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Comparison of the Performance of HVDC and HVAC Overhead Transmission Lines for the Itaipu System

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SUMMARY

The transmission system associated with the Itaipu 14000 MW power plant comprises two parallel sets of transmission lines that are not connected at the generating station due to the frequency difference. The Brazilian transmission system is owned and operated by Eletrobras-Furnas, a large federal power utility. The scheme, designed in the 1970s, includes many features new at the time and continues to be a very significant part of the Brazilian energy supply. This paper describes the performance of the overhead power lines of the Itaipu transmission system during a recent period of fifteen years of operation. The two sets of transmission lines discussed are one of three 765 kV AC at 60 Hz and the other of two ± 600 kV DC. While mainly analysing data from the overhead transmission lines, some operating features, present use, and significant experiences are also discussed.

Key words: Power transmission, overhead lines, EHV, HVDC, UHVDC, Itaipu,

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1. INTRODUCTION

This paper describes the performance of the overhead power lines of the Itaipu transmission system during a recent period of fifteen years of operation.

The Itaipu power plant is a Brazilian-Paraguayan joint venture with a total installed capacity of 14,000 MW that started operation in 1984. Due to the bi-national nature of the power plant and the difference in frequencies of the two countries, the generators are equally divided into 50Hz and 60 Hz sections in the dam. The 60 Hz units feed directly into the Brazilian network over three 765 kV AC lines to Southeastern Brazil while the 50 Hz units are connected at 500 kV to Paraguay and then to the 6300 MW converter station in Brazil. The 50 Hz power not required by Paraguay is transmitted to Brazil over two bipolar HVDC transmission lines at ± 600 kV.

Figure 1 is a semi-geographical diagram showing the interconnection of the Itaipu power plant with South/Southeast Brazil through the Furnas transmission system, with Figure 2 showing the arrangement of the transmission lines on separated Rights-of-Way.

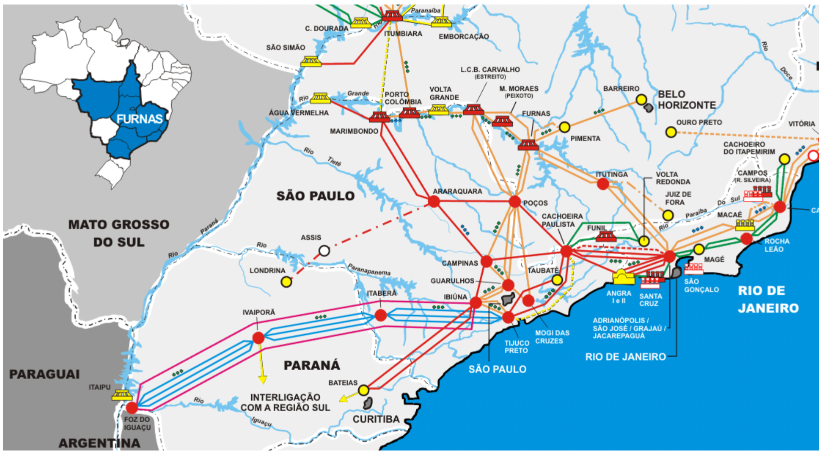


Figure 1 – Location of Transmission Lines

It can be seen in Figure 2 that the Rights-of-Way have a 10 km separation where possible, with each HVDC line on a separate RoW, while the first two 765 kV lines share a common RoW. The keraunic level along the route ranges from about 90 close to Itaipu down to 50 approaching São Paulo.

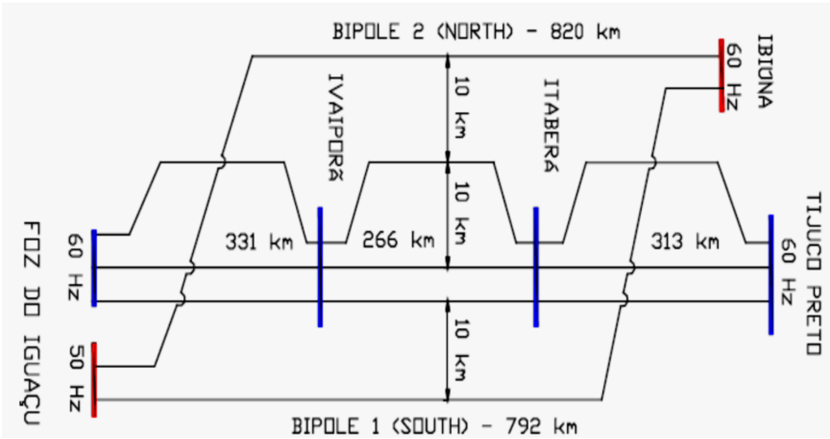


Figure 2 – Rights-of-Way

Figure 3 is a simplified one-line diagram showing the interconnection of the Itaipu power plant with South/Southeast Brazil through the Furnas transmission system.

