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## ITAIPU HVDC TRANSMISSION SYSTEM 10 YEARS OPERATIONAL EXPERIENCE

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### ABSTRACT

The Itaipu HVDC system has now transmitted power for 10 years. The scheme, designed in 1979, includes many features new at the time and continues to be the largest HVDC transmission, in both rating, 6,300 MW, and voltage,  $\pm 600$  kV. Major operating features, present use, significant experiences and availability performance are discussed. Since final commissioning it has shown excellent performance with a forced outage unavailability below half a percent.

**Key words:** Power transmission, HVDC, Itaipu,

### 1. INTRODUCTION

This paper describes the experiences of the Itaipu HVDC system during the first ten years of operation. The present use of the transmission and the system dynamic performance is discussed, together with significant events and availability performance.

The Itaipu power plant is a Brazilian Paraguayan joint venture with a total installed capacity of 12,600 MW, the majority of which is transmitted to Southeastern Brazil, that is about 28% of the total system capacity. Due to the difference in frequencies of the two countries, half of the generation is at 50 Hz (Paraguay) and half at 60 Hz (Brazil).

Figure 1 is a simplified one-line diagram showing the interconnection of the Itaipu power plant with South/Southeast Brazil through the FURNAS transmission system.

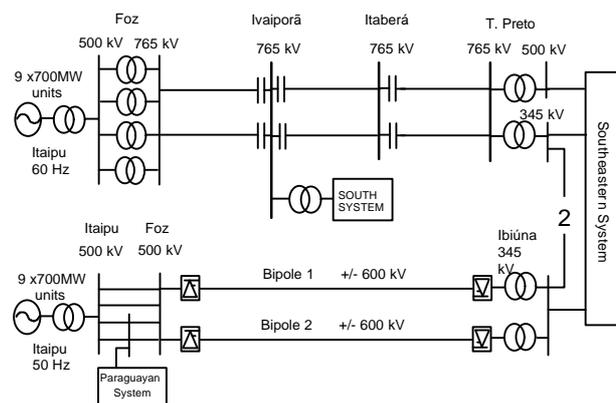


Figure 1. *Simplified diagram of the Itaipu Transmission System*

Studies indicated a hybrid solution for the power transmission, the power from the 60 Hz generators transmitted by AC lines via intermediate stations and the power from the 50 Hz generators transmitted by an HVDC system.

The Itaipu 60 Hz 765 kV HVAC transmission system is operating over two series compensated lines with the aid of a digital emergency control scheme (ECS) to match generation and transmission capability in case of disturbances in the electrical system.

For the 6,300 MW HVDC transmission, detailed studies, including firm bid prices for the converter stations, showed  $\pm 600$  kV to be the optimum voltage. The subsequent performance confirms this choice of  $\pm 600$  kV, with the attendant economical advantages. The two bipoles are designed to operate independently of one another under normal conditions. Figure 2 gives an outline of the main circuit, including the staged construction of the HVDC transmission.

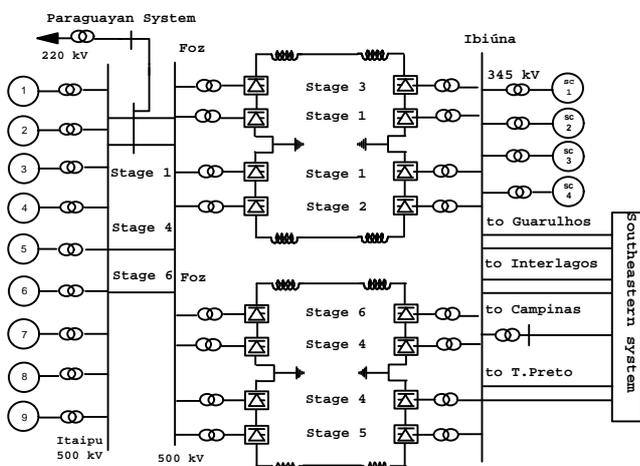


Figure 2. Itaipu HVDC System main circuit and evolution

The stations are connected over two bipolar transmission lines each approximately 800 km in length, which follow separate rights of way, at least 10 km apart, except at the approaches to the stations. Either transmission line can carry the rated output of the station using the facility of parallel operation.

The first stage was put into commercial operation in November 1984 and the last commissioning activities were completed in September 1990.

The Itaipu HVDC system is a landmark in HVDC technology with regard to several features:

- Highest power rating and highest voltage,  $\pm 600$  kV
- A large step in converter rating, specially thyristor and transformer
- The use of gapless ZnO arresters
- Massive use of microprocessor-based controls
- Integrated factory system test of control equipment

## 2. THE USE OF THE HVDC TRANSMISSION

The integrated system of South-Southeastern Brazil had a peak demand of 33,700 MW and an annual load of 210 TWh in 1994. Of this 35.5 TWh was supplied from the Itaipu 50 Hz machines, over the HVDC system.

