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14-101

Session 2002

A SURVEY OF THE RELIABILITY OF HVDC SYSTEMS THROUGHOUT THE WORLD DURING 1999-2000

by

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On behalf of Study Committee 14

Summary

CIGRE Working Group 14.04 collects data annually on the reliability performance of HVDC systems in operation throughout the world. This report is a summary of the reliability performance of HVDC systems in operation throughout the world during 1999 and 2000. The summary was developed through data prepared by utilities that operate the HVDC systems and submitted to Working Group 04 of CIGRE Study Committee 14 (DC Links). The report contains data on energy availability, energy utilization, forced and scheduled outages and other data in accordance with a reporting protocol developed by the Working Group which was revised in January 1997. The report contains statistics on the frequency and duration of forced outages for the years 1999 and 2000 and combined with previous data to present a cumulative average of forced outages by frequency and duration covering the years 1988 to 2000. The cumulative averages are categorized by back-to-back stations and stations with one and two or more converters per pole.

The data in this report, together with that published in previous reports, provide a continuous record of reliability performance for the majority of HVDC systems in the world since they first went into operation. This now constitutes about 440 system-years of data on thyristor valve systems.

KEYWORDS: Survey - Reliability - HVDC Systems.

Background

Working Group 14.04 was formed specifically to assemble and publish data on the reliability and operational experience of HVDC systems in service around the world. The Working Group developed definitions for the reliability terms and parameters of prime interest at that time and prepared a protocol for use in collecting and compiling the data.

The protocol has been revised periodically as experience was gained in collecting and interpreting the data. The most recent revision was adopted by Study Committee 14 in January 1997 and can be obtained by contacting any member of WG14.04 [1].

Utilities that operate the HVDC systems collect the data for their systems in accordance with the protocol and prepare a report for each year of operation. These reports are submitted to the Working Group where they are compiled into a summary report.

The data were first collected in 1968, covering four dc systems utilizing mercury-arc valves. Data on the first thyristor valve system were compiled in 1972. For this paper reports were received on 23 thyristor valve systems and five mercury-arc valve systems for both 1999 and 2000.

The data contained in this survey report cover operation during 1999 and 2000. Data for earlier years can be found in previous reports [2] [3] and in the list of references given in those reports. The data in this report, together with that of the previous years, provide a continuous record of reliability performance of HVDC systems for the past 33 years. 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.

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The Working Group also maintains a Compendium containing the main data for all existing HVDC schemes. A copy of the compendium can be made available through regular members of Study Committee 14.

HVDC System 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 utilizing overhead line and/or cable systems.

A report was received for 1999 for Leyte-Luzon system, however the data was not in the WG protocol and is not included in this report. The Working Group encourages all systems to report and is willing to assist anyone who would like to become a correspondent for their HVDC system.

Table 1 shows the year of commissioning, the maximum continuous transmission capacity, energy availability, energy utilization and energy unavailability for the HVDC systems covered by this report.

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 Utilization 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.

It can be seen in Table 1 that some systems operate at very low energy utilization, i.e. they are used primarily for standby capacity, and other systems at very high energy utilization, i.e. approaching maximum rated capacity.

Table 1 - System Energy Availability, Energy Utilization and Converter Station Energy Unavailability

System	Year Commissioned	Maximum Continuous Capacity MW	Energy Availability percent		Energy Utilization percent		Forced Energy Unavailability percent (2)		Scheduled Energy Unavailability percent	
			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

(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

Forced Energy Unavailability (FEU) is the amount of energy that could not have been transmitted over the dc system due to forced outages. Only converter station equipment outages are considered, i.e. transmission line and cable outages are excluded.

Scheduled Energy Unavailability (SEU) is the amount of energy that could not have been transmitted over the dc system due to scheduled outages. 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 generally conducted concurrently with station maintenance.

Scheduled outages have less impact on the performance 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 due 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 to 5 inclusive. In Table 2, the data on forced outages are classified into six categories as follows:

- AC and Auxiliary Equipment (AC-E)
- Valves (V)
- Control and Protection (C&P)
- DC Equipment (DC-E)
- Other (O)
- Transmission Line or Cable (TL)

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 Table 2A for 1999 and Table 2B for 2000. Equivalent forced outage hours is the sum of the actual forced outage hours after the outage duration has been adjusted for the percentage of reduction in capacity due to the outage. For example, for an outage of one pole of a bipole system (50% loss of capacity) which lasted two hours, the equivalent outage hours would be one hour.

