ELECTRIC POWER RESEARCH INSTITUTE

Life Extension Guidelines of Existing HVDC Systems

1012516

Life Extension Guidelines of Existing HVDC Systems

1012516

Technical Update, March 2007

EPRI Project Manager

R. Adapa

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

High Energy Inc. (Prime Contractor)

Electranix Corporation

Indoor Environmental Solutions, Inc.

Lavier Engineering, LLC

Lone Wolf Engineering, LLC

Manitoba HVDC Research Centre

Winfield Enterprise, LLC

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

High Energy Inc.
625 Hudson Street
Denver, CO 80220

Principal Investigator
R. Johnson

Electranix Corporation
107-865 Waverley Street
Winnipeg, Manitoba R3T 5P4 Canada

Principal Investigator
D. Woodford

Indoor Environmental Solutions, Inc.
10227 West Roxbury Avenue
Littleton, CO 80127

Principal Investigator
W. Mele

Lavier Engineering, LLC
2300 East 13th Street
The Dalles, OR 97058

Principal Investigator
B. Lavier

Lone Wolf, LLC
10020 La Paz Drive N.W.
Albuquerque, NM 87114

Principal Investigator
G. Wolf

Manitoba HVDC Research Centre, Inc
244 Cree Crescent
Winnipeg, Manitoba R3J 3W1 Canada

Principal Investigator
R. Wachal

Winfield Enterprise, LLC
1660 Winfield Circle
Lakewood, CO 80215

Principal Investigator
D. Torgerson

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Life Extension Guidelines of Existing HVDC Systems, EPRI, Palo Alto, CA: 2007, 1012516.

ABSTRACT

High Voltage Direct Current (HVDC) converter stations and transmission lines represent a significant investment and source of revenue for the electric utilities owning them. Many installations are approaching or exceeding 30 years of service. Components are aging. Manufacturers may no longer be in business or have merged and consolidated their resources with different business priorities. Engineering and technical staffs are retiring and the knowledge base is being lost. Technology is advancing making existing technology obsolete or so dated it no longer functions efficiently. Owners and Operators are in need of guidelines describing an approach to extend the life of these facilities. These procedures can be as simple as selective refurbishment/replacement of equipment or as complex as the complete replacement of the scheme. In addition, maintenance practices can impact the facility life expectancy and are discussed in the guideline. The Owners and Operators of these facilities are now being faced with the decision of what action to pursue. In most cases, the transmission path provided by operating HVDC converter stations is not only profitable but is needed for reliability; life extension is not an option, it is a necessity. HVDC converter station equipment and systems are complex and have varying lifetimes. With an infrastructure of 25 to 30 years of service, much of the facility equipment needs attention. It is in need of replacement or refurbishment. This guideline is intended to serve as a resource to the Owners and Operators for the development of program for the assessment of their aging HVDC facility and to assist in developing a program of maintenance to enhance the life of the facility.

ACKNOWLEDGEMENTS

This interim report was prepared under the EPRI project management of Dr. Rambabu Adapa. High Energy Inc. led by Ruth Johnson directed the project team contributing to this effort including Dennis Woodford of Electranix Corporation, Bill Mele of Indoor Environmental Solutions, Inc., Bruce Lavier of Lavier Engineering, LLC, Gene Wolf of Lone Wolf Engineering, LLC, Randy Wachal of Manitoba HVDC Research Centre and Duane Torgerson of Winfield Enterprise, LLC.

This report has benefited from discussion held during a project kick-off meeting in Denver, Colorado that was attended by approximately 19 interested utilities and project participants with another 5 participants interacting via a conference phone connection. A summary of this meeting and list of attendees is included in Appendix A.

CONTENTS

1

LIST OF HVDC CONVERTER STATIONS

Introduction

The objective of the "List of HVDC Converter Station" Chapter is to identify all of the known High Voltage Direct Current (HVDC) converter stations currently in service in the world. These stations have been identified from publications by the Institute of Electrical and Electronic Engineers (IEEE) and the Comité International des Grands Réseaux Electrique (CIGRE). Most recently this list has been compiled and updated by the IEEE's Power Engineering Society's (PES) Transmission and Distribution Committee's HVDC and FACTS Subcommittee. The updated list was distributed during the HVDC and FACTS Subcommittee's meeting held during the June 2006 the PES General Meeting in Montreal, Quebec, Canada.

Using this list, a simple survey was sent out to operators of the HVDC converter stations that were identified as being upgraded or where life extension activities have been undertaken. A summary description is provided from this list. Known information and published descriptions are used for this compilation, starting with the published CIGRE report "Guide for Upgrading Transmission Systems with HVDC Transmission" SC 14 WG 14.11, 1998 [1].

The life extension activities summarized herein serve as a reference for those contemplating such activities at their own HVDC converter stations. The actual converter stations included in the summary are not specifically identified.

Existing HVDC Facilities

HVDC converter stations that are included in the updated IEEE list are summarized in Table 1-1 and Appendix B:

Table 1-1
Summary of HVDC Schemes in the World

Classification of HVDC Schemes	Number
Number of HVDC schemes with overhead transmission lines	24
Number of HVDC schemes with undersea cables (with thyristor converters)	28
Number of back-to-back schemes	34
Number of voltage sourced converter transmission schemes	5
Total number of operating HVDC schemes (2006)	91
Number of de-commissioned HVDC schemes	10
Number of HVDC projects in construction, planned or future	37

The distribution of these schemes throughout the world, by regions, is assembled in Table 1-2.

Table 1-2

Regions of the world where HVDC transmission schemes are installed

Regions of the World	Number of DC Links	Average Age of Converters (Years)
North America	25	22
Northern Europe	13	17
Europe and Mediterranean	6	14
India	9	9
China	6	9
South America	7	14
North East Asia	10	15
South East Asia	2	7
Russia	5	24
Africa	2	27
Australia and New Zealand	6	14

The largest numbers of HVDC converter stations are located in the U.S.A. and Canada, followed by northern Europe. India and China are currently building the largest rated converters for HVDC interconnections between asynchronous regions.

The oldest operating HVDC converter stations are located in Africa and Russia. North America has the largest number of aging HVDC converter stations in service.

HVDC Life Extension Activities

A simple survey was sent to operators in eight countries to determine the HVDC life extension activities that have begun or were completed. Replies were received from 26 HVDC interconnections. The survey requested whether life extension activities had been started on the interconnection's major equipment. The major equipment included converter transformers, valves, valve electronics, controls, valve cooling, ac filters, smoothing reactors and switches/circuit breakers.

For each piece of major equipment, the life extension activities are summarized over time in the following charts. Each chart show for five year spans the percentage of the HVDC converter stations commissioned in that span that have the designated equipment refurbished or replaced. Table 1-3 shows the number of converter stations reported for each five year span.

Table 1-3
Converter stations reporting life extension activities each 5 year span

5 Year Span	65-69	70-74	75-79	80-84	85-89	90-94	95-99	00-05
No. of Converter Stations	2	2	5	2	7	1	2	5

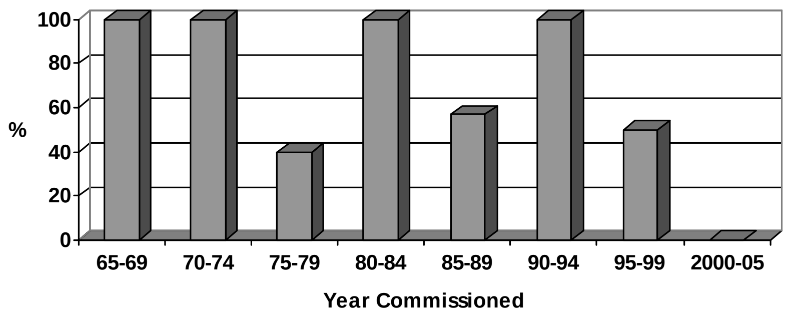

Figure 1-1
Life extension activities for converter transformers undertaken since commissioning

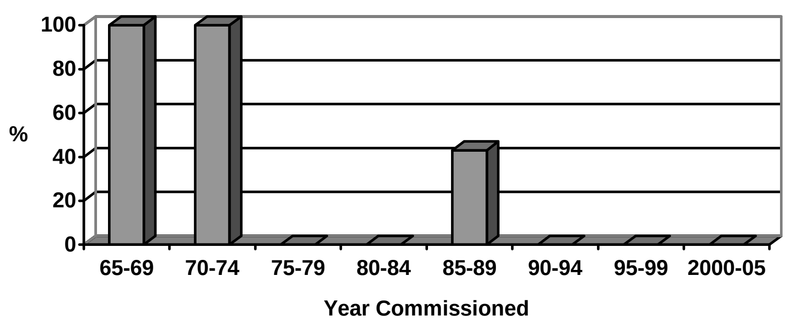

Figure 1-2
Life extension activities for converter valves undertaken since commissioning

The valve activities prior to 1974 were the replacement of mercury arc valves with thyristor valves. Two thyristor schemes have also undergone the complete replacement of their thyristor valves in the period from 1985-89.

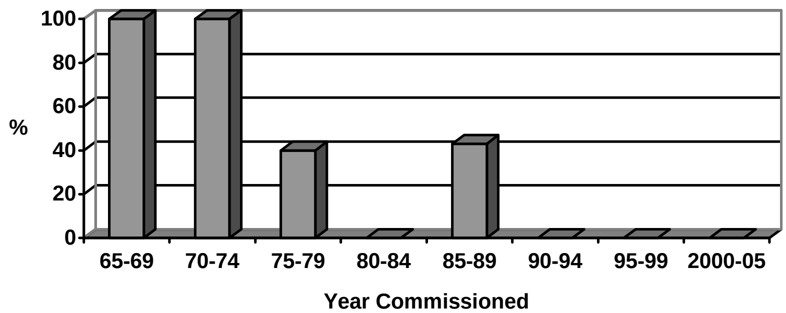

Figure 1-3
Life extension activities for valve electronics including valve base electronics

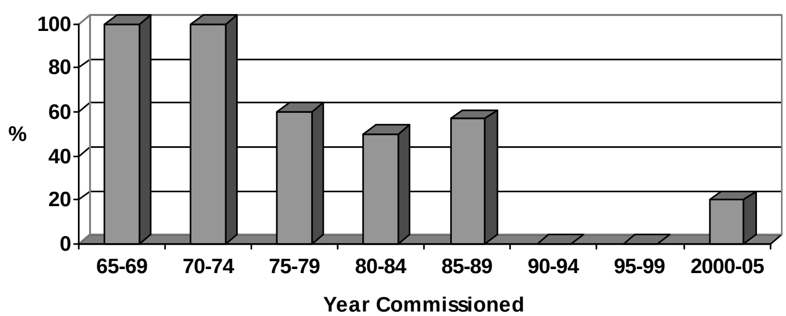

Figure 1-4
Life extension activities for HVDC system controls undertaken since commissioning

The survey revealed an interesting data point. For the period between 2000 and 2005, the activity reported described the replacement of the control system in the first of two back-to-back HVDC converters to match the controls of the second, with both built by the same supplier at the same location.

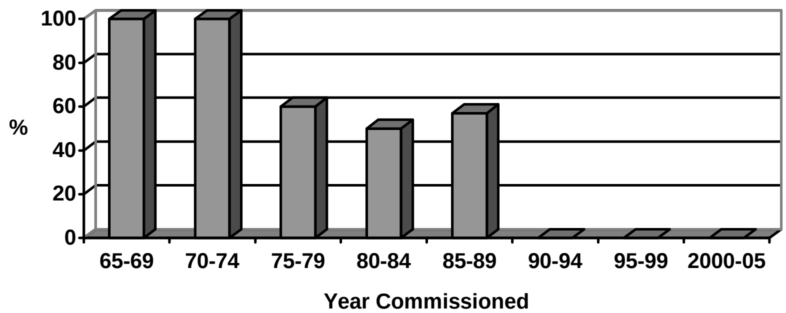

Figure 1-5
Life extension activities for HVDC valve cooling undertaken since commissioning

Comparison of figures 1-4 and 1-5 indicate that life extension activities of HVDC controls and valve cooling equipment are similar.

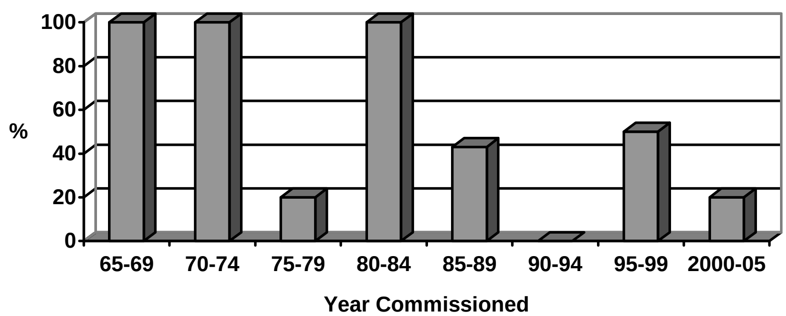

Figure 1-6
Life extension activities for ac filters undertaken since commissioning

The recent life extension activities reported for the ac filters shown in Figure 1-6 for the years 1995-99 and 2000-05 were included as upgrades and replacement of measurement and protection systems.

