ATP simulation of the Out-of-step phenomenon in the Batlle thermal power plant

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Abstract—Due to a fault in the 500 kV network, a unit in the Batlle thermal power plant was tripped by an out-of-step relay. From a preliminary analysis of this disturbance, it was concluded that the thermal unit did not lose synchronism. This fact led to an evaluation of the present settings of the out-of-step relay in order to determine if they were correct or not. This paper focuses on the most important aspects of the issues: a) the relaying principle, its settings and ATP (Alternative Transients Program) modeling b) the main conclusions resulting from the simulation of the sequence of events which led to the trip of the thermal generator c) the evaluation of the out-of-step relaying performance during electromechanical oscillations. They were simulated with ATP program.

Keywords: Loss of synchronism phenomenon, thermal unit, disturbance, out-of-step relay, ATP, MODELS.

I. INTRODUCTION

On March 25th 2002 at 8:15 pm, a single phase-to-ground fault happened in a transmission line belonging to the 500 kV network of Uruguay. The protection system removed the faulted line and then the 500 kV and 150 kV networks became weakly interconnected.

This incident led to the following sequence of events in the 150 kV network: a) the total network was divided into several subsystems, which were weakly interconnected through long transmission lines b) a low voltage profile developed because of the long electric distance between generation and load c) a load shedding scheme was triggered by undervoltage relays d) a thermal unit in the Batlle thermal power plant was tripped by an out-of-step relay.

From a preliminary analysis of the sequence of events, it was concluded that the thermal unit did not lose synchronism. The National Dispatch Center raised the following question: would it be possible to reduce the size of the impedance diagram of the out-of-step relay in order to avoid tripping the thermal unit in similar situations?

In order to answer this question an evaluation of the out-of-step relaying principle and its present settings was conducted. Therefore, loss-of-synchronism conditions, stable swings and the disturbance mentioned above were simulated with ATP.

The ATP Program was utilized as a tool due to the following reasons: a) the out-of-step relay under study measures the apparent impedance in phase coordinates b) the influence of balanced and unbalanced faults on the relay performance was studied c) transient recovery voltage appearing between circuit breaker terminals during current interruption was simulated in order to determine the time that the relay must give the tripping signal.

II. THE OUT-OF-STEP PHENOMENON [1][2][3]

When a generator loses synchronism, there are large cyclic variations in currents and voltages of the machine under this condition, the frequency being a function of the rate of slip of its poles. The resulting high peak currents and off-nominal frequency operation can cause winding stresses and pulsating torques, which can excite mechanical resonances that can damage the shafts. To avoid these dangerous effects on the generator unit, it is recommended that the out-of-step relay give a trip signal to the generator circuit breaker, within the first slip cycle.

III. THE OUT-OF-STEP RELAY

In this section the most important aspects of the out-of-step relay of the Fifth unit in the Batlle thermal power plant and its ATP modeling are going to be presented.

A. Relay Principle and Settings

Manufactured by ASEA, the out-of-step relay consists of: a static directional overcurrent relay type RXPE40, an impedance measuring unit RXZF21 and auxiliary relays for tripping logic.

The operating characteristic of RXPE40 is nearly a straight line due to its present settings.

The impedance unit RXZF21 is of static design and consists of a measuring element having a concentric operating characteristic which is an oval in the R-X plane. Figure 1 shows the operating characteristics in the R-X plane for both relays. The reach Z_α in the reactive direction of the oval is 0.4657 Ω (primary value), which was suggested by the manufacturer. The reach in the resistive direction is preset to about 0.5 times the reach in the reactive direction.

