Assessment of power swing blocking functions of line protective relays for a near scenario of the Uruguayan system

C. Sena, R. Franco, A. Giusto.

Abstract - **During normal operation of an electrical power system, there will be some conditions like faults or other disturbances which may cause loss of synchronism between areas. When loss of synchronism takes place, asynchronous areas should be separated to avoid equipment damaged or extensive outages.**

This paper describes the assessment of the protection system of a part of the Uruguayan power system.

The focus is on the incorporation of a big consumer with generation capacity. The involved added apparent power generation is about 10% of the maximum historical Uruguayan load.

The article describes a set of studies on the protective system associated to transmission lines feeding the new consumer. Particular attention is paid to blocking power swing functions of the involved relays.

Power system simulations and relay tests have been performed, to evaluate the performance of the relays under power swing conditions. The foreknowledge makes possible to avoid undesired operation.

Index Terms - **Out-of-step, Power swing, Power swing blocking, Power system stability, Power system transient stability.**

I. INTRODUCTION

POWER systems are subjected to a broad number of small or larger disturbances during normal operating conditions. Small disturbances, like changes in loading conditions, are always present. The power systems must remain stable to these changing conditions and continue to operate within the desired limits of voltage and frequency [1].

The transient stability of a power system is a complex phenomenon that involves its dynamic response, including the action of the control and protective devices, in the face of a disturbance. Sudden events as the loss or application of large blocks of load, line switching, generator disconnection, or faults often originate a significant transient response that leads the system to another equilibrium point. Large system disturbance could cause large power flow swing and could lead to unwanted relay operation and power blackouts.

PDT (Ministerio de Educación y Cultura - Programa de Desarrollo Tecnológico) does the financial support of the project "Short Term Scenarios Stability Studies in the Uruguayan Electric System" of Facultad de Ingeniería – UdelaR. This paper presents one of its studies and results.

The Uruguayan network qualitatively consists of both thermal and hydro-electrical units facing a sustained growing power demand and the addition of significant generators and industrial consumers. It is strongly connected with the Argentinian system through a double link in 500kV, and with the Brazilian system via a 70 MVA back-to-back converter. The voltages of the transmission networks are 500kV and 150kV, and the voltages of the sub-transmission and distribution networks are 60kV and 30kV.

The power system has the characteristic that major generation comes from the hydro-electrical units that are located in the north and centre of the country. The major consumer centre is located in the south of the country with the thermal electrical units.

The Uruguayan power system is now facing the incorporation of new consumers with the possibility to operate as consumers or generators. These new consumers have installed thermal electrical units for 140MW, consuming 90 to 120MW, and injecting the surplus to the Uruguayan power system.

When long distance separates the load centre from the supply, the power system weakening between the two areas may lead to out-of-step conditions and cascading lines outages because of distance relays operations.

Section II summarizes the relevant relationships between power system stability and distance protection. Section III and Section IV describe the simulations and tests performed and its results. Finally the conclusions are presented in Section V.

II. DISTANCE PROTECTION AND POWER SYSTEM STABILITY

There are many technical books and papers describing power system stability and its relation with distance protection. Following there is a brief review based on the description in [2]-[5].

Power oscillations are normal balanced events in power systems. They may be the consequence of any disturbance in the power system such as line switching, faults, load shedding and generators tripping. During normal operation the magnitude of the oscillations are usually small and very attenuated. But during abnormal operation the oscillations can be larger.

The loss of synchronism between areas affects the transmission lines relays. Distance relays elements may operate during a power swing, if the impedance locus enters the distance operating characteristic.

A. *Distance relays*

Distance relays respond to positive-sequence quantities. The impedance measured by the distance relay during a power swing depends on the phase angle separation δ between the two equivalent system source voltages. During a power swing, zone 1 distance relay function and pilot functions will be the functions with more chances to operate. Fig. 1 shows the operation of a distance relay when the impedance measured goes into the operating characteristic.