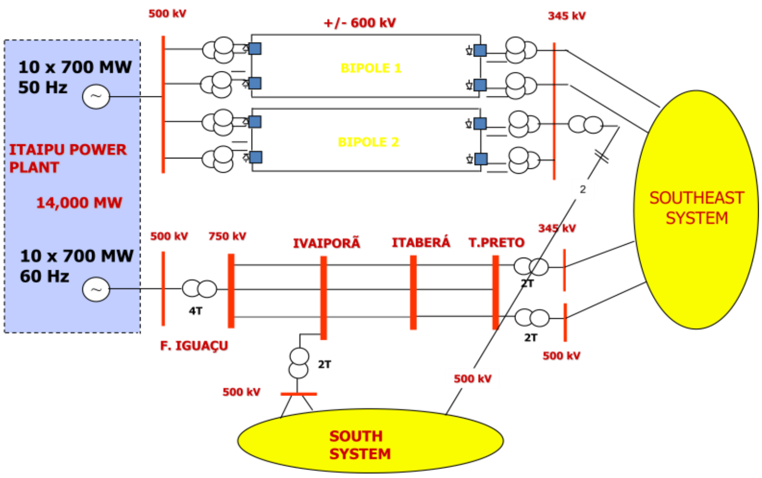


Figure3 – Simplified diagram of Itaipu Transmission system

In its final configuration, the Itaipu Transmission System is composed of three AC circuits (765kV) and two DC bipoles (± 600kV), shown in figure 3. The three AC circuits, between Foz do Iguaçu (state of Paraná - PR) and Tijuco Preto (state of São Paulo - SP) are, approximately, 900km long, and have two intermediate substations, at Ivaiporã (PR) and Itaberá (SP). The three lines are series compensated to an average level of about 46%.

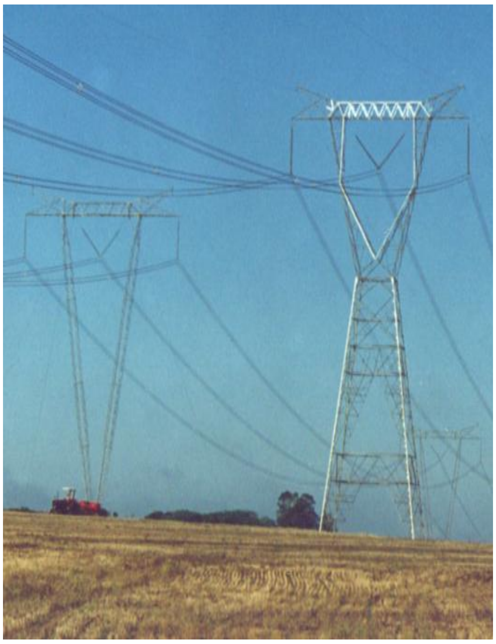
The two HVDC bipoles, between Foz do Iguaçu and Ibiúna (SP) are approximately 800km long.

Rated at 3150 MW, ± 600 kV DC, each bipole has two 12-pulse converters per pole. The HVDC converters have a current overload rating of 12% for two hours at rated ambient temperature of 40°C or continuous if below 30°C, which permits transmission of close to full power for a converter outage. There is also a five second overload rating of 30%, which ramps down to 12% according to thyristor junction temperature. This assists dynamic stability of the interconnected system. In addition either transmission line can carry the rated output of the station using the facility of bipole parallel operation.

As shown in Figure 2 above, it can be seem that the transmission lines run in paralleled over most of the route, about 750 km before the HVDC lines divert to Ibiuna. This makes the system very suitable for a comparison of overhead line performance. It should be remembered that while the lines run in parallel, this is not a true AC/DC parallel system as the two are not synchronously connected at the generating station. It is also notable that the system was put into operation during the 1980s, and is still an important participant, today transporting almost 20% of the electrical energy consumed in Brazil.

2. TRANSMISSION LINE CHARACTERISTICS

2.1 EHV 765 kV AC Overhead Lines



The 765 kV lines, on average, are about 65% guyed Vee with an typical weight of 8500 kg, while the self supporting towers are about 14000 kg. The average span is about 460 m. Shortly before 2000, Furnas carried out mechanical reinforcement of selected towers [1].