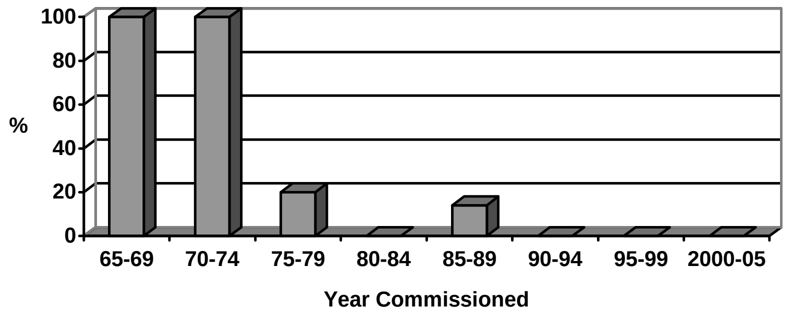

Figure 1-7
Life extension activities for dc smoothing reactors since commissioning

Although a report on dc filters was not specifically requested in the life extension survey, it was noted in one case that the dc filters were more of a problem than the ac filters. The original dc filters were replaced because of the high frequency of outages related to the filters. Within a few years, the replacement capacitors were all replaced again and then individually as they continued to fail. At the other end, they have been replaced one additional time during other life extension project. The dc filters installed at each end of the HVDC transmission lines are not redundant and are therefore critical to the operation of the HVDC system.

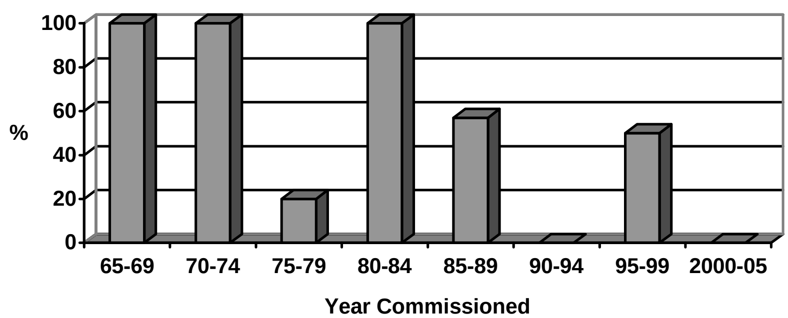

Figure 1-8
Life extension activities for ac switches and circuit breakers since commissioning

Summary

The results from the survey of the 24 HVDC interconnections indicated that most converter stations older than 10 years are undergoing some form of life extension upgrade. Most of the owners of HVDC transmission systems have expressed an interest in extending the life of their investment. They have also indicated they have maintenance programs in place to keep the stations operational. The older projects such as the Pacific HVDC Intertie and the Nelson River bipoles have substantial maintenance programs in place. They also continue to upgrade their investments to ensure the systems continue to operate reliably [3]. In addition, the survey results from the Nelson River bipoles concluded that: "It is safe to say Nelson River has a continual life extension project active in one form or another." This statement accurately reflects the intent of the owners of most of the HVDC projects responding. The lifetime of converter stations require the stations to be extended as long as the associated transmission lines remain serviceable.

It is worthwhile to note that 10 HVDC transmission schemes have been decommissioned as indicated in Table 1-1. The reasons for decommissioning vary, and include being replaced by larger more efficient transmission lines, small ratings that served little purpose in networks that outgrew them and poor maintenance resulting in deteriorating reliability.

From the results of the survey on life extension activities, the following summary observations are made:

- HVDC projects with mercury arc valves commissioned prior to the early 1970's have now, for the most part, had replacement thyristor valves installed. Even some older projects with thyristor valves have replaced or are intending to replace those thyristor valves with new thyristor valves.

- Converter transformers are key elements in HVDC systems. In some HVDC projects the transformers have been replaced or undergone rebuilding to correct design problems. There is also an unresolved debate on what has caused performance problems or the rapid aging of the converter transformers. In some HVDC schemes however, the converter transformers have aged exceedingly well and have not been a problem.

- When converter valves or thyristors have been replaced, the converter electronics including the valve base electronics have been replaced also. When HVDC control systems are replaced, the valves are typically not replaced. The valve based electronics, if operating satisfactorily, may not be replaced with control system replacement either.

- Control systems of the early HVDC transmission systems were analog based and usually lasted as long as the valve systems. Recent trends of maintenance staff retiring have had an impact on those systems. Unfortunately those retiring are the most familiar with the analog control systems. This has led to control system replacements that are digital, programmable, and supportable by both the owner and the manufacturer. The useful lifetime or the ability of a supplier to continue supporting digital control systems is a pertinent question being asked by HVDC transmission owners.

- Wet valve cooling systems require consideration. Typically they are a source of high maintenance. They also require replacement at an accelerated rate compared to other system at a converter station. They are one of the major equipments that impact life extension requirements. Some HVDC facilities are considering or have replaced wet heat exchanger systems with dry (air cooled) systems to reduce maintenance, remove hazardous chemicals, and eliminate water usage. Liquids are still the cooling medium of choice for valve cooling by the manufacturers.

- AC filter life extension is often focused in replacement capacitors. In earlier systems this was precipitated by the need to phase out capacitor cans containing polychlorinated biphenyls (PCBs). Capacitors for dc filters however are designed differently from ac filters and are damaged or their useful life reduced with high speed polarity reversals. Commutation failure is a common cause of transient voltage reversals and affects the life of dc filter capacitors.

- Smoothing reactors have fared well over time, suggesting a 30+ year lifetime.
- Switchgear, particularly where switched capacitor, filter and reactor banks are concerned have required replacement or refurbishment due to the constant use.

Chapter References

[1] Guide for Upgrading Transmission Systems with HVDC Transmission, CIGRE Brochure Ref. 127, SC14, WG 14.11, 1998.

[2] J.A.C. Forrest, B. Allard, Thermal Problems Caused by Harmonic Frequency Leakage Fluxes in Three-Phase, Three-Winding Converter Transformers, IEEE Transactions on Power Delivery, Vol. 19, No. 1, January 2004, pp 208-213.

[3] J.J. Cochrane, M.P. Emerson, J.A. Donahue, G. Wolf, A Survey of HVDC Operating and Maintenance Practices and their Impact on Reliability and Performance, IEEE Transactions on Power Delivery, Vol. 11, No. 1, January 1996, pp 514-518.

[4] I. Vancers, F.J. Hormozi, A Summary of North American HVDC Converter Station Reliability Specifications, IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993, pp 1114-1122.

[5] P. Lips, Water Cooling of HVDC Thyristor Valves, IEEE Transactions on Power Delivery, Vol. 9, 1994, pp 1930-1937.

2
CIGRE HVDC SYSTEM PERFORMANCE DATA

Introduction

This chapter summarizes key HVDC system performance metrics. They are based upon a review of published CIGRE HVDC reliability data gathered throughout the world from 1993 to 2004 [1, 2, 3, 4, 5, 6]. The summary information includes data on energy availability, energy utilization, forced energy unavailability, scheduled energy unavailability, thyristor cell failure rates and an examination of equipment categories resulting in outages or loss of HVDC system capacity. CIGRE's HVDC reliability data is reported worldwide using a protocol for collecting operational performance of HVDC systems developed by Advisory Group B4.04 of CIGRE Study Committee B4 (HVDC and Power Electronics). The CIGRE protocol is published for reference in IEEE Std. 1240, IEEE Guide for the Evaluation of the Reliability of HVDC Converter Stations [7].

Performance Metrics

The CIGRE performance data that have been reviewed represents information compiled from 51 different converter stations throughout the world over a period of twelve years. The converter station's commissioning dates begin in 1972 and extend through 2004, with ratings between 150 MW to 3,000 MW. The statistics presented in this Chapter have been grouped into the following three age groups based on their commissioning dates:

- Age < 10-years
- 10-years ≤ Age < 20-years
- Age ≥ 20-years

HVDC transmission line statistics have not been included.

Energy Availability

Energy availability (EA) statistics reported by CIGRE indicate a measure of the energy, which could have been transmitted except for limitations of capacity. These limitations are due primarily to scheduled and forced outages of converter station equipment, dc transmission lines, or cables. Factors that are involved in the CIGRE calculation of EA include the HVDC system's total equivalent forced and scheduled outage hours (EOH) and period hours (PH) for the reporting period. EA is expressed as a percentage based on the following formula:

$$EA\ (\%) = 100 - (EOH)/(PH) \times 100$$

The EA data is provided in the 1993-2004 CIGRE reports for 51 HVDC systems, each with its own energy availability statistics. The CIGRE data has been sorted into the three age groups shown in Table 2-1. It is interesting to note that the data defines an average and median age of 15-years for the converters. The published MW rating and EA for each of the 51 HVDC systems is used to calculate total maximum energy ratings and total energy available ratings. These are used to obtain combined average energy availability for each age group (see Table 2-1 and Figure 2-1).

Table 2-1
Summary of HVDC System Energy Availability

Age Group of Systems (Years)	Total Rating of Stations Reporting (MW)	Total Maximum Energy Ratings (MW-Hr)	Total Energy Available Ratings (MW-Hr)	Average Energy Availability (%)
Age < 10-years	14,700	250,888,800	234,975,516	93.66%
10-years ≤ Age < 20-years	21,693	1,092,872,880	1,031,897,322	94.42%
Age ≥ 20-years	13,994	998,432,184	942,373,496	94.39%
Average/Median Age = 15-years				94.32%

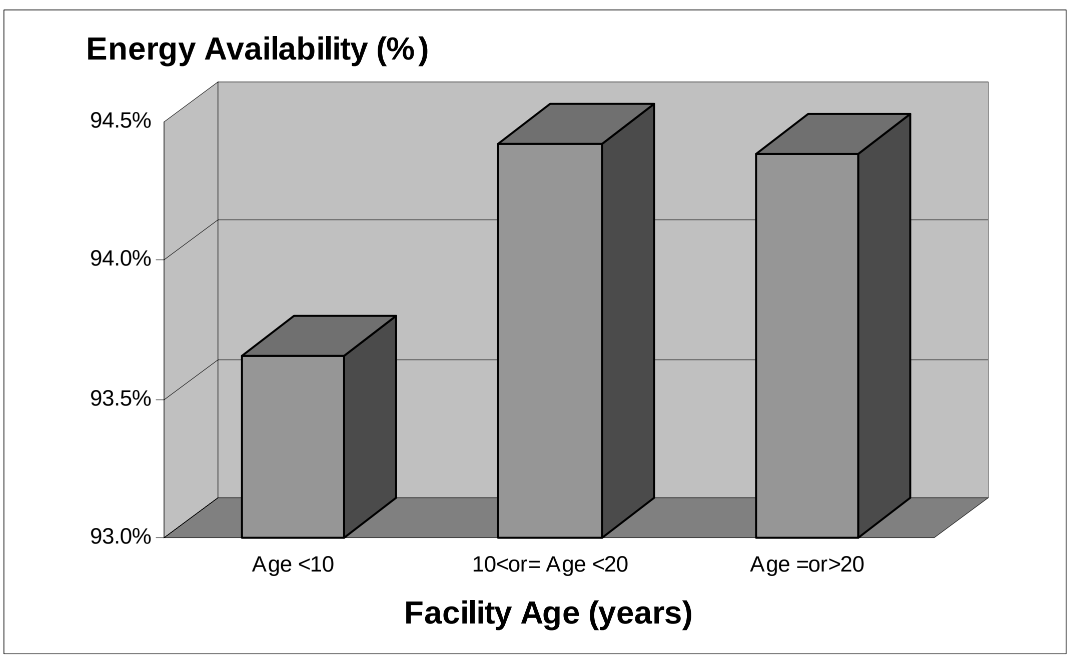

Figure 2-1
HVDC System Energy Availability (1993-2004)

Energy Utilization

Energy utilization (U) statistics reported by CIGRE represents a measure of the energy actually transmitted over the HVDC system. Factors that are involved in the calculation of U include the HVDC systems maximum continuous capacity (Pm), total energy transmitted and period hours (PH) for the reporting period. U is expressed as a percentage based on the following formula:

U (%) = [(total energy transmitted)/(Pm x PH)] x 100

The CIGRE energy utilization data has been sorted into the three age groups shown in Table 2-2. The published MW rating and U for each of the 50 HVDC systems that reported their utilization data is used to calculate total maximum energy utilization ratings and total energy utilization ratings. These are used to calculate the combined average energy availability for each age group (see Table 2-2 and Figure 2-2). It should be noted that one of the 51 HVDC systems reporting EA statistics did not report their U statistics.

