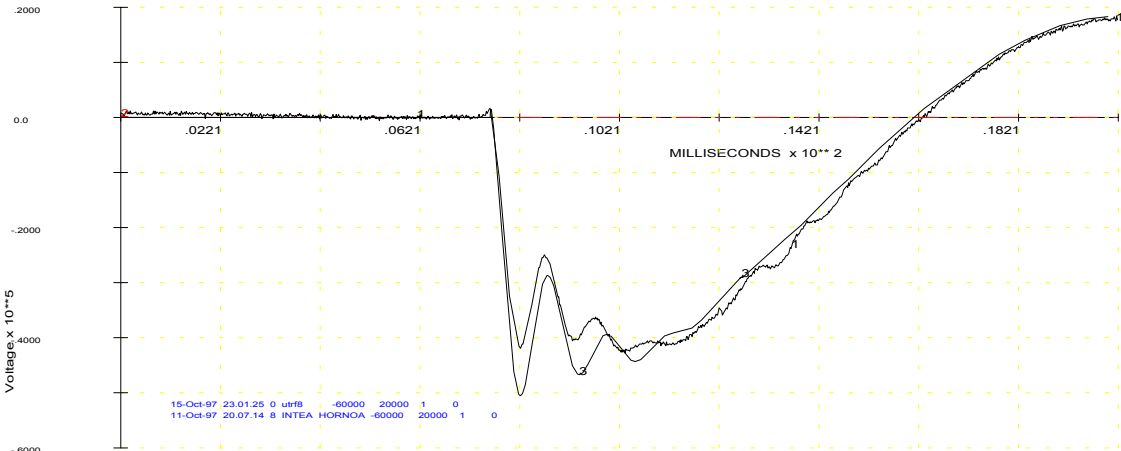


Figure 8 Transiente recovery voltage, measured (1) and simulated (3).

6.3 Closing the circuit breaker.

The closing of the circuit breaker does not produce high stresses in the system, but the recording of this transients is useful because it permits to observe fast transients, similar to those which can appear when a re-ignition of the arc occurs.

Since the occurrence of a re-ignition during the breaking of the load or the no load currents is a random phenomena, it is more easy to recorded the surges of short front time which always occur in the energization.

Figure 9 show the recorded voltage to ground in one phase of the transformer. The wide of the each step that is observed in the waveform, is the double of the travel time in the 0.35 km cable, which connects the arc furnace with the main feeding transformer of the plant. The travel time measured from the field record is 2.2μs, that is $v=159000$ km/s

Since it is known that the capacitance of the cable is 0.19μF, it is deduced that its characteristic impedance is $Z_c= 1/Cv = 33\Omega$ (each cable).

With this data was simulated the closing operation and the waveform obtained is shown for comparison in the same Figure 9, and it is observed a good agreement between both curves.