The main electrical characteristics are:

Conductor:	4xBluejay 564 mm² ACSR
Phase spacing:	15,80 m guyed
Phase spacing:	14,30 m self support
Subconductor spacing	457 mm
Shield Wire	3/8” steel (ACSR close to stations)
Shield Wire Spacing	29,7 m guyed
Shield Wire Spacing	28,9 m self support
Suspension string:	I-V-I, 35 insulators 145 x 254 mm
Right-of-Way:	95 m one line (Line 3)
Right-of-Way:	178 m two lines (Lines 1&2)

Each line section between all stations is fully transposed. One series capacitor bank is located in each line section at an intermediate substation with compensation values between 40% and 50%. Fixed shunt reactors are located at each line entrance, with an average compensation value of about 80%. The lines have auto-reclose for single-phase faults while multi-phase faults are tripped permanently.

2.2 HVDC ± 600 kV Overhead Lines

The HVDC lines, on average, are about 80% guyed mast with an typical weight of 5000 kg, while the self supporting towers are about 9000 kg. The average span is about 450 m.

The main electrical characteristics are:

Conductor:	4xBittern 644 mm² 45/7ACSR
Pole spacing:	16,40 m
Subconductor spacing:	457 mm
Shield Wire:	3/8” steel
Shield Wire Spacing:	13,4 m
Suspension string:	32 insulators, 510 mm creep, 27 mm/kV
Right-of-Way:	72 m one line (Lines 1&2 each)

The lines have automatic restart following de-energisation by forced retard at the rectifier. There are three attempts at full voltage, followed by one at reduced voltage (450 kV) and then lock-out if unsuccessful.

3. COMPARISON OF TRANSMISSION LINE PERFORMANCE

In order to compare the performance of the systems, two approaches were used, firstly the number of faults of different types and secondly a calculation of Forced Energy Unavailability (FEU) [2].

3.1 Number of faults in the AC Lines and DC Lines

Table 1 shows the number of successful reclosures (transient fault) and permanent faults for the 3 lines for the 765 kV AC Transmission System in the period from 1995 to 2009. As the third line started its operation in 2000, line length is also presented. All outages were considered, including those caused by tower failures.

This table considers treats the three parallel lines from Foz do Iguassu to Tijuco Preto as separate circuits.

Table 1 - 765 kV AC Transmission Line Performance

	Line 1			Line 2			Line 3		
	Trans	Perm	Length	Trans	Perm	Length	Trans	Perm	Length
1995	0	4	891	1	11	891			0
1996	1	13	891	0	7	891			0
1997	0	6	891	2	13	891			0
1998	1	9	891	1	15	891			0
1999	1	26	891	1	9	891			0
2000	3	12	891	3	11	891	2	7	602
2001	2	3	891	3	5	891	2	3	915
2002	4	8	891	1	6	891	0	7	915
2003	2	6	891	5	10	891	2	4	915
2004	1	5	891	2	8	891	0	3	915
2005	2	6	891	0	11	891	0	4	915
2006	2	5	891	0	6	891	0	2	915
2007	0	4	891	4	16	891	0	4	915
2008	3	2	891	0	2	891	1	3	915
2009	4	9	891	5	12	891	1	6	915
Total	26	**118**	13365	28	**142**	13365	8	**43**	8837
15 y ave	1,73	**7,87**		1,87	**9,47**		0,80	**4,30**	*(10 y ave)*

Considering all lines, the average value is 0.174 faults with successful reclose (one attempt) per 100 km per year. For permanent and unsuccessful reclosed faults, this number increases to 0.852 faults per 100 km per year, including those caused by tower failures. Remember that the auto-reclose is used for single-phase faults only, with one attempt.

There were several occasions of tower failures, mainly due to winds, all in the section Foz do Iguassu to Ivaiporã: Circuits #1 and # 2 in 1997 and again in 1998; circuit #1 in 1998; circuit #3 in 2004; circuits #1 and # 2 and then circuits #2 and # 3 in 2005; and circuits #2 and # 3 in 2006.

The performance of the HVDC lines is shown in Table 2 where the number of successful restarts at full voltage (transient fault) and at reduced voltage (3 attempts at full voltage, plus 1 attempt at 450 kV) and unsuccessful restarts (permanent faults) in the period from 1993 to 2012 are given, with a separate calculation from 1995 to 2009 to cover the same period as the 765 kV lines. The data is presented per pole. All outages were considered, including those caused by tower failures.

Average values for all DC lines comparable 15 years are:

- 0.488 pole faults per 100 km per year for transient faults (successful restart at full voltage);
- 0.057 pole faults per 100 km per year for transient faults (successful restart at 450 kV reduced voltage);

- 0.169 pole faults per 100 km per year for permanent faults (unsuccessful restart). Tower failures are included in the average value calculation.

