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INTERIM REPORT ON THE STATE-OF-THE-ART
OF SOLID-STATE MOTOR CONTROLLERS.
PART 4. FAILURE-RATE AND
FAILURE-MODE DATA

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INTERIM REPORT
ON THE STATE-OF-THE-ART OF SOLID-STATE MOTOR CONTROLLERS:
PART 4 - FAILURE RATE AND FAILURE MODE DATA

ABSTRACT

An assessment of the reliability of solid-state motor controllers for nuclear power plants is made. Available data on failure-rate and failure-mode data for solid-state motor controllers based on industrial operating experience is meager; the data are augmented by data on other solid-state power electronic devices that are shown to have subcomponents similar to those found in solid-state motor controllers. In addition to large nonnuclear solid-state adjustable-speed motor drives, the reliability of nuclear plant inverter systems and high-voltage solid-state dc transmission-line converters is assessed. Licensee Event Report analyses from several sources, the open literature, and personal communications are used to determine the reliability of solid-state devices typical of those expected to be used in nuclear power plants in terms of failures per hour.

EXECUTIVE SUMMARY

As part of a program to assess the use of solid-state motor controllers in commercial nuclear power plants, the development of a reliability data base using industrial experience is warranted. Our investigations showed that there is no organized and consistent reporting system on the reliability of solid-state motor controllers in industrial applications and there is very limited use of solid-state motor controllers in nuclear power plants. There was, therefore, no possibility of using the monthly utility-generated Licensee Event Reports directly as a source of failure data on solid-state motor controllers. It was possible, however, to use the Licensee Event Reports indirectly by studying the failures of the widely used solid-state inverters, which supply uninterruptible power to vital-instrument busses. All subcomponents of these static inverters are found in solid-state motor controllers and are susceptible to the same failure modes.

The reliability of inverters used in nuclear power plants was studied using References 1, 2, and 3. Our assessment of these sources indicates that for periods between 1972 and 1983 and for an experience base of as many as 2644 inverter-years, the failure rate was in the range of 1 to 2×10^{-5} failures/hour.

In the development and use of large-load commutated-inverter adjustable-

speed motor drives, both General Electric and Westinghouse have estimated the reliability of such motor drives based on experience with subcomponents but have not compiled reliability data on complete units. The solid-state motor controllers range up to 17,500 hp in size and have a calculated reliability of from 5 to 12×10^{-5} failures/hour and availabilities of 99.9%. Reliability in these units can be enhanced greatly by the use of redundant and parallel subsections.

A very well-organized system for collection of reliability data on high-voltage dc transmission-line converters exists worldwide. Ten transmission systems using solid-state converters of 320-1920 MW each were assessed for the period 1979-1980. Unit reliability was found to be 51.2×10^{-5} failures per hour and availability 99.0%. Redundancy is not reflected in this design.

It is evident from the data that size and complexity of solid-state devices play a very large part in determining their reliability, and that the solid-state semiconductors themselves are only a minor contributor to the total failure rate.

1. INTRODUCTION

Solid-state motor controllers are being considered by industry for use in nuclear power plants. A solid-state motor controller (SSMC) is a device composed of electronic components (e.g., integrated circuits, microcomputers, fiber optics, high-power transistors, and silicon-controlled rectifiers) arranged to control the starting, stopping, operating, and fault characteristics of AC and DC motors, and maintain them safely within their design parameters. The purpose of the project for which this report is being written is to investigate the use of solid-state motor controllers in nuclear power plants to determine whether their use would be acceptable from a regulatory standpoint.

This interim report covers work performed since the initiation of the program at Argonne National Laboratory in March 1983. It covers Task 2.2.1 of the Statement of Work: "Compile failure rate and failure mode data base for solid-state motor controllers and associated circuits for use in estimating their reliability." The specific objective is to determine if SSMCs currently on the market are sufficiently reliable for use in safety systems in nuclear

power plants.

2. NUCLEAR POWER PLANT INVERTER EXPERIENCE AS A BASIS FOR SSMC RELIABILITY ESTIMATION

Although there is only very limited evidence of the use of solid-state motor controllers (SSMCs) in nuclear power plants, we have estimated probable failure rates of these devices should they be so employed. In dealing with SSMCs, failure rates generated from computer, microprocessor and instrumentation and control equipment experience may be of limited value due to the much-lower power ratings of these components. We have sought instead to learn from the experience gained on heavier-duty solid-state devices presently used in nuclear power plants. Although they are not motor controllers, devices such as battery chargers and inverters

Are of sufficiently high power to be of interest,

Use many of the subcomponents found in SSMCs, and

Are presently used in nuclear power plants in safety-related, Class 1E applications, including vital-instrument bus-power supplies and diesel-generator field supplies and controls.

