A survey of HVDC reliability

How reliable are high voltage DC links? Data collected by CIGRE gives some of the answers.

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Working Group 4 of Cigré (*Conseil International des Grands Réseaux Électriques*) study committee 14, now renamed 4B, was formed specifically to assemble and publish data on the reliability and operational experience of HVDC systems in service around the world. To this end it collects information annually from the operators of such systems, and at two year intervals, publishes it. The resulting report contains data on energy availability, energy utilisation, forced and scheduled outages and other data, in accordance with a standardised reporting protocol, as well as statistics on the frequency and duration of forced outages, for the years 1999 and 2000. Combined with previous data it also presents a cumulative average of forced outages by frequency and duration covering the years 1988 to 2000 and categorised by back-to-back stations and stations with one, and two or more, converters per pole.

The reporting protocol has been revised periodically as experience was gained in collecting and interpreting the data. The most recent revision was adopted in 1997 and can be obtained through Cigré's Paris HQ.

Data were first collected in 1968, covering four DC systems utilising mercury-arc valves. Data on the first thyristor valve system were compiled in 1972. This report covers 23 thyristor valve systems and five mercury-arc valve systems for operations during 1999-2000.

The accumulated data provide a continuous record of reliability performance of HVDC systems throughout the world during the 33 years following their first operation. For thyristor valve systems, which are of most interest to utilities that are considering HVDC transmission for their systems, the data represent approximately 440 system-years of operation over a period of 29 years. The working group also maintains a compendium containing the main data for all existing HVDC schemes. A copy can be obtained through Cigré.

HVDC reliability performance

The overall reliability statistics for all systems for which reports were received for 1999 and 2000 are given in Table 1. Six of the systems are back-to-back systems and the remainder are point-to-point transmission systems utilising overhead line and/or cable systems. A report was received for 1999 for Leyte-Luzon system but the data was not in the protocol format and is not included here.

Table 1 shows the maximum continuous transmission capacity, energy availability, energy utilisation and energy unavailability for the systems covered. Energy availability is a measure of the amount of energy that could have been transmitted over the HVDC system, except as limited by forced and scheduled outages of converter station equipment and DC transmission lines or cables. Energy utilisation is a measure of the amount of energy actually transmitted. Both parameters are expressed as a percentage based on the maximum continuous capacity of the HVDC system.

Table 1 shows that some systems operate at very low energy utilisation, ie they are used primarily for standby capacity, and other systems at very high energy utilisation, ie approaching maximum rated capacity.

Forced energy unavailability (FEU) is the amount of energy that, because of forced outages, could not have been transmitted over the DC system. Only converter station equipment outages are considered; transmission line and cable outages are excluded.

Scheduled energy unavailability (SEU) is the amount of energy that, because of scheduled outages, could not have been transmitted over the DC system. Although transmission line and cable scheduled outages are included in the data in Table 1, it is believed that in most cases the scheduled energy unavailability shown closely approximates that for converter stations only, since most scheduled maintenance on transmission lines and cables is conducted concurrently with station maintenance. Scheduled outages have less impact on the per-

Table 1. System energy availability, energy utilisation and converter station energy unavailability