Table 2 - ± 600 kV DC Transmission Line Performance

Itaipu HVDC ±600 kV	Bipole 1						Bipole 2					
	P1 -			P2 +			P3 -			P4 +		
	Trans	Red. V	Perm	Trans	Red. V	Perm	Trans	Red. V	Perm	Trans	Red. V	Perm
1993	0	0	1	7	2	2	2	0	3	2	0	0
1994	3	0	3	3	0	1	1	2	3	3	0	1
1995	4	0	0	3	0	1	0	0	0	3	1	0
1996	2	0	0	6	0	0	0	0	0	5	0	0
1997	5	1	5	0	1	1	0	0	0	2	0	1
1998	2	1	0	4	1	2	0	0	1	1	0	1
1999	2	0	0	3	0	0	2	0	1	2	0	1
2000	5	0	1	6	1	1	2	0	0	2	1	0
2001	1	0	1	1	0	1	0	0	1	0	0	1
2002	0	0	1	2	0	2	1	0	0	0	0	2
2003	5	0	0	2	0	0	0	0	0	2	0	0
2004	7	2	3	0	0	0	0	0	0	0	0	0
2005	1	0	2	3	1	1	4	0	0	2	1	1
2006	6	0	0	3	1	0	1	0	0	4	1	1
2007	1	0	0	4	0	0	0	0	1	0	1	0
2008	1	0	0	1	0	3	1	0	0	1	0	3
2009	0	0	0	0	0	0	0	0	1	3	0	0
2010	2	0	0	1	0	0	0	0	0	1	0	0
2011	0	0	0	3	0	0	0	0	0	1	0	0
2012	0	0	0	4	0	0	0	0	1	0	0	1
Total	**47**	**4**	**17**	**56**	**7**	**15**	**14**	**2**	**12**	**34**	**5**	**13**
20 y ave	**2,35**	**0,20**	**0,85**	**2,80**	**0,35**	**0,75**	**0,70**	**0,10**	**0,60**	**1,70**	**0,25**	**0,65**
Total 15 y	**42**	**4**	**13**	**38**	**5**	**12**	**11**	**0**	**5**	**27**	**5**	**11**
15 y ave	**2,80**	**0,27**	**0,87**	**2,53**	**0,33**	**0,80**	**0,73**	**0,00**	**0,33**	**1,80**	**0,33**	**0,73**

Although Table 2 presents the data by pole, each bipolar line has experienced tower failures. A tower failure always affects two poles: pole 1 and pole 2 if the problem is in the bipole 1 or pole 3 and pole 4 in case of bipole 2. For the 1993 – 2012 period, there were five occasions of tower failures, mostly due the wind: Two in the line of bipole 2 in 1997 and 2012, plus three in bipole 1; 1998, 2005 and 2006. The failure in 2012 was due to a truck hitting a stay.

3.2 Forced Energy Unavailability (FEU) for AC and DC Transmission Lines

Table 3 presents the forced energy unavailability for 765 kV HVAC Transmission System in the period from 2000 to 2009. Data is presented per line, considering the transmission system composed by three independent transmission lines. Year 2000 was chosen as the initial year as line 3 was not fully in operation before that. Due to this consideration, outage of part of the line was considered as unavailability of the whole line. For instance, if for any reason circuit #2 was tripped, it was considered that line 2 was not available. On the other hand, unavailability of other equipments, especially the problems on the 765kV/500kV transformers were not considered. Values presented here as FEU of a specific line considered is the arithmetic sum of the FEU of the three different lines that composes it, as probability to have problems in more than one part of the line during the same time is very low. The 10-year average value for each AC line is also shown.

Table 3 – Furnas (Itaipu) HVAC Transmission Line - Forced Energy Unavailability (FEU)

Itaipu HVAC	FEU (%) - TL only		
	Line 1	Line 2	Line 3
2000	0,091	0,035	0,051
2001	0,013	0,017	0,024
2002	0,071	0,074	0,141
2003	0,015	0,655	0,643
2004	0,010	0,045	1,466
2005	4,952	4,306	2,387
2006	0,014	1,418	0,774
2007	0,094	0,100	0,049
2008	0,004	0,007	0,001
2009	0,892	1,201	0,034
10 y ave.	**0,616**	**0,786**	**0,557**

The performance of the HVDC lines is shown in Table 4 where the forced energy unavailability (FEU) for Furnas (Itaipu) HVDC System in the period from 1993 to 2010 is given. Data is presented by bipole. Two different values are presented. First two columns show the values of FEU per year for each bipolar line while the last two columns show the values of FEU per year for each complete bipole including the transmission line. The years 2011 and 2012 are not presented as the data for the stations is still not available. The fact that one bipolar line is capable of transmitting the total HVDC power using parallel operation was not considered in terms of FEU. Two different averages were calculated: 18-year average value for each bipole considering all data presented and also 10-year average value for each bipole considering the 10-year period which also corresponds with the period available for the 765 kV lines.