Because failure data on these systems appear in the Licensee Event Reports (LERs), they are a good source of reliable data on utility experience with highly qualified, well-maintained equipment of a type very similar to SSMCs.

2.1 NRC INVERTER FAILURE ASSESSMENT

A summary of inverter failures [1]* indicates that in the seven years up to 2/11/81 there had been 186 inverter failures from all causes reported in operating nuclear power plants. Of these, 118 have been in PWRs, 64 in BWRs and 4 in HTGRs. Of particular significance was a group of 17 PWRs, representing ~97 reactor-years of operation, that have experienced 46 inverter failures resulting in 40 reactor trips and/or 20 safety injections. Assuming 4 inverters per plant, this would indicate an inverter failure rate of 0.118 inverters per reactor-year, or 1.35×10^{-5} failures/hr. Of this same group of 17 PWRs, the total number of reactor trips from all equipment failure causes for the same time period was ~344. Therefore, inverter failures alone caused ~12% of the total number of reactor trips during this time period in this group of PWRs. The causes for the 186 inverter failures in the group of 17 PWRs are shown in Table 1.

2.2 BNL UNPUBLISHED DATA

A more thorough evaluation of inverter failures was conducted by Brookhaven National Laboratory (BNL) using LERs from December 1972 to December 1981 and other Nuclear Safety Information Center (NSIC) data [2]. The BNL data were updated by ANL using LERs appearing in the monthly compilation

*Numbers in brackets [] are reference numbers.

Table 1. Inverter Failure Causes in 17 Selected PWRs
Totalling 97 Reactor-Years of Experience

Failure Cause	Number of Incidents
Unidentified cause	40
Current/voltage surges	22
Human error	20
Capacitor	17
Silicon controlled rectifier	9
Input voltage trip	6
Diode	7
Excess ambient temp.	6
Constant voltage transformer	5
Mechanical	4
Oscillator card	3
Transistor	3
Transformer	3
Circuit board	3
Relay	3
Faulty components	2
Frequency card	2
AC/DC protection card	2
Choke	2
Resistor	5
Design w/o auto transfer	2
Fan motor	1
Output filter	1
Driver sync. board	1
Master logic board	1
Gate driver board	4
Dirty circuits	1
Local components overheating	1
Control module	7
Clock card	1
Power supply	2

reports from January 1982 through March 1983. The inverter failures considered included only those inverters associated with the 120-V ac vital-power systems supplying uninterruptible power to instruments and controls. The dc input to the inverters and the switchgear on the 120-V ac vital busses was not considered.

In most modern nuclear plants, 4 channels of uninterruptible power using an inverter in each are assigned among 2 or 4 instrument divisions. In older plants where high-rated inverters were not available, "master" and "slave" inverters frequently were used in parallel to achieve the required load demand.

During the last 10 years the design of the inverters has changed significantly. Four basic inverter designs currently are in use:

The ferroresonant transformer,

The quasisquare wave,

The pulse-width modulated, and

The step wave.

Although inverter designs vary greatly and are essentially "custom made" for Class 1E applications, certain basic similarities in design allow for allocation of specific failures to individual subcomponents. In general, the 120-V ac vital-bus inverters are composed of subcomponents, many of which are found in prototypic SSMCs. The inverter subcomponents are described in Table 2.

Table 2. Vital-Bus Inverter Subcomponents

Subcomponent	Function
Input circuit breaker	Interrupts high instantaneous input currents.
Over/under voltage detector	Monitors safe range of input voltage and prevents damage due to large transients through DC input filter (see below).
Reverse polarity detector	Prevents failed inverter from loading by its associated normal or emergency power source.
dc input filter	Protects dc lines from inverter-generated noise and protects inverter from unwanted modulation harmonics and excessive voltage spikes.
dc/ac inverter module Thyristors (SCRs)	Usually several bridge-connected units working together; firing pulse is applied to alternate pairs in each bridge by the drive module (see below).
Commutator/voltage surge suppression and snubber capacitors	Protect against commutation failure, over-load currents, and voltage changes and out-of-phase load currents.
Diodes and fuses	Additional protection against overcurrent and voltage changes.
Drive module	Provide gating currents for all SCRs. Generally contain as many amplifiers and output channels as there are SCRs. Amplifiers form the appropriate shape and magnitude of gating pulses obtained from the oscillator/synchronizer module (see below).
Oscillator and synchronizer module	Determines operating frequency of inverter and directs sequence pattern of driving pulses and regulates their phases.
Internal power supply	Provides power to drive module, oscillator and synchronizer module; usually of conventional design.
Harmonic reduction transformer	Ferroresonant transformer used in early inverters to decrease unwanted harmonics.
Output filter	Improves sine-wave characteristics with reactive elements.
Regulation and control module	Compares ac output voltage with stable reference voltage and applies the error signal to the drive module and/or synchronizing module.
Output circuit breaker/static transfer	Protects against load shorts and overloads automatic recovery feature.

