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**ANALYSIS OF HVDC THYRISTOR
CONVERTER TRANSFORMER
PERFORMANCE**

**Joint Task Force
B4.04 /A2-1**

February 2004



**ANALYSIS OF HVDC THYRISTOR
CONVERTER TRANSFORMER PERFORMANCE**

CIGRÉ -- International Council on Large Electric Systems

SC A2 Transformers

SC B4 HVDC and Power Electronics

JTF B4.04/A2-1

(Formally JTF 14.04/12-1)

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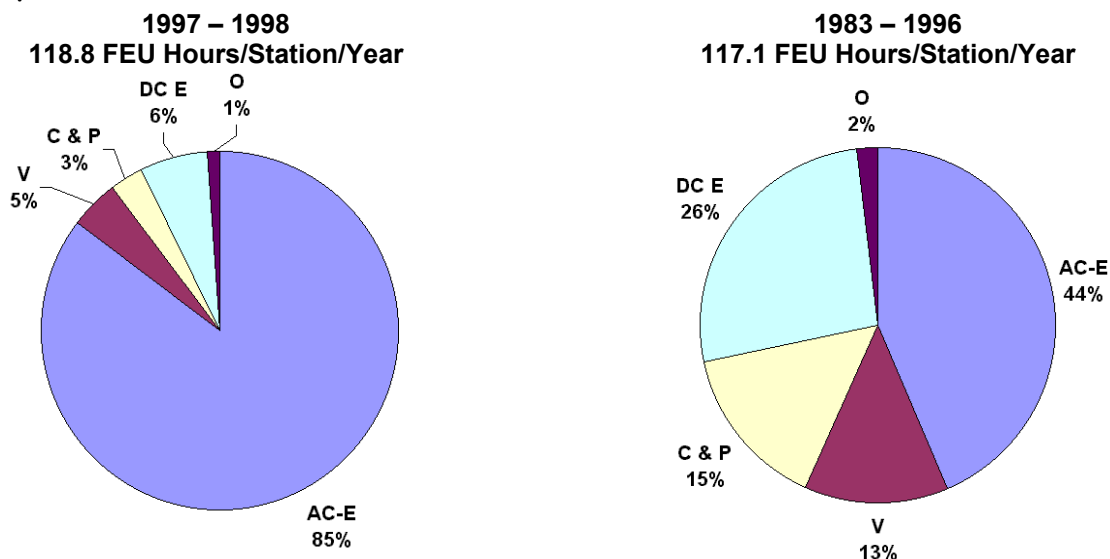
ABSTRACT

Performance of HVDC converter transformers is a major concern of the utility industry and is the subject of many discussions. A report in ELECTRA [1] summarized performance of thyristor systems operating from commissioning through 1990. A Joint Task Force (JTF) from SC B4, WG B4.04 and SC A2 was formed at the CIGRE 2000 SC B4 meeting under JTF B4.04/A2-1 to respond to a Special Reporter question relative to the relationship of converter transformer reliability and HVDC System performance. The JTF proceeded with a survey of thyristor HVDC system converter transformer in-service failures encountered between 1991-2002. The collected information is presented in performance summaries with failure areas described and classified as bushings, valve windings, AC windings, static shields, load tap changers, core and magnetic shields or internal connections and leads together with short descriptions of the failures. Present transformer test methods are also evaluated for adequacy. Comparisons with the previous report are included.

KEY WORDS: Transformer, Converter, HVDC, Performance, Reliability, Tests, Design Review.

INTRODUCTION

Each year SC B4, WG B4.04 collects reliability performance data on HVDC systems in commercial service. The information is compiled and presented at CIGRE Paris Biennial Technical Sessions and is useful in planning, design, construction and operation of HVDC systems. The concern for the reliability of HVDC converter transformers was raised during the WG B4.04 technical presentation [2] at the CIGRE 2000 meeting. The presentation included Figure 1, a breakdown of average Forced Energy Unavailability (FEU) by electrical category*.



**Figure 1 - CIGRE WG B4.04 All Reporting Thyristor HVDC Systems
Breakdown of Average FEU By Electrical Category***

(AC-E - AC and Auxiliary Equipment, V - Valves, C-P - DC Control and Protection Equipment, DC-E Primary D.C. Equipment and O - Other)

* Refer to WG B4.04 Reporting Protocol [3] for definition of electrical categories.

HVDC systems are continuing to perform satisfactorily (118.8 FEU current, versus 117.1 FEU historical) however, the AC and Auxiliary Equipment (AC-E) portion has grown substantially from a 1983 – 1996 value of 44% to the current 1997 – 1998 value of 85%. This increase with time is due to the effect of a number of converter transformer failures, however, the reason for the increase transformer outages was incomplete. One set of the CIGRE2000 SC B4 special reporters questions relative to the WG B4.04 technical paper were:

“Are the converter transformer problems unique to only those specific systems? Is it a quality control issue, a design management issue or a maintenance, testing and diagnostic issue? Is there something that SC B4 can do in this regard?”

The CIGRE2000, WG B4.04 Technical Session presenter recommended a Joint Task Force B4.04/A2-1 (JTF) be established to respond to the question. The Terms of Reference of the JTF include investigating the performance of converter transformers in relation to HVDC system performance based upon the annually collected data. The data will be used to prepare a summary report to illustrate trends in converter transformer failures based on specific criteria of HVDC systems. Using that report, and based on previous work, converter transformer failures will be identified with respect to types of failures. Conclusions and recommendations are intended to be included with comparisons made on the original work in ELECTRA [1].

The JTF first proceeded with a survey by directly contacting the utilities using HVDC systems. The boundaries set for the survey were:

- Rated power 50 MW or more
- Rated voltage 50 kV or more
- Insulation Oil and paper
- Valves Thyristors
- Time span 1991 to end of 2002

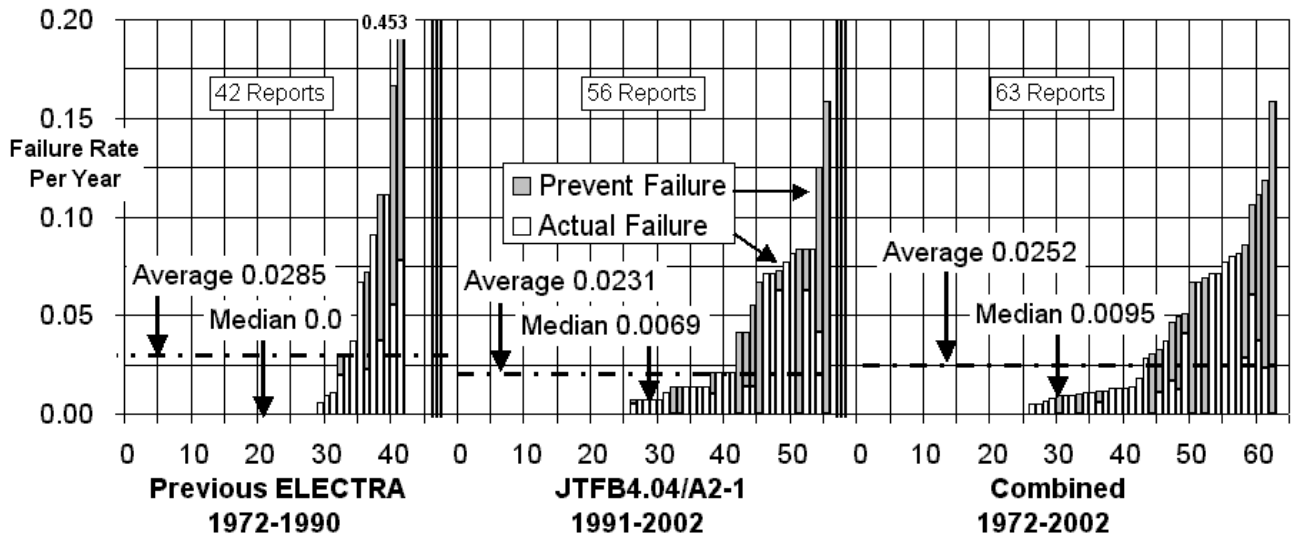
Failures are defined as actual, a failure requiring the removal of a unit from service because of major damages to active parts or preventive, a potential failure of active parts following diagnostic testing such as dissolved gas-in-oil analysis (DGA), high insulation power factor, or failure of similar unit(s). Apart from the general pertinent data, a description of the failure was requested together with the apparent cause(s) as suspected by the utility and/or by the manufacturer and the relation, if any, with the factory design/routine tests performed on that unit. The survey did not cover external bushing flashovers related to pollution.

The JTF presented at a CIGRE conference in China [4] an analysis of WG B4.04, 1991-1998 data in advance of receiving the survey information. This report demonstrated transformer failures were causing the high AC-E unavailability, which was, attributed to a system without spare converter transformers.

Following the completion of the survey, the JTF reviewed the data and classified the failures according to defined classes relating to the specific area involved in the failed unit and to the most likely primary cause for the failure. This information was used to analyze and define the general trends and relate them to actual tests normally performed. Appendix I lists performance data for 1972 through 1990 from the Previous Report with 42 reporting systems and subsystems (stages of systems commissioned in separate years are listed and counted separately to calculate the transformer years properly). Appendix II contains the JTF B4.04/A2-1, 1991 through 2002 data having 56 systems/subsystems and Appendix III lists the survey data obtained from all 63 reporting systems/sub systems. The 63 -- 53 difference is due to not including seven reports within the Previous Report in the JTF report. This document summarizes performance from 1972 through 2002 by combining the data of the Previous Report with the JTF B4.04/A2-1 report.

The system/subsystem data was reviewed on an individual basis to answer the Special Reporter question. Figure 2 is a bar chart with individual system/subsystem reported transformer failure rates sorted (minimum to maximum) for the Previous ELECTRA [1], JTF B4.04/A2-1 and Combined Reports.

Figure 2 – Sorted Individual System/Subsystem Failure Rates*



* The seven systems not included in the JTF Report that were in the Previous Report are as follows:
 Hamil, Inga Shaba, Eddy County and Vindhyachal did not respond to the survey.
 Dürrohr was de-commissioned.
 Des Cantons and Comerford are normally not operating.

The failure rates per year illustrated in Figure 2 indicate a relatively high and somewhat consistent average of 2.85% for 1972 – 1990, 2.31% for 1991 – 2002 and 2.52% for the combined 1972 – 2002 periods. In regard to the Special Reporter question: “Are the converter transformer problems unique to only those specific systems?” There are several systems having failure rates greater than 5% per year with seven (17% of the reports) for 1972 – 1990, 12 (21% of the reports) for 1990 – 2002 and 14 (22% of the reports) for the combined 1972 – 2002 period. Transformer forced outage time for major failures is dependent on having spare transformers, which has a direct effect on system availability. The outage time, to some degree, may be determined from the failure descriptions of each transformer within this report. The median failure rates discount the effects of the higher values and are 0 (29 reports or 69% with no failures) for 1972 – 1990, 0.69% for 1990 – 2002 and 0.95% for the combined 1972 – 2002.

