# 500 kV IBIUNA-BATEIAS TRANSMISSION LINES AUTO-RECLOSING SCHEME EVALUATION – CONSEQUENCES REGARDING COMUTATION FAILURES PERFORMANCE

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***Abstract*** *- This paper presents a brief summary of the main results from electrical studies that have been carried out by Furnas for fast auto-reclosing scheme evaluation of the 500 kV Ibiúna-Bateias transmission lines. Here, the main concern of such studies refers to the consequences of auto-reclosing operation regarding the commutation failures performance within the Furnas' HVDC inverter station of Ibiúna.*

*The two circuits of the Ibiúna-Bateias transmission lines are very important interconnecting ties between the power systems of the Southern and Southeastern regions of the Brazilian national transmission grid (National Interconnected System - SIN). The operation of the Ibiúna-Bateias lines allows a substantial increase of power and energy interchange between these two regions.*

*This Ibiúna-Bateias 500kV lines, together with the 800kV Itaipu AC transmission system, are the main interchange ties between these two power system regions. And Ibiúna is also the receiving end (inverter station) of the HVDC transmission system owned by Furnas, and responsible for the integration into the Brazilian national grid of the Itaipu power generated with the industrial frequency of 50 Hz (from the half of Itaipu rated generated power which belongs to Paraguay, and being not used by this country)*

*One important conclusion of this study is that the application of single-phase auto-reclosing schemes, near inverter stations of bulk HVDC transmission systems, should be of great concern, since this auto-reclosing mode (single phase operation) may cause several commutation failures (CF) in sequence in the inverter station after the OH line short circuit application and the opening of only its faulted phase.*

*This CF process is caused by the big asymmetry among the 3 phase-to-phase AC voltages applied to the thyristor valves of the inverter station during the dead time of the auto-reclosing scheme. The operation of the OH line with only two sound phases and one open phase during the dead time of the auto-reclosing scheme establishes an uneven condition for the system operation, i.e., the three phase voltages at the AC side in the inverter station are strongly unbalanced, causing the asymmetry of voltages applied to the thyristor valves.*

*The results of the study also showed that it is possible to operate the Ibiúna-Bateias OH lines using the three phase auto-reclosing scheme, being the CF performance of the Ibiúna inverter station quite acceptable in all operating conditions. In this case, the leader and slave terminals of the auto-reclosing scheme must be Ibiúna and Bateias, respectively. And the dead-time (idle time) should be set with a minimum value of 900 milliseconds. With the activation of the 3-phase auto-reclosing scheme of the Ibiúna-Bateias 500kV transmission lines, the overall reliability of the Brazilian National Interconnected Grid (SIN) is improved in a substantial way. Also the discount of the permitted revenue of such assets (the Ibiúna-Bateias 500kV OH lines) can be decreased to the value related only to the period when the lines should be out of operation for maintenance purposes.*

***Keywords:*** OH Transmission Line Auto-reclosing schemes, HVDC Transmission System Performance, Commutation Failure Evaluation

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## 1 INTRODUCTION

This paper presents a brief summary of the main results from electrical studies that have been conducted by Furnas for fast auto-reclosing scheme evaluation of the 500kV Ibiúna-Bateias transmission lines. Here, the main concern of such studies refers to the consequences of auto-reclosing operation regarding the commutation failures performance within the Furnas' HVDC inverter station of Ibiúna.

The two circuits of the Ibiúna-Bateias transmission lines are very important interconnecting ties between the power system grids of the Southern and Southeastern regions, the two most industrialized ones of the Brazilian national transmission grid (National Interconnected System - SIN). The biggest and main load centres of the country are located in these two regions. The great importance of the 500kV Ibiúna-Bateias transmission lines refers to the fact that, when in operation, they allow a substantial increase of power and energy interchange between the Southern and Southeastern regions.

Below it is presented a brief summary of Furnas history, its main assets and the context where the Ibiúna-Bateias inter-tie play its important role.

One desirable consequence of the activation of the 3-phase auto-reclosing scheme for the Ibiúna-Bateias 500kV transmission lines refers to the fact that the overall reliability of the Brazilian National Interconnected Grid (SIN) is improved in a substantial way.

## 2 FURNAS - HISTORY AND MAIN ASSETS

Furnas is responsible for supplying electric energy for distribution companies, mostly in the southeastern and middle-west regions of Brazil, where 8 different states and the Federal Government District depend upon this supply of electric energy from Furnas. In this region live about 90 million people; there are 65% of the Brazilian GDP and 55% of the total electric energy consumption of the country.

Furnas also plays another important role in the Brazilian power system, giving the main interconnections from the southeastern region grid (which is the most developed region of the country, and where the company has most of its transmission and generation assets) with the other regional grids, like the southern regional transmission grid and the northern + northeastern regional transmission grids.