The conventional relaying approach to detect a loss-of-synchronism condition is to supervise the variation of the apparent impedance as seen from the generator terminals. The principle on which this out-of-step relaying scheme is based is:

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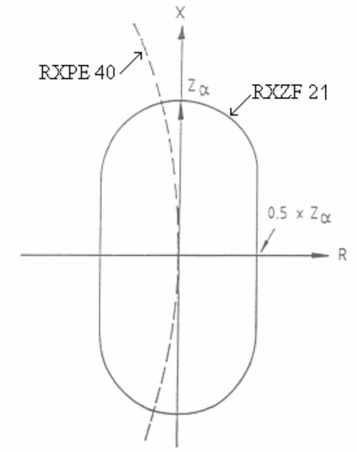

Fig.1 – Operating characteristics

a) if after fault clearing, there is a swing only, the apparent impedance will come out of the oval on the same side of the X-axis it entered.

b) if the fault results in a loss-of-synchronism condition, the apparent impedance will come out of the oval on the opposite side of the X-axis. Thus, the active power flow will be in opposite direction to normal running. When passing through the X-axis, the directional relay RXPE40 and auxiliary relays pick up, and this will correspond to a rotor angle of more than 180°. In order to have a safety margin and to give a trip signal at a more favourable rotor angle, the trip signal is not given until the impedance comes out of the oval, which corresponds to a rotor angle of 250-300°.

B. ATP modeling

The input signals of the out-of-step relay are phase instantaneous current and phase-to-ground instantaneous voltage measured from one phase of the generator.

The performance of this relay is dependent on obtaining accurate estimates of the fundamental frequency components (I and E) of the current and voltage signals from a few samples. The sampling frequency is equal to 1 kHz.

The Discrete Fourier Transform is used to estimate the fundamental frequency (50 Hz) 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 [4], was implemented as a part of the relay model developed with MODELS option of the ATP Program [5], [6].

The apparent impedance measured by the impedance unit RXZF21 is given by the following formula, which was implemented as another part of the relay model.

$$Z_{apparent} = \frac{E}{I}$$

From this model, it is possible to derive an apparent impedance locus in the R-X plane during a loss-of-synchronism condition. The out-of-step relay performance is analyzed by plotting its operating characteristics and the apparent impedance locus on the same R-X plane.

IV. DISTURBANCE SIMULATION AND ANALYSIS

On March 25th 2002 at 8:15 pm, a single phase-to-ground fault happened in the transmission line Palmar-MB500 (length equal to 220.3 km) belonging to the 500 kV network of Uruguay. Prior to this disturbance, the power system schematically shown in Fig. 2 had the following conditions: a) total load equal to 1050 MW. The areas of major consumption were II and III. b) Salto Grande and Palmar hydroelectric power plants supplied 701.2 MW and 330 MW respectively c) Fifth Unit in the Batlle thermal power plant generated 18.8 MW. The 500 kV network had the second transmission line between Palmar – MB500 out of service. As a result of this the Fifth Unit was put into service.

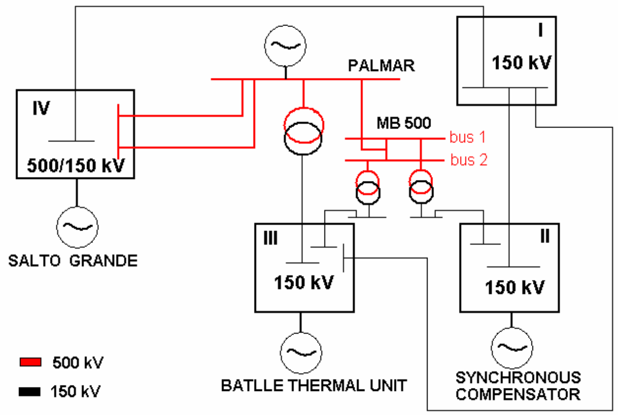

Fig.2 – Network configuration prior to disturbance

The protection system removed the faulted line and then the 500 kV and 150 kV networks became weakly interconnected as can be seen in Fig. 2.

Table I shows the sequence of the most important events.

TABLE I

Time (s)	Event
0.0	(1) Phase-to-ground fault in Palmar-MB500 line
0.055	(2) Three-phase circuit breaker opening at MB500
0.108	(3) Three-phase circuit breaker opening at Palmar
0.220	(4) Line between areas I and II was removed
0.255 – 0.375	In area II a load-shedding scheme was triggered
0.470	(5) In area III a load-shedding scheme was triggered
0.815	(6) Fifth Unit was tripped

The Fifth Unit was tripped by the out-of-step relay described in item III. It is a steam thermal unit of 100 MVA apparent power rating, voltage rating 11 kV, one pair of poles, nominal speed 3000 rpm, inertia constant 3.45 s. In order to analyze if the Fifth Unit lost synchronism or not, the power system pre-fault conditions and the sequence of the events shown in Table I, except event (6), were simulated with the ATP program. Fig.3 shows the rotor angle time response of the Fifth Unit. It can be observed that the generator did not lose synchronism.

