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OPERATING EXPERIENCE AND AGING-SEISMIC ASSESSMENT OF BATTERY CHARGERS AND INVERTERS

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ABSTRACT

This report provides an assessment of the aging of battery chargers and inverters which are vital components of the nuclear power plant electrical safety system, and was conducted under the auspices of the NRC Nuclear Aging Research (NPAR) Program. The objectives of this program are to identify concerns related to the aging and service wear of equipment operating in nuclear power plants, to assess their possible impact on plant safety, to identify effective inspection, surveillance, and monitoring methods, and to recommend suitable maintenance practices for mitigating aging-related concerns and diminish the rate of degradation due to aging and service wear.

Battery charger and inverter design and materials of construction are reviewed to identify age-sensitive components. Operational and accidental stressors are determined, and their effect on promoting aging degradation are assessed. Variations in plant electrical designs, and system and plant level impacts have been studied. Failure modes, mechanisms, and causes have been reviewed from operating experiences and existing data banks. The study has also considered the seismic correlation of age-degraded components within battery chargers and inverters.

The performance indicators that can be monitored to assess component deterioration due to aging or other accidental stressors are identified. Conforming with the NPAR strategy as outlined in the program plan, the study also includes a review of current standards and guides, maintenance programs, and research activities pertaining to nuclear power plant safety-related battery chargers and inverters.

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SUMMARY

An aging assessment of battery chargers and inverters was conducted under the auspices of the NRC Nuclear Plant Aging Research (NPAR) Program. The intentions of this program are to resolve issues related to the aging and service wear of equipment and systems at operating reactor facilities and to assess their impact on safety.

Inverters and battery chargers used in nuclear power plants perform significant functions related to plant safety and availability. The specific impact of a battery charger or inverter failure varies with plant configuration. Operating experience data have demonstrated that reactor trips, safety injection system actuations, and inoperable emergency core cooling systems have resulted from inverter failures; and dc bus degradation leading to diesel generator inoperability or loss of control room annunciation and indication have resulted from battery and battery charger failures. For the battery charger and inverter, the aging and service wear of subcomponents have contributed significantly to equipment failures.

To identify aging and service wear effects and appropriate inspection/surveillance/monitoring techniques, it was necessary to examine potential failure modes, mechanisms, and causes. This was achieved by reviewing Battery Charger and Inverter design and materials of construction, by establishing the stressors that are both operational and accident related, and by reviewing existing failure related data. Aging-seismic correlation was addressed during this phase of the program. An interim review of current standards, manufacturer's recommendations, and condition monitoring techniques was performed to aid in the determination of future work.

The three types of battery charger designs are the Silicon Controlled Rectifier (SCR) solid state type, the controlled ferroresonant, and the magnetic amplifier (mag amp). Although all three types are used at nuclear facilities, the SCR or thyristor solid state charger is most commonly used, making up nearly 75% of the population, and, in fact, is the only charger type that is qualified to IEEE-323 and IEEE-650.

Four basic inverter designs are currently in use: the ferroresonant transformer, the pulse-width modulated, the quasi-square wave, and the step wave. The first two types are used most often, with the last two types making up less than 20% of the inverter population.

The charger and inverter subcomponents most susceptible to aging are capacitors, transformers and inductors, and silicon controlled rectifiers (including diodes). High voltage, current, humidity, or temperature will affect all these components. A large number of charger and inverter failures have resulted from fuse operation. Some of these failures may be due to thermal fatigue of the fuse. This possibility will be investigated further.

Plant configurations help determine battery charger and inverter reliability. Those plants that have a standby charger or a second full capacity charger generally are the most reliable. For inverters, those plants with transfer switches, which allow a separate bypass ac feed appear to be the most reliable. Those plants with rectifiers providing an alternate dc feed to the inverter, have not been nearly as reliable.

The weak links that may be susceptible to seismic excitation are cabinet mountings to floor or wall, subcomponent mountings, wire and cable connections, relays and circuit breakers, transformers, oil filled capacitors, and fuse holders.

Battery charger and inverter failures exhibit the typical "bathtub" curve when plotted against component age. That is, a high number of failures occur in the first year of operation with a pronounced wear-out effect in the fifth and sixth years of operation.

Over a nine year period, forty two reactor trips have been attributed to inverter failures, thereby demonstrating the safety significance of this component. Inoperable Emergency Core Cooling Systems (ECCS) and inadvertent safety system actuations have also been attributed to inverter failures.

Specific utility source information is presented which demonstrates that battery charger and inverter performance can be improved through a comprehensive preventive maintenance program supported by appropriate personnel training. In addition, a review of some of the key subcomponents employed in both battery chargers and inverters reveals that certain performance indicators may be effective in predicting failure due to aging of the equipment, several of which may be performed while the equipment is supplying station loads.

Because of the extensive systems interactions related to charger and inverter failures, it is recommended that proper procedures be in place to respond to these potential failures. Additionally, periodic capacity testing should be conducted to ensure that the capability of this equipment to supply the required loads is not diminished because of the aging of key components. Capacity testing, while performed by many plants for battery chargers, is not regularly conducted for inverters.

Future work, in accordance with the NPAR strategy, will consist of testing naturally aged battery chargers and inverters under normal and accident conditions to validate the performance indicators. Additionally, final recommendations will be established for inspection, surveillance, monitoring, and maintenance programs.

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1.0 INTRODUCTION

1.1 Background

Nuclear power plants use battery chargers and inverters to supply power to safety-related equipment, instrumentation, and controls. A battery charger converts alternating current (ac) to direct current (dc) to provide power to dc-driven equipment and components as well as to keep the standby batteries fully charged. Some plants are designed with a standby charger in addition to the required number of units (typically two to four per plant). On the other hand, inverters are used to supply ac-power to safety related equipment and equipment important to plant operation after converting the dc-power source to an ac output. A typical plant design requires at least two such units to distribute power to various control equipment vital to power and safe shutdown operations. Plant systems such as the Reactor Protection System (RPS), Emergency Core Cooling System (ECCS), Reactor Core Isolation Cooling (RCIC) System, and the ac/dc distribution system use these devices to satisfy certain nuclear power station safety requirements. Loss of a battery charger or inverter could significantly impact plant safety due to any of these systems becoming inoperable.

Both battery chargers and inverters are considered together in this study because of their similarities in design, construction, parts and materials. The sub-components, particularly the electronic elements such as diodes, relays, capacitors, integrated circuits, etc. are the same in both equipment. They also serve related safety functions in the plant and experience the same environment as well as similar operational stresses. In recent years, improvements in design and construction have been made on chargers and inverters to mitigate some of the earlier problems associated with their older counterparts. Despite the continuous effort in improving the product, this equipment can fail because of a malfunction or failure of one or more subcomponents such as capacitors, fuses, and relays. Because of their safety implications, it is absolutely necessary to detect defects and, if possible, to characterize charger and inverter performance to assure their availability during all phases of plant operation, including postulated accident conditions.

Surveys [1] of several failure data sources which are based on the operating experience of control devices in nuclear power plants within the United States have indicated that battery chargers and inverters significantly contribute to the loss of power to essential ac and dc loads. Several studies by government agencies [2] and industry organizations [3] have suggested some measures to improve reliability. However, these studies have concentrated primarily on the inverter failures rather than battery charger, and used only one of the failure data bases.

A comprehensive study of battery charger and inverter aging, service wear, and the potential for degradation due to operational as well as accident stresses is essential. Development of a cost effective maintenance and surveillance program based on successful monitoring techniques identified by this study can improve plant safety and performance. In achieving this goal, it will be important to understand the functions of this equipment during both normal power operations and accident events.

During normal power operation, battery chargers have the dual role of supplying dc loads while maintaining the station batteries in a fully charged state. In the event of a loss of ac power, which renders the battery charger inoperable, the batteries must be fully charged in order to have sufficient stored capacity to meet the design requirements for safe shutdown of the reactor. These specific design requirements are identified in the plant Final Safety Analysis Report (FSAR) and generally specify that the battery be capable of supplying safety-related equipment following a loss of ac power for up to eight hours.

In addition, once ac power is restored either from offsite or from the emergency diesel generator, the charger must be capable of supplying dc loads while recharging its associated battery within the required time frame. A simplified sketch of one dc bus, including the battery charger, is illustrated in Figure 1-1. Included in this figure is the boundary assumed for NPAR failure analysis, namely, from the input to the output circuit breakers inclusively. The importance of maintaining an adequate dc power supply is best illustrated by highlighting some of the dc loads typically found in BWRs and PWRs. These include:

- Emergency diesel generator controls and field excitation circuitry
- Auxiliary feedwater and Emergency Core Cooling System logic
- Inverters for vital ac systems and instrumentation
- Switchgear and electrical load center control power
- Reactor trip and protection systems
- Main Turbine Generator protection functions (non-safety)

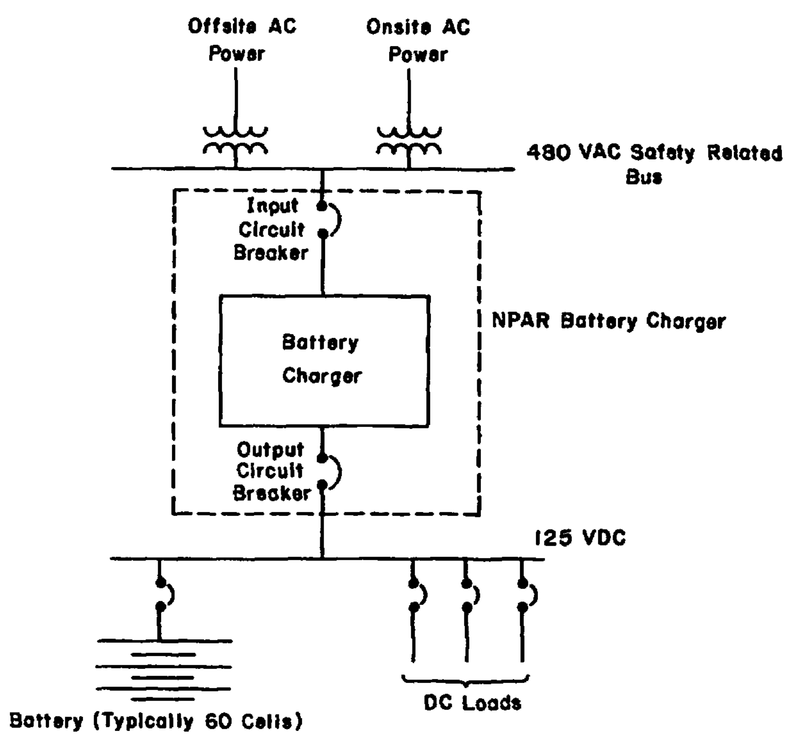


Figure 1-1: Simplified Sketch of Nuclear DC System

During normal operation, the inverter is generally supplied by the dc bus (battery charger) and provides power to important 120 volt ac loads. These loads are both safety and non-safety related. Upon a loss of ac power to the station, the inverter output is uninterrupted, since the dc bus remains energized from the battery. The dc power is converted to ac power by the inverter to maintain the vital bus energized. An alternate supply to the vital bus from a reliable ac supply is typically provided, and in some cases automatic switching between power sources is also available. A simplified sketch of one vital bus is provided in Figure 1-2. Included here is the boundary assumed for the inverter, i.e., input breaker to output breaker inclusively. The ac loads supplied by the inverters include:

- Emergency Core Cooling Instrumentation and Logic
- Feedwater Controls (non-safety)
- Annunciators
- Neutron Flux Monitoring
- Reactor Protection System
- Emergency Diesel Generator Auxiliaries

As illustrated in the lists of equipment typically supplied by battery chargers and inverters, maintenance of these important components in an operable condition is essential both to reactor safety and to plant availability. Despite the use of redundant equipment and buses, failures, especially inverter failures, have resulted in reactor trips, inadvertent safety system injections, and emergency core cooling system unavailability. Within the program outline and guidance provided by the Nuclear Plant Aging Research (NPAR) Program [4] sponsored by the NRC Office of Research, a comprehensive examination of the aging and service wear characteristics of battery chargers and inverters was conducted using the operating plant experience data. Particular emphasis was given to the root causes of subcomponent degradations based on several failure data bases. The significant consequences of inverter and charger failures necessitated a review of the various configurations used by the nuclear industry in their dc and vital ac supply schemes. The differences found among plant electrical system designs were also analyzed to determine if system level transients on the charger and inverter varied as a result of the system design. In addition, the charger and inverter types, construction, and materials were reviewed in detail, with special attention to the age and/or wear related aspects of these areas.

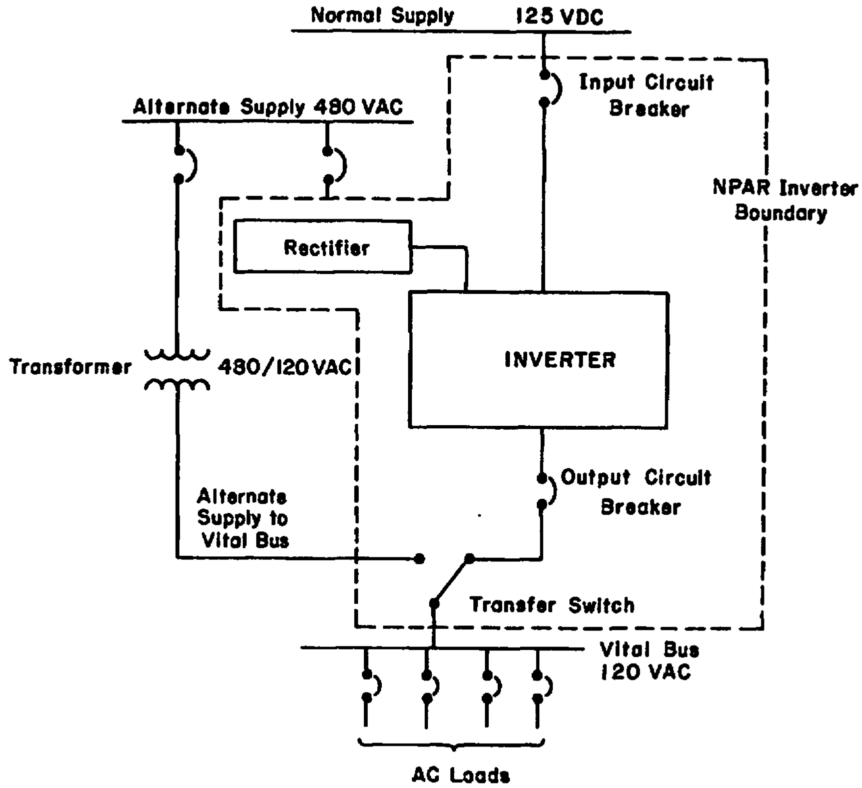


Figure 1-2: Simplified Sketch of Inverter and Vital AC System

1.2 Objective

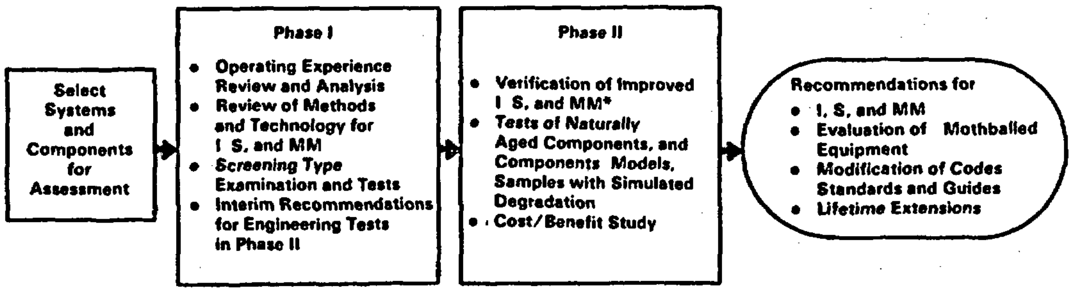
In accordance with the NRC-NPAR Program Plan, the following are the primary goals of the study:

1. To identify and characterize aging and service wear effects which, if unchecked, could cause degradation of structures, components, and systems and thereby impair plant safety.

2. To identify methods of inspection, surveillance and monitoring, or of evaluating residual life of structures, components, and systems, which will assure timely detection of significant aging effects prior to loss of safety function.

3. To evaluate the effectiveness of storage, maintenance, repair, and replacement practices in mitigating the effects of aging and diminishing the rate and extent of degradation caused by aging and service wear.

To achieve these goals for the equipment, a number of subtasks must be accomplished such as a detailed review of the operating experience of this equipment at nuclear facilities, a detailed review of the operation of the equipment, and an analysis of the operational, environmental, and accident related stressors. Figure 1-3 delineates the phase one subtasks as well as other program goals.



* I, S, and MM - Inspection Surveillance and Monitoring Methods

Figure 1-3: Research Approach - NPAR Program

1.3 Scope

In characterizing the aging and service wear effects of battery chargers and inverters, this study considers the predominant designs used by the nuclear industry, including the size and arrangement of this equipment in operating stations. It is to be noted that this equipment is typically located in mild environments and is not subject to containment level environmental parameters. Because of their importance for safe shutdown of the plant, this equipment is required to be environmentally and seismically qualified according to industry standards. A discussion of the effects of component performance under operational and environmental conditions is provided. Several failure data bases including Licensee Event Reports (LER), In-Plant Reliability Data Systems (IPRDS), Nuclear Plant Reliability Data Systems (NPRDS), and Nuclear Power Experience (NPE) are reviewed to determine the failure modes, causes and mechanisms experienced in recent years by the nuclear industry and to set priorities for the most significant modes of failures. The study also includes a discussion of manufacturer recommendations for maintaining reliable equipment, as well as a review of industry and government standards relating to testing and maintaining of this equipment. Standards from the Institute of Electrical and Electronics Engineers (IEEE) and the National Electrical Manufacturers Association (NEMA) specifically address battery chargers and inverters.

The four types of inverters and three battery charger types currently used in nuclear applications are discussed in detail with the advantages and disadvantages of each type noted. Equipment size varies with the electrical bus configuration used at the plant, with larger sizes typically employed on a two-division configuration vs. a four-division design. Exceptions to this occur when individual utilities add non-safety but operationally important loads to the inverters or chargers which dictate that a larger unit be employed. The data received indicated a range of station battery charger sizes from ratings of 100 to 600 amps, while station inverter sizes ranged from ratings of 5 to 200 kilowatts. For inverters, data were also collected for specific application inverters such as those used with the HPCI, RCIC, and Auxiliary Feedwater systems. These smaller inverters are generally rated less than one kilowatt. Some lower voltage battery chargers (24 and 48 volts) were also included in the data if a significant effect was clearly indicated, such as a loss of nuclear instrumentation. Manufactured by the same suppliers of the larger station chargers which usually operate at 125 volts, these smaller units were found to operate on the same principles and contain the identical components as the larger units.

In several reports which discuss uninterruptible power systems in a nuclear power plant, "typical" arrangements of battery chargers and inverters are presented. Perhaps the most commonly represented configuration is the two division ac/dc electrical distribution system illustrated in Figure 1-4. Although used in only a small number of plants, generally the older designs, this simple arrangement is useful in depicting the relationships of offsite power supplies, emergency diesel generators, battery chargers, batteries, and inverters. Worthy of note are the following:

- The ac supply to the battery charger is from a safety related source connected to the emergency diesel generators.
- The output of the battery charger is connected to the battery which provides the dc input to the inverter, a dc input to the emergency diesel generators, dc control power to safety and non-safety switchgear, and dc control power to switchyard devices.
- The inverter is connected in parallel with a supply from the safety related bus to power the "vital" ac bus.
- The two divisions are electrically isolated at the charger/inverter with no cross-connect capability, in order to satisfy the single failure criteria.

The study will analyze the various charger/inverter configurations and compare them to the failure data reviewed for this report to determine if a correlation between design and failure effect exists.

1.4 Strategy

To determine the entire scope of inverter and battery charger failures, it was first necessary to review and analyze the operating experiences of this equipment in nuclear power plants. In contrast to previous studies of this equipment, this was accomplished by an in-depth review of Licensee Event Reports (LERs), the Nuclear Plant Reliability Data System (NPRDS), the In-Plant Reliability Data System (IPRDS), Nuclear Power Experience (NPE) data, and direct correspondence with various nuclear plants. These data were input to a computerized data base to allow easy sorting by various categories such as failure mechanism, failure mode, and failure effect.

To evaluate these important data, several sources of information were called upon to obtain the design, construction, and materials information for battery chargers and inverters typically used in nuclear power plant applications. Manufacturers of the equipment provided detailed instruction manuals including schematics. Tours of charger and inverter manufacturing facilities also enhanced our understanding of the testing performed and the assembly work involved.

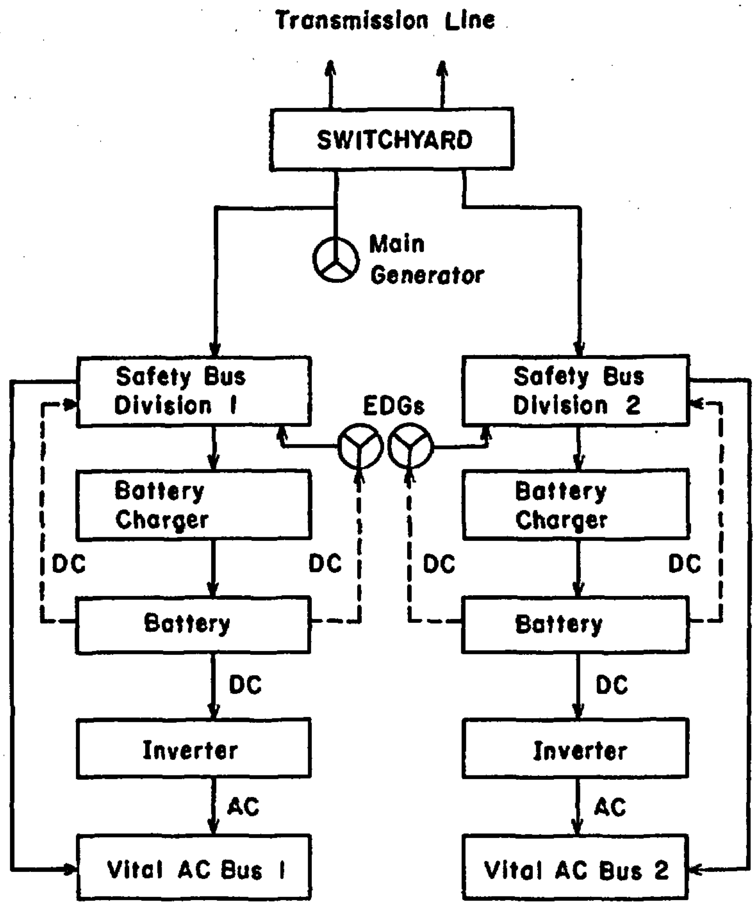


Figure 1-4: Typical Two Division Electrical Distribution System

Expert knowledge and industry practice experience were sought through discussions with Ebasco Services and nuclear power station maintenance personnel. The objective of these discussions was to analyze reported failures to determine aging and service wear significance, to determine system interaction effects, and to identify current inspection, testing, and maintenance practices. Equipment qualification reports obtained from one battery charger manufacturer and one inverter manufacturer also provided insight into component operating ranges for voltage, current, and temperature including limitations on the qualified life of certain components based on accelerated aging techniques.

Section 2 of this report provides a general understanding of charger and inverter construction, design, and principles of operation. Contained here are the technical descriptions of the types of chargers and inverters used in the nuclear industry, including a description of system configurations. Section 3 describes the internal and external stressors contributing to equipment failure and how these stressors relate to normal, accident, and seismic events. Section 4 describes in detail the data evaluation from the sources used relating these failures to the time domain and emphasizing the impact of equipment failure on safety system performance and plant availability. An interim review of methods and technology available for inspection, surveillance, and monitoring as defined by industry standards and regulatory guides is presented in Section 5, while Section 6 summarizes the efforts in this report and describes the direction of activity to achieve the results required in phase 2 including a discussion of the performance indicators which may be monitored to determine equipment degradation prior to failure.

2.0 BATTERY CHARGER AND INVERTER OPERATING CHARACTERISTICS

This section describes the materials, construction, and operating principles of the battery chargers and inverters used in nuclear power plants. It provides a detailed description of the various types of battery chargers and inverters employed by the nuclear industry as well as some of their key components. An analysis of these key components and their material characteristics is presented. Failure of subcomponents under normal/accident conditions and its impact on the overall performance of the equipment are discussed.

2.1 Battery Charger Types and Principles of Operation

The basic feature common to all ac to dc converters is that they are connected to a source of ac voltage which, through a rectification process, provides a dc power output. A number of circuits are used in this process, ranging from the simple half wave single phase rectifier used for low current dc power supplies to the three phase multipulse converters commonly used in nuclear battery charger applications. The three types of battery charger designs that will be described are the Silicon Controlled Rectifier (SCR) solid state types, the controlled ferroresonant battery charger, and the magnetic amplifier (mag amp) circuit based charger. Although all three types are used at nuclear facilities, the SCR or thyristor solid state type charger is the most widely used charger in safety related nuclear applications making up nearly 75% of the charger population, and, in fact, it is the only type now qualified to IEEE-323-1974 [5] and IEEE 650-1979 [6]. The mag amp and controlled ferroresonant type chargers comprise the remaining types used and are approximately equal in population. The advantages of each type are summarized in Table 2-1.

As illustrated in Figure 2-1, the basic circuit capable of providing a continuous dc output to a load from an ac input consists of two diodes. A diode is an electronic device that allows normal current flow in one direction only. Diode 1 conducts during the positive ac cycle with diode 2 used to maintain a closed dc load circuit by conducting during the negative half periods of the ac supply. The periodic conduction from one rectifier element to another as the input current changes is called the commutation process. It occurs at the instant that the respective diode voltages are the same. Full wave rectification is achieved which results in a uniform output current wave form.

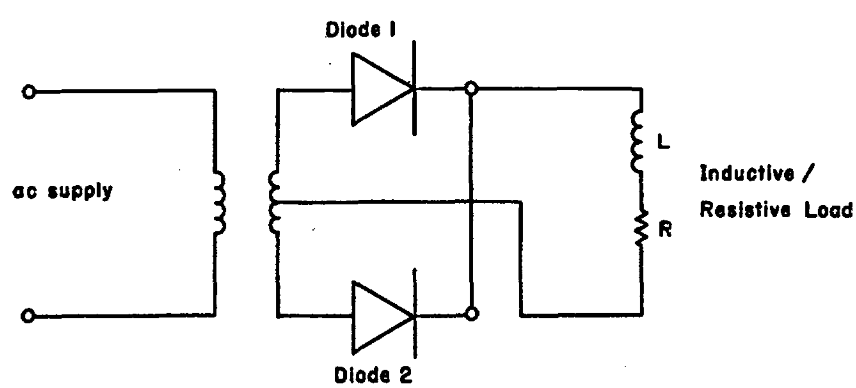


Figure 2-1: Basic AC to DC Conversion Circuit

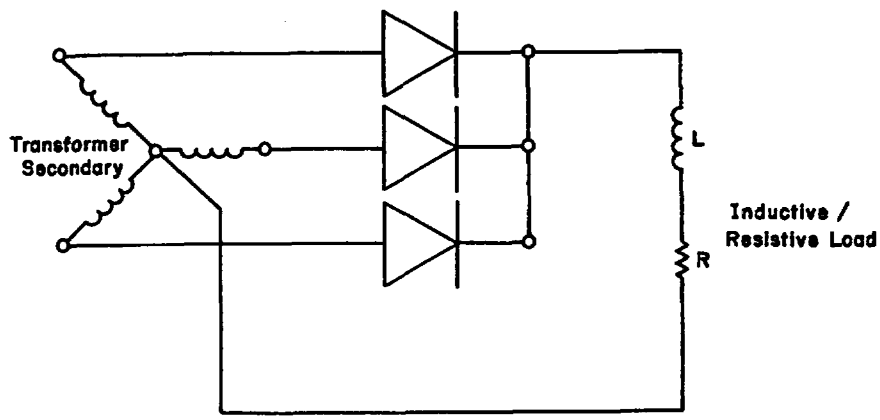


Figure 2-2: Three Phase ac to dc Conversion Circuit

Extension of this basic arrangement to the three phase application most common to large industrial chargers produces the circuit illustrated in Figure 2-2. Because each phase of the three phase supply is 120 degrees out of phase with each of the other phases, a forward voltage is applied to two diodes simultaneously. The diode with the greatest positive (forward) voltage will conduct and conduction will be commutated naturally from one diode to the next as the ac input voltage waveform progresses. The dc output voltage fluctuation compared with the single phase operation is reduced.

In the configurations of Figures 2-1 and 2-2 the ac-dc conversion is considered uncontrolled. When the diodes are replaced by thyristors, however, a fully controlled converter is achieved. [A thyristor, often called a silicon controlled rectifier (SCR), is a diode that blocks current flow in either direction until a third terminal on the device, called a gate, is pulsed with a positive voltage. This pulsing, often called firing, controls the conduction time of the thyristor which changes the output voltage amplitude (shown schematically in Figure 2-3.)] The average dc output voltage can therefore be controlled by changing the point at which the thyristors are fired, thereby forcing commutation to occur as required by load demands.

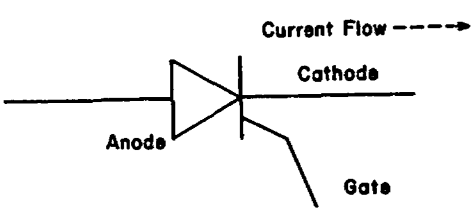


Figure 2-3: Thyristor Schematic Symbol

A circuit with two diodes and two SCRs is used most often to provide the rectification process. The more complex SCR fired battery chargers like the ones used in nuclear power plants also use a "freewheeling diode". This diode provides a current path when the terminal voltage instantaneously tends to go negative as in the case when no thyristors are conducting. A bypass is therefore provided for inductive load currents if the supply was disconnected. At the same time, the output wave shape is improved as a result of filtering accomplished by the diode.

2.1.1 SCR Solid State Charger

The SCR solid state type battery charger employs SCRs (thyristors) with integrated circuit and transistor control circuits to satisfy variable load requirements while maintaining its associated battery fully charged. The basic operation of this type of charger is illustrated in the block diagram of Figure 2-4.

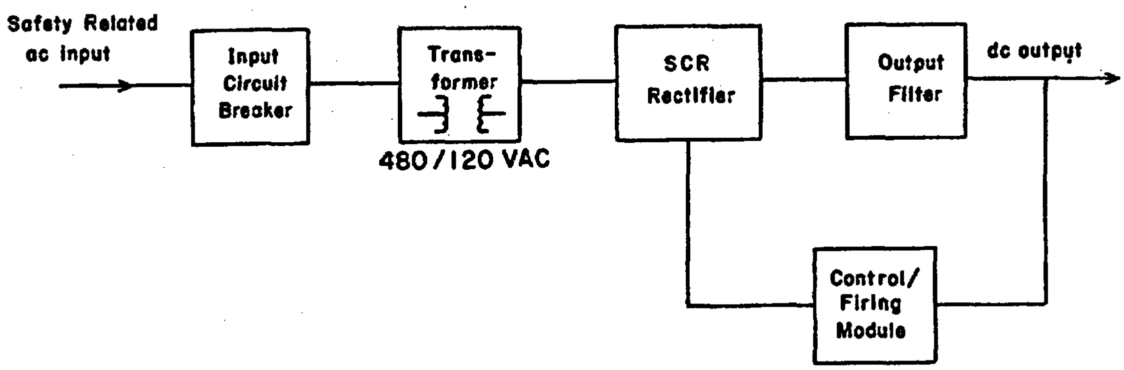


Figure 2-4: SCR Solid State Type Charger

As with other types of battery chargers, power is provided from a safety related ac source through an input circuit breaker which is an integral part of the charger unit. Most commonly used is a 3 pole thermal magnetic molded case circuit breaker. Power, usually 480 volts ac, is then reduced to 120 volts ac by a transformer which supplies the full wave rectifier. The thyristors and diodes making up the rectifier maintain a constant average voltage output dc value. The rectifier output voltage is filtered to eliminate harmonics and ripple depending upon the application. For most nuclear applications, a maximum of 2% ac ripple, which is the imposed ac on the dc output, is permitted. The dc output which is routed to dc loads through a circuit breaker, also provides feedback to the solid state control and firing circuits which generate pulses to the SCR gates to maintain proper voltage regulation.

Figure 2-5 is a block diagram of a three phase battery charger revealing some additional details found in SCR solid state type chargers. While circuit arrangements and terminology may differ from one manufacturer to another, the basic description that follows is common.

A three-phase ac input voltage is supplied to three power transformers, one phase to each transformer. The transformers change the voltage level of the ac input and provide isolation between the ac and dc circuits. The transformer secondaries feed three rectifier units, each unit being a full wave bridge consisting of two SCRs and two silicon diodes, or four SCRs. The SCRs are used to control the dc output as well as for rectification. Control is accomplished by regulating the conduction time of the SCRs, which is done by providing pulses to the SCR gates. The outputs of the rectifiers are tied together in parallel so that current is additive. The rectified output is then fed to the dc output of the charger through an output filter consisting of choke(s), capacitor(s), and resistor(s) arranged to reduce the ripple from several volts to the millivolt level.

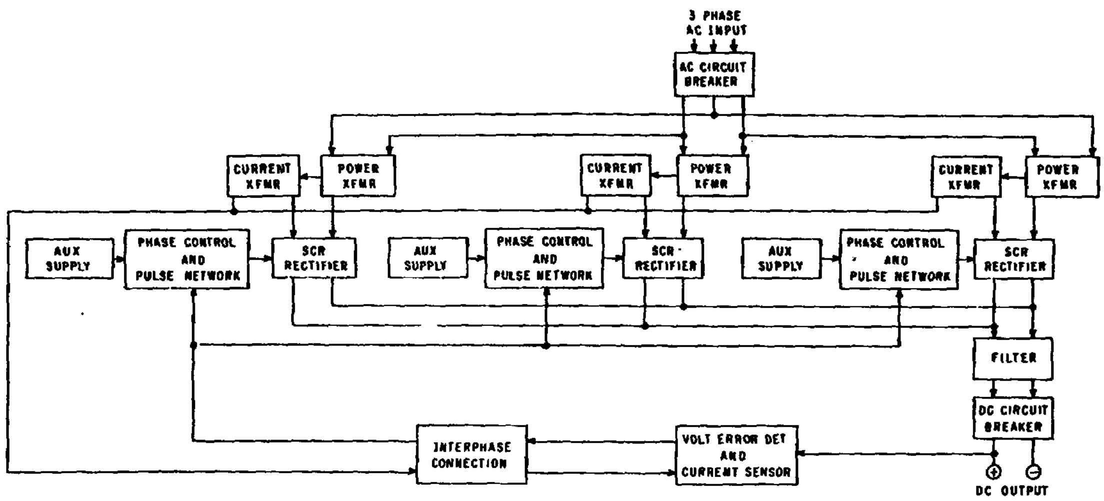


Figure 2-5: Block Diagram of Typical Three Phase SCR Type Battery Charger

The control circuits consist of three parts as illustrated by Figure 2-5: a phase controlling circuit, a voltage sensing circuit, and a current sensing circuit.

