

# Power transformers in parallel which share a neutral resistance: how to manage the circulating current between the secondary windings

M.Sc. Eng. G.Calzolari, Member, IEEE, M.Sc. Eng. C.Saldaña, Member, IEEE

**Abstract--** This paper presents the problem of a circulating current which appears due to the connection of power transformers in parallel which share a neutral resistance. Because of the actual protection scheme adopted, the circulating current might produce undesirable overcurrent relay trips, causing the interruption of the supply. This paper focuses on the most important aspects of the ATP (Alternative Transients Program) modelling of the overcurrent relays, the analysis of the circulating current resulting from ATP simulations of some disturbances, a new trip logic developed for solving the problem mentioned above as well as the test of its performance with digital simulations.

**Keywords:** circulating current, overcurrent relay, MODELS, power transformer.

## I. INTRODUCTION

Nowadays, in the transmission network of Uruguay, power transformers have been connected in parallel in order to supply the demand and improve the reliability of the power system.

These transformers are three-phase, three-winding core type, group of connection YNYn0D5, with the neutrals of the secondary windings earthed through a common resistance, in order to reduce the short-circuit current. The neutrals of the primary windings are directly earthed.

Regarding the transformers, it is important to remark that they have been bought on different occasions and from different manufacturers, so their apparent power and the nominal ratings of their delta-connected tertiary windings are quite distinct.

Current transformers, feeding overcurrent relays, are located in the secondary windings in order to detect fault currents and a residual current. There is also a current transformer, feeding an overcurrent relay, located in the neutral resistance in order to detect fault currents in the low voltage side.

Some disturbances such as faults in the high voltage side, transformer switchings in the low voltage side, three-phase reclosing schemes in the high voltage side, etc. can produce

circulating currents between the secondary windings. In other words, residual currents flowing between the secondary neutrals might produce undesirable overcurrent relays operation causing the interruption of the supply, without the presence of a fault in the low voltage side.

To avoid these prejudicial trips, different disturbances were simulated in order to know the behavior of the circulating current and how to modify the actual protection scheme.

Because of the nature of the circulating current, the need for detailed modelling of power transformers and overcurrent relays, the non-linearities involved, the pole span of the circuit breakers, etc., it was decided to use the ATP program as a tool for the analysis.

## II. NEW TRIP LOGIC

At this moment, it is important to point out that many of the stations connected to the transmission network do not have voltage transformers for protection purposes due to economic reasons. In this way it is impossible to use directional overcurrent relays in order to detect circulating currents and avoid undesirable trips. As a consequence, a new trip logic was developed without the need to buy new equipment. The main goal is to apply the new trip logic in all the stations where power transformers are connected in parallel sharing a neutral resistance.

A typical station in the 150 kV voltage level named Colonia, was chosen for conducting the studies.

Fig. 1 shows the one-line single diagram of the Colonia station, which bears the following characteristics:

a) one power transformer T1 of 40 MVA apparent power rating and voltage ratings 150/31.5/6.9 kV. The transformer short-circuit impedances (primary P, secondary S and tertiary T) in the positive sequence are:  $Z_{PS+}=9.03\%$ ,  $Z_{PT+}=12.4\%$ ,  $Z_{ST+}=3.3\%$ , all based on 40 MVA at 50 Hz. The transformer short-circuit impedances in the zero sequence are:  $Z_{PS0}=7.27\%$ ,  $Z_{PT0}=10.98\%$ ,  $Z_{ST0}=3.22\%$ , all based on 40 MVA at 50 Hz.

b) another power transformer T2 of 25 MVA apparent power rating and voltage ratings 150/31.5/13.8 kV. The transformer short-circuit impedances (primary P, secondary S and tertiary T) in the positive sequence are:  $Z_{PS+}=8.91\%$ ,  $Z_{PT+}=11.0\%$ ,  $Z_{ST+}=2.5\%$ , all based on 25 MVA at 50 Hz. The transformer short-circuit impedances in the zero sequence are:  $Z_{PS0}=7.51\%$ ,  $Z_{PT0}=10.37\%$ ,  $Z_{ST0}=2.73\%$ , all based on 25 MVA at 50 Hz.