Figure 3 shows the monthly transmitted energy and the peak power since 1991, the first full year of commercial operation for the complete system. The Actual Energy and Power Limits (AEPL) are the rated power limits minus the power of the generators not available; normally one machine is in maintenance. The Expected Energy Use (EEU) is AEPL times 0.65, the hydrological capacity factor.

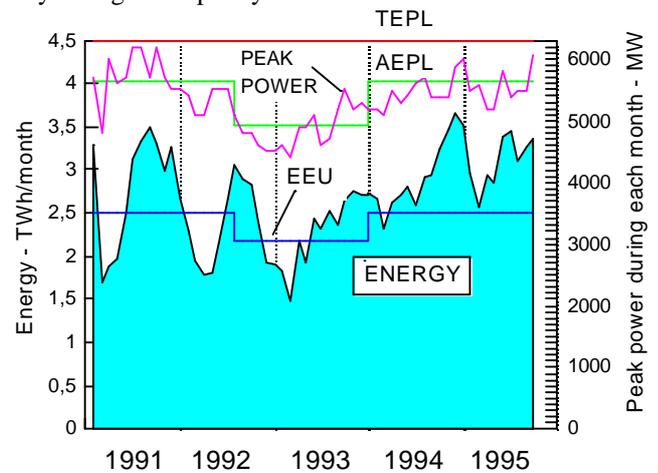


Figure 3: Itaipu HVDC Transmission: Monthly energy and peak power

It can be seen from figure 3 that the actual transmitted energy in most years has exceeded the expected energy usage. This is due the considerations used when deciding the energy dispatch in the Itaipu 50 Hz power plant, that is:

- Itaipu supply to Paraguay ranges from 100 to 500 MW.
- The system spinning reserve contribution for Itaipu is about 350 MW.
- The South-Southeastern Brazilian electrical system is 95% hydraulic.
- Different hydrological conditions influence the operation of the reservoirs. As an example the rivers in the south region have relatively small reservoirs.
- From 1992 to 1994 there were excellent hydrological conditions. The energy available was much greater than the load.
- When the hydrological conditions so allow, other power plants closer to the load centers are chosen to generate.

- Since July 1994 the energy consumption in Brazil has experienced a high rate of increase.

Thus the HVDC system is designed to operate over a large range to meet the full load cycle, from peak load on a work-day to about 25% capacity at weekend light load. A routine of converter maneuvers, shunt capacitor switching, filter switching and high Mvar consumption is used frequently to fulfill the operative requirements.

### 3. CONTROL SYSTEMS - OPERATING FEATURES AND EXPERIENCES

The control and protection systems for the HVDC are almost completely based on microprocessor systems. While this may not seem very remarkable today, at the time of design, 1979, this was a very radical decision. The control and protection systems are based on an hierarchical design, see figure 4, starting at the converter level, then pole, bipole and finally station. The aim is that any failure, main-circuit or control equipment, should reduce the transmission capacity as little as possible.

In general, the main control functions are carried out using the ASEA DS-8 control system, based on the Intel 8088 processor. This system provides for a large quantity of I/O, both analog and digital, as well as serial and parallel communication, being very suitable for the tasks involved. Two control functions requiring higher speed and accuracy, converter firing control and the current control, use a system based on the Intel 8086 processor with specially designed hardware for the I/O functions.

At the pole and converter levels the equipment is not duplicated, but a hardware back-up with limited control possibilities is provided for the DS-8 systems. At Bipole and Station levels the DS-8 systems are duplicated, providing automatic transfer if necessary.

Figure 4. Control hierarchy structure

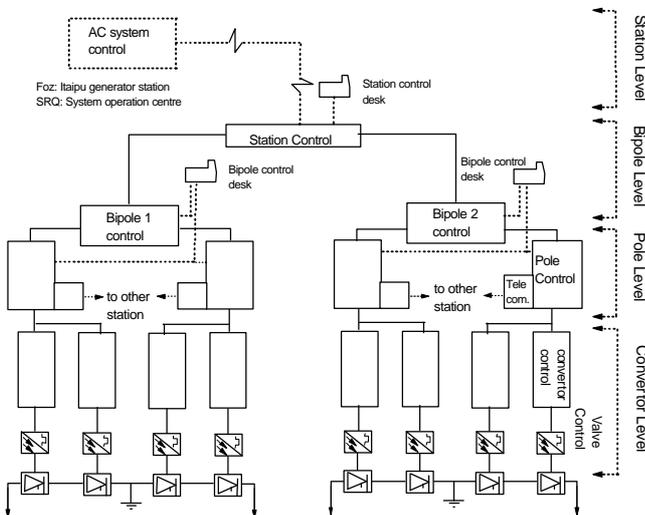
In practice, the microprocessor systems have proved very reliable and more maintenance and interference problems have been associated with the few hardware systems than with the computer systems. Additionally, the possibility to make fast changes, plus debugging with an on-line monitor, makes these systems much more convenient to use.