The phase controlling circuit consists of several printed circuit boards. each controlling a pair of SCRs in a rectifier unit. The purpose of these boards is to form pulses that will turn on the SCRs at the proper time. The earlier in the cycle the SCRs are turned on, the more output is produced.

The voltage sensing circuit compares the output voltage with a reference voltage produced within the circuit. When an error develops between the output voltage and the reference voltage, an error signal is fed to the phase controlling boards causing them to fire the SCRs at the proper time to maintain the output voltage.

The current sensing circuit receives a signal from the current transformers. When the output current increases beyond the current limit setting, the signal from the current sensing circuit overrides the voltage sensing circuit and feeds a signal to the phase control boards which fires the SCRs at the time necessary to limit the output current to the set level.

Another board that is part of the control circuits ties the signal from the voltage sensing and phase controlling circuit boards to the signal from the current transformers. This ensures that the outputs from each of the rectifier units are at equal levels.

Power is provided to the control circuits by three auxiliary transformers, each with fused secondaries. The primaries of these transformers are connected to auxiliary windings on the power transformers. The secondary voltages of the auxiliary voltage transformers are in phase with the power transformer voltages that supply the rectifier units. These voltages supply the phase control boards which in turn control voltage and frequency of the rectifier units.

An ac circuit breaker on the input to the charger protects the charger from overloads and short circuits and serves as the disconnect means when maintenance is being performed on the charger. AC input capacitors are frequently installed to dampen any voltage distortions created by the firing of the SCRs that could feedback to the ac source. Fuses on the rectifier units also protect the rectifier against overload currents. A surge suppressor, consisting of a capacitor and resistor in series, may be connected across the rectifier unit to prevent high voltage spikes from appearing across the rectifier unit. Surge suppression may also be provided by selenium rectifiers or metal oxide varistors designed to reduce voltage transients to a level that will not damage the power diodes or thyristors (SCRs). A dc circuit breaker on the output of the charger protects against external faults and allows the battery to be connected to the charger without causing arcing due to the capacitors charging or discharging. Contacts are typically supplied on the ac and/or dc circuit breakers to provide local and/or remote alarm capability.

2.1.2 Controlled Ferroresonant Battery Charger

The conventional Ferroresonant Constant Voltage Transformer sometimes referred to as a CVT, is the heart of the controlled ferroresonant battery charger and has been used extensively in the past on dc power supplies. In that application, its function was to correct for line voltage variations and transform an input voltage to the level required by the rectifier and dc circuit. At a constant frequency, any increase in voltage results in increased exciting current for the saturable transformer. As illustrated by Figure 2-6, the output winding is connected in series opposition with a buck winding to reduce the change in output voltage in response to input voltage changes.

In modern battery chargers the conventional ferroresonant transformer is modified to obtain the desired output control necessary. Although the conventional design provides satisfactory voltage regulation, high efficiency, and transient suppression capability, this modification was necessary to improve the input frequency sensitivity characteristics of the conventional ferroresonant circuit to meet the design performance requirements for a highly regulated battery charger. This modification makes use of the control capabilities of solid state circuitry to externally regulate against line, load, and (most important) frequency variations.

Developed within the past ten years, the controlled ferroresonant type charger offers a higher efficiency and tighter voltage regulation than the SCR types. Although not environmentally qualification tested to nuclear industry standards, it appears capable of meeting those requirements since it contains components similar to those of equipment that has satisfactorily completed environmental qualification testing.

The block diagram in Figure 2-7 depicts the use of the CVT in a battery charger application . The ac output from one of the transformer secondary windings is rectified by a circuit consisting of diodes and is filtered prior to supplying dc loads. The dc output voltage is monitored and regulated through the use of a control circuit which provides an input back to the transformer secondary. Within this control circuit may be discrete devices such as an operational amplifier, zener diode, triac, saturable reactor and/or a capacitor to provide the necessary monitoring and regulation.

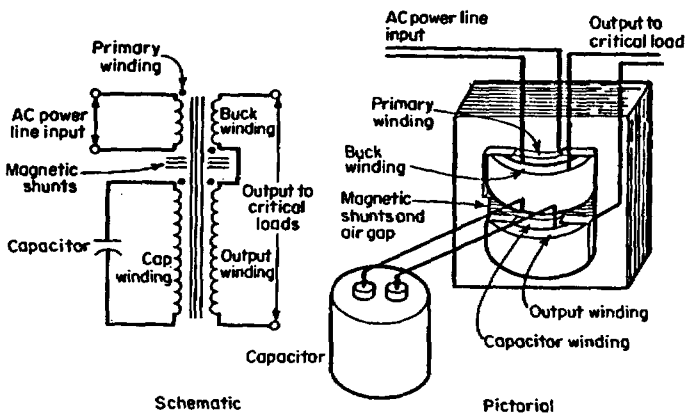


Figure 2-6: Ferroresonant Transformer [7]

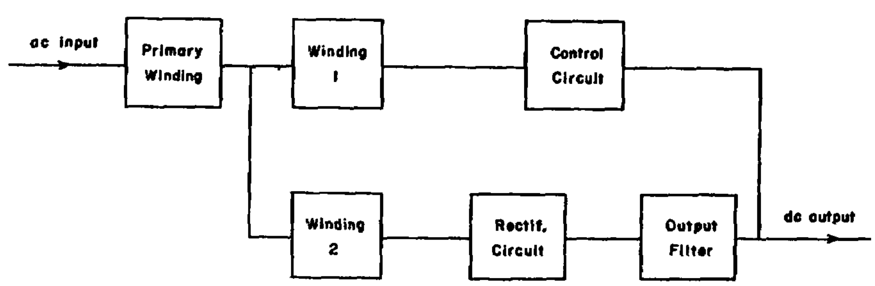


Figure 2-7: Block Diagram of Ferroresonant Charger

2.1.3 Magnetic Amplifier Battery Charger

A third type of battery charger design found in nuclear applications uses a magnetic amplifier (mag amp)circuit. Mag amps resemble transformers in construction and are considered rugged and reliable devices. Making use of a device known as a saturable reactor, the mag amp is used in battery charger applications by connecting it in series with a rectifier and a transformer to obtain a constant dc output independent of the supply voltage. By definition [8], a saturable reactor is an adjustable inductor in which the current versus voltage relationship is adjusted by controlling the inductor core properties. This same source defines a magnetic amplifier as "a device using saturable reactors either alone or in combination with other circuit elements to secure amplification or control." A small dc input to the mag amp provided by feedback from the output voltage is sufficient to modify its impedance characteristic due to the particular magnetic core design selected. The impedance change directly affects the dc output voltage obtained.

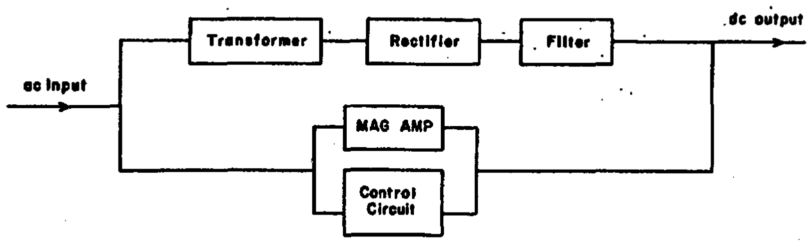


Figure 2-8: Magnetic Amplifier Type Battery Charger

Figure 2-8 is a block diagram of a mag amp battery charger application in use at several operating nuclear power plants. This charger has five basic components: transformer, mag amp (saturable reactor), rectifier, output filter and a transistorized control circuit. The transformer's function is identical to that of the transformer discussed previously, that is, to transform the incoming ac voltage to the level required by the internal battery charger components while isolating the incoming power from the output. Likewise, the filter circuit is very similar to other chargers. The rectifier is made up of silicon diodes connected in a full wave center tap or full wave bridge configuration. The transistorized control circuit monitors the output from the filter and, by application of a transistor which effectively shunts or bypasses the mag amp, is able to control the saturation condition of the mag amp. The mag amp ultimately regulates the power output of the transformer because it changes impedance as it moves in and out of saturation as a result of the transistor shunting operation. When the mag amp departs from saturated operation, the impedance increase causes a reduction in the transformer primary voltage, thus decreasing the charger output. The impedance balance of the transformer reactor combination compensates for a line voltage variation of approximately 10% of the nominal ac voltage specified on the nameplate, making it therefore relatively immune to the input voltage changes typically seen in power plant applications [9]. Control of the primary voltage versus control of the secondary voltage is the significant difference between the mag amp and ferroresonant circuit.

In summary, magnetic amplifiers make use of the property of saturable reactors to control large amounts of power by means of small currents. They provide sensitive amplification by means of feedback paths, which introduce a small part of the ac load current after rectification into a control winding of the saturable reactor. Combined with semiconductor rectifiers, the mag amp charger is a rugged device frequently employed in commercial applications and in use at some older nuclear stations.

Table 2-1: Summary Comparison of Battery Chargers

	SCR SOLID STATE	CONTROLLED FERRORESONANT	MAGNETIC AMPLIFIER
1. Simple logic		X	
2. Simple output filter	X	X	X
3. High efficiency		X	
4. Regulating range		X	X
5. Transient Response Time	X		
6. IEEE 650-1979 Qualified	X		
7. Low Cost			X
8. Ruggedness			X
9. Low noise generation		X	X
10. Low Susceptibility to Transient		X	X
11. Adjustable current limiting	X		
12. Load carrying capability (range)	X		

2.2 Inverter Types and Principles of Operation

The basic inverter converts dc to ac power thereby providing low voltage ac to vital plant equipment and instrumentation from a reliable source of power - the station battery. In addition to dc to ac conversion, the inverter must also maintain a constant frequency output and a regulated output voltage with minimal distortion in order to ensure satisfactory performance of the instrumentation and controls typically supplied by the inverter.

The simplest inverters include switching devices which have the ability to interrupt current flow. Because silicon controlled rectifiers have a high power rating and can provide very fast and reliable switching action, they are utilized as the switching device in nuclear power plant inverters.

The inverter is composed of the following functional components as illustrated in Figure 2-9.

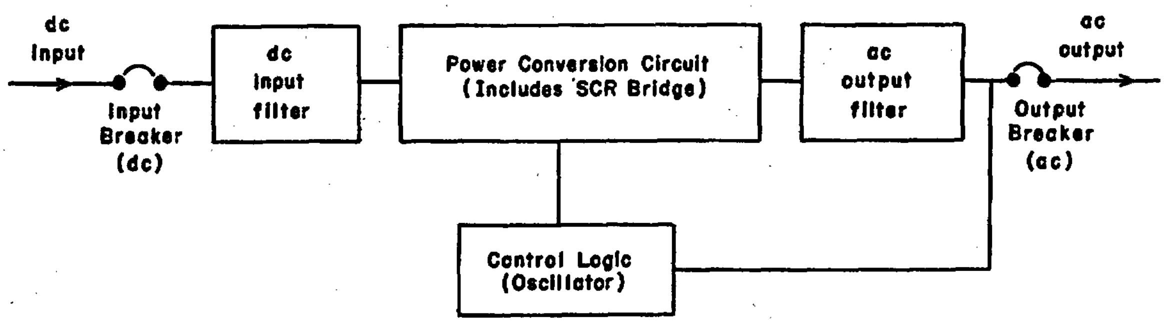


Figure 2-9: Inverter Block Diagram

The input dc and output ac circuit breakers are similar to the breakers used in battery chargers. The dc input filter protects the inverter switching bridge and control logic circuitry from transients that may occur on the dc supply bus (mainly from the battery charger output). In addition, switching transients generated by the inverter are isolated from the battery and the components supplied by the dc bus. The power conversion circuit contains several stages of fast turnoff SCRs which when operated in a commutative mode, provide the desired ac power output. In general, the simple rectifier circuit described earlier can be used for the inversion process by making two basic modifications: (1) the two rectifying devices must be replaced with controlled rectifier elements, and (2) a reliable means of commutation must be incorporated into the circuit. In the simple rectifier, current is transferred from one device to the next naturally and automatically. The commutation process is generally more difficult to accomplish reliably in an inverter requiring a fairly sophisticated control circuit.

The control logic for firing the SCR is typically an oscillator type circuit, such as a solid state multivibrator circuit which is a highly stable temperature compensated device. This segment of the inverter is designed to maintain the frequency within specified limits over a wide temperature and input voltage range. Amplification of the signal and proper sequencing to the SCR gates are necessary to achieve the correct commutation rate. Besides frequency control and voltage regulation, this portion of the inverter usually provides the current limiting control and synchronization capability to external sources.

The ac output filter eliminates unwanted harmonics generated so as to provide a sinusoidal waveform output with a minimum of distortion. This filtering can be achieved by several methods, as described later. The size of the ac filter is dictated not only by the amount of unwanted harmonics, but also by the frequency of these harmonics, with low harmonic frequencies requiring larger filters. Consequently, design of the power conversion circuit to reduce or eliminate lower order frequencies results in smaller ac filters.

In many vital bus inverter applications, the inverter is designed to operate from a rectified ac source or a dc supply. In normal operation, power is supplied by the ac power source to operate the inverter. A diode in the feed from the dc bus is prevented from conducting by the higher voltage of the ac power supply. When the ac source is unavailable or its voltage is lower than the blocking voltage of the diode, the dc bus instantly supplies power to the inverter until the ac line returns to service.

While inverters are "custom-made" for class IE applications using comprehensive specifications, four basic inverter designs are currently in use: the ferroresonant transformer,the pulse-width modulated, the quasi square wave, and the step wave inverters.

The Ferroresonant or Constant Voltage Transformer (CVT) and Pulse Width Modulated (PWM) designs are most often found in nuclear applications with the ferroresonant type existing in older plants and the PWM now being employed in many new installations. The quasi square wave and the step wave inverters make up less than 20% of the total population but are discussed in order to provide a complete picture of nuclear inverter applications.

2.2.1 Ferroresonant Type Inverter (CVT)

The most common inverter type used in the nuclear industry is the ferroresonant inverter, which is relatively simple in design although not without problems (IE INFO Notice 84-84). Employed in nearly 50 % of the nuclear facilities, these inverters are generally in the small to medium size range with 7.5 KVA the most popular. The circuit, depicted in Figure 2-10, consists of the basic components described earlier except that a ferroresonant or constant voltage transformer is used for ac filtering. The square wave produced in the SCR bridge circuit is transformed to the proper voltage level prior to input to the CVT. The CVT is a current limiting device, in that it will provide no more output current than its capacity. At constant frequency, it is also a voltage regulating circuit. Therefore, the regulation and current limiting is totally magnetic, requiring no electronics. In addition, the control and power conversion circuits consisting of an oscillator circuit and a pair of SCRs (or four SCRs in a bridge configuration) convert the dc voltage to a square wave alternating current at the frequency of the oscillator.Three phase operation is achieved by use of three CVT type inverters with each inverter output displaced in phase by 120 electrical degrees by a phase shift synchronizing network. Alternatively, a three phase CVT may be used as the output filter, supplied by three identical SCR conversion circuits.

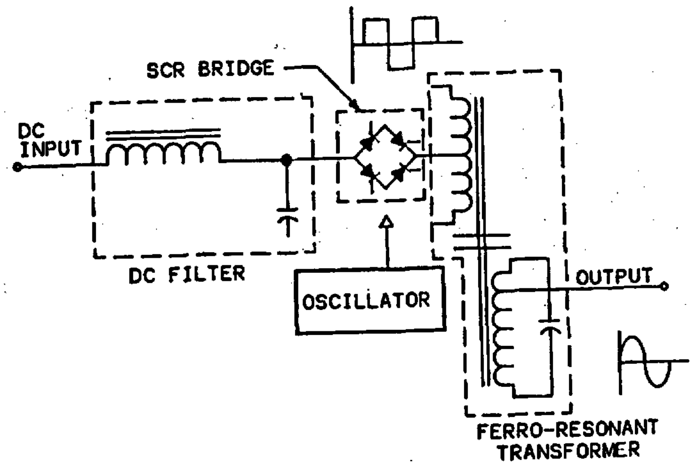


Figure 2-10: Ferroresonant Transformer Inverter [3]

Although generally used on smaller inverters, including the inverters used for the HPCI and RCIC systems (<1KVA), this type of inverter is frequently arranged for parallel operation with one inverter being a master and the other being slaved to it. For example, a 7.5 KVA rated ferroresonant inverter may actually consist of one 5.0 KVA and one 2.5 KVA inverter arranged in this master-slave mode. At least one manufacturer modifies the single phase Ferroresonant transformer circuit by using a "Scott T" transformer connection to obtain three phase performance. This classic connection is used to obtain three phase output from a two phase input. In a Scott connected inverter system, two SCR bridge assemblies are connected to two single phase ferroresonant transformers. The phase relationship between the two transformers (typically set at 90 degrees) determines the inverter output. Feedback to either SCR bridge circuit alters the phase relationship to maintain balanced transformer loading during unbalanced load operation [10].

As mentioned earlier, this type of inverter has the advantage of being simple in both the logic and power conversion states. Additionally, it has inherent current limiting and voltage regulation because of the use of the CVT. Its main disadvantage is, however, that it is unable to operate for extended durations under light load conditions because of overheating due to over-excitation of the transformer. A second disadvantage is its slow transient response to load changes because of the dependence of its operation on magnetic action. Other disadvantages include the following:

1. The output voltage cannot be field adjusted.

2. Total harmonic output waveform distortion is high (>5%).

3. Voltage regulation is limited to about ± 2%.

4. Efficiency decreases sharply as the load decreases (overheating concern).

5. It is incompatible with specialized loads such as large motors and phase controlled power supplies because of the nonlinear circuit of the CVT.

2.2.2 Pulse Width Modulated (PWM) Inverter

The Pulse Width Modulated (PWM) Inverter, the most advanced of the four inverter designs to be discussed, is used at many of the newer nuclear plants. As illustrated in Figure 2-11, this design is more complex than the ferro-resonant inverter, containing sophisticated timing and logic circuits to obtain voltage regulation. The PWM inverter uses a power conversion circuit which generates square waves at much higher frequencies than the desired output frequency, usually 600 or 1200 Hz. Operation at these higher frequencies restricts the harmonics generated to multiples of these high frequencies, thereby allowing the filter size to be reduced and improving the transient performance.

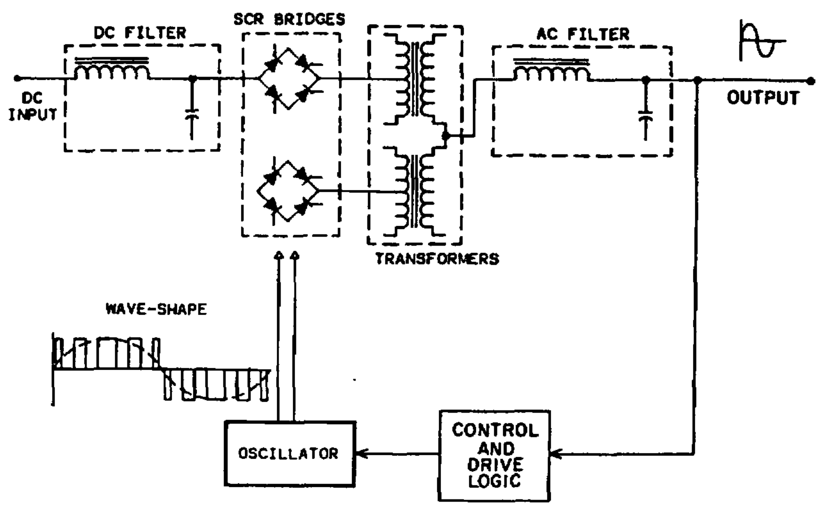


Figure 2-11: Pulse-Width Modulated Inverter [3]

In a three phase PWM inverter applicable to a vital ac inverter in a nuclear station, input dc is fed to three identical SCR bridge assemblies. The outputs from these assemblies are grouped to form two three phase bridges, each is used to drive one of the two summing transformers. The output signal from each bridge section is a square wave phased differently from each other square wave, as dictated by the logic circuitry. Because of the ability of the SCR to turn off and on extremely fast, it is possible to have multiple conduction intervals during a single half cycle of the fundamental frequency. For example, using the equivalent bridge circuit illustrated in Figure 2-12, if SCR1 and SCR4 were gated on, then commutated off again ten times in a half cycle of the inverter frequency, (similarly for SCR2 and SCR3 on the other half cycle) the lowest harmonic present in the output would be the twentieth harmonic or the repetition rate of the pulsing used. The filtering required to provide a sinusoidal output with acceptable harmonic content is considerably reduced as compared to that required for a square wave. The PWM inverter output voltage is regulated by varying the width of the pulses supplied by each bridge section. Inverter output frequency is held constant by an oscillator operating at 60 Hz.

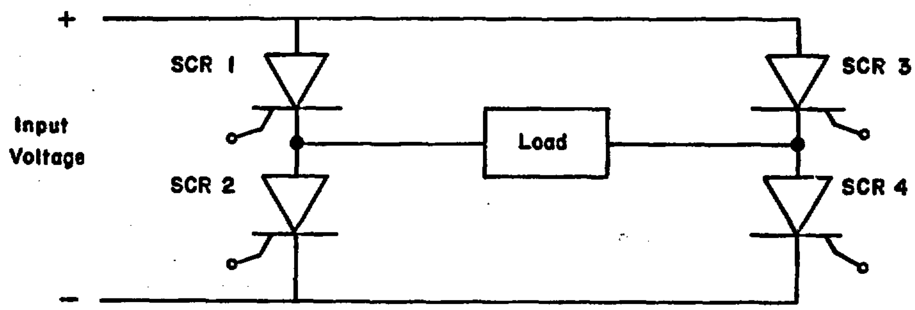


Figure 2-12: Equivalent SCR Bridge Circuit

Increasing the pulse repetition rate permits further reduction of the filtering required. However, there is a definite practical limit to the repetition rate because of the fixed turn-off time of the SCRs used in the circuit. The shortest nonconducting time must be greater than the specified turn-off interval for the SCR. In addition, the losses due to commutation are proportional to the number of commutations per second. As a result, the efficiency of the inverter is reduced as the repetition rate is increased [11].

In summary, this type of inverter has the following advantages: (1) smaller output filters, (2) fast transient response, (3) large load unbalances, and (4) suitability for large (> 10 KVA) designs due to the filter design advantage. Its major disadvantage is the complexity of the logic circuitry required to provide the critical timing for the SCR switching and commutation process.

2.2.3 Quasi-Square Wave Inverter

The quasi-square wave inverter employs a power conversion stage which switches a waveform of two offset square waves. The square waves produced are transformed to the desired voltage level and then added in series to produce a "quasi-square wave". The quasi-square wave is then fed to an ac filter composed of discrete inductors and capacitors to reduce the undesirable harmonics. Voltage regulation and current limiting are accomplished by controlling the phase difference between the two square waves. For example, if both square waves are exactly 180° out of phase, than the sum is a square wave of twice the amplitude which thereby produces maximum inverter output voltage. This would occur when one side of the transformer winding shown in Figure 2-13 is positive while the other side is negative. The firing of the SCRs feeding the transformer is controlled from an oscillator circuit which approaches the complexity of the PWM inverter, since this circuit electronically controls the voltage regulation and current limiting function.

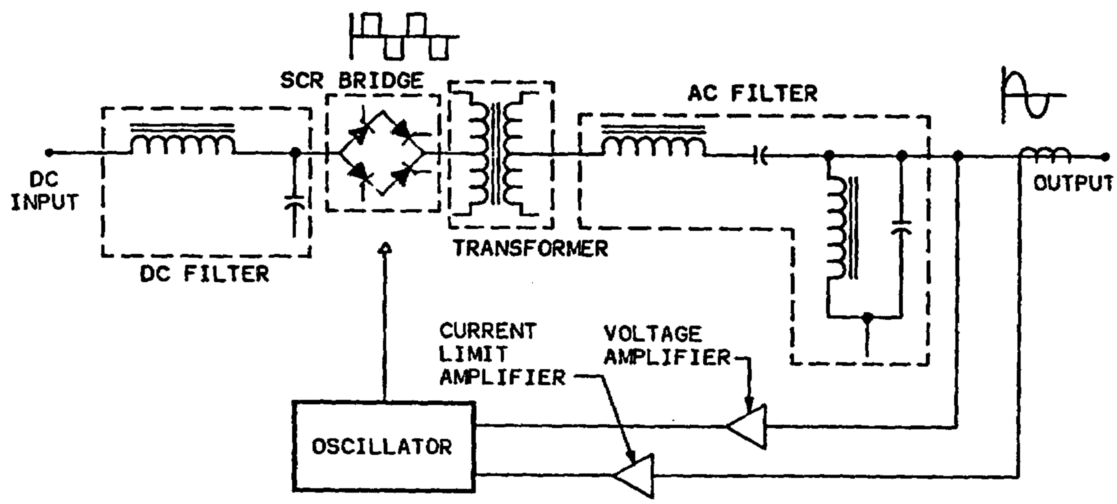


Figure 2-13: Quasi-Square Wave Inverter [3]

Three phase operation using the quasi-square wave inverter is generally accomplished by using three separate inverters synchronized 120 electrical degrees apart. However, with the addition of more switching stages, special transformers, and filters, the three phase output can be accomplished within one inverter.

This type of inverter can provide 2% voltage regulation with varying dc input, and varying inverter frequency. The output voltage can easily be adjusted in the field to compensate for distribution load changes. Modern inverters using this design can also withstand short term overload capability for inrush conditions, such as starting motors, without actuating the current limit circuit [12]. Because of the need to filter low order odd harmonics, the filter circuit is fairly large.

2.2.4 Step Wave Inverter

In an effort to maintain the advantages of the quasi-square wave inverter while reducing the ac filter size, the step wave inverter was developed and adapted for use in nuclear power station applications. To reduce the size of the ac filter and thus improve inverter transient response, the low harmonics had to be eliminated prior to the output filter stage. This is accomplished in the step wave inverter by employing a series of SCR bridges displaced from each other by an amount necessary to produce a step waveform depicted in Figure 2-14.

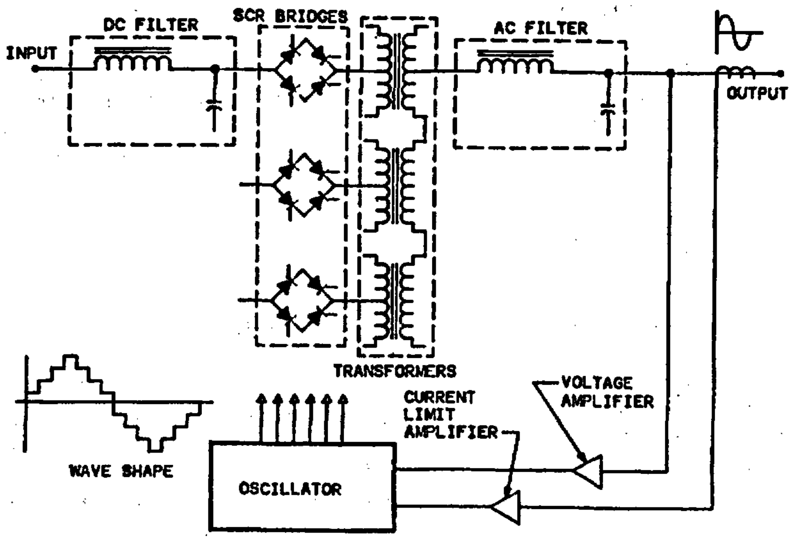


Figure 2-14: Step Wave Inverter (6 Steps) [3]

For instance, in a large 125 KVA unit manufactured for use at a nuclear facility, a twelve step design is used with each step, or inverter leg, consisting of half a bridge circuit. Each adjacent pair of legs constitutes a complete bridge circuit which supplies square wave ac to one of the primary windings of the power transformers. Secondary windings of the transformers are connected so that the resultant output is a balanced three phase delta voltage with each line-to-line voltage appearing as a near sine wave consisting of twelve steps. The twelve step wave inverter has a maximum total harmonic distortion (prior to ac filtering) of just over 15% compared to 30% to 50% total harmonic distortion for the quasi-square wave inverter. Therefore the ac output filter can be made smaller and improved transient performance obtained. The twelve step waveform is filtered to provide a clean sine wave at the output terminals by the action of the ac output filter and by inductors connected between adjacent pairs of inverter legs.

In smaller step wave inverters, the voltage regulation and current limiting functions are accomplished by controlling the dc input voltage thereby reducing the number of bridge circuits required while still achieving a fairly low harmonic distortion. This type of regulation is not practical, however, in larger inverters.

Large inverters of 400 KVA or greater can be built employing this design without using paralleling techniques because multiple power SCR stages are used with each power stage providing a portion of the output power. As mentioned earlier, this design provides good voltage transient performance because of the smaller output filter required. Since transient performance is a function of the number of power stages or steps that are used in an inverter, the twelve step design being used in nuclear applications can provide a maximum transient tolerance of ±20% for full load step changes. Duration of the transient is also directly related to the number of steps in the output waveform. The more steps, the faster the regulating action correcting for the transient [12].

The logic for the twelve step inverter is complex because it must control SCR firing in six complete bridge circuits while regulating the output voltage and providing the current limiting function. Control circuits in the control logic portion of the inverter also maintain the necessary phase separation between the square waves produced.

2.2.5 Summary of Inverter Types

Inverters are used to supply reliable power to the 120 volt ac vital buses in nuclear power plants. Specific plant electrical configurations, including the nature of the loads being supplied by the vital bus, determine the inverter type to be employed. The four types of inverters described are the general designs used in the nuclear industry, although a further generalization into two basic types can also be made. That is, inverters with an electronic feedback control circuit for voltage regulation consisting of the PWM, step wave, and quasi-square wave types, and those with a ferroresonant transformer for regulating the output voltage. Each of the four types represents changes in design made with time to accommodate specification requirements in the computer industry as well as the nuclear industry. Table 2-2 compares the features of each type, although it is not intended to indicate superiority of one over another. For certain applications, the ferroresonant type is perfectly suitable rendering use of a later design type neither necessary nor desired.

Table 2-2: Summary Comparison of Inverters (12)

	Ferroresonant (CVT)	Quasi-Square Wave	Step Wave	PWM
1. Simple dc to ac conversion stage	X			X
2. Simple logic	X			
3. Simple output filter			X	X
4. Simple parallel load sharing	X			
5. Three phase can be unbalanced 100%	X	X		X
6. Applicable to single & three phase	X	X		X
7. Low cost (below 5 KVA single phase) (below 15 KVA three phase)	X			
8. Low cost (above 5 KVA single phase) (above 15 KVA three phase)		X		X
9. Low cost (above 30 KVA three phase)			X	
10. Adjustable & removable current limit)		X	X	X
11. Good voltage regulation at low power factor		X	X	X
12. Good transient voltage regulation			X	X
13. Less than 5% harmonic distortion		X	X	X
14. Compatible with almost all loads			X	X
15. Adjustable output voltage		X	X	X
16. Adjustable output frequency				X

2.3 Battery Charger and Inverter Components

Battery chargers and inverters consist of a number of discrete subcomponents whose operation is directly related to the achievement of satisfactory equipment performance. These sub-components and their basic functions are listed below.

- Molded Case Circuit Breakers - Control and distribute power and protect the individual devices in the inverter and charger.
- Transformers - Provide instrumentation and control power used in the switches, relays, and electronic components inside the inverter and charger as well as providing the proper voltage to the rectifier.
- Integrated Circuits - Provide control logic and instrumentation functions throughout major assemblies of the inverters and chargers.
- Silicon-Controlled Rectifiers - Provide rectification and regulation of power in major assemblies.
- Diodes - Provide reference voltage and blocking functions in the auctioneering device.
- Relays - Provide time delays, under-voltage and over-voltage protection, and remote operation of the various components.
- Switches - Provide for control and operation of various relays.
- Resistors, Capacitors, and Inductors - Provide filtering and alteration of the current/voltage phase relationship necessary for operation of certain components in electronic circuits.
- Transistors - Provide amplification and switching of digital signals in control logic.
- Terminal Blocks - Provide locations for connecting power to the various devices.
- Fuses - Provide overcurrent protection for the transformers, relays, and switches.
- Fuse Blocks - Provide support and electrical connections for the various fuses.

As determined from the operating experience data, several of these discrete components are identified as contributors or causes of charger/inverter failures. The most frequently mentioned components were therefore reviewed to ascertain if degradation of materials, electrical characteristics, or manufacturing methods could have contributed to their failure, with emphasis on those components which could be affected by age. The discrete components to be addressed include magnetic components such as transformers and inductors, capacitors, silicon controlled rectifiers (SCRs) including diodes, and fuses. Other components such as resistors, transistors, switches, fuse blocks, and integrated circuits are not specifically discussed because of their relatively minor individual contribution to inverter/charger failure. Relays, circuit breakers, and cable are being addressed in detail in other NPAR program studies. Their aging mechanism, if any, will be discussed in those reports. Input from those studies will be applied to Phase II recommendations, as appropriate.

2.3.1 Magnetic Components

Common to the described inverter and battery charger types are the magnetic components, namely transformers and inductors (chokes). Transformers with ratings from 10 to 50 KVA are typically found in the battery charger input section and in the inverter output following the dc-ac conversion. In addition, smaller transformers may be used for metering or control purposes. Inductors or chokes are commonly used in both chargers and inverters for filtering dc (output of charger, input of inverter). They are typically sized in the low millihenry range at the required dc ampere rating (300 amps is common).

The life of transformers and inductors is directly related to their insulation condition. Standards such as IEEE 259-1974, IEEE Standard Test Procedure for Evaluation of System of Insulation for Specialty Transformers, and IEEE 392-1976, IEEE Recommended Practice for Achieving High Reliability in Electronic Transformers and Inductors, address the testing requirements for transformers and inductors and focus on the effects of higher ambient temperatures on the insulation. Material degradations due to chemical interactions and harmful decomposition products can also ultimately lead to an insulation breakdown.

Environmental conditions degrade transformers and inductors in the following manner [13]:

- Maximum operating temperature affects the life of the insulation used.
- Low temperatures can affect the moisture seals and cause them to crack.
- The magnetic core material characteristics can vary with temperature.
- The normal resistance change experienced in the winding wire as the temperature increases may be about 1.0% for every 1.5°C rise in temperature.
- The temperature limits of the insulation and impregnated materials should be selected to give required life.
- Moisture must be prevented from reaching the winding, otherwise corrosion or serious reduction of dielectric strength or insulation resistance will occur.
- Insulation between windings or between winding and core or ground can fail in service when subjected to high voltage stress. The effect is to cause local heating and deterioration of the material and results in complete dielectric failure. Also radio frequency noises are often generated by the electrostatic discharges which may affect the circuit operation.