G.Calzolari is with the Department of Projects and Studies, UTE, Av. Millan 4016, Montevideo 11700, Uruguay (e-mail: gcalzolari@ute.com.uy).

C.Saldaña is with the department of Power System Protection, UTE, Av. Millan 4016, Montevideo 11700, Uruguay (e-mail: gracclau@adinet.com.uy).

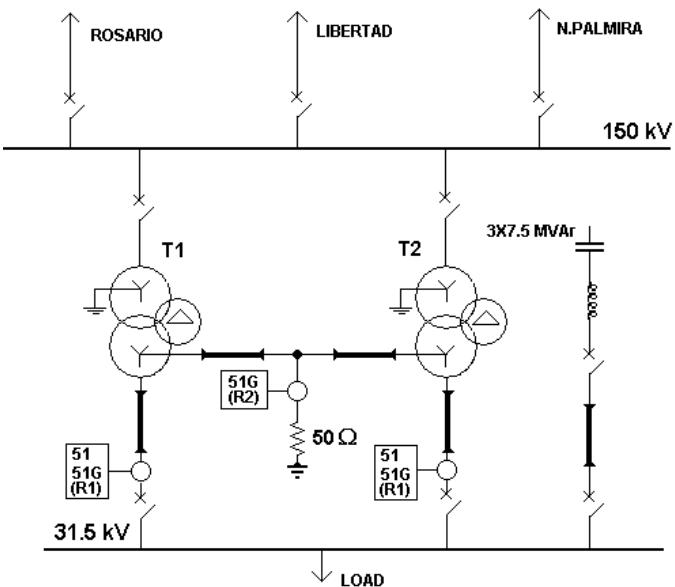


Fig. 1 - Colonia station

- c) three transmission lines connect the Colonia station to the 150 kV voltage level network.
- d) a secondary neutral resistance of  $50\ \Omega$ .
- e) three capacitor banks of 7.5 MVAr each are connected to the 31.5 kV bus bar for reactive compensation.
- f) the load is fed by five radial circuits.

The relays 51G shown in Fig. 1 are inverse time overcurrent relays. Their characteristics "very inverse" have the following mathematical expression [5]:

$$t = \frac{13.5}{(I/I_s) - 1} * k \quad (1)$$

where:  $t$  - operating time     $k$  - constant  
 $I_s$  - setting current     $I$  - current in the relay

For the relays named R1 located in the secondary windings the parameters of (1) are:  $k$  equal to 0.3 and  $I_s$  equal to 60 Arms (primary side). The pick up current is  $1.1*I_s$ .

For the relay named R2 located in the neutral resistance the parameters of (1) are:  $k$  equal to 0.5 and  $I_s$  equal to 40 Arms (primary side). The pick up current is  $1.3*I_s$ .

With the present protection scheme the circulating current might produce undesirable operation of each relay R1 causing the interruption of the supply and no operation of the relay R2.

It is very important to remark that when the circulating current flows between the secondary windings no current flows through the neutral resistance. Based on the previous fact, a new trip logic was developed in order to avoid undesirable trips.

The first attempt for a new trip logic was:

**[R1 operates] .AND. [R2 operates]**

and this could be synthesized in a electric circuit as shown in

Fig. 2a. It works in the following way: a) When a circulating current flows, R1 operates (contact closes) and R2 does not operate (contact remains open). The AND expression is equal to zero, it means there is no circuit breaker operation. b) For faults involving the earth, in the low voltage side, R1 operates (contact closes) and R2 operates (contact closes). The AND expression is equal to one, so the circuit breakers open.

For faults involving the earth, in the low voltage side, the current through the neutral resistance is roughly twice the residual current through the secondary windings. Taking into account the relay characteristics, it is expected that R2 relay will operate faster than R1 relays. As a result, this new trip logic introduces an undesirable time delay for circuit breakers openings. This difficulty was overcome by introducing the following modification to the logic:

**{[R1 operates] .AND. [R2 operates]}.OR.[R2 operates]**

and this could be synthesized in a electric circuit as shown in Fig. 2b.