Table 4 – Furnas (Itaipu) HVDC Transmission System - Forced Energy Unavailability (FEU)

Itaipu HVDC	FEU (%) - TL only		FEU (%) includ. TL	
	Bip 1	Bip 2	Bip 1	Bip 2
1993	0,002	0,001	0,179	0,191
1994	0,002	0,003	0,354	0,229
1995	0,001	0,000	0,052	0,486
1996	0,000	0,000	0,226	0,087
1997	0,004	0,004	0,860	0,126
1998	0,001	0,008	0,029	0,611
1999	0,001	0,001	0,221	0,713
2000	0,000	0,000	0,048	0,047
2001	0,001	0,002	0,260	0,104
2002	0,007	0,052	0,367	0,845
2003	0,000	0,000	0,524	0,293
2004	0,013	0,000	0,401	9,358
2005	**1,333**	0,001	1,509	0,101
2006	0,000	0,005	0,405	0,150
2007	0,000	0,001	0,220	0,013
2008	0,002	0,000	0,152	0,122
2009	0,000	0,000	1,847	0,330
2010	0,000	0,000	0,775	0,018
18 yr ave	**0,076**	**0,004**	**0,468**	**0,768**
10 yr ave	**0,136**	**0,006**	**0,573**	**1,136**

It can be seen that 2004 to 2005 was a bad period for HVDC! The Bipole 1 transmission line suffered a particularly bad outage due to high winds coupled with poor access due to heavy rains, while Bipole 2 suffered a long outage due to converter transformer failure with no readily available spare in 2004. Notwithstanding this, the overall availabilities are very good.

4. DISCUSSION AND OTHER CONSIDERATIONS

It is very difficult to directly compare performance of EHVAC and HVDC systems as their designs are different, however both failure rate and forced unavailability give good indications. When considering the 765 kV system it must be remembered that the design permits full power transmission for an N-1 situation, that is if one line section is tripped, then the remaining two circuits can carry full current continuously as the series capacitors are rated accordingly. As noted in 3.1 above, outages of station equipment are not included in this calculation. If one of the remaining two circuits is tripped, then generation disconnection is activated to ensure safe transmission. Similarly, for the HVDC stations the loss of one converter, or one eighth of rated capacity, is compensated by the two hour overload of the converters, or permanently in the case of low ambient operation (<30^{o}C), however station equipment outages are included in the second set of unavailability data. Further, in the case of loss of a complete line (tower failure) full rated power can be restored using parallel operation [3].

The reasons for the overhead transmission line faults can be summarised, roughly in order of incidence:

1. Keraunic activity (thunderstorms).
2. High winds (often associated with 1 above).
3. Fires and agricultural burning close to the Right-of-Way.
4. Growth of vegetation on the Right-of-Way.
5. Accidents with agricultural and other off-road vehicles.

Thus it is not unreasonable to expect the two sets of lines, following essentially the same route, to have similar performance. For the 765 kV lines we have an average value is 0.174 faults per 100 km per year with successful reclose plus 0.852 permanent faults per 100 km per year, or a total of about 1,03 per 100 km per year. This compares to 0.545 pole faults per 100 km per year for transient faults (including reduced voltage), plus 0,169 permanent, giving a total of 0,714 pole faults per 100 km per year. In fact the total number of faults is similar, however the HVDC shows significantly better performance when comparing transient to permanent faults.

Similarly when looking at the FEU, the HVDC lines are much better, however this difference is reduced when including the station equipment in the HVDC figures.

5. CONCLUSIONS

Analysis of the historical performance of the overhead power lines of the Itaipu transmission system during a considerable time, including recent periods of fifteen and ten years of comparable operation, has shown that the HVDC lines show considerably better performance with respect to permanent faults. This shows that a much higher number of faults are successfully restarted, giving a higher availability of the lines. As they follow essentially the same route, it is not unreasonable to expect the two sets of lines to have similar performance. In fact this is roughly true for the total number of faults, however the HVDC lines show significantly better performance when comparing transient to permanent faults.

It is important to remember that for both systems the performance of the overhead transmission lines is very good, with forced unavailabilities well below 1%.

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