Random failures, defined as those due to wear-out or failure of properly operated subcomponents, constitute the major source of plant inverter failures. Table 3 lists these subcomponents together with other specialized and miscellaneous components and gives the number of failure events reported for each in LERs between December 1972 and March 1983.

Table 3. Causes of Random Failures of Inverter Subcomponents
in Nuclear Power Plants, December 1972 through March 1983

Subcomponent	Number of Failures
Input circuit breaker	1
Over/under voltage and reverse polarity detector	9
dc input filter	4
dc/ac inverter module	
SCRs	11
Commutator/surge suppression/snubber capacitors	3
Diodes and fuses	7
Drive module	10
Oscillator and synchronizer module	13
Internal power supply	7
Harmonic reduction transformer	6
Output filter	16
Regulation and control module	11
Output circuit breaker/static transfer	10
Unidentified subcomponents	
Capacitors	6
Fuses	12
Mechanical failures	9
Failures due to unknown causes	26
Auxiliary transformers	5
Total random failures	166

In addition to random failures, several other categories of failure have been considered in analyzing the LER data:

Environmental effects include conditions that are incompatible with normal use, such as high temperature, high humidity, dirt, lightning, fire, etc.

Miscellaneous external failures involve failures whose cause have some common character, such as design error, manufacturing or installation failure, or incorrect operating instrumentation or procedure.

Human errors include failures caused by the plant personnel in normal operation or maintenance.

Transient failures are those unavoidable instances where the inverter is tripped correctly in response to various transients with no failed subcomponent resulting from the cause of the trip.

These nonrandom failures are further subdivided as shown in Table 4; also shown are the number of failure events reported for each in LERs in the same time period as those for the random failures in Table 3 and the percent of total represented by each subcategory.

Table 4. Causes of Nonrandom Inverter Subcomponent Failure in Nuclear Power Plants, December 1972 through March 1983

Failure Mode	Failures
	Number (% of Total)
Environmental effects	
High ambient temperature, low ventilation	15
Lightning	5
Dirt, foreign material	2
Subtotal	<u>20</u> (7%)
Miscellaneous external failures	
Design failure	4
Manufacturing/installation failure	3
Incorrect instruction	1
Subtotal	<u>8</u> (3%)
Human error	
Operation-related	25
Maintenance-related	23
Installation testing	1
Procedure-related	2
Subtotal	<u>51</u> (19%)
Transient failures	
Voltage/current transients resulting in open breakers/fuses	<u>29</u> (11%)
Total nonrandom failures	<u>108</u>
Total random failures (from Table 3)	166 (60%)
	<u>274</u> (100%)

The number of random inverter failures ($N_r = 166$, from Table 3) is an indication of the quality of the custom-made inverters to be found in nuclear plants and is a strong guide to the performance that could be expected from SSMCs. The total number of failures shown in Table 4 ($N_T = 274$) characterizes the availability and risk of inverters operating in a nuclear plant environment. Unfortunately, the LERs do not provide information about the time spent for repairs, so it is not possible to estimate the true availability of the inverters based on these reports.

The number of reactor-years of operating experience between December 1972 and March 1983 is estimated to be 661 reactor-years. Assuming four 120-V ac vital-bus inverters per plant for a total experience of 2644 inverter-years, the failure rates (λ) are:

$$\lambda(\text{random}) = \frac{166 \text{ (inv. failures)}}{2644 \times 9760 \text{ (inv. hr)}} = 0.717 \times 10^{-5} \text{ failures/hr}$$

and

$$\begin{aligned} \lambda(\text{total}) &= \frac{274}{2644 \times 8760} = 1.18 \times 10^{-5} \text{ failures/hr} \\ &= 0.104 \text{ failures/yr} \end{aligned}$$

2.3 NUCLEAR SAFETY ANALYSIS CENTER DATA

A third study of inverter failures was conducted by the Nuclear Safety Analysis Center of the Electric Power Research Institute [3]. In assessing I&C power supply hardware, the study showed that inverters were the leading cause of failure. The study detailed 181 reported failures, based again on LERs, but included (in addition to inverters) components of I&C power supplies other than just those associated with the 120-V ac vital instrument busses. In our analysis of this study, to obtain a failure rate we have determined the rate both with and without the non-inverter components included. Thus we consider the total I&C power supply, as shown in Figure 1, and the inverter only.