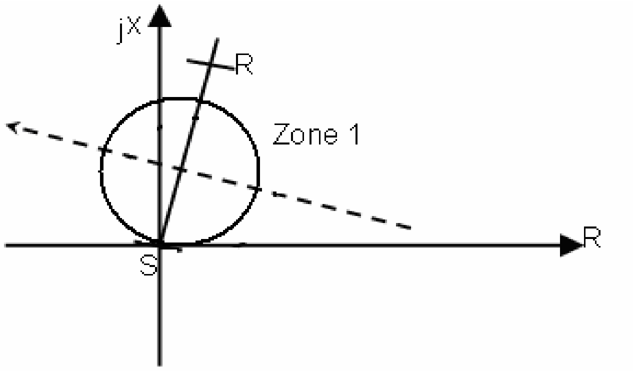


Fig. 1: Zone 1 Characteristic

B. *Impedance measured during a power swing*

The two machine system in Fig. 2 can be used to describe the performance of distance protection during power swings. The impedance seen by the relay at C during a power swing can be determined by (1).

$$Z_C = \frac{V_C}{I_L} = \frac{(Z_A + Z_B + Z_L)}{2}\left(1 - j\cot\frac{\delta}{2}\right) - Z_A \qquad (1)$$

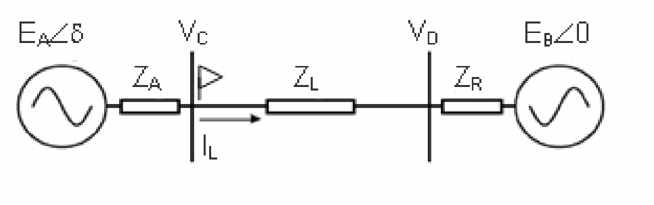


Fig. 2: Two machine system

During a power swing the angle δ will vary. For stable swing, the angle δ increases to a maximum value when the trajectory shifts direction and δ decreases to a minimum where the trajectory shifts direction again. This sequence repeats until the power swing ends. For unstable swing, the trajectory reaches δ=180°.

Fig. 3 shows the trajectory of the impedance measured. The trajectory of the impedance measured by the distance relay is a straight line when $|E_A| = |E_B|$. For $|E_A| > |E_B|$ and $|E_A| < |E_B|$, the trajectory is circular.

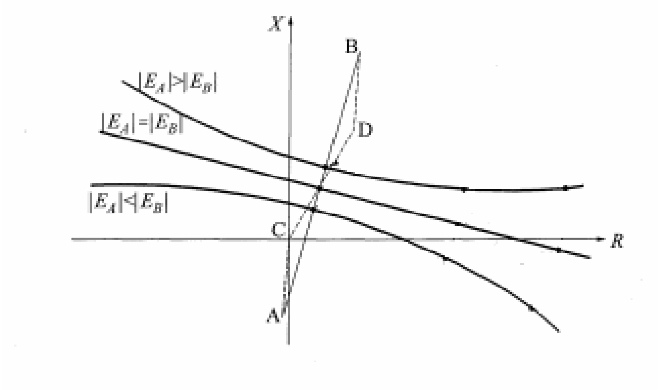


Fig. 3: Trajectory of the impedance measured during a power swing

C. *Power swing Detection methods*

The traditional and most common method used in power swing detection is based on measuring the positive-sequence impedance and the transition time through a blocking impedance area in the R-X diagram. The movement of the impedance for short circuit faults is faster compared to the movement for a power swing. Fig. 4 shows two different characteristics of a scheme used for power swing detection.