The Appendices contain performance summaries of transformer operation years with the number of actual and prevent failures, which are summarized in Table 1. In the previous report, the 48 transformers at Itaipu had 192 operation years with a total of 15 actual and 72 prevent failures and this has a large impact on the failure rates for the entire report. The Table 1 failure rates are high but decreasing. Note the rates per year are 6.39% for 1972 – 1990 and 1.79% for 1991 – 2002 with a combined failure rate of 3.19% for 1972 – 2002. If Itaipu performance between 1972 – 1990 is removed, the rates per year become 2.00% for 1972 – 1990 with a combined failure rate of 1.85% for 1972 – 2002.

**Table 1
 All Systems Performance Summary**

Report	Period	No. of Tfrs.	Tfr. Years	No. of Failures		Average Failure Rates			Yrs per Failure
				Actual	Prevent	Actual	Prevent	Total	
Previous <i>ELECTRA</i>	1972 -- 1990	307	1895	33	88	0.0174	0.0465	0.0639	15.7
Itaipu Removed		259	1703	18	16	0.0106	0.0094	0.0200	50.0
JTF B4.04/A2-1	1991 -- 2002	405	4350	53	25	0.0122	0.0057	0.0179	55.8
Combined	1972 -- 2002	445	6252	86	113	0.0138	0.0181	0.0318	31.4
Itaipu Removed	1972 -- 1990	409	6052	71	40	0.0117	0.0068	0.0185	54.1

The Combined System list in Appendix III has 26 systems with no failures, 14 with one failure, 11 with two failures, four with three failures and 8 with four or more failures including Itaipu with 91 failures. Systems with a large number of failures are also having transformers in the same location fail more than once. Further examination of data and failure descriptions may be required to reach any absolute conclusions although this preliminary review indicates:

- In the Combined report (Appendix III), four of the 63 system/subsystems reporting account for over 65% of the failures.
- The previous report when compared with this JTF survey data indicates average failure rates are high and decreasing slightly.
- Median Failure Rates indicate acceptable performance however; the Median is increasing with time.

FAILURES REPORTED

The failures were also classified in the category of failure with the most likely cause as follows:

Category of failure	Most likely cause
A- Bushings	1- Mechanical
B- Valve Windings	2- Dielectric
C- AC Winding	3- Thermal
D- Static Shield	4- Induced Current
E- On-Load Tap Changer (LTC)	5- Operational Error
F- Core and Magnetic Shields	6- Unknown
G- Internal Connections and Leads	

In most cases the service conditions at or prior to the failure were normal unless specifically mentioned. The results of the survey indicate a total of 53 (actual) and 25P (preventive) transformer failures that are listed by category and cause in Table 2. There are a few failures involved in more than one category noted with an "*" which are counted as one failure.

**Table 2 - Summary of Transformer Failures
1991 -- 2002**

Category ->	A Bushings	B Valve Wdgs	C AC Wdgs	D Static Shields	E LTC	F Core & Magn. Shields	G Internal Conn.
Mech 8+ 8P	1-H.Hnsh1 1-Itaipu 1-PIE-Ex 1P-Itaipu 1P-F.Skan		1-Radsn*		2-C.C. 2-Kontek 2P-F.Skan 1-Radsn	1P-K.Skn2 1P-NR2 1P-PIE-UG	1P-Skagrk
Dielect 34 + 10P	1-Skagrk 2-Gezhba	3-Chnd-Pg 2-Chatgy 1-NR1 6-NR2 1-Haenam 2-Itaipu 10-R.Dadri 4P-Chatgy	1-NR1 1-R.Dadri 1-R.Dadri*		1-F.Skan 1-Gzhba 1-R.Dadri	1-Haenam* 2P-K.Skn2 1P-Vyborg	1-C.C. 3P-C.C.
Thermal 2 + 3P		2-NR2				1P-C.C. 2P-SwPol	
Ind. Curr 1 + 3P		1-H.Gate 2P-H.Gate		1P-K.Skn2			
Operator 1 + 0P					1-IPP		
Unknown 7+ 1P	1-S.Pond 1-V.Smith 1P-Madws		1-S.Butte	1-PIE-Upg	1-Eel R 1-Haenam 1-Welch		
Total 53+25P	8 + 3P	28 + 6P	3 + 0P	1 + 1P	12 + 2P	0 + 9P	1 + 4P

* Failure involved more than one category

FAILURE DESCRIPTIONS

All reporting systems were requested to submit descriptions of failures of converter transformers used with thyristor valves. Nelson River Project, which is composed of mercury-arc and thyristor valves as listed in Table 3, submitted failure descriptions for both the mercury-arc and thyristor valve transformers. Mercury-arc operation years of Nelson BP1 Pole 1 (1973 – 1991) and BP1 Pole 2 are excluded from the performance data to conform to the previous report. However, the failure descriptions are included to support the monitoring and design review recommendations.

Table 3 Nelson River Bipole 1 and 2 Schemes

Bipole/Stage	Commission Year	Transformers					Comments
		kV	MW	Phase	Wdgs	No.	
BP1 Pole 2	1973	464	900	1	3 (2)	18	Mercury Arc
BP1 Pole 1	1992 (1)	464	900	1	3 (2)	18	Thyristor Valves 1992
BP2, Stage1	1978	500	1000	3	2	8	Thyristor Valves
BP2 Stages 2 & 3	1984-85	500	1000	3	2	8	Thyristor Valves

(1) Mercury-Arc operation 1973 – 1991

(2) Tertiary winding used for synchronous condenser at receiving end.

The following describes the failures by category:

A) Bushings, 8 + 3P Failures (Mercury-arc excluded from count)

1P Failure - Fenno-Skan,

Oil leak from transformer DC bushing on the valve hall floor in Rauma in 1992. The valve in the top of the bushing was leaking.

2 Failures - Gezhouba - Nanqiao

In 1997 at Gezhouba, an AC bushing exploded causing 3641 hours forced outage and in 2001 another AC bushing exploded causing 26 days forced outage.

1 Failure - Hokkaido Honshu 1

Bushing damage occurred as a result of an earthquake.

1 +1P Failures - Itaipu

Transformer serial number 7197213 failed in Aug 22, 1994 was removed from service due to the breaking of the bushing rod of valve winding

On Oct 22, 2000 an oil leakage through cracks in the porcelain near the X1 bushing top flange was detected during an inspection of Transformer serial 57861.

1 P Failure - Madawaska

This converter has been operated regularly at the maximum available power overload corresponding to low ambient temperature for prolonged periods of time. The secondary bushings are located within the valve hall. Numerous oil leaks have been noticed at the end of these secondary bushings. Inspections revealed that the O-ring seals inside the bushings had suffered accelerated aging and had lost their flexibility due to extended operation at high valve hall temperatures.

1 Failure - Nelson River (Mercury-arc Valves)

Dorsey T21 A Failure - Outage duration - about 175 days (Repaired)

Dorsey T21 A phase converter transformer tripped by main differential protective relaying on August 10, 1993. The 230 kV bushing failed catastrophically, caught fire and was extinguished manually. There was extensive damage to the tank but the core and coils were intact. A new tank was fabricated and the unit was repaired using the old core and coils.

1 Failure - Pacific Intertie Expansion

Converter 2 A-phase transformer failed on September 26, 1995 at Celilo. An internal flashover across the X1 bushing caused major internal damage and created mechanical stress that shattered the porcelain on two additional bushings. The spare transformer was moved into the A-phase position and the Converter was returned to service.

1 Failure - Sandy Pond

On November 7, 2002 the Pole 2 converter was tripped out by P2-T1 PH-A gas (Bucholz) relay resulting from gas that developed due to a ground fault within transformer. Oil was pouring out of the base of HO 2 bushing that had been damaged by short-circuit forces. Inspection revealed that it had failed at the lower part just below the ground sleeve. The bushing was replaced with a spare, the transformer oil was degassed and filtered and the unit was returned to service.

1 Failure - Skagerrak

A short circuit occurred in the 109 kV bushing phase R in Kristiansand in 1991, probably directly through the transformer oil. Clear footprints from the short circuit were seen at the field distributing ring and an earthing bus when opening and dismantling the bushing. Samples of transformer oil indicated highest gas concentration in the 109 kV bushing. The transformer gas relay tripped the

transformer and the DC-side short circuit relay tripped the link. The reason for the short circuit has not been found.

1 Failure - Virginia Smith

Primary 230 kV converter transformer bushing on east phase b unit failed catastrophically on May 31, 1999 resulting in fire and physical damage to the transformer unit. The coils and core (2-legged) were not damaged. The transformer required cleaning and repair of the lead bus at a transformer repair facility. The station was returned to service on June 24, 1999 or 24 days later.

Power transfer was approximately 50 Megawatts. The east bus differential cleared the fault in three cycles. The weather was misty with high humidity following rain the night before.

The bushings were power factor tested on a three-year basis. The converter transformer bushings were power factor tested two years prior to the incident and did not show any problems.

The five remaining primary converter transformer bushings were power factor tested and two others were found to be degraded. All six of the 230-kV primary bushings were replaced with new bushings.

B) Valve Windings, 28 + 6P Failures

3 Failures - Chandrapur-Padghe

One forced outage happened in 2001 and two forced outages occurred in 2002. In all cases the valve winding was damaged due to turn-to-turn faults. DGA prior to the above failures did not indicate any abnormality during operation of these transformers.

2 + 4P Failures - Chateauguay

The transformers were tripped by sudden pressure gas relays. The secondary winding on Leg 1 had suffered severe damage. A turn-to-turn short-circuit had developed involving turns on the first two upper discs. Inspection revealed that the six (6) discs at both winding ends (upper and lower) had overheated badly with carbonized paper under all the keyspacers. Analysis revealed that the cooling of the winding ends was not sufficient. The end discs had been designed to form "semi-solid discs" around the ends that greatly affected the cooling efficiency, especially under ONAN conditions. These converters had been used frequently at 50% loading so that for long periods of time had been without any cooling pump running, as per design.

All the transformers, except the original spare, were repaired/modified in turns. The first failed unit was repaired but not modified, as the actual problem had not been clearly identified at that time. The original spare has not been modified, as it had never been operated before. These two units now have a restriction that they can only be used with at least one of the cooling pumps running.

1 + 2P Failures - Highgate

One transformer failed in service, two failures were prevented by removal. Extensive damage was found on the two end turns of the low voltage windings due to harmonic induced eddy current heating combined with reduced cooling due to added insulation. From 1985 to 1988 the transformers were operated up to 175 MVA. From 1988 to 1995 the transformer were operated up to 235 MVA. From 1995 until the failure in 1996 the transformers were operated up to a maximum of 260 MVA. Further details can be found in [5].

