800 KV-AC AND 600 KV-DC BRAZILIAN TRANSMISSION SYSTEMS
EXPERIENCE AND FUTURE TRENDS


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SUMMARY
This paper is basically divided in two parts and aims to present the Brazilian experience regarding UHV transmission systems and the foreseen future trends related to the use of such technology. The first part shows Brazilian knowledge and experience on dealing with UHV transmission systems (800 kV AC and ± 600 kV DC), describing some aspects and faced problems, from planning and operating experience point of views. FURNAS Centrais Elétricas, as a generation and bulk power transmission utility, owned by the Brazilian Federal Government, 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), among other tasks. FURNAS was created in 1957 and started the operation of the 800 kV AC and ± 600 kV DC systems in 1982 and 1984, respectively, integrating the Itaipu power plant generation into the ‘Brazilian National Transmission Network’, and then, being the utility detainer of the Brazilian know-how on UHV transmission issues [1]. 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 owned by both governments of Brazil and Paraguay in equal shares. The power plant has 20 generating units of 700 MW each, resulting in a 14,000 MW installed power capacity enterprise enable to produce around 100 TWh of energy per year. As these countries rated 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. This has been established as a consequence of an international treaty celebrated between both countries. However, Brazil has agreed, by contract, to buy the whole of 50 Hz energy, except that consumed by Paraguay, which means that 75 % of the 50 Hz energy, in average, was consumed by the Brazilians in the last year. In the second part of the paper the Brazilian future trends and challenges regarding the use of such UHV transmission system technologies are presented, as for the transmission solution associated to the foreseen planned major hydro power plants in the Amazon region (transfer of high amounts of power between 6,000 and 10,000 MW across long distances of about 2,400 km. The consequent impacts on existing network are considered by pointing out the need of reinforcing the receiving network, as well as the need of investigating procedures for limitation of short-circuit current levels exceeding existing equipment ratings. Also, the new challenges may demand IEC standards review, due to the special UHV new equipment withstand requirements.

KEYWORDS
UHV long distance transmission, planning, engineering, construction, operating experience, equipment, specification, tests, erection on site, future trends
INTRODUCTION
The Brazilian Electric Power System has some particular features that should be highlighted: the bulk supply is typically provided by long EHV transmission lines belonging to the national transmission grid, not only to connect far hydroelectric power plants to the main load centers, but also to interconnect power systems of different regions, and from distinct geographical areas. Due to the long distances between load centers and major generation plants, several transmission lines and substations of 550kV up to 800kV had to be built in the country, soon after these voltage levels started to be used by utilities in other parts of the world.

BRAZILIAN EXPERIENCE
Considering such a frame as above described, 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 owned by both governments, of Brazil and Paraguay, in equal shares. The power plant has 20 generating units of 700 MW each, resulting in a 14,000 MW installed power capacity enterprise, enable to produce around 100 TWh of energy per year. As in these countries the 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. This has been established as a consequence of an international treaty celebrated between both countries. However, Brazil has agreed, by contract, to buy the whole of 50 Hz energy, except that consumed by Paraguay, which means that 75 % of the 50 Hz energy, in average, was consumed by the Brazilians in the last year. FURNAS Centrais Elétricas, as a generation and bulk power transmission utility, owned by the Brazilian Federal Government, was responsible for developing the transmission solution in order to integrate Itaipu powerplant 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. FURNAS was created in 1957 and started the operation of the 800 kVAC and ± 600 kVDC systems in 1982 and 1984, respectively, integrating the Itaipu powerplant generation into the ‘Brazilian National Transmission Network’, and then, being the utility detainer of the Brazilian know-how on UHV transmission issues. The building up of the Brazilian knowledge and experience on dealing with UHV transmission systems have started with the initial investigation studies, carried out considering the first engineering alternative for the transmission system associated with Itaipu powerplant, which consisted of a 800 kVAC five line-transmission-corridor. After the decision of the government of Paraguay to keep its electrical network nominal frequency in 50 Hertz, instead of accepting the Brazilian offer to convert the whole country electrical network into 60 Hz, it became necessary to review those first investigation studies, in order to define a hybrid transmission system of 3 x 800 kVAC transmission lines and 2 bi-pole ± 600 kVDC transmission system. This hybrid UHV-AC/DC transmission system planned, shown in Figure 1, 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. Its importance is not only due to the usage of some of the highest voltage levels in commercial operation worldwide, but also because of the high capacity of the transmitted power (rated to 12,600 MW) for a long distance (about 1,000 km).