System	Year commissioned	Maximum continuous capacity MW	Energy availability per cent		Energy utilisation per cent[1]		Forced energy unavailability per cent[2]		Scheduled eergy unavailability per cent	
			1999	2000	1999	2000	1999	2000	1999	2000
Skagerrak 1 & 2	1976/77	550	96.4	98.0	30.2	43.8	0.40	0.19	3.19	1.81
Skagerrak 3	1993	500	97.2	97.9	44.0	57.2	0.15	0.02	2.61	2.05
Vancouver Island Pole 2	1977/79	550	91.7	77.2	66.4	53.6	0.64	1.23	7.61	21.58
Square Butte	1977	550	95.9	94.8	78.9	77.0	0.10	0.38	2.37	4.44
Shin-Shinano 1	1977	300	98.7	98.0	4.3	0.01	0.00	0.00	1.27	2.04
Shin-Shinano 2	1992	300	90.9	99.1	11.7	8.1	0.00	0.00	9.09	0.91
Nelson River BP1[3]	1973/93	835	76.5	92.4	51.2	68.0	22.9	7.12	0.56	0.50
Nelson River BP2	1978/83	2000	93.4	87.8	60.4	63.8	2.38	10.1	4.26	2.08
Hokkaido-Honshu	1979/93	600	97.1	90.4	11.9	10.4	0.00	0.04	2.92	7.34
CU	1979	1138	97.0	99.5	71.7	76.3	0.04	0.15	2.96	0.38
Gotland 2 & 3	1983/87	320	99.6	98.7	27.7	28.9	0.01	0.81	0.40	0.52
Itaipu BP1	1985/86	3150	97.2	97.7	78.0	77.4	0.22	0.05	2.55	2.24
Itaipu BP2	1985/86	3150	98.0	97.3	78.0	77.4	0.71	0.05	1.28	2.64
Highgate	1985	200	98.3	100.0	81.6	79.0	0.09	0.00	1.60	0.01
Cross Channel Bipole 1	1985/86	1000	96.1	95.5	85.9	82.1	0.01	2.73	3.86	1.80
Cross Channel Bipole 2	1986	1000	96.2	97.9	86.1	83.0	0.06	0.22	3.71	1.91
Virginia Smith	1988	200	73.8	97.5	24.2	64.7	17.6	0.18	8.61	2.36
Konti Skan 2	1988	300	98.1	97.2	22.0	43.1	0.10	1.01	1.81	1.76
McNeill	1989	150	95.7	95.5	47.9	61.1	0.82	0.38	3.50	4.10
Fennoskan	1990	500	98.4	97.9	32.0	45.0	0.04	0.65	1.59	1.49
SACOI[4]	1992	300/300/50	86.1	93.2	37.9	42.4	0.29	0.20	9.07	5.69
New Zealand Pole 2[3]	1992	500	98.5	98.4	48.8	57.9	0.03	0.08	1.20	1.49
Sakuma	1965/93	300	91.6	98.0	2.0	0.4	0.35	0.15	8.00	1.90
Mercury-arc valves										
Konti Skan 1	1965	275	97.9	97.7	20.8	49.5	0.31	0.14	1.84	2.18
New Zealand Pole 1	1965/92	500	94.6	95.4	32.7	40.9	0.72	0.87	4.27	3.75
Vancouver Island Pole 1	1968/69	312	76.3	37.4	58.1	4.8	12.9	1.47	10.9	61.12
Pacific Intertie	1970/89	3100[5]	88.0	88.9	40.5	31.9	2.87	1.70	8.90	9.40
Nelson River BP1 Pole 2	1973/77	835	95.3	95.4	51.2	68.0	2.43	1.66	2.28	2.97

Notes (1) Based on maximum continuous capacity (2) Converter station outages only (3) Thyristor pole (4) Three terminal monopole system (5) Includes capacity of thyristor valve groups