Furnas bulk generation assets in operation has now-a-days an amount of about 10 GW of installed power capacity. From this generation installed power, about 9,000 MW are available from 11 hydro power plants and 1,000 MW from 2 thermal ones. At the moment Furnas is dealing with the construction of 7 new hydro power plants, at the same time, enrolling an additional installed power capacity of about 4,850 MW (considering Furnas the stand-alone owner or even within joint venture dedicated companies).

The bulk transmission assets of the company already in operation sum up almost 20,000 km of transmission lines, since the voltage level of 138 kV up to 800 kV. They interconnect 46 substations, where the company has the total rated power transformer capacity of more than 101 MVA.

Figure 1 below gives a general picture regarding the geographical distribution of Furnas generating and transmission main assets.

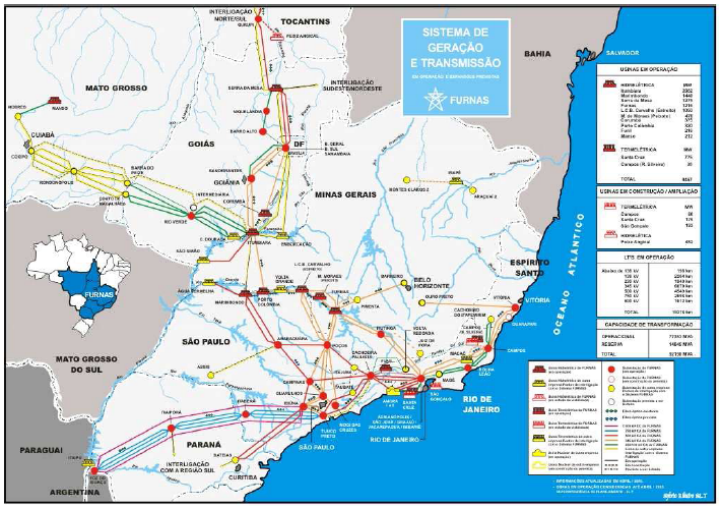


Fig. 1. Furnas Main Assets

## 3 ITAIPU TRANSMISSION SYSTEM MAIN CHARACTERISTICS

Itaipu hydroelectric power plant is located on Paraná River, at the border between Brazil and Paraguay, and belongs to a company of same name: "Itaipu Binacional". It is a power generation utility having its total shares owned by both governments, of Brazil and Paraguay, in equal shares for each country. The power plant has 20 generating units of 700 MW each and resulting in a 14,000 MW installed power capacity. It enables to produce around 100 TWh of energy per year.

As in these countries the rated (nominal) power frequencies are different from each other, the frequency of half of the generating units, belonging to Brazil, is 60 Hz, while the other half, belonging to Paraguay, has a frequency of 50 Hz. However, Brazil has agreed, by contract, to buy the whole of 50 Hz energy, except that consumed by Paraguay, which means that more than 75 % of the 50 Hz energy, in average, was consumed by the Brazilians in the last year.

Furnas was responsible for developing the transmission solution in order to integrate Itaipu power plant generation into the Brazilian national transmission network, performing the planning studies, equipment specification, factory and laboratory tests, erection on site, commissioning tests (factory and on-site acceptance tests), amongst other tasks. Thus, Furnas started the operation of the 800 kVAC and ± 600 kVDC systems in 1982 and 1984, respectively, integrating the Itaipu power plant generation into the Brazilian National Transmission Network', being, then, the detainer utility of the Brazilian know-how on transmission issues of such voltage levels, completing now 25 years of existence.

The HVDC transmission system consists of two bipoles of ± 600 kV CC and 3150 MW. Each bipole has two stations, rectifier (Foz do Iguaçu) and inverter (Ibiuna) stations, connected by an 800 km line long.

This hybrid AC/DC transmission system planned, shown in Figure 2, is one of the most important in the occidental world, due to its nominal voltage levels, rated power capacity and importance for the Brazilian electric industry.