Table 2-2
Summary of HVDC System Energy Utilization

Age Group of Systems (Years)	Total Rating of Stations Reporting (MW)	Total Maximum Energy Utilization Ratings (MW-Hr)	Total Energy Utilization Ratings Achieved (MW-Hr)	Average Energy Utilization (%)
Age < 10-years	14,700	250,888,800	128,672,702	51.3%
10-years ≤ Age < 20-years	21,693	1,092,872,880	564,858,547	51.7%
Age ≥ 20-years	12,994	971,924,424	580,570,717	59.7%
Average/Median Age = 15-years				55.0%

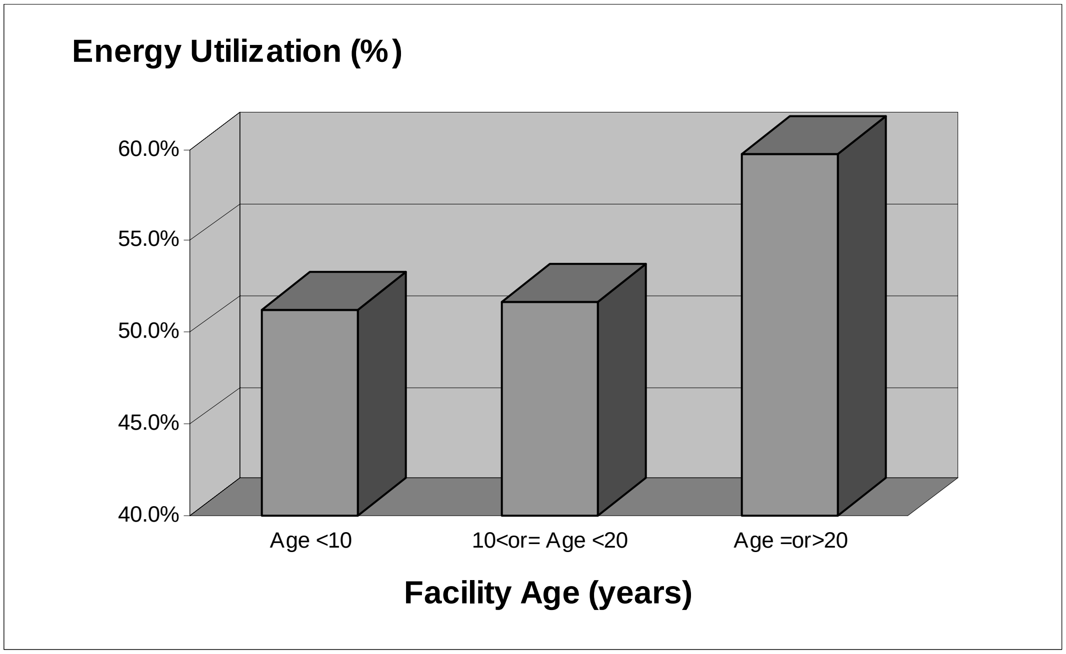

Figure 2-2
CIGRE HVDC System Energy Utilization (1993-2004)

Forced and Scheduled Energy Unavailability

Energy unavailability is a measure of the energy, which could not be transmitted due to outages. The HVDC system is unavailable for operation at its maximum capacity due to an event directly related to converter station equipment or dc transmission line. AC system related outages are not included in HVDC system unavailability calculations. Additionally, outages taken for major reconfiguration or upgrading of a converter station is not reported.

A scheduled outage is one that is either planned or which can be deferred until a suitable time. Scheduled outages are typically planned well in advance for preventive maintenance purposes and may be an indication of annual maintenance activities. If a scheduled outage is extended due to additional work, which would otherwise have lead to a forced outage, the excess period time is considered as a forced outage. Forced outages are events in which the converter station equipment is unavailable for normal operation but is not in the scheduled outage condition.

Forced energy unavailability (FEU) is calculated by determining the equivalent forced outage hours (EFOH) for the period hours (PH) based on the following formula:

FEU (%) = (EFOH/PH) x 100

Likewise the scheduled energy unavailability (SEU) is calculated by determining the equivalent schedule outage hours (ESOH) for the period hours (PH) based on the following formula:

SEU (%) = (ESOH/PH) x 100

It should be noted that on an annual basis the PH are 8760 hours except during leap years when PH are 8784 hours.

The CIGRE forced and scheduled energy unavailability data is sorted into the three age groups shown in Table 2-3 and Table 2-4. The published MW rating and corresponding FEU and SEU for each of the 51 HVDC systems reporting has been used to calculate the total maximum energy ratings and total energy forced and scheduled unavailability ratings. These are used to obtain the combined average energy unavailability for each age group (see Table 2-3, Table 2-4, Figure 2-3 and Figure 2-4).

Table 2-3
Summary of HVDC System Forced Energy Unavailability

Age Group of Systems (Years)	Total Rating of Stations Reporting (MW)	Total Maximum Energy Ratings (MW-Hr)	Total Forced Energy Unavailable (MW-Hr)	Average Forced Energy Unavailability (%)
Age < 10-years	14,700	235,120,800	5,232,983	2.2%
10-years ≤ Age < 20-years	21,693	1,082,360,880	18,104,685	1.7%
Age ≥ 20-years	13,994	998,432,184	15,394,243	1.5%
Average/Median Age = 15-years				1.7%

Table 2-4
Summary of HVDC System Scheduled Energy Unavailability

Age Group of Systems (Years)	Total Rating of Stations Reporting (MW)	Total Maximum Energy Ratings (MW-Hr)	Total Scheduled Energy Unavailable (MW-Hr)	Average Scheduled Energy Unavailability (%)
Age < 10-years	14,700	235,120,800	8,301,170	3.5%
10-years ≤ Age < 20-years	21,693	1,082,360,880	35,566,098	3.3%
Age ≥ 20-years	13,994	998,432,184	38,680,357	3.9%
Average/Median Age = 15-years				3.6%

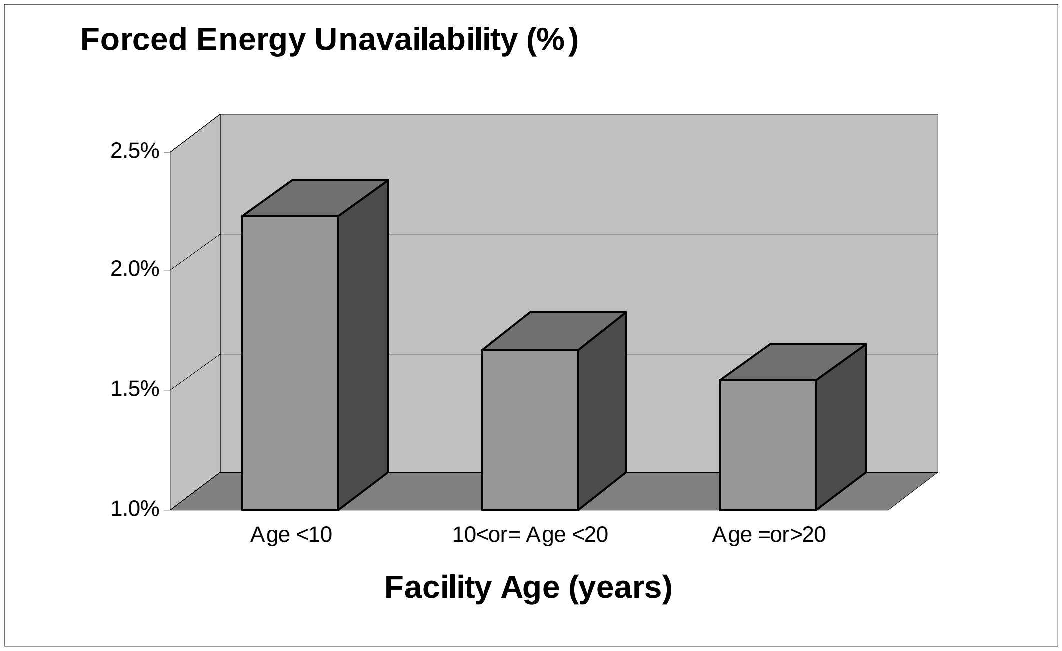

Figure 2-3
CIGRE HVDC System Forced Energy Unavailability (1993-2004)

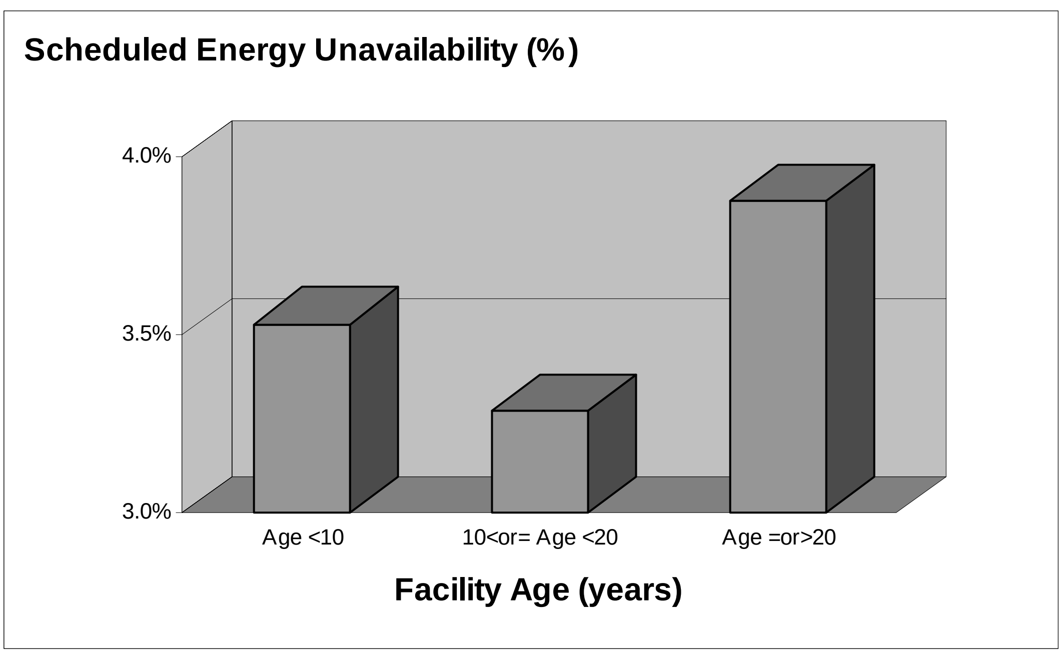

Figure 2-4
CIGRE HVDC System Scheduled Energy Unavailability

Thyristor Cell Failure Rates

The CIGRE data is used to calculate thyristor cell failure rates. It combines the total number of cells installed in each facility with the number of years for which data was reported to calculate the total thyristor cell-years included in Table 2-5. This data is sorted into the three age groups shown in Table 2-5. The published total thyristor cell failures in Table 2-5 are used to determine the annual percent cell failures with the trends indicated in Figure 2-5 for each age group.

Note: CIGRE defines a thyristor cell as an individual thyristor with its associated auxiliary circuits.

Table 2-5
Summary of HVDC System Thyristor Cell Failure Rates

Age Group of Systems (Years)	Total Rating of Stations Reporting (MW)	Total Thyristor Cell-Years Reported (Cell-Years)	Total Thyristor Cell Failures Reported (Cells)	Annual Percent Cell Failures (%)
Age < 10-years	6,900	34,992	18	0.051%
10-years ≤ Age < 20-years	15,505	341,160	243	0.071%
Age ≥ 20-years	12,009	872,208	1,111	0.127%
Average/Median Age = 15-years				0.110%

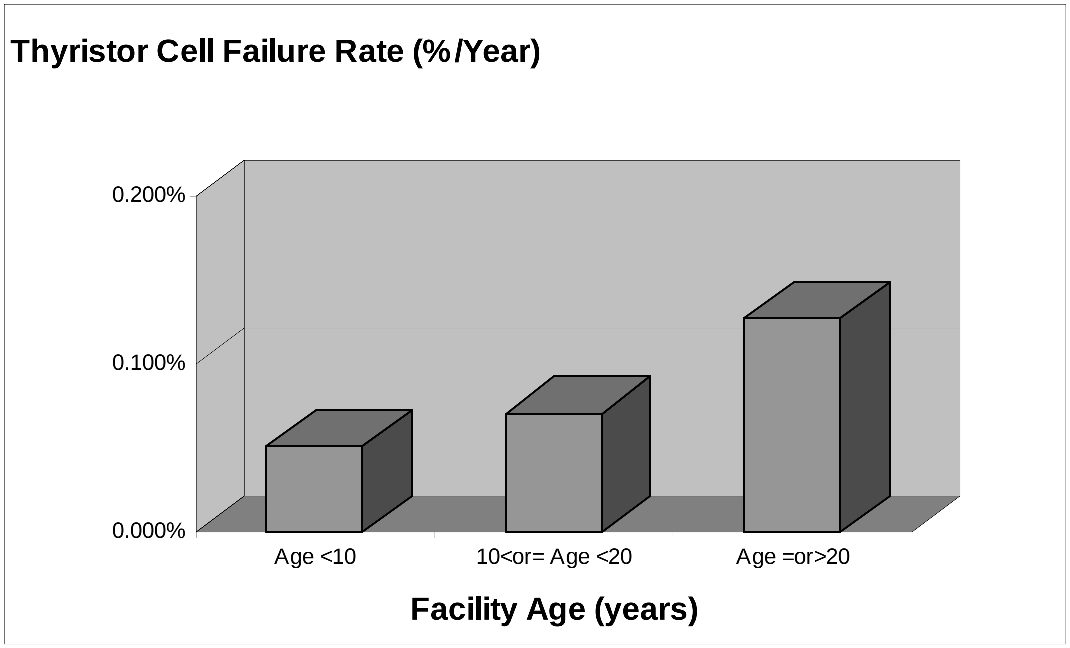

Figure 2-5
CIGRE HVDC System Thyristor Cell Failure Rate

Forced Outage Statistics

The CIGRE reports define the total number of forced outage events (2,639) and corresponding total forced outage hours (39,563) between 1993 and 2004. CIGRE further defined outages for each of the equipment categories listed below. These statistics do not include outages due to dc transmission lines and cables, which would have added 478 outage events and 12,741 hours.