1 Failure - Haenam

A combination valve winding and core ground caused a winding flashover and transformer failure in 1998. The transformer outage time was about 64 days.

2 Failures - Itaipu

Transformer serial number 7197213 failed in service on Apr 22, 1997 in converter number 3; phase C at Foz de Iguaçu. The converter was tripped by the differential relay and combustible gas was found in the gas relay. No oscillograms of the fault exist. During inspection at site it was found that the fault

was located in C1 winding (600 kV valve winding with terminals X1 and X2). A breakdown in the upper part of the C1 winding was found. The fault probably started as a fault between turns in the C1 winding.

Transformer serial 57842 was tripped on June 17, 1999 at Foz de Iguacu substation, and 50 seconds after the trip the gas relay alarmed. Measurements performed at site indicated damage at the valve winding C1.

9 Failures - Nelson River (Thyristor Valves)

Dorsey BP2 Stage1, T31S Failure - Outage duration about 273 days (Repaired)

Dorsey T31S converter transformer was manually blocked due to a slow gas alarm on February 21, 1994. Tests and an internal inspection indicted a short circuit in the DC winding.

Henday BP2 Stage 1, T31S Failure - Outage duration 30 days (Repaired)

Henday T31S converter transformer tripped by DC side valve overcurrent (7500 Amperes) and AC side ground differential protection on May 6, 1998. The failure was caused by overheating at the top of the line side winding.

Henday BP2 Stage 1, T41D Failure - Outage duration 21 days (Replaced)

Henday T41D converter transformer was tripped on August 26, 1998 by Pressure Relief Device operation. An internal inspection revealed copper splatter and particles from the X1 to X3 DC winding due to overheating.

Dorsey BP1 Pole 1, T11C Failure - Outage duration 243 days (Replaced)

Dorsey T11 C phase converter transformer was tripped on July 16, 1999 by sudden pressure relay operation. Failure occurred due to overheating of the valve winding. This unit was approximately 27 years old.

Dorsey BP2 Stage 1, T31D Failure - Outage duration 169 days (Replaced)

Dorsey T31D converter transformer tripped on November 6, 1999 on fast gas trip operation. This unit was approximately 22 years old. An internal inspection revealed damage to Leg 2 of the valve winding on the line side of the transformer due to arcing caused by conductor insulation failure.

Dorsey BP2 Stage 1, T41S Failure - Outage duration 139 days (Replaced)

Dorsey T41S converter transformer tripped on February 14, 2000 on fast gas trip operation. Internal inspection revealed damage to Leg 2 of the valve winding due to arcing caused by conductor insulation failure.

Henday BP2 Stage 1, T31D Failure - Outage duration 11 days. (Replaced)

Henday T31D converter transformer on September 21, 2000 had a slow gas alarm at 21:39, followed by a trip by Pressure Relief Device operation at 22:02. Winding resistance indicated that Leg 1 of the Valve winding was open circuited. An internal inspection revealed copper splatter and pieces of winding strands found near the H1 winding.

Dorsey BP2 Stage 2, T32S Failure: Outage duration 458 days (Replaced)

The Pressure Relief Device tripped Dorsey T32S converter transformer on September 13, 2001. An internal inspection revealed copper splatter on the line winding lead exit from Leg 1 as well as damage to the outer valve winding wraps due to overheating. It was determined that the overheating was caused by a lack of oil flow in the area of the failure. A detailed analysis of winding failures of Nelson River scheme is given in reference [6].

Dorsey BP2 Stage 3, T42S Failure - Outage duration 254 days (Replaced)

The Pressure Relief Device tripped Dorsey T42S converter transformer on November 10, 2001. An internal inspection revealed the origin of the failure to be on Leg 3 of the valve winding in the core window on the line side. It was determined that the overheating was caused by a lack of oil flow in the

area of the failure. Additional cooling capacity has been added to the existing transformers of similar design to extend their life.

10 Failures - Rihand-Dadri

Four failures occurred during the first eight years of operation [7]. Repairs were made without any changes in design by replacing all windings of the affected limb. In 2000 these same units failed again. In all cases the failure was caused by turn-to-turn failures in one valve winding and in two cases the same winding was involved. The repairs after the second failure have been undertaken by using modified conductors. In the original conductor design there were 2 bare conductors and an isolation strip (epoxy coated) between them in radial direction was used as an insulating medium. In the modified conductor one strand has been enameled in addition to the isolation strip provided between the two conductors for better withstand margins between the parallel conductors. The windings of both limbs were completely replaced together with the main insulation. In 2002 two new failures occurred. These transformers showed the similar mode of failure. In these cases the valve windings at the other limb failed. In all above cases the dissolved gas analysis has not provided any significant increasing trend indicating impending failure.

C) AC Windings, 3 + 0P Failures (Mercury-arc excluded from count)

1 Failure - Nelson River (Thyristor Valves)

Dorsey BP1 Pole 1, T13A Failure - Outage duration about 580 days (Replaced)

Dorsey T13 A phase converter transformer tripped by fast gas protective relaying on July 18, 1997. The 230 kV winding was found to be open circuit due to an internal fault. The failure is a turn-to-turn short in an area of transposition. Excessive moisture was determined to be the cause of failure. As a result the transformers in the other two phases were dried using hot oil spray.

1 Failure - Nelson River (Mercury-arc Valves)

Dorsey BP1 Pole 2, T22B Failure - Outage duration 19 days (Replaced)

Dorsey T22B converter transformer tripped on November 28, 1999 on slow gas alarm operation. The transformer had been gassing for some time due to a suspected bad connection that could not be located by previous internal inspections. This unit had been kept in service for several years by use of on-line degassing and on-line monitoring and had been expected to fail. After reviewing the status of the unit it was decided that the unit was to be taken out of service immediately and replaced with an available spare transformer.

1P Failure - Nelson River (Mercury-arc Valves)

Radisson BP1 Pole 2, T21A Repair - Outage duration 34 days (Repaired)

Transformer T21A was removed from service in Sept 2, 1995 due to abnormal capacitance readings and the valve group was placed back in-service Sept 17, 1995. It was thought that the tertiary winding may have shifted as its blocking was suspect. The repaired unit was received back at Radisson in mid-Sept 96. An outage was taken on Oct 28, 1996 to remove the spare from service and the valve group was returned to service November 27, 1996.

1 Failure - Rihand-Dadri

One unit failed due to a turn-to-turn fault in limb 1 of the ac winding. A second failure involved both dc and ac windings as indicated in the AC Windings column of Table 2.

1 Failure - Square Butte

Extensive damage occurred to the high voltage winding. Targets were Transformer Differential, Sudden Pressure, Main and LTC Pressure Relief. Visual inspection indicated a cracked seam weld with a small amount of oil expelled. One pole breaker failed to open resulting in 10.5 cycle clearing by Breaker Failure protection.

D) Static Shield, 1 + 1P Failures

1P Failure - Konti-Skan 2

No connection between core and the bottom stray current shield. A DC bushing was not properly tightened. Sept. 1995.

1 Failure - Pacific Intertie Upgrade

A transformer failure occurred in Valve Group 8 B-phase at Sylmar (Upgrade). The B-phase converter transformer in Valve Group 8 at Sylmar tripped due to a sudden pressure build-up in the main tank caused by internal arcing. The 6-pulse thyristor valve group was out-of-service until October 2, 1995, when transformer repairs were completed. The spare transformers for this valve group had been damaged during the earthquake and were unavailable for service.

E) On-Load Tap Changer (LTC), 12 + 2P Failures

2 Failures - Cross Channel

At Sellindge two failures occurred one year apart (1993 and 1994) following the build up of pyrolytic carbon on the rotating switch contacts causing first an open circuit selector switch which flashed-over and tripped and secondly the sticking of the contacts in one tap position requiring a “controlled” forced outage.

1 Failure - Eel River

The tap changer of one transformer failed in 1994. The failure resulted in a forced outage and the tap changer was repaired on site. Because of this problem, Eel River Interconnection operated at half power for a period of 30 days.

1 Failure + 2P- Fenno-Skan

A gas leak occurred in the tap changer overpressure valve in Rauma in 1991. Failure outage hours 27.

An oil leak occurred in the tapchanger cap in Rauma in 1998.

In Rauma in 2001 the LTC in phase T had been totally blocked and failed to operate. A week later it worked properly again and has done so since then. The reason was never found but most likely water had penetrated into the ball bearing in the shaft system and at cold weather it froze and stopped the motion.

1 Failure - Gezhouba - Nanqiao

In 1997 at Nanqiao, a converter transformer caught fire caused by OLTC, resulting 649 hours forced outage

1 Failure - Haenam

An On-Load Tap Changer problem in 1998 caused a converter transformer failure resulting in a 311-hour transformer outage.

1 Failure - IPP

There has only been a single failure for IPP caused by human error, not a manufacturing problem. Following a routine overhaul station personnel failed to operate the tapchanger throughout its operation range. Upon energization arcing occurred.

2 Failures - Kontek

Dirt in the overflow control between LTC and expansion tank caused two trips in 2001, one in Bjaeverskov and one in Bentwisch.

1 Failure - Radisson (Hydro Quebec-New England Multiterminal)

A selector switch failed most probably due to mechanical reasons. The mechanical damages were augmented due to the fact that the LTC was automatically ordered to move back to position 1 after the trip. The supplementary damage was so extensive that it prevented any precise identification of the

initial mechanical problem. The control has now been modified to freeze the LTC following a trip initiated by a transformer protection.

1 Failure - Rihand-Dadri

During the detailed investigation it was concluded that the failure of one of the transformers in Rihand was due to a design error for the tie in resistors of the tap changer. The cause of the breakdown was high operating temperature of the tie in resistors, which led to a flashover and finally the OLTC was mechanically damaged.

1 Failure - Welch

In 2001 the LTC of a converter transformer failed while the dc power was ramping down prior to power reversal. The failure developed into a winding failure. The damaged unit was replaced by a spare within 72 hours.

F) Core and Magnetic Shields, 9P Failures (Mercury-arc excluded from count)

1P Failure - Cross Channel

At Les Mandarins in 2000 one unit had very high gas levels. The unit was exchanged for a spare following a routine DGA sample.

3P Failures - Konti-Skan 2

Insulation failure in the terminal boxes on motors for pumps both on the Swedish and the Danish side in 1993. All pumps have been repaired currently.

In Vester Hassing in 1998 there was a minor leakage of oil when the transformer was cold.

1P Failure - Nelson River (Thyristor Valves)

Henday BP2 Stage 1, T41D Prevent - Outage duration about 380 days (Repaired)

Henday transformer T41D was gassing due to stray flux and when examined in the factory the core steel had to be replaced.