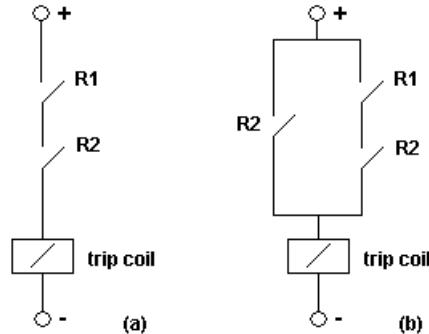


Fig. 2 – New trip logic

### III. ATP MODELLING [1][2][3][4]

In this section the most important aspects of the ATP modelling of the Colonia station and overcurrent relays are going to be presented.

#### A. Colonia Station

The power transformers T1 and T2 were modelled through the matricial model [A]-[R] using the BCTRAN supporting program. The iron core losses were represented as lumped resistances placed across the terminals of the primary windings. The saturation effects were taken into account through the Pseudo-nonlinear reactor (Type 98) and the Pseudo-nonlinear hysteretic reactor (Type 96) placed across the terminals of the primary windings. The residual fluxes in the core were assumed equal to 0.7 pu, 0.0 pu and -0.7 pu.

The neutral resistance and the capacitor banks were represented as lumped elements. The load is also represented as lumped elements in a delta circuit.

The transmission lines were modelled through the transposed distributed-parameter transmission line model. The cables shown in Fig. 1 were represented through  $\pi$  circuits.

The circuit breakers were modelled either as time-controlled switches or as statistical switches. The pole span was assumed to be 5 ms.

The Colonia station model was included in a complete model of the 500 kV and 150 kV transmission networks.

### B. Overcurrent Relays

The performance of the overcurrent relays is dependent on obtaining accurate estimates of the fundamental frequency components of current signals from a few samples. The currents are sampled at a sampling frequency equal to 1kHz.

The Discrete Fourier Transform is used to estimate the fundamental frequency components, in this case full-cycle algorithm at twenty samples per cycle was chosen. The algorithm implemented has a data window of twenty samples, that is, as a new sample becomes available, the oldest of the twenty sample values is discarded and the new sample value is included in the calculation. The recursive form of the full-cycle algorithm, described in reference [3], was implemented as a part of the complete overcurrent relay model developed with MODELS option of the ATP Program.

The inputs signals of the overcurrent relay model are phase instantaneous currents of the secondary windings and the instantaneous current through the neutral resistance. Other inputs are switch status representing fault application or circuit breaker operations.

The overcurrent relay model takes into account: a) the calculation of the magnitudes and angles of the fundamental frequency phasors of the residual currents in the secondary windings and the current through the neutral resistance. b) the computation of the times from which the relays will pick up. c) the calculation of the operating times, resulting from the implementation of (1) for each relay. d) the computation of the logical value of the new trip logic developed in order to know if there will be circuit breakers openings.

The outputs signals of the overcurrent relay model are the magnitudes and angles of the current phasors, the pick up times, the operating times and the new trip logic value.

## IV. RESIDUAL CURRENT ANALYSIS AND NEW LOGIC PERFORMANCE

In order to analyze the circulating current and to test the new logic performance, a number of transients studies have been carried out to calculate circulating current following: faults involving the earth in the high voltage side, faults involving the earth in the low voltage side and transformer energizations. The network conditions before these disturbances correspond to a maximum load with hydraulic and thermal dispatches.

### A. Zero sequence equivalent electric circuit

In order to get a better comprehension of the circulating current phenomenon a zero sequence equivalent circuit per phase was derived for the power transformer connection shown in Fig. 1. This equivalent circuit resulted from a set of equations which takes into account the fundamental

relationships between electric and magnetic variables of both power transformers. Fig. 3 shows the equivalent circuit where  $Z_{PT1}$ ,  $Z_{PT2}$ ,  $Z_{ST1}$ ,  $Z_{ST2}$ ,  $Z_{TT1}$ ,  $Z_{TT2}$ , are the impedances of the well-known star circuit.