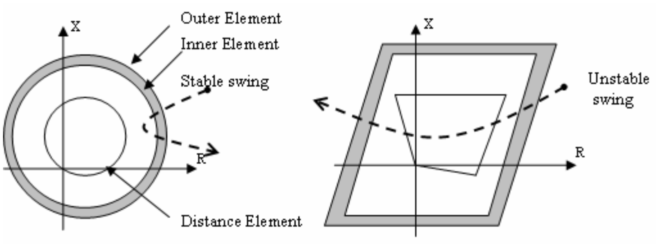


Fig. 4: Circular and quadrilateral power swing detection characteristic

A timer is started when the impedance measured enters the outer characteristic. If the measured impedance remains between the inner and outer characteristic for the set time delay, it is considered a power swing and the tripping of the relay is blocked during a certain time. But if that impedance crosses the inner and outer characteristic in a time shorter than the set time delay, it is considered a short circuit and the tripping of the relay is allowed.

Other modern methods detect power swings based on permanent measurements, and are applied alone or combined. They are possible because of numerical relays implementation.

Some of these methods consist on permanent measurements that in the R-X diagram evaluate trajectory speed, trajectory monotony, trajectory coincidence between loops, trajectory in zones of steady state instability, electrical system centre estimation, etc.

III. Power System Modeling

This section describes the simulations and tests that have been performed, to study in the Uruguayan System the behavior of some relays under power swing conditions. The objective was to obtain, by simulation, power swing conditions relative to the new generators incorporated to the electric system.

Time-domain simulations of the network have been carried out by using ATP [7] and DSAT [8] programs, while laboratory tests have been done in relays using secondary injection test equipment.

Both numerical and experimental investigations of the power swing phenomena were performed in order to study the behavior of the line protections relays of the transmission lines near the new consumer.

The technique chosen in this research was to simulate the power system in great detail using ATP, with previous transient stability studies in DSAT.

A number of different technologies and techniques are available to test a relay. One of them is to feed relays with the output of the ATP program (.pl4 file format) using secondary injection test equipment.

A. The power system under study

The grid configuration has both, thermal and hydro-electrical units in service. As it has been mentioned, the hydro-electrical units are located in the north of the country, while the thermal electrical units and the load centre are in the south. The new big industrial generator-consumer which is located near Fray Bentos (FBE) 150 kV substation, in the west of the country. Fig. 5 presents the network disposition of the investigated part of the Uruguayan transmission power system.

The protection relays that are installed in the transmission lines under study have quadrilateral power swing detection characteristic. These relays are SIEMENS 7SA611 and 7SD522, and use modern methods to detect power swings, evaluating trajectory speed, trajectory monotony, trajectory coincidence between loops, and trajectory in zones of steady state instability, with an outer quadrilateral characteristic element for power swing detection covering the inner quadrilateral fault detection element and all distance zones (zone 1 to zone 5) [6]. Those relay's combined algorithms produce the "Power Swing" internal signal in order to block tripping.

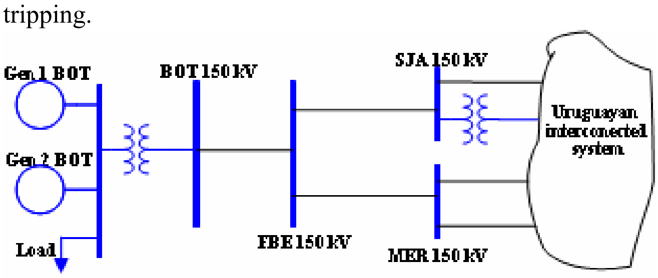


Fig. 5: Power system under study

B. Simulation of power swings in the Uruguayan electric system with DSAT.

The scenarios under study and their operational parameters had to be defined as part of the inputs to begin the studies. This was done by migrating to DSAT the original PSS/E model of the Uruguayan system including detailed excitation control models.

With the help of DSAT database scenarios, it have been possible to carry out the first part of the power swing studies in TSAT program, in order to define the contingencies to simulate and analyze.

Faults in 150 kV lines near Fray Bentos were simulated in order to obtain power swings for the new generator against the rest of the system. Critical clearing times (CCT) were calculated for each interesting fault.

Three phase faults are the worst cases, that determinate the shorter clearing critical times, so these faults were the first ones to be studied.

Then stable and unstable power swings near critical clearing times were simulated and analyzed with the help of the impedance diagrams of the distance protections in the transmission lines.