UHV 800 KVAC TRANSMISSION SYSTEM – REMARKABLE ASPECTS
The HVAC transmission system interconnects Foz do Iguaçu substation (close to Itaipu powerplant) to Tijuco Preto substation in São Paulo area (close to São Paulo metropolitan region), one of the main load centers of the Brazilian electrical network. Foz do Iguaçu substation contains both the UHV 800kVAC switchyard and the ± 600kVDC converter substation (rectifier side). Together they form one of the biggest substations in operation, in terms of power and size. The three circuits of 800 KVAC, each one of about 895 km long as shown in Figure 2, are able to transmit to the Brazilian interconnected network the rated generated power from the now-a-days 10 generating units operating with the nominal frequency of 60 Hz, and to interchange energy between the southern and southeastern geographic regions of the Brazilian interconnected network as well. The electrical requirement for the 800 kVAC equipment has been defined in the late 70s and early 80s. At that time, the Brazilian network consisted of several sub-networks weakly connected to each other. Although
each sub-network could be considered as solidly grounded, the network as a whole could not. Besides, the 800 kV Brazilian network would not be a meshed network but a radial one consisting of 3 parallel circuits. Thus, the planning engineers at that time decided to adopt conservative requirements for the equipment of such a new and unknown high voltage level in Brazil, derived from system simulations under severe operation and emergency conditions.

![Figure 1: FURNAS transmission system for the integration of Itaipu power plant with the Brazilian electrical network](image1)

In the middle of the 80s the full power of Itaipu power plant corresponded to more than 35% of the whole installed power in the Brazilian power network (now-a-days it corresponds to less than 14%, even considering the expansion of the Itaipu power plant). In the beginning of the Itaipu power plant operation, during the light load period in the late 80’, the generated power of Itaipu station corresponded to more than 50% of the dispatched power in the Brazilian interconnected network.

![Figure 2: UHV 800 KVAC transmission corridor subsystem](image2)

Therefore, the Itaipu transmission system, in this context, was of major importance to the Brazilian electric bulk network. It had to be designed considering, on one hand, the use, for the first time in the country, of such high voltage levels, equipment rated power and all the related technological aspects and, on the other hand, it was absolutely necessary to assure that the equipment withstand levels would cope with the system requirements, as reliably as possible. These system requirements should consider, for equipment designing purposes, the worst conditions regarding switching transients. Thus, it was decided at the beginning of designing works to take into account, for instance, the criteria of switching transients derived from total 'opposition-of-phase' – OP (i.e., 180 degrees instead of 120 degrees, foreseen in the international standards at that time). This was reasonable to consider at that time for this transmission system, since the 800 kVAC system would be, in practical terms, not only the connection system of the Itaipu powerplant into the Brazilian interconnected grid, but also the
main interconnection-tie between the Brazilian southern and southeastern regional transmission grids, the two major sub-system of the country at that time. Before the existence of the Itaipu transmission system, these two regional transmission grids were weakly interconnected, since they had only few tie-lines using voltage levels of 88kV, 138 kV and 230 kV in the border between the state of São Paulo (south border of southeastern regional grid) and the state of Paraná (north border of southern regional grid). Considering the same reason for the choice of OP premise, as above said, it was adopted, then, the value 2.0 for out-of-phase factor for all TRV parameters. For the use of an amplitude-factor of 1.64 for Uc of TRV, instead of 1.25 defined by IEC at that time, the reason for that is the adopted 'grounding criteria', since, although each regional grid could be considered as solidly grounded, the major Brazilian network as a whole could not, as said before. Following this idea of adopting conservative criteria for defining the equipment withstand requirements (for such a new and unknown high voltage level in Brazil at that time), derived from system simulations under severe operation and emergency conditions, it was also found necessary to define other requirements based on rigid premises, such as the maximum overspeed during total load rejection in the 800 kVAC system as 1.1 of nominal frequency (66 Hz), instead of adopting the standard value of 1.05fn (63 Hz). This rigid overspeed criteria was used to verify the possibilities of self-excitation regarding the Itaipu generators, and also to define the withstand requirements of switching equipment due to overvoltage transients caused by full load rejection. Finally, as other example, the value of 800 kV was defined as the 'maximum operating voltage', which means only 1.045pu of the nominal operating voltage (765 kV).