Table 2A. Number of forced outages and equivalent outage hours, 1999

System	AC-E No.	AC-E Hours	V No.	V Hours	C & P No.	C & P Hours	DC-E No.	DC-E Hours	O No.	O Hours	TL No.	TL Hours	TOTAL No.	TOTAL Hours
Skagerrak 1 & 2	1	1.8	0	0.0	2	24.7	1	8.7	2	0.3	1	1.1	7	36.5
Skagerrak 3	8	12.8	0	0.0	0	0.0	0	0.0	1	0.1	1	5.7	10	18.6
Vancouver Island Pole 2	2	1.6	0	0.0	1	0.0	4	54.7	0	0.0	1	3.8	8	60.2
Square Butte	4	7.9	1	0.8	1	0.1	0	0.0	0	0.0	11	143.4	17	152.2
Shin-Shinano 1	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	-	-	0	0.0
Shin-Shinano 2	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	-	-	0	0.0
Nelson River BP1 Pole 1	11	1996.4[1]	0	0.0	2	0.8	5	3.3	7	4.8	0	0.0	25	2005.3
Nelson River BP2	10	191.0	9	5.7	3	3.5	6	1.8	5	6.3	0	0.0	33	208.3
Hokkaido-Honshu	0	0.0	0	0.0	1	0.3	0	0.0	0	0.0	0	0.0	1	0.3
CU	2	1.4	0	0.0	2	1.8	0	0.0	1	0.1	0	0.0	5	3.3
Gotland 2 & 3	1	0.4	0	0.0	0	0.0	0	0.0	1	0.5	0	0.0	2	0.9
Itaipu BP1	1	10.4	0	0.0	1	0.0	4	8.5	1	0.4	0	0.0	7	19.3
Itaipu BP2	2	42.5	0	0.0	10	11.7	3	5.8	2	2.4	2	0.1	19	62.4
Highgate	1	7.7	0	0.0	0	0.0	0	0.0	0	0.0	-	-	1	7.7
Cross Channel Bipole 1	0	0.0	0	0.0	0	0.0	0	0.0	1	0.5	0	0.0	1	0.5
Cross Channel Bipole 2	4	3.9	0	0.0	0	0.0	0	0.0	1	1.0	0	0.0	5	4.9
Virginia Smith	3	1536.9[2]	7	1.0	2	3.2	0	0.0	1	0.3	-	-	13	1541.4
Konti Skan 2	0	0.0	0	0.0	4	2.7	2	6.1	0	0.0	0	0.0	6	8.9
McNeill	0	0.0	2	59.2	2	12.3	0	0.0	0	0.0	-	-	4	71.5
Fennoskan	0	0.0	1	1.1	0	0.0	2	1.7	1	0.5	0	0.0	4	3.3
SACOI	9	21.3	1	0.2	5	4.1	0	0.0	0	0.0	35	399.9	50	425.4
New Zealand Pole 2	0	0.0	0	0.0	3	2.4	0	0.0	0	0.0	1	24.4	4	26.8
Sakuma	0	0.0	0	0.0	1	30.7	0	0.0	0	0.0	-	-	1	30.7

Notes (1) Converter transformer failure (2) Converter transformer bushing failure.

Table 2B. Forced outages and equivalent outage hours, 2000

System	AC-E No.	AC-E Hours	V No.	V Hours	C & P No.	C & P Hours	DC-E No.	DC-E Hours	O No.	O Hours	TL No.	TL Hours	TOTAL No.	TOTAL Hours
Skagerrak 1 & 2	2	9.8	0	0.0	0	0.0	2	6.5	0	0.0	0	0.0	4	16.3
Skagerrak 3	2	2.2	0	0.0	0	0.0	0	0.0	0	0.0	2	1.9	4	4.0
Vancouver Island Pole 2	1	0.5	3	10.0	1	11.0	3	86.2	0	0.0	0	0.0	8	107.8
Square Butte	2	10.9	0	0.0	1	0.5	2	17.0	3	4.9	2	30.7	10	64.0
Shin-Shinano 1	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	-	-	0	0.0
Shin-Shinano 2	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	-	-	0	0.0
Nelson River BP1 Pole 1	4	608.8[1]	1	2.5	1	0.0	5	10.2	2	2.2	0	0.0	13	623.8
Nelson River BP2	30	865.6[1]	9	7.8	3	8.1	6	2.4	3	0.6	2	0.0	53	884.5
Hokkaido-Honshu	0	0.0	0	0.0	1	3.5	0	0.0	0	0.0	2	190.9	3	194.4
CU	0	0.0	0	0.0	6	5.6	1	7.5	0	0.0	0	0.0	7	13.1
Gotland 2 & 3	0	0.0	2	71.3	0	0.0	0	0.0	0	0.0	0	0.0	2	71.3
Itaipu BP1	3	3.4	0	0.0	1	0.4	0	0.0	3	0.4	2	0.0	9	4.2
Itaipu BP2	2	1.6	0	0.0	2	2.3	0	0.0	2	0.3	0	0.0	6	4.1
Highgate	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	-	-	0	0.0
Cross Channel Bipole 1	6	230.1[2]	2	8.5	0	0.0	1	0.8	0	0.0	0	0.0	9	239.5
Cross Channel Bipole 2	2	3.6	1	2.0	3	11.1	1	2.3	0	0.0	0	0.0	7	19.0
Virginia Smith	3	1.4	1	4.1	0	0.0	0	0.0	2	10.4	-	-	6	16.0
Konti Skan 2	3	63.5	0	0.0	4	24.8	0	0.0	0	0.0	0	0.0	7	88.4
McNeill	2	22.2	1	1.5	0	0.0	0	0.0	3	9.4	-	-	6	33.1
Fennoskan	2	13.5	0	0.0	1	43.3	0	0.0	0	0.0	0	0.0	3	56.8
SACOI	11	15.6	0	0.0	6	2.2	0	0.0	0	0.0	31	77.0	48	94.8
New Zealand Pole 2	0	0.0	0	0.0	2	6.7	0	0.0	0	0.0	3	1.0	5	7.7
Sakuma	1	12.9	0	0.0	0	0.0	0	0.0	0	0.0	-	-	1	12.9