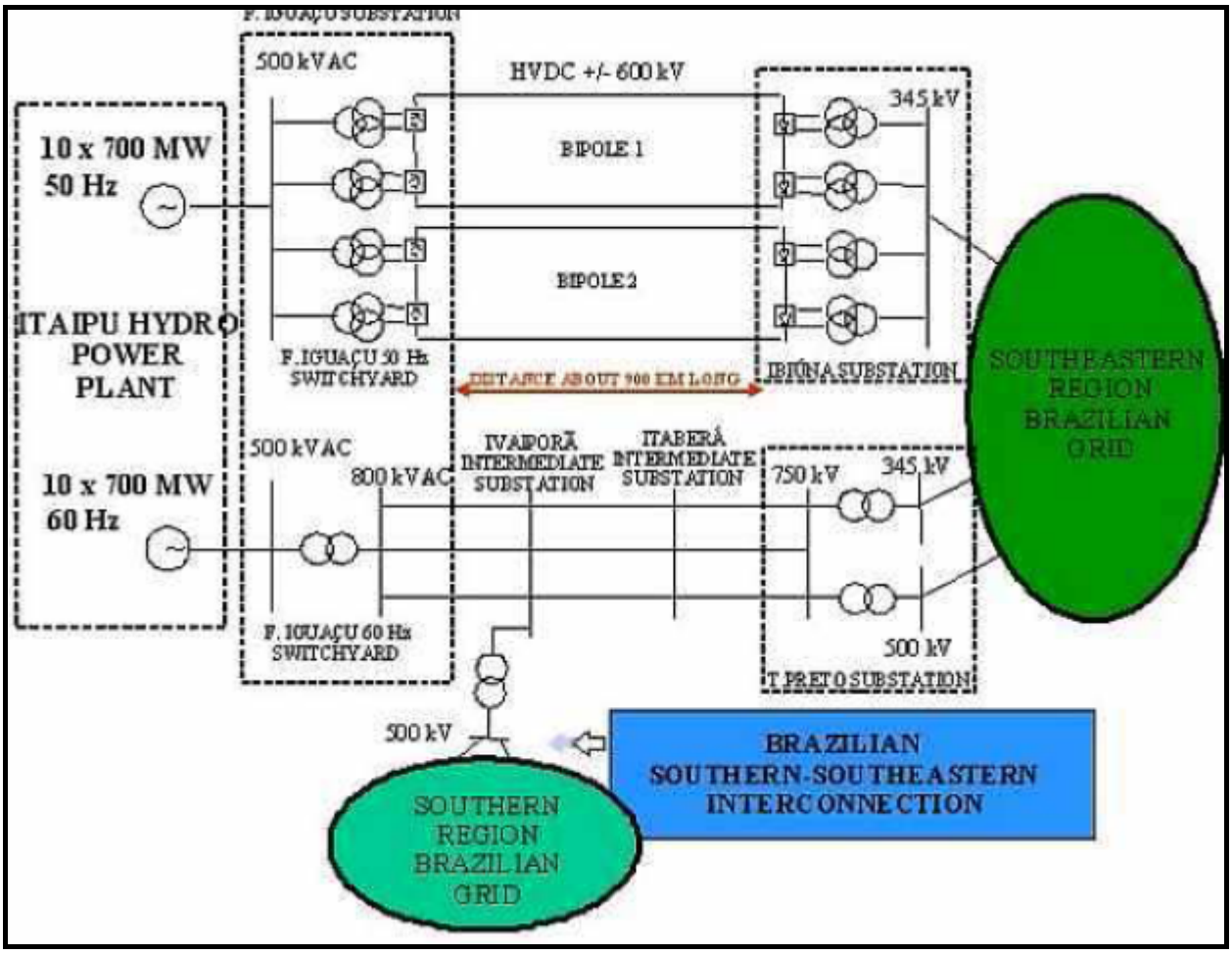


Fig. 2. Furnas transmission system for the integration of Itaipu power plant

## 4 THE IBIÚNA-BATEIAS TRANSMISSION SYSTEM

This Ibiúna-Bateias 500kV transmission lines, together with the Itaipu AC transmission system (composed by 3 circuits of 800kV voltage level), are the main interchange ties between the Southern and Southeastern power system regional grids.

And, as seen above, Ibiúna is also the receiving end (inverter station) of the HVDC transmission system, owned by Furnas, and responsible for the integration into the Brazilian national grid of the Itaipu power generated with the industrial frequency of 50 Hz.

The great importance of the 500kV Ibiúna-Bateias transmission lines refers to the fact that, when in operation, they allow a substantial increase of power and energy interchange between the Southern and Southeastern regions (regarding the both directions of interchange, i.e., from the power grid of the Southern region to Southeastern and vice-versa).

The Ibiúna-Bateias transmission lines were conceived, during the planning stage of such transmission system, in order to have two parallel circuits at the same tower structures, always shunt compensated at both ends (Ibiúna and Bateias), as indicated in Figure 3 below.