- AC and Auxiliary Equipment (AC-E): This category covers loss of station capacity resulting from all ac main equipment at a converter station. It starts at the incoming ac connection and extends to the external connection on the valve winding bushing of the converter transformer. This equipment includes ac filters, shunt compensation, PLC filters, ac control and protection, converter transformers, synchronous compensators, auxiliary equipment, auxiliary power, cooling systems, civil works, ac circuit breakers, disconnect switches, grounding switches, surge arresters buswork, insulators, etc.
- Valves (V): This category covers loss of station capacity as a result of all parts of a thyristor valve including all auxiliaries and components integral with the valve. The valve cooling system associated with a valve failure includes only that part of the cooling system at high potential.
- Control and Protection (C&P): This category covers loss of station capacity due to equipment used for the control, monitoring and protection of the overall HVDC system.
- DC Equipment (DC-E): This category covers loss of station capacity due to all other HVDC equipment, including dc smoothing reactors, dc switching equipment, dc ground electrode, dc surge arresters, wall bushings, current and voltage measuring devices, insulators, etc…
- Other (O): Loss of station capacity or an extension of outage durations due to human error or unknown causes is assigned to this category.

The percentage of total number of forced outage events and equivalent forced outage hours for each category are shown in Figure 2-6 and Figure 2-7 respectively. The 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. Of particular interest is the fact that while converter transformer outages account for approximately 146 events in the AC-E category of Figure 2-6, they also account for approximately 23,052 of the forced outage hours shown in Figure 2-7.

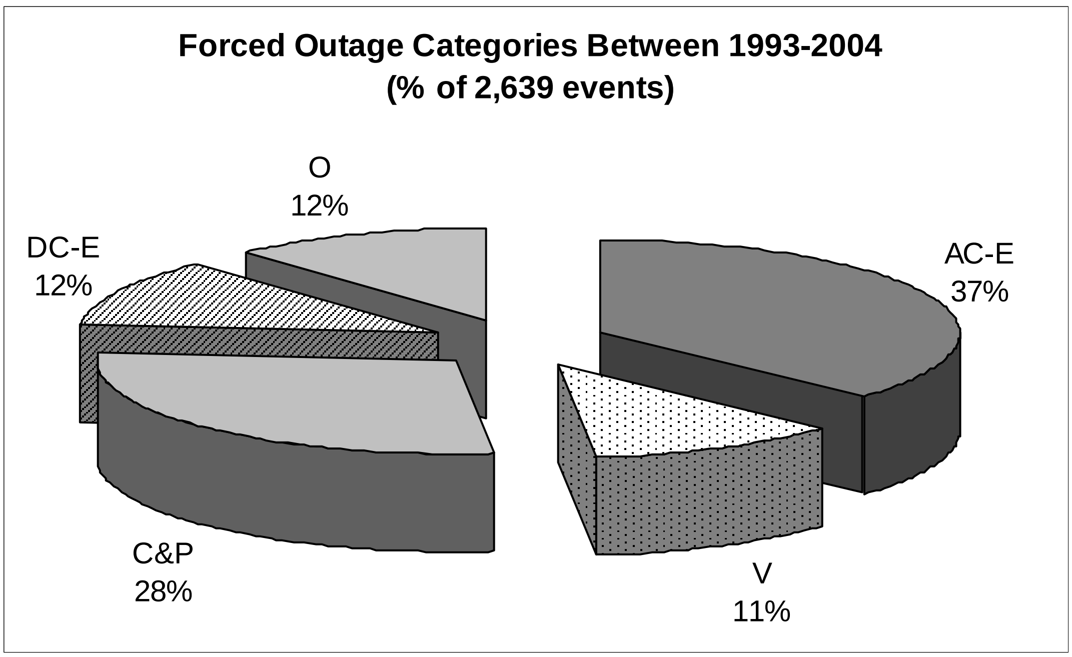

Figure 2-6
CIGRE HVDC System Forced Outage Categories by Events (1993-2004)

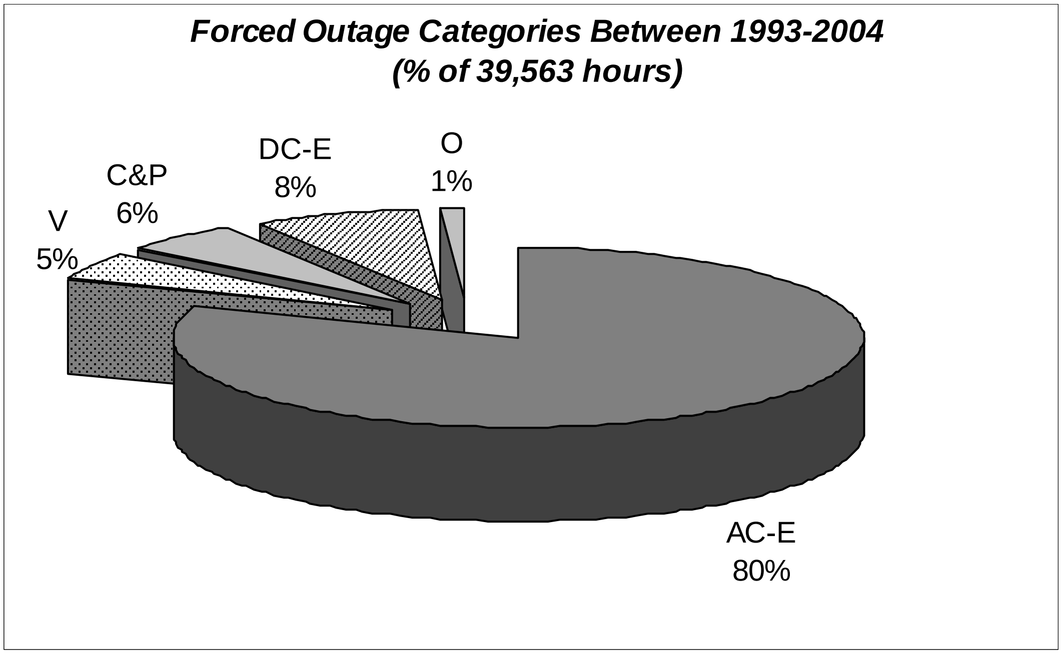

Figure 2-7
CIGRE HVDC System Forced Outage Categories by Hours (1993-2004)

Summary

Various performance statistics from HVDC systems, which reported their data to CIGRE between 1993 and 2004 have been reviewed and reported in this Chapter. The following are the summary observations:

- The average energy availability of HVDC systems, as a function of age, tends to rise after the first 10-years of operation and remain relatively constant. The overall average EA is approximately 94.3%.
- The average energy utilization of HVDC systems, as a function of age, tends to rise significantly for those facilities greater than 20-years of age indicating a high value is placed on their use.
- Forced energy unavailability tends to improve with age perhaps indicating improved diagnostics as HVDC systems age.
- Scheduled energy unavailability increases for those facilities greater than 20-years of age, perhaps indicating a higher level of maintenance is required for older HVDC systems.
- Thyristor cell failure rates tend to rise significantly for those facilities greater than 20-years of age.
- The total number of forced outage events between 1993 and 2004 is greatest for ac equipment (AC-E) and least for thyristor valves (V).

- The total number of forced outage hours between 1993 and 2004 is greatest for ac equipment (AC-E) and least due to human error or unknown causes (O).

In particular, a significant observation drawn from the forced outage data shown in Figure 2-6 and Figure 2-7 is the impact on the number of events and hours that the AC-E equipment category (AC and Auxiliary Equipment) has on the forced outage performance. Although the AC-E number of events is an important performance metric, the hours associated with these events is more critical, since each outage hour represents an hour where the HVDC system is not generating revenue for the owners. This in turn, leads to a conclusion that emphasizes the need for extending the life of ac equipment to maintain overall HVDC system reliability.

Chapter References

[1] CIGRE 1996:14-101, A Survey of the Reliability of HVDC Systems Throughout the World During 1993-1994, Paris, France

[2] CIGRE 1998:14-102, A Survey of the Reliability of HVDC Systems Throughout the World During 1995-1996, Paris, France

[3] CIGRE 2000:14-102, A Survey of the Reliability of HVDC Systems Throughout the World During 1997-1998, Paris, France

[4] CIGRE 2002:14-101, A Survey of the Reliability of HVDC Systems Throughout the World During 1999-2000, Paris, France

[5] CIGRE 2004:B4-201, A Survey of the Reliability of HVDC Systems Throughout the World During 2001-2002, Paris, France

[6] CIGRE 2006:B4-202, A Survey of the Reliability of HVDC Systems Throughout the World During 2003-2004, Paris, France

[7] IEEE Std 1240-2000, IEEE Guide for the Evaluation of the Reliability of HVDC Converter Stations, Appendix B – CIGRE's "Protocol for Reporting the Operational Performance of HVDC Transmission Systems"

3
COMPONENT LIFETIMES

Introduction

The basic intent of this chapter is to identify the expected service life of major equipment items associated with HVDC converter stations. Additionally, a high-level assessment of typical cost breakdowns and representative replacement outage times for each of the equipment items are addressed in this Chapter.

Expected Lifetimes

In general, the service life of electrical equipment is defined as that period of time prior to breakdown or failure during which a set of equipment is expected to operate satisfactorily and used economically, while meeting specific performance requirements. A chart indicating the expected service lives of HVDC converter station equipment items is included in Appendix C. The data shown in Appendix C is based on published information and from experience of project team members [1, 2]. An important consideration that must be factored into any equipment life expectancy is the initial design, operational use, maintenance and whether or not the equipment has been overloaded during its lifetime.

The chart in Appendix C is divided into the following five major categories to coincide with the CIGRE data-base presented in a previous Chapter:

- AC & Auxiliary Equipment: This category of equipment includes ac filters, reactive compensation, ac switching equipment, ac line, ac surge arresters, ac buswork, ac instrumentation, ac control and protection, cooling equipment, and converter transformers.
- Thyristor Valves: This category includes all parts of the converter valve including thyristors, grading capacitors, fiber optics, snubber circuits, reactors, heat-sinks, cooling tubing, electronics and other components and auxiliaries integral to the valve.
- HVDC Control and Protection: This category includes the equipment used to control, monitor, and protect the overall HVDC system.
- DC Equipment: This category includes the dc filters, dc smoothing reactors, dc switching equipment, dc ground electrode and electrode line, dc-side arresters, dc buswork, dc wall bushings and dc instrumentation.
- Other: The other category shown in Appendix C is reserved for costing information only and is not used to indicate information related to service lives or replacement times.

AC & Auxiliary Equipment

AC Filters

AC current harmonics are generated by a converter station as a result of the ac/dc conversion process. AC filters are installed in order to limit the level of ac voltage distortion and communication system interference caused by these harmonics. The conversion process also causes the converter to consume reactive power, which is compensated, in part, by the ac filter banks. The total reactive power from the ac filters can range from 10% to 40% of the active power transfer of the converter station. The filters considered in this Guideline are of the non-active type consisting of fixed capacitors, reactors and resistors arranged in an outdoor configuration.

- Individual capacitor units associated with ac filter capacitor banks are typically of all film design as used in substation shunt capacitor banks. However, many of the older HVDC facilities have been around long enough to have capacitor units with PCB dielectric fluids. If they do have these style capacitors, the units are often replaced to bring the facility into compliance with current PCB regulations independent of life expectancy. Capacitor units are replaced during the course of normal maintenance as a function of spare parts availability. An average service life of 25 years (this is an average figure, a light duty cycle may extend the lifetime well beyond averages) has been assigned to ac filter capacitor banks [2].
- Reactors associated with ac filter equipment are typically single phase and either dry air core or oil immersed iron core type. An average service life of 25 years has been assigned to dry air core reactors and 35 years for oil immersed units (these are average figures, a light duty cycle may extend the lifetime well beyond averages) [2].
- Power resistors used in ac filters are typically the fixed resistance wire wound power or steel plate design type. An average service life of 40 years has been assigned to these types of resistors based on calculations per MIL-HDBK-217F (Military Handbook – Reliability Prediction of Electronic Equipment).

Reactive Compensation

The reactive power demand of HVDC systems is typically 50% to 60% of the active power transferred during normal operation. The reactive power design for HVDC systems needs to consider the following criteria:

- AC bus voltage regulation.
- Stability and speed of the HVDC control system.
- Overvoltage due to load rejection.

The majority of HVDC systems use switched shunt capacitors in combination with ac filters to meet the reactive power demand. Additionally, shunt reactors are sometimes used to reduce steady-state overvoltages associated with low dc power transfers.

Individual capacitor units associated with shunt capacitor banks are typically replaced during the course of normal maintenance as a function of spare parts availability. An average service life of 25 years has been assigned to shunt capacitor banks [2].

Shunt reactors associated with reactive compensation equipment are typically single phase and either dry air core or oil immersed iron core type. An average service life of 25 years has been assigned to dry air core reactors and 35 years for oil immersed units [2]. The life expectancy of air core reactors is effected by the environmental conditions (farming, coastal, heat, etc.) of the location of the installation. Oil filled reactors are protected by the steel tank.