*Key: AC-E – AC and auxiliary equipment; V – Valves; C&P – Control and protection; DC-E – DC equipment; O – Other; TL – Transmission line or cable. **Notes** (1) Converter transformer failure (2) Converter transformer bushings*

formance of the power system than forced outages since planned outages can usually be taken during periods of reduced system load or when some reduction in transmission capacity can be accepted. Hence scheduled energy unavailability can vary substantially from system to system owing to differences in utility maintenance practices and policies, and the requirement for transmission capacity.

Forced outage data

Data on forced outages are given in Tables 2 and 3. Data are classified into six categories by equipment type.

The number of forced outage events and the equivalent forced outage hours within each category, together with the totals for each DC system, are shown in Tables 2A and 2B. 'Equivalent forced outage hours' is the sum of the actual forced outage hours after the outage duration has been adjusted for the percentage reduction in capacity owing to the outage. For example, for an outage of one pole of a bipole system (50 per cent loss of capacity) which lasted two hours, the equivalent outage hours would be one.

The protocol separates out reporting events which caused a reduction in transmission capacity but did not lead to a forced trip of the HVDC equipment. Table 2C summarises capacity reductions included in the statistics reported in Tables 2A and 2B. Capacity reductions are not included in the values reported in Tables 3 to 5 as these outages did not lead to a forced trip of equipment.

Approximately 89 per cent of all forced outages in 1999 and 2000 were attributed to equipment on the AC side of the converters. This compares to about 7 per cent of all forced outages attributed to the major DC equipment (valves 3 per cent, other DC equipment 4 per cent). Control and protections account for 3 per cent of the outages and "other" causes, which includes human error, account for 1 per cent. The large proportion of FEU for AC equipment is attributable to the converter transformer outages which occurred in 1999 and 2000.

Table 2C. Number of capacity reductions and equivalent outage hours[1]

System	1999 No.	1999 Hours	2000 No.	2000 Hours
Skaggerak 3	-	-	2	1.9
Vancouver island pole2	1	1.4	-	-
Nelson River BP1 pole 1	1	2.9	2	1.3
Nelson River BP2	3	141.9	8	728.4
Cross Channel bipole 1	-	-	1	2.6
New Zealand pole 2	-	-	1	6.3

Note: (1) Outage statistics includedin Tables 2A and 2B.

Frequency and duration

Table 3 shows the frequency and duration of forced outages and the cumulative average of this data from 1988 to 2000. Table A covers back-to-back converter stations, B covers systems with one converter per pole, and C covers systems with two or more series-connected converters per pole. The data for systems reporting operation of less than one full year has been adjusted in these tables to an annual basis for the year, but the cumulative average is calculated for the actual reporting period.

Table 3A shows the average frequency (number) and average duration of station outages for back-to-back converter stations. Tables 3B and 3C show the average frequency and duration of converter, pole and bipole outages for two-terminal and multi-terminal systems. The frequency of outages is given on a per terminal basis. The data contained in Table 3 in particular should be of value to planning engineers using HVDC reliability studies.