Due to these advantages microprocessor systems have become accepted as the standard for HVDC controls and although nowadays the systems are much more powerful, with more on-line resources, Itaipu can be seen as the first of this new generation of control equipment.

In view of the rapid development in microprocessor technology between 1979 and 1995, FURNAS is considering upgrading the control and protection systems, taking advantage of developments in the latest generation of ABB equipment. The faster and more powerful microprocessors allow an expressive reduction in the number of components, permitting complete digitalization and redundancy at pole, converter and valve levels. Besides the increased reliability and availability that could be achieved by duplicating controls at converter and valve levels, a significant reduction in routine maintenance work can also be expected.

#### 3.1. MAN-MACHINE INTERFACE

The majority of the control actions are made by the operators at the inverter station and only in special cases is this done at the rectifier station. From the regional dispatch center the following controls are available: bipole power ramping; synchronous compensator set point; AC filters maneuvers. The two last features are normally used to control the voltage at the 345 kV bus of Ibiúna.



Synchronous Power Control is the normal control mode and it is only in this mode that all facilities are available, i.e. overload, frequency control and so on. The name Synchronous Power Control means that the current controllers at both the rectifier and inverter are synchronized; i.e., during ramping or other variations in power order, the two are kept equal using the telecommunication system. In asynchronous operation, the power or current order at both rectifier and inverter must each be set by the operator.

#### 3.2. AUTOMATIC CONTROL ACTIONS

The HVDC transmission represents a rather high percentage both for 50 Hz and 60 Hz loads. Hence it was necessary to include transient and dynamic

automatic controls to ensure the correct performance of the integrated systems. These controls have to attend the sometimes conflicting requirements of the South/Southeastern Brazilian system and the interconnected 50 Hz Itaipu/Paraguayan system.

To do that, additional power orders derived from auxiliary controls are added to the order set by the operators. The resulting value is checked against a power order limit, being the minimum of a set of limitations and an automatic value depending on the number of 50 Hz generators in operation.

The main automatically initiated features are:

- Stabilization of frequency in the rectifier end
- Short-time Overload
- Transfer of power between poles and bipoles
- Reactive Power Modulation (Foreseen for SE system stabilization, but now not required)

### 3.3. AC VOLTAGE CONTROL

The operators have the task of controlling the AC system voltage, assisted by "Station Control", a system that monitors the situation and gives information, including minimum filter requirements, maximum permitted filter at Foz and AC bus-voltage control in Ibiúna, with high and low Mvar warning set-points for the Synchronous Compensators.

At high loads, in addition to the need to supply more reactive power to the converters, in Ibiúna there is also a need to supply the network. This can be met by adding filters above the minimum requirement and by adding shunt capacitors. The four 300 Mvar synchronous compensators are available for fine control of the AC voltage. They are normally operated with sufficient reserve capacity to cover a single contingency failure, i.e. trip of a filter-bank or loss of an AC line.

In Foz do Iguaçu there is a limit to the total capacity of filters which may be connected, as a function of number of generators, in order to avoid a potential self-excitation situation. The generators are designed with a 0.85 pu power-factor and consequently contribute greatly to the reactive power balance.

At light loads in Ibiúna, the minimum filter requirements may be such as to require other measures to absorb reactive power. For this condition High Mvar Control is provided where the inverter firing angle is forced to increase, dropping the DC system voltage and increasing the current. Hence the reactive power absorbed by the converters is increased. High Mvar Control has proved to be one of the most useful additional facilities for the regulation of the AC voltage, minimizing switching of filters and

capacitor banks and hence reducing maintenance of circuit breakers.

### 3.4. PARALLEL OPERATION

For reasons of reliability, given the possibility of an extended transmission line outage, the HVDC system is equipped for parallel operation at both bipoles on one bipolar transmission line. In one case when a logging truck hit an HVDC tower, causing a permanent bipolar outage, the repair of the line was possible without any load shedding in the Brazilian south/southeast system. In fact the transmission lines have proven very reliable and parallel operation has been used more for routine maintenance of both the transmission line and the station line end equipment.

The actual sequences required to enter into parallel operation are fully commanded from the station control room in Ibiúna. In general all of the operator controls used in normal operation are available in parallel operation. From the operators' point of view the power on the parallel poles is set in exactly the same way as in normal operation, although the poles obviously are part of different bipoles. Parallel operation is permitted only at 600 kV, i.e. two converters per pole. Reduced Voltage Operation may be ordered by the line protection when in parallel operation. Deparalleling may be ordered by protection operation.

### 4. SYSTEM DYNAMIC EXPERIENCE

A Dynamic Performance Study (DPS) was performed during the design stage and continued throughout the commissioning as the various stages were put into operation. The fundamental objective was to demonstrate that the transmission system would meet the required performance as defined in the technical specification. Exceptions to the specified performance were sometimes found necessary to provide satisfactory performance for the integrated networks.