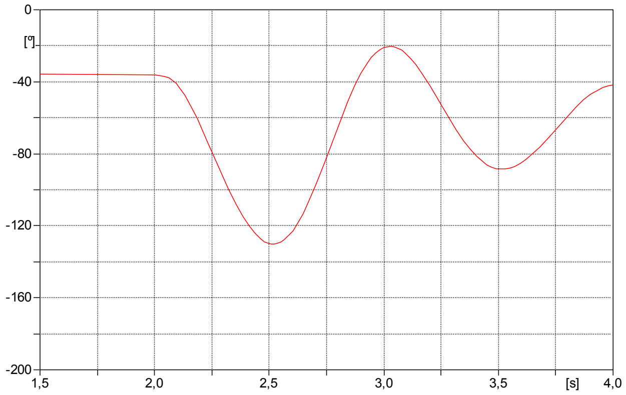

Fig. 3 – Rotor angle response

Fig. 4 shows the time variation of the voltage at Fifth Unit terminals in p.u. and also the events mentioned in Table I. It can be observed the strong drop of voltage due to the sequence of events.

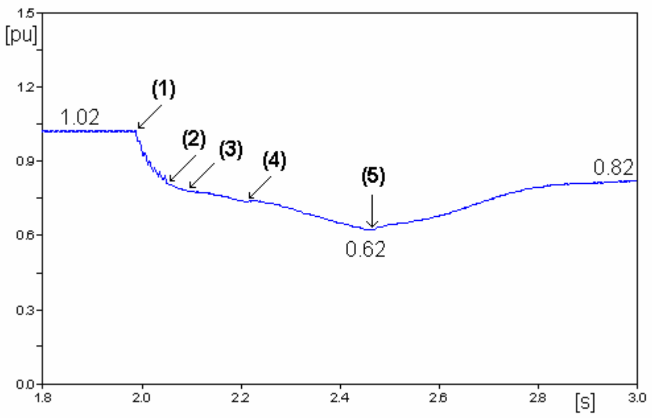

Fig. 4 – Fifth voltage terminal

From the ATP simulations the apparent impedance locus seen from the Fifth Unit terminals was plotted on an R-X plane together with the relay characteristics, as can be seen in Fig.5. In the figure above, **A** represents the pre-fault condition, **B** represents the opening at MB500, **C** represents the opening at Palmar, **D** represents the removal of the line between areas I and II, **E-F** represent the load triggered in area III by a load-shedding scheme.

Fig. 6 shows how the apparent impedance locus entered and came out of the oval from the +R to the -R region and it remained inside the oval during a period of time of 100 ms. From the very moment that the locus came out of the oval until the generator circuit breaker opened, 190 ms elapsed. This happened because of the low voltage profiles developed in the 150 kV network, which in turn, were a consequence of the events mentioned in Table I.