Thyristor valve performance

Data on thyristor failure rates are given in Table 4, which shows the number of failed cells in 1999 and 2000 for each of the DC systems for which data were provided.

A thyristor cell is an individual thyristor (with its associated auxiliary circuits) while a thyristor level is the assembly of one or more thyristor cells connected in parallel. A number of thyristor levels connected in series forms a valve.

The thyristor cell failure rate is the ratio of the number of cell failures to the total number of cells in the system and is an indication of the inherent failure rate of the thyristors and their associated circuitry. In most cases the thyristor cell failure rate is well below 0.5 per cent.

The commutation failure start rate is shown in Table 5. CFS are usually caused by AC system voltage disturbances (see recordable AC fault column) but may be internal to the converter station. More frequent CFS could be indicative of valve and control system problems.

Table 3A. Frequency and duration of forced outages – back-to-back converter stations

System	1999		2000		Average to 2000		
	f_s	d_s	f_s	d_s	Years	f_s	d_s
Shin-Shinano1	0.00	0.0	0.00	0.0	11	0.73	1.1
Shin-Shinano 2	0.00	0.0	0.00	0.0	7.6	0.39	0.2
Highgate	1.00	7.7	0.00	0.0	12	2.00	10.2
Virginia Smith	13.00	118.6	6.00	2.7	11	5.27	29.2
McNeill	4.00	17.9	6.00	5.5	7	9.57	6.2
Sakuma	1.00	30.7	1.00	12.9	7.5	0.67	17.1

Key to Table 3

f_s number of station outages per block for back-to-back converter stations per year
f_c number of converter outages per converter per terminal per year
f_p number of pole outages per pole per terminal per year
f_b = number of bipole outages per bipole per terminal per year
d_s average duration of station outages in hours
d_c average duration of converter outages in hours
d_p average duration of pole outages in hours
d_b average duration of bipole outages in hours
These systems are all a single independent back-to-back converter circuit consisting of one rectifier and one inverter.

Table 3B. Frequency and duration of forced outages – 2 terminal systems, 1 converter per pole

System	1999				2000				Average to 2000				
	Pole		Bipole		Pole		Bipole			Pole		Bipole	
	f_p	d_p	f_b	d_b	f_p	d_p	f_b	d_b	Years	f_p	d_p	f_b	d_b
Skagerrak 1 & 2	1.50	11.8	0.00	0.0	0.75	9.3	0.50	2.4	12	1.94	19.2	0.17	1.0
Skagerrak 3[1]	4.50	1.4	-	-	1.00	1.1	-	-	7	1.71	1.6	-	-
Square Butte	1.50	2.9	0.00	0.0	1.75	8.4	0.50	3.9	10	3.08	7.3	0.35	1.5
CU	1.25	1.3	0.00	0.0	1.75	3.7	0.00	0.0	12	2.13	2.0	0.21	2.7
Gotland 2 & 3	0.50	0.9	0.00	0.0	0.50	71.3	0.00	0.0	12	0.33	17.7	0.29	1.2
Cross Channel Bipole 1	0.00	0.0	0.50	0.5	1.50	77.3	1.00	2.5	12	0.60	29.8	2.92	3.0
Cross Channel Bipole 2	0.00	0.0	2.50	1.0	1.00	3.9	1.50	3.8	12	0.42	5.1	2.92	5.7
Konti Skan 2[1]	3.00	1.5	-	-	3.50	12.6	-	-	12	3.29	3.1	-	-
Fennoskan[1]	2.00	0.8	-	-	1.50	18.9	-	-	11	3.18	6.1	-	-
SACOI[2]	5.00	1.7	-	-	5.67	1.0	-	-	8	4.79	2.7	-	-
New Zealand Pole 2[3]	1.50	0.8	-	-	0.50	0.4	-	-	9	1.83	2.6	-	-

Notes (1) Monopolar System (2) Three terminal monopolar system (3) One pole

Table 3C. Frequency and duration of forced outages – 2 terminal systems, two or more converters per pole