Operational experience acquired since the start of operation, as well as the normal evolution of the AC networks resulting in a stronger inverter, indicate that different dynamic performance is possible today. Consequently FURNAS is in the process of revising the dynamic performance study.

There are multiple objectives for the revised study:

- It is hoped that several control features, added to achieve the specified performance can be removed or simplified.
- Relaxing slightly the allowed levels of AC harmonic distortion, (i.e. operation with less AC filtering) more convenient reactive power control may be possible.

- Introducing automatic power limits based on the topology of the inverter AC network (runback limiter) can maintain the inverter SCR at acceptable levels during contingencies.
- Faster AC fault and commutation failure recoveries can reduce frequency excursions in the sending end AC system.
- Power modulation of the HVDC link may be advantageous in enhancing the stability of the FURNAS 765 kV AC transmission system.

The tools available to perform this study today have also evolved compared with the early 1980's. The HVDC simulator, with its detailed DC controls, continues to be essential. However a more complete AC network representation is now available using the RTDS™ (Real Time Digital Simulator) which is interfaced with the HVDC Simulator.

## 5. SIGNIFICANT OPERATING EXPERIENCES

During these ten years of operation a considerable number of interesting experiences have occurred, especially during the first five years which were concurrent with construction and commissioning. The division of the work into stages which were constructed and put into operation sequentially followed the schedule for the generating units in Itaipu and permitted continuous transmission of the available energy. This simultaneous commissioning and operation, while not restricting energy transmission, can be seen in the higher forced outage figures in the first years. This section will not try to cover all events from these ten years, but concentrate on the most significant items.

### 5.1. HARMONIC EXPERIENCE

The service experience, both with respect to level of harmonics and to consequent interference, has shown the performance to be well within specified requirements.

#### 5.1.1. AC side harmonics

The method of calculating the level of AC side harmonics is very conservative. It takes into account a range of possible resonances with the AC system as well as worst case parameters, e.g. combinations of tolerances in transformer impedances and unbalances in firing angles.

In practice, these factors are not as bad as assumed and the AC side harmonics are less than calculated, especially for non-characteristic harmonics, and the interference levels well within the specified levels.

One interesting factor is that a filter is included for the non-characteristic third and fifth harmonics. This filter was included for performance reasons, when calculating with pessimistic assumptions. In actual operation, it has been found that the loading of this filter is well above the expected level. However, this is due to fifth harmonic currents originating in the AC network. The sources of these harmonics are diverse, and at the moment not completely identified, but for sure influenced by industrial loads and to a large quantity of TV sets with single pulse rectifiers.

On a weekend and during a final match of the 1995 South America Football Cup, measurements taken at the Ibiúna station demonstrated clearly the heavy influence of TV sets on the fifth harmonics levels.

#### 5.1.2. PLC harmonics

The technical specification gave very strict requirements regarding PLC interference to reduce the noise generated by the converter stations over the frequency range 30-500 kHz. Theoretical calculations indicated that this may not be met over the range 30-120 kHz. However, in view of the potential cost savings, it was agreed to postpone any decision on PLC filters until measurements could be made on the operating system.

As part of the final commissioning, measurements of PLC noise were made at the coupling capacitors on the AC lines. These measurements, made over the 30-500 kHz range, showed that the noise somewhat exceeded the specified level at frequencies below 100 kHz, but was acceptable, especially when considering actual and proposed PLC frequencies. Accordingly, it was decided not to install the PLC noise filters, see reference 3.

### 5.2. FLASHOVERS ON 600 kV WALL BUSHINGS

Operation with 600 kV started in July 1985 in the negative pole of Bipole 1, with no apparent problems. Less than 3 months later a flashover occurred on the DC pole bushing at Foz do Iguaçu. The bushing was checked, but no defect found. Pollution samples showed a low level compared to those normally found in connection with pollution flashovers. At the time of the occurrence it had been raining heavily for about half an hour.

By the end of the year, a total of five flashovers had occurred at Foz do Iguaçu and two flashovers at Ibiúna, on both the positive and negative poles for five different bushings, all under heavy rain conditions. By that time it had become clear that this was a general problem for the 600 kV wall bushings

and full voltage tests had been started to determine the reason for the flashovers. The tests were supplemented with data collection from other sites and comprehensive meteorological observations from the Foz and Ibiúna stations.

It was confirmed that a rain shadow close to the wall decreased the withstand voltage considerably, see figure 5, and that the length of the dry zone was an important parameter for withstand strength. A minimum withstand dry zone could be found and figures as low as 350 kV were recorded. Observations at site established that a rain shadow gave a dry zone on the bushings close to the wall. Later electrical field measurements confirmed that a dry zone causes a steep increase in the electric field and that this is the cause of the flashover.