- It is possible for connecting wires between seals and coils to fracture under severe vibration if they are pulled too tight when soldering. This should be detected by the manufacturer during conduct of the acceptance test procedure.

- Reduction in insulation resistance due to insufficient or poor impregnation and consequent penetration of moisture. Once moisture penetrates, there is a progressive building up of moisture which penetrates the enamel on the wire causing the insulation resistance to fall. Degradation is then rapid and the transformer fails.

- Transformer noise caused by loose laminations is generally due to poor design and/or manufacturing techniques.

A review of a battery charger and inverter qualification reports revealed that for the main magnetic components, i.e., input/output transformer and filter choke, a 40 year life was predicted. This "qualified life" determination was based on analysis of the thermal degradation of the insulating materials which consists of layer to layer and wire insulation. The coating on the copper magnetic wire used was classified as 220°C insulation, while the layer to layer insulation used was a polyamide polymer classified as class H insulation. It should be noted, however, that in the inverter application, two small transformers using a polyamide polymer insulation were recommended to be changed out every 2.6 years because of the limited life of the mylar tape utilized. Therefore, even though magnetic components consist of copper magnet wire, steel core material, and insulation materials, it is the insulation materials which govern the transformer life.

The actual assembly and testing of the magnetics used in class IE battery charger applications was observed as part of a detailed tour of one manufacturer's facilities. Periodic checks made during assembly and overvoltage testing conducted just before final packaging assures that the straight forward assembly procedure has been completed properly and that no material defects exist. Judging by the manner in which this important but standard component is manufactured, it is unlikely that failures due to fabrication errors will result in charger or inverter degradation.

However, a recent event associated with ferroresonant transformers (IE Info Notice 84-84) resulted in degraded inverter operation at a plant in its initial testing phase. The particular deficiency detected was of a mechanical nature, i.e., the windings were inadequately secured which allowed the center leg to shift and vibrate while energized. This, in turn, caused an insulation breakdown between the transformer core and coil. This short circuit resulted in a collapsed voltage output and occurred early in transformer life. Although not directly associated with magnetics fabrication, the manner in which the transformer was supported caused a failure in the magnetics.

As far as inductors are concerned, the performance of a ferrite core inductor is governed by the quality of the ferrite. No single grade of ferrite can cover the complete frequency range, so adjustments are usually made by partial shunting of the air gap. To ensure long term stability, a support is usually necessary for the shunt, however, the material used must be dimensionally stable and not change the position of the cylinder with temperature, since temperature change is the most common disturbance causing temporary instability of an inductor in static equipment [13]. An inductor used in the filter circuit of a typical nuclear inverter uses a DuPont "Nomex 410" insulating material rated at 220°C with a polyester polyamide coated magnetic wire rated at 200°C, and polyester based support rated at 130°C. This combination of materials is intended to achieve the temperature stability required.

2.3.2 Capacitors

Many types of capacitors are used in nuclear power battery charger and inverter applications. However, the most common cause of inverter and battery charger failure is the aluminum electrolytic capacitor used primarily for output filtering. Figure 2-15 is an electrical schematic of an electrolytic capacitor illustrating the parameters which embody the capacitor function.

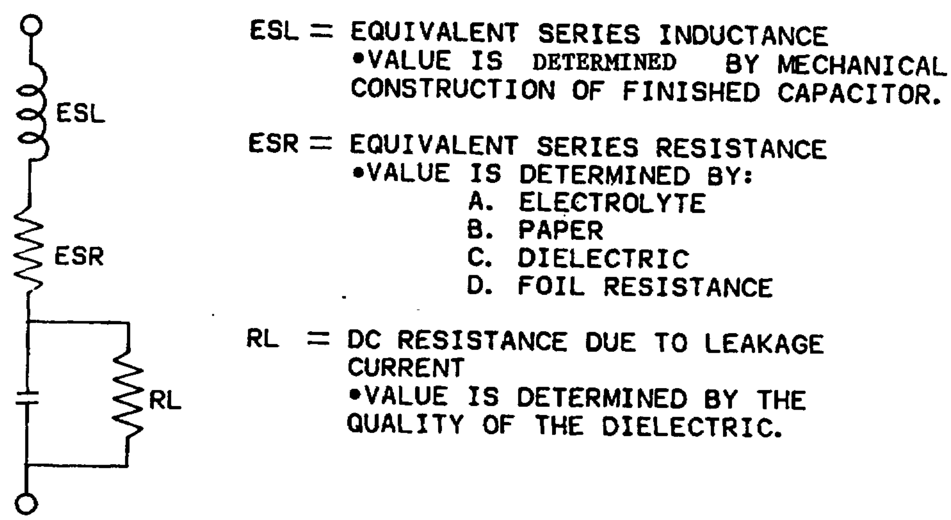


Figure 2-15: Electrical Schematic of Electrolytic Capacitor [3]

The important characteristics of these types of capacitors are leakage, power factor, and impedance. Leakage denotes the amount of direct current that will flow steadily through an energized capacitor. The power factor characteristic gives the total capacitor losses, which include dielectric losses due to leakage and dielectric absorption, and ohmic losses due to contacts, leads, and frequency skin effects. The better the capacitor, the lower the power factor as demonstrated by the following:

Power Factor $= \frac{E.S.R.}{\sqrt{(E.S.R)^2+X_c^2}}$ where E.S.R. = equivalent series resistance in ohms,

and X_c = capacitive reactance in ohms [13].

impedance is introduced in the form of an inductive reactance for the electrolytic capacitor. In many cases, actual capacitor impedance at the operating frequency is a direct indication of capacitor performance.

The life of an electrolytic capacitor in filter applications is proportionately related to the core temperature, working voltage, and ripple current. One manufacturer of electrolytic capacitors has generated failure rate curves for various grades and types of electrolytic capacitors. Based on operation at rated voltage and at the design operating temperature, a life of five to twenty years is expected based on the different models and configurations used [14]. The report also states that the failure rate during this expected life period is a constant or decreasing failure rate. However, no data for failure mechanisms such as corrosion or outgassing which have been reported to occur in nuclear plant battery chargers and inverters were available. On the basis of the capacitor manufacturer input, this inverter manufacturer, along with several others, recommends a five year replacement interval for all electrolytic capacitors.

Another manufacturer of ferroresonant type inverters points out in the instruction manual that even though the oil filled and electrolytic capacitors are rated for more than ten years, application experience indicates a life of only five to seven years. They therefore recommend replacement of these capacitors every three to four years.

Similarly, a supplier of a qualified battery charger using a different electrolytic capacitor has used specific curves such as the life multiplier curve shown in Table 2-3 to demonstrate an expected life of approximately ten years. Although this is not considered equivalent to an end of life value, the charger manufacturer recommends changing out the electrolytic capacitors every 10 years. Because the electrolytic capacitor life is sensitive to temperature, voltage and ripple current, longer capacitor life would be achieved by utilizing a capacitor having a higher rated voltage than operating voltage, and ensuring that the average operating temperature doesn't exceed 55°C.

It is also important to note that failure for a capacitor does not mean catastrophic failure. As indicated by one manufacturer's qualification test report, failure is defined as a 10% change in capacitance value or an increase in equivalent series resistance (ESR) greater than 175% of the initial measured value. Another source [13] discussing characteristic changes which occur over long periods of storage indicates that a 50% capacitance loss, or an increase of either power factor or leakage current by a factor of 10 would render the capacitor unfit for further service. The capacitance value and the equivalent series resistance are measurable parameters that could be used as an input for determining capacitor replacement.

As indicated by Figures 2-16 through 2-18, useful life varies with temperature, voltage, and percent ripple current, respectively, and can be predicted fairly accurately. The useful life is inversely proportional to the applied voltage and increases tenfold for every 25% decrease in applied voltage. Conversely, it decreases by a factor of about 2 for every 10°C increase in operating temperature.

Table 2-3: Life Multiplier for Type 86F/84F Capacitor (Rated at 95°C)

Core Temperature (°C)	% Rated Voltage 50	60	70	80	90	100
95	5.3	4.1	3.0	2.2	1.5	1.0
85	12.4	9.3	6.6	4.6	3.1	2.1
75	28.9	20.8	14.4	9.7	6.4	4.2
65	66.5	45.8	30.8	20.3	13.3	8.6
55	151.0	99.8	65.2	42.2	27.2	17.5

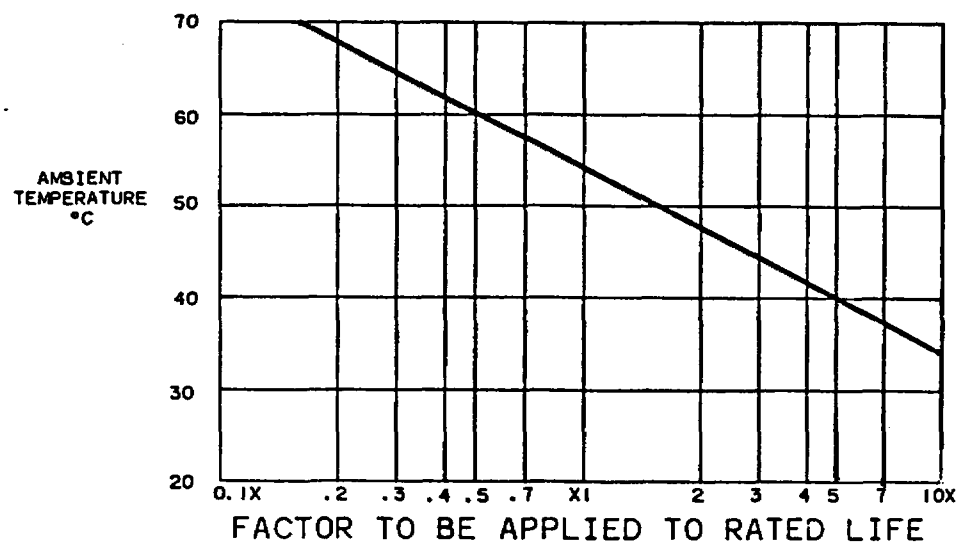


Figure 2-16: Effect of Temperature on Capacitor Life [3]

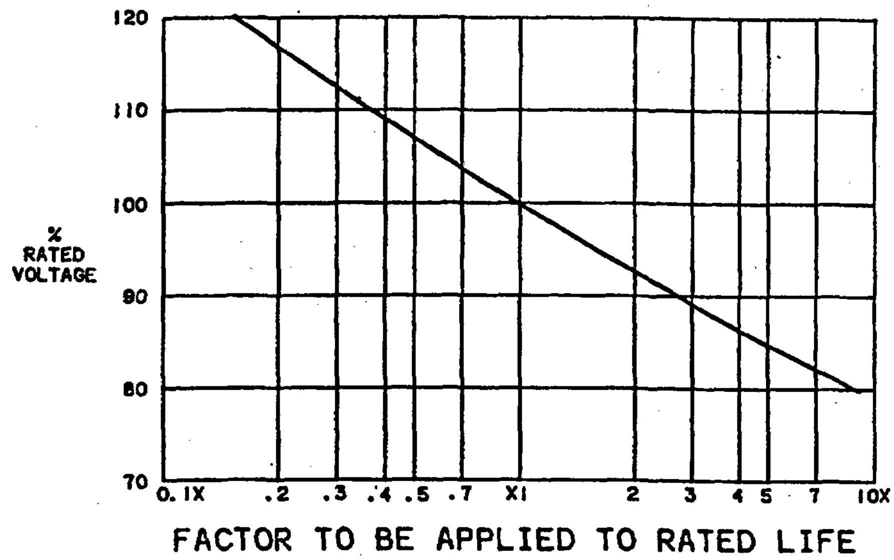


Figure 2-17: Effect of Voltage on Life For a Typical Capacitor [3]

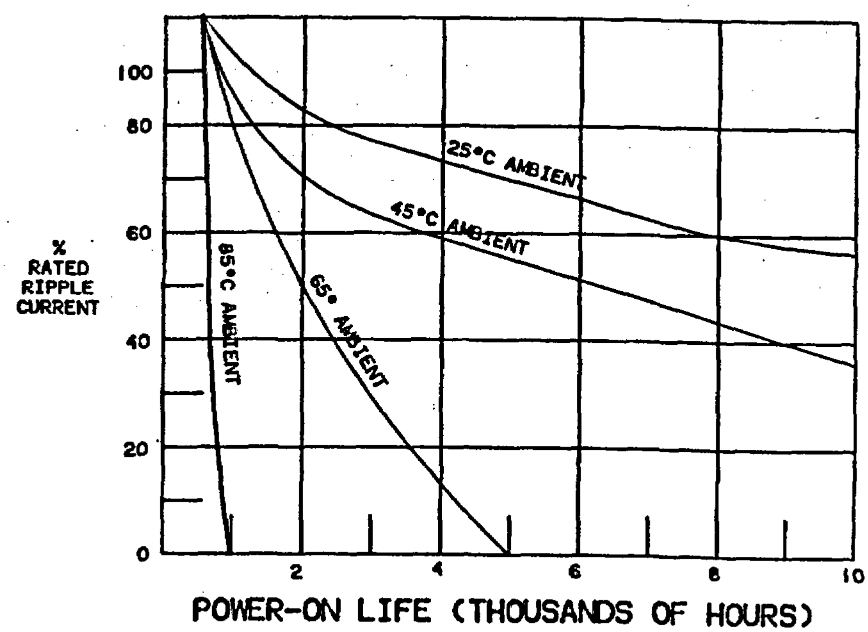


Figure 2-18: Life vs Percent Rated Ripple Current & Ambient Temp. [3]

Other types of capacitors used in battery chargers and inverters are tantalum, ceramic, glass, mica, paper, and polyester. An inverter manufacturer's qualification test report states that industry testing on these types of capacitors has resulted in the position that they are "insensitive to aging". For instance, in tests continuously performed from 1960 to 1972 on polyester (mylar) dielectric capacitors, data were extrapolated to demonstrate a device life well in excess of 40 years. Similarly, for tantalum capacitors, while some failures occurred in the first two hours of testing, continued testing at elevated temperatures and voltages demonstrated an expected life of over 100 years. Testing of ceramic capacitors by one capacitor manufacturer indicated that no age related problems should be experienced during the normal operating life of the charger or inverter. However, they also state that the capacitor life could be increased significantly if the capacitor is operated at 50% of its rated voltage at ambient temperature.

The primary advantage of an electrolytic capacitor is the large capacitance value that can be put in a small case. The capacitance-to-volume ratio is larger for an electrolytic capacitor than for any other type of capacitor [15]. Even though it has a much shorter expected life than other capacitor types, electrolytics are the optimum type of capacitor for low frequency filtering, bypassing, and coupling. For maximum life, the figures presented indicate that they should be operated at no greater than 80% of their rated voltages.

2.3.3 Silicon Controlled Rectifiers (SCR) and Silicon Diodes

The Silicon Controlled Rectifier (SCR) is a solid state switch capable of rectifying alternating current into direct current. Also known as a thyristor, this device has three terminals called the anode, cathode, and gate, schematically displayed in Figure 2-3 and pictorially illustrated in Figure 2-19. With a reverse voltage applied to its anode-to-cathode terminals (positive cathode voltage), the device will not conduct any appreciable current. When the anode is made positive with respect to the cathode, and a small positive voltage pulse is applied across the gate-to-cathode terminals the device switches on. Once the SCR is conducting, the gate signal is no longer required to maintain the switch in the on condition. The SCR will continue to conduct until the current falls below the holding current level or the current is reversed as is automatically done in alternating current. The conducting time is typically controlled by an external circuit in a battery charger or inverter called the firing module. Degradation of the firing module output will affect the SCR conducting time, thereby rendering the current output uncontrollable and the charger/inverter inoperable.

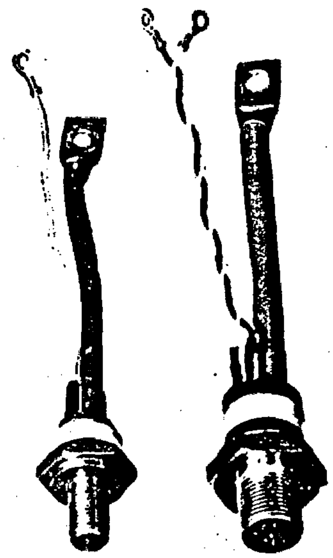


Figure 2-19: Typical SCR used in Rectifier Applications

In forced commutation applications, the thyristor turnoff time is important and generally ranges from 10 to 50 microseconds. An SCR which has been carrying current is force commutated off by suddenly reducing the current to zero at a rapid rate and then applying a reverse bias to ensure a maintained off condition. The off condition must be maintained for a finite period of time before a forward voltage is applied. If applied too soon after turn off, the SCR may fire prematurely causing the circuit to malfunction. A forward voltage applied too rapidly can also cause the SCR to fire prematurely [11]. In battery charger and inverter applications where forced commutation is used, the logic circuitry which controls the SCR conducting time and sequencing is therefore extremely important. Deviation from the required operating condition results in output voltage or frequency changes.

As mentioned in the discussion of the Pulse Width Modulated (PWM) inverter in Section 2.2.2, the SCR switching rate is limited not only by the fixed turn-off time of the SCRs in the circuit but also as a result of the efficiency reduction as the repetition rate is increased. The losses due to switching are caused by the finite time required for the anode-to-cathode voltage to decrease and the anode current to increase. An approximate empirical formula to evaluate this loss is [11]:

$P = \frac{Vm\ Im}{4.6}$, where P = power loss in watts

Vm = anode-to-cathode rms voltage prior to switching

Im = anode rms current after switching

At higher switching frequencies, as in the PWM inverter, switching losses are the major contributor to heat generation and dictate the size of the heat sink to be used. In some cases, forced air cooling is required because of the temperature effects obtained. Manufacturer's specification sheets for SCRs also provide sufficient information such as leakage current and gate power so that the total power losses may be calculated.

The reverse voltage applied from the anode to the cathode of the SCR to obtain proper commutation is frequently specified by the SCR manufacturer and is known as the peak reverse voltage (PRV) rating and is the maximum repetitive reverse voltage that can be applied from anode-to-cathode. Some device manufacturers also indicate a transient PRV rating in excess of the repetitive PRV. If the transient or repetitive PRV rating is exceeded, the SCR may conduct continuously in the reverse direction (avalanche breakdown) and could be damaged if the anode current is not limited [11].

In cases of SCR failures reported in battery chargers and inverters, voltage transients and over temperature conditions could easily contribute to premature failure. Voltage transient sources typical in chargers and inverters include flux variations in inductive loads or a supply transformer, and capacitive load changes externally and internally. Internal circuit capacitance and inductance resulting in voltage transients can occur when the SCR is switching from its low to high impedance state. These transients may be suppressed by the use of a capacitor and a damping resistor in series with it. At least one battery charger manufacturer uses a selenium surge suppressor and metal oxide varistors to reduce voltage transients on the ac input to a level that will not damage the SCRs.

Silicon diodes are subject to similar failure modes as discussed for the SCR. Heat due to overcurrent conditions must be dissipated because increasing temperature can cause increasing current and thereby precipitate thermal "run away"[13]. Voltage transients many times in excess of steady state voltages can occur in switching circuits which employ inductors and capacitors. If these voltages exceed the maximum reverse voltage, failure of the diode may result from excessive reverse power dissipation.

2.3.4 Fuses

Fuses in battery chargers and inverters are used to protect semiconductors, instrumentation, and power and control circuits. Equipment unavailability due to a blown fuse or fuses occurs often enough to investigate this component more closely. Although it is sometimes difficult to ascertain from the failure reports whether the fuse operated as designed or failed prematurely for reasons other than an overcurrent condition, it is possible that some equipment malfunctions were due to spurious blown fuses. This viewpoint is partially based on recorded licensee followup action which was simply to replace the fuse and verify that the charger/inverter operated properly. Although the root cause was not indicated in most of these cases, no other component degradation was reported that would lead to fuse operation.

As many as 15 to 20 fuses may be used in a battery charger or inverter. Many of these, however, are considered "non-safety" in that if the fuse blows, the equipment will continue to operate. These fuses are employed in metering or display panel circuits. The more significant fuses which could cause charger/inverter malfunction include those installed on the 120 volt ac secondary of the power transformer which supplies voltage to the control circuitry including the firing modules. The SCRs used to make up the rectifier circuit will often be fused at the cathode to protect this component from an overload failure. In a three phase charger/inverter application, failure of this fuse on one phase will result in overload conditions on the two unaffected phases and ultimately trip the input circuit breaker. Fuses are sometime installed in series with the output filters. A blown fuse in this portion of the circuit may not directly result in a charger/inverter trip, but could cause output problems due to a distorted waveform. One particular design also contains current limiting fuses located in the circuit between the transformer secondary and the rectifier diodes. Care must be taken to replace these fuses with exact duplicates in type and rating in order to ensure equipment protection.

IEEE Standard 650-1979 [6] for the qualification of chargers and inverters states that fuses which have been properly applied in circuits with respect to ampacity, voltage, and temperature have no age related common mode failure mechanisms. Temperature is the important factor to consider in that a temperature rise at the fuse or fuse holder termination will have the same effect on the fuse as an overload condition.

In contradiction to the above is the belief that fuse failure due to thermal fatigue is a possibility [3]. The only evidence of this found in the data reviewed was an inverter failure due to a fuse failure in 1983. Analysis by the utility indicated that because the fuse failed at the cap rather than in the link itself, it was possible that the fuse was defective which eventually led to a thermal fatigue failure. This potential age related failure mode will be investigated further in the Phase 2 Study.

2.4 Battery Charger/Inverter Plant Configurations

In addition to the different types and sizes of battery chargers and inverters, one must also consider the arrangement of the equipment in order to assess aging and service wear effects at a plant safety level. Rather than analyzing a "typical" nuclear power plant, it was decided to examine a number of actual plants. For battery chargers, the bus configurations of 23 nuclear plants were compiled and are listed in Table 2-4. As illustrated, the nuclear system suppliers are all represented as are plants of various ages. Plants with no LERs as well as plants with many LERs were selected and are listed by plant type in this table.

A wide variation in battery charger configurations was found to exist, including two dc buses with one charger per bus and no standby as shown in Figure 2-20, two full capacity chargers per bus with no standby charger as depicted by Figure 2-21, and four dc buses having one charger per bus along with standby capability as illustrated in Figure 2-22. These configurations, along with the infrequently used arrangement of a standby charger in conjunction with two full capacity chargers per bus, are summarized in Table 2-5, indicating the number of failures that have been documented by LERs and the accumulated number of reactor operating years of the plants using these designs. Note the addition of a standby charger or a second full capacity charger dramatically reduces the number of issued LERs. Even more important, of course, is the obvious improvement in plant safety achieved by these arrangements due to the increased reliability of maintaining the batteries in a fully charged condition, given a charger failure. The ability to place a standby charger in service or quickly have a redundant charger pick up the load when a failure occurs results in minimal battery depletion.

Table 2-4: Battery Charger Configurations

Plant Type	Criticality Date	Number of Batteries	Number of Chargers Per Bus	Number Standby Chargers	Charger Capacity (amps)
PWR-W	77	2	1	1	600
PWR-W	81	2	1	1	600
BWR-GE	75	2	2	1	400
BWR-GE	79	3	1	0	100
BWR-GE	84	2	2	0	400
BWR-GE	70	2	1	1	200
BWR-GE	72	2	1	1	150
PWR-W	71	2	1	0	----
PWR-B&W	77	2	2	1	200
BWR-GE	75	2	2	0	----
BWR-GE	77	2	2	0	----
PWR-W	86*	2	2	0	150
PWR-CE	77	2	2	1	300
PWR-CE	85	2	2	0	150
PWR-W	75	2	1	1	----
PWR-W	78	2	1	1	----
PWR-CE	72	4	1	0	----
PWR-CE	75	4	2	0	400
PWR-CE	77	4	2	0	400
PWR-B&W	77	4	1	2	----
PWR-W	76	4	1	0	150/300
PWR-W	77	4	1	0	100A

*Scheduled to commence operation in 1986.

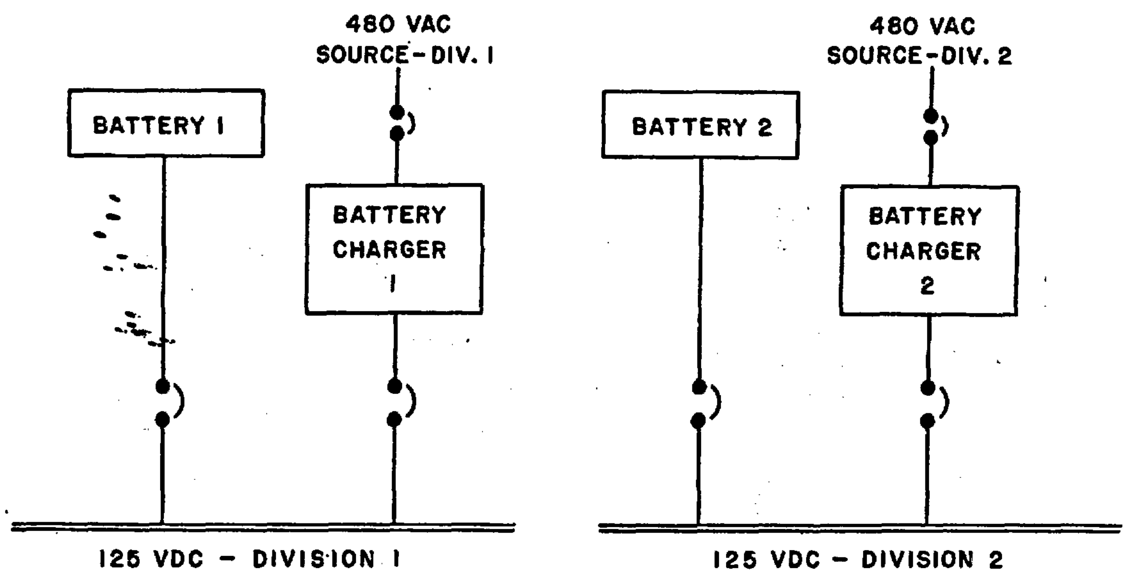


Figure 2-20: Two Division System - One Battery Charger Per Division

Table 2-5: Battery Charger Configuration Summary

Configuration	Number of Plants	Total Number of Chargers in Operation	Number of LERs	Number of Years of Reactor Operation
One charger per bus, no standby	5	17	20	45
One charger per bus, with standby	7	16*	6	57
Two chargers per bus, no standby	8	36	9	38
Two chargers per bus, with standby	3	12*	1	17

* Does not include number of spare battery chargers.

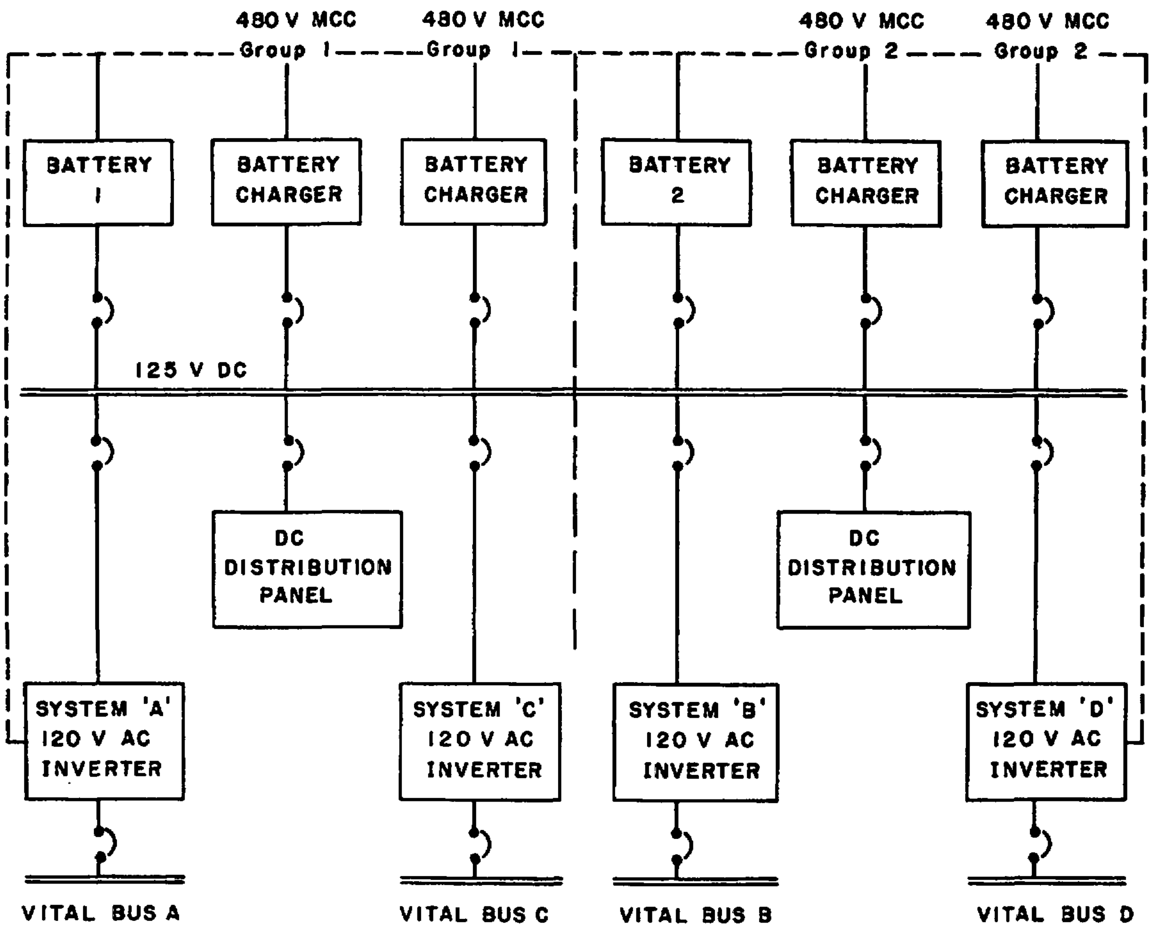


Figure 2-21: Two Division System With Two Battery Charger/Inverters Per Division - No Standby

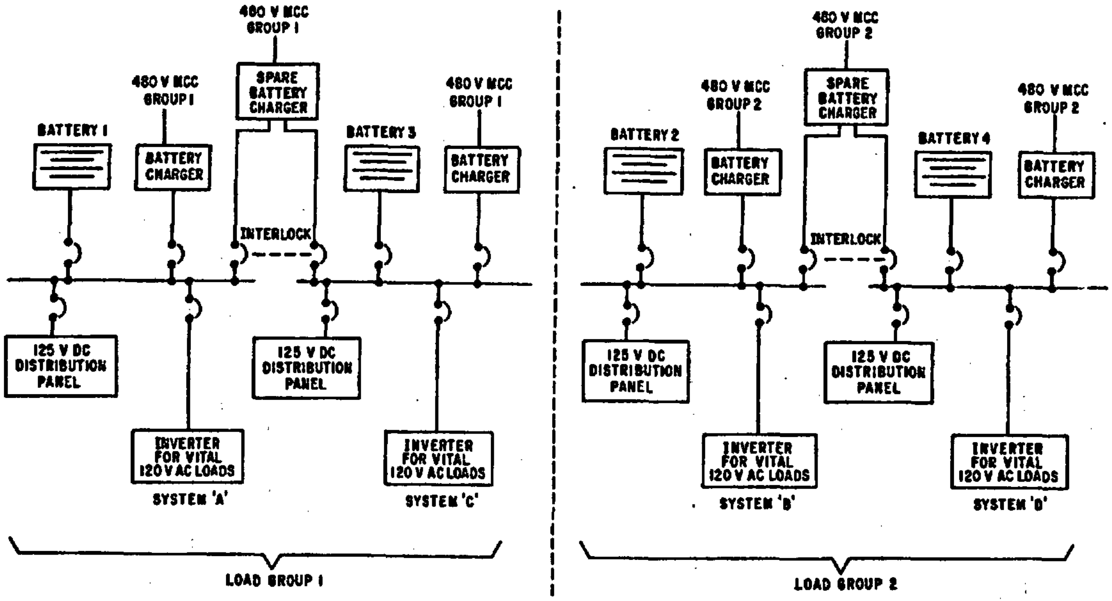


Figure 2-22: Typical 4 Division System with Spare Battery Charger Concept

For inverters, on the other hand, of the 15 plants selected, all were PWRs. This is justified by the fact that more than 90% of the reactor trips and safety injection system actuations resulting from inverter failures occurred in PWRs. The information about the 15 PWRs examined is summarized in Table 2-6. Again, as in the case of battery chargers, a wide variation in configurations was revealed. The significant differences in the designs include the existence and type of transfer switch, the application of a dedicated rectifier to provide an alternate dc source to the inverter, and the number of dc buses supplying power to the inverters. The transfer switch provides a means of bypassing the inverter in the event of scheduled maintenance or inverter failure. If an inverter fails the manual transfer switch is used to restore power to the vital bus within a few minutes. An automatic transfer switch senses the loss of power and automatically supplies the vital bus from an alternate ac source within a few cycles without apparent loss of power to the bus. In the six plants which have a manual transfer switch without a dedicated rectifier, the results indicated by Table 2-7 demonstrate a relatively superior level of performance in that only one reactor trip resulted, and for 30 inverters with 44 reactor years of operation, only 13 LERs were issued. A dedicated rectifier which is very often part of the inverter panel assembly was used in the design of 8 of the 15 plants reviewed. The rectifier provides an alternate dc source to the inverter by converting ac to dc in parallel with the battery charger output. If the charger fails or battery maintenance is being performed, the alternate supply through the rectifier keeps the inverter energized. In an inverter failure, the redundant dc supply via the rectifier cannot be used. As illustrated in Table 2-7, the use of a rectifier even with the availability of a manual transfer switch, resulted in 11 reactor trips and a total of 35 LERs for 24 inverters with a total of 24 reactor years. This poor record could be due to the additional complexity of an added component. No relationship to a specific manufacturer or inverter type was evident.

Table 2-6: Inverter Configurations

Plant Type	Criticality Date	Number of dc Buses	Dedicated Rectifier	Transfer Switch	Number of Inverters & Size
PWR-CE	72	4	No	None	4-
PWR-CE	75	4	No	Manual	8-7.5 KW
PWR-CE	77	4	No	Manual	8-7.5 KW
PWR-CE	85	2	Yes	Manual	4-20 KW
PWR-CE	78	2	No	Manual	4-10 KW
PWR-CE	83	2	No	Manual	4-10 KW
PWR-B&W	77	4	Yes	Manual	4-10 KW
PWR-B&W	77	4	Yes	Auto	4-30 KW
PWR-W	77	4	Yes	Manual	2-20 KW 2-25 KW
PWR-W	77	2	Yes	Manual	2-5 KW 4-7.5 KW
PWR-W	81	2	Yes	Manual	2-5 KW 2-7.5 KW
PWR-W	76	4	No	Manual	4-7.5 KW
PWR-W	71	2	No	Manual	2-7.5 KW
PWR-W	75	2	Yes	None	4-5 KW
PWR-W	78	2	Yes	None	4-5 KW

Table 2-7: Inverter Performance by Bus Configuration
(Total of 15 plants - all PWRs - with 102 years of operating experience.)