System	1999						2000						Average to 2000						
	Converter		Pole		Bipole		Converter		Pole		Bipole		Years						
	f_c	d_c	f_p	d_p	f_b	d_b	f_c	dc	f_p	d_p	f_b	d_b		f_c	d_c	f_p	d_p	f_b	d_b
Vancouver Pole 2[1]	1.00	1.9	1.00	25.6	-	-	1.50	11.0	1.00	37.5	-	-	9	1.64	32.6	1.50	5.7	-	-
Nelson River BP1 Pole[1]	3.67	273.0	1.00	0.3	-	-	1.33	230.1	1.50	3.0	-	-	5	1.97	350.2	1.40	0.9	-	-
Nelson River BP2	2.75	10.6	2.00	2.0	0.00	0.0	4.38	16.0	2.25	3.5	0.00	0.0	12	3.99	23.6	2.17	2.6	0.25	3.8
Hokkaido-Honshu[2]	0.00	0.0	0.25	0.6	0.00	0.0	0.00	0.0	0.25	7.1	0.00	0.0	12[3]	0.04	23.4	0.46	3.3	0.06	324.5
Itaipu BP1	0.38	16.2	0.75	4.5	0.50	0.4	0.63	2.9	0.50	0.5	0.00	0.0	12	17.7		0.73	7.2	0.17	1.3
Itaipu BP2	1.38	20.3	1.50	2.2	0.00	0.0	0.63	3.3	0.25	0.1	0.00	0.0	12	1.62	72.7	1.17	2.0	0.08	3.6

Notes: (1) One pole only (2) Two converters in first pole, one in second pole (3) 7.8 years bipolar operation

Table 4. Thyristor calendar failure rate

System	Total levels	Total cells	Number of failed cells		Thyristor cell failure rate per cent/year[1]	
			1999	2000	1999	2000
Skagerrak 1 & 2	6912	6912	16	20	0.23	0.29
Skagerrak 3	1440	1440	0	4	0.00	0.28
Vancouver Island Pole 2	4320	8640	2	2	0.02	0.02
Square Butte	6912	6912	6	9	0.09	0.13
Shin-Shinano 1	3744	5184	2	0	0.04	0.00
Shin-Shinano 2	672	672	0	0	0.00	0.00
Nelson River BP1 Pole 1	2952	2952	2	0	0.07	0.00
Nelson River BP2	9216	18432	21	8	0.11	0.04
Hokkaido-Honshu	4008	4008	0	0	0.00	0.00
CU	8640	8640	16	34	0.19	0.39
Gotland 2 & 3	864	864	0	13	0.00	1.50
Highgate	432	432	0	0	0.00	0.00
Cross Channel Bipole 1	5304	10608	27[2]	32[2]	0.25	0.30
Cross Channel Bipole 2	5304	10608	24[2]	18[2]	0.23	0.17
Virginia Smith	960	960	0	0	0.00	0.00
Konti Skan 2	1152	1152	0	0	0.00	0.00
McNeill	276	276	1	1	0.36	0.36
Fennoskan	1584	1584	0	0	0.00	0.00
SACOI1	1344	1344	4	8	0.30	0.60
New Zealand Pole 2	1584	1584	0	0	0.00	0.00
Sakuma	672	672	0	0	0.00	0.00

Table 5. AC faults and commutation failure starts

1999			2000		
Recordable AC faults	Number of CFS External	Number of CFS Internal	Recordable AC faults	Number of CFS External	Number of CFS Internal
12	12	7	38	16	11
13	17	4	38	16	2
-	78	2	-	12	4
19	11	-	15	10	-
0	0	0	0	0	0
11	0	1	0	0	0
5	29	206	12	155	251
5	11	20	12	58	67
21	5	-	24	9	-
10	6	3	8	11	3
11	11	0	4	4	0
10	15	0	19	11	-
29	56	4	32	41	24
26	48	8	26	38	10
2	2	0	0	0	0
0	4	0	0	18	0
-	-	-	0	0	0
40	2	4	0	0	12
0	0	30	0	4	69
8	4	2	6	3	2
0	0	0	0	0	0

Notes (1) Suverto & Codrongianos terminals only (2) Majority of failures at Les Mandarins terminal.