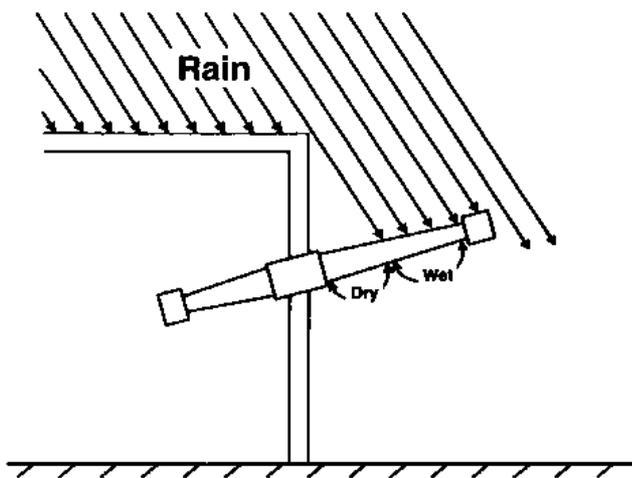


Figure 5. Rain shadow

From the investigations it became evident that it was necessary to either decrease the stresses over the dry zone or increase its withstand capability. The most promising method seemed to be to make the insulator surface non-wetting and thereby decrease the steep electrical field increase in the transition between the wet and dry zones. This could be made by application of a hydrophobic coating on the insulator surface by silicone grease or room temperature vulcanized silicone rubber (RTV).

In June 1986 silicone grease was applied to all 600 kV wall bushings as a temporary measure while the investigations continued. Evaluation was made of coated insulators, both compared to other possible countermeasures and also between RTV and silicone grease. No conclusive improvements could be found from other measures such as alternative porcelains or booster sheds. Both RTV and silicone grease seemed to give considerable improvements and the experiences from the temporary silicon grease application was excellent, preventing further

flashovers. Thus, further work was concentrated to these solutions.

RTV had shown good performance in other installations and had indicated longer life-times than silicone grease, but application is more difficult and it is uncertain if it can be removed easily. During an investigation on test specimens on site, RTV exhibited an unexpectedly rapid loss of its hydrophobic properties. This was followed up by laboratory experiment that showed that if exposed to water over a long time, RTV would lose its hydrophobicity. Thus it seems that RTV may not be efficient in tropical climates with heavy and abundant rain. The conclusions were that silicone grease of the type chosen could most probably get a lifetime of 4 to 5 years in a clean ambient atmosphere and that thickness and evenness were not a problem. Even a fairly thin layer would protect the hydrophobicity and thereby prevent rain flashovers. This was confirmed by an on site test program for various types of silicone grease and RTV, including application to energised test insulators at 600 kV. On the wall bushings the time between exchanges was increased, for the original grease type, under close supervision of characteristics, especially hydrophobicity, see figure 6.



Figure 6. Foz do Iguazu 600 kV wall bushing. Hydrophobicity test on silicone grease after 38 months exposure time.

Actual experience has shown that removal and reapplication can be considerably facilitated by control of the chemical composition and the use of simple hand tools that were developed. Now, with more than nine years successful use of silicone grease, the procedures developed have led to fast and well controlled grease renewal. A minimum four-year lifetime is proven by operation experience for the conditions prevailing at the Itaipu converter stations.

### 5.3. CONVERTER TRANSFORMERS

During the early years of operation significant problems were experienced with the converter transformers. This was distributed fairly evenly between the rectifier and the inverter and between 300 kV and 600 kV. The four types have the same conceptual design, although they are not identical in detail.

The first indications were given mid-1985, after about six months of operation, when gas in oil analysis showed gassing, at a low rate, in some transformers. In October 1985 a failure occurred in one transformer at the inverter station and was traced to the AC winding. Shortly after a second failure occurred in the rectifier, located at the DC winding outlet. One of the failed transformers had shown gassing, including acetylene, while the other one did not show more gas than had been generally expected.

The examination of the first failed unit, together with inspections in another gassing unit, revealed bad contacts between a copper plate and an aluminum plate. This was evaluated as the cause of the gassing. A program to modify the contacts was carried out during early 1986.

After a few months operation, gas in oil was found again in some modified transformers. In May 1986, another transformer failed in the inverter, with the failure in the AC winding. Special investigations were undertaken at the factory and an extended heat run test indicated that the gassing had its origin in induced currents circulating in the core.

A second modification of all transformers to reduce the induced currents was undertaken and again carried out on site and in the workshop. The site modification was carried out while the link was in commercial operation and this meant that a considerable time elapsed, even though extra spare units were delivered to facilitate the execution of the work and to give more security against service interruptions.

In 1989 the work to execute the modifications was finalised. During this time further failures occurred, some of which were after the second modification had been completed.

A detailed analysis of the failures was presented in the CIGRÉ 1993 Joint Task Force 12/14, 10-01 and will not be repeated here. A summary is given below, where it can be seen that the failures are concentrated in the first years of a transformers operation.