Configuration	# of Plants	Total # of Inverters	# of LERs	# of Reactor Trips	# Years Reactor Operation
No Transfer Switches	3	12	11	7	27
Manual Transfer Switch - No Rectifier	6	20	13	1	44
Manual Transfer Switch - Dedicated Rectifier	5	24	35	11	24
Auto Transfer Switch - Dedicated Rectifier	1	4	9	3	7

The number of dc buses varied as well with 8 of the 15 units using a two bus design and 7 using a four bus design. Except for one case where only two inverters exist, the remaining plants reviewed have at least four inverters with as many as eight inverters existing in two of the units. There was no correlation between the number of existing buses and the failure data, however, it is apparent that the more buses existing, the better the separation of dc loads can be. With a four bus design, the likelihood of one dc bus causing multiple system failures is reduced.

3.0 OPERATIONAL STRESSORS AND CORRELATION WITH ACCIDENT SCENARIOS

One of the goals of the NPAR Program is to examine the impact of equipment aging on the capability of plant safety systems to mitigate the consequences of accident and transient events. In general, a study of the effects of equipment degradation on the loss of the plant's ability to achieve a safe shutdown condition must include an evaluation of the accident caused stresses that are imposed on the equipment, as well as the potential for the failure of an aged equipment to initiate such a transient. This section of the report examines the various stresses placed on battery chargers and inverters during normal and transient conditions at both the system and component levels, and describes the impact that these stresses have on the aging process and the performance of an aged equipment.

Before describing the effect on safety of these stresses, it is important to emphasize the significance of the battery charger and the inverter in achieving safe nuclear power plant operation.

The battery charger and the battery are the two principal components of the dc system. The dc system is the direct source of power for systems such as High Pressure Coolant Injection (HPCI) and Reactor Core Isolation Cooling (RCIC) in a BWR and Auxiliary Feedwater (AFW) in a PWR, and provides control power for circuit breaker operation and for instrumentation and logic relays in both BWRs and PWRs. A partial loss of dc power, as documented by actual occurrences, may cause reactor and turbine trips and can impair the operator's ability to respond to the resulting transient because of a loss of indicating instrumentation, controls, and/or annunciation. For instance, the loss of one of two redundant and independent dc buses at a PWR [16] had the following consequences:

- reactor trip
- total loss of control room annunciation
- inability to trip the turbine generator
- loss of important control room indication
- inadvertent start and subsequent trip of an Emergency Diesel Generator (EDG)
- trip of instrument power supplies making it "difficult for operators to control the reactor"

A similar event at a second PWR [16] also resulted in a reactor trip and a loss of control room annunciation. In addition, the unit experienced an emergency safeguards actuation and an EDG fire due to prolonged generator overload. Reactor operation in the natural circulation mode was necessary during this event.

A system interaction study of a Westinghouse PWR performed by BNL for the NRC [17] discovered that the loss of one dc bus would prevent automatic actuation of low pressure injection subsystems following a LOCA event involving a partial loss of offsite ac power. This was due to the use of dc for circuit breaker control power and bus transfer logic schemes which rendered two trains of RHR inoperable.

The preceding paragraphs emphasize the complex plant interaction involved with the dc system of which the charger is an integral part. A catastrophic or degraded battery charger failure which is not detected and corrected in a timely manner could result in depletion of its associated battery and a partial loss of station dc power as described above. Similarly, if the battery charger failure occurs at the time of the transient condition, the plant's ability to achieve a long term safe shutdown condition could be significantly impaired.

Inverters are employed to assure continuous power to essential components even in the event of a loss of offsite and onsite ac power. Particularly in plants with only two vital ac buses, single inverter failures have initiated reactor trips and safety system actuations. In addition, important safety related systems such as HPCI, RCIC, and Low Pressure Coolant Injection (LPCI) have been made inoperable by inverter failures. If they should occur under accident conditions when maximum loads may be applied, inverter failures would severely impair the ability of the operator to respond since instrumentation and controls affecting emergency system operation could be inoperable, providing either no information or misinformation about important reactor parameters. Actual challenges to safety systems, approximately 50 in number, have included feedwater system excursions which have resulted in reactor trips and/or safety injection system actuations. These significant transients place a demand on the safety systems and the operating personnel, especially when additional circumstances develop, such as steam line isolation or inadvertent opening of steam dump valves. Four examples of actual events are depicted to indicate the safety implications of inverter failure.

- A reactor trip, safety injection, and steam line isolation occurred as a result of an inverter failure.
- An inverter failure resulted in a reactor trip and safety system injection which was complicated by the inadvertent opening of the condenser steam dump valves.
- An inverter failure also interrupted power to the pressurizer pressure controller rendering both shutdown cooling loops inoperable.
- Two feedwater pumps tripped because of a loss of speed control resulting in a reactor trip and safety system injection.

3.1 System Level Stresses

The battery charger and inverter are closely coupled in most nuclear plant applications and are therefore subjected to a very similar system level stresses. That is, the charger output is normally connected to the inverter input, and the ac supply to the battery charger also provides alternate power to the vital bus, either directly or through a rectifier in the inverter module. This is illustrated in Figure 3-1 which also depicts the alignment of offsite and onsite emergency ac sources.

System level stresses which could accelerate inverter and charger aging resulting in equipment failure or degradation include the following:

- loss of ac power
- accident conditions
- electrical disturbances during normal operation

Each of these stresses will be discussed in the subsequent paragraphs.

3.1.1 Loss of ac Power

An extended loss of offsite power coupled with a loss of onsite ac power places loading stress on both the charger and the inverter. During the loss of ac power event, the battery charger is deenergized and the station battery provides the input to the dc bus which supplies the dc loads including the inverter. While the inverter load remains fairly constant during this event, load changes on the dc bus due to the startup of the standby motors and initiation of switching operations cause dc voltage transients (reductions) on the inverter input with a duration ranging from a cycle to several seconds. This type of transient is similar to ones associated with short circuits, transmission system disturbances, and large motor starts. The inverter circuitry is designed to maintain a constant ac voltage with a dc input as low as 105 volts, however, fast control and firing module responses are required to obtain this goal under this type of transient condition. SCRs and transistors, the primary components providing the control function, must sense the voltage dip and increase the firing rate to maintain the required output parameters. Overcompensation by these modules could cause a high voltage inverter trip. Similarly, the input current of the inverter rises as the dc voltage decreases to provide a constant power output. A momentary decrease in dc bus voltage could result in sufficiently high currents to cause operation of a circuit breaker, or a fast-acting thyristor fuse. Either of these operations would render the inverter inoperable or degraded.

When ac power is restored, the battery charger must be capable of supplying sufficient dc power to supply all of the dc loads while recharging the depleted battery. Current limiting circuitry prevents the charger from exceeding its overload rating of 115 to 125% of capacity. However, even this amount of overload causes stresses which could result in delayed effects including the premature failure of electrical components such as fuses, capacitors, and SCRs which are all susceptible to the high temperature conditions produced during charger overload.

An attempt was made to correlate inverter and battery charger failures to significant loss of offsite power events which have occurred at a number of sites. In the cases reviewed, emergency diesel generator operation restored power to the ac bus thereby reducing, if not eliminating, the stresses resulting from a total loss of ac power previously described. The event descriptions did not indicate detailed plant configurations during the event such as motor control center load shedding which, in some plants, will intentionally make the charger inoperable unless manual action is taken to restore power to that bus. Some examples of charger/inverter failure events possibly related to loss of offsite power events are denoted in Figure 3-2.

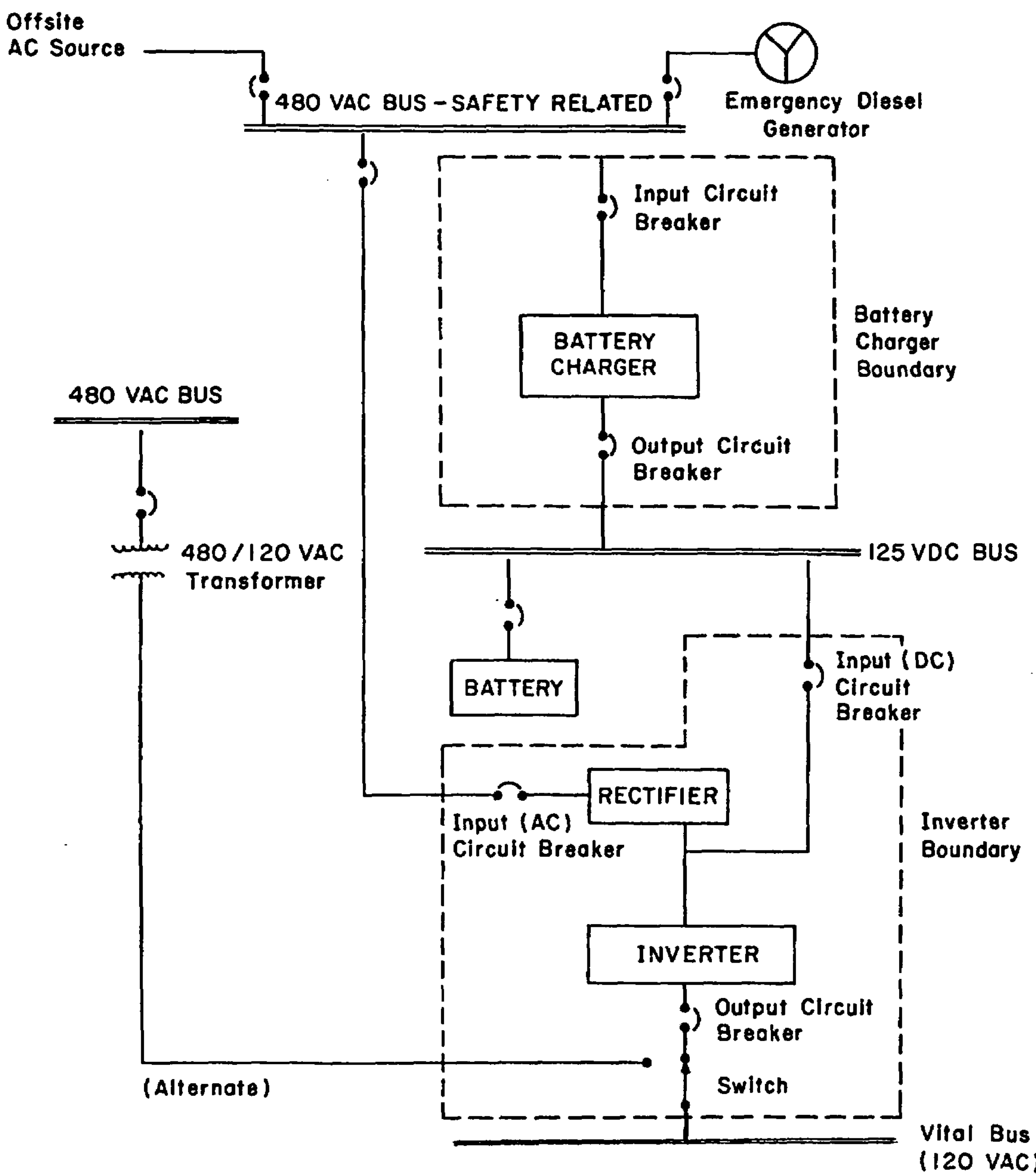


Figure 3-1: Battery Charger - Inverter Alignment

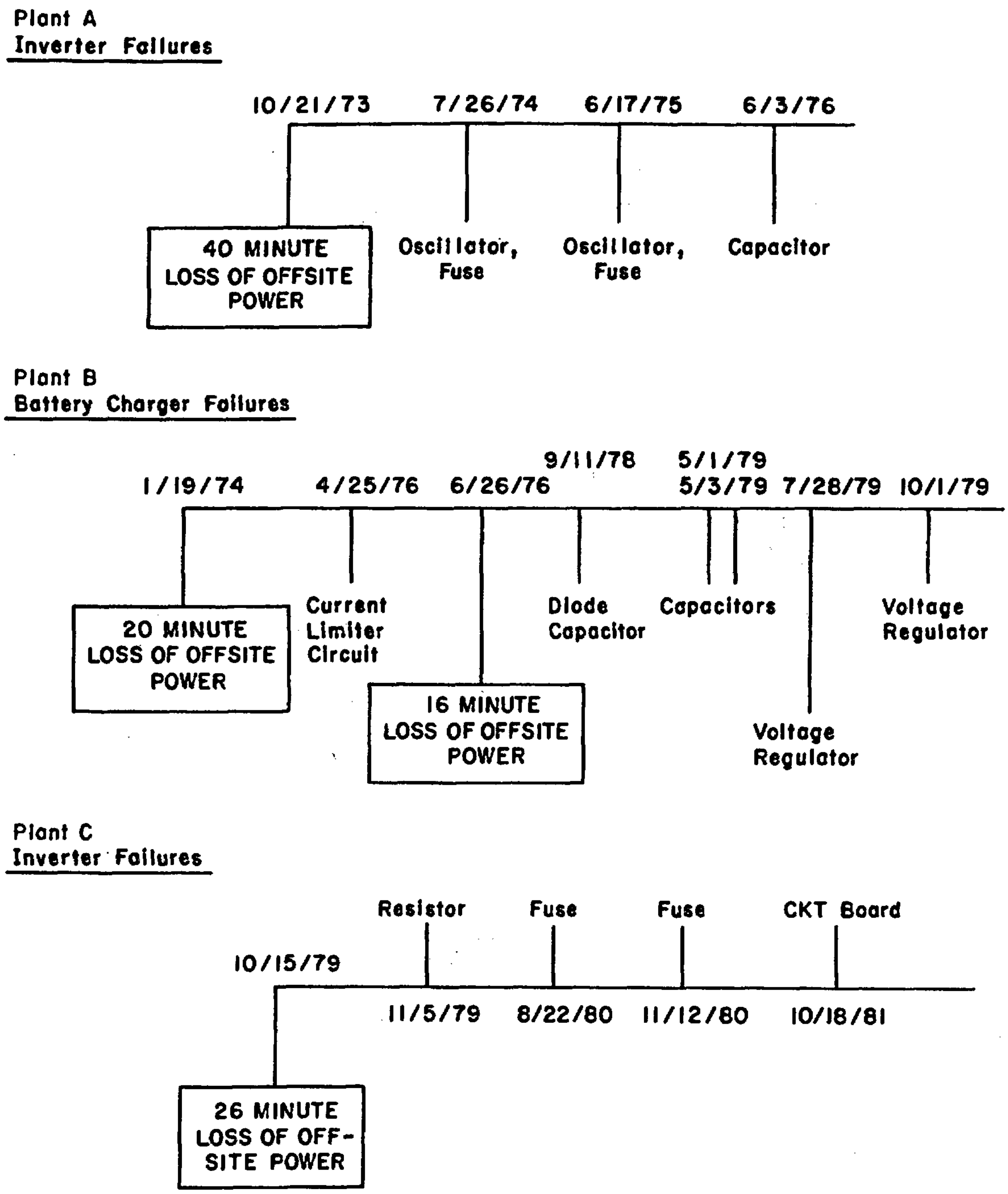
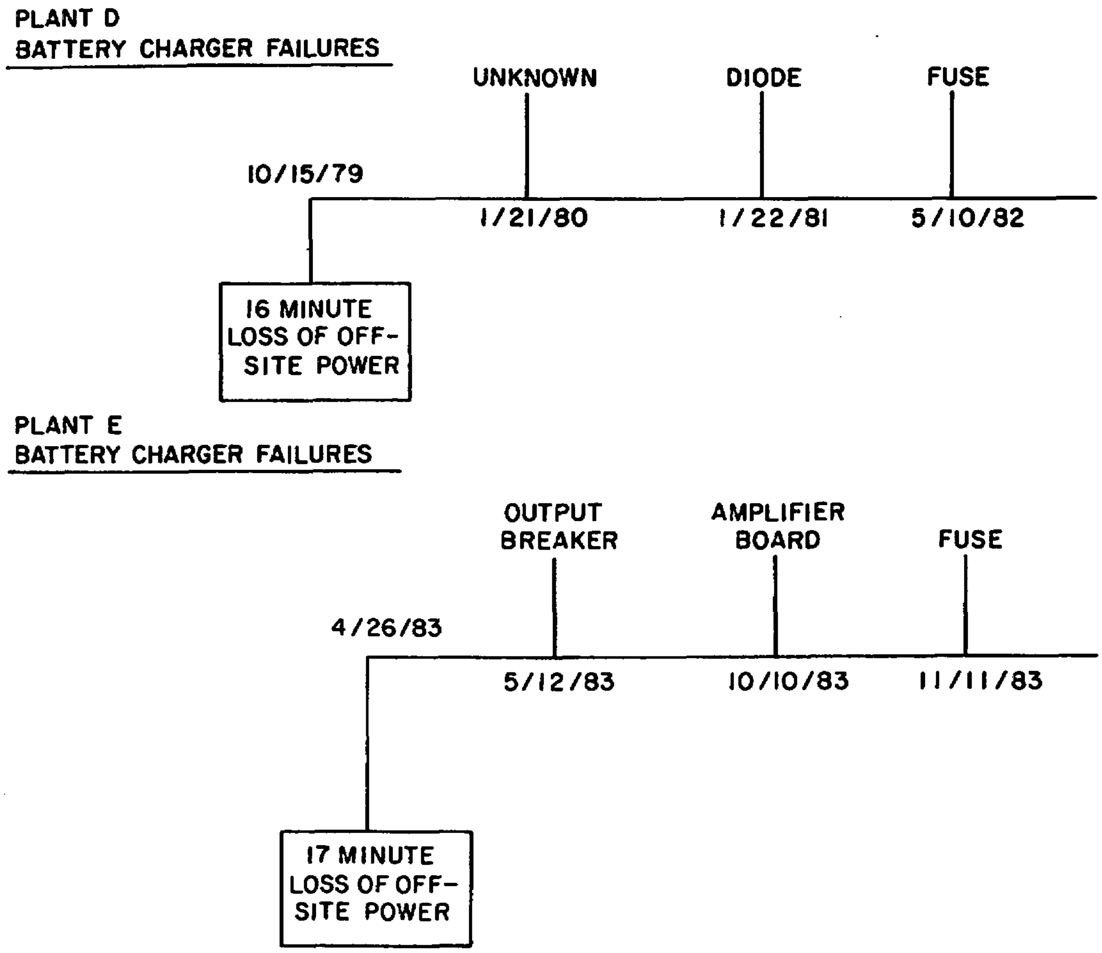


Figure 3-2: Time Line Diagrams of Effects of Offsite Power Outages (LERs and NPRDS)

Figure 3-2 (Cont'd)



3.1.2 Stresses Incurred During Accident Conditions

Accident conditions could result in electrical system stresses similar to those experienced during a loss of ac power. One major difference, however, is associated with the ac input supplying the battery charger and the alternate supply to the inverter. As with a loss of offsite power, the emergency diesel generators receive an automatic start signal under accident conditions and will power the various emergency busses upon loss of the normal supply. Subsequent sequencing of emergency loads causes swings on the diesel generator output voltage and frequency which are imparted to the electrical and electronic components associated with voltage and frequency control circuits in the charger and/or inverter. Frequencies as low as 57 cycles and voltage reductions as much as 20% below normal have been experienced in simulated accident conditions such as those established during preoperational testing. Although these parameters are within the design range of the charger and inverter, when they are combined with the heavy electrical loading due to safety equipment starting and other potential external influences such as a loss of area ventilation, significant stresses will be placed on the chargers and inverters. In particular, for the three phase ferroresonant transformer type inverter, any phase unbalance resulting from an abnormal load distribution will cause circulating currents within the transformer producing undesireable heat. Besides the electronic components in the voltage and frequency control circuits, overheating will affect the transformer insulation characteristics thereby making these components more susceptible to failure.

Two specific instances of inverter failure were reported where diesel generators were involved with carrying the emergency bus loads during testing.

- A 7.5 KVA ferroresonant inverter tripped in April 1984, when a fuse blew during emergency diesel generator testing. A utility contact revealed that this was a recurring problem which had caused at least one reactor trip. In some cases, the high voltage sensing relay had initiated a circuit breaker trip. Consideration was being given to replacing these inverters. The root cause of this failure could be the electrical transients occurring when breaker sequencing operation occurs, or the wider voltage variations experienced during diesel operation.

- A 20 KVA ferroresonant inverter tripped in May 1980, when voltage overshoot on the diesel generator was passed through the battery charger to the input of the inverter where it caused blown fuses in 4 to 5 msec in the dc control circuit and in the dc power circuit. As a result of loss of the vital bus, a reactor trip and safety injection occurred.

3.1.3 Stress Due to Electrical Disturbances

A subset of stresses due to major perturbations, such as a loss of offsite power, are those imposed during electrical transients common to power plant electrical systems. These disturbances originate from lightning effects, internal station switching operations, and the impact of major equipment operation including fault conditions.

A review of the LER and NPRDS data banks revealed that "electrical transient" was listed as the cause of 29 inverter failures and five battery charger failures. In a large majority of these events, circuit breaker and/or fuse operation occurred which prevented further immediate damage to the inverter/charger circuitry. However, the component was unavailable until power was restored by replacing the fuse or closing the circuit breaker. Only eight cases were noted where the transient directly resulted in a component failure, with capacitors and SCRs being most susceptible to this type of occurrence. This breakdown is illustrated by Figure 3-3.

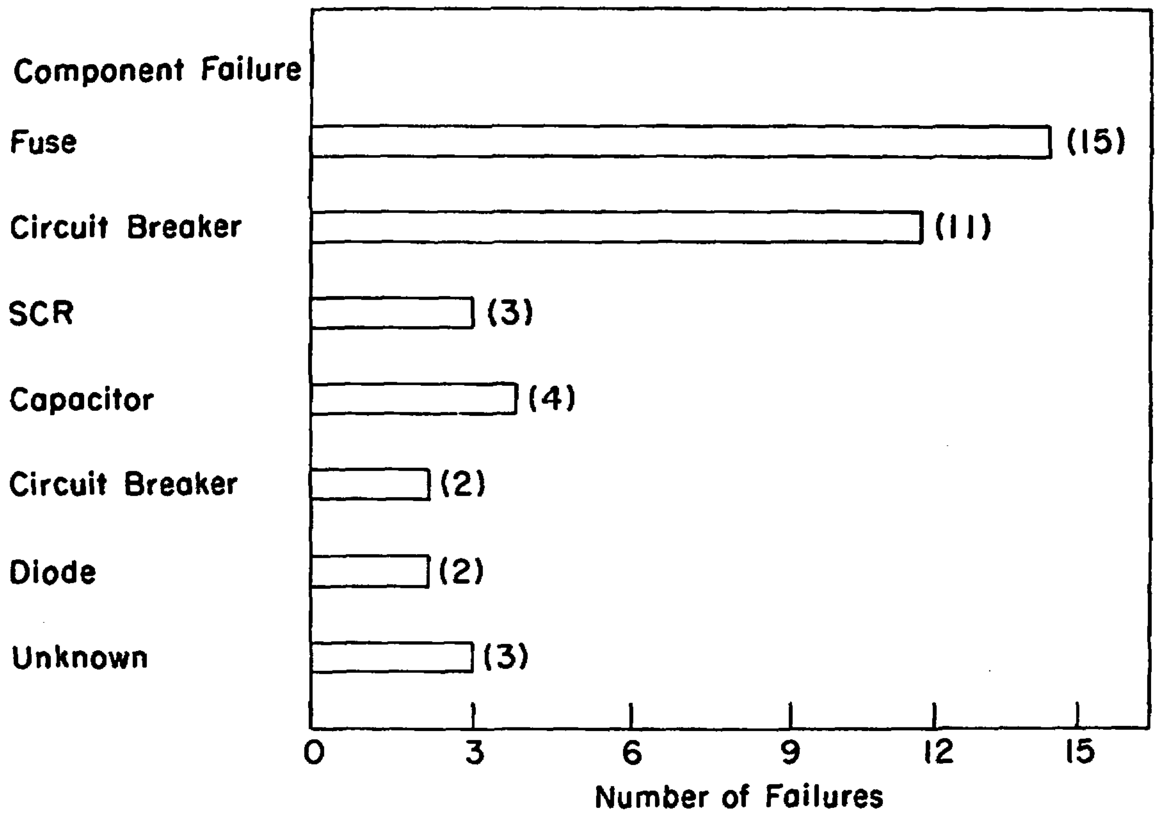


Figure 3-3: Component Failures Due to System Electrical Disturbances
(LER and NPRDS Data 1974-1984)
[Inverters and Battery Chargers]

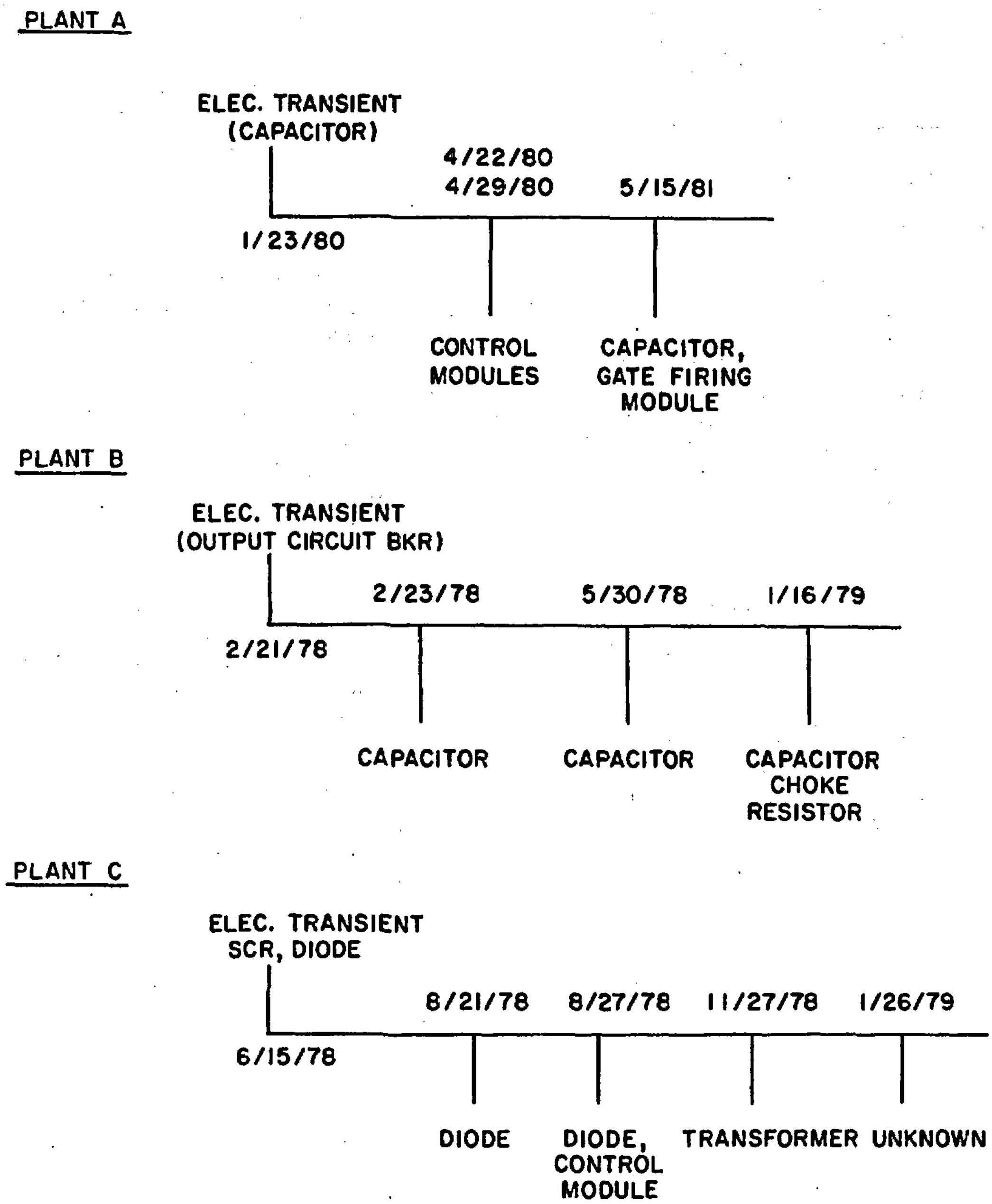


Figure 3-4: Time Line Diagrams of Transient Effects on Equipment Failure (LERs and NPRDS)

Although it is impossible to determine precisely that inverter failures due to electrical transients also resulted in subsequent premature component failures, several examples were found where a delayed effect is evident. These are illustrated on the time lines of Figure 3-4. It should be noted that present day charger and inverter designs incorporate an internal surge suppressor which is intended to direct transients safely to ground without damaging sensitive electronic circuitry. This feature may not be common to some older designs in use.

3.2 Component Level Stresses

As discussed in Section 2.3, the most significant environmental contributor to battery charger and inverter aging is temperature. Chargers and inverters are typically located in mild environments; that is, temperature and humidity are relatively closely controlled and monitored and they are immune from the high radiation or steam /humidity potential of the harsh environment. Nevertheless, increases in ambient or internal temperatures can have a dramatic effect on inverter and charger performance. Twenty-five inverter failures and 10 battery charger failures due to overheating were documented. Of some interest is that 20 of the 35 failures occurred within a three month period (summer) when slightly higher ambient temperatures and humidity in a power plant are likely to exist.

Figure 3-5 illustrates the component failures which are associated with overheating. Note that at least one inverter manufacturer has incorporated a thermostat within the inverter module which trips the input circuit breaker when the temperature exceeds 85°C. Six inverter "failures" occurred because of proper operation of this switch. In four cases, high ambient temperatures existed, while in two reports cooling fan failures caused the internal overheating condition. These 6 events are not included in Figure 3-5, since no component failure resulted from the excess temperatures. Also not included are 4 fuse operations caused by capacitor failures. In these events it was determined that the fuse properly operated because of the capacitor failure and not as a direct result of overheating.

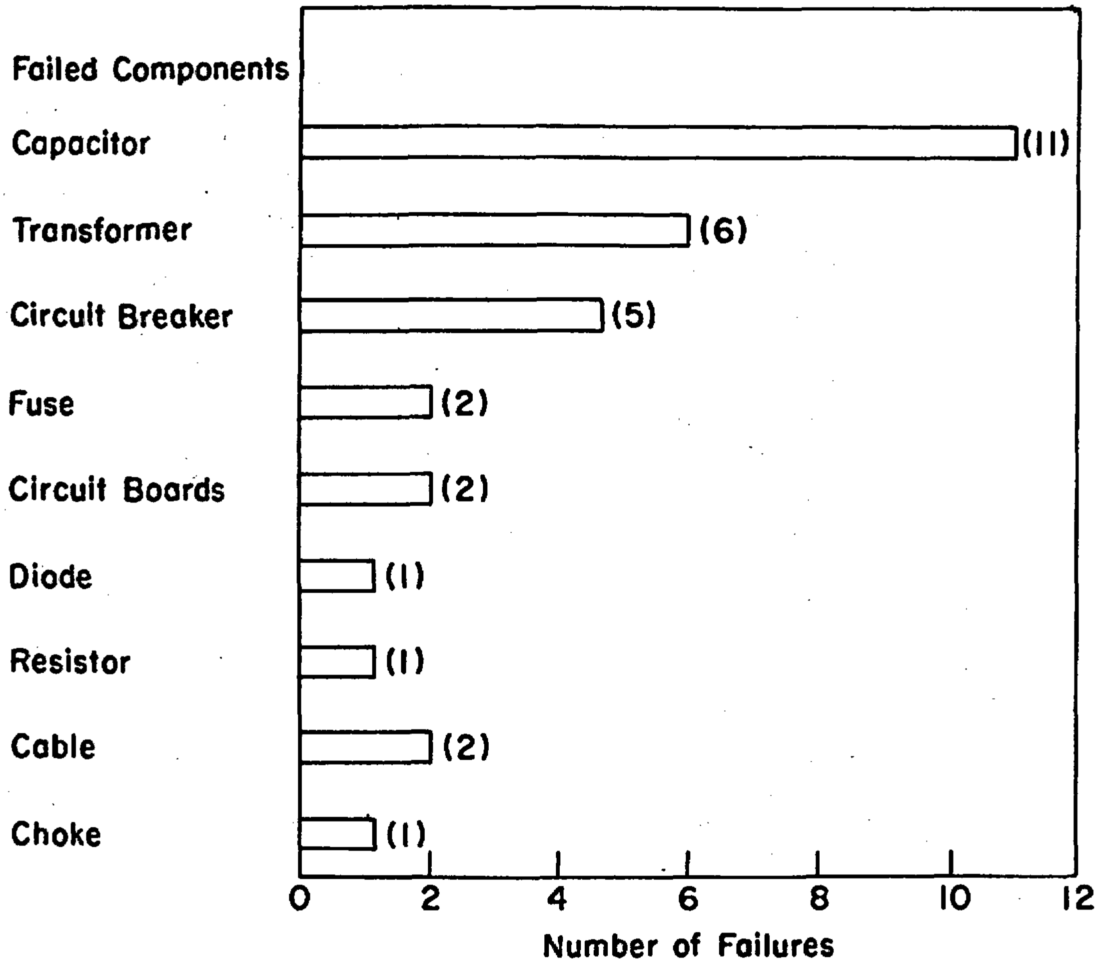


Figure 3-5: Component Failures Due to Overheating
(LER and NPRDS Data 1974-1984)

Several additional items of interest were gathered from the failure reports which indicate improvements being made in materials to combat the effects of temperature.

- Two cases of cable degradation due to overheating were noted . In one case the battery charger cable was replaced with cable having a higher temperature rating. It is probable that the elevated temperatures experienced were not anticipated and, therefore, inadequate designs may have resulted.

- Of the six transformer failures, five occurred in the ferroresonant type inverter. The remaining transformer failure occurring on a battery charger resulted in replacement of the input transformer with one of Class F insulation. Present day qualification reports for inverters and battery chargers specify Class H insulation for transformers.

Several inverter capacitor failures at one nuclear station occurred in recent years because of overheating. It is documented in the LER data that the failed commutating capacitor was replaced by a "new generation commutating capacitor which had a higher dielectric strength and a higher temperature rating." The same capacitor in the other inverters was also replaced. Ventilation to the inverter enclosures was also enhanced. Because this change was made in June 1984, additional time is necessary to evaluate the effectiveness of the modification. The effect of temperature on the life of a capacitor is indicated by Figure 2-16. If one considers that a ten year life is predicted for an electrolytic capacitor based on a maximum ambient temperature of 40°C, an increase of ambient temperature to 60°C would decrease the expected life to one year according to this curve. Similarly, capacitance value can also change due to the surrounding temperature (Figure 3-6). Although the percentage capacitance change from 20°C to 60°C will not be more than 10%, operating parameters resulting from the cumulative effects of all capacitors could be significant.