Reactive compensation and voltage support can also be supplied by the use of synchronous condensers.

AC Circuit Breakers

Converter stations are connected to ac systems with conventional circuit breakers rated to carry full load current, interrupt fault currents and energize the converter transformers. Additionally, ac circuit breakers are used for switching and protection of reactive compensation and ac filters. In these applications, the normal life expectancy can be reduced by the extreme number of operations switching the filter banks off and on. It is not unusual for filter breakers to reach 10,000 operations in less than twenty years (AC applications of circuit breakers consider 2,000 operations a normal lifetime). The user needs to consider many factors with each application of ac circuit breakers including voltage and current ratings, system growth, closing sequence, interrupting capacity, and operating (close/open) times. Most components within an ac circuit breaker can be replaced during the course of normal maintenance as a function of spare part availability. An average service life of 35 years has been assigned to ac circuit breakers [2].

Interrupting Switches

Interrupting switches are air break switches equipped with an interrupter device used to control the insertion or removal of shunt reactive power equipment. Interrupting switches are typically refurbished or replaced during the course of normal maintenance as a function of the number of operations and spare parts availability. An average service life of 20 years has been assigned to these type switches [2].

Circuit Switchers

Many HVDC converter schemes use circuit switchers as the interrupting device of choice for insertion or removal of shunt reactive power equipment. Circuit switchers are typically refurbished or replaced during the course of normal maintenance as a function of the number of operations and spare parts availability. An average service life of 25 years has been assigned to these type switches.

Disconnecting Switches

Disconnecting switches are used to isolate equipment from buses or other energized apparatus and are generally not used for load break applications. Grounding switches are typically used in conjunction with disconnect switches to provide equipment grounding provisions. Disconnecting and grounding switches are typically refurbished or replaced during the course of normal maintenance as a function of the number of operations and spare parts availability. It is not unusual to replace only the live parts of the switch to extend its life or increase its circuit rating. An average service life of 35 years has been assigned to these type switches [2].

Surge Arresters

Surge arresters applied in the ac portion of converter stations are for standard overvoltage protection as well as nonstandard applications such as ac filter component protection. The following arresters are typically installed:

- Bus arresters
- Filter reactor arresters
- Shunt reactor arresters
- Converter transformer arresters

Choosing the protective voltage levels and energy rating of specific arresters is an involved process requiring a detailed insulation coordination study. Failures can be detected by laboratory testing or catastrophic failure. Typically catastrophic failures cause a forced outage and requires immediate replacement. Non-catastrophic failures can be replaced during normal maintenance cycles as a function of replacement parts availability. An average service life of 35 years has been assigned to surge arresters [2].

It should be noted, the standard surge arrester used prior to the late 1970s was the gapped silicon carbide design. Many utilities removed this style device from their systems and replaced them with the metal oxide types. This was due in part to the aging characteristics of the silicon carbine and in service failures experienced by the industry.

Line Traps (Carrier Wave Traps)

Line traps (sometimes referred to as wave traps) are used in protective relaying schemes, where a high frequency carrier signal is coupled to a transmission line to transmit information. The line trap is a tuning device used to decouple the carrier signal and prevent shorting of the carrier signal by an external transmission line fault. An average service life of 20 years has been assigned to line traps [2].

Buswork, Insulators and Structures

Buswork, insulators and structures are used in combination with electrical grade tubing and cable conductors to provide electrical interconnections and safe clearances within substations. This type of equipment should not deteriorate except for environmental conditions, material flaws or changes to the electrical network that result in original design limits being exceeded. Individual failed buswork, insulators or structures are typically replaced during the course of normal maintenance as a function of replacement parts availability. An average service life of 50 years has been assigned to buswork, insulators and structures.

AC Control & Protection

AC control and protection equipment can be electro-mechanical to highly sophisticated digital packages. Typically they are comprised of electronic panels for monitoring, controlling and protecting major equipment within a substation. Individual components, panels or boards are typically replaced during the course of normal maintenance due to failure or obsolescence. Improvements in technology, design, hardware and software, as well as changes in network conditions, tend to make the service life of these equipment items relatively short. An average service life for the digital devices of 15 years has been assigned to ac control and protection equipment [2].

Instrument Transformers

Conventional ac instrument transformers are used for the following functions:

- Revenue Metering: Wound type potential and current transformers.
- Capacitive Voltage Transformer (CVT): Used for control, indication and protection.
- Capacitor Coupled Voltage Transformer (CCVT): Used for the same control, indication and protection functions as the CVT, but also has a coupling device to allow it to be used for power line carrier (PLC) functions.
- Bushing Type Current Transformer (CT): Protection and control.
- Freestanding Current Transformer: Protection and control.

Individual instrument transformers are typically replaced during the course of normal maintenance due to failure. An average service life of 30 years has been assigned to instrument transformer equipment [2].

Cooling Systems

Heating, ventilating and air conditioning (HVAC) systems are installed to accommodate converter station control buildings and valve halls. Although valve halls may not include air conditioning, air-cleaning equipment may be provided to prevent contaminant accumulation within the valve structures. Valve halls may also be equipped with fire detection and/or prevention systems. An average service life of 20 years has been assigned to building HVAC and valve hall fire prevention systems assuming continued cleaning and routine maintenance.

Thyristor valve cooling systems use air, glycol, de-ionized-glycol, or de-ionized water as the primary heat transfer medium. Heat is transferred from the thyristor heat-sinks and other valve equipment, requiring cooling, to the cooling medium. Water-cooled systems use a treated de-ionized water solution to transfer the heat to outside cooling towers. In like manner, air cooled systems transfer the heat to a liquid water-glycol solution to outside cooling towers. Cooling towers typically utilize a dry or wet surface design for heat transfer. An average service life of 15 years has been assigned to wet surface cooling towers and 20 years to dry surface cooling towers assuming continued cleaning and routine maintenance.

Converter Transformers

Converter transformers are used to transform the ac system voltage to a voltage level required for the dc rectification or inversion conversion process. Converter transformers may be designed as single-phase or three-phase units with three or four windings. The configuration depends on ratings, reliability, maintenance and spare requirements. Features that make a converter transformer different from conventional ac power transformers include the following:

- Valve-side secondary windings are configured with one set of delta and one set of wye floating windings.
- The valve-side windings are subject to dc bias voltages.
- Windings carry cyclic dc current with a rectangular waveform and associated harmonic currents.

- The core is subjected to small amounts of dc current and must be able to handle those currents.
- The difference in impedances between phases must be less that 5%.
- Load tap changing (LTC) mechanisms are typically coordinated with the station reactive power requirements and valve firing controls with a representative LTC range of 20% in 1% to 2% steps.
- Leakage inductance is a critical parameter that forms the converter's primary source of commutating reactance.

An average service life of 40-year has been assigned to converter transformers following review of expected lifetimes of ac transformers [2] and the CIGRE Joint Task Force technical report [3].

It is of interest to note that a study of the CIGRE data provided in Chapter 2 indicates that converter transformers have been a major source of outages within the "AC and Auxiliary Equipment" category. A CIGRE Joint Task Force (JTF) was established in an attempt to identify the transformer failures and the probable causes [3]. Although there remain uncertainties in making any conclusion regarding the JTF findings, there appear to be a couple of items of particular interest, e.g., (1) 15 of the 24 failures in 2000 and 2001 (62.5%) were reported by three systems; (2) Systems without spare transformers were a major contributor to unavailability; (3) Transformer failures for the reporting period 1972 to 2002 excluding one major system were 54.1 years/failure; (4) Transformer failures for the reporting period 1972 to 2002 including the previously excluded major system were 31.4 years/failure.

Civil Works

Civil works generally refer to the physical works and facilities making up the converter station. They include grading, drainage, concrete placement, steel erection, geotechnical issues, surveying, structures, service roads, buildings, etc. An average service life of 50 years has been assigned to civil works assuming continued maintenance such as cleaning, painting and building roof replacement as part of routine maintenance.

Auxiliary Power Equipment

Auxiliary power equipment associated with converter stations are similar to large ac substation installations and include redundant power for critical loads. Converter station loads that are typically critical include the following:

- Control and Protection: AC and dc service to control panels, protection panels, operator controls, switchgear, etc.
- Valve Cooling: Valve cooling pump stations, heat exchanger fans, etc.
- Building: Lighting, heating, ventilating, air conditioning, fire protection, security systems, etc.
- Yard: Equipment heaters, lighting, maintenance service, etc.

An average service life of 20 years has been assigned to battery chargers, 15 years to batteries and 40 years to station service transformers assuming routine maintenance and availability of spare parts [2].

Thyristor Valves

Thyristor valves are built in different physical arrangements depending on the application and manufacturer. A single thyristor cell or parallel connected thyristor cells and their associated components (for control, voltage grading, protection and monitoring) constitute a single voltage level within a thyristor valve. Each thyristor valve is comprised of a number of series connected thyristor levels, with a snubber circuit composed of a resistor and capacitor and reactors to limit the rate of change of voltage across the thyristor. The reactors are designed to limit the rate of rise of current when the thyristor valve is triggered. The thyristor valve turn-on (trigger) process is initiated by an electrical gate pulse from ground potential via the valve base electronics (VBE) unit. The VBE provides the individual thyristor levels with a pulse that triggers each thyristor level via a thyristor control unit (TCU) located near each thyristor cell. Recently developed direct light triggered thyristors are not covered in these guidelines.

Thyristor valves are protected from overvoltages by arresters typically installed within the valve hall at the following locations:

- DC bus arrester to ground.
- Valve arrester across each thyristor valve.
- Bridge arrester across each 6-pulse bridge.
- Midpoint arrester between the 6-pulse bridge and ground.

Choosing the protective voltage levels and energy rating of specific valve arresters is an involved process requiring a detailed insulation coordination study.

Other components associated with a thyristor valve include fiber optics, heat-sinks, cooling tubing and cooling system electrodes. Individual components of a thyristor valve are generally considered replaceable items assuming spare parts are available and obsolescence has not become an issue. An average service life of 30 years has been assigned to thyristor valve equipment [2].

HVDC Control and Protection

Analog Electronics

It is technically possible to repair and refurbish existing analog control systems. The long-term challenge of this approach is obtaining and retaining the knowledge base, components, staffing and funding to undertake such a program. Replacement of analog control system with digital technology has been considered by many utilities while others continue to maintain analog control systems as long as components and staff expertise can be obtained. An average service life of 25 years has been assigned to analog electronic systems assuming routine maintenance and availability of spare parts.

Digital Electronics

Improvements in technology, design, hardware and software as well as changes in system requirements tend to make the service life of digital electronics relatively short. An average service life of 15 years has been assigned to digital electronic systems assuming routine maintenance and availability of spare parts.

Power Supplies

Uninterruptible power supply (UPS) systems provide a reliable power source for critical station equipment following interruption of the main power system. Changing UPS technologies and station equipment loads can often be cause for replacement of UPS equipment. An average service life of 10 years has been assigned to UPS systems assuming routine maintenance and availability of spare parts [2].

DFR and SER

Digital fault recorders (DFR) and sequence of events recorders (SER) are used for recording system faults, transients and disturbances. Improvements in technology, hardware and software as well as changes in system requirements tend to make the service life of these instruments relatively short. An average service life of 15 years has been assigned to DFR and SER components assuming routine maintenance and availability of spare parts [2].

SCADA

Supervisory Control and Data Acquisition (SCADA) systems can perform individual control operations as well as obtain numerous quantities of equipment or system operating data. These systems typically consist of: (1) A remote terminal unit (RTU); (2) A Human-machine interface (HMI) system; and (3) A central processor or computer. Changing technologies and equipment obsolescence are considerations when determining the service life of SCADA, RTU and HMI equipment. An average service life of 10 years has been assigned to SCADA and RTU components including the HMI system assuming routine maintenance and availability of spare parts [2].

Communication Systems

Telephone networks, microwave transmitter and receiver, and fiber optics communications systems are typically constructed of many replaceable parts, which can be serviced under normal maintenance programs. However, complete replacement of networks or systems may be required at intervals because of changes in requirements or obsolescence. An average service life of 10 years has been assigned to communication systems assuming routine maintenance and availability of spare parts [2].

DC Equipment

Smoothing Reactor

DC smoothing reactors can be either oil or air insulated and functionally provide several key features, including:

- Smooth the dc current to prevent discontinuous current at low power transfer levels.
- Decrease the incidence of commutation failures.
- Prevent steep-front surges from the dc line or dc yard from entering the valve hall.
- Provide a part of the overall dc harmonic filtering.

An average service life of 25 years has been assigned to air core smoothing reactors and 35 years to oil insulated smoothing reactor assuming routine maintenance and availability of spare parts.

The life expectancy of air core reactors is effected by the environmental conditions (farming, coastal, heat, etc.) of the location of the installation. Oil filled reactors are protected by the steel tank.

Switching Equipment

DC switching equipment, such as disconnecting switches, is used to isolate equipment from buses or other energized apparatus and is not used for load break applications. Grounding switches are typically used in conjunction with disconnect switches to provide equipment grounding provisions. Disconnecting and grounding switches are usually repaired and replaced during the course of normal maintenance as a function of the number of operations and spare parts availability. An average service life of 35 years has been assigned to these type switches.