Fig. 1. Major Components in a Typical ICPS Configuration.

The typical I&C power supply has components that, except for the battery, can be found in most SSMCs. Unfortunately, the battery or battery charger is the chief failure source outside the inverter, hence our decision to consider both total I&C power supplies and inverters only.

Categorization of the failures in a manner similar to that used in Reference 2, both with and without battery related failures (29 of a total of 181 failures), results in the percentage distribution of failures shown in Table 5. The percentages of failures within these categories compare favorably with those given in Reference 2.

Table 5. Percentage Distribution of Categorized Failures

Failure Category	%, Based on Total Failures	%, Based on Total Less Battery Failures
Random failures	56	67
Human-error failures	10	12
Transient failures	7	8
Environmental failures	3	4
Miscellaneous failures	24	9

Reference 3 listed 181 failures in 50 different nuclear plants in the time period 1977-1981. Our estimate of the total reactor-years of nuclear plant operating experience for this time period is 251 reactor-years. By subtracting the failures attributable to batteries or battery chargers from the total we can determine, as nearly as possible, a failure rate on the same bases as in References 1 and 2. Clearly the Reference 3 data are not as complete as the Reference 2 data. Nevertheless, if we assume the same four inverters per plant and neglect the failures attributable to batteries or battery chargers, we arrive at the following failure rates:

$$\lambda(\text{total}) = \frac{(181-29) \text{ total failures not battery-related}}{(4 \times 251 \text{ inverter-years}) \times (8760 \text{ hr/yr})}$$

$$= 1.73 \times 10^{-5} \text{ failures/hr}$$

and

$$= 0.151 \text{ failures/yr}$$

$$\lambda(\text{random}) = \frac{0.67(181-29) \text{ random failures not battery-related}}{(4 \times 251) (8760)}$$

$$= 1.16 \times 10^{-5} \text{ failures/hr}$$

$$= 0.101 \text{ failures/yr.}$$

2.4 SUMMARY OF INVERTER RELIABILITY ESTIMATES BASED ON LERS

In summarizing the inverter failure rates determined from References 1, 2, and 3 (see Table 6), we are concerned that the estimates be compared on the same basis. Inaccuracies are present due to

The limited failure descriptions found in LERs,
 The operating time of each plant,
 The number of inverters in each plant,
 The precise boundary of the inverter component, and
 The number of plants considered in the analysis.

Lack of consistency in degree of detail and nomenclature used in LERs makes difficult their use for establishing reliability of a particular system or component.

Table 6. Inverter Reliability Estimates

Source	Time Period	Inverter-Yrs (4 per plant)	No. Failures from All Causes	Failure Rate per Hour
Ref. 1	1974-2/11/81	388	46	1.35×10^{-5}
Ref. 2	12/72-3/83	2644	274	1.18×10^{-5}
Ref. 3	1977-1981	1004	152	1.73×10^{-5}

The conclusion can be drawn from the Reference 2 and 3 studies that the principal cause of inverter failures is in random failures of inverter components. Detailing of specific failures into subcomponent categories is not possible with any degree of reliability due to the inconsistencies in LERs mentioned above.

3. RELIABILITY OF LARGE LOAD-COMMUTATED-INVERTER ADJUSTABLE-SPEED MOTOR DRIVES

One type of SSMC that has undergone major development is a system to provide variable frequency and voltage to an ac synchronous motor allowing motor operation over a wide speed range. Both General Electric and Westinghouse have developed this system, which uses load-commutated, phase-controlled power converter technology to supply power to the stator winding of a synchronous motor. Other types of solid-state motor drive systems also are widely used in industry, including

- dc drives,
- Self-commutated-converters,
- Forced-commutated inverters,
- Modified Kraemer drives, and
- Rectifier-inverter drives.

These systems differ in their circuitry but all contain similar subcomponents.

In reviewing the extent of usage of large solid-state speed control systems, we have found none employed in current or planned nuclear power plants. However, based on current General Electric and Westinghouse views, the most probable candidate for use in nuclear plants is the load-commutated inverter. General Electric, which has extensive experience with such inverters, has proposed to those utilities owning older BWR plants that they retrofit the main recirculating water pumps with load-commutated inverter drive systems, eliminating the motor-generator drive system currently in use. Although the variable-speed drive system for the recirculating water pumps is not safety-related, pump speed control is necessary to maintain proper void fraction in the reactor core with changing load. These pumps are generally 4000 hp or more and are the only large variable-speed motor-driven loads in current light-water reactor plants. Westinghouse also has extensively developed load-commutated inverters; this development was described in our Interim Technical Letter Report No. 2 ("State-of-the-Art of Solid State Motor Controllers Usage in Various Industries Including Nuclear," April 1983), where the extensive use of load-commutated inverters by Westinghouse for induced-draft fans in fossil energy plants was discussed.