In all other Brazilian voltage levels the maximum operating voltage (non-continuous operating voltage limit, for emergency operating conditions) is 1.10 pu of the rated or nominal voltage value (138kV/152kV; 230kV/253kV; 345kV/380kV; 440kV/484kV; 500kV/550kV).

UHV ± 600 KVDC TRANSMISSION SYSTEM – REMARKABLE ASPECTS

The HVDC transmission system consists of two bi-poles of ± 600 kVAC, each one of about 806 km long, one AC/DC rectifier side at Foz do Iguaçu substation and one DC/AC inverter side at Ibiúna substation, sited very close to São Paulo city, shown in Figure 3. The HVDC transmission system is rated to transmit 6,300 MW from the generated power produced by the other 10 generating units of 50 Hz owned by the Paraguayan side of the bi-national Itaipu powerplant. In order to build up the Brazilian know-how on HVDC transmission, being used for the first time in the country, the following constrains have been established: services, equipment and products should be nationalized; Brazilian enterprises/engineers should take part on the planning studies, designing, building and operation of the HVDC transmission system; technology transfer “on the job training” should be practiced.

The UHV ± 600 kVDC transmission system main characteristics are as follows:

- Two substations (Foz do Iguaçu the rectifier side and Ibiúna, the Inverter side);
- Nominal Power: 6,300 MW;
- Nominal Voltage: ± 600 kV(DC);
- Nominal Current: 2,625 A(DC);
- Two Bipoles (± 600 kV);
- Each Bipole composed by two poles;
- Each Pole composed by two 300 kV series-connected convertors.

Both AC/DC rectifying and DC/AC inverting processes require great amounts of reactive power and produce harmonic currents that cannot be injected into the related AC network. At Foz do Iguaçu substation AC filters totaling 1,540 Mvar have been installed. Because of its vicinities to Itaipu power plant, the needed reactive power has been mostly supplied by the power plant itself, performing the filters the role of not allowing the harmonic currents flow into the AC network. At Ibiúna substation, besides AC filters totaling 2,480 Mvar have been installed, shunt capacitors, totalizing 590 Mvar and 4 synchronous compensators of 300 Mvar each were defined to supply the needed reactive power and proper short circuit power level. It is important to point out that there were no existing IEC Standards [2] at that time for such a huge HVDC transmission system. In this sense, some aspects and faced problems, from planning and operating experience points of view, concerning the hybrid UHVAC and UHVDC features and equipment, had to be deeply investigated since the beginning, such as:
a- comparison between ‘equivalent’ solutions of HVAC and HVDC systems and between ‘equivalent’ GIS and AIS equipment, in terms of engineering and economics issues (considering environmental and regulatory issues);