Sudden line openings were simulated, but they generate no relevant power swings.

Unexpected loss of generation and load shedding were studied too, and some cases were decided to be studied further.

After all these studies, a set of pairs: contingency – protection line relays of interest, was selected to be simulated further in ATP.

C. Simulation of power swings in the Uruguayan electric system with ATP.

The three phase power system has been modeled for the purpose of generating currents and voltages at relays locations. The signals were obtained by simulating the power system using the ATP. The power system model is heavily based on a previous Uruguayan – Argentinian electrical network model [9].

It was created and included the ATP model of the big industrial generator-consumer incorporated recently to the Uruguayan power system (reason of this study). After that, it was possible to simulate the studies of interest in order to perform the relay's tests.

The contingencies selected before in the TSAT studies and simulated in ATP, were:

a) three phase short-circuit over critical time, without automatic reclosing, in FBE-SJA 150 kV line, near FBE,
b) three phase short-circuit over critical time, without automatic reclosing, in MER-YOU 150 kV line, near MER,
c) sudden total load shedding in BOT,
d) sudden loss of one of two generators in BOT.

In these simulations, voltage and current signals in selected lines were generated and stored in pl4 format.

IV. Simulation and Test Results

The signals generated with ATP were injected to real distance protections, equal or similar to the ones installed in the selected points of the power system.

An OMICRON CMC256-6 test set for secondary voltage and current injection was used to perform dynamic transient tests of SIEMENS 7SD522 (87L/21) and 7SA611 (21) protective relays.

Results of the simulation of the four contingencies selected are shown below.

In the short circuit contingencies, the simulated voltages and currents consist of 500 ms pre-fault, then the fault that last more than critical clearing time, and post–fault up to 5 s of total simulation time.

In the load rejection contingency and the generator rejection contingency, the simulated voltages and current consist of 1s pre-contingency, and 5 s of post-contingency.

The R-X plots were generated with SIGRA (SIEMENS) managing oscilography software. Each plot shows the corresponding distance zones and the locus of seen impedance, but do not show the outer quadrilateral characteristic of power swing detection that is at least 1 Ω higher than distance zones.

A. Three-phase short-circuit in FBE-SJA 150 kV line, near FBE, for over critical clearing time, cleared by both ends' relays without automatic reclosing, in FBE-SJA 150 kV line, near FBE.

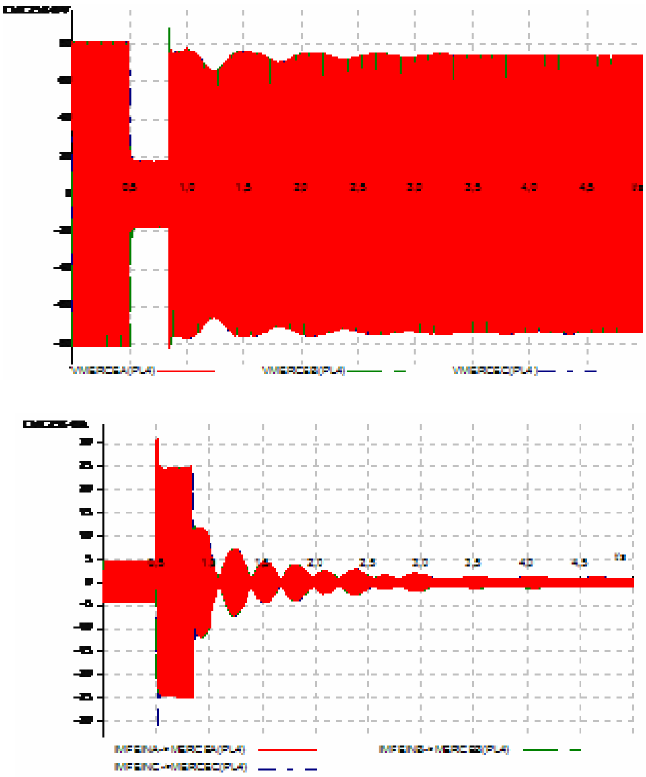


Fig. 6: Example. Voltages and currents injected to MER→FBE protection.