3.1 GENERAL ELECTRIC DRIVE SYSTEM

In proposing to utilities the use of load-commutated inverters in place of motor-generator sets to provide variable frequency/voltage to main recirculating water pumps in BWR plants, GE has made some claims for reliability of their drive system. The reliability estimates are based on experience with principal subcomponents including the thyristors, and have been determined by combining subcomponent failure rates to give an overall rate.

In industrial applications, more so than in nuclear applications, an owner must be concerned with availability more than reliability. This is because availability in a nuclear plant often is dictated more by the time required to perform specific regulatory functions following an equipment failure, rather than the time required to repair. Because much of the downtime is attributable to functions not directly associated with actual repair, repair time loses much of its significance when nuclear power plant failures are considered. The relationship between availability, reliability, and time to repair is as follows:

$$\text{availability} = \frac{1}{1 + \frac{\text{MTTR}}{\text{MTBF}}},$$

where MTTR is mean time to diagnose, repair, checkout and return to service, and MTBF is mean time between failures.

Load-commutated inverter systems give high availabilities because of the relatively long MTBF and, more importantly, the short MTTR compared to rotating equipment. MTTR for static electric systems is generally less than 8 hours. However, in a nuclear plant the MTTR may not necessarily be the "critical path" in a return to power operation.

In analyzing the reliability of large load-commutated inverters for

synchronous motors [4], GE has divided the system into four broad categories of subcomponents and has assigned what they believe to be realistic failure rates to each category. Subcomponent categories, failure rates, and availabilities are shown in Table 7. Total system availability would be the product of the four subcomponent availabilities shown in the table.

$$\begin{aligned}\text{Total availability} &= 0.99917 \times 0.99975 \times 0.99993 \times 0.99997 \\ &= 0.9988.\end{aligned}$$

This availability value suggest that this system will be operating or capable of operating 99.88% of the time or be out-of-service 10.5 hours per year. More meaningful to a nuclear plant operator is the failure rate of the entire load-commutated inverter system, which is the sum of the subcomponent failure rates (12.09×10^{-5} failures per hour). As can be seen, this value is most heavily dependent on the failure rate assigned to the power and control electronic subcomponent, the greatest source of failures. The basis for the GE reliability values is GE's extensive experience with the conventional subcomponents (switchgear, transformers and reactors) and their carefully developed estimates of the solid-state device reliability.

Table 7. GE Load-Commutated-Inverter System Subcomponent Categories, Failure Rates, and Availability

Subcomponent	Failure Rate per Hour	MTBF (hr)	MTTR (hr)	Availability*
Power and control electronics	10.4×10^{-5}	9,578	8	0.99917
Switchgear	1.15×10^{-5}	86,956	21.6	0.99975
Transformers	0.34×10^{-5}	294,118	20	0.99993
dc reactors (filters)	0.16×10^{-6}	625,000	18	0.99997

*Percent of time; i.e., a subcomponent with an availability of 0.99917 would be operating or capable of operating 99.92% of the time.

The overall failure rate, 12.09×10^{-5} per hour, is conservative, based on GE data. A recent report by GE on load-commutated inverters [5] gives a somewhat lower failure rate. The report states that the MTBF has been significantly improved by manufacturing and quality control techniques and that the calculated MTBF for a load-commutated inverter of the type discussed above is 15,000 to 20,000 hours (6.67 to 5×10^{-5} failures per hour). The availability based on these failure rates is 99.95%, again due to the very short time for repair of these solid-state systems.

The reliability of load-commutated-inverter motor-drive systems can be improved by redundancy in both the power and control circuits. Redundant thyristors are typically included in the power circuit to provide rated power

output with one thyristor device failed in any of the converter legs. Redundant control can be achieved, but often leads to complexities that promote additional failures. A more favorable approach to redundancy is two completely independent power/control systems. This method, used by both GE and Westinghouse, simply parallels two six-pulse converter/inverter systems and uses their short-term emergency overload capabilities to achieve true redundancy.