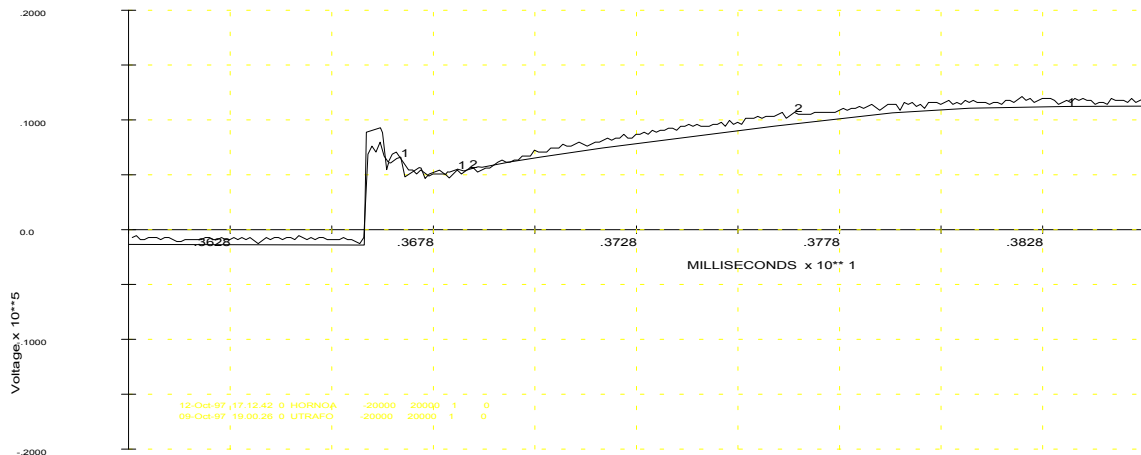


Figure 9. Phase to ground voltage at transformer terminal: (1) simulated, (2) measured.

7. Re-ignition simulation with the digital model

From the measurements, and simulations of breaking of the magnetizing current in different unfavorable situations, it was concluded that there are practically no probability of finding re-ignitions in this maneuver, due to the low initial slope the TRV between contacts of circuit breaker.

But, as already pointed out, this is not the case when breaking the load current of the arc furnace, in which the TRV grows up very quickly. Then, the digital model was used to see what happens if re-ignition occurs in this situation, using the circuit breaker implemented in MODELS.

We considered that the slope of the recovery withstand voltage between contacts of the circuit breaker is 33400 V/ms, and the instant of mechanical separation of the contacts is such that the re-ignitions occur when the transient recovery voltage is maximum. The resulting phase to ground voltage at the transformer is shown in Figure 10.

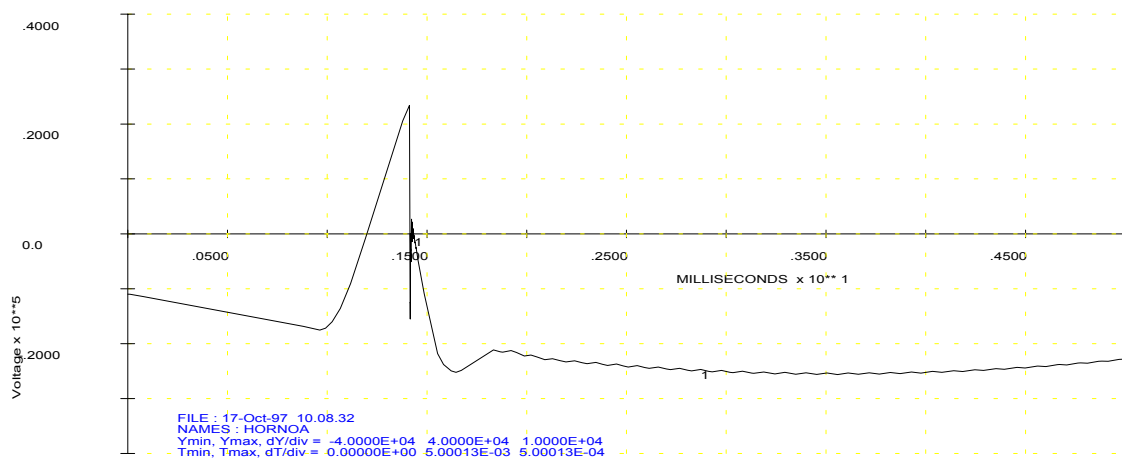


Figure 10. Phase to ground voltage at transformer terminal when a re-ignitions occur.

Considering that the BIL of transformer is 250 kV, it is observed that the re-ignition does not produce a high stress on the insulation.

Figure 11 shows the simulated circuit breaker current. It has been considered in the model that the maximum slope of the current, that the circuit breaker can interrupt is 100 A/μs when passing through zero, but in this figure it can be observed that after the re-ignition the current never goes through zero, so this value is not very important.

Also, the instantaneous value of the current after re-ignition is always above 100 A, which is much more than the current which the circuit breaker can chop. Hence, the circuit breaker cannot interrupt the re-ignition current.