In the beginning of post-fault power swings, the frequency measured by relays of interest is approximately 3.2 Hz.

The impedance loci seen by the relays in this contingency are shown in Figs. 7 to 10.

Relays have seen the impedance entering their protective zones (in the event of the fault) and leaving them (when the fault is cleared). In both events, the not so fast transition effect of relays' phasors calculation moving data window, is shown as not so fast loci movements in the R-X figures produced by SIGRA software too.

Power swings were detected in post-fault, and relays set their "Power Swing" internal flag on from 10 to 60 ms to block tripping if protection picks-up. But in general later power swings are stable and do not even enter protective zones as shown in Figs. 7 to 10, so relays do not pick-up during post-fault, except BOT→FBE relay in Fig. 10.

In Fig. 7 FBE→MER relay picks-up in the reverse time-delayed zone and in the non-directional time-delayed zone when short-circuit happens.

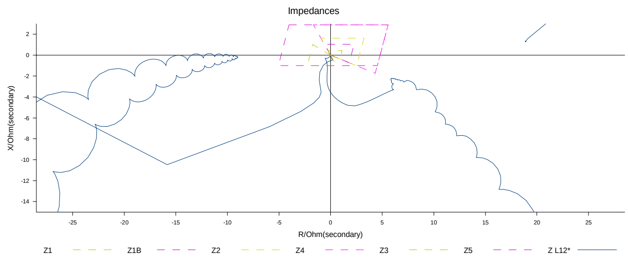


Fig. 7: Impedance seen by FBE→MER 7SA611 protection.

In Fig. 8 MER→ FBE relay picks-up in the forward time-delayed zone when short-circuit happens.

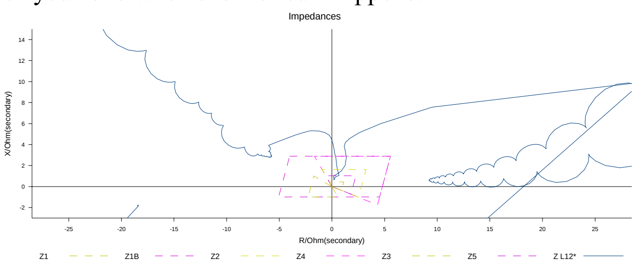


Fig. 8: Impedance seen by MER→ FBE protection.

In Fig. 9 FBE→BOT relay picks-up in the reverse time-delayed zone when short-circuit happens.

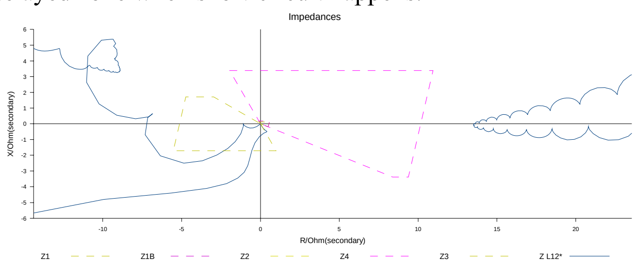


Fig. 9: Impedance seen by FBE→BOT 7SD522 protection.

In Fig. 10 BOT→ FBE relay picks-up in the forward time-delayed zone when short-circuit happens.

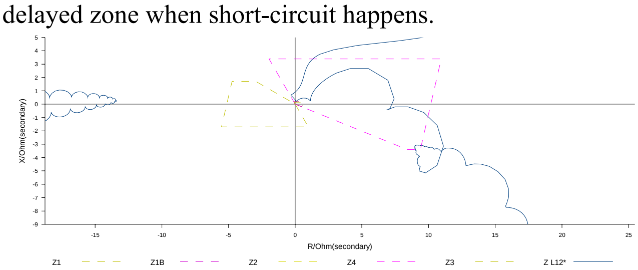


Fig. 10: Impedance seen by BOT→FBE 7SD522 protection.