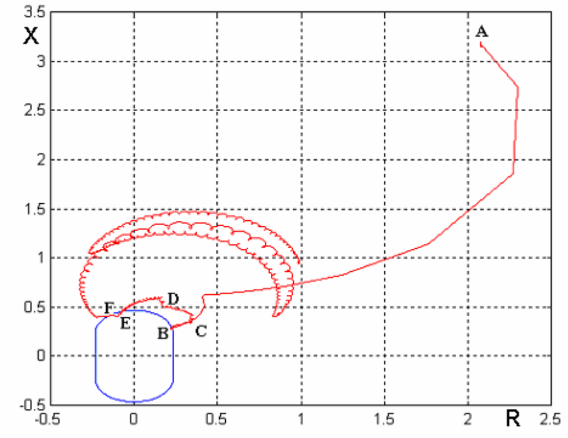

Fig. 5 – Apparent impedance

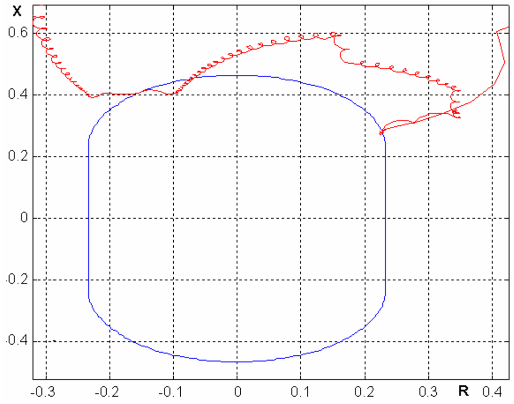

Fig. 6 – Apparent impedance (detailed)

Due to the aforementioned, the out-of-step relay gave a trip signal to the generator circuit breaker. Based on the relaying principle, this operation was correct.

Fig. 7 shows the time variation of the Fifth Unit armature currents during the sequence of events.

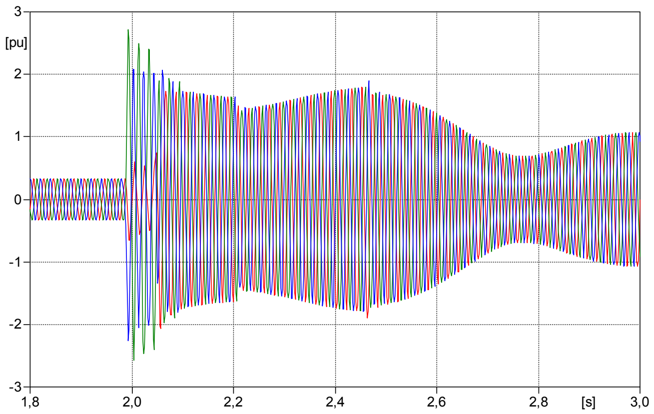

Fig. 7 – Armature currents

From this figure, high current values 1.6 pu during 0.5 s can be observed. In particular, when the locus entered the oval, the armature currents reached the highest values.

The electrodynamic forces produced by these currents might lead to the mechanical collapse of the stator winding. At the end of the coils, where the magnetic field lines bend, the forces exhibit significant components that cause mechanical stress.

Tripping for stable swings is undesirable in relation to the power system operation, so the National Dispatch Center requested an evaluation of the present settings of the relay.

Since the Fifth Unit was put into service in 1970, an evaluation of the out-of-step relay performance has never been conducted. At that time, there were no tools to conduct these kinds of studies. For these reasons, parametric studies were carried out in order to analyze the relaying principle and its settings.

V. LOSS-OF-SYNCHRONISM AND STABLE SWINGS SIMULATIONS

The application of loss-of-synchronism relaying scheme on a generator is not a simple procedure. It requires extensive stability studies to determine apparent impedance loci under unstable and stable swings, expected armature current levels, average generator slip, etc.

The loci of apparent impedances under out-of-step conditions and stable swings were calculated taking into account: different fault-clearing times, the automatic voltage regulator in and out of service, leading and lagging power factor loadings, different system impedances and two types of faults (three-phase and double line-to-ground).

A. Power System Operating Conditions

For the power system of Uruguay the following operating conditions were assumed in the digital simulations carried out with the ATP: a) the network configuration corresponded to a thermal dispatch b) the maximum load was equal to 1792 MVA c) Fifth Unit generated 80 MW with a lagging power factor equal to 0.82 and its automatic voltage regulator was in service.

B. Three-phase fault

The slip will be a function of the generator inertia, accelerating torque and fault-clearing times. Maximum accelerating torques will be produced by close three-phase faults on the high voltage system. This fault was applied at the 150 kV high voltage terminals of the step-up transformer of the Fifth Unit.

The critical fault-clearing time (CFCT) is that switching time for which the Fifth Unit is on the verge of instability. From the simulations the CFCT resulted equal to 334 ms.

1). Loss-of-synchronism simulations

A fault-clearing time greater than CFCT was utilized in order to simulate a loss-of-synchronism condition. Fig. 8 shows the apparent impedance locus together with the oval characteristic of the relay, corresponding to a fault-clearing time of 335 ms. This figure shows how the apparent impedance locus enters and comes out of the oval from the +R to the -R region. The relay will give a trip signal after the locus comes out of the oval showing that its principle is correct.