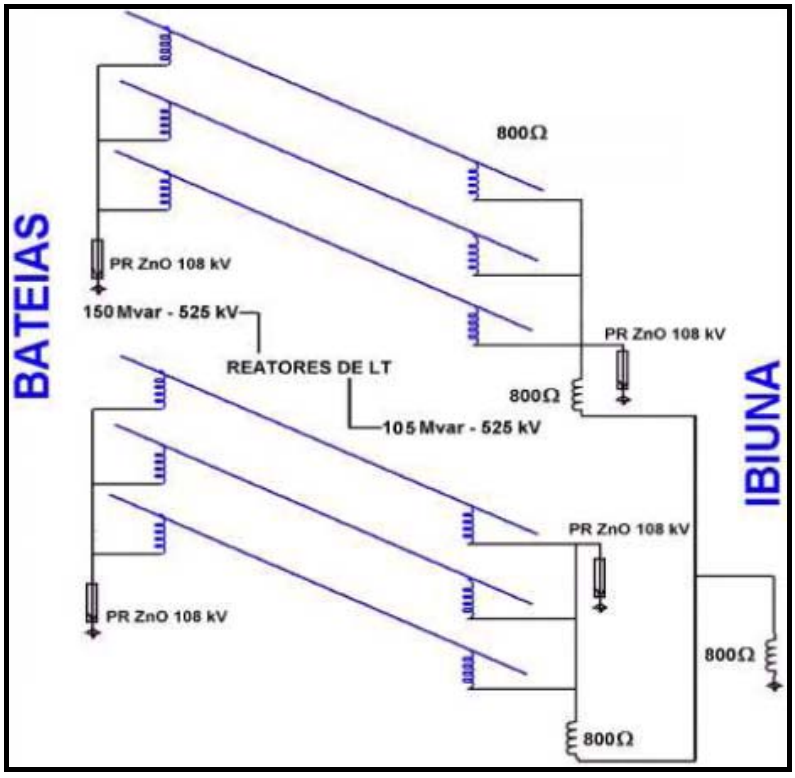


Fig. 3. Configuration of shunt reactors arrangement at Ibiúna-Bateias lines for SPAR scheme activation

With the activation of auto-reclosing scheme for the Ibiúna-Bateias 500kV transmission lines, the overall reliability of the Brazilian National Interconnected Grid (SIN) is improved in a substantial way. Also the discount, related to the period these assets are not in operation, and applied to the permitted revenue of such assets (the Ibiúna- Bateias 500kV OH lines), can be decreased to the value related to the period when the lines should be out of operation for maintenance purposes only.

Thus, the outages caused by untimely occurrences (short-circuits) can be brought to zero, considering the successful operation of the auto-reclosing scheme regarding these transmission lines.

Another point that should be highlighted here refers to the fact that the permitted revenue of the Ibiúna-Bateias transmission function is one of the biggest of the Furnas' transmission assets, and, therefore, the discount applied to such revenue is also considerable affecting the economical performance of such assets.

Therefore, the results of the electrical studies performed to evaluate the possibility of activation of the auto reclosing scheme for these transmission lines aim to define, as precisely as possible, the implications to the commutation failure performance within the inverter station of Ibiúna, which belongs to the HVDC

transmission system responsible for integrating into the Brazilian national grid the power and energy generated at Itaipu hydro power-plant by the half of generating units belonging to Paraguay.

## 5 AUTO-RECLOSING STUDY - MAIN RESULTS AND REMARKS

The application of single-phase auto-reclosing schemes, near inverter stations of bulk HVDC transmission systems, should be of great concern, since this auto-reclosing mode (single phase operation) may cause several commutation failures in sequence within the inverter station, after the application of a short-circuit to the OH line, and the opening of only its faulted phase.

This CF process is caused by the big asymmetry among the 3 phase-to-phase AC voltages applied to the thyristor valves of the inverter station during the dead-time of the auto-reclosing scheme. The operation of the OH line with only two sound phases and one open phase during the dead-time of the auto-reclosing scheme establishes an uneven condition for the system operation, i.e., the three phase voltages at the AC side in the inverter station are strongly unbalanced, causing the asymmetry of voltages applied to the thyristor valves.

The results of the study also showed that it is possible to operate the Ibiúna-Bateias OH lines using the three phase auto-reclosing scheme, being the CF performance of the Ibiúna inverter station quite acceptable in all operating conditions. In this case, the leader and slave terminals of the auto-reclosing scheme must be Ibiúna and Bateias, respectively. And the dead-time (idle time) should be set with a minimum value of 900 milliseconds.

With the activation of the 3-phase auto-reclosing scheme of the Ibiúna-Bateias 500kV transmission lines, the overall reliability of the Brazilian National Interconnected Grid (SIN) is improved in a substantial way. Also the discount of the permitted revenue of such assets (the Ibiúna-Bateias 500kV OH lines) can be decreased to the value related only to the period when the lines should be out of operation for maintenance purposes.

Regarding the definition of the leader and slave terminal for the 3-phase auto-reclosing scheme, the major factor which has capital influence upon the CF performance at Ibiúna inverter station is the transient active power impact, when closing the slave terminal by the auto-reclosing scheme. In this sense, the choice of Ibiúna as the slave terminal leads to the worst situation in terms of CF performance, since the transient active power impact occurs very close to the thyristor valves and interferes with the commutation process.