Concluding, in this contingency relays' distance functions pick-up but never trip due to power swings, and relays' power swing blocking function operates properly.

B. Case: three phase short-circuit in MER-YOU 150 kV line, near MER, for over critical clearing time, cleared by both ends' relays without automatic reclosing, in MER-YOU 150 kV line, near MER.

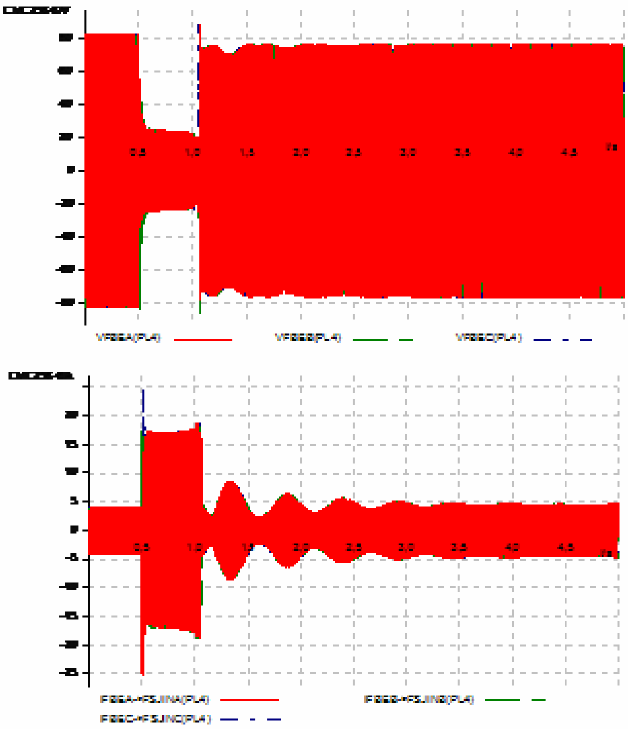


Fig. 11: Example. Voltages and currents injected to FBE→ SJA protection.

In the beginning of post-fault power swings, the frequency measured by relays of interest is approximately from 2.4 Hz to 3.6 Hz.

The impedance loci seen by relays of interest in this contingency are shown in Figs. 12 to 16.

Relays have seen as power swings both: impedances during fault and impedances after fault is clear. Transitions of impedance due to the effect of protection's moving data window are not so notorious, because of the slowness of power swings during fault and post-fault.

When power swings were detected in post-fault, relays set their "Power Swing" internal flag on from 130 to 150 ms for block tripping if protection picks-up. But later power swings are stable and do not even enter protective zones as shown in Figs. 12 to 16, so relays do not pick-up during post-fault.

But power swings were also detected by SJA→FBE and BOT→FBE relays during fault, as explained below for Figs. 14 and 16. Relay's "Power Swing" signal is also set on during most of the fault, when locus enters and leaves protective zones.

In Fig. 12 FBE→SJA relay picks-up the reverse time-delayed zone and the non-directional time-delayed zone only at the end of short-circuit.

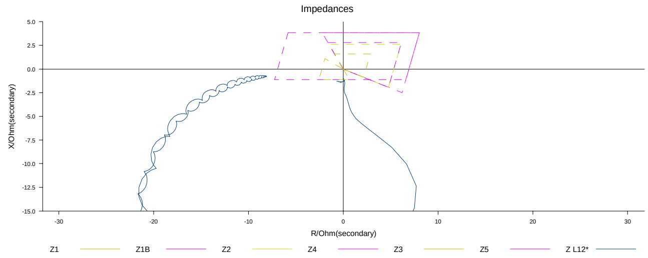


Fig. 12: Impedance seen by FBE→SJA 7SA611 protection.

As an example, FBE→SJA relay's "Pickup" flag, and "Power Swing" flag in post-fault power swing in the left of Fig. 12 are shown in Fig. 13.