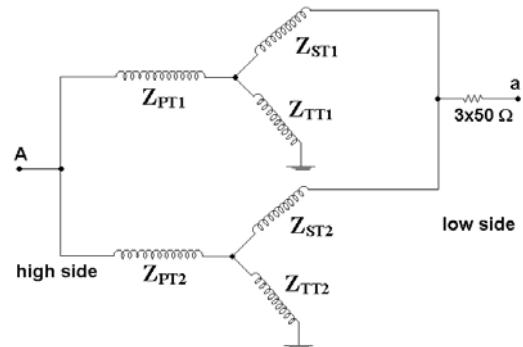


Fig. 3 – Zero sequence equivalent circuit

### B. Single line-to-ground faults in the 150 kV network

If a single line-to-ground fault is applied to the 150 kV network a circulating current between the secondary windings flows. In other words, the injection of a zero sequence current into terminal A of the equivalent circuit of Fig. 3 produces a circulating current through the impedances  $Z_{ST1}$  and  $Z_{ST2}$ .

Several studies were carried out in order to consider the influence of different: a) fault locations b) instants of time of fault application c) economic dispatches d) numbers of transmission lines connecting Colonia station to the grid e) stabilizing windings characteristics. From the results obtained, it can be concluded that the stabilizing winding has a strong influence on the magnitude of the circulating current. The following cases will show the circulating current and the new trip logic performance obtained from ATP simulations.

#### 1) Case I

In this case a single line-to-ground fault is applied to the 150 kV bus bar at Colonia station. Both power transformers have their stabilizing windings closed. Fig. 4 shows the time variation of the magnitude of the circulating current and the magnitude of its fundamental frequency phasor (MODUIA).

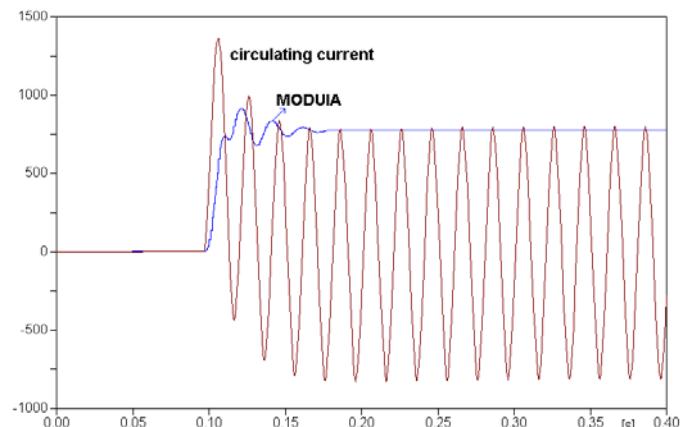


Fig. 4 – Circulating current

In this case the magnitude of the phasor is equal to 780 A peak, therefore each relay R1 operates and R2 does not operate because there is no current through the neutral resistance. The operating time is 516.9 ms which is comparable to zone 2 distance relay operating time of the transmission lines feeding Colonia. Regarding the new trip logic performance, the R2 contact remained open and the R1 contact closed, so no trip signal is generated.

### 2) Case 2

In this case a single line-to-ground fault is applied to the 150 kV bus bar at Colonia station. Power transformer T1 has its stabilizing winding open and power transformer T2 has its stabilizing winding closed. In this case the magnitude of the fundamental frequency phasor (MODUIA) is equal to 7273 A peak, which is nine times the value obtained in Case 1. Therefore, each relay R1 operates and R2 does not operate. The operating time is 68.2 ms which is comparable to zone 1 distance relay operating time of the transmission lines feeding Colonia. The new trip logic performance is correct.

These results suggest avoiding an operating condition where one of the stabilizing windings is open.

### 3) Case 3

In this case a single line-to-ground fault is applied to the 150 kV bus bar at Colonia station. Power transformers have their stabilizing winding open. In this case there is not a circulating current.