b- characteristics of HVDC system facilities, such as the so-called ‘Dynamic Performance feature’ (concerning impacts caused to the AC systems connected to the converter substations, both ‘rectifier’ and ‘inverter’ HVDC system sides, in terms of mitigation/elimination of dynamic electromechanical transients/oscillations); HVDC transmission system ‘Forced Isolation protection scheme’ (implemented to give protection against electrical transients derived from partial or total load shedding); ‘High MVAr consumption’ operating mode; ‘automatic fast switching’ from one faulted DC line to another one under unrecoverable short-circuit conditions in the first line;

c- HVDC reliability features specification (ability of the system to transmit the rated power under contingency conditions and outages), such as: operation modes (bipolar/monopolar) and related engineering/environmental issues; temporary overloading/overcurrent capacity; AC System Faults/configurations that may create commutation failures mainly in the inverter station;

d- importance/advantages of analogue/digital simulation facilities for HVDC/HVAC transmission systems (necessity/usefulness of simulation tools for HVDC transmission systems in terms of planning/specification/operational optimization and economics);

e- DC switchyard bushing isolation problems and the implemented mitigation solutions;

f- issues related to filtering requirements (short circuit level criteria, filter overloading, “active filters” usage since they are not a sink for harmonics other than their own, which can be decisive in filtering performance, etc);

g- HVAC shunt and series compensation devices (and the related inherent aspects in terms of voltage profile control, overvoltage transients and protection issues);

h- importance of equipment withstanding requirements definition in the planning phase, taking into account the possible/foreseen evolution/expansion of the AC grid/network (up-grading in short-circuit level requirements);

i- enterprise staging definition, i.e., intermediate stages of transmitting power capacity, considering cost constraints, needs of scaling the power transmission, time interval between stages, etc (series connection of converter groups per pole easily allows the staging of 25%, 50%, 75%, and 100% of the total rated power);

j- oil chemistry issues of HVDC converter transformers;

k- possibilities of controlled switching usage.

**FUTURE TRENDS/CHALLENGES REGARDING UHV TRANSMISSION IN BRAZIL**

Stepping into the future and trying to foresee possible needs, trends and challenges, regarding the use of UHV transmission in Brazil [3], we have on one hand, 180 GW corresponding to the remaining Brazilian hydroelectric potential still not used. A high percentage of it (around 70%) is located in the Amazon region, according to the official estimates. On the other hand, the consumption of energy is spread all over the country according to the following geographical distribution:

- Isolated Systems in Amazon Region (2% of consumption)
- Interconnected System in North/Northeast (19% of consumption)
- Interconnected System in South/Southeast/Central-West (79% of consumption)

In terms of the Brazilian power system growth, it is reasonable to say that it will be necessary to transport huge amounts of energy produced mainly in the Amazon region to the main load centers of the country, covering distances of more than 2,400 kilometers, as shown in Figure 5. Considering such a frame, the use of UHV transmission systems (DC links and overhead lines) seems to be quite competitive and suitable alternatives, in both economic and environmental views/aspects. In this case, it isn’t necessary to change the frequency from the rectifier AC side to the inverter AC side, since it is just a matter of a set of issues such as: stability, loss reduction, compactness, environmental friendliness and costs from the far amazonic powerplants to the main load centers. The Amazon region has a lot of water resources on a quite plain geographic area, that is, without water falls, and the rivers having huge and sustained water flows. Thus, generation of electricity can be obtained by water flow rather than by potential energy (difference in water level provided by dams). In order to minimize environmental and social impacts, preliminary prospective studies of the region suggest, as the more suitable solution, the
construction of hydroelectric powerplant dams with very low height and the intensive use of “bulb-type” turbines, as shown in Figure 4. The next project in the Amazon region, still under consideration by the Brazilian federal government, is known as ‘Madeira river project’. It consists of an enterprise complex including two hydroelectric power plants in Madeira river: one is ‘Santo Antonio’, near Porto Velho city, the capital of the state of Rondônia and the other one is ‘Jirau’, near the border between Brazil and Bolivia, both enterprises totaling an installed power of 6,450 MW. The complexity inherent to the project requires a lot of efforts from the government in order to obtain the environment licenses needed to start the process of its installation. According to the Brazilian regulatory rules for the electric sector, the enterprise owners, who will be responsible for the construction and operation of the hydroelectric power plants, as well as for the transmission system regarding their integration within the Brazilian electrical network, have been defined by public biddings. This procedure has been recently announced by the Brazilian Regulatory Agency for the electric sector – ANEEL [4]. Besides, the long distances to be covered and access difficulties bring challenges to new transmission corridors in Amazon region, with concern to equipment size, logistic and transportation.