3.2 WESTINGHOUSE DRIVE SYSTEM

The most significant development of load-commutated-inverter motor-drive systems has been conducted by Westinghouse and resulted in their "Varichron"* line of synchronous motor drives. Our Interim Technical Letter Report No. 2, ("State-of-the-Art of Solid State Motor Controllers Usage in Various Industries Including Nuclear," April 1983), lists Varichron systems currently in service and ordered--fifty-one systems totaling 331,900-hp. The typical circuit used is very similar to the General Electric designs and may be treated in common for purposes of reliability estimates. Of course, each inverter design, whether by Westinghouse or General Electric, is unique to its application but is sufficiently similar to the others to permit comparison.

Westinghouse has received operational reports on their Varichron units in service [6]. This type of customer report is difficult to use for establishing reliability values because of the bias placed on the report by the customer, whose Varichron unit may still be under warranty. As an example, Toledo Edison, who has had four 3500-hp Varichron units in boiler induced-draft fan application since 1980, reported 24 failures in the first year of operation. Westinghouse estimates that two-thirds of these were due to operator errors not related to equipment. The reliability assessments done by Westinghouse are used to satisfy customer requests or as a managerial decision tool to improve designs, and as such are specific to particular designs. From data produced for a 1200-hp unit at Texas Eastman Elliot, Westinghouse determined that the probability of operating the unit 2-1/2 years without a failure was 0.36.

Complete failure-rate estimates have been made by Westinghouse on typical large Varichron units based on published military specification data found in MIL-HDBK 217C and on some experience judgements. A typical Varichron failure rate, assuming no redundancy in a total 6- or 12-pulse drive system, was found to be 86.7 failures per 10^6 hours or 8.67×10^{-5} failures/hour at 25°C. Westinghouse stressed heavily the importance of low ambient temperature. They predicted that improved designs now in production will result in failure rates of 2 to 5×10^{-5} failures/hour, with the higher value result of operation at 40°C rather than 25°C ambient temperature.

In estimating failure rates, Westinghouse has used a widely accepted

*Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

value for thyristor reliability [7]; the reported mean-time-between-failure for thyristors was 1000 years or $\sim 0.011 \times 10^{-5}$ failures/hour.

4. HIGH-VOLTAGE DC TRANSMISSION-LINE CONVERTER RELIABILITY RELEVANT TO SSMC'S

As is the case with solid-state vital-bus inverter systems in nuclear plants, experience with high-voltage solid-state dc transmission systems is a good source of reliability data on components and integrated systems similar to those found in SSMCs. Several modern high-voltage solid-state dc transmission systems have been built that

- Rectify high-voltage ac at one end of a transmission line,
- Transmit power at high-voltage dc to a distant receiving station, and
- Invert the dc to ac for local distribution.

The circuits used in these conversion systems are similar to those used in the large load-commutated inverters for adjustable-speed motor drives, although of much higher capacity. Six- or 12- pulse convertor systems using large thyristor banks and a dc-link interconnection typify the designs used. One could think of a solid-state adjustable-frequency synchronous motor-drive system as a very short dc transmission-line conversion system.

At the end of 1980, worldwide there were 10 high-voltage dc transmission systems using solid-state conversion of ac to dc to ac. The dc transmission voltages range from 80 to 535 kV and power from 320 to 1920 MW. The reliability performance of these systems has been reported consistently by the utilities to Working Group 04 of Study Committee No. 14 of CIGRE and summarized every two or three years at an International Conference on Large High-Voltage Electric Systems. The latest report [8] has been selected as a source of reliability information pertinent to SSMCs. In the report, emphasis is placed on the availability of the transmission line rather than failure rates of components, and a distinction is made between failures causing forced outages and those not causing outages. These systems contain very large numbers of thyristors in series, where individual failed thyristors are replaced only during scheduled maintenance outages. For the reasons stated in Section 3.1, we will concern ourselves more with reliability than availability--chiefly, the reliability of families of equipment that cause forced outages. We believe these results are directly applicable to the same families of equipment in SSMCs.

Table 8 lists the 10 high-voltage dc (HVDC) solid-state transmission systems in world service in 1979-1980. The magnitude of these systems is reflected in their total capacity (6606 MW) and in the total number of power thyristors used (74,680). Data given in Reference 8 allow categorization of failures into families of equipment that typify SSMCs as well as HVDC systems. In Table 9, the 10 HVDC systems are listed again, together with the numbers of failures occurring in 5 categories of equipment.