Years of Operation	Number of Failures
0 - 1	6

1 - 2	3
2 - 3	2
3 - 4	1
4 -10	0

The failure rate for these converter transformers has been higher than one would normally expect for this type of equipment. This can be explained as due to a large step in converter transformer development especially with regard to unit rating, coupled with severe transport restrictions. This resulted in a relatively large number of new techniques which, although extensive prototype testing was made, were still not fully controlled during the manufacturing process. However the last five years of operation make us feel confident in the present and future service performance of these transformers.

#### 5.4. VALVE HALL FIRE

In May 1989 a fire broke out in Converter 5 at the Foz do Iguacu substation. This was due to an unfortunate combination of circumstances which are summarised here.

Information from personnel present at the time, plus event recorder printouts and a detailed inspection made in the valve hall, identified the following failure sequence:

1. A water tube between two thyristor levels in valve 2, close to the top of phase A quadruple valve, comes loose and water leaks at approximately 1 l/s.
2. A water leakage alarm is emitted, however the protection system does not trip as the trip signal is inhibited due to an open by-pass valve.
3. Water flows down in quadruple valve A during at least 8 minutes, corresponding to approximately 500 liters. The conductivity of the originally deionized water increases when flowing over the valve modules, due to contamination with the small amounts of dust and dirt it picks up.
4. A flashover occurs in the bottom valve of phase A and gives a short circuit across that.
5. The flashover strikes the damping capacitors in the bottom valve of phase A and starts a fire in some.
6. The fire spreads upwards in the quadruple valve structure where it increases in heat generating capacity and intensity, so that aluminum and plastics melt and porcelains crack.
7. The fire is discovered. The ventilation system is closed and after some hours the fire has self-extinguished.

A full scale experiment in which the corresponding water tube was cut open was made and the sequence recorded. This confirmed that the trip signal was not

given due to the fact that the by-pass valve for rapid refill was erroneously left in the open position.

Phase A quadruple valve was damaged by fire. The other two quadruple valves were not directly damaged by fire, but rather by smoke. A large amount of hydrochlorides from burning plastic was precipitated on all equipment. Due to this contamination the major part of the equipment was replaced. Only the busbars and some very special items were not manufactured new. The valve hall was put back into operation in slightly less than 14 months and entered into operation in July 1990.

After the fire incident some modifications to the system were introduced:

- A locking key on the by-pass valve for rapid refill was installed to avoid operation of the thyristor valves if this valve is left open.
- A new trip function was introduced, based on the derivative of the water level.
- The start of the make-up pump was delayed 10 minutes in order to ensure operation of the low water level trip at a leakage rate of more than 0.14 l/s.
- A new frequent make-up alarm was included.
- The Bipole II water connections between thyristor levels were exchanged for the type used in Bipole I, having a superior ferrule fixing.

Later a full scale test of incipient fire detectors was made. Testing demonstrated the possibility to identify a pre-combustion condition by detecting submicron particles emitted from overheated plastic material. The successful testing led to the decision of a full scale installation of such detectors in all converters. This installation was completed in August 1994.

## 5.5. VALVE COOLING SYSTEM

After several years of operation, discoloration was noticed on the stainless steel pipe couplings used to connect the fine water PEX pipes between modules. In some converters actual corrosion of the tubes in certain positions had taken place, but the process was far from uniform and not necessarily worse in converters having longer operating times. As this effect occurred only at the anodic ends of the tubes a process of electrolytic corrosion was suspected. In fact the design allowed for some corrosion of the tubes over a 50 year period, however in many cases a faster effect was seen. This was the case even though the water quality had been maintained at the low levels of conductivity required to limit the stray currents in the cooling water. A series of investigations both in the laboratory and at site determined that the foreseen electrolytic corrosion was accelerated by the presence of free negative ions.

The origin of these ions was probably the water treatment resins used on the system, the ions being released at the time of exchange of resins.

There were several ways to resolve this situation, however the chosen solution was to modify the cooling water pipe couplings to make them resistant to this phenomenon. In summary the stainless steel pipe couplings were replaced by plastic couplings, in which an inert electrode is utilised to ensure satisfactory voltage distribution within the water circuit. In addition to laboratory tests on the materials used and thermo- mechanical life cycle testing on the new couplings, a full scale dielectric test program was carried out. Also finer water filters were introduced to replace the original filters.

The work to change the pipe couplings and also to clean the valves of corrosion products and possible remaining catalytic agents was carried out during the first half of 1994. The results of monitoring the modified cooling system indicate that the solution adopted is giving fully satisfactory performance.

## 5.6. MAINTENANCE

Preventive maintenance is an activity having a significant influence on the system operation, both from the point of view of manpower and performance. In order to evaluate the impact of the preventive maintenance activities on the availability of the power transmission, a trial preventive maintenance was performed. This determined the duration to be used as a maximum for the availability guarantee calculations.