The following topics have been analyzed in detail in order to establish the reference UHV transmission alternatives [5] and [6]:

- Line configuration /insulation/ clearances;
- Corona and field effects performance of the line;
- Level of power to be transmitted;
- Weight and size of the equipment for shipping and transport (mainly the transformers for AC and DC alternatives);
- Power losses;
- Spare parts;
- Series connection of converter groups per pole (DC alternative);
- Overload/ Stability requirements;
- Need of reinforcing the receiving network;
- Need of investigating procedures for limitation of short-circuit current levels exceeding existing equipment ratings.

Despite of the described Brazilian experience on hybrid parallel UHV AC 800 kV and UHV DC ± 600 kV systems, due to the big challenges related to the new foreseen Amazon transmission system requirements, and depending on the outcoming UHV transmission alternative references, that have been defined by the Brazilian federal government, the existing IEC Standards may not cover all the equipment special withstand requirements. This will lead to the necessity of developing new specification standards that might be of the concern of the following IEC Technical Committees:

- TC 7, Overhead electrical conductors;
- TC 10, Fluids for electrotechnical applications;
- TC 11, Overhead lines;
- TC 13, Electrical energy measurement, tariff- and load-control;
- TC 14, Power transformers;
- TC 17, Switchgear and controlgear;
- TC 20, Electric cables;
- SC 22F, Power electronics for electrical transmission and distribution systems;
- TC 51, Magnetic components and ferrite materials;
- TC 55, Winding wires;
- TC 68, Magnetic alloys and steels;
- TC 112, Evaluation and qualification of electrical insulating materials and systems.

In this sense, regarding the development of new equipment specification/standards, it is worth to mention here that the CIGRÉ is already performing an intense work, for instance, under the WG A3-22 (‘Technical requirements for substation equipment exceeding 800kV’) [7]. This work is at the moment
related to an information survey on the existing knowledge worldwide regarding UHV transmission facilities. Also, in order to face the challenges foreseen, several Brazilian scientific organizations, universities and utilities are preparing themselves by means of studying new technologies and developing know-how. One example of such an effort is the following Research and Development (R&D) projects being conducted by FURNAS utility, in cooperation with Brazilian universities:

- Secondary arc behavior on single-phase auto-reclosing of 500 kV lines;
- Optimization of non conventional high capacity 500 kV transmission lines.

CONCLUSIONS

The Brazilian Electric Power System supply is typically provided by long EHV transmission lines. Therefore, the building up of the Brazilian knowledge and experience on dealing with UHV transmission systems has started with the initial investigation studies for the integration of Itaipu powerplant within the Brazilian interconnected grid. The Itaipu transmission system, planned, built and operated by FURNAS, 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. It is important to point out that there were no existing IEC Standards at that time for such a huge UHV transmission system, mostly regarding the HVDC link. Around 70% of the remaining Brazilian hydroelectric potential still not used is located in the Amazon region, while the consumption of energy is spread all over the country. Thus, it will be necessary to transport huge amounts of energy covering distances of more than 2,400 kilometers. Due to the big challenges related to the Amazon transmission systems requirements, the existing IEC Standards may not cover all the equipment withstand requirements, leading to the necessity of developing new standards/specification. In order to face the challenges foreseen, several Brazilian scientific organizations, universities and utilities are preparing themselves by means of studying new technologies and developing know-how.

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