1P Failure - Nelson River (Mercury-arc Valves)

Dorsey BP1 Pole 2, T21A Prevent - Outage duration 14 days (Replaced)

VG 21 was blocked on April 28, 2000 in order to remove and replace Dorsey T21A converter transformer, as a result of high gassing rates and limited loading of 1800 Amps. The transformer had been gassing for some time due to shorting of the core. After reviewing the status of the unit it was decided that the unit was to be taken out of service prior to its failure and replaced with an available spare transformer.

1P Failure - PIE Upgrade

Sylmar Failure - Planned Outage - duration 13 days 3 hours (Repaired)

At Sylmar (Upgrade segment) in 2002, a Transformer DGA test indicated gases were being generated internally. The transformer was inspected during a planned outage and a broken bolt found that attached the static shield internally near the bushing was replaced. The 1994 earthquake may have been the cause of the broken bolt.

2P Failures - SwePol Link

Two failures, one at each station occurred in 2001. The units were inspected due to high levels of gassing. The cause has not been found and is still a matter of concern.

1P Failure - Vyborg

Outage duration 4 days

In Oct. 2002 the transformer TI-4, phase B was taken out of service due to high DGA. The oil was drained and a visual inspection found a core to yoke ground connection on the low voltage side. Also the Vyborg terminal has performed considerable maintenance during scheduled outages consisting of

rebuilding/replacement of LTC Contacts, LTC Mechanical Operators, Cooling Pumps, Cooling Motors, Radiators, Conservator/Main Tanks and Bushings.

G) Internal Connections, 1 + 4P Failures

1 Failure + 3P Failures - Cross Channel

At Sellindge in 2000 in BP1 an internal bushing flashover followed a prolonged period of internal discharging within the “dry type” Epoxy Resin Impregnated Paper (ERIP) 280 kV bushing. Further inspections showed evidence of discharging on each of the other 3 “upper bridge” transformer units. The total outage time was about 11 days.

At Sellindge three inspections were carried out in 2000 on other units because of the above failure. All 12 suspect upper bridge bushings have been or will be replaced by the end of 2003.

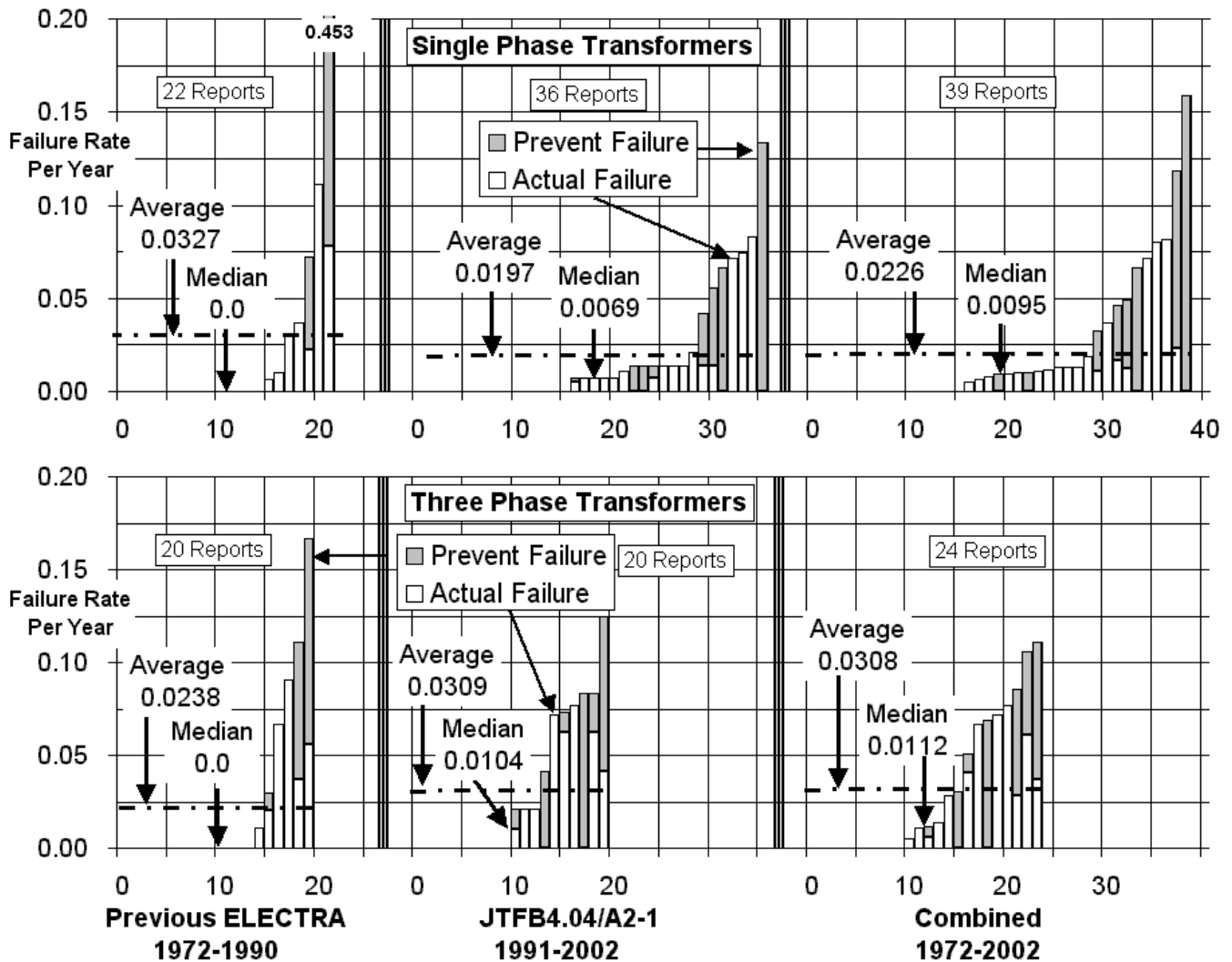
1P Failure - Skagerrak

A failure occurred in the transformer cooling equipment. An oil pipe from the tank to the oil pump cracked due to vibrations from an unbalanced fan. The unit was taken out of service to weld the pipe and balance the fan.

SINGLE PHASE – THREE PHASE COMPARISON

A comparison of single-phase with three-phase transformers is illustrated in Figure 3 on a bar chart with individual system/subsystem reported transformer failure rates sorted from minimum to maximum for each report.

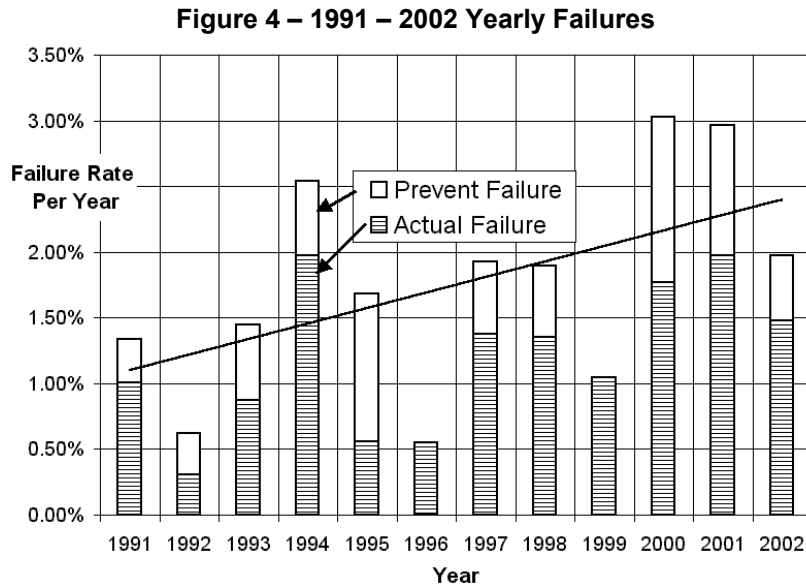
**Figure 3 – Single Phase – Three Phase
Sorted Individual System/Subsystem Failure Rates**



The Figure 3 comparisons of single-phase with three-phase transformer failure rates per year indicate single-phase transformers have a lower failure rate except for the Previous ELECTRA [1] report. This is caused by Itaipu failure rate of 0.453 based on 192 operation years with 15 actual and 72 prevent failures. If Itaipu is removed the average failure rate is reduced from 0.0327 to 0.0127. If the Itaipu 1972 – 1990 data is removed from the Combined Report the average failure rate is reduced from 0.0226 to 0.0197.

FAILURE TRENDS

Figure 4 is a bar chart of the annual failure rate data in Table 4 obtained from the JTF 1991 -- 2002 survey. Although the previous report when compared with the JTF survey data indicates average failure rates are high and have decreased slightly, the trend line of Figure 4 illustrates an increasing failure rate from 1991 through 2002.



**Table 4
Transformer Failures Per Year**

Year	Failures		No. of Tfrs
	Actual	Prevent	
1991	3	1	299
1992	1	1	322
1993	3	2	345
1994	7	2	354
1995	2	4	357
1996	2	0	361
1997	5	2	363
1998	5	2	369
1999	4	0	381
2000	7	5	396
2001	8	4	405
2002	6	2	405

There remain uncertainties in making any conclusion on the failures listed in Table 4. For instance, for 2000 and 2001, 15 of the 24 failures (62.5%) were reported by three systems. The question on transformer life cycle remains open and emphasizes the need to report performance annually to CIGRE SC B4, WG B4.04 to verify if the 2000 and 2001 failures are unique or the beginning of a trend.

ON-LINE TRANSFORMER MONITORING

Periodic DGA measuring has been proven to be successful in determining the integrity of transformer components. Also, on-line monitoring may be beneficial to use on suspect transformers to provide an early indication of transformer deterioration. Gas in oil on-line monitoring is currently being used on the Nelson River Project for early warning and multi gas analysis. In addition, online monitoring of bushing dielectric characteristics has been used successfully on AC transformers and recently has been demonstrated on a three-phase converter transformer on the CU Project. Also for AC transformers, the Technology exists to perform Partial Discharge (PD) measurements on equipment while it is in operation.

The following paragraphs are based on the HVDC experience. Complementary information relative to AC transformers can be found in the guide for life management techniques for power transformers of the WG A2.18 [8]

A) Early Warning

One type of early warning system uses a hydrogen-in-oil monitoring (Hydran) sensor that is calibrated for H₂ and reads a composite value of gases in ppm (H₂ (100%), CO (18%), C₂H₂ (8%), C₂H₄ (1,5%)). As hydrogen is a key gas for problems in the active part, an increase in the output signal of the sensor is an indication for irregularities such as partial discharge or hotspots. The output of these sensors can be networked together and monitored on a single PC. The information can also be accessed remotely via Internet. The system can be used to generate an automatic alarm.