### 4) Case 4

As mentioned before, the new trip logic is going to be applied in all the stations that have similar layout to Colonia station. For the stabilizing windings, only their apparent powers are specified, so a large number of different delta-connected windings is found. Also, a large difference between the circulating currents obtained from cases 1) and 2) could be observed. For all these reasons, it was decided to conduct a sensibility analysis of the circulating current taking into account all the different power transformers in the Uruguay network with voltage ratings 150/31.5 kV and stabilizing windings.

The procedure of the sensibility analysis consists of:

a) the reactance values in p.u. (based on 100 MVA), of the star circuit for power transformers T1 and T2 were calculated, as shown in Table I.

TABLE I

	X <sub>P</sub> p.u.	X <sub>S</sub> p.u.	X <sub>T</sub> p.u.
T1	0.22754	0.000035	0.08247
T2	0.3482	0.0082	0.0918

b) from the data of the transformers, each reactance of the star circuit was characterized by the mean value, the maximum and minimum values and the standard deviation assuming normal distribution. Table II shows the results in p.u. (based on 100 MVA) corresponding to the stabilizing winding.

TABLE II

	X <sub>T</sub> p.u.
Mean value	0.15755
Deviation	0.11706
Maximum	0.46202
Minimum	0.07035

c) from the values of Table I it can be concluded that the stabilizing winding reactances of transformers T1 and T2 are close to the minimum value indicated in Table II. Then a new case, where the power transformer with the highest value of X<sub>T</sub> was connected in parallel with T1, was analyzed. This power transformer named T3 has a reactance X<sub>T</sub> value equal to 0.52663 p.u. (based on 100 MVA).

A single line-to-ground fault is applied to the 150 kV bus bar at Colonia station. In this case the magnitude of the fundamental frequency phasor (MODUIA) is equal to 6024 A peak, which is eight times the value obtained in Case 1. Therefore each relay R1 operates and R2 does not operate. The operating time is 78 ms which is comparable to zone 1 distance relay operating time of the transmission lines feeding Colonia. The new trip logic performance is right. These results suggest to allocate power transformers in parallel with similar stabilizing windings impedances whenever it is possible.

### C. Single line-to-ground faults in the 31.5 kV network

When a fault is applied in the 31.5 kV network the new trip logic must generate trip signals with the purpose to clear the fault. In order to test its performance a single line-to-ground fault is applied to the 31.5 kV bus bar at Colonia station.

Both power transformers have their stabilizing windings closed. The magnitude of the phasor (MODUIA) is equal to 229 A peak. The magnitude of the fundamental frequency phasor (MODUIB) of the current through the neutral resistance is equal to 536 A peak. Therefore each relay R1 has an operating time equal to 2.4 s and relay R2 has an operating time equal to 816 ms. If the logic were implemented according to the circuit shown in Fig. 2a a time delay of 1.58 s would be introduced in the trip signal generation. The OR implementation shown in the circuit of Fig.2b overcame this delay, so that one trip signal was generated 816 ms after the fault application.

Due to the high value of the neutral resistance, no variations in the results were observed with the stabilizing windings open or closed.

### D. Energization of power transformers at Colonia station from 31.5 kV bus bar

Let's consider that power transformer T1 is in service and power transformer T2 is out of service. When the transformer T2 with its primary winding disconnected from 150 kV bus bar is energized from the 31.5 kV bus bar, a circulating current is produced due to the inrush currents. This could be

observed in the diagram of Fig. 5.

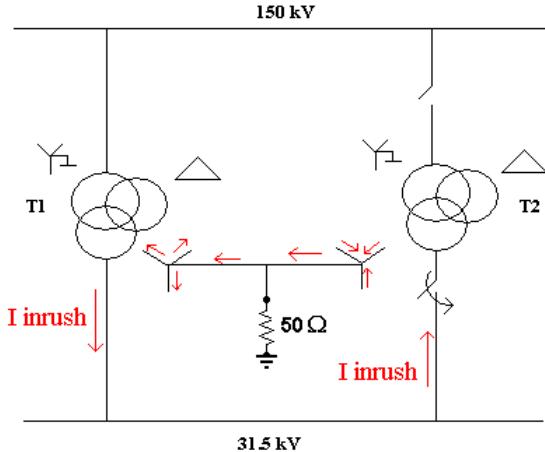


Fig. 5 – Inrush and circulating currents

In order to analyze the circulating current and to test the new logic performance, a number of energization studies have been carried out.