It was expected that solid state components would have been susceptible to failure due to overheating, however, this was not supported by the operating data. The internal or junction temperature of a solid state device has considerable influence on the terminal characteristics of the device. For instance, the reverse leakage current of a pn junction increases rapidly with temperature. In a thyristor, this leakage current in the blocking state is similar to gate current so that if the junction temperature is high, the circuit may malfunction due to the inability of the thyristor to block. Constant thyristor conduction could result in the output circuit breaker tripping or operation of internal thyristor fuses.

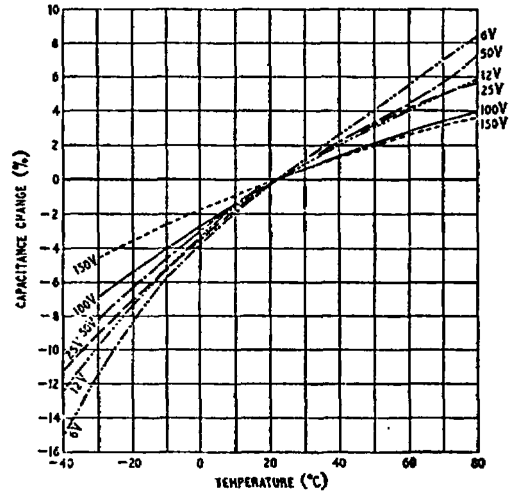


Figure 3-6: Change in Capacitance Value With Temperature

3.3 Testing Induced Stresses

Technical specifications require that capacity testing be performed on the station battery and its associated battery charger at a regular interval (typically every refueling outage for the charger). The capacity test is intended to simulate the loads calculated to exist under an accident condition where the charger must carry the dc loads while recharging the depleted battery within a specified time. These dc loads consist of pumps, MOVs, instrumentation, and controls. This same criteria is used for sizing the charger and can be shown as follows:

$A_c = \{[(A_H)(K)/T] + L\} K_1K_2 = AK_1K_2.$

A = Required charger output (amps).

A_c = Corrected charger size for temperature and altitude (amps).

A_H = Capacity removed from the battery in ampere hours.

T = Time required to recharge the battery to 95% capacity (hours).

L = Continuous load on dc system during recharging (amps).

K = Charger conversion factor based on battery type (Lead Acid Cells, $K = 1.1$, Nickel-Cadmium Cells, $K = 1.4$).

K_1 = 1.20 for temperatures between 40°C and 50°C, 1.56 for temperatures between 50°C and 60°C.

K_2 = 1.06 for altitude between 3300 and 5000 feet.

At least a 20% design margin should also be included in the sizing calculation to allow for load growth on the dc system. The addition and/or modification of nuclear plant systems has resulted in an increase in battery charger demands sometimes even requiring the installation of new chargers and batteries.

To verify that the charger is capable of meeting its design loading, large resistor banks and sophisticated control equipment are used to simulate the accident loading conditions. Misoperation of this equipment may have contributed to some of the test failures reported, although, the number of failures (13) occurring during testing, especially in the case of battery chargers, remains significant. As illustrated in Figure 3-7, capacity testing resulted in a large number of circuit board failures, consisting of firing modules and control modules. It is believed that if the testing had not been performed, normal operation at lower loads could have continued. Therefore, the testing was useful in detecting weak links. Several examples are indicated where capacity testing provided information important to the charger's ability to perform its safety function:

- When the output was increased on a magnetic amplifier type charger to meet the capacity test requirements, arcing was observed across a bad electrical wiring connection.

- During load service testing on an SCR type charger, fuses blew as a result of a failed gating filter module. The SCR firing module was adjusted to assure current balance in all three phases.
- During a battery discharge test, the output fuse blew on an SCR type charger. The combination of high current and temperature caused the soldered linkage to separate.
- During a charger load test, the output circuit breaker tripped at lower than designed load conditions.
- A battery charger failed its capacity test because of a control card which was loose in its socket.

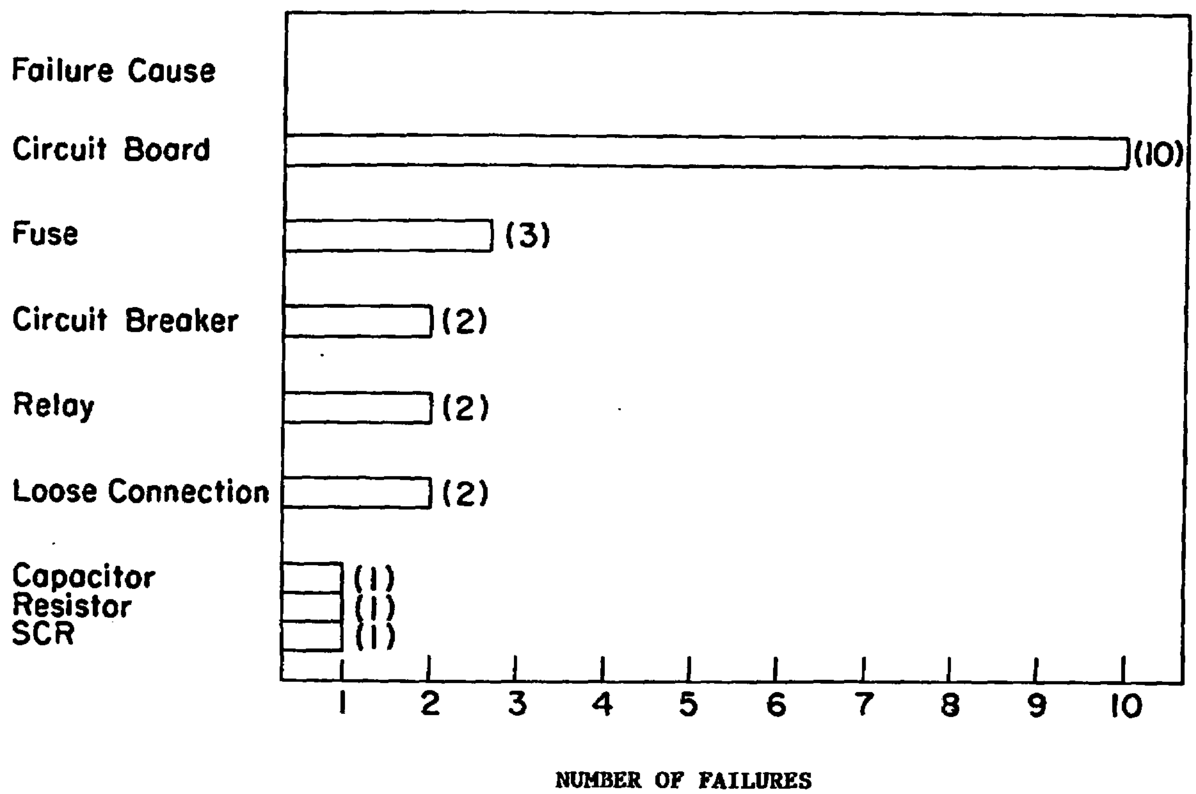


Figure 3-7: Battery Charger Test Failure Cause
(NPRDS and LER 1976-1984)

The present standard technical specifications (tech spec) do not delineate any specific testing for inverters and require only that the vital bus be energized. An evaluation has been performed [18] to determine if action statements should exist in the tech specs, however, no ruling has been issued in this area to date. Nevertheless, some manufacturers recommend periodic testing of the inverters and many utilities incorporate these recommendations into their Preventive Maintenance (PM) Program. As reported in several LERs, inverter failures were discovered during testing even though this is generally not a reportable occurrence. The consequences of the inverter failure, however, resulted in entering a Limiting Condition for Operation (LCO) and were therefore reported.

Typical of these failures are the following:

- Performance of a load transfer test resulted in the loss of two inverters and a loss of shutdown cooling during refueling operations. The inverter input fuses blew because of "leaky" SCRs.

- During inverter testing, the input fuse blew resulting in a loss of power to the pressurizer pressure controller which rendered both loops of shutdown cooling inoperable. Improper fuses were discovered (design error).

- During transfer testing, the inverter failed to shift to the battery backup upon loss of normal ac power.

- Cycling of RHR motor operated valves to meet tech spec requirements resulted in an overvoltage trip on the inverter. The voltage regulation circuit boards overcompensated for the load.

Similarly, the other six inverter failures which occurred during testing were attributed to circuit breaker or fuse operation, probably due to the inability of the inverter to respond to the applied load changes.

The application of design loads to a battery charger or an inverter on a refueling interval frequency appears reasonable and, when performed, has been beneficial in detecting potential problems that were not obvious during normal operation. It is possible, however, that the degradation which resulted in the test failure could have been detected during normal operation by condition monitoring techniques. Monitoring of output waveforms or internal SCR gating operations, for example, may be useful in assessing equipment performance. This aspect of the charger/inverter operation will be investigated at great depth in Phase 2 of the NPAR Program Plan.

3.4 Human Factors

Because of the inherent complexity of large high performance battery chargers and inverters, human errors in the design, manufacture, operation, and maintenance of these devices are possible and, in fact, have been committed. Human errors related to inverter failures were reported to account for 17.8% of all inverter failures in one report [2] and 12.0% in another report [19]. When the LER and NPRDS data for battery chargers and inverters were combined, human error accounted for ~15% of the failures, with 65 inverter failures and 19 battery charger failures documented. As indicated by Figure 3-8, the clear majority of human errors were attributed to operating and maintenance personnel at the plant.

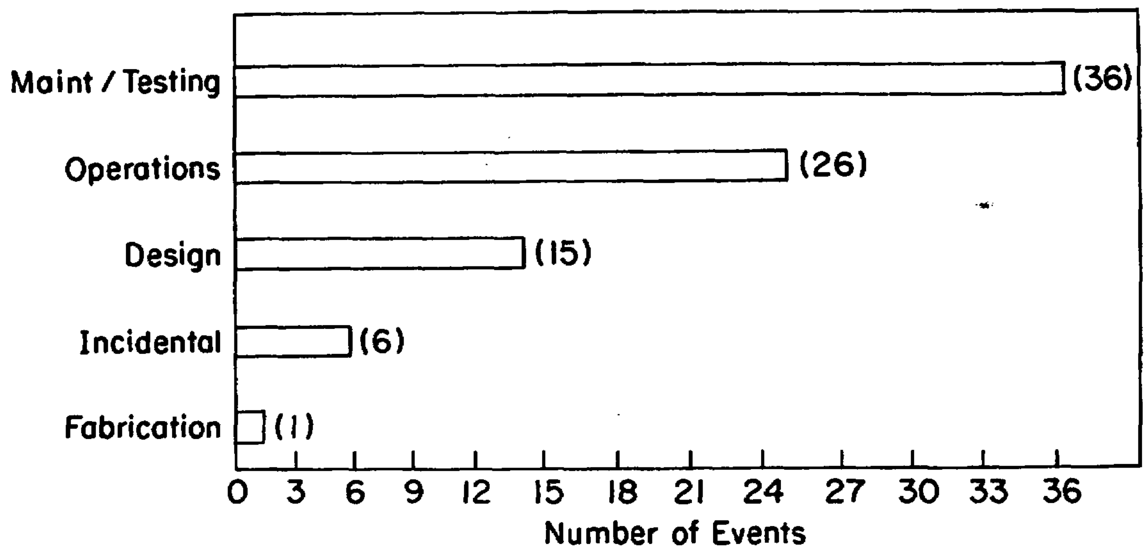


Figure 3-8: Personnel Errors - Battery Chargers and Inverters

Maintenance and testing errors include incorrect calibration of circuit breaker trip settings, short circuits caused by test equipment wiring, and improper adjustment of float/equalize potentiometers. Operation errors were generally of a less technical nature such as the mistaken opening of input or output circuit breakers, neglect or improper response to equipment trouble alarms, and incorrect "lining up" of the equipment (dc supply not connected to energized inverter). Design errors deal with capacitor rating, fuse sizing, and transformer insulation along with an incorrect set point for a charger high voltage trip. Several inverter and charger failures were attributed to personnel errors external to the charger/inverter boundary including accidental bumping of a circuit breaker and a short circuit on the supplied equipment due to personnel contacting energized equipment. These failures are classified as incidental. The one fabrication error in the data base is interesting in that the licensee reported "a gradual decay of float voltage level" due to defective zener diodes. Zener diodes are used in the voltage regulation circuitry of inverters and chargers, and could exhibit changing characteristics with time (aging) due to certain undersireable impurities introduced during the manufacturing process.

The consequences of personnel errors were significant as noted below:

- Four reactor trips resulted from personnel errors associated with inverters.

- A battery charger output circuit breaker opened causing an alarm, however, no operator response was made. The battery discharged, rendering HPCI inoperable. An attempt to use HPCI on a subsequent plant transient failed because of the low dc voltage condition.

- An inverter was energized from an ac supply with the dc supply breaker inadvertently left open. Loss of ac power would have de-energized the vital bus.

3.5 Synergistic Effects

As indicated in Appendix A of IEEE 650-1979 [6], stress on resistors, capacitors, and semiconductors may be calculated on the basis of the applied value of certain parameters, such as current and voltage, as compared to their rated values. Worst case operating mode conditions when applied singularly provide a conservative analysis since in actuality, worst case conditions cannot occur for all components simultaneously. When considering silicon base semiconductors, however, Appendix B of IEEE 650-1979 states that these components "never wear out if constructed and used according to specifications." As the failure data base indicates, events such as electrical transients or personnel error can exceed specifications and lead to accelerated aging of even these stable components.

Humidity by itself is not considered an aging mechanism for inverters and chargers located in a mild environment. However, when coupled with insulation or connector degradation, the moisture could provide an electrical path between the component and ground. Loose connections, cited as an important failure mode in chargers and inverters, allow moisture to enter the contact surface which could increase the corrosion rate on contact surfaces.

Similarly, circuit breakers, relays, and switches will age because of the wear out nature of cycling these devices. A review of recent equipment qualification tests demonstrates that a large amount of conservatism is built into the design of these devices, since in practice, monthly cycling is the maximum conceivable cycling anticipated, yet the design allows for hourly cycling.

As indicated earlier in this report, electrolytic capacitor life is proportional to temperature, voltage, and ripple current. The combined effects of these parameters on capacitors is difficult to assess but is generally considered to be additive.

3.6 Aging - Seismic Correlation

The correlation of seismic effects on aged battery chargers and inverters is difficult to establish quantitatively because of the complexities associated with the age related degradation of the many subcomponents used in this equipment. However, by making certain reasonable assumptions, including the consideration that battery chargers and inverters are identical in construction and subcomponent composition, qualitative analysis of seismic effects on battery chargers and inverter operation can be performed.

The present state of the art in this area includes three different approaches that can be used to establish the aging-seismic correlation for any equipment. Two of the methods relate to assessing equipment which has been subjected to laboratory seismic tests or to actual seismic events. The fragility of nuclear power plant equipment is also being studied and may provide important input in this area [38]. The third approach is an analytical method suggested by Sugarman [20] which requires identification of equipment "weak links," and a determination of how these weak links will act when subjected to seismic stress. This study is concerned with the latter analytical approach and contains the following elements as they relate to battery chargers and inverters:

- assumptions/equipment interfaces
- equipment dynamic characteristics
- equipment aging characteristics
- age degraded components vulnerable to seismic loads

3.6.1 Assumptions/Equipment Interfaces

Battery chargers and inverters are cabinet-mounted equipment directly secured on a skid, wall, or floor as illustrated by Figures 3-9 and 3-10. Figure 3-9 is a typical three phase battery charger which is skid mounted, whereas Figure 3-10 depicts a wall mounted charger. Inverters would likewise be similar in size and layout. Subcomponents are enclosed inside the cabinet and are mounted to the cabinet structure. Some meters, annunciators, cables, and other connectors are mounted on the front door panel for easy access in operating the equipment. The equipment has an electrical interface with the plant power distribution systems through input and output cables. These cable connections are generally located in the back of the cabinet with the cables

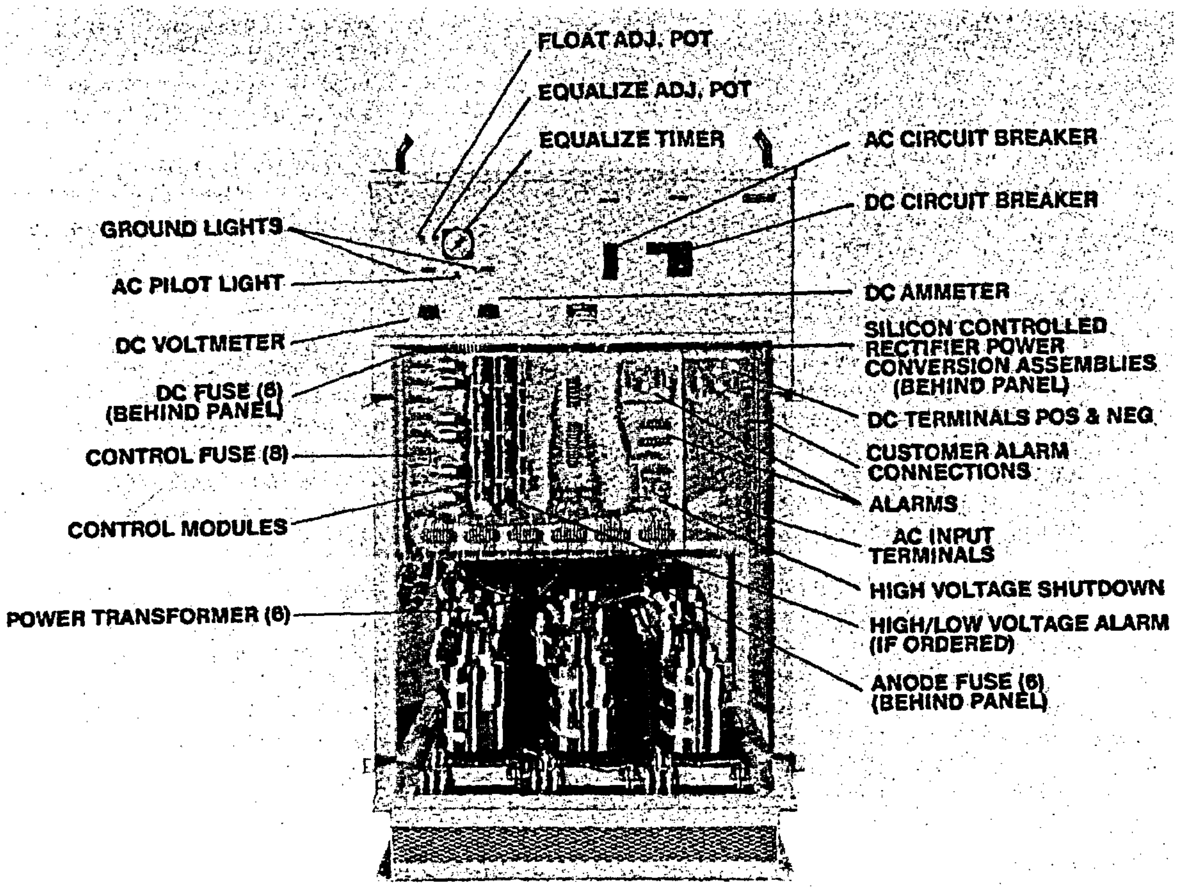


Figure 3-9: Skid Mounted Three Phase Battery Charger

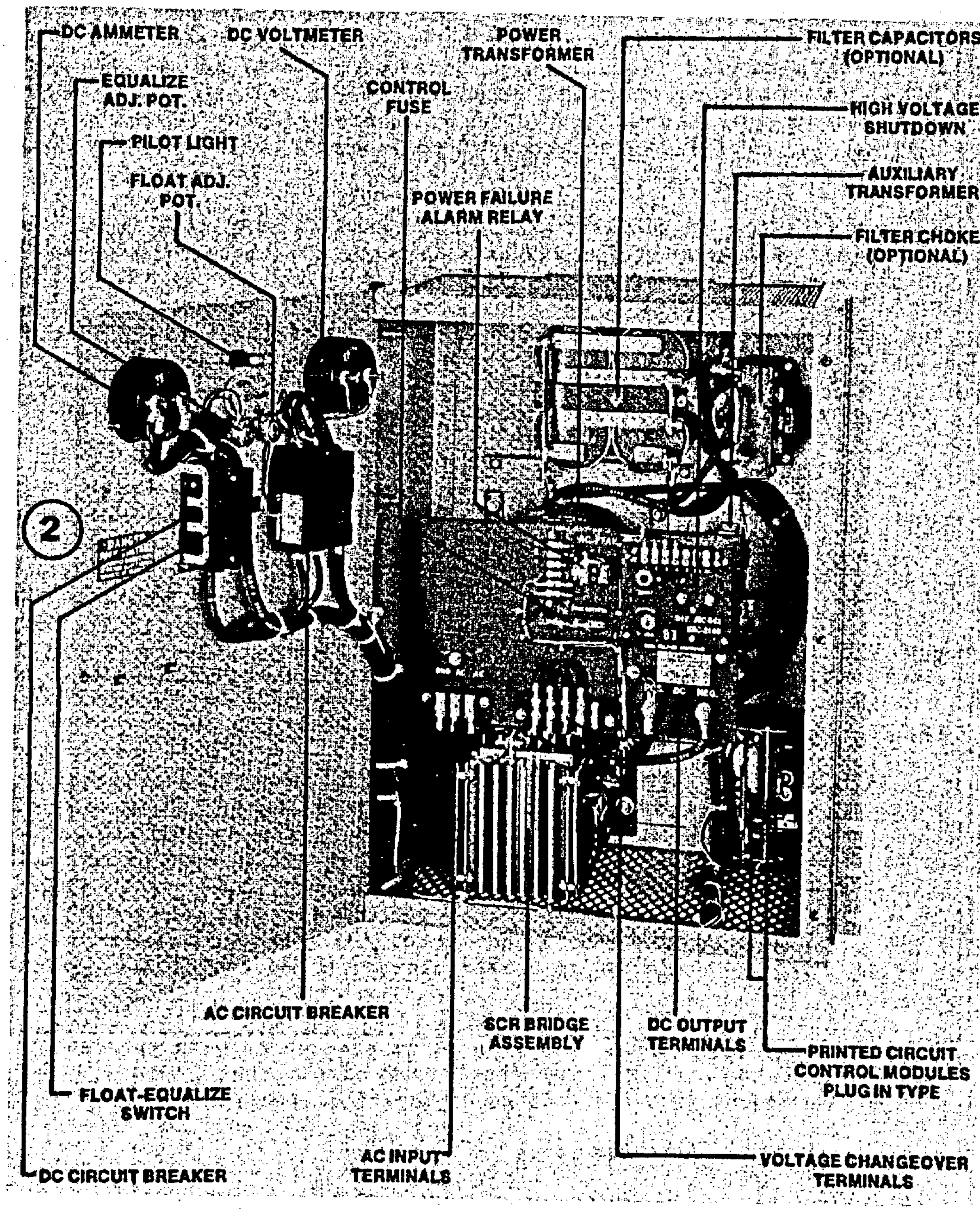


Figure 3-10: Wall Mounted Single Phase Battery Charger

passing through the cabinet at the bottom or the side. It is important that the cable be sufficiently flexible in the connection area to allow for vibration displacement. A second interface of this equipment is the structural connection with the floor, wall or skid. The manner in which the charger or inverter is mounted is considered part of this evaluation, whereas the supporting structure construction (floor, wall, etc.) is not. Failure of either the electrical interface due to cable disconnection or of the structural interface due to failure of the structure itself would result in equipment failure.

In addition to the above two interfaces, falling objects dislodged from nearby structures or equipment, or debris on or around, the equipment could result in equipment malfunction. All of these conditions are assumed out of scope in this analysis. Proper protective barriers should be built to isolate the equipment from any water/steam/chemical spray, missiles, or broken live electrical connectors. On the basis of the above, the boundary of the equipment is thus defined as the battery charger or inverter cabinet along with the subcomponents within the cabinet and the mounting of the cabinet to a supporting structure.

Most of the battery chargers and inverters used in nuclear power plants were manufactured by six primary vendors. Although there exist several different designs, the physical appearance and construction of the units including the mounting of subcomponents inside the cabinet are similar. The size of an inverter is designated by its voltage-ampere rating. The weight of an inverter varies from as little as 30 lb for a 0.5KVA rated unit to 4000 lb for a 200 KVA unit. Similarly, battery chargers have weights ranging from 60 to 5000 lbs. The physical size of the equipment also varies significantly. An average sized charger/inverter weighing about 1000 to 1500 lbs is considered for this analysis.

Although aged components vulnerable to dynamic loads will be identified in this section, it is imperative to note that the equipment along with all the subcomponents attached to the cabinets are mounted as specified in the original qualification report and are maintained that way throughout the life of the equipment. Random failures caused by loose screws, inadvertent tripping of a switch, and improper maintenance practices are not part of this evaluation. It is further assumed that manufacturer's recommended component replacements such as electrolytic capacitors are performed during the life of the equipment.

Considering the above assumptions, an attempt is made to discuss as well as identify the problem sources and root causes that could result in aged battery charger or inverter failure at the time of maximum system demand.

3.6.2 Dynamic Characteristics

Equipment construction and subcomponent layout information is required to define its overall dynamic characteristics. The inertial load generated by the equipment mass as a result of self induced or externally induced vibratory excitations are obtained on the basis of the mass distributions of the equipment. In the case of a battery charger or inverter, the major weight contribution is the steel cabinet structure which amounts to almost 70% of the total weight of the equipment. The remaining 30% of the total weight is from the many electrical elements. The power transformers, which constitute one-third of this weight, are located in the bottom portion of the equipment. Thus, dividing the entire panel into three compartments, the total weight distribution from bottom to top is 45%, 30%, and 25%, respectively. Vital components such as relays, circuit breakers, SCRs, and PC-boards are located in the central compartment. The top compartment holds some capacitors, lights, meters, and switches. In addition to these compartments, some control boards may be mounted on the front door panel which is made of a thicker steel plate than the remaining cabinet sides.

With regard to the structural strength (i.e., stiffness) of the equipment, the frame of the equipment is generally one piece consisting of the four corner legs and the cross beams connecting them at the top and bottom, and sometimes at intervals between depending on the total height of the equipment. Except for the front plate, the sides are braced and covered with thin sheet metal. The front plate, particularly the door, is generally made of thicker plate and adds strength to the overall structure. Several subframes are built inside the cabinet from the parent frame structure to support the electrical components. It should be noted that the electrical components by themselves add no strength to the equipment. Based on this design, the equipment can be considered to be flexible either in flexural (side-side/front-back) or torsional (about vertical axis modes only) motion. Additionally, the structure would exhibit rigid body motion in any of the translational directions along with the entire building structure housing the component.

Another factor that would affect the equipment structural ability is the mounting condition. Most larger units are skid mounted on the floor of a building. They are either bolted or fillet welded (4 inch welds are typical) with uniform spacing between welds, with the floor rails anchored to the floor concrete. In addition to the type of anchoring, rows of cabinets are often installed side by side and/or back to back, connected to each other with a damped material (spacer) between them. Unlike a single cabinet case, this arrangement sometimes eliminates the flexural and torsional deformation of the equipment by stiffening the overall structure. Many smaller sized units used in the fire protection system, or some other specific system applications, are wall mounted. In this case, as well as in an array of cabinets installed together, the equipment primarily experiences rigid body motion under dynamic loads.

Mounting of individual electrical components within the cabinet frame is considered separately. Each of these components, such as capacitors, breakers, relays, transformers, etc. is an individual equipment item by itself. However, with respect to the charger/inverter assembly it is sufficient to assume that these components exhibit only rigid body motion except for such spring loaded elements as relays and breakers. Proper maintenance programs should be instituted to keep these components securely attached to the frame.

As with mounting considerations, the sizes of the overall equipment cabinet as well as the individual components could affect the dynamic characteristic of the equipment. Taller units are more susceptible to dynamic failure than the shorter ones. For the equipment under consideration, most units are not under the former category and hence, the size of this equipment has little effect on the overall dynamic behavior. However, each individual component, such as a printed circuit board, is screwed to the cabinet at different points on the supporting frame raised from the cabinet. In this case, care must be taken to ensure that no relative motion between these supporting points can be possible under a dynamic condition.

Materials used in the construction are another factor which influences the dynamic behavior. The cabinet material is steel which provides strength to the equipment and helps to withstand any dynamic load. Many individual components are made of nonmetallic materials such as polymers. Some of these polymers are brittle or could become brittle with age, and are sensitive to any sort of bending forces acting on them.

Taking all the above factors into account, a simple calculation has indicated that the subject equipment has a flexural and torsional natural frequency well above the seismic range of 33 Hz. However, a manufacturer's seismic test of a battery charger has revealed that one of the horizontal frequencies is on the order of 16 Hz which is within the seismic strong motion range. It is not clear from the test whether this frequency is corresponding to the bending mode or any of the side panel vibration (localized plate vibration) where the accelerometer may have been attached. Although the dynamic characteristic of every individual design is different, it is reasonable to assume that the overall dynamic behavior of a typical battery charger or inverter will be the rigid body motion of the equipment. The bending or torsional effects on the equipment components will be minimal. This conclusion is subjected to the following conditions:

- The doors and wall panels are maintained rigidly attached to the cabinet frame.
- Mountings of the cabinet as well as the individual components are rigid.
- All electrical boards (PC or control) experience no relative motion from the supporting structure.

3.6.3 Aging Characteristic

Battery chargers and inverters, as mentioned earlier, consist of a metal cabinet which houses many electrical components. This equipment, designed to provide power to equipment vital to plant safety, is primarily located in the control building. The control building maintains a controlled environment because of the electronic components vulnerable to a hostile environment such as high humidity, high temperature and high radiation. Therefore, the subject equipment can be assumed to experience a mild environment during its lifetime.

Based on the above assumption as well as the operating experience study performed, the environmental parameters include dust/dirt, temperature and humidity. In addition to this, the equipment itself generates heat which might raise the cabinet temperature to cause thermal and thermal fatigue types of damage. It should be noted that the bottom cabinet section is often louvered to dissipate the heat from components located in that area, especially the transformers. Other age-related degradation include wear of certain components, and carbon deposits due to arcing on components with contacts. Humming noise generated due to cyclic forces within the transformers or any high voltage components also induce high frequency vibration inside the cabinet. For a forty year design life, the equipment has the normal service condition defined as:

Ambient Temperature: 85°F
Relative Humidity: 20-90%
Total Integrated radiation: 1E3 rad gamma

Radiation levels in the control building are very low. Several radiation studies indicate that the lowest radiation damage threshold applicable to the equipment components exceeds the specified radiation requirement by an order of magnitude. Therefore, radiation exposure is not a concern.

Temperature of the cabinet environment is augmented by the heat dissipated from the transformers and other devices. Since in the vicinity of these devices the temperature may be well above the value mentioned above, temperature sensitive components such as fuses and capacitors, should be mounted away from these heat sources. The cooling fan, if forced air cooling is used, should be properly maintained to remove as much heat as possible during the life of the equipment. Relative humidity of the control building should be kept low to avoid any shorts in the control boards or corrosion of metal components. For plants located in high humidity regions, additional precautions should be taken to maintain a lower humidity inside the control building. The existence of carbon deposits on the contact points of relays and breakers, or dust or dirt buildup in the cabinet should be checked periodically. Transformer insulating systems can also degrade when the high temperature is accompanied by a humid atmosphere as well.

On the basis of the above, Tables 3-1 and 3-2 identify the components that are not critical for equipment performance and those that are very critical for proper equipment operation. In addition, Table 3-2 identifies components sensitive to aging which should be included in a maintenance program to maintain their design function. Another form of aging caused by mechanical loads such as noise and internally induced vibration affect the soldering and compression types of connections of PC boards, capacitor leads, and contacts of relays and circuit breakers.

Corrosion of mounting bolts and cracking of mounting welds for the cabinet are another form of age-related failures. Loose mounting bolts, both for cabinet mountings and other electrical components inside the cabinet, and loosening of fasteners holding certain devices could cause serious problems under vibratory loads.

Table 3-1: Components Whose Failure Causes No Equipment Failure

Component	Function
Paper Oil Capacitor	Filter ac noise from charger.
Fuses with Fuse Holders	Protects ac capacitors.
Ammeter/Voltmeter	DC current/voltage monitor.
Timer	Equalize battery.
Power Light Assembly	AC power indication.
Resistor	Voltage dropping.
Low Voltage Alarm	Low dc voltage alarm.
Relays	Alarm, indicating light.

Table 3-2: Components Whose Failure Causes Equipment Failure

Component	Function
Circuit Breakers	ac/dc protection
* Thyristor/Diode	Rectification control/blocking circulating.
Amplifier/Firing Boards	Control
Transformers	Power transformers
Choke/Capacitors	Filter
Resistor/Potentiometer	Bleeder
* Surge Suppressor	Transient protection
Fuses With Fuse Holders	Protection
Terminal Blocks	ac/dc connections
Relay Sockets	Hold relays
Relays	Over-voltage
Wire & Cable	Interconnection
Switch	On/off selection
* Heat Sink/Thermal Compound	Cooling
* Plastic Channel/Insulator	Mounting capacitor/heat sinks

* Components with no age-related seismic degradation

3.6.4 Age-Degradable Components Vulnerable to Seismic Loads

The main objective of this section is to establish whether inverters and battery chargers are vulnerable to seismic vibrations under aged conditions. As mentioned earlier, the most important aspect of an equipment ruggedness to seismic types of loading is the mounting condition of the equipment itself as well as fastening of individual components or subcomponents to their respective supporting structures. If any of the above violates the seismic design requirements, irrespective of any age-related degradations, the risk of equipment failure due to seismic load alone is significantly increased. This particular failure mode should be well understood prior to analysis of any other age-degraded modes and, therefore, the maintenance practices should include it in the check list each time the equipment is inspected. Additionally, this failure mode can also be caused by one of the aging mechanisms degrading the bolt torque as a result of corrosion or creep, and developing cracks. The same consequence can result, leading to equipment failure.

The laboratory controlled testing [21] of this equipment revealed certain modes of failures, including opening of relay contacts, blown fuses, extinguished lamps, and shorted bulbs which further tripped relays. Some of these modes have resulted in declaring the particular equipment to be failed. After tightening their mountings and replacing several with new units, these failures were avoided for the remainder of the test. Note that some of these failures are attributed to blown fuses or relay trips, which are designed to operate under abnormal conditions. Other studies based on the real earthquake experience data [22] have indicated that in nonnuclear facilities, cabinet type components not mounted to the floor have displaced from their original location with effect on the equipment function. Protective relays are also noted to trip under the real earthquake loads.

Certain components such as relays and circuit breakers are inherently prone to trip or chatter under dynamic loads. It has not been established whether this behavior will worsen as these components age. Since some of the relays used for this equipment are of the protective type, relay chatter or relay movement in its socket could trip the circuit breaker and cause the equipment to fail. Thus, tripping of circuit breakers is one of the modes which could be expected during a seismic event.