The evaluation of this measuring signal, together with the analysis of the temperature of the oil and the load current, provides a reliable basis for the continuous operation of the transformer. In the event of an increase of gas-in-oil content, an immediate reaction can be taken via an off-line DGA to determine the concentration of the other components dissolved in the oil in order to clarify the cause of the potential damage.

B) Multigas Analysis

A multigas analyzer provides a complete on-line gas analysis of the oil. Using well-known analysis techniques it can also identify the nature of the fault on-line. Once the Hydran unit shows that a fault is developing in a particular unit, a multigas analyzer can be used to identify the type of fault. Depending on the severity of the fault and the gassing rate, the transformer can be kept in service by connecting an on-line degassing unit.

C) Bushing Monitoring

On-line monitoring of the bushing dielectric characteristics has been successfully utilized for several decades on AC systems and may be available for monitoring HVDC converter transformers. The original concept is quite simple: The current that can be obtained from the test or potential tap of a bushing contains both reactive and active components representing respectively bushing capacitance and power loss. Three bushings are normally available on transformers or transformer group (including CTs and CCVTs). Assuming that at least one bushing is in a good condition, a comparison between the three currents can be made and diagnostic conclusion can be derived on this comparison. It would be highly unusually that more than one bushing would deteriorate at the same rate at the same time. Normally, only one of the three bushings would be in poor condition at the same time.

D) On-Line Partial Discharge Measurements

For AC Transformers, Partial Discharge (PD) measurements may be accomplished while in operation. These tests can closely parallel those in the factory, but are performed in the field. This technology is also being examined for HVDC converter transformers. Application of Periodic On-Line Partial Discharge Measurements in Nelson River scheme are described in reference [9].

E) Experience With Monitoring at Nelson River System

The Nelson River HVDC system consists of two bipoles. Bipole 1 has 36, nominal 115 MVA single-phase transformers and Bipole 2 has 16, nominal 275 MVA three phase transformers (see Table 3). All the transformers have continuous on-line Hydran sensors. Several units have multi-gas analyzers for more detailed information refer to [10]. The Hydran relays are networked for data acquisition purposes.

The monitoring system at Nelson River can initiate alarm and trip signals for each unit being monitored. However the level at which the alarm is generated varied from unit to unit. On some units the gas content changed with loading. The magnitude of change in gas and the rate of change were also different between units. As a result a universal alarm level setting could not be used. It was found that to make the alarms secure, the alarm was supervised by a rate of change setting.

Since 1996 a total of 12 transformers have failed in service at Nelson River. Most of these transformers failed due to turn-to-turn faults. However, the monitoring system did not provide any prior indication of the impending failures [11]. In 2001, two converter transformers failed due to insulation failure caused by localized overheating. In both cases periodic DGA and continuous on-line hydrogen in oil monitoring did not indicate significant overheating.

The on-line monitoring, however, was very useful in detecting faults that involved the core. On one unit the monitoring system indicated a steady increase in gas content. The transformer was taken out of service and an internal inspection revealed overheating at the core clamps. Since the transformer could not be easily repaired on site and could not be removed from service due to shortage of HVDC capacity, an on-line degasifier and an on-line gas analyzer were connected to the transformer. The gasses-in-oil were continuously monitored. Whenever the gas level exceeded a preset level, the on-line degasifier was started to bring the gas content to an acceptable level. This unit was kept in service for several years with the on-line degasifier. The revenue from the power sale due to added capacity paid for the monitoring equipment several times over. The same procedure has been used to extend the life of a few other units.

The following points were concluded:

- DGA and furn in oil [12] measurements may not detect localized overheating if there is no oil circulation at the hot spot.
- In the case of turn-to-turn faults no advance warning of failure was provided by the monitoring system.
- Continuous on-line gas-in-oil analysis has been useful for problems related to the core and its support structure.
- Adding on-line degasifiers has extended the life of several transformers.

F. Vyborg Transformer monitoring [13]

Basic differences of the transformer equipment monitoring at Vyborg BTB from known similar systems are:

- Monitoring and control system allow to inspect power equipments condition and to determine refusals of elements of a cooling system to minimize power consumption and to transmit the information to substation Automatic Control Systems (ACS);
- Monitoring pressure and temperatures of oil in transformers bushings with the help of microprocessor transmitters installed on flanges of bushings;
- Monitoring of tap changers positions with the help of special noncontact microprocessor transmitters transmitting the information on tap changer to the dispatcher and to other subsystems of the ACS.

PREVIOUS TEST RECOMMENDATIONS

The previous report in ELECTRA [1], gave a summary of performance of converter transformers for the time period 1972 to the end of 1990 and it was concluded that there was a large number of failures. Appendix I show a summary of the failure categories and their most likely causes. The most occurring fault categories are bushings (six), valve windings (eight), AC windings (five) and static shields (eight) failures.

Many of the failures were associated to lack of appropriate tests, which represent the special operation modes, the HVDC transformers will be exposed to. Some recommended additional tests to be carried out at the manufacturer's plant, prior to delivery are:

- Separate routine tests of valve side bushings at higher voltage than the winding
- Extended heat-run test with overload
- Testing of inter-strand insulation between parallel conductors

It was recommended that the above tests be performed as routine tests.

The previous report also proposed a number of items to be specifically covered in a design review that should especially focus on aspects and properties, which will not be fully tested before delivery.

NEW ISSUES ABOUT CONVERTER TRANSFORMER TESTS

This report, covering the 1991 -- 2002 performance, shows a failure picture with categories not too different from the previous report. Now the most dominant categories are bushings (11), valve windings (34), AC windings (three) and LTC (14) failures.

It can be concluded that the years per failure occurring in the 1991-2002 period have a slight improvement over those in the previous period. The years per failure has improved from 50 with Itaipu 1972 – 1990 performance removed in the previous report to 55 for this report. However, Figure 4 indicates there is an increasing failure rate per year trend line from 1991 to 2002. Further investigation will be required to predict the transformer life cycle but any suspect transformers may warrant on-line gas analysis, bushing or partial discharge (when proven) monitoring.

Since a small number of projects contribute to a large number of failures, it is very likely that the failure mechanism are the same for multiple failures on the converter transformers with the same design produced in the same period of time by the same manufacturer for one specific project. The challenge is how to prevent these failures in the future. Appropriate specification and test requirements, and thorough design review will certainly contribute to this.

The converter transformer suppliers are usually in the opinion that the existing IEC standards are already very strict, while the buyers often require a number of additional test items and acceptance criteria above IEC based on their experiences. In the end, a compromise is usually reached somewhere in between. Of course this kind of compromise varies from project to project. The reality is actually that IEC standards are used as a minimum test requirement. Perhaps the adequacy of the IEC standards for converter transformer tests should be discussed again.

In 2001 IEC 61378-2 became the standard for test requirements on converter transformers for HVDC applications covering the required routine and type test items, as well as the acceptance criteria [14]. Up to this time test requirements were mainly the same as for AC power transformers with some additional tests for the valve windings as recommended by ELECTRA [1, 15].

However, there are still some areas where the test requirements of IEC 61378-2 can be subject to different interpretations. Therefore it is important to specify the test requirement as clearly as possible and to check the test results thoroughly.

The following issues are subjects of discussions within the JTF. The detailed proposals regarding these issues will be considered by a new CIGRE JTF.

- The importance to keep a certain sequence of dielectric tests
- Whether or not should the PD acceptance level being further reduced from < 300 pC
- Test procedure of the AC applied voltage test on valve windings with partial discharge measurement
- Method of determination of harmonic losses and extra losses caused by DC bias current
- Should the temperature rise test become a routine test and should its duration be extended
- What kind of acceptance criterion of the DGA results should be used for temperature rise test
- Method of determination of winding hot spot temperature rises and the use of fiber optic technology for determination of winding hot spot temperature rise as well as on-line temperature monitoring
- The necessity and condition of performing oil flow electrification test

Clearly this work is not yet finished. It is recommended that a new CIGRE JTF A2/B4 whose scope would include the consideration of detailed test recommendations to relevant IEC and IEEE committees undertake future work.

According to the failure rate trends it could be worth to anticipate within the new JTF a review of the different means to help users to manage the HVDC transformer fleets. The new JTF should mainly

consider the ageing equipments, including the monitoring of suspicious transformers, the replacement of failed units (tests to be applied on spares, repaired units, ...). Some activities in the field of existing standards for new transformers can be also in the scope with if possible an appropriate collaboration with IEC and IEEE.

DESIGN REVIEW

JTF members recommend power transformers customers conduct design reviews with manufacturers of converter transformers to ensure there is a common understanding of the applicable standards and specification requirements. Documents that may be used as a guide for conducting the review are as follows:

- The CIGRE SC A2, WG 12.22 Report, Guidelines for conducting design reviews [16].
- The Previous Report recommendations for design review contained in Appendix I [1].
- The information documented in the Previous Test Recommendations and testing proposals defined in the New Issues About Converter Transformers sections of this report.

These documents do not include design limits or parameters. It is the responsibility of the customer to ensure sufficient expertise is available to understand, and evaluate the design.

CONCLUSIONS

The CIGRE 2000 WG B4.04, 1997 – 1998 Performance Report [2] presented at CIGRE 2000 indicated that AC-E was responsible for 84% of the FEU for all reporting HVDC systems. This created an SC B4 Member concern on converter transformer failures (the major component of AC-E). The next report [17] presented at CIGRE 2002 illustrated a higher portion of AC-E unavailability (89% of the total). The JTF was established to identify the transformer failures and probable cause. Preliminary findings presented at the CIGRE International Conference on Power Systems, September 2001, Wuhan, China [4] confirmed transformer failures are the primary component of AC-E unavailability and indicated systems without emergency spare transformers were a major contributor. The JTF continued to survey all HVDC Systems to identify the transformer failures and cause. Due to the unique HVDC applications, Converter Transformers are being analyzed extremely thoroughly as CIGRE monitors performance of HVDC systems worldwide. As shown in Appendix III, the median failure rate of 0.0095 or 105 Years per Failure indicates a sound, reliable basis of performance for Converter Transformers.

This report contains a description of each failure. Of the bushing failures, only two appear to be related to dc operation, the Pacific Intertie Expansion and Skagerrak. A number of the valve winding failures involve overheating, either because of insufficient cooling and/or because of harmonic currents. In many converter schemes the converter operates at close to or even above full rating (at reduced ambient). In this respect converter transformers may be considered to operate under the same manner of loading as generator transformers. However, converter transformers also must contend with additional losses caused by harmonic currents. As well, small dc current components in the magnetizing current lead to core saturation, which results in high levels of vibration as noted by the corresponding levels of audible noise.