Because: a) the closings times of the circuit breakers may occur at any point of the power frequency voltage wave with equal likelihood b) the closings of the three poles of a circuit breaker do not occur at the same instant of time c) it is not possible to predict in advance the switching operating times which result in the maximum circulating current, each energization study consisted of 100 statistic energizations in which circuit breakers poles were represented by a statistic switch model.

Fig. 6 shows the time variation of the magnitude of the circulating current and the magnitude of its fundamental frequency phasor (MODUIA) for the case corresponding to the highest peak value. From this figure it could be observed that the circulating current presents a quick damping and the peak value of MODUIA is equal to 1126 A. Therefore, each relay R1 will pick up but not operate. Relay R2 does not pick up because there is no current through the neutral resistance. The new trip logic performance is correct.

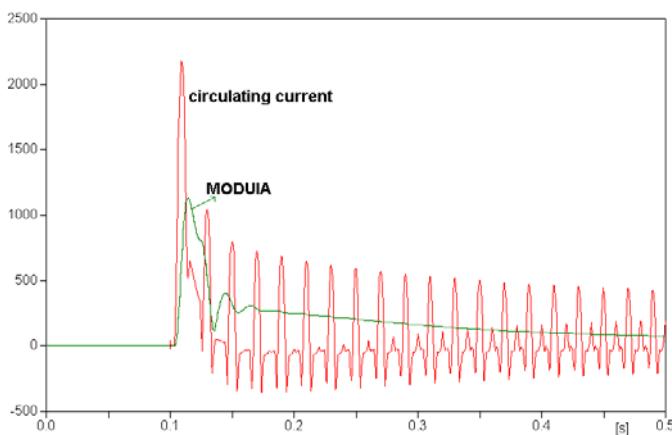


Fig. 6 – Circulating current

The presence of residual flux, the fact of having different stabilizing windings, and the choice of which transformer would be the second to be energized led to the same results presented above: each relay R1 will pick up but not operate and relay R2 will not pick up.

#### E. Energization of other transmission equipment

It was analyzed if the energization of other equipment, not only the power transformers at Colonia station, might produce circulating current. Two cases were selected: 1) the energization of the second transformer at one station belonging to the 500 kV grid 2) the energization of one of the lines feeding Colonia station, assuming that a fault is applied to that line. Each study consisted of 100 statistic energizations in which circuit breakers poles were represented by a statistic switch model.

##### 1) Case 1

A second power transformer at one station belonging to the 500 kV network was energized from its primary side. The other transformer is in service as well as the transformers at Colonia station. Regarding transformers T1 and T2, two situations were considered: both stabilizing windings closed and one of them open and the other closed. Fig. 7 shows the time variation of the magnitude of the circulating current and the magnitude of its fundamental frequency phasor (MODUIA) for the case corresponding to the highest peak value and the second situation. From this figure it could be observed that the circulating current presents a slow damping and the peak value of MODUIA is equal to 11 A.

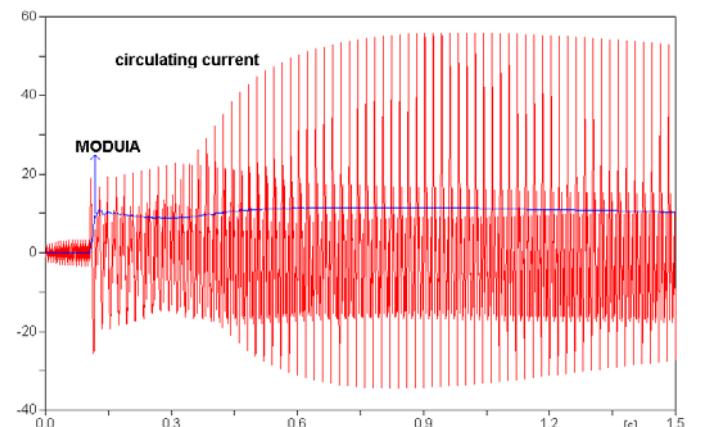


Fig. 7 – Circulating current

Therefore, each relay R1 and relay R2 will not pick up. It is important to point out that these results depend on which station is being analyzed, how the grid is grounded and how many points are earthed.