Ground Electrode

The American National Standards Institute (ANSI) standard ANSI C2, National Electrical Safety Code (NESC) 2002 indicates, in part, that monopolar operation of a bipolar HVDC system is permissible, for limited periods, during emergencies and maintenance. Additionally, transmission networks can not be designed to use the earth normally as the sole conductor for any part of the circuit. Based on the limited use of ground electrodes an average service life of 40 years has been assigned to ground electrodes. At least one HVDC facility has inspected electrodes that have been in service for 29 and 34 years and found no indication of deterioration.

Surge Arresters

Arresters applied on dc equipment typically include the following:

- DC filter reactors.
- Smoothing reactors.
- DC transmission line poles.
- Neutral bus.

Choosing the protective voltage levels and energy rating of specific arresters is an involved process requiring a detailed insulation coordination study. Failures can be catastrophic in nature. Typically this causes a forced outage and requires immediate replacement. Non-catastrophic failures can be replaced during normal maintenance cycles as a function of replacement parts availability. An average service life of 35 years has been assigned to surge arresters [2].

DC Filters

HVDC converters create harmonics on dc transmission lines that can cause interference in nearby telecommunications systems. DC filters installed at the converter ends and electrode lines of HVDC transmission systems are designed to eliminate these interference effects. Normally they are considerably smaller and less expensive than filters on the ac side. The filter components are comprised of passive components such as capacitors, grading resistors and reactors. Active dc filters using power electronic as a means to reduce harmonic interference are not covered in these Guidelines. Usually no filters are needed for back-to-back or cable transmission systems. An average service life of 20 years has been assigned to dc filters.

Wall Bushings

DC wall bushings form the transition for the electrical connections between the indoor valve hall equipment and outdoor yard equipment. DC bushings have a different design from AC bushings requiring longer creepage distances or different shed profiles than ac bushings of similar peak rating due to contamination issues related to dc fields. An average service life of 35 years has been assigned to dc wall bushings.

Instrumentation

DC potential and current transducers are installed for control, protection and indication purposes. An average service life of 30 years has been assigned to dc instrumentation.

Buswork, Insulators and Structures

Buswork, insulators and structures are used in combination with electrical grade tubing and cable conductors to provide electrical interconnections and safe clearances within converter stations. This type of equipment should not deteriorate except for environmental conditions, material flaws or changes to the converter station that result in original design limits being exceeded. Individual failed buswork, insulators or structures are typically replaced during the course of normal maintenance as a function of replacement parts availability. An average service life of 50 years has been assigned to buswork, insulators and structures.

Costs

A critical step in determining whether to refurbish equipment items or replace a converter station is the methodology used to evaluate the associated cost. Factors that should be considered include:

1. A project evaluation plan combining objectives, assessment criteria, present value analysis model and schedule.
2. Existing equipment performance, civil works, building, land and environmental issues.
3. Outage impact on customers and revenue.
4. Maintenance history, spare parts, staffing and lead time to replace existing or failed equipment.
5. Impact of increasing or decreasing converter station rating.
6. Existing or new design and performance constraints.
7. Discussion with potential suppliers and impact of new technologies, market conditions and currency exchange rates.
8. Develop a refurbishment or replacement strategy that addresses all equipment items within a converter station.
9. Contractual terms and conditions that could impact refurbishment or replacement costs such as liquidated damages, warranty provisions, schedule, etc.
10. The difference between forced and scheduled outages on sales, reliability, and availability.

The available options along with the many factors that need to be considered make it very difficult to render specific cost factors for refurbishing or replacement of a converter station without a custom evaluation of a specific converter station's requirements [4]. The percentage costs of various converter station categories has been cited in literature and included in Appendix C for reference [5, 6, 7, 8].

Replacement Times

Representative converter station outage times for equipment replacement are included on the chart in Appendix C. These outage times are included only for reference. Actual time to replace various pieces of equipment will vary depending on the type of installation, skill of personnel, availability of heavy equipment, spare parts, etc. Each utility should evaluate the cost impact associated with outages when evaluating the options of refurbishing or replacing converter station equipment recognizing that work could be scheduled during scheduled annual maintenance periods.

Chapter References

[1] Guidelines for the Life Extension of Substations, EPRI, November 2002 Update, Technical Report 1001779

[2] Replacements – Units, Service Lives, Factors, Western Area Power Administration and Bureau of Reclamation, May 2006

[3] Analysis of HVDC Thyristor Converter Transformer Performance, CIGRE, SC A2 Transformers and SC B4 HVDC and Power Electronics, JTF B4.04 and A2-1, Technical Brochure No. 240, 2004

[4] Guide for Upgrading Transmission Systems with HVDC Transmission, CIGRE Brochure No. 127, Working Group 14.11, August 1998.

[5] HVDC Power Transmission Technology Assessment, ORNL/SUB/95-SR893/1, April 1997, http://www.osti.gov/energycitations/servlets/purl/580574-UUQq72/webviewable/580574.pdf

[6] EPRI, High Voltage Direct Current Handbook, Chapter 8, First Addition, Project RP3158-01, TR-104166, 1994

[7] High Voltage Direct Current (HVDC) Transmission Systems, Technical Review Paper, Joint World Bank & ABB, http://www.worldbank.org/html/fpd/em/transmission/technology_abb.pdf

[8] Economic Assessment of HVDC Links, CIGRE Brochure No. 186, Final report of Working Group 14.20, June 2001

4
DRAFT OUTLINE FOR LIFE EXTENSION OF EXISITNG HVDC SYSTEMS

Introduction

The guidelines outlined in this chapter are the first of a two phase multi-year effort. Phase I addresses the life extension of HVDC converter station equipment including those summarized in Appendix C. The Phase I Guidelines will examine natural commutated converters that utilize thyristors (single or parallel combinations) connected in series to build up thyristor valves. The Guidelines will not specifically address forced commutated converters or capacitor commutated converters although many of the principles covered here can be applied.

Phase II will address the life extension of HVDC transmission lines and cables. Phase II will be defined and funded separately following the successful completion of Phase I. Phase II will also include a training course on the life extension guidelines for the operation, maintenance and reliability assessment strategies of HVDC systems. As a result, the emphasis of this Chapter is placed on the HVDC converter station and its associated equipment. This approach is based on experience indicating that HVDC converter station life extension is the primary need at this time. The majority of HVDC converter station equipment is approaching the end of its useful operating lifetime. It requires attention before HVDC transmission lines due to the longer operating lifetime of those transmission lines.

Background

The aging infrastructure of HVDC converter stations and transmission line systems is of growing concern to utilities interconnected with those systems. In most cases, the transmission path provided by operating HVDC converter stations is profitable and life extension is not only an option, but a necessity. With many installations approaching 25 to 30 years of service, the justifications for extending the converter station's life needs to be addressed before reliability and availability are impacted.

The choices facing the industry are:

- Refurbishing the systems.
- Replacing aging components.
- Building new facilities.
- Phasing out the old facilities.

Purpose of the Guidelines

These Guidelines are intended to be used in conjunction with a utility's in-house procedures and to supplement industry standards and manufacturers' recommendations. Where in-house procedures are minimal, these guidelines can assist in forming the basis for extending existing maintenance practices.

These Guidelines will help utilities:

- Establish refurbishment strategies to extend equipment life of existing HVDC converter stations.
- Evaluate Operating and Maintenance (O&M) and reliability performance improvement methods for existing HVDC converter stations.
- Increase existing asset utilization by extending the life of HVDC converter stations and improve return on investment.

Guideline Format

A draft outline of the Guidelines has been developed and is described in this section. There are many HVDC converter station equipment items, subsystems and components, which are similar in type and functionality to those found in conventional ac substations. Those items that are similar to those in conventional substations are covered by EPRI's existing "Guidelines for the Life Extension of Substations" [1]. As such, only equipment items, subsystems and components unique to HVDC converter stations will be discussed in these Guidelines.

The Guidelines will consist of eight (8) main chapters with associated sections and appendices as follows:

1. Introduction
    - Background
    - Purpose
    - How to use
2. Framework of Maintenance Decisions
    - Overview
    - Maintenance philosophies
    - Maintenance considerations
    - Data management
    - Asset management
    - Performance metrics
3. AC & Auxiliary Equipment
    - AC harmonic filters
    - Reactive compensation
    - AC control & protection
    - AC circuit breakers
    - Others

4. Converter Transformers
5. Cooling Systems
    - Building and valve hall heating, ventilating and air conditioning (HVAC)
    - Thyristor valve cooling
6. Thyristor Valves
7. HVDC Control, Protection and Communication Systems
8. Grounding and Static Shielding System
    - Grid and equipment grounding review in relation to the latest revision to IEEE-80
    - Lightning protection coverage review of the total facility
9. DC Equipment
    - Smoothing reactors
    - Switching equipment
    - Ground electrodes
    - Filters
    - Wall bushings
    - Instrumentation
    - Insulators and buswork

After the introductory and framework chapters, each of the equipment items, in the remaining chapters, will be divided into the following sections:

- Description: This section will provide a description of the main characteristics of the subject equipment including the different types of equipment used, their function in converter stations and the various ways in which the equipment is applied.
- Trouble Modes: This section will describe common aging and failure modes for the subject equipment and methods for detecting these failures. Causes of these failure modes will also be reviewed.
- Maintenance: Maintenance will be defined as periodic scheduled inspection and testing of equipment to ensure trouble-free performance. Maintenance will also include the refurbishment of equipment components that are replaced periodically. The maintenance section will include information on routine maintenance and inspection procedures commonly applied to the subject equipment.
- Condition Assessment: Condition assessment will be defined as that testing outside the scope of testing normally performed as part of scheduled maintenance. The tests performed as part of a condition assessment program will be undertaken to determine the status and reliability of equipment. Other topics include reasons for performing these tests and the use of these test results.
- Replacement/Refurbishment: The factors to be considered when deciding on the replacement or refurbishment of a piece of equipment will be reviewed. The costs to be accounted for in this process and the methodology to be used will also be discussed including, (a) spare parts, (b) new technologies, (c) replacement costs and minimizing converter station downtime, (d) increasing capacity, (e) control system replacement “plug-and-play” strategies, (f) equipment service life estimations and (g) present value analysis procedures.

Chapter References

[1] Guidelines for the Life Extension of Substations, EPRI, November 2002 Update, Technical Report 100

A
APPENDIX

October 4, 2006 Meeting Notes

Background

HVDC facilities represent a significant investment and revenue source for electric utilities. As these facilities age, utilities are in need of guidelines to extend the life with selected system refurbishment or placement, maintenance practices, or complete replacement.

EPRI is starting a project to produce Guidelines for Life Extension of Existing HVDC Systems (EPRI Project Number 062819-1). These guidelines will initially focus of HVDC Converter Stations. High Energy Inc. (HEI), an engineering consulting company, has been retained to prepare these guidelines. HEI's project team consists of Ruth Johnson, Bruce Lavier, Bill Mele, Duane Torgerson, Randy Wachal, Gene Wolf and Dennis Woodford.

Introductions/Opening Remarks

A meeting was held on October 4, 2006 to officially begin the project, discuss the purposes and expectations, and obtain input from interested utilities. An attendance list is attached.

Dr. Ram Adapa, the EPRI project manager for this project, welcomed participants to the meeting and discussed the need for this project. He invited utility participants to have a continuous open dialog with the project team so the guidelines can reflect the highest priority items, provide experiences with life extension efforts, and issues and problems with HVDC systems.

EPRI has a complimentary project for life extension of High Voltage AC Substations which is available on a compact disk. Ram will obtain copies of this CD for the project team for use on this specific project.

Ram also mentioned several other related projects EPRI is pursuing, including:

- Advanced HVDC systems that operate at 800kV and above.
- HVDC Reference Guide.
- An HVDC Conference, possibly in the Winnipeg, Canada area early next year. There was an HVDC conference recently held in South Africa.

Expectations of Project

It is expected the guidelines will provide a useful tool for utilities interested in life extension of HVDC systems. The guidelines will initially focus on converter stations. The guidelines will initially focus on the converter components identified as the highest priority items, then as more funding for the project becomes available, provide detailed guidelines on all components and eventually include information on HVDC transmission lines.

The guidelines should provide some guidance on maintenance practices, methods of measuring and forecasting remaining life, some projections on timeframes for refurbishment and replacement activities so they can be scheduled, and help with financial justifications of projects.

Project Tasks

The scope of work for the current project involves the following six distinct tasks:

- Task 1 – Kickoff Meeting
- Task 2 – List of HVDC Converter Stations
- Task 3 – Review of CIRGE HVDC Outage Statistics
- Task 4 – Component Lifetimes
- Task 5 – Draft Outline for Life Extension for Existing HVDC Systems
- Task 6 – Prepare "Life Extension for HVDC Systems"

It is planned the work through task 5 will be completed by the end of 2006.