Table 8. Worldwide Solid-State High-Voltage DC Transmission Systems, 1979-1980

System (Country)	Year of Commission	Capacity (MW)	Type of Converter	Total No. of Thyristors	Operating Time in 1979-80 (hr)
Eel River (Canada)	1972	350	12-pulse	9,600	17,257
Skagerrak (Denmark)	1976-77	500	12-pulse	6,912	13,140
Hamil (USA)	1977	110	12-pulse	2,880	13,841
Cahora-Bassa (S. Africa)	1977-79	1920	6-pulse	22,656	10,161
Vancouver (Canada)	1977-79	476	6-pulse	8,640	14,804
Square Butte (USA)	1977	550	12-pulse	6,912	16,732
Shin-Shinano (Japan)	1977	300	6-pulse	5,184	16,469
Nelson River (Canada)	1978	1000	12-pulse	9,216	5,431
Hokkaido-Honshu (Japan)	1979-80	300	-	2,712	1,664
CU (USA)	1979	1100	-	8,640	7,358
		<u>6606</u>		<u>74,680</u>	<u>116,857</u>

Table 9. Component Failures Causing HVDC System Outages in 1979-1980

System	Number of Component * Failures					Total
	AC-E	Thyristors	C&P	DC-E	Other	
Eel River	28	3	36	1	10	78
Skagerrak	17	1	15	3	1	37
Hamil	3	1	0	1	1	6
Cahora-Bassa	38	0	170	13	10	231
Vancouver	18	3	6	26	13	66
Square Butte	19	2	32	5	19	77
Shin-Shinano	0	0	2	0	0	2
Nelson river	19	0	22	23	21	85
Hokkaido-Honshu	0	0	1	0	1	2
CU	5	2	2	2	3	14
Total	147	12	286	74	79	598

*AC-E (ac and auxiliary equipment) - all ac power equipment for the HVDC station, including converter transformers, conventional ac protection, and ac auxiliary equipment.

Thyristors - the complete array forming the converter bridge, including all auxiliaries and components integral with the thyristors and part of the array.

C&P (control and protection equipment) - equipment used for the control, monitoring, and protection of each HVDC station, except the conventional type, which is included in "ac and auxiliary equipment."

DC-E (primary dc equipment) - dc equipment including dc reactor, dc switchgear, reactor surge arresters, dc filters, earth electrodes, etc.

Other - unknown and operator errors.

Table 9 indicates a high total number of failures (598). However, as stated earlier, the operating utilities are concerned mainly with outage duration, not with numbers of failures. The 598 failures caused only 1,160 hours of downtime out of a total operating time of 116,857 hours (from Table 8), for an unavailability of about 1%. This is an acceptable unavailability for a HVDC transmission system compared to the normal scheduled maintenance downtime of 1-5%.

Of greatest relevance to SSMCs is the reliability of the thyristors in these HVDC systems. The surprisingly low total of only 12 thyristor failures

out of 74,680 thyristors in 116,857 operating hours is deceptive. HVDC systems are designed such that from one to four thyristors are connected in parallel to form a thyristor "level," referring to voltage level. A very large number of levels in series constitute the total solid-state "valve." For a thyristor failure to cause an outage and thus qualify for Table 9, it must cause, by itself or in combination with others in series, a loss of the entire valve. This is unlikely because HVDC systems are conservatively designed to allow operation with a number of thyristors failed by shorting, awaiting a scheduled outage to be routinely replaced. One of the reasons for such thorough reporting of HVDC system failures is to study thyristor reliability in an effort to optimize the number of excess levels of thyristors in a bridge leg so that prolonged operation with failed thyristors can take place with minimum likelihood of total valve failure.

A direct calculation of the failure rates (λ) of the five categories of equipment that cause outages can be made using Tables 8 and 9. We should be cautious in comparing these failure rates with those given in Section 2 of this report. We are dealing with a very small number of units (10), individually much more complex than an ac vital-bus inverter.

Failure rates of the five equipment categories (see Table 9) are:

AC-E (ac and auxiliary equipment)

$$\lambda_{AC-E} = \frac{147 \text{ (failures)}}{10 \text{ (no. of units)} \times 116857 \text{ (hrs)}} = 12.6 \times 10^{-5} \text{ failures/hr,}$$

Thyristors (total valve failure)

$$\lambda_{thy} = \frac{12}{10 \times 116857} = 1.03 \times 10^{-5} \text{ failures/hr,}$$

C and P (control and protection equipment)

$$\lambda_{C \text{ and } P} = \frac{286}{10 \times 116857} = 24.5 \times 10^{-5} \text{ failures/hr,}$$

DC-E (primary dc equipment)

$$\lambda_{DC-E} = \frac{74}{10 \times 116857} = 6.33 \times 10^{-5} \text{ failures/hr, and}$$

Other

$$\lambda_o = \frac{79}{10 \times 116857} = 6.76 \times 10^{-5} \text{ failures/hr.}$$

The total failure rate for an HVDC system resulting in an outage is 51.2×10^{-5} failures/hour.