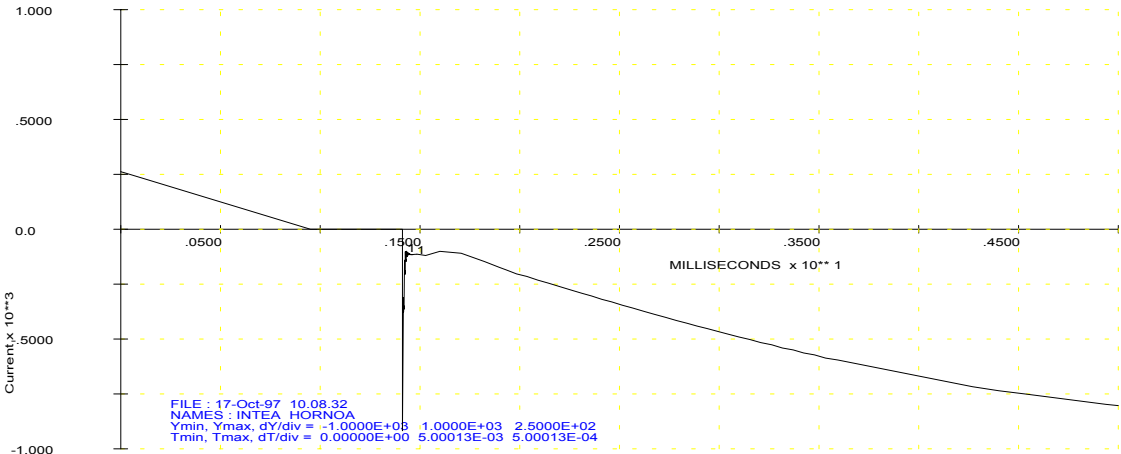


Figure 11. Current in the circuit breaker when a re-ignition occur.

The current could not be recorded during the field measurements, so the model was of help to analyze the probability of occurrence of multiple re-ignitions.

Several situations were analyzed with the model, simulating the occurrence of re-ignitions in different instants after the mechanic separation of the contacts. The conclusions was that, with respect to the breaking of the load current of the transformer, one re-ignition can occur, but it is practically impossible the occurrence of ‘multiple’ re-ignitions.

8. Conclusions.

Whit respect to the breaking of the magnetizing current:

In the construction of the model to simulate the breaking of the magnetizing current, it was found that some aspects of the behavior of the transformers magnetic circuit, which are difficult to be obtained and to include in the model, such as the effects of residual flux, influence the waveform of the overvoltage. If there are not included in the model, then the available magnetic energy at the moment of current chopping it will not be correctly considerate. The saturation of the magnetic circuit of the arc furnace transformer should be included in order to get a good representation for the first cycle of the transient.

The RC suppressors provide an adequate protection of the transformer. There are not overvoltages due to current chopping and the probability of occurrence of re-ignitions due to this phenomena is practically nil.

With respect to the breaking of the load current of the transformer:

It is important a correct representation of the arc in the arc furnace in order to obtain a good model of the system. If this is modelled as a symmetrical load, then the results are pessimistic.

This maneuver does not produce overvoltages in the system, but it increases the slope of the transient recovery voltage between contacts of the circuit breaker and, hence, the probability of occurrence of re-ignitions of the circuit breaker arc, even with the RC suppressors connected.

From the field measurements of the closing maneuver, were obtained the data that permit a good representation of the system for high frequencies, allowing to make simulations of re-ignitions.

The studies accomplished with the model permit to know that, in the breaking of the load current, re-ignitions of the arc will be rare events. However, if one occurs, it will not produce a severe stresses in the system by itself, though due to the frequent operations of the arc furnace, it is recommended that this maneuver be avoided whenever possible.

In general terms:

For the purpose of the present study, to analyze the effectiveness of the protection of the arc furnace, with a very simple model of the transformer, circuit breaker and cables, its possible to build an acceptable digital model of the network,.

From the records obtained in the field measurements, as well as from the simulations accomplished with the digital model, there were not observed overvoltages that imply the operation of the surge arresters. However, they constitute the backup protection, and the operation of their counting surges device is an indication of a possible damage of the RC suppressors.

9. References

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