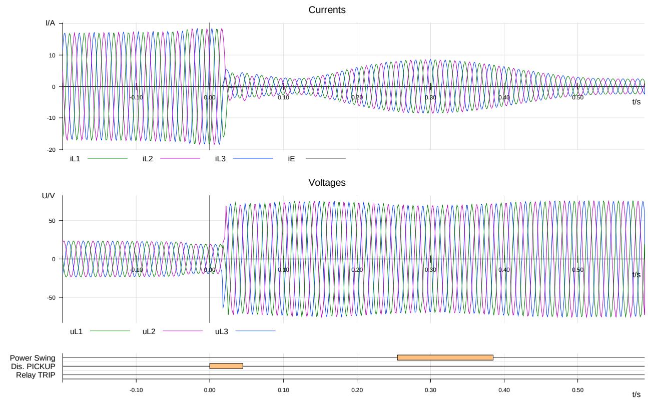


Fig. 13: Currents and voltages recorded by FBE→SJA 7SA611 protection; power swing and pickup relay's signals are shown (fault and post-fault record).

In Fig. 14 SJA→FBE relay picks-up the forward time-delayed zone and the non-directional time-delayed zone only at the end of short-circuit. Relay's "Power Swing" signal is set on during most of the fault.

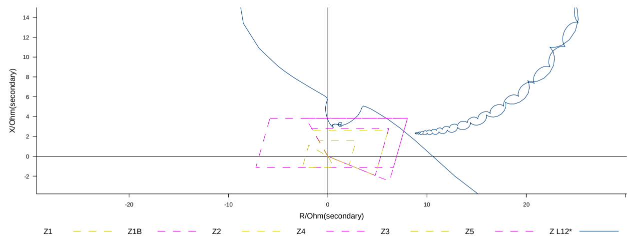


Fig. 14: Impedance seen by SJA→FBE protection.

In Fig. 15 FBE→BOT relay picks-up the reverse time-delayed zone only at the end of short-circuit.

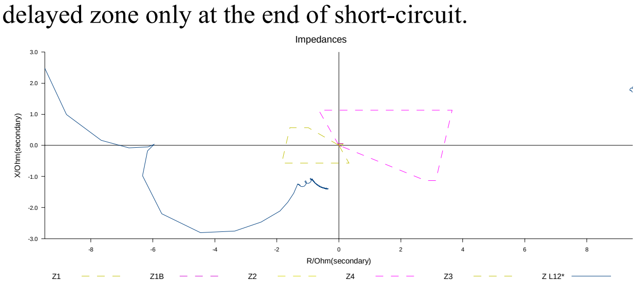


Fig. 15: Impedance seen by FBE→BOT 7SD522 protection.

In Fig. 16 BOT→FBE relay picks-up forward time-delayed zone. Relay's "Power Swing" signal is set on during most of the fault.

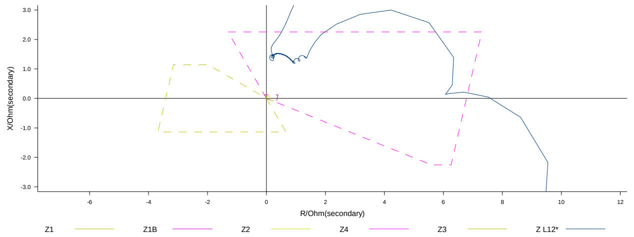


Fig. 16: Impedance seen by BOT→FBE 7SD522 protection.

Concluding, in this contingency, relays' distance functions pick-up but never trip due to power swings, and relays' power swing blocking function operates properly.