The protocol makes a distinction for reporting events which caused a reduction in transmission capacity but did not lead to a forced trip of the HVDC equipment. Table 2C summarizes the number of capacity reductions included in the statistics reported in Table 2A and Table 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.

Table 2A - Number of Forced Outages and Equivalent Outage Hours – 1999

System	AC-E		V		C & P		DC-3		O		TL		TOTAL	
	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	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

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

Table 2B - Number of Forced Outages and Equivalent Outage Hours – 2000

System	AC-E		V		C & P		DC-E		O		TL		TOTAL	
	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	Hours	No.	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

(1) Converter transformer failure (2) Converter transformer bushings

Table 2C - Number of Capacity Reductions and Equivalent Outage Hours - (1)

	1999		2000	
	No.	Hours	No.	Hours
Skagerrak 3	-	-	2	1.9
Vancouver Island Pole 2	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

(1) Outage statistics included in Tables 2a and 2b

Table 3 - Average Actual Outage Duration for Converter Station Forced Outages

System	1999		2000	
	No. of Outages (1)	Average Duration Hours	No. of Outages (1)	Average Duration Hours
Skagerrak 1 & 2	6	11.8	4	7.6
Skagerrak 3	9	1.4	2	1.1
Vancouver Island Pole 2	6	9.8	8	17.6
Square Butte	6	2.9	8	7.8
Shin-Shinano 1	0	0.0	0	0.0
Shin-Shinano 2	0	0.0	0	0.0
Nelson River BP1 Pole 1	24	250.3	11	168.1
Nelson River BP2	30	8.3	44	13.4
Hokkaido-Honshu	1	0.6	1	7.1
CU	5	1.3	7	3.7
Gotland 2 & 3	2	0.9	2	71.3
Itaipu BP1	7	8.9	7	2.2
Itaipu BP2	17	13.9	6	2.7
Highgate	1	7.7	0	0.0
Cross Channel Bipole 1	1	0.5	8	58.6
Cross Channel Bipole 2	5	1.0	7	3.8
Virginia Smith	13	118.6	6	2.7
Konti Skan 2	6	1.5	7	12.6
McNeill	4	17.9	6	5.5
Fennoskan	4	0.8	3	18.9
SACOI	15	1.7	17	1.0
New Zealand Pole 2	3	0.8	1	0.4
Sakuma	1	30.7	1	12.8

(1) Excludes capacity reduction.

Table 4 - Number of Forced Outages By Severity

System	Number of Forced Outages							
	1999				2000			
	All Outages	Bipole Outages	Pole Outages	Converter Outages	All Outages	Bipole Outages	Pole Outages	Converter Outages
Skagerrak 1 & 2	6	0	6	0	4	1	3	0
Square Butte	6	0	6	0	8	1	7	0
Nelson River BP2	30	0	8	22	44	0	9	35
Hokkaido-Honshu	1	0	1	0	1	0	1	0
CU	5	0	5	0	7	0	7	0
Gotland 2 & 3	2	0	2	0	2	0	2	0
Itaipu BP1	7	1	3	3	7	0	2	5
Itaipu BP2	17	0	6	11	6	0	1	5
Cross Channel Bipole 1	1	1	0	0	8	2	6	0
Cross Channel Bipole 2	5	5	0	0	7	3	4	0

Figure 1 shows a summary of the average FEU of all reporting systems for 1999 and 2000 on the basis of the major equipment categories as reported in Table 2A and Table 2B but excluding outages due to transmission/cables. Approximately 89% of all forced outages in 1999 and 2000 are attributed to the equipment on the ac side of the converters. This compares to about 7% of all forced outages attributed to the major dc equipment (valves 3%) plus other dc equipment (4%). Control and protections account for 3% of the outages and "other" causes which includes human error account for 1%. The large proportion of FEU for ac equipment in Figure 1 is attributable to the converter transformer outages which occurred in 1999 and 2000. At the CIGRE2000 session the WG14.04 Technical Session presenter recommended a Joint Task Force, between SC14 and SC12 be established to investigate performance of converter transformers in relation to HVDC system performance. A first report of the Joint Task Force was presented to CIGRE ICPS2001, in September 2001 [4]. Figure 1 can be compared to Figure 2 which shows the average FEU by category of all reporting systems from 1983 to 1998.