Cracking of PC boards, terminal blocks, and other nonmetallic brittle components, or embrittlement or warping/twisting of components with age (i.e., heat) are possible modes of failure under seismic conditions. The design and mounting of these components should be such that no relative displacement is experienced at its opposite ends while vibrating. Caution should be taken not to mount components of this type to the sheet metal sides used to form the enclosure. Localized plate vibration of these walls could induce twisting and bending forces. It is a good practice to build a subframe from the cabinet main frame to support all these components. If any latching devices are used, such as in the case of the door lock, caution should be taken that they remain securely fastened. Some noncritical items are attached to the doors and could become dislodged or broken and affect the equipment integrity. Interconnecting cables between different electrical devices should be sufficiently flexible to be able to dampen some of the vibratory input rather than snapping out of their connecting ends. It is prudent to tie these cables/wires to the cabinet walls intermittently to avoid any bouncing or colliding effect on adjacent components.

One important age-degraded connection which could fail under dynamic motion is the soldered connection of devices mounted on PC boards. These joints degrade because of oxidation during the life of the charger or inverter. A small dynamic force could impose a sufficient load to detach the lead from the devices.

Transformers used in this equipment are primarily dry type. Their insulating systems degrade with age, which result in cracks or voids. This increases the leakage current and under dynamic loads, the growth of these cracks or voids could accelerate which would render the component inoperable. Capacitors, on the other hand, are electrolytic or oil filled, and loss of oil or electrolyte makes the component incapable of holding a charge. Degraded capacitors could leak after experiencing shocks or disconnect themselves from the system at their leads.

It has been established that this particular equipment would experience rigid body motion under seismic excitation. Provided all components are attached to the main frame rigidly, they would also experience rigid body motion in any of the three global directions. Wyle tests [21] on such components indicated no aging-seismic related failures except for relays. However, this particular test does not simulate the real nuclear plant environment, specifically the synergism of various environmental parameters, errors caused by improper maintenance, and other factors causing component failures and not well defined by the researchers. It is true that components still do fail in nuclear power plants for unknown reasons. Hence, preventive measures against known failures would generally improve the availability of the equipment,as well as increase the plant availability and safety.

3.6.5 Conclusions

Few test or experience data are available to support the existence or non-existence of an aging-seismic correlation for battery chargers and inverters. However, certain components such as circuit breakers and relays are inherently sensitive to failure (trip) under dynamic or vibratory excitation. Other components which degrade with age become vulnerable to cracks or discontinuity under seismic loads. These include fuses, capacitors, insulation of magnetics, resistors, and printed circuit boards where material embrittlement, for instance, can be an age related characteristic. In conclusion, battery chargers and inverters qualified to nuclear industry standards do not appear to exhibit any aging-seismic correlation provided the design characteristics are maintained by implementing preventive maintenance as summarized below.

- Physical inspection of cabinet mountings to the floor, wall, or supporting structures.
- Physical inspection of all components and subcomponents (in particular printed circuit boards) mounted to the supporting frames inside the cabinet.
- Physical inspection of wires and cables connecting various vital components for their seismic fasteners as well as their end connections (i.e., weakening or degradation of connectors, soldering, terminal blocks, etc.)
- Electrical tests (insulation resistance)/physical tests on age-sensitive components identified in Table 3-2 for possible weakening effects detrimental to seismic loads.
- Physical inspection of relays/breakers for possible contact carbon deposits, or degraded coils, etc.
- Insulation tests on transformers for increased leakage current through cracks or voids resulting from aging, which could fail under vibratory loads.

4.0 DATA EVALUATION AND ASSESSMENTS

Nuclear power plant battery charger and inverter operating experience information was obtained from five different data sources, namely, Licensee Event Reports (LERs), In-Plant Reliability Data Systems (IPRDS), Nuclear Plant Reliability Data Systems (NPRDS), Nuclear Power Experience (NPE) reports, and Plant Maintenance records. While some common data existed among these sources, each offered certain unique information which made it desirable and necessary to review all of them in detail. The cumulative information from these data sources offered insight into subcomponent failure modes, plant response to failures, equipment design information (capacity and type), and corrective actions taken by the utility.

4.1 Licensee Event Report (LER) Review

LER abstracts were obtained from the computerized data file of the Nuclear Safety Information Center (NSIC) maintained by Oak Ridge National Laboratory. The abstracts obtained were based on key words such as inverter, battery charger, battery, uninterruptible power, vital power, and direct current (dc) equipment. More than one thousand abstracts were reviewed for information addressing charger and inverter failures occurring between January 1976 and July 1984 and from this information approximately three hundred failure events were selected for further analysis. The types of LERs excluded from the final data base were those addressing licensee test scheduling errors, failures of batteries unrelated to charger performance, and LERs associated with instrument power supplies which perform a specific function not relevant to either charger or inverter operation.

Valuable input to this time consuming review was provided by several other studies, including two LER Data Summaries performed by Brown and Trojovsky [19, 23] and an analysis of inverter failures by Bozoki and Papazoglou [2]. These reports categorized LERs and provided some insight into the data base population and the type of information obtainable from LERs. Because of the specific goal of identifying and characterizing aging and service wear effects, the summary information provided by these reports could not be used as a direct input to this study. Often, subjective judgements must be made regarding the root cause failure or the plant impact of the failure since the LER is not sufficiently descriptive. It is important, therefore, that when analyzing data for aging/wear related trends that these judgements be made consistently by the same team of reviewers. In a number of instances, the entire LER with all attached correspondence was obtained from the NRC Public Document Room in order to ensure that accurate and complete information was entered into the data base. In the few cases when this also proved to be insufficient, correspondence with the licensee or NRC resident inspectors provided the information required. In order to analyze trends, combinations of events, and time-domain failure characteristics, the LER failure data for chargers and inverters were placed into a BNL developed computerized data base system. Information such as failure modes, mechanisms, effects, and description, manufacturer name, equipment rating, plant name, power level at which the failure occurred, and systems affected were entered into the data base by plant name and LER number. A subprogram which simply calculates the plant age at the time of failure by comparing the date of first criticality to the date of the failure event, provided age related information which was used for various sorts. Note that in calculating the age of the equipment it was assumed that the equipment was not replaced subsequent to plant criticality. This was necessary since the equipment history for each plant was not available for determining the exact equipment age. These sorts were analyzed and pertinent ones are displayed in graphical form in this report.

Because of the extensive work accomplished in the LER data area, Brown and Trojovsky were contacted to discuss a small number of differences between their data summaries and the BNL LER listing developed from the NSIC input. These variations were resolved which resulted in an accurate and complete data base from which the analysis was conducted.

LERs made up the largest single source of data on inverter and battery charger failures. Although possessing certain limitations, this data bank did provide relevant information on failure mechanisms, modes, and effects. The following qualifications are noted in order to place the conclusions derived from these data in the proper perspective.

Because 16 plants, including 15 BWRs, do not classify their vital bus inverters as safety related, inverter failures at these sites would not be reported via an LER. It should be noted that inverter failures at these plants could affect safety system operation or at least result in challenges to these systems. This observation is based on a review of FSAR information for several of the plants.

A second qualification is that a number of older plants have no technical specification requirements for inverters and/or battery chargers even though this equipment is considered safety related. For instance, one plant which has a battery charger for each of its two batteries along with one charger in standby has only one tech spec requirement for chargers, and that is to have two of the three available before taking the reactor critical. A charger failure during operation does not violate tech specs and therefore would not require an LER. Additional evidence that no tech specs for safety related inverters exists at older plants was obtained by direct contact with three older facilities. Plant personnel verified that inverter failures had occurred (several even resulting in reactor trips), although no inverter related LERs had been issued by any of these units.

Additionally, units with two connected full capacity battery chargers per battery are not in violation of tech specs upon failure of one charger and would therefore not initiate an LER for that event Therefore, single battery charger failures at these plants would not be documented by an LER.

From the above, it is estimated that LER data would be representative of inverter failures at approximately 50 of the 80 plants in operation during the period reviewed, and of battery charger failures at 60 of the 80 plants. Bearing in mind the above qualifications, a sufficiently large data base existed to conduct an analysis which resulted in the observations and conclusions summarized in the following paragraphs.

As illustrated by Figure 4-1, when battery charger and inverter failures are plotted against the plant age at the time of failure, a graph similar to the classic "bathtub curve" characteristic between years 1 to 6 is obtained. A high number of failures occur in the first year of operation with a pronounced wearout region occurring in the fifth and sixth years. Plant age is defined here as the failure event date referenced to the date at which the plant first went critical. In addition to the "burn-in" failures typical of electronics equipment, it is possible that personnel unfamiliarity with the complex equipment also contributes to the failures during initial plant operation. A second potential contributor to early charger and inverter failures is the difficult service these devices are exposed to during the power ascension test program, where the plant undergoes a large number of planned transients to insure proper plant responses. These involved test programs often require up to 12 months to complete.

Reported battery charger and inverter failures have decreased during the past three years as illustrated in Figure 4-2 which plots LER failures by calendar year. Because of LER reporting requirement changes which became effective in 1984, this trend will be difficult to monitor accurately in the future since many of the previous charger and inverter failures reported in LERs no longer require that an LER be initiated. With the recent NPRDS standardization, this data source is expected to provide the important trending information required for continued equipment performance analysis. This positive trend in charger/inverter performance can be attributed to several factors, including

- An increased awareness of the impact that poor equipment performance has on system and plant availability being translated into additional preventive maintenance, personnel training, and/or equipment monitoring.

- More rigorous manufacturer acceptance testing, including equipment burn-in periods based on recent industry standards. Weak link components responsible for premature failures are more likely to be detected.

- Improvement in equipment designs to eliminate recurring component problems.

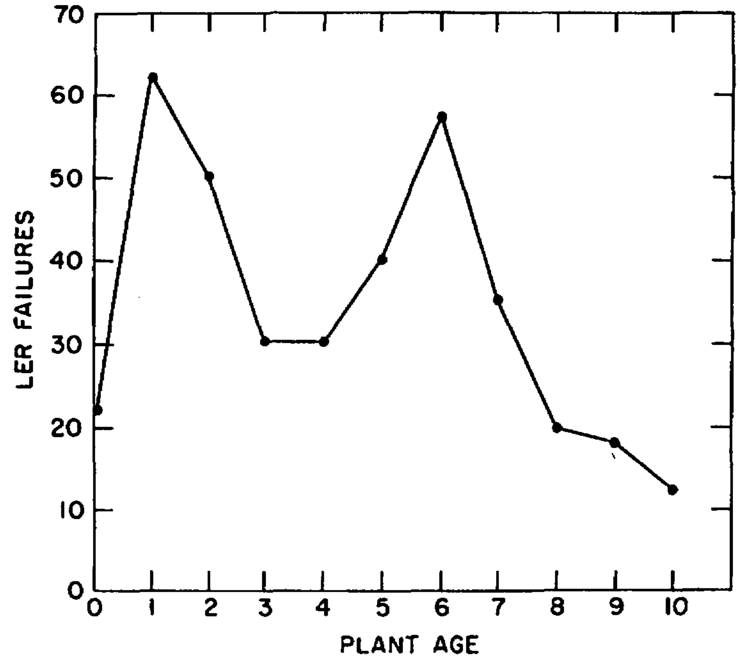


Figure 4-1: Battery Charger and Inverter LERs (1976-1984)

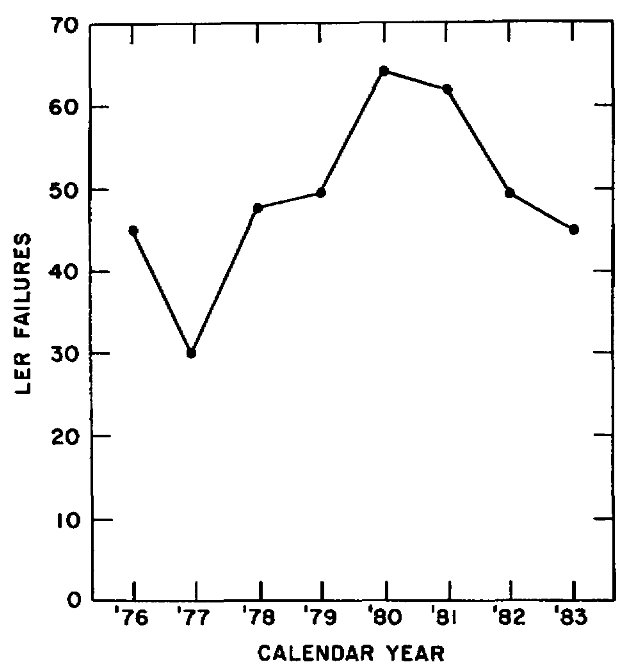


Figure 4-2: Battery Charger and Inverter LERs by Year

The LER data also provided subcomponent information including that for capacitors, whose failure has resulted in inverter degradation that displays an aging/wearout characteristic. As illustrated in Figure 4-3, LER data support the observation that the life of electrolytic capacitors is limited to 4 to 6 years. Figure 4-3 uses raw failure data which, if "normalized" to reflect the smaller population of plants with ten or more years of operation, would reveal a clearer trend for increasing capacitor failures with increasing plant age. For instance, the failures recorded for plants in their tenth year of operation would be multiplied by a factor of two. This multiplier reflects the fact that the number of plants with at least ten years of operating experience is approximately one half the number of plants with at least one year of operating experience. Following the recommendation of some manufacturers, many utilities replace capacitors at frequencies ranging from four to ten years.

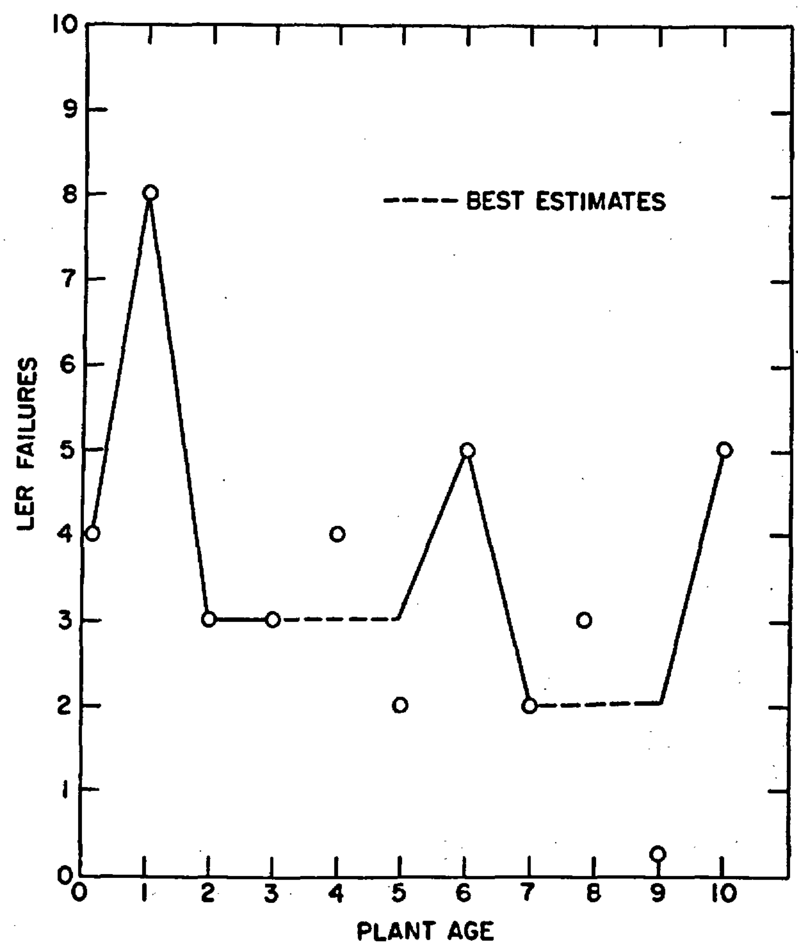


Figure 4-3: Capacitor Failures by Plant Age
[LERs 1976-1984]

A single inverter failure can have significant effects on plant operation and safety as reported by the LER information. Of these effects (summarized in Figure 4-4), the large number of reactor trips is the most visible and dramatic, although, the inverter failures which rendered emergency core cooling and decay heat removal systems inoperable are no less important. Frequently linked to feedwater or turbine-generator control systems, a failed inverter can initiate a severe plant transient requiring a reactor trip and/or safety injection system actuation. These unnecessary challenges to the safety system provide the greatest incentive to improve inverter performance through better understanding of the failure modes and mechanisms.

Battery charger failures documented by LERs revealed more subtle plant effects such as a degraded voltage on the dc bus or a loss of certain plant instrumentation. Although posing no immediate threat to plant safety, these effects could result in safety equipment unavailability during an accident condition.

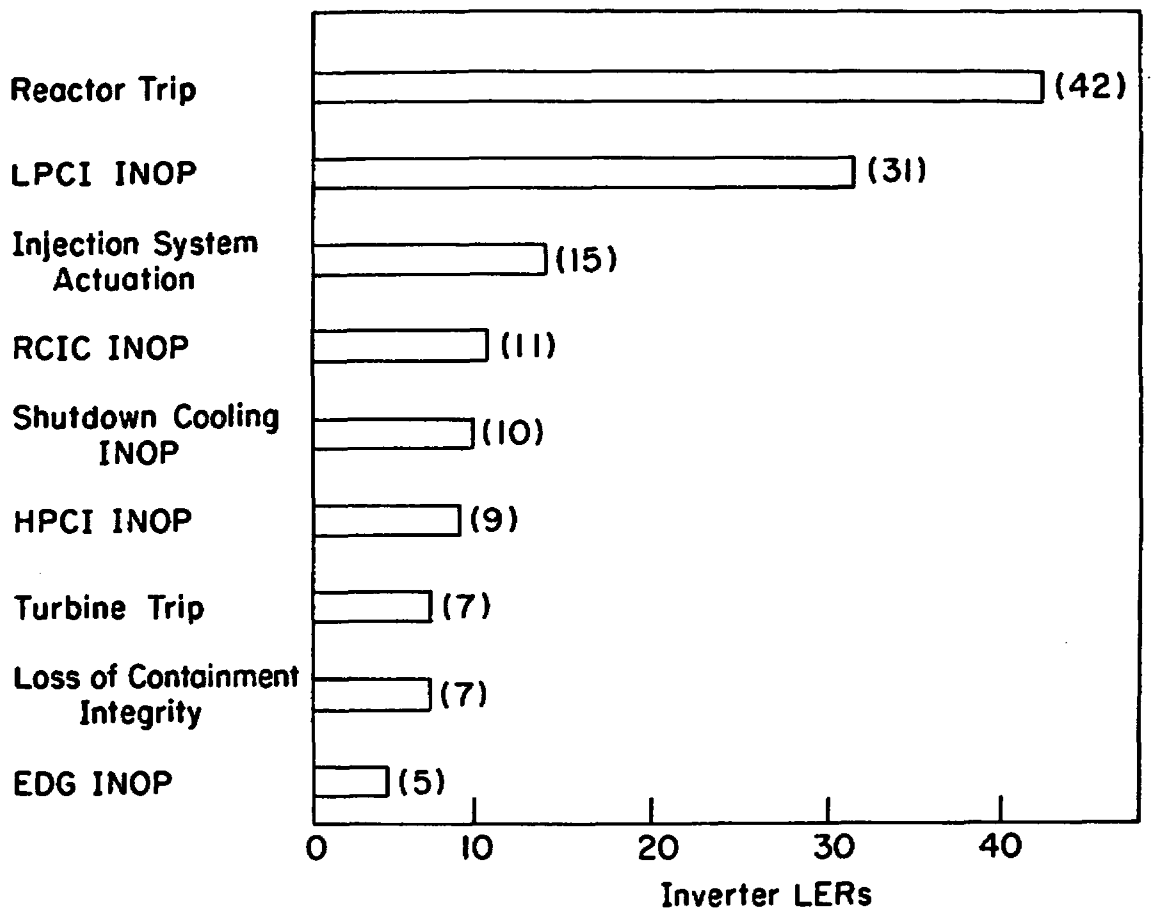


Figure 4-4: Inverter Failure Effects on Plant Performance
(LERs 1976-1984)

Other subcomponent information obtained from the LER data base is illustrated in Figure 4-5. Added to the high number of capacitor failures which caused inverter trips are the significant number of firing module and related SCR failures as well as failures of transformers and diodes. Although Figure 4-5 indicates that nearly one hundred LERs identified circuit breakers or fuses as the failure mechanism, it is probable that only a small percentage are actually component failures. In many cases the circuit breaker or fuse acted as designed to protect the inverter or charger from transient conditions. Unfortunately, the root cause of the circuit breaker or fuse operation was not determined or was not reported in the LER.

Figure 4-6 illustrates battery charger subcomponent failures obtained from the LER data base. Control cards, relays, and voltage regulators are identified as the three non protection type components which cause battery charger failures. Of interest in comparing the failure mechanisms of chargers and inverters is the impact of capacitors, which are identical components in both types of equipment. A capacitor failure in a battery charger allows ac ripple to exist on the dc output but does not necessarily lead to a catastrophic failure. Therefore, a charger capacitor failure may not be detected until preventive maintenance is performed, and would not require an LER. In most inverters, however, commutating and ac filter capacitors will blow a fuse upon failing, thereby rendering the inverter inoperable.

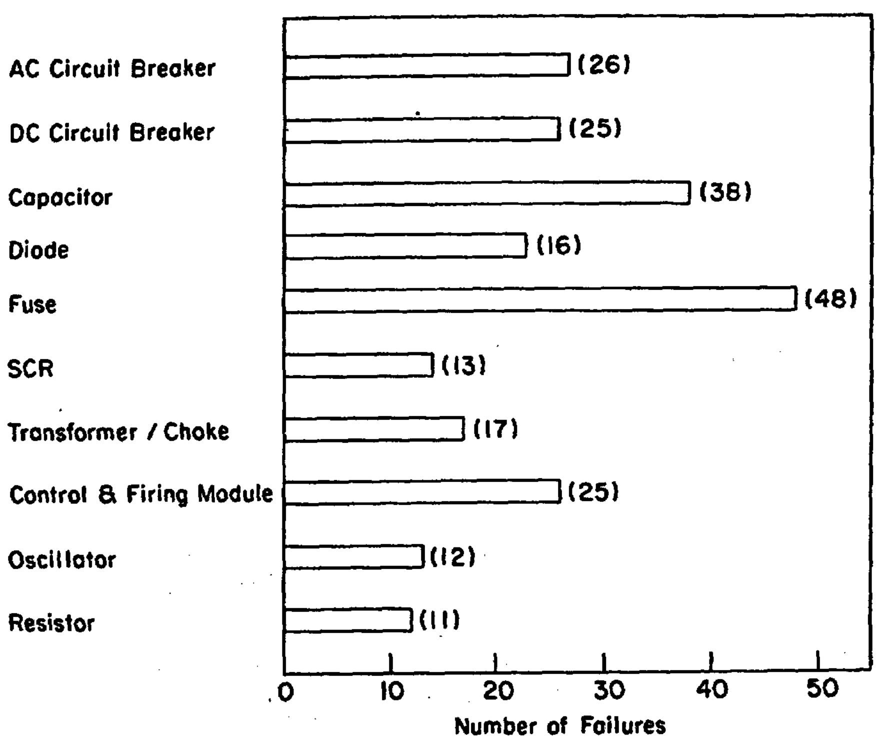


Figure 4-5: Inverter Failure Mechanisms
[LERs 1976-1984]

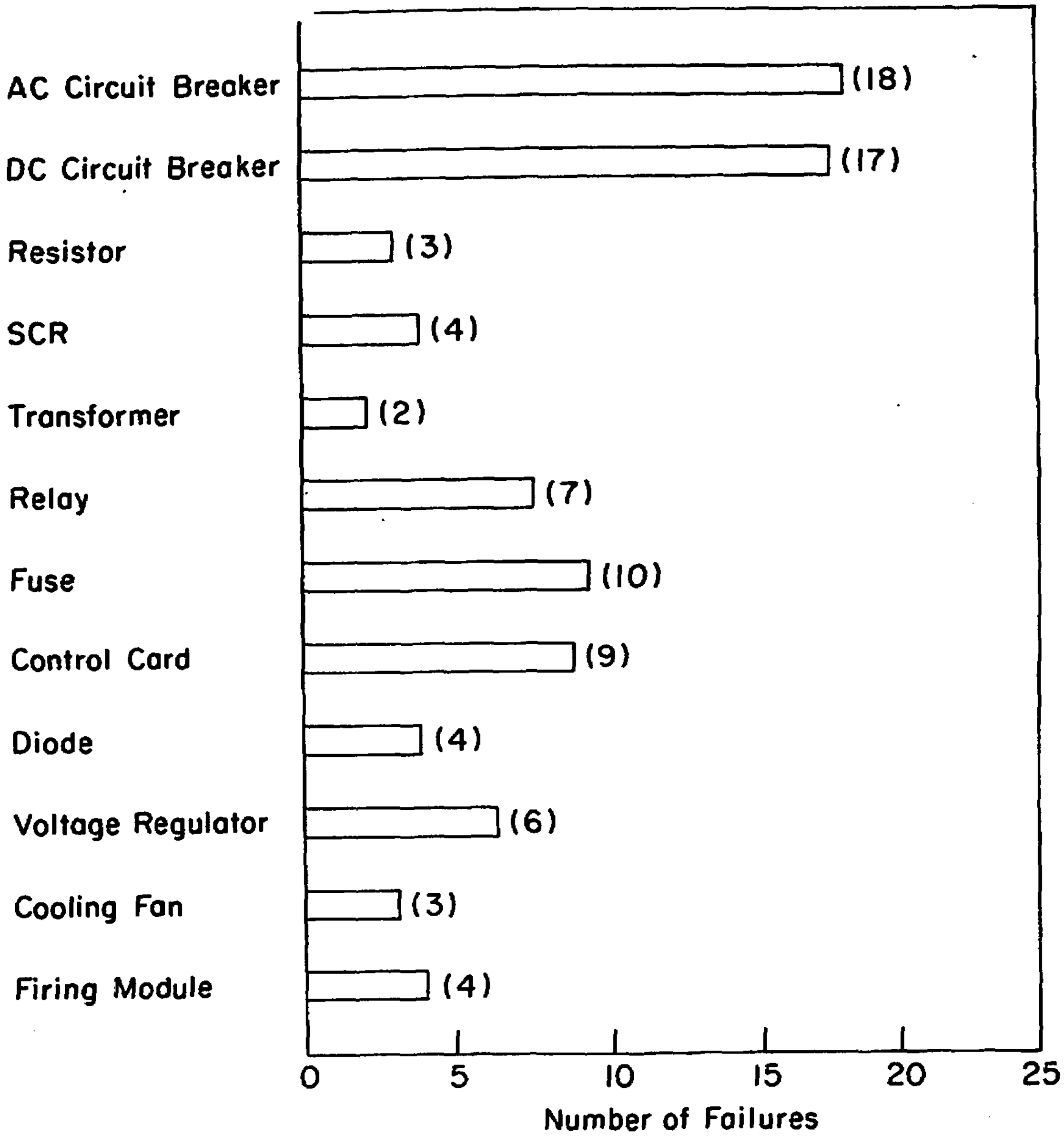


Figure 4-6: Battery Charger Failure Mechanisms [LERs 1976-1984]

The LER data base also provided failure mode information which is summarized in Table 4-1. Containing similar circuitry, it is not surprising that both the inverter and charger are susceptible to failures from overheating and electrical transients. Also, because of their complexity, failures due to personnel error and testing are significant. The very high percentage of failures that occur for which the cause is unknown raises the concern that failures are not sufficiently investigated because the primary goal is to replace the failed subcomponent and return the equipment to service as soon as possible. In some cases, the failure of one component, perhaps due to wear-out, may indicate the likelihood that other identical components will fail in the near future. Several LERs noted that some plants replaced all capacitors or all SCRs as a precautionary measure when one failed. This type of action can reduce the effect of component aging.

Table 4-1: Battery Charger and Inverter Failure Modes
[LERs 1976-1984]

Failure Mode	Inverter	Battery Charger
Overheating	21	8
Electrical Transient	21	5
Overvoltage	5	7
Aging	7	2
Open/Short Circuit	24	2
Testing	13	13
Loose Connection	4	12
Personnel Error	42	13
Unknown	111	39

4.2 In-Plant Reliability Data System (IPRDS) Review

The IPRDS extracts failure and repair information from specific plant Maintenance Work Requests (MWR). This information is supplied in a format which includes, when it is available in the MWR, component type, vendor, failure cause, failure mode, failure severity, and a very brief description of the failure. Specific age related information is not available, however, dates of failure event versus plant age comparisons may be made to correlate failure frequency to years of equipment service.

Failures are classified in IPRDS in one of three categories - catastrophic, degraded, or incipient [24]. By definition, a catastrophic failure is one in which the component is "completely unable to perform its function". For battery chargers and inverters, a catastrophic failure would be no electrical output. A degraded failure is categorized as one in which "the component operates at less than its specified performance level". For battery chargers and inverters, a degraded failure consists of events in which the electrical output is not in specification, or operation is erratic. An incipient failure is one in which "the component performs within its design envelope but exhibits characteristics which, if left unattended, will probably develop into a degraded or catastrophic failure". Battery charger and inverter incipient failures as classified by IPRDS include overheating, faulty indication, and lack of cleanliness. One of the goals of the NPAR Program is to identify methods of detecting aging effects prior to failure. Knowledge of incipient type failures is therefore important, and they were closely examined in IPRDS since none were reported in any other data base. Because of some differences in the data accumulated in IPRDS, further analysis of these data will be treated separately for battery chargers and inverters.

4.2.1 Battery Charger IPRDS Data

The IPRDS battery charger data reviewed consisted of 50 failure events reported by five nuclear facilities over the period from 1974 to 1981. Of these events 12 failures were classified as catastrophic, 25 degraded, and 13 as incipient. Data summaries are displayed graphically in Figures 4-7 and 4-8 and by specific failure causes in Table 4-2. From these summaries the following conclusions may be drawn.

- Failure rate increases with plant age.
- A limited number of component types, namely relays, fuses, capacitors and diodes account for the majority (27 of 45) of the hardware related failures. This input is particularly important for focusing inspection, surveillance, and monitoring methods.

Analysis of the IPRDS data reveals the following:

- Figure 4-7 graphically depicts the catastrophic failures recorded for the five facilities. This type of failure results in a loss of the safety related equipment but affects safety only if the battery has a low capacity. Such failures require plant actions including proceeding in an orderly manner to a shutdown condition. The time frame for completing such action coincides with the ampere-hour rating of the battery. Figure 4-7 illustrates an increasing failure rate as the plant ages, with 10 of the 12 events occurring in years 3, 4, and 5.

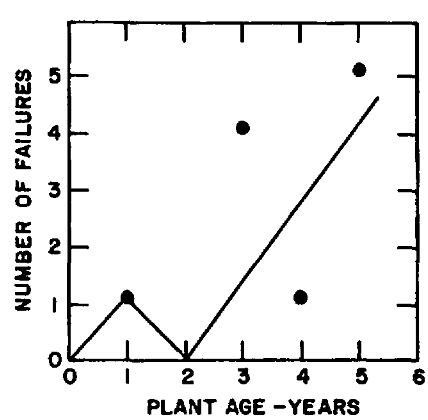


Figure 4-7: Battery Charger Catastrophic Failure/Age Correlation [IPRDS 1974-1981]

- Figure 4-8 combines the catastrophic, degraded, and incipient failures which occurred in four facilities and indicates a strong failure versus age correlation. It should be noted that the degraded type failure for a battery charger could result in the same safety impact as the catastrophic failure. For example, a low voltage output from a battery charger would result in the station battery carrying the dc loads. In the event of a loss of ac power, the battery life could be significantly shortened.

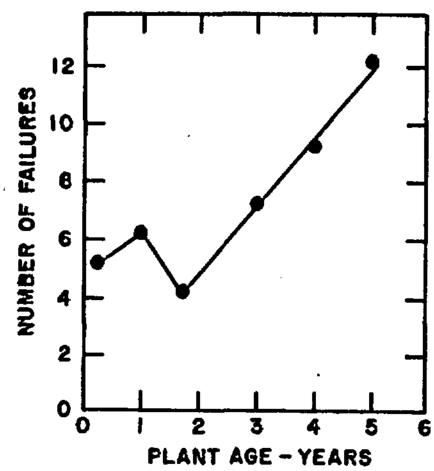


Figure 4-8: Battery Charger Combined Failure/Age Correlation [IPRDS 1974-1981]

- Table 4-2 summarizes the battery charger failure mechanisms depicted in the IPRDS data base. Of interest is that relay failures are the dominant catastrophic and incipient failure mechanism. Also of significance is that four components - fuses, relays, capacitors, and diodes - account for a majority of the hardware related failures.

Table 4-2: Battery Charger Failure Mechanisms
[IPRDS 1974-1981]

I. CATASTROPHIC FAILURES - 12 EVENTS

a.	Relays	5
b.	Capacitors	2
c.	Resistors	2
d.	Diodes	1
e.	Fuses	1
f.	SCRs	1
g.	Unknown	1

II. DEGRADED FAILURES - 25 EVENTS

a.	Fuses	6
b.	Loose Connectors	5
c.	Capacitors	3
d.	Diodes	3
e.	Circuit Boards (Firing Module, Control Module)	3
f.	Unknown	2
g.	Potentiometers	2
h.	Loss of Alternate Supply	1
i.	SCRs	1
j.	Transformers	1
k.	Filters	1
l.	Alarm relays	1

III. INCIPIENT FAILURES - 13 EVENTS

a.	Lamps	2
b.	Cleaned contacts (alarm relays)	4
c.	P.M. - replace surge suppressor	1
d.	P.M. - "work performed"	1
e.	Voltmeter Indication Problems	3
f.	Unknown	1
g.	Timer Knob replaced	

IV. COMPOSITE FAILURE - MAJOR CAUSES

a.	Fuses	7
b.	Relays	10
c.	Capacitors	6
d.	Loose Connectors	5
e.	Diodes	4
f.	Total	45 "hardware" related failures

4.2.2 Inverter IPRDS Data

The IPRDS inverter data base consisted of 102 failure events which occurred at three facilities comprising five nuclear plants with a total operating experience of 18 years. These events consisted of 33 catastrophic failures, 43 degraded failures, and 26 events classified as incipient failures. Two of the five facilities included in the IPRDS do not have inverters, but use motor-generator sets to provide power to the vital buses. This data base clearly indicated the following:

- The major causes of inverter failure can be attributed to fuses, capacitors, and diodes which accounted for 57% of the known failures.
- A wearout period of approximately 3 to 4 years exists for components which could lead to inverter failure.
- A high failure rate early in plant life exists.

Figure 4-9 graphically demonstrates the correlation of inverter failures to plant age. This figure consists of 43 events occurring during 18 reactor years of operation on 13 inverters at two facilities. These 43 events consist of 10 catastrophic, 18 degraded, and 15 incipient failures. Resemblance to the "bathtub" reliability curve exists with a relatively high number of failures occurring in the first year and wearout indicated in the fourth year. As mentioned earlier, two facilities use M-G sets rather than inverters and therefore data from those units were not applicable. One facility reported 50 failure events for five inverters. However, these data were not used for trending purposes since all these events occurred over only a two year period commencing approximately one year prior to commercial operation. This facility did not submit maintenance reports for IPRDS use beyond that time frame. Therefore, these data were used for failure cause and effect analyses only.