##### 2) Case 2

Transmission line Colonia-Libertad voltage rating 150 kV with length equal to 123.1 km was energized from Colonia

bus bar. A single line-to-ground fault was applied into the line during the switching. The following fault locations were taken into account: near Colonia station and near Libertad station.

In both cases the resulting circulating currents led each relay R1 to operate and relay R2 not to pick up. The operating times obtained were very different, 3.52 s for fault application near Libertad and 628.2 ms near Colonia. The new trip logic performance is right.

## V. CONCLUSIONS

In the present work the phenomenon of a circulating current due to the connection of power transformers in parallel which share a neutral resistance was investigated.

In order to know the time domain behavior of this current, different disturbances in the high voltage and the low voltage sides were simulated with ATP program. The most important aspects of the ATP modelling of the overcurrent relays and power equipment were presented.

Because of the actual protection scheme adopted, the circulating current might produce undesirable overcurrent relay trips, causing the interruption of the supply.

The description of a new trip logic for solving this problem was included. Under the disturbances mentioned above, its performance was tested..

From the results obtained through the application of faults involving the earth at 150 kV voltage level can be concluded that:

- a) A circulating current was detected between the secondary windings. As a consequence, the overcurrent relays located in the secondary windings operated and the overcurrent relay located in the neutral resistance did not operate.
- b) The presence of stabilizing windings has strong influence in the magnitude of the fundamental frequency phasor of the circulating current.
- c) When one of the power transformers had its stabilizing winding open and the other had its stabilizing winding closed, the highest value of the phasor magnitude was obtained. In this case, the relay operating time was comparable to zone 1 distance relay operating time of the transmission lines feeding Colonia station.
- d) If both stabilizing windings are closed but have different reactance values the same comments of item c) are true.
- e) The new trip logic did not send any trip signal to the 31.5 kV circuit breakers.

From the results obtained due to the application of faults involving the earth at 31.5 kV voltage level can be concluded that:

- a) No circulating current was detected.
- b) The overcurrent relays located in the secondary windings operated and the overcurrent relay located in the neutral

resistance also operated.

The new trip logic sent trip signals under fault conditions and did not add any time delay.

- c) No variations in the results were observed with the stabilizing windings open or closed.

The results obtained due to the transformer energizations at Colonia station, from 31.5 kV side, showed that:

- a) A circulating current was detected. It has high peak value and quick damping.
- b) The overcurrent relays located in the secondary windings picked up but did not operate. The overcurrent relay located in the neutral resistance did not pick up.

In relation to the circulating current due to the energization of other transmission equipment, it could be said that its wave shape and magnitude strongly depend on the type of equipment, location in the grid, the presence of a fault during the switching, how the grid is grounded, etc. From the results presented in this work it can be concluded that the new trip logic performance was correct.

Finally, the new logic of tripping solves the problem described in this work. At this time, a project is developing in order to implement this new logic.

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## VII. BIOGRAPHIES

**Graciela Calzolari** (M'1990) was born in Montevideo, Uruguay, on May 25, 1957. She received the B.S. degree from Universidad de la Repùblica, Montevideo, Uruguay, in 1986 and M.S. degree from Escola Federal de Engenharia de Itajubá, Itajubá, Brazil, in 1990.

She has been with UTE electrical company of Uruguay, since 1984. Her special fields of interest include electromagnetic transients studies, the modelling of power system components and their technical specification, artificial intelligence.

**Claudio Saldaña** (M'1990) was born in Montevideo, Uruguay, on Sept. 20, 1956. He received the B.S. degree from Universidad de la Repùblica, Montevideo, Uruguay, in 1986 and M.S. degree from Escola Federal de Engenharia de Itajubá, Itajubá, Brazil, in 1990.

He has been with UTE electrical company of Uruguay, since 1984. His special fields of interest include electromagnetic transients studies, the protection of power system, artificial intelligence.