Table 3 gives data for each of the dc systems on the number of forced outages that have occurred and the average duration of the outages. It should be noted that the durations are given in actual lapsed time, i.e. the capacity lost during the outage is not considered. Some outages may be converter (valve group) outages, some pole outages and others bipole outages.

Figure 1
Breakdown of Average FEU By Equipment Category of All Reporting Thyristor HVDC Systems (1999-2000)

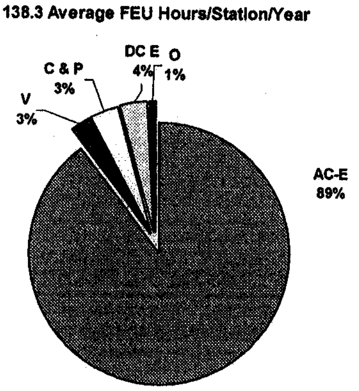

Figure 2
Breakdown of Average FEU By Equipment Category of All Reporting Thyristor HVDC Systems (1983-1998)

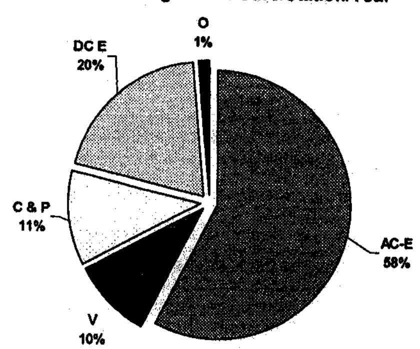

Table 5 - Frequency and Duration of Forced Outages

(A) Back-to-Back Converter Stations

System	Blocks	1999		2000		Average to 2000		
		f_s	d_s	f_s	d_s	Years	f_s	d_s
Shin-Shinano 1	1	0.00	0.0	0.00	0.0	11	0.73	1.1
Shin-Shinano 2	1	0.00	0.0	0.00	0.0	7.6	0.39	0.2
Highgate	1	1.00	7.7	0.00	0.0	12	2.00	10.2
Virginia Smith	1	13.00	118.6	6.00	2.7	11	5.27	29.2
McNeill	1	4.00	17.9	6.00	5.5	7	9.57	6.2
Sakuma	1	1.00	30.7	1.00	12.9	7.5	0.67	17.1

(B) 2 Terminal Systems - 1 Converter per Pole

System	1999				2000				Years	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		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	-	-

(1) Monopolar System (2) Three Terminal Monopolar System (3) One Pole

(C) 2 Terminal Systems - Two or More Converters per Pole

System	Converter		Pole		Bipole	
	f_c	d_c	f_p	d_p	f_b	d_b
1999						
Vancouver Pole 2 (1)	1.00	1.9	1.00	25.6	-	-
Nelson River BP1 Pole 1	3.67	273.0	1.00	0.3	-	-
Nelson River BP2	2.75	10.6	2.00	2.0	0.00	0.0
Hokkaido-Honshu (2)	0.00	0.0	0.25	0.6	0.00	0.0
Itaipu BP1	0.38	16.2	0.75	4.5	0.50	0.4
Itaipu BP2	1.38	20.3	1.50	2.2	0.00	0.0
2000						
Vancouver Pole 2 (1)	1.50	11.0	1.00	37.5	-	-
Nelson River BP1 Pole 1 (1)	1.33	230.1	1.50	3.0	-	-
Nelson River BP2	4.38	16.0	2.25	3.5	0.00	0.0
Hokkaido-Honshu (2)	0.00	0.0	0.25	7.1	0.00	0.0
Itaipu BP1	0.63	2.9	0.50	0.5	0.00	0.0
Itaipu BP2	0.63	3.3	0.25	0.1	0.00	0.0