For the aspect raised immediately above, It is quite important to highlight here that the concern associated with the transient active power impact, caused by the auto-reclosing scheme operation, is related to the time-domain consequences, in terms of distortions on the voltage waves of the 3 AC phases at the inverter station of the HVDC link, rather than to the frequency-domain consequences of such transient active power impact caused by the auto reclosing scheme operation. In this sense (in the frequency-domain analysis), it doesn't matter where the slave terminal of the auto-reclosing scheme is defined, as the active power impact is the same, considering Ibiúna or Bateias as the slave terminal, when such condition is analyzed by a electromechanical transient simulation tool.

Nevertheless, the time-domain consequences for the AC voltages (considering the 3 phases) at the inverter station is quite different, depending on the definition of the leader and slave terminals. This definition will affect greatly the results of the commutation process performance within the thyristor valves at the inverter station, especially during the recovery process of the DC parameters after the transient commutation failure caused by the application of short-circuit near the inverter AC busbars. Therefore, taking these aspects into account, the definition of Ibiúna as the leader terminal and Bateias as the slave terminal for the 3-phase auto-reclosing scheme activation is the only acceptable alternative in terms of CF performance for the Ibiúna inverter station.

The worst conditions (regarding transient switching overvoltages and regarding the transient energy absorbed by the metal-oxide surge arresters) that were observed in the obtained results from the auto-reclosing simulations performed, refer to the cases of auto-reclosing without success (i.e., having the short-circuit applied permanently, even after the re-closing of the CB at leader terminal)

The special Shunt Reactor arrangement of the Ibiúna-Bateias transmission lines has two main purposes: (a) – to cope with steady-state and transient requirements, regarding overvoltages; (b) – to allow the implementation of auto-reclosing schemes at both parallel circuits (3-phase – TPAR - or single phase auto-reclosing – SPAR).

Soon after starting operation, the Shunt Reactors placed at Ibiúna terminal of both circuits showed to have some design/construction problems (related to insulation withstand and cooling process for preventing

temperature rise), which led to the forced outage from service of some single phase units of SR at Ibiúna terminal.
As it is likely to happen again such problems with the SR units at the Ibiúna terminal, two possibilities were investigated to overtake this operating problem: (a) – to make an evaluation analysis of operating the Ibiúna-Bateias transmission lines without SR at its Ibiúna terminal; (b) to connect other SR units (similar single phases units) but having different rated reactive power (existing as spare parts at other substations of Furnas transmission system).
This second alternative is an undesirable operating condition for the Ibiúna inverter station, as this unbalanced arrangement for the 3-phase shunt reactor placed at the Ibiúna terminal of the Ibiúna-Bateias OH line would cause severe uneven operating conditions for the 3-phase AC voltages applied to the thyristor valves, causing the increase of the probability of successive commutation failures (after a short-circuit clearing by the protection system in one transmission line directly connected to the AC side of Ibiúna inverter station, for instance).
Thus, the study developed recently, using the RTDS tool, additionally proceeded the evaluation of operating such transmission lines without SR at the Ibiúna terminal. The results of the analysis performed showed it is possible to operate one or even both lines without the SR at the Ibiúna terminal. Also, it is still possible to have the auto reclosing scheme activated in this operating condition for the Ibiúna-Bateias transmission system.
In this special operating condition some switching constraints for these OH lines energizations were established.
The energization procedure in such condition is more stringent than in the normal operating condition (with the SR connected at both terminals).
Therefore, the energization procedure, when operating one or two lines without the SR at the Ibiúna terminal, is only feasible to be done from the Ibiúna terminal. It is forbidden to be done from the Bateias terminal, due to the high transient switching overvoltages that may occur, especially with sustained short-circuit from one phase to ground (i.e., considering permanent faulted condition).
As already said above, regarding the auto-reclosing scheme (TPAR), the study concluded that it is still possible to have it activated, considering one or even two circuits without the SR at the Ibiúna terminal. There may be in this operating condition high transient switching overvoltages, especially with sustained short-circuit from one phase to ground (i.e., considering permanent faulted condition).
Thus, considering this special operating condition, it is highly recommended to have the metal-oxide surge arresters of the SR bay still connected to the line in order to divide (to share) the transient energy stress derived from the “statistical” transient switching overvoltages (The term statistical means that such transient switching overvoltages may occur, depending on the statistical closing time span of the line circuit breakers at the leader terminal). For such aim, it is possible to keep the surge arrester of the SR bay still connected to the line, even if the SR is disconnected, by simply dismounting the phase connections between the SR bushings and the arresters, and keeping the disconnector of the SR bay at its “closed” position.