List of HVDC Converter Stations

This task will focus on the creation of a list of HVDC converter stations along with a high level summary of life extension efforts that have taken place or are planned. The list will be started through the use of IEEE and CIGRE lists and will focus on facilities located in North America. The project team will make attempts to gather information on facilities in other parts of the world; this will be done through CIGRE, by contacting utilities that are CIGRE members. Duane Torgerson has a list of all DC links around the world. Ram will send to Ruth an electronic copy of it. Also, Irina Merson of HEI has contacts in Russian Federation utility (which is also an EPRI member). Also, Irina will find appropriate contacts at Minnesota Power and New Brunswick Utility.

Also, it was recommended that the team contact the United Kingdom's National Grid, which owns the facility near Boston.

A draft copy of the list will be available by the end of October. Additional information will be added to the list as it is received.

Review of CIRGE HVDC Outage Statistics

The team will obtain and review the outage statistics collected and published by CIGRE from HVDC converter stations. These statistics will be used as a starting point for correlations with known life extension upgrades.

There was some discussion of the "manufacturer-supported user groups" as a possible source of additional information. It was suggested that Los Angles Department of Water and Power (LADWP) may have information on such "user groups".

For example: the information could be grouped and better analyzed, with more specific recommendations, for facilities equipped by the same manufacturer (GE, or Siemens, or ABB).

Component Lifetimes

The project team will consider published information on component lifetimes to create a chart of typical component lifetimes. There was a desire among utility representatives to include information on how to determine the remaining life of equipment specific to their converter station.

There will also be some discussion in the guidelines of spare parts and the role they play in life extension efforts. There was a study done by Siemens several years ago to determine if thyristors age while on the shelf. It was determined at that time that they do not: there were no changes in their parameters. The question was raised at the meeting: what truly is the life expectation of the thyristor unit? There are several stations that have experienced very few thyristors failures while others have experienced many failures.

Also discussed at the meeting was the issue of converter transformer performance, related to their aging and failures. EPRI is considering a project to study this issue in detail. Meanwhile, the guidelines will consider this issue in as much detail as possible.

The Bonneville Power Administration (BPA) has information on aging of equipment; it was furnished to the project team during the meeting.

The Western Area Power Administration (Western) periodically publishes a document on typical lifetimes for equipment. The representatives from Western will check if they can obtain a copy of this document for the project team; they will send it to Ruth.

It is desired from the utility representatives the guidelines contain information on when equipment needs replacing, with possible lead times and some justifications. It is also desired the guidelines be a complete, in-depth report. Since there is a limited budget for the project, the highest priority components will be discussed in detail with lower priority components discussed in as much detail as the budget allows.

Draft Outline for Life Extension for Existing HVDC Systems

The outline for the guidelines will be prepared in draft form. This outline will contain a section on transmission lines; however, transmission line components will be covered at only a very high level.

There are many components in an HVDC converter station that are also contained in traditional AC stations. Where these components are covered in other EPRI publications, those publications will be referenced and discussion will be provided only if it is unique to DC stations. The AC equipment in HVDC stations is an important component, since AC equipment operates a lot.

Prepare "Life Extension for HVDC Systems"

The guidelines will be prepared using information gathered in the above tasks. The guidelines are intended to be a guide for utilities to use for determining remaining life of an HVDC converter stations and methods of extending this life.

The guidelines will also contain information required to help utilities make business cases for replacement or refurbishment of components within the HVDC converter stations.

Input from Industry Advisors/Interested Utilities

There was interest in including information on the personnel element of converter station operation and maintenance, both of which can affect station availability and life extension efforts. Detailed knowledge of converter stations, both from engineering and craft personnel, is typically gained over many years of experience with a specific station. As the workforce ages, there is concern about losing this knowledge through retirements. Education of the future work force is an important task.

Several people also mentioned concern over the control and cooling systems of converter stations. For example, in Colorado and New Mexico, the water tables have been dropping as the population has been growing; this creates a serious issue for the station cooling systems.

There were questions on live line work of HVDC transmission lines and stations. There is consideration of the creation of a live line HVDC project within EPRI at a later date. During this project, the list will be developed of the potential problems related to transmission lines connecting HVDC stations.

Future Project Updates

Ruth Johnson of HEI will send out periodic updates of the project via e-mail, to a mailing list consisting of meeting participants and invited guests, as well as to any other interested parties. Anyone else who is interested in being on the mailing list should contact Ruth.

Future Opportunities for Project Input from Interested Utilities

The team welcomes input from utilities for development of priorities for the guidelines; on past and planned efforts in life extension; and on special issues they would like considered in the guidelines.

Project Funding

This project is funded through EPRI program 162 – HVDC Systems. Utilities that fund this target will be eligible to receive copies of the guidelines; all utilities interested in this project are encouraged to discuss their organization's funding of this program area with their utilities MEP.

This project is funded through the end of 2006. Funding of work in 2007 will be dependent upon the funding levels of this program by member utilities. It has been proposed that by the end of 2007, the report would be published – if the sufficient funding is available – on most critical components of HVDC stations, such as valves, controls, cooling systems, converter transformers (creating prioritized list of components will be part of Task 5).

A-1
Kickoff Meeting Attendance

EPRI Project No. 062819-1: LIFE EXTENSION OF EXISTING HVDC SYSTEMS Project Meeting - October 4, 2006 (11:00 am to 4:00 pm) Tri-State G&T - Westminster, Colorado				
Attend	**Name**	**Company**	**email**	**phone**
1	Adapa, Ram	EPRI	radapa@epri.com	650-855-8988
1	Blaquiere, Ben	Western Area Power Administration	blaquier@wapa.gov	406-232-8306
1	Britton, Greg	Tri-State G&T	gbritton@tristategt.org	303-254-3444
1	Hurst, Jack	Tri-State G&T	jhurst@tristategt.org	303-254-3605
1	Johnson, Ruth	High Energy Inc.	ruth.johnson@highenergyinc.com	303-494-3328
1	Lavier, Bruce	Lavier Engineering LLC	blavier@gorge.net	541-980-8881
1	Litzenberger, Wayne	Bonneville Power Administration	wlitzenberger@bpa.gov	360-619-6291
1	Mander, Art	Tri-State G&T	amander@tristategt.org	303-254-3323
1	Mele, Bill	Indoor Environmental Solutions, Inc.	bmele@msn.com	303-948-0500
1	Merson, Irina	High Energy Inc.	irina.merson@highenergyinc.com	303-399-1098
1	Michael, Randy	Xcel Energy Services	Randy.Michael@xcelenergy.com	806-796-3325
1	Mitchell, Bruce	Tri-State G&T	bmitchell@tristategt.org	303-254-3411
1	Poggi, Ernie	Xcel Energy Services	ernest.poggi@xcelenergy.com	303-273-4703
1	Ramsay, Dill	Tri-State G&T	dramsay@tristategt.org	303-254-3450
1	Schmidt, Ernie	Western Area Power Administration	schmidt@wapa.gov	308-254-3046
1	Selman, Jeff	Tri-State G&T	jselman@tristategt.org	303-254-3403
1	Torgerson, Duane	Winfield Enterprise, LLC	drtorgerson@msn.com	303-202-3933
1	Wolf, Gene	Lone Wolf Engineering, LLC	lonewolfengineering@comcast.net	505 898-9491

I	Woodford, Dennis	Electranix Corporation	daw@electranix.com	204-953-1832
P	Chase, Don	Vermont Electric Power Company	dchase@velco.com	802-770-6299
P	Mehraban, Ben	American Electric Power Service Corp.	bmehraban@aep.com	614-552-1742
P	Mortensen, Karl	Great River Energy	kmortensen@grenergy.com	763-241-2365
P	Recksiedler, Les	Manitoba Hydro	lrecksiedler@hydro.mb.ca	204-474-3192
P	Wachal, Randy	Manitoba HVDC Research Centre	rww@hvdc.ca	204-989-2149
I	Bier, Michael	Kansas City Power & Light Co.	mike.bier@kcpl.com	816-245-3987
I	Crist, Paul	Lincoln Electric System	pcrist@les.com	402-467-7615
I	Holladay, Damon	Hoosier Energy Rural Electric Coop., Inc	holladay@hepn.com	812-876-0290
I	Jensen, Darwin	El Paso Company	djensen@epelectric.com	915-543-2094
I	Keri, Albert	American Electric Power Service Corp.	ajkeri@aep.com	614-552-1965
I	Ludington, Ron	Texas New Mexico Power Company	ronald.ludington@tnmp.com	505-538-3768
I	Oliver, Jonathan	Arkansas Electric Cooperative Corp.	joliver@aecc.com	501-570-2488
I	Pillay, Logan	ESKOM	logan.pillay@eskom.co.za	02-711-629-5170
I	Saum, Steve	Richmond Power & Light	steves@rp-l.com	765-973-7410
N	Bhuiyan, Mukhles	Los Angeles Department of Water & Power	Mukhlesur.Bhuiyan@ladwp.com	213-367-2532
N	Dalloul, Iyad	Public Service Electric & Gas Co.	iyad.dalloul@pseg.com	908-412-7687
N	Goosen, Piet	ESKOM	piet.goosen@eskom.co.za	
N	McNichol, John	Manitoba Hydro	jrmcnichol@hydro.mb.ca	
N	Osborne, Mark	National Grid Company plc	mark.osborne@uk.ngrid.com	44-192-665-5517
		BC Hydro		
		EDF (Electricite de France)		
	Bilodeau, Hubert	Hydro-Quebec	bilodeau.hubert@hydro.qc.ca	
		Minnesota Power		
		New Brunswick Power Transmission		
	Wu, Tim	Los Angeles Department of Water & Power	Chuan-Hsier.Wu@ladwp.com	213-367-0650

19	<-- Attending	I => Invited
5	<-- Phone-in	n=> Not attending
24	<-- Total	p=> Phone-in

B

APPENDIX

List of HVDC Transmission Schemes

(This list is in the public domain by courtesy of IEEE HVDC and FACTS Subcommittee and CIGRE Study Committee B4)

HVDC PROJECTS LISTING
Prepared for the
DC and Flexible AC Transmission Subcommittee
of the
IEEE Transmission and Distribution Committee
by the
Working Group on HVDC and FACTS Bibliography and Records

SYSTEM / PROJECT	HVDC SUPPLIER	YEAR COMMISSIONED	POWER RATING (MW)	DC VOLTAGE (kV)
MOSOW-KASHIRA (retired from service)	RUSSIAN	1951 (____)	30	±100
GOTLAND I (retired from service)	ASEA	1954 (1986)	20	±100
GOTLAND EXTENSION (retired from service)	ASEA	1970 (1986)	30	±150
GOTLAND II	ASEA	1983	130	150
GOTLAND III	ASEA	1987	260	±150
GOTLAND HVDC LIGHT	ABB	1999	50	±60
ENGLISH CHANNEL (retired from service)	ASEA	1961 (1984)	160	±100
VOLGOGRAD-DONBASS	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1962/65	720	±400
NEW ZEALAND HYBRID INTER ISLAND LINK	ASEA	1965	600	±250
NEW ZEALAND HYBRID INTER ISLAND LINK	ABB	1992	1240	+270/-350
NEW ZEALAND HYBRID INTER ISLAND LINK		PLANNED		
KONTI-SKAN 1	ASEA	1965	250	±250
KONTI-SKAN 1	AREVA	2005	250	±250
KONTI-SKAN 2	ASEA	1988	300	285

SAKUMA (retired from service)	ASEA	1965 (1993)	300	2x125
SARDINIA (retired from service)	ENGLISH ELECTRIC	1967 (1992)	200	200
VANCOUVER I	ASEA	1968/69	312	±260
VANCOUVER II	GENERAL ELECTRIC	1977/79	370	±280
PACIFIC INTERTIE	ASEA/GE	1970	1440	±400
PACIFIC INTERTIE	ASEA/GE	1982	1600	±400
PAC INTERTIE UPGRADE	ASEA	1985	2000	±500
PACIFIC INTERTIE EXPANSION	BROWN BOVERI	1989	3100	±500
KINGSNORTH (retired from service)	ENGLISH ELECTRIC	1972 (1987)	640	±266
EEL RIVER	GENERAL ELECTRIC	1972	320	±80
NELSON RIVER 1	ENGLISH ELECTRIC/GEC ALSTHOM	1973	1854	±463
NELSON RIVER 1	GEC ALSTHOM	1992/93	1854	±463
NELSON RIVER 1	SIEMENS	2001/02	1854	±463
NELSON RIVER 1	SIEMENS	2004	1854	±463
NELSON RIVER 2	AEG/BBC/SIEMENS	1978	900	±250
NELSON RIVER 2	AEG/BBC/SIEMENS	1985	2000	±500
SKAGERRAK I	ASEA	1976	275	±250
SKAGERRAK II	ASEA	1977	275	±250
SKAGERRAK III	ABB	1993	500	±350
SHIN-SHINANO 1	HITACHI/TOSHIBA/NIS SHIN	1977	300	125
SHIN-SHINANO 2	HITACHI/TOSHIBA/NIS SHIN	1992	300	125
SQUARE BUTTE	GENERAL ELECTRIC	1977	500	±250
DAVID A. HAMIL	GENERAL ELECTRIC	1977	100	±50
CAHORA-BASSA	AEG/BBC/SIEMENS	1977/78/79	1920	±533
C.U.	ASEA	1979	1000	±400
HOKKAIDO-HONSHU	ASEA	1979	150	125
HOKKAIDO-HONSHU	HITACHI/TOSHIBA	1980	300	250
HOKKAIDO-HONSHU	HITACHI/TOSHIBA	1993	600	±250
ACARAY	SIEMENS	1981	50	±25.6
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1981	355	1X170(±85)

VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1982	710	2x170
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1984	1065	3x170
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1999	4x405	±85
ZHOU SHAN PROJECT		1982	50	100
INGA-SHABA	ASEA/GE	1982/83	560	±500
DUERNROHR 1 (retired from service)	AEG/BBC/SIEMENS	1983 (1997)	550	145
EDDY COUNTY	GENERAL ELECTRIC	1983	200	82
CHATEAUGUAY	BBC/SIEMENS	1984	2x500	2x140.6
OKLAUNION	GENERAL ELECTRIC	1984	200	82
ITAIPU 1	ASEA	1984	1575	±300
ITAIPU 1	ASEA	1985	2383	±300
ITAIPU 1	ASEA	1986	3150	±600
ITAIPU 2	ASEA	1987	3150	±600
BLACKWATER	BBC	1985	200	57
SACOI	CGEE/ALSTHOM	1985	50	200
SACOI THREE TERMINAL	ANSADO/GENERAL ELECTRIC	1993	300	±200
HIGHGATE	ASEA	1985	200	±56
MADAWASKA	GENERAL ELECTRIC	1985	350	130.5
MILES CITY HVDC SYSTEM (MCCS)	GENERAL ELECTRIC	1985	200	82
BROKEN HILL	ASEA	1986	40	2x17 (±8.33)
INTERMOUNTAIN POWER PROJECT (I.P.P.)	ASEA	1986	1920	±500
CROSS CHANNEL BP 1+2	CGEE-ALSTHOM/GEC-ALSTHOM	1985/86	2000	±270
DES CANTONS-COMFERFORD	GENERAL ELECTRIC	1986	690	±450
QUEBEC-NEW ENGLAND THREE TERMINAL	ABB	1990-92	2250	±450
VIRGINIA SMITH	SIEMENS	1987	200	50
GESHA (GEZHOUBA-SHANGHAI)	ABB/SIEMENS	1989	600	500
GESHA (GEZHOUBA-	ABB/SIEMENS	1990	1200	±500

SHANGHAI)				
VINDHYACHAL	ASEA	1989	500	2x69.7
McNEILL	GEC ALSTHOM	1989	150	42
FENNO-SKAN	ABB/ALCATEL	1989/98	572	400
FENNO-SKAN 2		PLANNED 2010	800	500
BARSOOR LOWER SILERU	BHEL	1989/91	100	±200
BARSOOR LOWER SILERU	BHEL	FUTURE	400	
RIHAND-DELHI	ABB/BHEL	1991	750	500
RIHAND-DELHI	ABB/BHEL	1992	1500	±500
NICOLET TAP	ASEA	1992	2000	
SAKUMA	HITACHI/TOSHIBA/MIT SUBISHI/NISSHIN	1993	300	±125
ETZENRICHT (retired from service)	SIEMENS	1993 (1997)	600	160
VIENNA SOUTH-EAST (retired from service)	SIEMENS	1993 (1997)	600	145
URUGUAIANA	TOSHIBA	1994	50	15
BALTIC CABLE	ABB	1994	600	±450
WELSH	SIEMENS	1995	600	162
KONTEK	ABB/NKT CABLES	1995	600	400
HAENAM-CHEJU	GEC ALSTHOM	1997	300	±180
CHANDRAPUR-RAMAGUNDUM	GEC ALSTHOM	1997/98	1000	2x205
CHANDRAPUR-PADGHE	ABB	1998	1500	±500
LEYTE-LUZON	ABB/MARUBENI	1998	440	350
VISAKHAPATNAM	GEC ALSTHOM	1998	500	205
MINAMI-FUKUMITZU	HITACHI/TOSHIBA	1999	300	125
VIZAG 1	GEC ALSTHOM	1999	500	205
VIZAG 2	ABB	2005	500	±88
KAALAMO		PLANNED 1999	40	20
NORTH-SOUTHEAST		PLANNED 1999	1000	
SWEPOL LINK	ABB	2000	600	±450
DIRECTLINK	ABB	2000	3 x 60	±80
KII CHANNEL	HITACHI/TOSHIBA/MIT SUBISHI	2000	1400	±250
KII CHANNEL		FUTURE	2800	±500
GARABI 1	ABB	2000	1100	±70
GARABI 2	ABB	2002	2000	±70
RIVERA	GEC ALSTHOM	2000	70	20

GRITA	PIRELLI/ABB	2001	500	400
TIAN-GUANG	SIEMENS	2001	1800	±500
HIGASHI-SHIMIZU	HITACHI/TOSHIBA	2001	300	125
MOYLE INTERCONNECTOR	SIEMENS	2001	2x250	2x250
THAILAND-MALAYSIA	SIEMENS	2001	300	±300
MANTARO-SOCABAYA		PLANNED 2001	300	±190
CROSS SOUND	ABB	2002	330	±150
MURRAYLINK	ABB	2002	200	±150
SASARAM	GEC ALSTHOM	2002	500	205
IB VALLEY-JAIPUR		PLANNED 2002	3000	
EUROCABLE		PLANNED 2002	600	500
RAPID CITY TIE	ABB	2003	2 x 100	±13
EAST-SOUTH INTERCONNECTOR	SIEMENS	2003	2000	±500
BAKUN			2130	3x±500
STOREBAELT		PLANNED 2010	600	400
THREE GORGES-CHANGZHOU	ABB/SIEMENS	2003	3000	±500
THREE GORGES-GUANGDONG	ABB	2004	3000	±500
GUI-GUANG	SIEMENS	2004	3000	±500
TROLL A	ABB	2004	2x40	±60
LEYTE-MINDANAO		PLANNED 2004	400	
VIKING CABLE		PLANNED 2004	600	450
LAMAR	SIEMENS	2005	211	±63
EAST-WEST ENERGY BRIDGE		PLANNED 2005	500	600
EAST-WEST ENERGY BRIDGE		PLANNED 2010	1000	
ICELAND-SCOTLAND LINK		PLANNED 2005	550	400
ICELAND-SCOTLAND LINK		FUTURE	1100	±400
NORWAY-UK		PLANNED 2005	800	
MEPANDA UNCUA		PLANNED 2006	500	
BASSLINK	SIEMENS	2006	500	400
ESTLINK	ABB	UNDER CONSTRUCTION 2006	350	150
LEWIS DE-ICER	AREVA	UNDER CONSTRUCTION 2006	250	±17.4
LONG ISLAND CABLE PROJECT		2007	600	±450
TEXAS-COLORADO		PLANNED 2007	400	

RUSSIA-CHINA		PLANNED 2007	2500	
NORNED		UNDER CONSTRUCTION 2007	700	±450
THREE GORGES-SHANGHAI		UNDER CONSTRUCTION 2007	3000	±500
NEPTUNE	SIEMENS	UNDER CONSTRUCTION		±500
SAPEI	ABB	PLANNED 2008/09	500	±500
CHINA-RUSSIA (HEIHE)		PLANNED 2008	750	
NORTHEAST-NORTH (GOALING)		PLANNED 2008	1500	
YUNNAN-GUANGDONG		PLANNED 2009	5000	800
LINGBAO EXPANSION		PLANNED 2009	750	
AL FADHILI	AREVA	UNDER CONSTRUCTION 2009	3 x 600	3 x 222
HUGO INTERTIE		PLANNED 2010	375	
STOREBAELT		PLANNED 2010	600	400
FAREAST (RUSSIA) - NE CHINA		PLANNED 2010	3000	
HULUNBEIR (INNER MONGOLIA) - SHENYANG		PLANNED 2010	3000	
NINGXIA-TIANJING		PLANNED 2010	3000	
NW-SICHUAN (BAOJI-DEYANG)		PLANNED 2011	3000	
NORTH SHAANXI-SHANDONG		PLANNED 2011	3000	
SHANDONG-EAST		PLANNED 2011	1200	
GEZHOUBA-SHANGHAI EXPANSION		PLANNED 2011	3000	
XIANJIABA-SHANGHAI		PLANNED 2011	6400	800
JINGPING-EAST CHINA		PLANNED 2012	6400	800
NORTH-CENTRAL		PLANNED 2012	1000	
JINGHONG-THAILAND		PLANNED 2013	3000	
XILUODU-HUNAN		PLANNED 2014	6400	800
LABRADOR-NEWFOUNDLAND (LOWER CHURCHILL PROJECT)		PLANNED 2015		
IRKUTSK (RUSSIA) - BEIJING		PLANNED 2015	6400	800

XILUODU-HANZHOU		PLANNED 2015	6400	800
NUOZHADU-GUANGDONG		PLANNED 2015	6400	800
HUMENG-SHANDONG		PLANNED 2015	6400	800
JINSHA RIVER II - EAST CHINA		PLANNED 2016	6400	800
HUMENG-TIANJING		PLANNED 2016	6400	800
GOUPITAN-GUANGDONG		PLANNED 2016	3000	
HUMENG-LIAONING		PLANNED 2018	6400	800
JINSHA RIVER II - FUJIAN		PLANNED 2018	6400	800
HAMI-C.CHINA		PLANNED 2018	6400	800
JINSHA RIVER II - EAST CHINA		PLANNED 2019	6400	800
TALCHER-BANGALORE	SIEMENS	FUTURE	2000	±500
CEPA (RASPIER-RAJASTHAN)		FUTURE	2000	500
ISACCEA		FUTURE	600	
OUTAOUAIS		FUTURE	2x625	
POLAND-LITHUANIA		FUTURE		
UK-NETHERLANDS		FUTURE		

The above HVDC List was based on the 2005 version of the CIGRE Compendium of HVDC Schemes Throughout the World.

Initial changes to the CIGRE list were made by incorporating changes from:

Mike Barhman, ABB - January 2006

Neil Kirby, AREVA – April 2006

Robyn Taylor, Teshmont - modifications based on the detailed descriptions from the 2005 version of CIGRE AG B4.04, COMPENDIUM OF HVDC SCHEMES THROUGHOUT THE WORLD

Robyn Taylor, Teshmont - modifications based on the IEEE HVDC Projects Listing, January 2000 Issue

C
APPENDIX

Service Life, Cost Breakdown and Replacement Time

Table C-1

Category	Typical Percent of Cost (%)	Equipment	Items	Estimated Service Life (Years)	Representative Replacement Outage Time (Hours)
AC & Auxiliary Equipment	9%	a) AC Filters	Capacitors	25	Maint.
			Resistors	40	Maint.
			Air Reactors	25	Maint.
			Oil Reactors	35	Maint.
		b) Reactive Compensation	Capacitors	25	Maint.
			Air Reactors	25	Maint.
			Oil Reactors	35	Maint.
		c) AC Circuit Breakers		35	64 †
		d) Interrupting Switches		20	32 ††
		e) Circuit Switchers		25	32 ††
		f) Disconnecting Switches		35	32 †
		g) Surge Arresters		35	8
		h) Carrier Wave Traps		20	8
		i) Buswork, Insulators & Structures		50	Maint.
		j) AC Control & Protection		15	Maint.
		k) Instrument Transformers		30	12
		l) Cooling Systems		15	*
	19%	m) Converter Transformers		40	†††
	13%	n) Civil Works		50	Maint.
	2%	n) Auxiliary Power & Equipment	Chargers	20	12
			Batteries	15	24
			Transformer	40	12

Thyristor Valves	20%	Thyristor Levels		30	670
HVDC Control and Protection	7%	a) Analog Electronics		25	Maint.
		b) Digital Electronics		15	670
		c) Power Supplies	UPS	10	Maint.
		d) DFR and SER		15	Maint.
		e) SCADA		10	Maint.
		f) Communication Systems		10	Maint.
		HVAC System	Boilers Unitary Packaged Equipment	20 15	
DC Equipment	5%	a) DC Smoothing Reactor	Oil	35	120
			Air	25	40
		b) DC Switching Equipment		35	Maint.
		c) DC Ground Electrode		40	Maint.
		d) DC Surge Arresters		35	Maint.
		e) DC Filters		20	Maint.
		f) DC Wall Bushings		35	Maint.
		g) DC Instrumentation	Current	30	Maint.
			Voltage	30	Maint.
		h) Buswork, Insulators & Structures		50	Maint.
Other	8%	a) Erection & Commissioning		na	NA
	10%	b) Engineering		na	NA
	5%	c) Freight & Insurance		na	NA
	2%	d) Project Administration		na	NA

Notes:

1. Maint. => replace as required as part of maintenance.
2. NA => not applicable.

† Normal breaker removal can take 24 hours and installation of a new breaker up to 40 hours.

†† Ordinary switch removal takes 8 hours and installation of a new switch up to 16 hours. If a motor operator is part of the replacement add an additional 8 hours.

††† Transformer replacement has been done in 24 hours at converter stations equipped with rail systems and quick disconnect control wiring. If heavy cranes are required, the time for

replacement is dependent on their availability. Oil handling if required will add many days to the outage. Each utility should access their limitations and abilities.

*   Valve cooling system estimated life cycles vary with individual system designs and component selection. Fifteen years is a conservative estimate representing the most susceptible of component arrangements.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1012516

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com