Statistical data within this report includes the following:

- There are a few systems listed in Appendix III (Year commissioned through 2002) that have large number of failures – four of the 63 systems/subsystems reporting account for over 65 percent of the failures
- Median Failure Rates indicate acceptable performance however, the Median is increasing with time as illustrated in Table 5 as follows:

Table 5 - Median Failure Rates

Appendix	Report	Years	Failure Rate/Yr.
I	Previous <i>ELECTRA</i>	1972 -- 1990	0.0000
II	JTF B4.04/A2-1	1991 -- 2002	0.0069
III	Combined	1972 -- 2002	0.0095

- The previous report when compared with this JTF survey data indicates average failure rates are high and decreasing slightly. However, Figure 4 indicates there is an increasing failure rate per year trend for the 1991 – 2002 period. This needs further review to verify if the trend is unique and possibly due to a few systems having a large number of failures in 2000 and 2001.

In order to achieve acceptable HVDC converter transformer performance, JTF Members propose customers develop specifications based on this document with appropriate design limits and parameters, conduct design reviews before the start of fabrication and implement appropriate tests as agreed upon depending on the specific application, design or manufacturing methods. In addition JTF Members recommend all HVDC System owners report performance annually to CIGRE WG B4.04 with specific attention given to converter transformer performance. This recommendation is based on the commitment of CIGRE WG B4.04 to include a converter transformer performance summary with failure rate trends in future CIGRE Biennial SC B4 Technical session presentations. Achieving reasonable long-term reliability performance of converter transformers should be the goal of HVDC System users. Special consideration should be given to using good economic judgment on having emergency spare transformers, continuing use of periodic DGA and implementing on-line monitoring programs on suspect transformers.

There is also a need for CIGRE SC A2 and SC B4 to initiate a new JTF to primarily consider aging transformers together with reviewing the testing procedures described in the New Issues about Converter Transformer Tests section of this report.

ACKNOWLEDGEMENTS

JTF Members wish to thank all the contributors and users/owners of HVDC thyristor converters who have allowed us to write this report, by providing the valuable information on the performance of their thyristor converter transformers. Their comments have been most useful and have served to prepare this report that will benefit the Electrical Industry, and more precisely those who are seeking information on the reliability of HVDC thyristor converter transformers performance.

We express our sincere appreciation to CIGRE Study Committees A-2 and B-4 for support to the JTF on maintaining the schedule and the review with comments of the report.

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APPENDIX

Appendix I -- Previous Report Table II In-service performance of HVDC Converter Transformers and Oil-Cooled Smoothing Reactors *ELECTRA* No. 155 August 1994

Category->	A Bushings	B Valve Windings	C AC Windings	D Static Shields	E LTC	F Core & Magn. Shields	G Internal Conn.
Mechanical 11	3-Itaipu	2-Itaipu 1-Itaipu*		2-Durnr 1-Hamil*	1-Comerf 1-Oklaun		
Dielectric 13+2P	1-Blackw 1-IFA 2P-IFA	3-Itaipu 1-Itaipu*	5-Itaipu	1-S.Butte			1-CU
Thermal 5+35P			1-Eel Riv* 11-Eel Riv*	4-Eel Riv			24-Itaipu
Ind. Curr. 2+51P						2-Nelson 1P-Nelson 2P-Hamil 48P-Itapiu	
Operator 1					1-Inga		
Unknown 1	1-PIE*						
TOTAL 33+88P	6+2P	8+11P	5	8	3	2+51P	1+24P

Note: * = Could be also classified differently, see relevant text in report.

Appendix 1 (continued)

**Re: ELECTRA No. 155 August 1994, "In-service performance of HVDC Converter Transformers and Oil-Cooled Smoothing Reactors", (Reactors excluded in this report)
Data Range: Year Commissioned through 1990**

(5)	Thyristor Valves SYSTEM	Year(1)		Continuous Transformers(2)			Tfr.(3) Years	No. of Failures			Failure Rates(2)			
		Commissioned	kV Type(2)	MW	Tank	Wdgs		No.	Actual	Prevent	Actual	Prevent	Total	
1	Eel River	1972	80 BB	350	1	4	12	222.0	5	11	0.0225	0.0495	0.0721	
2	Skagerrak Cahora Bossa	1977	250 TL/SC	550	3	2	6	81.0	0	0	0.0000	0.0000	0.0000	
3	Vancouver Pole 2	1978	280 TL/SC	476	1	2	12	150.0	0	0	0.0000	0.0000	0.0000	
4	Hamil	1977	50 BB	110	3	3	2	27.0	1	2	0.0370	0.0741	0.1111	
5	Square Butte	1977	250 TL	550	1	2	12	162.0	1	0	0.0062	0.0000	0.0062	
6	Shin-Shinano Nelson River BP2	1977	125 BB	300	3	3	4	54.0	0	0	0.0000	0.0000	0.0000	
7	Stage1	1978	500 TL	1000	3	3	8	100.0	2	1	0.0200	0.0100	0.0300	
8	Stage2	1984	500 TL	500	3	3	4	26.0	0	0	0.0000	0.0000	0.0000	
9	Stage3	1985	500 TL	500	3	3	4	22.0	0	0	0.0000	0.0000	0.0000	
10	Hokkaido-Honshu	1980	250 TL/SC	300	3	3	4	42.0	0	0	0.0000	0.0000	0.0000	
11	CU Vyborg	1979	400 TL	1138	3	2	8	92.0	1	0	0.0109	0.0000	0.0109	
12	Inga Shaba	1982	500 TL	560	1	2	12	102.0	1	0	0.0098	0.0000	0.0098	
13	Dünnrohr	1983	145 BB	550	3	2	4	30.0	2	0	0.0667	0.0000	0.0667	
14	Gotland II	1983	150 TL/SC	320	3	2	4	30.0	0	0	0.0000	0.0000	0.0000	
15	Gotland III	1987	150 TL/SC	320	3	2	4	14.0	0	0	0.0000	0.0000	0.0000	
16	Eddy County	1983	82 BB	220	3	3	2	15.0	0	0	0.0000	0.0000	0.0000	
17	Chateauguay	1984	140 BB	1000	1	3	6	39.0	0	0	0.0000	0.0000	0.0000	
18	Oklauion	1985	82 BB	220	3	3	2	11.0	1	0	0.0909	0.0000	0.0909	
19	Blackwater	1985	56 BB	200	1	4	6	33.0	1	0	0.0303	0.0000	0.0303	
20	Madawaska	1985	130 BB	435	1	3	6	33.0	0	0	0.0000	0.0000	0.0000	
21	Itaipu BP1	1985	600 TL	3150	1	3	24	192.0	15	72	0.0781	0.3750	0.4531	
22	Itaipu BP2	1988	600 TL	3150	1	3	24	Included in BP1			0.0000	0.0000	0.0000	
23	Miles City	1985	82 BB	200	3	3	2	11.0	0	0	0.0000	0.0000	0.0000	
24	Highgate	1985	56 BB	200	3	3	2	11.0	0	0	0.0000	0.0000	0.0000	
25	PIE Upgrade	1985	500 TL	400(4)	1	2	18	99.0	0	0	0.0000	0.0000	0.0000	
26	PIE Expansion	1989	500 TL	1100	1	3	6	9.0	1	0	0.1111	0.0000	0.1111	
27	Cross Channel 1 France BP1	1986	270 SC	1000	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
28	UK BP1	1986	270 SC	1000	3	3	4	18.0	1	2	0.0556	0.1111	0.1667	
29	Cross Channel 2 France BP2	1986	270 SC	1000	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
30	UK BP2	1986	270 SC	1000	3	3	4	18.0	0	0	0.0000	0.0000	0.0000	
31	IPP	1986	500 TL	1920	1	3	12	54.0	0	0	0.0000	0.0000	0.0000	
32	Quebec/USA DesCantons	1986	450 TL	690	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
33	Commerford	1986	450 TL	690	1	3	6	27.0	1	0	0.0370	0.0000	0.0370	
34	Radisson	1990	500 TL	2250	1	3	6	3.0	0	0	0.0000	0.0000	0.0000	
35	Sandy Pond	1990	450 TL	1800	1	3	6	3.0	0	0	0.0000	0.0000	0.0000	
36	SACOI Lucciana	1987	200 TL/SC	50	1	3	3	10.5	0	0	0.0000	0.0000	0.0000	
37	Virginia Smith	1988	50 BB	200	1	3	6	15.0	0	0	0.0000	0.0000	0.0000	
38	Konti-Skan 2	1988	285 TL/SC	300	3	2	4	10.0	0	0	0.0000	0.0000	0.0000	
39	McNeill	1989	42 BB	150	3	4	2	3.0	0	0	0.0000	0.0000	0.0000	
40	Gezhouba-Nanqiao	1989	500 TL	1200	1	3	12	18.0	0	0	0.0000	0.0000	0.0000	
41	Vtndhyachal	1989	70 BB	250	3	2	8	12.0	0	0	0.0000	0.0000	0.0000	
42	Fennoskan	1989	400 TL/SC	500	1	3	6	9.0	0	0	0.0000	0.0000	0.0000	
43	Rihand-Dadri	1990	400 TL	1200	1	3	12	6.0	0	0	0.0000	0.0000	0.0000	
							Total	307	1895	33	88	0.0174	0.0465	0.0639
							Years Per Failure -->			57.41	21.53	15.66		
							42 Individual System/Subsystem	Failure Rate Per Year			Average	0.0285		
										Median	0.0000			

Notes:

1. Year commissioned taken from CIGRE WGB4.04 data.

2. Definitions

Transformer

Tank = Number of phases per tank

Wdgs = Number of windings per phase

No. = Number of transformers in service

Failures

Actual Failure = forced removal of the transformer from service because of major damages to active parts.

Prevent Failure = scheduled removal of a transformer from service because of potential failure of active parts following diagnostic testing such as gas-in-oil analysis, high insulation power factor, or failure of similar units.

3. Six months of operation are assumed for the commission year.

4. Series thyristor group 400 to 500kV at 2,000 amps per pole, 400 MW total.

5. Systems with stages commissioned in different years are listed and counted separately to properly calculate the transformer years.

Appendix I (continued)
ELECTRA No. 155 August 1994,
"In-service performance of HVDC Converter Transformers....", 1972 – 1990
RECOMMENDATIONS FOR DESIGN REVIEW

The JTF members recommend that the following aspects be covered in a careful design review, in addition to the aspects normally included, prior to the start of fabrication:

1) Valve side Bushings

Mechanical aspects in relation with the specific application including installation, possible verifications in the field, mechanical tests, and materials composition should be covered. The details of the representative mock-up and the voltage levels for the separate testing should be agreed to.

2) Currents induced in the core

If the design implies that the current must return from top to bottom between each tap winding, then the physical location of these leads must be carefully checked to minimize induced currents in the core or other metallic parts not designed for this purpose. Specific conditions for a long duration heat run type test involving tap winding current should be discussed.