## 6 STUDY PREMISES

The main adopted premises for developing the auto-reclosing study using the RTDS tool are as follows:
• The results, remarks recommendations and conclusions presented were obtained from the studies performed by Furnas using the facilities of its Power System Simulator lab. Such facility has two major simulation tools for power systems evaluation, regarding the aims of this study: (a)- the RTDS simulation tool, which consists of a digital real-time super-computing simulator, for electromagnetic transients evaluation in power systems; (b)- the RTDS digital simulator can be directly connected (by means of a proper analog/digital interface) with the Furnas analog HVDC simulator, which represents in deep details (mainly the controls and protection systems)the real HVDC system owned by Furnas, responsible for transporting the 50Hz generated power from Itaipu to the Brazilian national grid. Together (the RTDS and the analog HVDC simulator) they form the ‘hybrid’ analog/digital power system simulator of Furnas;
• The mentioned studies were developed considering high interchange operating conditions from the Southern and Southeastern power grids and also for high loading conditions of the Furnas HVDC (large amounts of generated power in Itaipu 50hz generating units);
• The two main objects of the auto-reclosing evaluation study performed are: (a)- the Commutation Failure (CF) performance within the HVDC link inverter station (Ibiúna), and (b)- the transient switching

overvoltages and transient energy in the metal-oxide surge arresters of the Ibiúna-Bateias lines. Both effects caused by the auto-reclosing operation;
• Regarding the modeling of circuit-breakers (CB) at Ibiúna-Bateias transmission lines, there were considered, for each operating condition studied, 100 (one hundred) different closing conditions for the auto-reclosing operation an the leader terminal (taking into account the Gaussian dispersion of CB closing times around a mean closing-time plus a typical standard deviation for 500kV CB closing switching).

## 7 MODELLING RELEVANT ASPECTS OF THE STUDY PERFORMED USING THE RTDS

For evaluation of the Ibiúna-Bateias auto-reclosing effects on the power system, the cases performed with the Furnas hybrid simulator (RTDS connected to the analog HVDC simulator) considered the modeling of power system equipment and operating conditions, as presented below:
• Non-linear characteristic (VxI curve) regarding the Shunt Reactors existing at the Ibiúna-Bateias transmission lines at both ends was represented. Also, for non-linear characteristic (VxI curve) regarding the metal-oxide surge (ZnO) installed at both line end bays and within the terminal substations of the Ibiúna-Bateias transmission lines;
• The Ibiúna-Bateias lines circuit-breakers have controlled switching devices. However, such devices are not activated on site at both line ends;
• The CB at the leader terminal of the auto-reclosing scheme were modeled in the traditional way for electromagnetic transient studies, i.e., with 3-phase closing action at random instants of the voltage wave at the source side of the leader terminal. Also, each phase (pole) of the leader CB was closed randomically (considering the Gaussian distribution of closing times, as above described). The presence of closing resistor of both CB (at leader and slave terminals) was also considered during the auto-reclosing switchings (for electromagnetic transients control/mitigation purposes);
• In the AC network model loaded in the RTDS simulation tool it was used a real unit of the auto-reclosing relay (one spare part of the units used in the line protection panels at site). For the study performed it was used only performing the function of the relay 25 of the slave terminal (for synchronism check before closing the CB of the slave terminal of the auto-reclosing scheme).
• The presence of harmonic pollution in the AC voltage of the inverter station (Ibiúna) was also considered. This harmonic pollution was simulated considering the highest levels ever measured, aiming to stress the transient operating condition at the inverter station thyristor valves;
• Single-phase short-circuit impedance considered in the range of 0.5 to 1.0 Ohm at Ibiúna and Bateias terminals. Such fault impedance values are intentionally very low, in order to stress the transient operating condition of the inverter station, considering the evaluation of CF derived from the short-circuit application to one line phase (always phase A);
• The HVDC analog simulator gives information regarding CF occurrence. This is done by means of an output signal from a specific electronic card of the pole control/protection board;
• The relevant electric parameters monitored in the simulations performed for the inverter station CF performance evaluation are (at both bipoles): the DC voltage, the DC current, DC power, active and reactive AC powers;
• The Series Compensation of the Ibiúna-Bateias transmission lines were also represented in the simulations performed with the RTDS tool, considering as well the by-pass scheme operation during the occurrence of internal faults (it was considered only application of short-circuits within the first protection zone of the line terminals;
• The Series Compensation arrangement defined for the Ibiúna-Bateias transmission lines has the series capacitor divided in two segments in series (each one having half of the whole effect in terms of longitudinal reactance compensation). This kind of arrangement allows a substantial increase of the equipment reliability, and gives much more flexibility regarding maintenance aspects. Refers to Figure 4 for details;
• Although the real equipment is conceived like above described, in the simulations performed using the RTDS tool, it was considered a one piece equivalent for the Series Capacitors of each line (including a model for the equivalent by-pass circuit as well).
In the power system model simulated in the RTDS tool, the check of consistency regarding the steady-state operating condition was done comparing the steady-state operating points obtained from the RTDS simulations with the conditions obtained with the official load-flow program used by Furnas (Anarede).