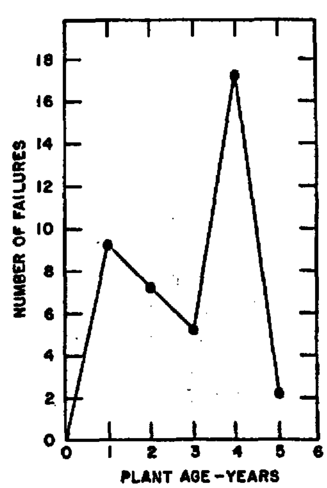


Figure 4-9: Inverter Failure/Age Correlation
[IPRDS 1974-1981]

Of the sub-components that have been identified as the cause of inverter failure, Table 4-3 shows fuses and capacitors to be the components that have failed most frequently; in some events both were found to be failed. In those cases, it is probable that the capacitor failure (short) caused the fuse to blow. Also significant is the large percentage (26%) of degraded failures in which the cause is classified as unknown. Again, this may indicate a lack of understanding of the equipment operation or a need to return the equipment to service to support plant operation without fully investigating the failure cause.

As they relate to the inverter, catastrophic, degraded, and incipient failures could all affect plant safety. A catastrophic inverter failure results in a loss of voltage to the vital or essential bus unless an automatic throw-over scheme exists which provides an alternate ac supply to the vital bus within several cycles of the inverter failure. A loss of power to the vital bus generally results in a loss of critical instrumentation and controls and requires operator action to restore conditions to normal. A degraded inverter failure could also affect safety because abnormal inverter voltage or frequency levels could impair instrumentation or control operability thereby resulting in incorrect information to the operator or in failure of the instrumentation. An incipient failure, such as the clogged or dirty filters reported by one facility, could cause premature component failure rendering the inverter inoperable or degraded.

Table 4-3: Inverter Failure Mechanisms
[IPRDS 1974-1981]

A. CATASTROPHIC FAILURES - 33 EVENTS

a.	Fuses	21
b.	Capacitors	11
c.	Diodes	7
d.	Circuit Boards	6
e.	Unknown	4
f.	SCRs	3
g.	Resistors	3

B. DEGRADED FAILURES - 43 EVENTS

a.	Unknown	11
b.	Fuse	7
c.	Capacitors	6
d.	Frequency not in spec.	5
e.	Circuit Boards	5
f.	Resistors	4
g.	Diodes	4
h.	Relays	2
i.	Alarms	2

Table 4-3 (cont'd)

C. INCIPIENT FAILURES - 16 EVENTS

a.	Inadvertent Alarm	4
b.	Unknown	4
c.	Indicators	3
d.	Filters	3
e.	Relays	2

TOTALS BY MAJOR COMPONENT FAILURE CAUSE

1.	Fuses	28
2.	Unknown	19
3.	Capacitors	17
4.	Diodes	11
5.	Circuit Boards	11
6.	Resistors	7
7.	Others	24
	Total	117
	Total Identified	98 (19 unknown)

		% of Known Failures
1.	Fuses	29%
2.	Capacitors	17%
3.	Diodes	11%
		57%

4.3 Nuclear Plant Reliability Data System (NPRDS) Review

With cooperation from the Institute of Nuclear Power Operations (INPO), a computer printout of the NPRDS data base for battery chargers and inverters was obtained. This data base consists of 183 inverter failure reports submitted by 36 nuclear power plants, and 70 battery charger inputs from 31 plants. The data cover the period from 12/73 to 9/84 and include both safety and nonsafety applications.

Each report contains important information such as manufacturer's name and model number, capacity, and testing frequency, including expected hours out of service. This type of information is not usually available from other data sources. A sample describing a failure due to component aging is included as Figure 4-10. The plant name, type, and commercial operating date are deleted for confidentiality reasons. Using the coded information as a guide, the NPRDS data bank was sorted by failure mechanism, mode, and effect.

Of overall significance to the NPAR program is that at least 30% of the reported NPRDS failures were considered by the utilities to be age related. This is indicated by the use of codes such as wearout, normal/abnormal wear, or aging/cyclic fatigue to describe the failure cause.

WM GUNTHER, BNL NPRDS COMPONENT FAILURE CANNED REPORT 24
Plant Type-

COMPONENT FAILURE REPORT
CLASS= NEW RECORD
KEY= 884573841
ENTRY DATE: 06/27/83

1 Utility/Plant/Unit........
2 NPRDS Component Code .. . . GENERA
3 Utility Component ID INVERTNO1
4. Discovery Date............... 821227
5. Discovery Number.... 1

6. Report Date. 830520
7. LER Report Number..............
8. System Affected by Failure.....EBF-PLANT AC POWER SYS. AND CONTROLS
9. Date Failure Occurred..........821227
10. Time Failure Occurred..........12:00
11. Date Failure Ended.............830104
12. Time Failure Ended.............13:00

13. Status Code. ... ...E-SUBSYS/CHNL IN SVC; OP/STANDBY
14. Severity Level Code............K-DEGRADED
15. Failure Symptom Code...........B-OUT OF SPECIFICATION
16. Failure Detection Code.........J-INCIDENTAL OBSERVATION
17. Cause Category Code.... ....H-WEAROUT
18. Cause Description Codes........AW-CIRCUIT DEFECTIVE
19. System Effect Code.............C-LOSS OF REDUNDANCY
20. Plant Effect Codes.............G-RESULTED IN NO SIGNIFICANT EFFECT
21. Corrective Action Code.........AH-REPLACE PART(S)
22. Documentation Codes............Z-NONE

23. Failure Description Narrative...
DURING ROUTINE OBSERVATION , NOTED AC VOLTS AND AMPS INDICATIONS WERE OSCILLATING FROM 117 TO 122 VOLTS .

24. Cause of Failure Narrative......
BAD OP-AMP H-200 . PROBABLE CAUSE OF FAILURE--AGE

25. Corrective Action Narrative.....
REPLACED OP-AMP .

COMPONENT ENGINEERING DATA
KEY= 7270375688 ENTRY DATE: UNKNOWN

Application Code........IPITGE
Location. ... . INSTRUMENT AC POWER
(NPRDS System Code= EBK)

Utility System Code.... E3

Data Start Date...... ..750101
In-Service Date.........680101
Out-of-Service Date.....

Safety Class............*
Critical Operation Mode.OPERATING
Drawing / Doc Number....DCN 74-7
Manufacturing Std. .....

Internal Environment....
External Environment....TEMP & HUM CONTROLLED
AMBIENT TEMP(-10F-120F)

Manufacturer............
Manufacturer Model No ..28718
Manufacturer Serial No..

Vendor................ ..
Vendor Serial No........INVERT NO 1

Engineering Codes

A. Type......... ....INVERTER
B. Voltage Range..........100-299 VAC SINGLE PHASE
C. Capacity...............1-9.9 KW
D. Output.................ALTERNATING CURRENT
E. Driver Type............
F. Application... ....
G. Rated Rotational Speed.
H Voltage Rating ..... . 120 VAC
J. Power Rating.. ...... 5 KW

% Time Operating When Reactor is Critical...100 %
% Time Operating When Reactor is Shutdown...100 %

Testing Performed	Frequency/Period	Hrs Out of Service
Check Testing	6 / DAY	0
Functional Testing	0 / NOT DONE	0
Calibration Testing	0 / NOT DONE	0

Figure 4-10: Sample NPRDS Data Input

Observations made from the NPRDS data include the following:

- As illustrated in Figures 4-11 and 4-12, capacitors and fuses were the two components most likely to cause an inverter failure while the control and firing modules were most critical to reported battery charger failures.

- Overheating, short circuits, wear, testing, and loose connections were frequent failure modes common to battery chargers and inverters. Table 4-4 tabulates the most common NPRDS reported failure modes.

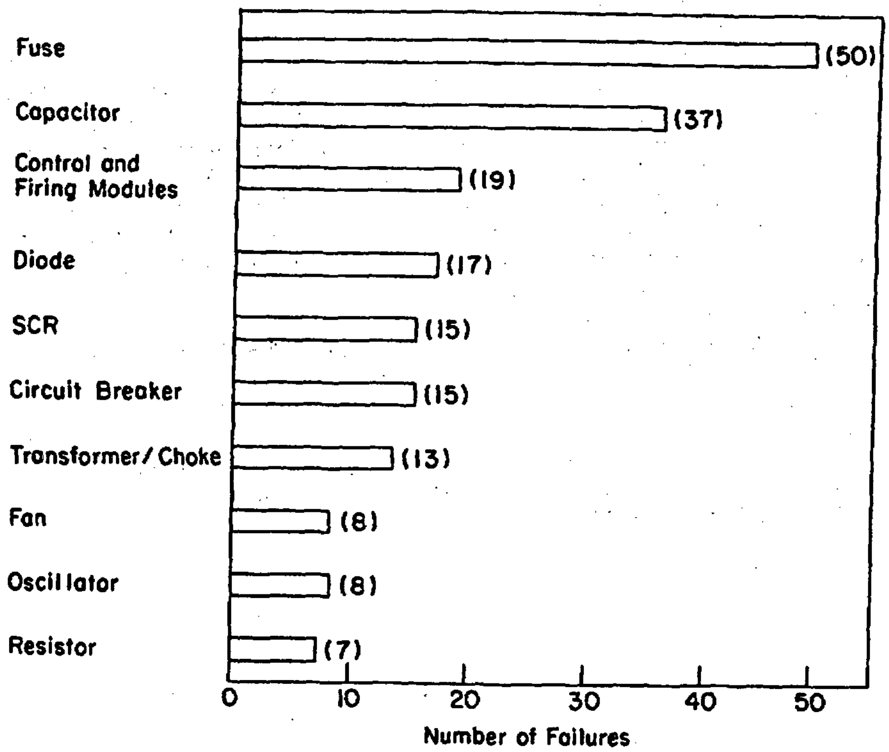


Figure 4-11: Inverter Failure Mechanisms (NPRDS 1973-1984)

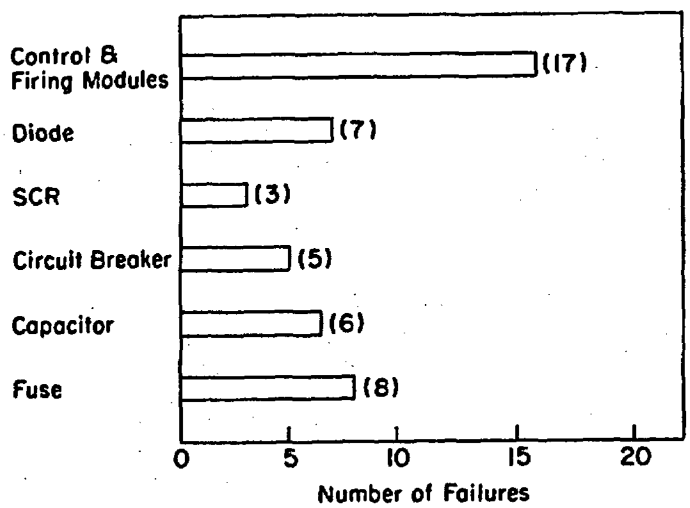


Figure 4-12: Battery Charger Failure Mechanisms (NPRDS 1973-1984)

According to INPO, as of mid 1984 all of the participating units are submitting failure data to NPRDS in a uniform format that can be easily input to the computer. This industry commitment should make the NPRDS data bank an excellent source of equipment failure data in the future. Conclusions drawn from the present data base must be qualified for several reasons. For instance, there is some overlap with the LER data base. This overlap consisted of 32 of the 183 inverter failure reports (17%) and 17 of the 70 battery charger reports (24%). Secondly, the NPRDS data bank consisted of failure reports from only 36 units for inverters and 31 units for battery chargers. Based on a comparison of the LER and IPRDS data reviewed, it is apparent that some plants were not fully documenting failures on inverters and chargers to the NPRDS data bank prior to 1984. Since then, however, INPO has published a Reportable Scope Manual that provides a uniform definition of which equipment is to be reported. Battery chargers and inverters are included in this Manual and are reported to NPRDS. Finally, only limited time domain analysis (plant age versus failure rate) can be performed using this data base since utility participation in this program was not consistent over the entire study period. For instance, five plants that went critical in the early 1970s did not begin reporting failures until 1983.

Table 4-4: Battery Charger and Inverter Failure Modes
[NPRDS 1973-1984]

Failure Mode	Inverter	Battery Charger
Overheating	14	3
Short Circuit	13	4
Aging/Wear	11	6
Testing	9	7
Loose Connections	9	10
Personnel Error	11	3

Past NPRDS annual reports were also reviewed to obtain reliability information and to determine the importance of charger/inverter failures relative to other component failures. Perhaps the most significant summaries provided by the 1983 NPRDS annual report deal with major component types which affect safety system operation. It is of concern that inverter and/or battery charger failures are high on the list of many important safety systems as described below.

A summary of the failures of the Reactor Protection Systems (RPS) and safeguards instrumentation systems employed at plants (Figure 4-13) indicated that inverter failure was the highest contributor of all the major component types which make up the systems. In fact, the NPRDS failure rate for inverters is nearly as high as that of all the other components combined. As verified in LER reports, inverter failures have resulted in reactor trips and safety injection system actuations. While "fail safe" in philosophy, these events certainly challenge the safety systems and place the plants in a transient condition which could contribute to additional equipment failures or impact plant life. Reactor pressure vessels, for instance, are designed for a limited number of transients.

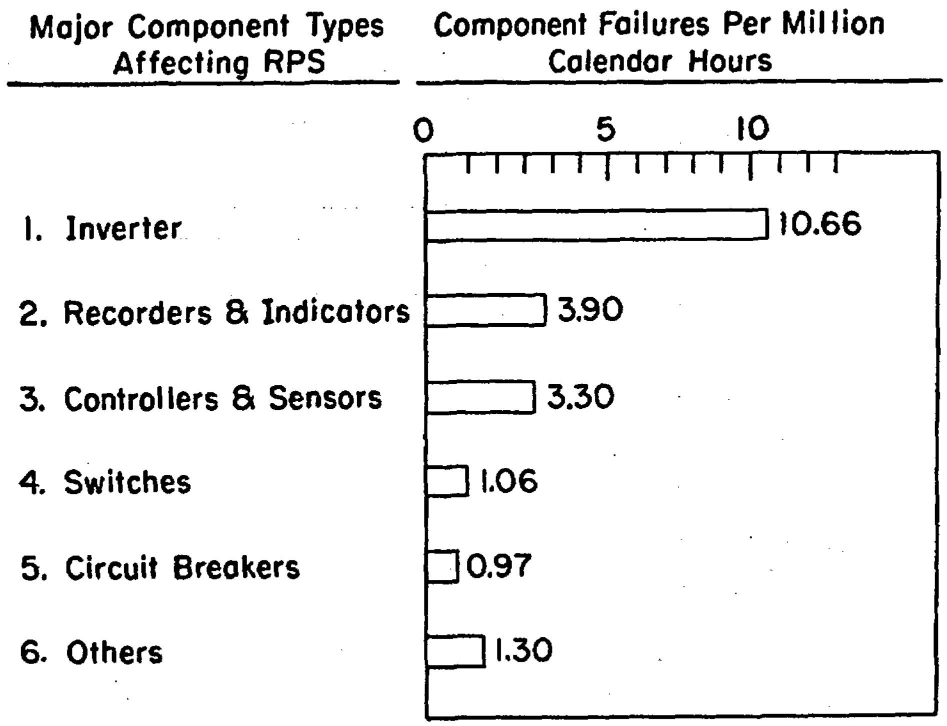


Figure 4-13: Reactor Protection System (RPS) Reliability Data [NPRDS Annual Report, 7/74 - 12/82]

The Emergency Core Cooling Systems (ECCS) reliability data for all the NSSS suppliers are combined in the 1983 NPRDS annual report and summarized in Figure 4-14. Of all the major components associated with ECCS, the inverter is the component with the single highest failure rate while batteries and chargers rank third. Between the two, they comprise over forty percent of the component failures for the systems. Perhaps the single largest inverter failure contributor is the inverter used in the LPCI system for a BWR. In this application the inverter is used to power various motor operated valves required for proper system operation. Similarly, for the Reactor Core Isolation Cooling (RCIC) System, inverters again rank as the highest single component failure contributor, outdistancing the next contributor by more than a two to one margin. In the RCIC system used in BWRs, inverters provide power to instrumentation and controls necessary for automatic system operation. Upon inverter failure, the system will automatically initiate when required but will run at minimum flow (recirculation) until manual control is taken.

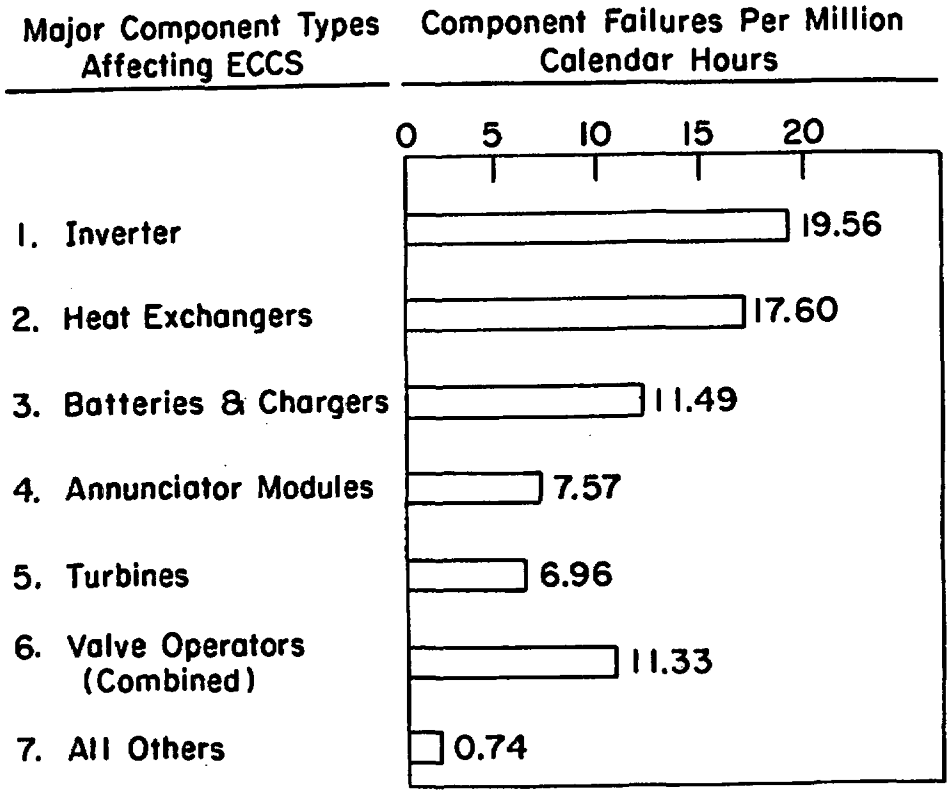


Figure 4-14: Emergency Core Cooling Systems Reliability Data [NPRDS Annual Report, 7/74 - 12/82]

4.4 Balance of Data Review

Of the data sources used to provide additional details on particular failure events which had significant plant effects or which strongly suggested that component aging was the failure cause, the two that contributed the most to this study were the Nuclear Power Experience (NPE) reports and the plant maintenance records.

4.4.1 Nuclear Power Experience (NPE) Reports

NPE [25] is a technical service which compiles information about significant events which occur at nuclear power plants. This service is updated monthly and is indexed by key component. For battery chargers and inverters, the NPE reports did not provide any failure events not included in the LER or the NPRDS data banks but did significantly supplement the information from these sources. For instance, the NPE provided a specific sequence of events in those cases where inverter failures caused reactor trips or safety injection system actuations. It also included repair and recovery information as well as measures taken to prevent recurrence including preventive maintenance or design changes. As of June 1985, this source contained over two hundred event descriptions related to battery charger and inverter failures, as illustrated in Table 4-5.

Table 4-5: NPE Event Descriptions

	BWRs	PWRs	TOTALS
Battery Charger	26	34	60
Inverter	51	117	168

4.4.2 Plant Maintenance Records

Following a review of the LER, NPRDS, and NPE data, a number of questions and concerns remained which could only be answered by the utilities directly. Letters were written to a number of plants requesting a maintenance personnel contact and completion of a questionnaire. The goal of this survey was to obtain insight into certain trends which had been discovered during the data review and to ascertain root causes for certain specific events which strongly suggested equipment failure due to aging. Most utilities responded to the questionnaire with frank assessments of equipment performance.

One plant which had experienced a large number of inverter and battery charger failures was particularly supportive in this effort. They were contacted because nearly all their failures had been recorded prior to 1981. The apparent drastic improvement in equipment performance subsequent to 1981 was contradictory to the anticipated effects of aging and could not be determined from the data bases available. Information obtained from the utility indicated that a number of actions had been taken to minimize the effects of aging and to improve equipment performance. For the station inverters, this included the following measures:

- Replacement of two of the four station inverters with new units supplied by a different manufacturer.

- Conduct of a vendor training program covering alignment and troubleshooting procedures for the old and new inverters. The vendor representative stated that previous testing by station maintenance personnel contributed to premature failures because of the abnormally high voltages that were applied across the filter capacitor banks.

- Replacement of all capacitors and thyristors in the two original inverters during the same outage in which the new inverters were installed and the training was conducted.

- Increase in the PM frequency from a refueling interval to 60 days. This included routine changeout of ventilation filters and a visual inspection for cleanliness and indications of overheating.

From the same utility, a copy was obtained of all of the Maintenance Work Requests(MWRs) associated with the four station battery chargers. This consisted of 30 documents covering a seven year period. These data, which were very similar in nature to IPRDS inputs in that they included degraded and incipient failures, revealed the following problems not noted in the LER and NPRDS data for this plant.

- Six MWRs addressed equalizing timer problems including contact pitting and timer mechanism "sticking". The equalizing timer controls the time that a charging voltage is applied to the battery and automatically reverts the charger to a "float" mode upon completion of the charge. A timer failure could result in battery damage due to grid corrosion or excessive gassing. Overcharging also increases the battery temperature which may lead to plate buckling [26].

- Several incidents of the equalize voltage drifting high were encountered. Adjustment of a potentiometer was required to correct this condition which could affect equipment supplied by the dc bus. In fact, reactor trips occurred at two different facilities as a result of inverter circuit breaker trips due to high input voltage from the charger.

- Heat generated in the charger cabinet caused degradation of the control and power cable and required replacement with cable having an operating temperature rating of 90°C ("GE VULKENE SIS-7275 or equivalent").

Likewise, another plant was contacted because in its long history of operation no LERs had been discovered for inverters or battery charger failures. Response from the utility revealed that nine inverter failures on the original two station inverters had led to several reactor trips and system transients. "After many more problems, these inverters were replaced ..." The replacement inverters are a solid-state design with an automatic static throwover switch, and a manual maintenance bypass switch which permits maintenance personnel to perform required PM during normal plant operation. "Constant monitoring" by the operating personnel is also credited with improving equipment performances. The only subsequent failures were related to indicating lights, a synchronizing board, and an oscillator board, none of which resulted in loss of the vital bus.

This same plant has made a number of changes in their battery chargers, including provision of cross tie capability to a nonsafety related charger. A later NRC ruling based on Regulatory 1.6 limited the use of this cross tie to shutdown conditions. Therefore, this utility is in the process of installing a second 100% capacity charger on each dc bus to improve reliability and availability. No aging related failures have been noted on the original units according to the electrical supervisor.

Other important information on charger and inverter failure causes and effects obtained from utility contacts include the following:

- Inverter trips during Emergency Diesel Generator (EDG) testing have been caused by frequency and voltage swings that occur as loads are picked up by the EDG. Under actual emergency conditions, the inverter would normally have switched to the battery as an input before the EDG coming on the bus.

- One utility stated that they had replaced all of the capacitors with one having a higher dielectric strength and a higher temperature rating. Improved battery charger performance resulted.

- An inverter manufacturer's representative stated that an inverter capacitor failure occurring at one station was caused by the excessive ripple voltage from the battery charger supplying the dc bus, coupled with the length of time the capacitor was in service. As a precautionary measure, all capacitors and SCRs in the inverter were replaced by the utility.

- One utility improved inverter performance by installing cooling fans on the top of each inverter cabinet.

- Fuse coordination was cited as a design problem by a maintenance supervisor whose plant had experienced several inverter trips due to blowing the input fuse to the inverter before the fuse in the branch circuit could operate. The fast acting fuses were required by the inverter manufacturer to ensure internal inverter circuitry protection.

Some of the actions taken by utilities who have experienced inverter and battery charger failures which affected plant safety and availability were to increase preventive maintenance scope and intervals, replace troublesome equipment, and improve system designs. Improvements in materials and procedures also help to reduce the failure rate and could explain the shape of the curve (Fig. 4-15) obtained when plotting inverter and charger failures against plant age.

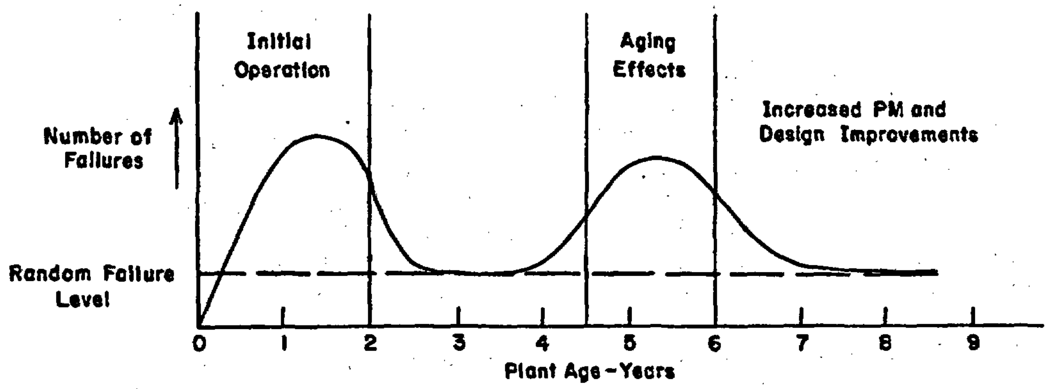


Figure 4-15: Battery Charger/Inverter Failure History

Failures early in plant life can be correlated to aging by considering the following:

- Electrical equipment is typically installed and energized early in the plant construction process. It is then subjected to electrical transients, dirt, extreme temperatures, and other stresses prevalent during the construction and preoperational testing phase which could contribute to failures when loads are placed on the equipment during early plant operation. Electrical overloads and dirt were two reasons given by an inverter manufacturer for equipment failures during plant startup. Feedback from field service personnel to the main office indicated that circuits had been subjected to extreme overload conditions due to the lack of isolation when testing adjoining electrical equipment (such as circuit breaker testing).

- Unfamiliarity with equipment operation can lead to personnel errors during operation or testing of the chargers and inverters. This may indirectly lead to premature equipment failure if degradation is not recognized.
- Long construction times typical of nuclear plants coming on line recently could contribute to failures occurring early in plant life because of the aging effects associated with equipment "storage". Moisture intrusion of key components during construction could lead to premature equipment failure.

4.5 Other Information Sources Including Published Reports

A number of other sources were consulted to obtain background information about battery charger and inverter operation, components, and testing. Some of these are described below.

4.5.1 NSAC/44; Investigations of Failures in I&C Power Supply Hardware [3]

This report studied instrument (vital) bus failures which caused reactor trips and identified inverter failures as the biggest contributor to the unavailability of Instrument and Control (I&C) power supplies. Additionally, this report identified excessive temperatures, currents, and voltages as the most common causes of inverter failures with capacitors and fuses being the components most susceptible to failure. The effect of design differences, bus configurations, system interactions, and analysis of components such as SCRs, diodes, and circuit boards was not covered in this study.

4.5.2 NUREG/CR-3808; Aging-Seismic Correlation Study on Class 1E Equipment [20]

This report presents a method for evaluating the aging/seismic effects in electrical equipment. According to this study, the primary failure mode attributed to battery chargers under seismic stress is the failure of relays due to fatigue and coil insulation degradation common to relays as well as other electromechanical devices. Additional failures with capacitors and circuit board assemblies could occur because of connector fatigue due to the vibration and thermal stresses. Furthermore, this report states that semiconductor devices such as diodes and transistors may experience failure acceleration because of the seismic vibration causing cracks to grow in the encapsulant, thereby permitting moisture and oxygen to enter and promote corrosion of the circuitry.

4.5.3 NUREG/CR-3156; A Survey of the State-of-the-Art in Aging of Electronics With Application to Nuclear Power Plant Instrumentation [27]

This study evaluated the performance of electronic components in nuclear power plants. While primarily concerned with the effects of radiation on electronic devices, the report also discusses general aging characteristics and mechanisms of electronics similar to those used in battery charger and inverter designs. This report concludes that "semiconductor devices and integrated circuits are probably the most environmentally and operationally sensitive electronic components." Because this report focuses on the survivability of components in containment environments, not all its conclusions are relevant to battery chargers and inverters which are located in mild environments.

4.5.4 Vendor Input

A tour of the Power Conversion Products (PCP) facilities in Illinois and discussions with PCP personnel regarding battery charger construction, materials, and operating characteristics provided background information necessary to understand the various failure data analyzed. PCP has tested a prototype charger in accordance with IEEE 650-1979 and permitted BNL to make a close examination of the prototype while providing a detailed description of the various aspects of the test program. Design modification information and field equipment service experiences were also supplied.

A tour of the Elgar facilities in San Diego and discussions with Elgar personnel covering acceptance testing, qualification analyses, and equipment operating experiences contributed greatly to understanding the current state-of-the-art in inverter design and construction. This company began manufacturing inverters for nuclear power plants in 1979 and is currently involved in a number of plant startups. Feedback on initial equipment performance was obtained from Elgar.

Manufacturer information including sample qualification reports, schematics, operating instructions, and recommended maintenance and storage procedures was solicited from past and present suppliers of battery chargers and inverters to nuclear power plants. This information was essential for learning the differences in designs and the details of the components used, the sizes and ratings of the equipment, and any limitations or warnings offered by the vendor.

4.6 Failure Modes/Mechanisms/Causes

Table 4-6 is a culmination of the review and analysis of operating experiences, applicable reports, manufacturer instruction and maintenance manuals, and equipment materials. It also indicates potential aging-seismic correlation, and identifies the failure category. Terms used to organize and classify the information presented in the table are defined below:

- FAILURE MODES indicate the basic manner in which the battery charger or inverter fails.

- FAILURE MECHANISMS details the materials and parts of the equipment affected by degradation thereby causing the malfunction to occur.

- FAILURE CAUSES explains the actual malfunction by describing the manner in which inverter/charger components degrade, short, open, overheat, burn (etc.) and thereby create the failure mechanism.

- The AGING and AGING-SEISMIC CORRELATION categories indicate whether the failure mode, mechanism, and cause are directly attributable or potentially susceptible to time-related effects and externally induced effects, respectively.

- PROBABILITY OF OCCURRENCE indicates the likelihood of the corresponding failure to occur on the basis of the characteristics of the failure cause and is assigned either a high, medium, or low probability.

Table 4-6: Battery Charger/Inverter
Failure Modes/Mechanisms/Causes

COMPONENT	FAILURE MODES	FAILURE CAUSES	FAILURE MECHANISMS	AGING	AGING SEISMIC	PROBABILITY OF OCCURRENCE
CIRCUIT BREAKER (Consists of contacts coil, mechanical linkages, case)	Fails to Operate	Build up of dirt, solidification of lubrication, bearing wear.	Increase in friction, binding.	Yes	Yes	Medium
	Fails Open	Metal fatigue, embrittlement & cracking of insulation.	Trip coil force becomes less than spring force.	Yes	Yes	Medium
		Oxidation & pitting of contact surfaces.	Loss of continuity across contacts.	Yes	No	Low
FUSE	Fails Open	Metal fatigue.	Equipment load cycling.	Yes	Yes	Medium
		Melting of link.	Heat generated by surrounding components.	No	No	Low
RELAY	Contacts Open	Oxidation & pitting of contact surfaces.	Loss of continuity across contacts.	Yes	Yes	Medium
	Open Circuit of Coil	Electromechanical action causing corrosion of fine wires.	Loss of continuity through coil wires.	Yes	No	Low
ELECTROLYTIC CAPACITORS	Loss of Capacitance	Overheating by internal stresses.	Loss of electrolyte.	Yes	No	High
	Open Circuit	Vibration.	Failure of leads.	Yes	Yes	Low
OIL FILLED CAPACITORS	Loss of Capacitance	Overheating forms gasses.	Dielectric breakdown.	Yes	No	High
	Open Circuit	Vibration.	Failure of leads.	Yes	Yes	Low

Table 4-6 (Cont'd)

COMPONENT	FAILURE MODES	FAILURE CAUSES	FAILURE MECHANISMS	AGING	AGING SEISMIC	PROBABILITY OF OCCURRENCE
MAGNETICS (Transformer Inductor)	Short Circuit-(turn to turn or to ground)	Temperature cycling/over heating. Low temperature.	Cracking of insulation. Cracking of moisture seals.	Yes	No	Medium
	Short circuit-(turn to turn or to ground)	High voltage stress.	Insulating material deterioration	No	No	Medium
	Change in inductance	Vibration/over temperature.	Change in shunting. Fracture of connecting wires.	Yes	No	Low
SILICON CONTROLLED RECTIFIER	Short or Open Circuit	Overheating.	Overvoltage, overcurrent due to transients.	No	No	Medium
RESISTOR	Open Circuit	Vibration.	Lead fails.	Yes	Yes	Low
	Change in Value	Internal or ambient temperature changes.	Decrease in resistance value as temperature increases.	No	No	Low
PRINTED CIRCUIT BOARDS	Change in Output	Temperature cycling.	Cracking of circuit lines.	Yes	Yes	Medium
		Corrosion.	Open circuit at terminals or within pcb.	Yes	No	Low
		Vibration.	Loose or open connection.	No	Yes	High
SURGE SUPPRESSOR	Short Circuit	Semiconductor barrier break-down due to overheating.	Overvoltage, overcurrent.	No	No	Low

Table 4-6 (Cont'd)

COMPONENT	FAILURE MODES	FAILURE CAUSES	FAILURE MECHANISMS	AGING	AGING SEISMIC	PROBABILITY OF OCCURRENCE
MISCELLANEOUS						
- Connectors	Open or Short Circuit	Installation stresses	Fatigue of wire at terminals.	Yes	Yes	Medium
- Meters	No Response (Stuck)	Buildup of dirt on movement.	Increase in bearing friction	Yes	No	Medium
		Overheating.	Coil insulation degrades causing shorting.	Yes	No	Low
- Switch	Fails Open or Closed	Contact pitting/corrosion.	Loss of continuity across contacts.	Yes	No	Medium
- Potentiometer	Open or Short Circuit	Thermal degradation.	Loss of continuity across wiper arm and coil.	Yes	Yes	High

5.0 DISCUSSION OF CURRENT METHODS, TECHNOLOGY, AND REQUIREMENTS

A significant part of the aging assessment of any equipment is the evaluation of the equipment design and specifications; the review of industry practices (standards) associated with the construction, installation, and testing of the equipment; and the monitoring, testing, and maintenance techniques applied to mitigate equipment failure due to aging.