Data on numbers of level failures not necessarily causing outages are given in Reference 8. By assuming that each level failure is caused by one thyristor failure regardless of the number of parallel thyristors in a level, one can estimate the individual thyristor failure rate, knowing the operating time and number of thyristors from Table 8. In Table 10, the number of levels and corresponding number of thyristors for each system, number of failed levels, and resulting thyristor failure rates are given.

HVDC systems occasionally have failures involving many levels of thyristors that are not due to thyristor defects. This occurred in the 1979-80 period at Skagerrak and CU. The multiple failures are not included in Table 10. The average failure rate for thyristors in HVDC in 1979-80 is 0.025×10^{-5} per hour, or about 0.22% per year.

Table 10. Thyristor Failure Rates in HVDC Systems

HVDC System	Total Levels	Total Thyristors	Failed Levels, 1979-80	Thyristor Failure Rate per Hour
Eel River	2,400	9,600	69	0.042×10^{-5}
Skagerrak	6,912	6,912	16	0.018×10^{-5}
Hamil	720	2,880	12	0.030×10^{-5}
Cahora-Bassa	11,328	22,656	24	0.010×10^{-5}
Vancouver	4,320	8,640	23	0.018×10^{-5}
Square Butte	6,912	6,912	20	0.018×10^{-5}
S'in-Shinano	3,744	5,184	3	0.004×10^{-5}
Nelson River	4,608	9,216	15	0.030×10^{-5}
Hokkaido-Honshu	2,712	2,712	0	0
CU	8,640	8,640	52	0.082×10^{-5}

5. SUMMARY

We should be very cautious in comparing solid-state-system failure rates derived from systems vastly different in size and complexity, or between systems meeting different objectives. Table 11 shows the variance in failure rates between the systems discussed in this report. The conclusion that larger systems are less reliable than smaller systems is not unexpected and is reflected in the failure rates.

In the case of load-commutated synchronous motor drives, loss of function can be significantly improved by redundancy, as is already done for ac vital-bus inverters.

Table 11. Summary of Solid-State System Reliability

Source	Type of System	Basis for Determination	System Failures per Hour
Ref. 1	Nuclear plant ac vital-bus inverters	398 inverter-years	1.35×10^{-5}
Ref. 2	Nuclear plant ac vital-bus inverters	2644 inverter-years	1.18×10^{-5}
Ref. 3	Nuclear plant I&C power systems less batteries	1004 inverter-years	1.73×10^{-5}
Ref. 4	GE load-commutated adjustable-speed drives for synchronous motors	Calculation from component experience	12.09×10^{-5}
Ref. 5	GE load-commutated adjustable-speed drives for synchronous motors	Calculation from component experience	5 to 6.67×10^{-5}
Ref. 8	World-wide HVDC transmission-line converters	20 converter-years	51.2×10^{-5}

REFERENCES

1. NRC Letter, J.E. Knight, Operating Experience Evaluation Branch, DST/NRR, to E. Adensam, Acting Chief, Operating Experience Evaluation Branch, DST/NRR, subject, "Inverter Failures," March 19, 1981.
2. G. Bozoki and I.A. Papazoglou, "Analysis of Inverter Failures in Nuclear Power Plants," Dept. of Nuclear Energy, Brookhaven National Laboratory, unpublished draft report (April 1983).
3. J.S. Bhatti, "Investigation of Failures in I&C Power Supply Hardware" by International Engineering Co., Inc., for the Nuclear Safety Analysis Center, NSAC-44, (Dec. 1981).
4. Personal Communication with Herbert W. Weiss, General Electric Co., Drive Systems Dept., Salem, Va, June 24, 1983.
5. Herbert W. Weiss, "Power Transmission to Synchronous Machines for Adjustable-Speed Pump and Compressor Drive Systems," IEEE 29th Annual Petroleum and Chemical Industry Conference Record, August 30-September 1, 1982, St. Louis, Mo.
6. Personal communication with David Hawkins and Neville Jacobs, Westinghouse Electric Co., Quality Assurance Dept., Buffalo, N. Y., July 12, 1983.
7. L.F. Stringer, "Synchronous Motor Adjustable Frequency Drive Systems for Large Mechanical-Draft Fans," Pro. Am. Power Conf., Vol. 42, April 21, 1980.
8. J. Knudsen and P.F. Albrecht, "A Survey of the Reliability of HVDC Systems Throughout the World During 1979-80," CIGRE International Conference on Large High Voltage Electric System, Sept. 1-9, 1982, Report No. 14-06.

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