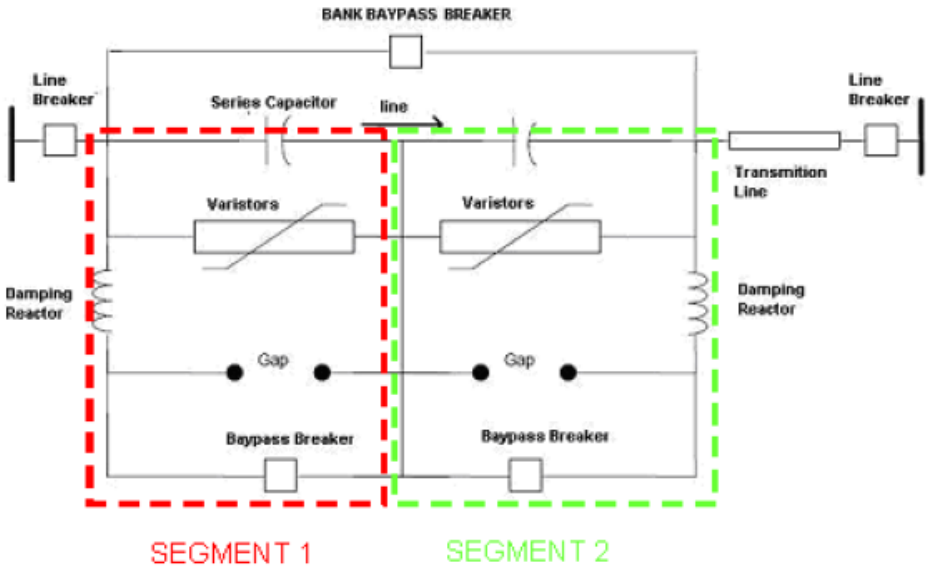


Fig. 4. Series compensation equipment used in the Ibiúna-Bateias lines

• Regarding the Synchronous Condensers of Ibiúna inverter station, it was used an up-dated model for the RTDS simulations performed.

For the whole study, in order to evaluate in a wide range of situations the CF performance at the Ibiúna inverter station, there were about 6,000 (six thousand) of single cases performed automatically by the RTDS tool (total amount of single-phase short-circuit application to the OH lines and the auto-reclosing scheme operation).

## 8 NETWORK TOPOLOGY USED FOR THE AUTO-RECLOSING STUDY

The Figure 5 below show the network topology considered to develop the studies performed using the RTDS, having the Itaipu HVCD analog simulator also connected, in order to allow the evaluation of commutation failure performance at the inverter terminal (Ibiúna).

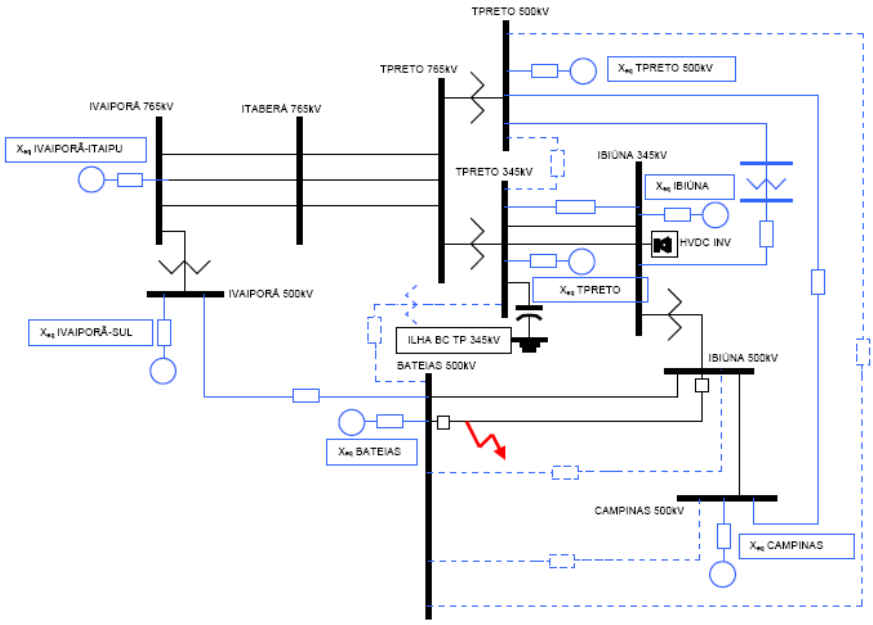


Fig. 5. Network topology considered for the studies performed with the RTDS Simulator

## 9 CONCLUSIONS

One pretty much important conclusion of this study is that the application of single-phase auto-reclosing schemes, near inverter stations of bulk HVDC transmission systems, should be of great concern, since this auto-reclosing mode (single phase operation) may cause several commutation failures in sequence within the inverter station, after the application of a short-circuit to the OH line, and the opening of only its faulted phase.