This trial consisted of an actual maintenance at Bipole, Pole and Converter levels of equipment for which the shutdown has an impact on the power transmission capacity. The activities to be carried out were defined by the Preventive Maintenance Plans for the substation and considered necessary for a good performance of the HVDC system and were based on the manufacturers recommendations, the previous experiences of the converter station supplier and the experience obtained by FURNAS in the operation of the converter station.

At converter level, the preventive maintenance of the By Pass Breaker was found to be time-consuming and this equipment proved critical for the converter outage time, much more than, for example, the valves. At Pole level the HVDC Control and Protection maintenance showed to be the most time consuming equipment, as expected. Disconnecting Switches, in spite of the large number, were maintained in only 7 hours. At Bipole level both Bipole Control and Protection and Common Yard equipment were maintained in around one and a half hour.

The evaluation of the times achieved during the trial maintenance resulted in outage to be used for the calculations of the Availability and Reliability Guarantee (see Table 1).

LEVEL	MAXIMUM OUTAGE TIMES
Bipole	2 hours per year and per bipole
Pole	11 hours per year and per pole of which 2 hours overlapping with bipole outage
Converter	18 hours per year and converter of which 11 hours overlapping with pole outage

Table 1: Outage times to be used for AR Guarantee

In practice the preventive maintenance is planned according to an annual time schedule, to a large extent based on optimisation of manpower. Two weeks before the maintenance, the central dispatch is informed about the equipment that will be under maintenance, so that all interconnected utilities can be informed. However, if for some reason any equipment is out of service, efforts are made to take advantage of this and preventive maintenance is performed.

So far, taking into account the use of the HVDC transmission, it has not been necessary to schedule maintenance in the manner in which the trial maintenance was performed. This is because it has been possible to shut down converters, except in the heavy load period, without prejudicing the power transmission, allowing more time for maintenance and reducing total maintenance staff and overtime. Such a procedure reduces costs, although the system availability decreases.

One interesting result of the maintenance activities is the very low thyristor level failure rates found. This has been consistently below 0.1% per year and in 1995 was 0.03%, that is three failures in more than 18 000 levels.

## 6. AVAILABILITY

Table 2 presents the availability of the Itaipu HVDC transmission system in two different formats. One according to CIGRÉ definitions and another according to the contract for the supply of the converter stations.

YEAR/ BIPOLE		UNAVAILABILITY BY CIGRÉ (%)		AVAILABILITY (%)	
		Forced	Schedule d	CIGRÉ	Contract
88	BP1	1.5	6.9	91.6	-
	BP2	-	-	-	-
89	BP1	4.6	6.9	88.5	-

90	BP2	15.6	7.8	76.6	-
	BP1	0.7	7.7	91.6	-
	BP2	14.2	10.6	75.2	-
91	BP1	0.6	12.3	87.1	-
	BP2	0.4	12.9	86.7	-
92	BP1	0.3	8.8	90.9	99.5
	BP2	0.7	6.4	92.9	98.9
93	BP1	0.2	2.6	97.2	99.1
	BP2	0.2	2.5	97.3	99.4
94	BP1	0.4	6.4	93.2	99.3
	BP2	0.2	5.9	93.9	99.4
95	BP1	0.1	2.1	97.8	99.4
	BP2	0.4	2.1	97.4	99.3

Table 2. Itaipu HVDC Transmission System Bipoles Availability

It can be seen from that table that the contractual figures do not match the reporting to CIGRÉ as the two formats are different. The main difference between the calculations is that the report to CIGRÉ does not take into account the actual maintenance procedures used at site, penalizing the availability figures, while the contractual figures consider that the maintenance could be performed, if necessary, according to the trial maintenance results, see 5.6, which corresponds to an equivalent unavailability of 0,28% per bipole and year.

Considering that scheduled maintenance is carried out taking advantage of periods of low utilization, the availability format used by CIGRÉ has been questioned by many utilities, including Manitoba Hydro and FURNAS, at the HVDC Users Conference held last September, 1995 in Winnipeg, Canada.

Another difference between CIGRÉ and contractual availability figures is that the contractual calculation gives less than proportional weight to outage of a converter than to outage of a complete pole, considering the design with series connected converters and the impact on power transmission of having one converter out of operation. Also certain type of events outside the contract such as DC line, AC network and human errors are excluded from the calculations based on the contract.

In table 2, the unavailability figures for Bipole 2 in 1989 and 1990 were affected by the valve hall fire. The 1994 scheduled unavailability for both bipoles reflect the outage time for installation of the incipient fire detection systems mentioned in 5.4 and the modification to the valve cooling circuits discussed in 5.5, which were carried out together, sequentially, in all converters

Table 3 shows the main causes of disturbances for the last eight years without giving weight to how large part of a pole is affected. In that table all forced outages for the two bipoles, with a total of eight converters per station, are summarised. It can be seen that there is a general trend for the annual number of converter equipment forced outages to reduce with time. The number of forced outages due to control and protection is significant, especially in 1989 when many were due to commissioning of the bipole paralleling system together with commercial operation. In recent years, there is a trend to decrease, except for 1992 and 1993, when they were high. These two years suffered from repetitive faults of transient nature that were hard to trace. In particular one fault in a pole current control amplifier and a series of similar faults in the power supplies to the valve control cubicles are responsible for most of the control faults.