3) Harmonic stray fluxes

The studies done and the steps taken to avoid large currents being induced by harmonic stray flux should be reviewed and adequate margins should be demonstrated since no pertinent factory test is usually done prior to operation in the field.

4) Short-circuit forces

For converter transformers, a short-circuit across a valve or phase-to-ground on a valve side terminal can result in a completely asymmetrical current for a few cycles and the resulting forces on the winding can be larger than for the normal power transformers where the asymmetry decays rapidly. If the valve side bushings are located outside, the probability of a phase-to-ground short-circuit is greater than if they are located inside the valve hall. External pollution related short-circuits have happened but no failures have been reported so far. Nevertheless, the JTF members recommend that this aspect be covered taking into account the control and protection strategies envisaged for the valve control during such events. If automatic firing of bypass pairs is used until the fault is cleared by the ac breakers, then a supplementary margin should be used to calculate the forces due to the short-circuit current and included in the mechanical rigidity design aspect of the windings.

5) Windings turn-to-turn insulation

The turn-to-turn insulation design, calculation of stresses, margins and manufacturing method should be discussed including paper wrapping technique. The winding terminations and connections design should also be covered thoroughly considering the need for a surrounding shield and the resulting inherent difficulties for adequate inspection during fabrication.

6) Winding cables interstrand insulation

A special attention should be paid to the interstrand insulation design if multiple strand cables are used. The manufacturing method should be discussed and specific tests during fabrication should be devised. Calculations of maximum interstrand voltages in relation with the highest repetitive di/dt's that will be imposed by the commutation process should be discussed and proper margins should be agreed to.

7) Load Tap Changers

Due to the high frequency of operation, the mechanical aspects of on-load tap changers should be reviewed thoroughly to insure that a robust design is being used (contacts wear, linkages, motor, relays, contactors, interlocks ...). Normally, some de-rating should be considered to account for the higher duty when compared to normal power transformers applications. Reference should be made to CEI/IEC 214:1989 standard.

8) Static shields

Specially for static shields around the windings, the currents induced by harmonic flux in those shields and the calculation method used to derive their maximum amplitudes should be discussed thoroughly. The mechanical robustness and stability of the shields themselves and of their electrical connections should be discussed taking into account the possible mechanical stresses during fabrication and operation. It should be verified that adequate margins are used considering that no factory test will be done that represents the actual situation with high dv/dt 's for converter transformers. If possible, tests during fabrication should also be devised.

Appendix II

JTF B4.04/A2-1

Analysis of HVDC System Converter Transformer Performance

1991 - 2002 Transformer Failures

(7)	Thyristor Valves SYSTEM	Year(1) Commissioned	Continuous Transformers(3)					Tfr.(6) Years	No. of Failures(3)		Failure Rates			
			kV Type(3)	MW	Tank	Wdgs	No.		Actual	Prevent	Actual	Prevent	Total	
1	Eel River	1972	80	BB	350	1	4	12	144.0	1	0	0.0069	0.0000	0.0069
2	Skagerrak 1&2	1977	250	TL/SC	550	3	2	8	96.0	1	1	0.0104	0.0104	0.0208
3	Skagerrak 3	1993	350	TL/SC	500	3	2	4	38.0	0	0	0.0000	0.0000	0.0000
4	Cahora Bassa Vancouver P2 Hamil	1978	280	TL/SC	476	1	2	12	144.0	0	0	No Response	0.0000	0.0000
5	Square Butte	1977	250	TL	550	1	2	12	144.0	1	0	0.0069	0.0000	0.0069
6	Shin-Shinano 1	1977	125	BB	300	3	3	4	48.0	0	0	0.0000	0.0000	0.0000
7	Shin-Shinano 2 Nelson River	1992	125	BB	300	3	3	4	42.0	0	0	0.0000	0.0000	0.0000
8	BP1 Pole 1	1992(2)	463.5	TL	900	1	3	18	189.0	2	0	0.0106	0.0000	0.0106
9	BP2, Stage1	1978	500	TL	1000	3	2	8	96.0	6	1	0.0625	0.0104	0.0729
10	BP2 Stages 2 & 3 Hokkaido-Honshu	1984-85	500	TL	1000	3	2	8	96.0	2	0	0.0208	0.0000	0.0208
11	Stage1&2	1979/80	250	TL/SC	300	3	2	4	48.0	1	0	0.0208	0.0000	0.0208
12	Stage3	1993	125	TL/SC	300	3	2	4	38.0	0	0	0.0000	0.0000	0.0000
13	CU Vyborg	1979	400	TL	1138	3	2	8	96.0	0	0	0.0000	0.0000	0.0000
14	V Stage1	1981	170	BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000
15	V Stage2	1980	170	BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000
16	V Stage3	1984	170	BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000
17	V Stage4	1999	170	BB	355	1	4	6	15.0	0	1	0.0000	0.0667	0.0667
18	Inga Shaba Gotland II	1983	150	TL/SC	320	3	2	4	48.0	0	0	No Response	0.0000	0.0000
19	Gotland III	1987	150	TL/SC	320	3	2	4	48.0	0	0	0.0000	0.0000	0.0000
20	Eddy County Chateauguay	1984	140	BB	1000	1	3	12	144.0	2	4	0.0139	0.0278	0.0417
21	Oklaunion	1985	82	BB	220	3	3	2	24.0	0	0	0.0000	0.0000	0.0000
22	Blackwater	1985	56	BB	200	1	4	6	72.0	0	0	0.0000	0.0000	0.0000
23	Madawaska	1985	130	BB	435	1	3	6	72.0	0	1	0.0000	0.0139	0.0139
24	Itaipu BP1 Itaipu BP2	1985 1988	600 600	TL TL	3150 3150	1 1	3 3	24 24	576.0	3 1	1	0.0052	0.0017	0.0069
25	Miles City	1985	82	BB	200	3	3	2	24.0	0	0	0.0000	0.0000	0.0000
26	Highgate	1985	56	BB	200	3	3	2	24.0	1	2	0.0417	0.0833	0.1250
27	PIE Upgrade	1985	500	TL	400(4)	1	2	12	144.0	1	1	0.0069	0.0069	0.0139
28	PIE Expansion Cross Channel 1	1989	500	TL	1100	1	3	12	144.0	1	0	0.0069	0.0000	0.0069
29	France BP1	1986	270	SC	1000	1	3	6	72.0	0	1	0.0000	0.0139	0.0139
30	UK BP1 Cross Channel 2	1986	270	SC	1000	3	3	4	48.0	3	1	0.0625	0.0208	0.0833
31	France BP2	1986	270	SC	1000	1	3	6	72.0	0	0	0.0000	0.0000	0.0000
32	UK BP2	1986	270	SC	1000	3	3	4	48.0	0	2	0.0000	0.0417	0.0417
33	IPP Quebec/USA(5)	1986	500	TL	1920	1	3	12	144.0	1	0	0.0069	0.0000	0.0069
34	Radisson	1990	500	TL	2250	1	3	6	72.0	1	0	0.0139	0.0000	0.0139
35	Sandy Pond	1990	450	TL	1800	1	3	6	72.0	1	0	0.0139	0.0000	0.0139
36	Nicolet SACOI 2	1991	450	TL	2138	1	3	6	66.0	0	0	0.0000	0.0000	0.0000
37	Lucciana	1987	200	TL/SC	50	1	3	3	36.0	0	0	0.0000	0.0000	0.0000
38	Codrongianos	1992	200	TL/SC	300	1	3	3	31.5	0	0	0.0000	0.0000	0.0000
39	Suvereto	1992	200	TL/SC	300	1	3	3	31.5	0	0	0.0000	0.0000	0.0000
40	Virginia Smith	1988	50	BB	200	1	3	6	72.0	1	0	0.0139	0.0000	0.0139
41	Konti Skan 2	1988	285	TL/SC	300	3	2	4	48.0	0	4	0.0000	0.0833	0.0833
42	McNeil	1989	42	BB	150	3	4	2	24.0	0	0	0.0000	0.0000	0.0000
43	Gezhouba-Nanqiao	1989	500	TL	1200	1	3	12	144.0	3	0	0.0208	0.0000	0.0208

Appendix II (continued)

JTF B4.04/A2-1															
Analysis of HVDC System Converter Transformer Performance															
1991 - 2002 Transformer Failures															
(7)	Thyristor Valves	Year(1)	Continuous			Transformers(3)			Tfr.(6)	No. of Failures(3)		Failure Rates			
	SYSTEM	Commissioned	kV	Type(3)	MW	Tank	Wdgs	No.	Years	Actual	Prevent	Actual	Prevent	Total	
	Vindhyachal											No Response			
44	Fennoskan	1989	400	TL/SC	500	1	3	6	72.0	1	3	0.0139	0.0417	0.0556	
45	Rihand-Dadri	1990	500	TL	1500	1	3	12	144.0	12	0	0.0833	0.0000	0.0833	
46	New Zealand Pole 2	1992	350	TL/SC	700	1	3	6	63.0	0	0	0.0000	0.0000	0.0000	
47	Sakuma	1993	125	BB	300	1	2	4	38.0	0	0	0.0000	0.0000	0.0000	
48	Baltic Cable	1994	450	SC	600	1	3	6	51.0	0	0	0.0000	0.0000	0.0000	
49	Welsh	1995	162	BB	600	3	4	2	14.0	1	0	0.0714	0.0000	0.0714	
50	Haenam	1996	180	SC	300	3	3	4	26.0	2	0	0.0769	0.0000	0.0769	
	Chandrapur	1998	205	BB	500	1	3	0				No Response			
51	Chandrapur-Padghe	1999	500	TL	1500	1	3	12	42.0	3	0	0.0714	0.0000	0.0714	
52	Leyte-Luzon	1998	350	TL/SC	440	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
53	Kontek	1998	400	SC	600	1	3	6	27.0	2	0	0.0741	0.0000	0.0741	
	India Nat. Experim. Line														
54	Stage 1	1989	100	TL	100	1	2	6	72.0	0	0	0.0000	0.0000	0.0000	
55	Stage 2	2000	200	TL	200	1	2	6	15.0	0	0	0.0000	0.0000	0.0000	
56	SwePol	2000	450	SC	600	1	3	6	15.0	0	2	0.0000	0.1333	0.1333	
Total									405	4357	53	25	0.0122	0.0057	0.0179
									Years Per Failure -->			82.21	174.28	55.86	
56 Individual System/Subsystem									Failure Rate Per Year			Average	0.0231		
												Median	0.0069		

Notes:

- Year commissioned taken from CIGRE WGB4.04 data.
- Nelson River BP1 transformer Years are based on thyristor operation since 1992. Mercury arc operation years (1971-1991) are excluded to conform with the *ELECTRA* No. 155 August 1994, report.
- Definitions

Transformer	Type
Tank = Number of phases per tank	TL = Overhead transmission line
Wdgs = Number of windings per phase	SC = Submarine cable(s)
No. = Number of transformers in service	BB = Back-to-Back Station
- Failures

Actual = forced removal of the transformer from service because of major damages to active parts.
Prevent = scheduled removal of a transformer from service because of potential failure of active parts following diagnostic testing such as gas-in-oil analysis, high insulation power factor, or failure of similar units.
- Series thyristor group 400 to 500kV at 2,000 amps per pole, 400 MW total.
- Des Cantons-Comerford DC transmission system is not included since it is normally not operating.
- For systems commissioned after 1990, six months of operation are assumed for the first year.
- Systems with stages commissioned in different years are listed and counted separately to properly calculate the transformer years.