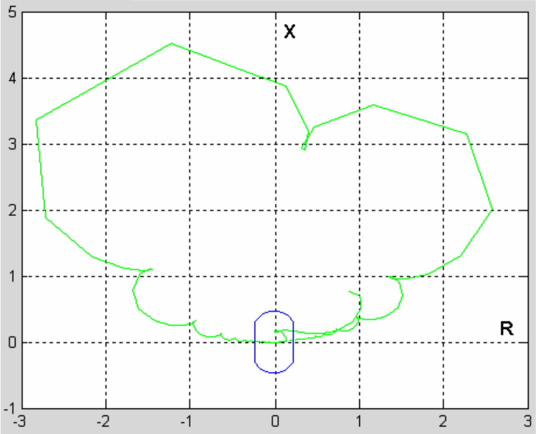

Fig. 8 – Apparent impedance locus (335 ms)

Fig. 9 shows the time variation of the Fifth Unit armature currents under this unstable swing. From this figure, high current values 5.25 pu during 360 ms can be observed.

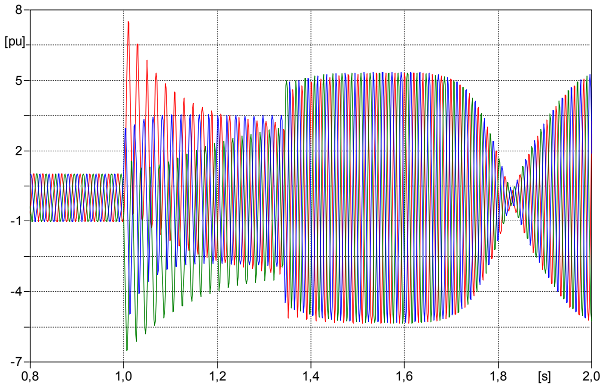

Fig. 9 – Armature currents (335 ms)

The effect of different fault-clearing times greater than CFCT was analyzed. It can be concluded that the longer the fault-clearing time, the faster the machine loses synchronism. However, the different apparent impedance loci enter and come out of the oval in a similar way.

The Thevenin impedance seen from the high voltage terminals of the step-up transformer was varied through the opening of some transmission lines in the 150 kV network in order to study its impact. As a result of this, an increase of 30.8 % in the Thevenin impedance value was obtained. The apparent impedance locus corresponding to a fault-clearing time equal to 335 ms, is similar to that shown in Fig. 8.

With the omission of the automatic voltage regulator (AVR) of the Fifth Unit, the internal machine voltage will decay during the fault and will remain at the resulting lower level after the fault is cleared. This produces apparent impedance locus having smaller diameter which may be more difficult to detect by the relay algorithm. The cases without AVR were considered in order to obtain the most pessimistic results. Fig. 10 shows the apparent impedance loci with and without AVR and the oval characteristic on the same R-X plane for a fault-clearing time of 335 ms.

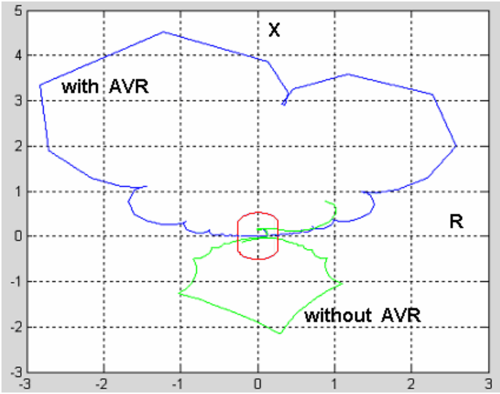

Fig. 10 – Apparent impedance loci (AVR)

From this figure, it can be observed that the apparent impedance loci are located on opposite sides of the R-axis. After fault clearing, and with the AVR in service, the Fifth Unit operated in the overexcited region whereas with the AVR out of service it operated in the underexcited region. This transition from the overexcited region to the underexcited region explains the different location of the loci.