The weighting counts one pole as a single unit, reducing the impact of converter outages to the significance that they have on power transmission.

Many of the counted outages were in fact the same failure, but the process of "trouble shooting" could have contributed to a further disturbance. This is illustrated in Table 3 by the values in parentheses, where the outages due to the same failure have been discounted.

This illustrates the advantage that would be obtained by the use of duplicated control equipment, which not only avoids the outage, but also permits on-line fault tracing, as well as routine maintenance. Such a system would therefore increase the availability, both forced outage and scheduled.

For the last four years the "equivalent weighted forced outage per bipole" has been monitored. This value excludes human errors and covers station equipment only.

DESCRIPTION	YEAR							
	1988	1989	1990	1991	1992	1993	1994	1995
AUXILIARY SERVICES	10	5	6	5	1(1)	4(3)	1	7(5)
CONTROL AND PROTECTION	22	60	29	5	23(16)	18(12)	9	9(7)
MAIN CIRCUIT EQUIPMENT	16	7	9	5	2(2)	4(4)	4	2
TOTAL CONVERTER EQUIPMENT	48	72	44	15	26(19)	26(19)	14	18
DC LINES	20	9	36	4	10	19	20	12
AC SYSTEM	2	3	-	-	-	-	-	-
HUMAN ERRORS	22	30	12	5	12	7	4	4
TOTAL	92	114	92	24	48(41)	52(45)	38	34
EQUIVALENT WEIGHTED OUTAGE PER BIPOLE					BP1/BP2 5.8/4.5	BP1/BP2 2.5/3.8	BP1/BP2 5.8/4.5	BP1/BP 2 1.5/4.0

Table 3. Itaipu HVDC transmission. Total forced outages

The figures given for the dc line include transient faults with successful restart. Many of the DC line faults in 1990 were caused by flashovers to a eucalyptus tree and in most cases the faults did not cause a pole outage. The performance of the  $\pm 600$  kV dc lines has proven to be very good. The two lines use 30 insulators per suspension string, giving a specific creepage of 27.7 mm/kV and have a total length of over 1600 km. In the last three years there have been a total of 51 faults, of which only 12 did not restart with success. This gives an average of two pole outages per bipole/year, which in general were restarted manually without any problem.

## **7. CONCLUSION**

The Itaipu HVDC Project, designed in 1979, includes many features new at the time and continues to be the largest HVDC transmission, in both rating, 6,300 MW, and voltage,  $\pm 600$  kV. During the now more than ten years since first power transmission, the system has operated continuously supplying a major part of the Brazilian load, always providing transmission capacity for the available generation. The early years experienced significant challenges in commissioning and operating the system, as one may expect in such a large project. The final stage of the project was fully commissioned in 1990, including the use of parallel operation. In the last five years since then, the average forced outage unavailability has been below half a percent.



Figure 8. View of Foz do Iguaçu station

## 8. REFERENCES

1. V. Madzarevic, C.A.O. Peixoto, L. Hagloef: "General Description and Principal Characteristics of the Itaipu HVDC Transmission System" from Conference Sharing the Brazilian Experience, Paper 1.1, Rio de Janeiro March 20-25, 1983
2. A.G Figueiredo, A. Praça, N.L. Shore: "Master Control of the Itaipu HVDC Transmission System" from Conference Sharing the Brazilian Experience, Paper 1.7, Rio de Janeiro March 20-25, 1983.
3. Marly R. Bastos, Jose Torquato P. de Souza, John Graham, "Interferencia das Conversoras de Corrente Continua no PLC do Sistema de Corrente Alternada." XI SNPTEE, Rio de Janeiro, 1991.
4. W. Lampe, D. Wikström, B. Jacobsson: "Field Distribution on an HVDC Wall Bushing during Laboratory Rain Tests" IEEE 1991 WM. 125-5 PWRD.
5. "In-service performance of HVDC Converter Transformers and Oil-cooled Smoothing Reactors". CIGRÉ Joint Task Force 12/14.10-01, 1993.
6. H. Arakaki, J. Lopes, A. Praça: "Itaipu HVDC Transmission. System-Analysis of Control System and Protection Performance after two years of Operation". Winnipeg, July 1987.
7. A. Farias, I. Oliveira, L. Correa et Al.: "Emergency Control Scheme for the 765 kV AC Itaipu Transmission System Using Logical Programmable Controllers". CIGRÉ Latin American Conference. May 1995, Foz do Iguaçu, Brazil.
8. Delfim P. Amaral, A. M. de Freitas, John Graham. "Implantação de Sistema de Detecção de Incendio em Valvulas Tiristoras - Experiencia de Furnas" XIII SNPTEE, Florianopolis, Brazil, 1995.