The results of the study also showed that it is possible to operate the Ibiúna-Bateias OH lines using the three phase auto-reclosing scheme, being the CF performance of the Ibiúna inverter station quite acceptable in all operating conditions. In this case, the leader and slave terminals of the auto-reclosing scheme must be Ibiúna and Bateias, respectively. And the dead-time (idle time) should be set with a minimum value of 900 milliseconds.

With the activation of the 3-phase auto-reclosing scheme of the Ibiúna-Bateias 500kV transmission lines, the overall reliability of the Brazilian National Interconnected Grid (SIN) is improved in a substantial way. Also the discount of the permitted revenue of such assets (the Ibiúna-Bateias 500kV OH lines) can be decreased to the value related to the period when the lines should be out of operation for maintenance purposes only.

Regarding the definition of the leader and slave terminal for the 3-phase auto-reclosing scheme, the major factor which has capital influence upon the CF performance at Ibiúna inverter station is the transient active power impact, when closing the slave terminal by the auto-reclosing scheme. In this sense, the possible choice, in theory, of Ibiúna as the slave terminal would lead to the worst situation in terms of CF performance, since the transient active power impact would occur very close to the thyristor valves and could interfere substantially with the commutation process performance, due to the transient impacts caused in the voltage and current amplitudes / wave shapes of Ibiúna converter station (345kV AC side).

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# ANNEX A

SOME TYPICAL RESULTS OBTAINED REGARDING THE THREE-PHASE AUTO-RECLOSING AND SINGLE-PHASE AUTO-RECLOSING SCHEMES

ANNEX A.1- TYPICAL EXPECTED INVERTER STATION ELECTRICAL PARAMETERS PERFORMANCE DURING THE 3-PHASE AUTO-RECLOSING SCHEME - OPERATION (WITHIN THE RECOMMENDED CONDITIONS)

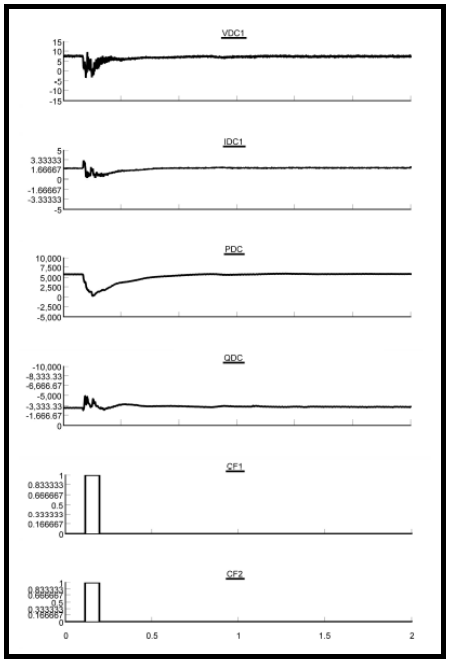


Fig. 1. TPAR operation: The electrical parameters recovery at the inverter station is quite acceptable after the CF derived from the single-phase fault

ANNEX A.2- UNDESIRABLE RESULTS REGARDING THE INVERTER STATION ELECTRICAL PARAMETERS PERFORMANCE DURING THE SINGLEPHASE - AUTO-RECLOSING SCHEME OPERATION

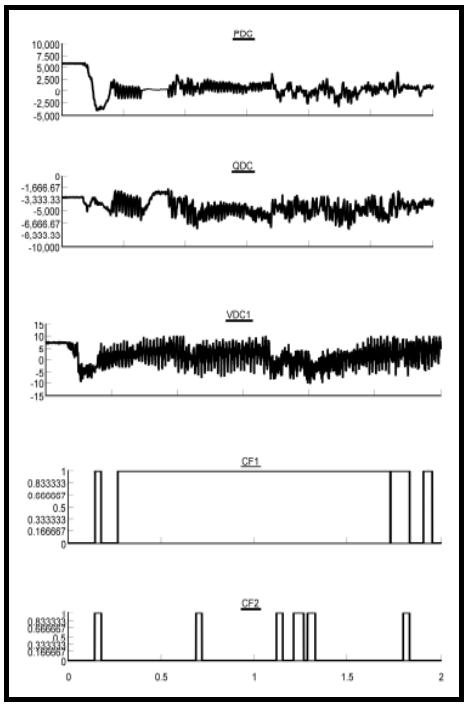


Fig. 2. SPAR operation: The possibility of a permanent CF occurrence, without the HVDC link recovery is unacceptable considering the studies premisses