The effect of different power factor loadings prior to the disturbance was analyzed. An unstable swing with a fault-clearing time of 335 ms was simulated, in which the Fifth Unit was initially operating at unity power factor. In this situation the generator terminal voltage value was less than the value obtained in the case with lagging power factor, consequently, the machine lost synchronism faster.

2). *Stable swings simulations*

For the purpose of analyzing the out-of-step relay performance under stable swings conditions, two different fault-clearing times were considered, 334 ms (CFCT, critical case) and 150 ms. Figs. 11 and 12 show the corresponding apparent impedance loci, coupled with the oval characteristic.

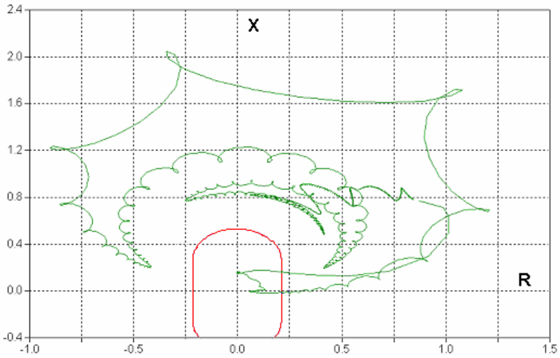

Fig. 11 – Apparent impedance locus (334 ms)

For the critical case the locus moves from the +R to the -R region outside the oval characteristic, while for the case shown in Fig. 12 the locus remains in the +R region. Other cases taking into account different power factor loadings, system impedances and with and without AVR were simulated. In all the cases, the impedance loci enter and come out of the oval on the same side of +R-axis, therefore, the out-of-step relay does not give a trip signal showing that its principle is correct.

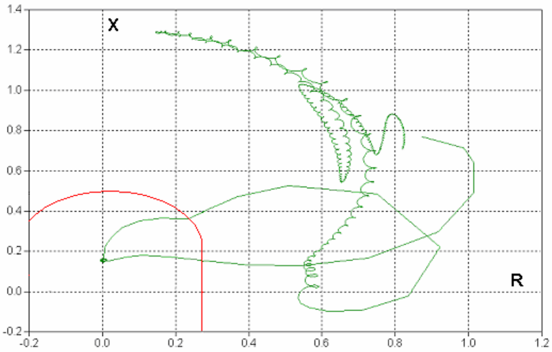

Fig. 12 – Apparent impedance locus (150 ms)

C. *Double line-to-ground fault*

The out-of-step relay is a single phase unit, so the authors raised the following question: Under an unbalanced fault what happens with the relay performance if it is located either on the unfaulted phase or on a faulted phase ?

In a decreasing order of severity, based on the accelerating torque, a double line-to-ground fault follows the three-phase fault. This fault was applied at the 150 kV high voltage terminals of the step-up transformer of the Fifth Unit.

A new operating point of the Fifth Unit was defined: unity power factor, with the AVR in service and a generation of 80 MW. In this case the CFCT resulted equal to 465 ms.

Fig. 13 shows the apparent impedance loci, seen from the generator terminals A,B,C accompanied by the oval characteristic of the relay, corresponding to a fault-clearing time of 475 ms.

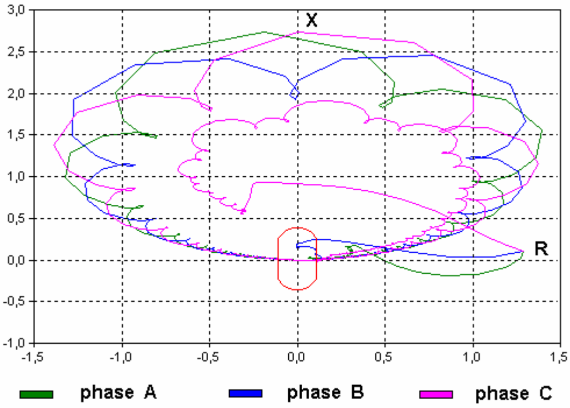

Fig. 13 – Apparent impedance loci (unbalanced fault)

This figure shows how each apparent impedance locus enters and comes out of the oval from the +R to the -R region.