C. *Case: sudden total load shedding in BOT.*

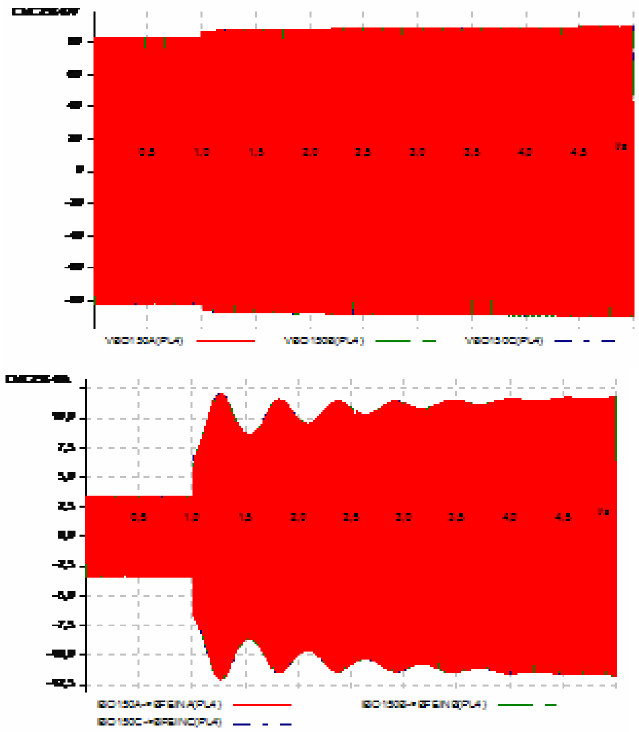
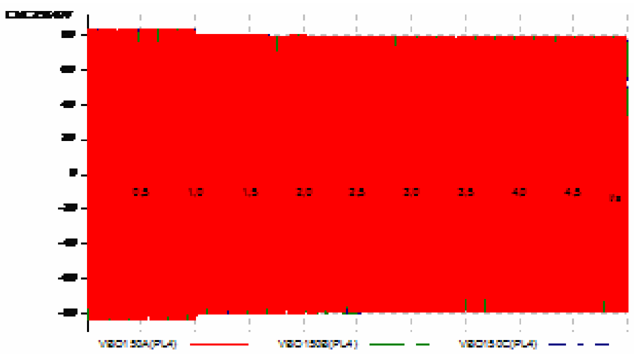


Fig. 17: Example. Voltages and currents injected to BOT→FBE protection.

Neither FBE→BOT nor BOT→FBE 7SD522 protections pick-up. No oscilography register was generated.

D. *Case: sudden loss of one of two generators in BOT.*



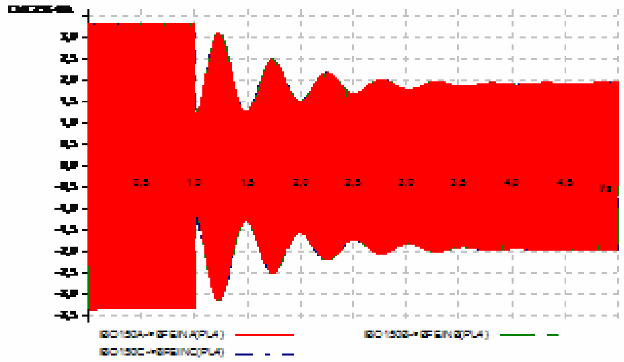


Fig. 18: Example. Voltages and currents injected to BOT→FBE protection.

Neither FBE→BOT nor BOT→FBE 7SD522 protections pick-up. No oscilography register was generated.

V. Conclusions

This paper describes the method, studies and tests to perform in distance protections in order to know its behavior under power swing conditions.

The new incorporation of a big industrial generator-consumer located near Fray Bentos 150 kV substation to the Uruguayan electrical power system, with generation capacity of 140MVA (near 10% of the maximum historical load), add to the system new power swings where new generator are involved.

Simulations and tests under different system conditions have shown that in order to maintain the integrity of the power system, the line protection relays operate in a properly way, detecting power swing and blocking trip.

This study shows that the distance protections located near the new consumer would be performed correctly under power swing conditions, blocking the relays avoiding them to operate and lead to major outages.

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VII. References

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VIII. Biographies

Celia Sena was born in Salto, Uruguay, in 1970.

She received her degree in Electrical Engineering from the Universidad de la República, Uruguay, in 1997.

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