System	Years	Average to 2000					
		f_c	d_c	f_p	d_p	f_b	d_b
Vancouver Pole 2 (1)	9	1.64	32.6	1.50	5.7	-	-
Nelson River BP1 Pole1 (1)	5	1.97	350.2	1.40	0.9	-	-
Nelson River BP2	12	3.99	23.6	2.17	2.6	0.25	3.8
Hokkaido-Honshu (2)	12 (3)	0.04	23.4	0.46	3.3	0.06	324.5
Itaipu BP1	12	1.33	17.7	0.73	7.2	0.17	1.3
Itaipu BP2	12	1.62	72.7	1.17	2.0	0.08	3.6

(1) One Pole Only (2) Two converters in first pole, one in second pole
(3) 7.8 years bipolar operation

Notes to Table 5

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
block	=	one independent back-to-back converter circuit consisting of one rectifier and one inverter

Table 4 shows the number of bipole, pole and converter forced outages that occurred in 1999 and 2000 for all the bipolar systems. The total number of all outages for each of the systems is also shown.

Table 5 shows the frequency and duration of forced outages for 1999 and 2000 and the cumulative average of this data from 1988 to 2000. The table is presented in three parts: (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 total reporting period.

Table 5(A) shows the average frequency (number) and average duration of station outages for back-to-back converter stations on a "per block" basis.

Tables 5(B) and 5(C) 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.

It is believed that the data in Table 5 will be useful to planning engineers involved with reliability studies of HVDC systems.

Thyristor Valve Performance

Data on thyristor failure rates are given in Table 6. The table shows the number of thyristor levels, the number of thyristor cells and 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) whereas a thyristor level is the assembly of one or more thyristor cells connected in parallel including the associated circuits. A number of thyristor levels are connected in series to form 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, expressed in percent. The thyristor cell failure rate indicates the inherent failure rate of the thyristors and their associated circuitry.

As indicated in Table 6, in most cases, the thyristor cell failure rate is well below 0.5 percent.

Table 6 - Thyristor Calendar Failure Rate

System	Total Levels	Total Cells	Number of Failed Cells		Thyristor Cell Failure Rate percent/year	
			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
SACOI (1)	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

(1) Suverto & Codrongianos terminals only

(2) Majority of failures at Les Mandarins terminal

Commutation Failure Start Rate

A parameter of interest in assessing valve and control system performance is the number of commutation failure starts (CFS). A CFS is the initiation of a distinct and separate commutation failure event. CFS are usually caused by the ac system voltage disturbances but may also be caused by events internal to the converter station. The number of recordable ac faults is an indication of the number of system disturbances. More frequent CFS could be indicative of valve and control system problems. The protocol calls for the inverter end commutation failures to be reported when the ac bus voltage drops below 90 percent.

Table 7 records the recordable ac faults, the CFS caused by ac system faults (external) and those initiated by control problems, switching events or other causes (internal) for 1999 and 2000.

Table 7 - Recordable AC Faults and Number of Commutation Failure Starts (CFS)

System	1999			2000		
	Recordable AC Faults	Number of CFS External	Number of CFS Internal	Recordable AC Faults	Number of CFS External	Number of CFS Internal
Skagerrak 1 & 2	12	12	7	38	16	11
Skagerrak 3	13	17	4	38	16	2
Vancouver Island Pole 2	-	78	2	-	12	4
Square Butte	19	11	-	15	10	-
Shin-Shinano 1	0	0	0	0	0	0
Shin-Shinano 2	11	0	1	0	0	0
Nelson River BP1 Pole 1 (1)	5	29	206	12	155	251
Nelson River BP2	5	11	20	12	58	67
Hokkaido-Honshu	21	5		24	9	-
CU	10	6	3	8	11	3
Gotland 2 & 3	11	11	0	4	4	0
Highgate	10	15	0	19	11	-
Cross Channel Bipole 1	29	56	4	32	41	24
Cross Channel Bipole 2	26	48	8	26	38	10
Virginia Smith	2	2	0	0	0	0
Konti Skan 2	0	4	0	0	18	0
McNeill	-	-	-	0	0	0
Fennoskan	40	2	4	0	0	12
SACOI (2)	0	0	30	0	4	69
New Zealand Pole 2	8	4	2	6	3	2
Sakuma	0	0	0	0	0	0

(1) Total thyristor plus mercury arc poles

(2) Suverto & Codrongianos terminals

Acknowledgement

The Working Group wishes to thank the System Correspondents for providing the annual reports that form the basis for the data in this paper and for their valuable comments and suggestions on improvements to the reporting procedure.

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