Appendix III

JTF B4.04/A2-1

Analysis of HVDC System Converter Transformer Performance

Year Commissioned - 2002 Transformer Failures

(9)	Thyristor Valves SYSTEM	Year(1) Commissioned	Continuous kV Type(3)	Transformers(3) MW	Tank	Wdgs	No.	Tfr.(6) Years	of Failures(3)			Failure Rates		
									Actual	Prevent	Total	Actual	Prevent	Total
1	Eel River	1972	80 BB	350	1	4	12	366.0	6	11	0.0164	0.0301	0.0464	
2	Skagerrak 1&2	1977	250 TL/SC	550	3	2	8	177.0	1	1	0.0056	0.0056	0.0113	
3	Skagerrak 3 Cahora Bassa	1993	350 TL/SC	500	3	2	4	38.0	0	0	0.0000	0.0000	0.0000	
4	Vancouver P2	1978	280 TL/SC	476	1	2	12	294.0	0	0	0.0000	0.0000	0.0000	
5	(7) Hamil	1977	50 BB	110	3	3	2	27.0	1	2	0.0370	0.0741	0.1111	
6	Square Butte	1977	250 TL	550	1	2	12	306.0	2	0	0.0065	0.0000	0.0065	
7	Shin-Shinano 1	1977	125 BB	300	3	3	4	102.0	0	0	0.0000	0.0000	0.0000	
8	Shin-Shinano 2	1992	125 BB	300	3	3	4	42.0	0	0	0.0000	0.0000	0.0000	
9	Nelson River BP1 Pole 1	1992(2)	463.5 TL	900	1	3	18	189.0	2	0	0.0106	0.0000	0.0106	
10	BP2, Stage1	1978	500 TL	1000	3	2	8	196.0	8	2	0.0408	0.0102	0.0510	
11	BP2 Stages 2 & 3 Hokkaido-Honshu	1984-85	500 TL	1000	3	2	8	144.0	2	0	0.0139	0.0000	0.0139	
12	Stage1&2	1979/80	250 TL/SC	300	3	2	4	90.0	1	0	0.0111	0.0000	0.0111	
13	Stage3	1993	125 TL/SC	300	3	2	4	38.0	0	0	0.0000	0.0000	0.0000	
14	CU Vyborg	1979	400 TL	1138	3	2	8	188.0	1	0	0.0053	0.0000	0.0053	
15	V Stage1	1981	170 BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000	
16	V Stage2	1980	170 BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000	
17	V Stage3	1984	170 BB	355	1	4	6	72.0	0	0	0.0000	0.0000	0.0000	
18	V Stage4	1999	170 BB	355	1	4	6	15.0	0	1	0.0000	0.0667	0.0667	
19	(7) Inga Shaba	1982	500 TL	560	1	2	12	102.0	1	0	0.0098	0.0000	0.0098	
20	(8) Dümrohr	1983	145 BB	550	3	2	4	30.0	2	0	0.0667	0.0000	0.0667	
21	Gotland II	1983	150 TL/SC	320	3	2	4	78.0	0	0	0.0000	0.0000	0.0000	
22	Gotland III	1987	150 TL/SC	320	3	2	4	62.0	0	0	0.0000	0.0000	0.0000	
23	(7) Eddy County	1983	82 BB	220	3	3	2	15.0	0	0	0.0000	0.0000	0.0000	
24	Chateauguay	1984	140 BB	1000	1	3	12	183.0	2	4	0.0109	0.0219	0.0328	
25	Oklauion	1985	82 BB	220	3	3	2	35.0	1	0	0.0286	0.0000	0.0286	
26	Blackwater	1985	56 BB	200	1	4	6	105.0	1	0	0.0095	0.0000	0.0095	
27	Madawaska	1985	130 BB	435	1	3	6	105.0	0	1	0.0000	0.0095	0.0095	
28	Itaipu BP1	1985	600 TL	3150	1	3	24	768.0	18	73	0.0234	0.0951	0.1185	
29	Miles City	1985	82 BB	200	3	3	2	35.0	0	0	0.0000	0.0000	0.0000	
30	Highgate	1985	56 BB	200	3	3	2	35.0	1	2	0.0286	0.0571	0.0857	
31	PIE Upgrade	1985	500 TL	400(4)	1	2	12	243.0	1	1	0.0041	0.0041	0.0082	
32	PIE Expansion	1989	500 TL	1100	1	3	12	153.0	2	0	0.0131	0.0000	0.0131	
33	Cross Channel 1 France BP1	1986	270 SC	1000	1	3	6	99.0	0	1	0.0000	0.0101	0.0101	
34	UK BP1	1986	270 SC	1000	3	3	4	66.0	4	3	0.0606	0.0455	0.1061	
35	Cross Channel 2 France BP2	1986	270 SC	1000	1	3	6	99.0	0	0	0.0000	0.0000	0.0000	
36	UK BP2	1986	270 SC	1000	3	3	4	66.0	0	2	0.0000	0.0303	0.0303	
37	IPP	1986	500 TL	1920	1	3	12	198.0	1	0	0.0051	0.0000	0.0051	
38	(5) Quebec/USA DesCantons	1986	450 TL	690	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
39	Commerford	1986	450 TL	690	1	3	6	27.0	1	0	0.0370	0.0000	0.0370	
40	Radisson	1990	500 TL	2250	1	3	6	75.0	1	0	0.0133	0.0000	0.0133	
41	Sandy Pond	1990	450 TL	1800	1	3	6	75.0	1	0	0.0133	0.0000	0.0133	
42	Nicolet	1991	450 TL	2138	1	3	6	66.0	0	0	0.0000	0.0000	0.0000	
43	SACOI 2 Lucciana	1987	200 TL/SC	50	1	3	3	46.5	0	0	0.0000	0.0000	0.0000	
44	Codrongianos	1992	200 TL/SC	300	1	3	3	31.5	0	0	0.0000	0.0000	0.0000	
45	Suvereto	1992	200 TL/SC	300	1	3	3	31.5	0	0	0.0000	0.0000	0.0000	
46	Virginia Smith	1988	50 BB	200	1	3	6	87.0	1	0	0.0115	0.0000	0.0115	

Appendix III (continued)

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Analysis of HVDC System Converter Transformer Performance Year Commissioned - 2002 Transformer Failures

(9) SYSTEM	Thyristor Valves	Year(1) Commissioned	Continuous Transformers(3)				Tfr.(6) of Failures(3)			Failure Rates					
			kV	Type(3)	MW	Tank	Wdgs	No.	Years	Actual	Prevent	Actual	Prevent	Total	
47	Konti Skan 2	1988	285	TL/SC	300	3	2	4	58.0	0	4	0.0000	0.0690	0.0690	
48	McNeil	1989	42	BB	150	3	4	2	27.0	0	0	0.0000	0.0000	0.0000	
49	Gezhouba-Nanqiao	1989	500	TL	1200	1	3	12	162.0	3	0	0.0185	0.0000	0.0185	
50 (7)	Vindhyachal	1989	70	BB	250	3	2	8	12.0	0	0	0.0000	0.0000	0.0000	
51	Fennoskan	1989	400	TL/SC	500	1	3	6	81.0	1	3	0.0123	0.0370	0.0494	
52	Rihand-Dadri	1990	500	TL	1500	1	3	12	150.0	12	0	0.0800	0.0000	0.0800	
53	New Zealand Pole 2	1992	350	TL/SC	700	1	3	6	63.0	0	0	0.0000	0.0000	0.0000	
54	Sakuma	1993	125	BB	300	1	2	4	38.0	0	0	0.0000	0.0000	0.0000	
55	Baltic Cable	1994	450	SC	600	1	3	6	51.0	0	0	0.0000	0.0000	0.0000	
56	Welsh	1995	162	BB	600	3	4	2	14.0	1	0	0.0714	0.0000	0.0714	
57	Haenam	1996	180	SC	300	3	3	4	26.0	2	0	0.0769	0.0000	0.0769	
	Chandrapur											No Response			
58	Chandrapur-Padghe	1999	500	TL	1500	1	3	12	42.0	3	0	0.0714	0.0000	0.0714	
59	Leyte-Luzon	1998	350	TL/SC	440	1	3	6	27.0	0	0	0.0000	0.0000	0.0000	
60	Kontek	1998	400	SC	600	1	3	6	27.0	2	0	0.0741	0.0000	0.0741	
	India Nat. Experim. Line														
61	Stage 1	1989	100	TL	100	1	2	6	72.0	0	0	0.0000	0.0000	0.0000	
62	Stage 2	2000	200	TL	200	1	2	6	15.0	0	0	0.0000	0.0000	0.0000	
63	Swepol	2000	450	SC	600	1	3	6	15.0	0	2	0.0000	0.1333	0.1333	
Total									445	6252	86	113	0.0138	0.0181	0.0318
									Years Per Failure -->			72.7	55.3	31.4	
63 Individual System/Subsystem											Average		0.0252		
											Failure Rate Per Year		Median	0.0095	

Notes:

1. Year commissioned taken from CIGRE WGB4.04 data.
2. Nelson River BP1 transformer Years are based on thyristor operation since 1992. Mercury arc operation years (1971-1991) are excluded to conform with the *ELECTRA* No. 155 August 1994, report.
3. Definitions

Transformer	Type
Tank = Number of phases per tank	TL = Overhead transmission line
Wdgs = Number of windings per phase	SC = Submarine cable(s)
No. = Number of transformers in service	BB = Back-to-Back Station

Failures

Actual = forced removal of the transformer from service because of major damages to active parts.

Prevent = scheduled removal of a transformer from service because of potential failure of active parts following diagnostic testing such as gas-in-oil analysis, high insulation power factor, or failure of similar units.
4. Series thyristor group 400 to 500kV at 2,000 amps per pole, 400 MW total.
5. Des Cantons-Comerford DC transformer performance for 1991-2002 not included since the terminals are normally not operating.
6. Six months of operation are assumed for the commission year.
7. Excludes 1991-2002 performance since there was no response to the JTF survey.
8. Dürnröhr and other de-commissioned systems are excluded from 1991-2002 performance data.
9. Systems with stages commissioned in different years are listed and counted separately to properly calculate the transformer years.