During the period of time between the pre-fault condition and the removal of the fault it can be observed that the loci shapes are different, this is more noticeable for unfaulted phase C. After the removal of the fault each locus enters the oval in a different way and comes out of the oval in a similar way. Independently the phase in which the relay is located, it will give a trip signal after the corresponding locus comes out of the oval.

Other cases, such as stable swings and loss-of-synchronism conditions, were simulated considering different power factor loadings and with and without AVR. From the results obtained it can be concluded that, for both balanced and unbalanced conditions the relaying principle is correct.

VI. TRANSIENT RECOVERY VOLTAGE

Considering the dangerous effects on the generator unit caused by the loss-of-synchronism condition, it is recommended to trip it with no intentional delay within the first slip cycle.

Under unstable swings, the apparent impedance locus will pass through the X-axis and the out-of-step relay will be ready to give a trip signal. With no intentional delay, this tripping can occur when the angle of separation between the generator and the system approaches 180°. This subjects the generator circuit breaker to a maximum transient recovery voltage (TRV) during current interruption. Therefore, the tripping is allowed when the impedance locus leaves the oval characteristic, which corresponds to a more favourable angle of separation between 250° and 300°. Figs. 14 and 15 show the TRV (red curve) coupled with the TRV limit (blue curve, IEC62271-100) corresponding to an opening of the Fifth Unit circuit breaker when the angle of separation was 164° (before leaving the oval) and 255° (after leaving the oval), respectively.

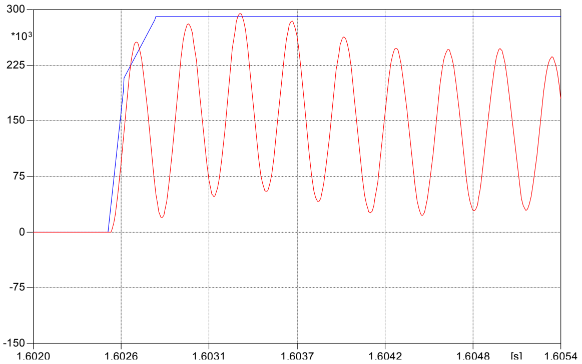

Fig. 14 – TRV (angle of separation of 164°)

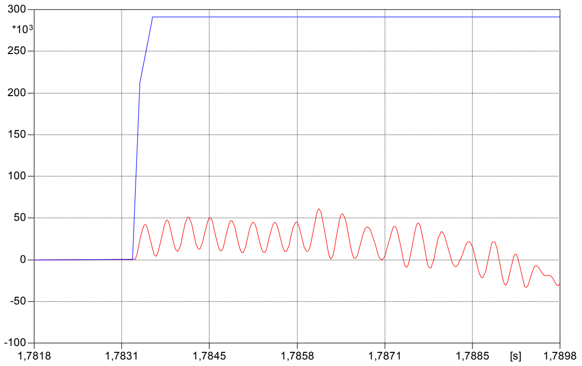

Fig. 15 – TRV (angle of separation of 255°)

It can be observed in Fig. 14 that the TRV exceeds the TRV limit, being this very stressful for the circuit breaker.

VII. CONCLUSIONS

The present settings of the out-of-step relay of the Fifth Unit were not modified, based on the following reasons:

a) From the ATP simulations of the loss-of-synchronism and stable swings it was possible to study the out-of-step relay performance for the first time. As a result of this study, the relay principle and its settings are considered correct.

b) The oval characteristic of the out-of-step relay, given by the manufacturer, defines a region of high armature current values of the Fifth Unit. Through the simulations of the disturbance (item IV) and stable and unstable swings was verified that the generator achieved these high armature current values.

c) Decreasing the present setting values results in a smaller oval characteristic, and this means allowing higher armature currents than the values defined by the manufacturer without taking any corrective action. Also, it has to be taken into account that the Fifth Unit has been in service for more than 36 years.

d) From the simulation of the sequence of events described in item IV, it can be concluded that the out-of-step relay tripped the generator because of the low voltage profile and high armature currents developed after the fault was cleared. This means both that the power system presented a critical topology prior to the disturbance, and that insufficient corrective actions were taken after the fault was removed.

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IX. BIOGRAPHIES

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