This section examines and summarizes available information covering the above subjects including selected manufacturer operating and maintenance manuals, IEEE standards, regulatory guides, and published reports. Information regarding work in progress is also included to illustrate the ongoing interest and concerns in this area.

5.1 Equipment Design and Specifications

Vendor operating and maintenance manuals, product literature, and a detailed user's specification provided information on the design data and operating requirements of the battery charger and the inverter. A number of important parameters specified by the user are readily available in the manufacturer's literature and include:

- output voltage regulation
- frequency control
- total harmonic distortion
- operating temperature and humidity limits
- transient response
- percent ripple
- current limit capability
- efficiency

Other items stated in user specifications but sometimes treated as options by the manufacturers are:

- metering
- alarm contacts
- indicating lights
- enclosure specifications (wall, skid, bolted, welded)
- type of cooling (forced air or convection)
- electrical protection
- voltage and phase unbalance specs for three phase systems

Because of the combination of required and desired items, each nuclear inverter and battery charger is unique, although certainly the major circuitries of each are similar for the specific models and manufacturers.

For a typical nuclear inverter, the specifications may be described as follows (these descriptions and the values provided have been taken from the manuals of several manufacturers):

- Voltage regulation is the variance in the output voltage and is normally $\pm$ 2% of the nominal voltage for output load variations and power factor from 0.8 to 1.0, or $\pm$ 1% for steady state, continuous loads.

- The output frequency is regulated to within 0.5% of nominal. This parameter requirement may vary with users; however, 0.5% is within the acceptable tolerance range of most loads that exist in safety related applications. The output of the inverter may be synchronized with another source or with a frequency standard. The impedance, voltage variation, and transient noise capability of the synchronizing signal to be used must be indicated in addition to the frequency.

- One measure of the output sine wave from an inverter is the amount of harmonics of the fundamental frequency which are present. The fundamental frequency is the component of lowest frequency and greatest amplitude. Specifications usually require that no more than 5% total harmonic distortion be allowed in the output sine wave with any one harmonic not exceeding 3%. As defined in IEEE-100-1977 [28], the total harmonic distortion is "the ratio of the root-mean-square (rms) value of all the harmonics to the rms value of the fundamental."

Some applications may not require the low harmonic outputs mentioned, especially if additional rectification or filtering is provided by the instrument power supplies being fed by the inverter. In fact, a square wave output could even be acceptable, although if a square wave inverter output is used in conjunction with external transformer loads, the transformers must be capable of handling the additional swing in flux (approximately 11%) without overheating. The square wave transformer input increases the total core loss and could lead to a temperature rise within the transformer which exceeds its rated value at full load. In general, even though a wider harmonic distortion tolerance in the specification results in reduced inverter size, cost, and weight, the wide variety of nuclear inverter applications dictate that harmonic distortion levels be minimized to achieve required performance.

- Efficiency is a measure of the power output divided by the input power. Depending upon the type of unit, efficiency can vary from 80% to 90%. Generally, efficiency is not given a high priority in nuclear power plant applications since the difference between an inverter system operating at 80% efficiency and another at 90% is not a significant, or even measurable, part of the plant operating cost. Reduced maintenance and service costs more than offset the minimal cost differences due to efficiency.

- Voltage unbalance is the relationship of the voltage of one phase with respect to each of the other two phases and is calculated by the equation:

$$\text{Unbalance (\%)} = \frac{\text{(maximum voltage - minimum voltage)}}{\text{Average voltage}} \times 100$$

The unbalance should be less than ± 2% for balanced loads and less than ± 5% for 100% unbalanced loads.

- For a three phase system, the three phases should be shifted 120 electrical degrees in relation to each other. A typical specification requires an unbalance of no more than 5 degrees from nominal.

- Several inverter specifications state that up to a 125% overload can be carried continuously by the inverter although current limiting circuitry is operable for only a short time, typically ten seconds for overloads as high as 200%. Because of the overload limitations, it is important that the load characteristic be carefully defined. Of specific importance are the load power factor, the load variation, and the maximum load to be switched at one time. The possibility of load short circuits should also be considered and fault clearing times factored into the current limiting requirement.

Similarly, battery charger manufacturer specifications include standard terminology summarized as follows:

- Automatic 115% current limiting protection is important in a nuclear application since the charger must be capable of recharging a depleted battery while supplying the emergency dc loads. Without this feature, the load demand might lead to a charger overload which could damage the charger or trip the input circuit breaker resulting in a loss of the dc bus.

- Output ripple no more than 2% rms when connected to a battery with an amp-hour capacity of four times the ampere output rating of the charger is typically specified. Charger manufacturers offer optimal 30 or 100 millivolt rms ripple levels which are usually required by the nuclear user specification. The additional filtering necessary to reduce the ripple to these levels consists of capacitors and inductors. This filtering aspect makes nuclear related applications somewhat different from the standard industrial models which have minimal filtering.

- Output voltage should vary no more than ± 1% from no load to full load, with ac input variations of ± 10%, and an input frequency range of 57 to 63 Hz.

- Complete protection features including input and output line fuses in series with the ac input circuit breaker and dc output circuit breaker, semiconductor protective fuses, and power failure relay alarms.

In addition, specifications are sometimes included on the potentiometers used for float and equalize voltage adjustments such as requiring settings adjustable to ± 5%.

Incorporated in the user specifications for battery chargers and inverters are the ratings or sizes of the units to be provided. The minimum size is dictated by the safety related loads that must be available to mitigate accident consequences as described in the plant Final Safety Analysis Report (FSAR).

As briefly discussed in Section 3.3, battery charger sizing is based on a number of parameters including the continuous load on the dc system, the type of batteries used, and the time required to recharge the battery to 95% capacity while simultaneously supplying the steady state dc load. Inherent in this requirement is that the recharge voltage must be less than the maximum allowable dc system voltage unless the battery and charger can be isolated from the dc system during recharging. In plants with a cross tie capability, there is evidence that this latter method has been used in the past. Equalizing voltages required for the battery may exceed maximum voltages permissible by the loads supplied from the dc bus, including the inverter or sensitive process monitoring instrumentation. This problem may be circumvented by removing one or two cells from the battery which lowers the required equalizing voltage by several volts.

5.2 Standards, Guides, and Codes

User specifications for nuclear safety related battery chargers and inverters reference three major industry standards for defining construction, design, and/or testing requirements. These are IEEE 650-1979, "IEEE Standard for Qualification of Class 1E Static Battery Chargers and Inverters for Nuclear Power Generating Stations," NEMA PE 5-1983, "Constant Potential-Type Electric Utility (Semiconductor Static Converter) Battery Chargers," and IEC Publication 146-2, "Semiconductor Converters." Each of these represents nationally or internationally recognized guidelines for charger/inverter manufacture, operation, monitoring, maintenance, and application. Each of these standards will be reviewed in detail. A fourth standard, IEEE P944, "Criteria for Application and Testing of Uninterruptible Power Supplies for Power Generating Stations," is currently in draft form. When issued, it will provide the industry with criteria and recommendations for the application and testing of vital ac systems.

IEEE 650-1979

To satisfy the equipment qualification requirements of IEEE 323-1974, the nuclear industry found it practical to develop a separate standard for battery chargers and inverters used in safety related electrical systems. This standard describes methods for qualifying battery chargers and inverters located in mild environments, but does not specify performance requirements, nor does it address maintenance and periodic testing.

The qualification methods in IEEE 650-1979 consist of a combination of type testing and analysis since the equipment is considered too complex to be qualified by analysis alone. The type testing specified includes a 100 hour burn-in and placing the equipment in an environmental test chamber in which the temperature and humidity are varied over the required service conditions while adjusting the loading. As stated in the standard, "this testing subjects the equipment to the worst case and nominal conditions of temperature, humidity, input voltages, and output loads." This type test can then be used to qualify chargers and inverters of a similar design.

The standard requires information which had not been consistently considered in earlier equipment specifications, e.g., identification of numerical values for parameters under normal, abnormal, design basis event (DBE), and post DBE conditions. These parameters include input and output conditions, harmonic distortion, and surge withstand capability. In addition, the environmental parameters resulting from the normal and accident conditions must also be known to ensure that the equipment will operate satisfactorily under these adverse conditions.

National Electrical Manufacturers Association (NEMA)PE5-1983

IEEE 650-1979 references NEMA PV 5-1976 as the industry standard for battery charger performance. PV 5-1976 has evolved to include information concerning the construction, testing and safety of utility type battery chargers in addition to performance and is now identified as NEMA PE 5-1983, Constant-Potential-Type Electric Utility (Semiconductor Static Converter) Battery Chargers. Several specific areas are discussed in this standard which are outlined below.

In the performance area, the standard directs that the charger be capable of operating continuously in a current-limiting mode without causing the protective devices to operate. The output current must be limited to a safe value even when supplying a fully discharged battery. In addition, limitations are placed on the following parameters:

- Floating voltage deviation not more than ± 1%.
- Equalizing voltage deviation not more than ± 2%.
- Output voltage or current oscillations not sustained for more than 10 seconds.
- Charger must return to stable operation within 2 seconds after a load change of 80% of rated current.
- The ac ripple voltage shall be filtered to either 30 or 100 millivolts rms as measured at the battery terminals.
- The charger (480 volt input) shall be capable of withstanding a transient pulse of 3000 volts at the ac supply terminals for 20 microseconds.

- The charger shall be capable of withstanding a transient pulse of 4000 volts on the dc terminals for 10 microseconds.

This standard provides guidance for input and output circuit breakers, voltage and current indication, the equalizing timer, and alarm relays (low voltage, overvoltage, low current, or loss-of-output). It is important to note, however, that these items are considered optional parts of the battery charger. In most nuclear applications they are found to exist, although the operating experiences reviewed suggested that several plants did not have alarm relays to indicate a charger failure. Instead, they were alerted to a charger failure by a degraded dc bus voltage.

NEMA PE 5-1983 provides ranges of service conditions for which the charger should be designed, including:

- An ambient air temperature of 0°C to 50°C.

- Ventilation and clearance adequate to allow cooling while preventing stagnation or entrapment of air.

- Relative humidity between 0 and 95 %.

- Cable loop voltage drop between charger and battery not exceeding 2 percent of rated voltage at full load.

- Freedom from damaging environmental conditions such as fumes, moisture, salt air, dust, vibration, and shock; although generally,unusual service conditions such as those indicated may require specific construction or protection.

Separate attention is given to seismic considerations and testing that should be performed to assure seismic withstand capabilities. Of interest here is the recommendation ("should") to run "exploratory continuous dynamic-vibration tests" on the complete assembly in the horizontal and vertical directions to determine the resonance frequency points of charger components. This standard specifies that Design Basis Earthquake (DBE) tests be made at the points of resonance and should include an acceleration of 0.4 g for a 20 second duration.

To determine the charger performance characteristics and its adherence to the NEMA standard, a number of design tests are specified, including a dielectric test, a no-load test, a temperature rise test, a ripple voltage measurement, and a transient voltage withstandability test. These and other tests are described along with indication that they need not be repeated unless design changes are made that would affect the test results. This latter point is difficult to control and monitor. Several minor modifications made over a long period of time may alter the performance characteristics just as aging of sub-components will affect overall charger capability. Either could warrant testing to ascertain that the NEMA standard requirements are being maintained.

International Electrotechnical Commission (IEC) 146-2-1974

IEC 146-2-1974, entitled "Semiconductor Converters," provides a number of recommendations addressing the design, application and testing of inverters with testing being the major emphasis. Although not solely addressed to nuclear inverter functions, the standard is consistent with nuclear inverter supplier specifications.

The standard indicates that inverters must be capable of operating under certain service conditions such as:

- Ambient air temperature between 0°C and 40°C.
- Input voltage variations of ± 15%.
- Input ripple of 15% peak-to-peak of the rated supply voltage.
- Input harmonic content of 10%.

With the input variations noted above, the standard requires that, as a minimum, the rated output voltage band be maintained within ± 5% while the frequency is maintained within ± 2%. Additional general guidelines are indicated for other parameters, however, the standard merely recommends that the user specify these parameters only if demanded by the usage.

The description of tests to verify performance characteristics is comprehensive and is generally applicable to tests performed by the manufacturer before shipment. The tests are divided into three categories: type tests required on at least one sample of every type of inverter; routine tests required on all inverters; and optional tests which are performed only if specified by the user. These tests are illustrated in Table 5-1. The following paragraphs briefly describe the tests which may be applicable to nuclear applications.

The first test is simply to operate the inverter at rated load conditions until the temperature of critical components have reached steady state. Transformer and semiconductor temperature rise are of particular concern and should be monitored periodically.

A second test determines the ability of the inverter to withstand transients on the input voltage supply by placing a capacitor across the input with an inductor inserted between the capacitor and the inverter input terminals. Applying this transient at rated load conditions, the inverter is required to continue operating during the course of this test.

A short circuit current capability test is performed by short circuiting the output terminals via a fuse at that point in the output cycle that allows the longest time for the fuse to break the short circuit. Again, this test is conducted at rated input voltage and rated continuous load and is used to determine the available fault current and time (I^2t) on a branch circuit supplied by the inverter.

To ensure proper starting of the inverter under full load at steady state temperatures, a "restart test" is recommended which requires at least five consecutive successful starts at rated temperatures.

A fifth test of significance is the output voltage unbalance test which is applicable to large three phase inverters. Voltage unbalance at no load and full load conditions is measured under balanced load conditions. The ratio of unbalanced voltages is then provided, which should be less than 5%.

These tests ensure that the inverter is capable of meeting design specifications, however, they are not readily applicable to field installations where it is desirable to minimize the wiring changes that would be required to accommodate much of this testing.

Table 5-1: Testing Identified in IEC 146-2-1974

Test	Type Test	Routine Test	Optional Test
Insulation	X	X	
Preliminary light-load	X	X	
Checking of auxiliary devices	X	X	
Temperature rise	X		
Temperature dependent frequency variation	X		
Output voltage tolerance	X	X	
Frequency tolerance	X		
Relative harmonic content	X	X	
Harmonic components	X		
Conversion factor			X
Power efficiency	X		
Current division	X		
Voltage division	X	X	
Radio frequency			X
Audible noise			X
Supply overvoltage and energy test			X
Short time current			X
Short-circuit current capability			X
Restart			X
Output voltage unbalance test			X
Frequency modulation			X
Periodic output voltage modulation			X
Voltage rise			X
Voltage dip			X
Hold-off interval	X		

<u>IEEE P944, "Criteria for Application and Testing of Uninterruptible Power Supplies for Power Generating Stations."</u> (DRAFT)

This standard was prepared by the Working Group on Vital AC Power, Nuclear Power Subcommittee of the Power Generation Committee of IEEE. While applicable to any generating station vital ac system, when combined with applicable portions of IEEE 650-1979, this standard is intended to provide application and testing information pertinent to nuclear power plant inverters. Application requirements for battery chargers are not included.

Although this standard reiterates some of the performance requirements described in the standards previously discussed, it also addresses areas not mentioned or thoroughly covered by them. It is important that these be highlighted here keeping in mind that this is a draft standard which could change before final publication.

- The first area is providing guidance for transfer switch performance. Since transfer switches exist in a large number of plants, it is important that acceptable limits be established. This standard recommends a maximum of 4.19 milliseconds (1/4 cycle) interruption in the power supply as the load is transferred from the inverter output to the bypass source or vice-versa. This minor interruption would have no effect on the supplied equipment.

- Addressing inverter sizing, the standard cautions that since the inverter has very little long term overload capability, and it is "not practical or economically sound" to size the inverter to handle inrush or short circuit current requirements, a solid state transfer switch should be used to compensate for the lack of capability. As an alternative, fault clearing devices on selected high inrush loads are recommended. In addition, it is recommended that loads be divided into many branch circuits with high speed fuses or breakers on each. This would minimize fault clearing times and minimize system disturbances.

- A number of plants use maintenance bypass switches to supply the vital bus loads when maintenance is being performed on the inverter. The standard recommends use of a "make-before-break" type switch when load interruption is undesirable.

- This standard provides guidance on the quality of the ac alternate supply, including the following:

  - $\pm$ 10 % voltage variation and $\pm$ 1/2 % frequency regulation,
  - a total harmonic distortion of 10 % shall not be exceeded,
  - voltage surges shall not exceed the nominal value by more than 20% and shall not last for more than 30 seconds,
  - voltage impulses shall not exceed 6 kV,
  - overcurrent impulses shall not exceed 3000 amps.

- Inverter testing recommended by this standard includes the design and routine tests listed in Table 5-1 as well as several of the optional tests including short time current, short circuit capability, restart, and output voltage imbalance.

Other industry standards indirectly relevant to battery chargers and/or inverters are also listed. These standards provide general background information only, except as indicated.

- IEEE 308-1980, "Criteria for Class 1E Power Systems for Nuclear Power Generating Stations." This standard requires that each battery charger have sufficient capacity to restore the battery from the design minimum charge to its fully charged state while supplying normal and post accident steady state loads.

- IEEE 323-1974, "Qualifying Class 1E Equipment for Nuclear Power Generating Stations."

- IEEE 336-1980, "Installation, Inspection, and Testing Requirement for Class 1E Instrumentation and Electric Equipment at Nuclear Power Generating Stations."

- IEEE 338-1977, "Standard Criteria for the Periodic Testing of Nuclear Power Generating Station Class 1E Power and Protection Systems."

- IEEE 344-1975, "Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations."

- IEEE 379-1977, "Standard Application of the Single Failure Criterion to Nuclear Power Generating Station Class 1E Systems."

- IEEE 381-1977, "Standard Criteria for Type Tests of Class 1 Modules Used in Nuclear Power Generating Stations."

- IEEE 384-1981, "Standard Criteria for Independence of Class 1E Equipment and Circuits."

- IEEE 420-1982, "Standard for the Design and Qualification of Class 1E Control Boards, Panels and Racks Used in Nuclear Power Generating Stations."

- IEEE 450-1980, "Recommended Practice for Large Lead Storage Batteries for Generating Stations and Substations."

- IEEE 484-1981, "Recommended Practice for Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations."

The industry has produced additional standards which relate to battery charger and inverter subcomponents including:

- IEEE 107-1964, Standard for Rating and Testing Magnetic Amplifiers

- IEEE 449-1984, "IEEE Standard for Ferroresonant Voltage Regulators. Of interest in this standard is the statement that a "ferroresonant regulator, when specially designed and followed by rectifiers, provides an ideal battery charger..." Consisting of only the ferroresonant transformer and the capacitor, the basic ferroresonant regulator requires no maintenance according to the standard.

- ANSI/IEEE C62.41-1980, "IEEE Guide for Surge Voltages in Low Voltage AC Power Circuits". Semiconductor sensitivity to the timing and polarity of a surge varies significantly according to evidence presented in this standard. Therefore, when performing surge testing, it is important to test various conducting points. The standard also points out that switching transients can result from fast acting current limiting fuses which leave trapped inductive energy in the upstream circuit. Upon collapse of the field, high voltages are generated which could cause other damage.

- ANSI/IEEE Std. 428-1981, "IEEE Standard Definitions and Requirements for Thyristor AC Power Controllers".

- ANSI/IEEE C57.12-1978, "IEEE Standard Requirements for Instrument Transformers."

- IEEE Std. 259-1974 (Reaffirmed 1980), "IEEE Standard Test Procedure for Evaluation of Systems of Insulation for Speciality Transformers".

- IEEE Std. 392-1976, "IEEE Recommended Practice for Achieving High Reliability in Electronics Transformers and Inductors".

  In the manufacture of magnetic components, many manual operations are involved, and human errors are more likely than in an automated operation. Careful in-process inspection is the most effective means of eliminating problems. For many electrical components such as semiconductors and capacitors, burn-in is recommended to eliminate substandard parts.

  This standard also recognizes that <u>aging takes place in magnetic components.</u> It discusses the validity and shortcomings of testing for the effects of aging. The recommendations of this standard will be further investigated during the phase 2 portion of the NPAR Program, which will include charger and inverter testing.

A number of regulatory guides were also reviewed to ascertain inverter/battery charger applications. These guides are vital to interpreting General Design Criterion 17 (GDC-17) "Electric Power Systems" of 10CFR Part 50 which states, among other things, that "the on-site electric power supplies, including the batteries, and the onsite electric distribution system, shall have sufficient independence, redundancy, and testability to perform their safety functions assuming a single failure."

Regulatory Guide 1.32 "Criteria for Safety Related Electric Power Systems for Nuclear Power Plants" generally endorses IEEE 308-1974 with several exceptions including one related to battery charger capacity. The Regulatory Guide indicates that the battery charger should be capable of restoring the battery from a minimum charge to a fully charged state while supplying the largest combined demands of the various loads-not limited to normal or post accident conditions. A second important exception taken to the IEEE standard 308-1974 is in the configuration area. The Regulatory Guide specifically considers sharing of dc power among units at a multi-unit site to be unacceptable.

Safety Guide 6 and Regulatory Guide 1.6 discuss the required independence between redundant standby (onsite) power sources and their distribution systems. Again, as in Regulatory Guide 1.32, the emphasis is to ensure that postulated single failures do not disable redundant sources. Specifically, this means that automatic paralleling of two sources is not permitted, no throwover of loads from one safety bus to another should exist, and interlocks should be provided to prevent an operator error that would parallel the sources.

Regulatory Guide 1.93 entitled "Availability of Electric Power Sources" discusses the operating aspects of a loss of an offsite or onsite power source including dc supplies. The intent to implement the safest operating mode whenever the available sources are less than the Limiting Conditions for Operation (LCO) is described in detail, including the possibility of maintaining a power condition versus proceeding to a shutdown condition when the number of available sources are less than the LCO.

Regulatory Guide 1.75, "Physical Independence of Electric Systems" discusses the physical independence of electric equipment associated with class 1E systems and "auxiliary or supporting systems" (battery chargers and inverters) which must be operable for systems to perform their safety related functions. This Regulatory Guide generally endorses IEEE standard 384-1974, however, it includes more than a dozen changes or clarifications to that standard.

5.3 Technical Specifications

Nuclear plant technical specifications (tech specs) for battery chargers and inverters vary from plant-to-plant because of different bus configurations, the varied safety impact of equipment failure, and plant age (minimal charger/inverter tech spec requirements exist for some older plants). The standard technical specifications for each type of commercial reactor (GE, Westinghouse, C-E, B&W) were reviewed and found to contain similar requirements for chargers and inverters. The G.E. BWR Technical Specification, as found in NUREG-0123, "Standard Technical Specifications for General Electric Boiling Water Reactors" requires restoration of an inoperable vital ac bus (inverter) within 8 hours or the plant must be placed in hot shutdown in the next 12 hours and cold shutdown in the following 24. The Standard Tech Spec assumes four 120 volt ac vital buses, but does not indicate a different LCO if there are different numbers of vital buses, automatic throw-over capability, or an alternate supply. Similarly for PWRs, the standard tech specs [29-31] indicate that if a vital ac bus is inoperable for 8 hours the plant should be placed in the hot standby mode in the next 6 hours and cold shutdown in the following 30 hours. This LCO is identical for the Westinghouse, C-E, and B&W standard tech specs.

Other selected PWR technical specifications revealed more stringent requirements including requiring bus restoration within 2 hours and proceeding to a hot standby status in the next 6 hours. Selected BWR technical specifications revealed no LCO for inverters.

For battery chargers, the standard technical specifications for BWRs requires restoration of an inoperable dc bus, charger, or battery within 2 hours or the plant has to be placed in a hot shutdown condition in the next 12 hours and cold shutdown in the following 24 hours. PWRs are similar except that if the charger is inoperable for 2 hours, the plant must be placed in hot standby in the next 6 hours and cold shutdown in the following 30 hours. Again, individual tech specs vary and include more relaxed restrictions than offered by the standard tech specs including the following:

- At a BWR with two dc buses, a charger that is inoperable in one division must be restored within seven days or the plant must proceed to a shutdown condition.
- At a PWR with two chargers per battery, operation can continue indefinitely with one charger inoperable in each battery division.

5.4 Manufacturer Recommendations

A review of battery charger and inverter manufacturer maintenance recommendations can be summarized by the general philosophy of keeping the equipment clean while periodically checking the tightness of wiring connections and replacing parts indicated in the qualification report to be age sensitive. More specific recommendations include the following. Unless specific to only one type of inverter or charger, it may be assumed that these recommendations could apply to both battery chargers and inverters.

- Oil filled and electrolytic capacitors should be replaced every seven years (some manufacturers recommend every four years, some every 10 years).
- The fans in large units with forced air cooling should be replaced every two years.
- Air filter should be cleaned.
- Monthly inspection should be made for evidence of overheating.
- Terminal connection tightness should be checked quarterly.
- The inside of the units should be cleaned (vacuumed) quarterly.
- Voltages should be measured quarterly.

- For extended storage before installation and prolonged idle periods after installation, equipment should be covered with plastic to protect against dust and moisture.

- Wiring connections should be soldered - the use of push on type connectors should be minimized.

- The rectifier assembly should be cleaned periodically to prevent these parts from running at too high a temperature.

- The ferroresonant inverter should not be operated at no load for longer than 72 hours to prevent overheating due to high losses in the regulating transformer.

- For optimum regulation of a ferroresonant inverter, the inverter should be loaded between two thirds full load and full load.

- Dust and dirt should be wiped from heat sink surfaces using a clean lint-free cloth dampened with carbon tetrachloride. (Note: restrictions on the use of carbon tetrachloride may make it unacceptable for use in a nuclear power station.)

- Open relay contact points and terminal posts should be inspected and cleaned with a clean lint-free cloth dampened with carbon tetrachloride. Burnish contact points if required.

- Terminal connections should be torqued tight annually especially high current conductor connectors.

5.5 NRC Experience, Expert Knowledge, and On-Going Research

Present NRC interest in vital ac power, of which the inverter is an integral part, is documented in Issue No. 48, LCO for Class 1E Vital Instrument Buses in Operating Rectors. Research [18] on this issue has resulted in recommendations such as the implementation of a 72 hour annual time limitation for energizing a vital ac bus from an interruptible power source, i.e., an alternate bus. Other potential recommendations include the standardization of technical specifications for vital ac buses, and the definition of minimum plant configuration requirements.

The Office for Analysis and Evaluation of Operational Data (AEOD) has continued to follow inverter performance and has found unsatisfactory improvement in failure rates and failure consequences despite substantial regulatory and industry recommendations/requirements in this area. Transients, including reactor trips and safety injections, continue to occur because of inverter failure or vital bus degradation. In addition, because of the potential for a significant plant impact when an inverter fails, a second NRC group studying issue A-17, "System Interaction," has also initiated research into inverter performance on the systems level. This includes a review of significant instrumentation which is powered by the vital bus and the effect of its loss on operator performance during a severe transient event.

Similarly, in the area of dc power of which the battery charger is an integral part, the NRC has studied, and continues to research, the performance of safety related dc power supplies and the impact that a loss of dc has on plant safety.

In July 1977, the NRC issued a report [32] which addressed the reliability of dc power supplies at operating nuclear power stations, and discussed the likelihood and the consequences of a postulated failure of all dc during normal operation of a plant. The NRC staff concluded that because of the importance of ac and dc power systems, efforts to review the reliability of these systems should continue.

In April 1981, a second study of dc power was performed by the NRC [33] as part of the work on Issue A-30, "Adequacy of Safety Related DC Power Supplies." The issue here is primarily one of dc independence to minimize the potential for common mode failure. This study was a probabilistic safety assessment to determine the relative contribution of dc power related accident sequences to the total core damage probability. A significant finding of this PRA study was that a potentially large contribution could be reduced by requiring dc power divisional independence, and improved test, maintenance, and surveillance of dc components, including batteries and chargers.

A paper [34] summarizing EPRI research in the qualification of safety related electrical equipment describes ongoing work devoted to improving equipment qualification technology including the comparison of aging techniques by comparing naturally and artificially aged devices, and to the development of a better understanding of the relationship between reliability and qualification.

After extensive testing on the seismic-aging correlation of electrical equipment, EPRI has concluded that certain components such as resistors, capacitors, diodes, and terminal blocks have no seismic-aging correlation and should be exempted from the requirement to age condition (thermally and operationally) before seismic testing. Studies continue in this area on additional component types.

In conjunction with the EPRI work, Gleason [35] further described the testing performed on electrical and electronic components typically located in mild environments. Describing the dominant aging mechanisms as thermal, radiation and operational cycling, the author proceeds to discuss the seismic performance of components that have been aged. This paper indicates that relays are being further evaluated as well as other safety related equipment, including naturally aged equipment.

A study [27] to evaluate the aging of electronic components such as semiconductors, capacitors, and resistors used in safety related instrumentation, particularly those used in harsh environments, revealed the following:

- Resistors are stable components, however, different types of resistors should be subjected to aging factors such as humidity and vibration to determine their total aging characteristics in a plant environment.

- Capacitors need further study to understand potential failure mechanisms and to determine the need for voltage endurance testing.

- Semiconductors and integrated circuits are environmentally and operationally sensitive components. New semiconductor technologies need to be reviewed since it should not be assumed that improvements are directly applicable to nuclear power plants.

Further work recommended includes investigation of the importance of humidity in accelerated aging, and identification of the factors unique to the nuclear plant environment and operation, and of other electronic components used both inside and outside containment.

A study [36] investigating the use of solid state motor controllers in nuclear power plants describes the performance of devices similar to controllers, namely battery chargers and inverters. Equipment qualification reports for nuclear chargers and inverters were reviewed. The authors noted that semiconductors and resistors were analyzed for margin of safety by evaluating the ratio of actual power divided by rated power. This "stress ratio" is defined as (applied power)÷(rated power) for semiconductors, integrated circuits, resistors, transformers, terminal blocks, and connectors, and as (applied voltage)÷(rated voltage) for capacitors.

In this analysis every component's stress ratio is determined (2686 individual components in this particular inverter) requiring a detailed circuit analysis to determine the electrical conditions applied at each component.

Many documents dealing with electronic component reliability and qualification address research performed by the military [37]. In some cases, the component military applications can be compared to nuclear plant use in the areas of temperature, humidity, seismic, and radiation. Guidance expressed in the referenced document indicates that electronics applications suffer from unreliability sometimes due to the recognized fact that the electronics art is "often in revolution."

Because inverters and battery chargers are located in mild environments, particular attention was paid to studies discussing electrical equipment qualification. One such paper [35] concluded that it is possible to demonstrate that "complex electronic equipment will perform its safety related function in a mild environment for 40 years without any common mode failures caused by aging." The methodology to do this was a combination of analysis and type testing.

As demonstrated by the number of standards and publications, it is clear that battery chargers and inverters and their subcomponents have been extensively studied. The continuing work in the systems interaction area is extremely important and, as illustrated in Section 4 of this report, is obviously warranted. In addition, the expanding influence that electronic components have on nuclear industry equipment performance makes it necessary for the industry to develop and/or modify existing standards to ensure that expected reliability levels are achieved.

From the review of manufacturer recommendations, user specifications, industry standards, and regulatory guidance, it is evident that the mechanisms are in place to incorporate additional or different testing, monitoring, and/or preventive maintenance measures to improve equipment and system performance.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Inverters and battery chargers used in nuclear power plants perform significant functions related to plant safety and availability. The specific impact of a battery charger or inverter failure varies with plant configuration. Operating experience data have demonstrated that reactor trips, safety injection system actuations, and inoperable emergency core cooling systems have resulted from inverter failures; and dc bus degradation leading to diesel generator inoperability or loss of control room annunciation and indication have resulted from battery and battery charger failures. For the battery charger and the inverter, the aging and service wear of subcomponents have contributed significantly to the history of equipment failure.

To identify and characterize aging and service wear effects which could cause battery charger or inverter degradation and thereby impair plant safety, a study has been completed of the battery charger and inverter designs employed in nuclear power stations, the configuration and alignment of this equipment within the plant's electrical scheme, the identification of subcomponent failures, and the effects that charger or inverter failures,especially those related to aging, have had or could have on plant performance and safety. In this report, actual nuclear power plant operating experiences are cited in support of a number of conclusions regarding the design, fabrication, operation, application, and maintenance of battery chargers and inverters. In addition, several interim recommendations are made with regard to the inspection, surveillance, and monitoring of battery chargers and inverters, as well as maintenance practices which may be effective in mitigating aging effects. Further analyses of the equipment operating characteristics coupled with the testing of naturally aged equipment are expected to result in maintenance and/or testing techniques which are not only technically feasible, but are practical as well.

6.1 Conclusions

6.1.1 Design and Fabrication

Sections 2 and 3 addressed the basic principles of operation of the three types of battery chargers and the four types of inverters used in nuclear power stations, and described the major subcomponents which make up this equipment along with some of the environmental and operational factors that affect their performance.

Perhaps the most significant problem related to the aging and service wear of components is the limited life of the electrolytic and oil filled capacitors used in every type of charger and inverter. On the basis of the poor operating experience identified by the data, and the documented relationship of capacitor life to applied voltage and ambient temperature, it may be concluded that use of capacitors with higher voltage and temperature ratings would increase capacitor life and therefore improve equipment performance. It should be noted that an inverter design such as the PWM type, which requires smaller filter capacitors because of the higher frequency harmonics associated with the output waveform, may not be as susceptible to the capacitor failures experienced by other types.

Other design or fabrication related conclusions reached include the following:

- Battery charger and inverter subcomponents are susceptible to damage from electrical transients. Surge suppression schemes on the input to the equipment have been effective in minimizing this concern, especially when used to protect the SCRs in the rectifier circuit.

- From the number of component failures attributed to overheating, it is concluded that reliance on convection cooling principles is inadequate for certain designs and installations. Filtered forced air cooling is generally available as an option.

- Zener diodes can change characteristics with time because of impurities introduced during the manufacturing process.

- Transformer insulation rating is an important attribute for extending the service life of this key component. Recent upgrades by several utilities to higher temperature insulation ratings leads to the conclusion that equipment internal temperatures are higher than anticipated, and materials, especially insulating materials used in older equipment, are not at present day standards, i.e., class B versus class H insulation.

- Battery charger failures at certain plants are not detected until the dc bus voltage has decreased to the point that an alarm is obtained. The battery life at that time has been sufficiently shortened that the battery would be unable to supply the required dc loads for the time period specified in the plant design documents (FSAR).

6.1.2 System Interactions

The operating experience data have revealed the significant impact that the loss of a vital ac or dc bus can have on plant safety and availability. Reactor trips, safety injection system actuations, emergency core cooling system inoperability, and loss of decay heat removal capability are some of the consequences of inverter and battery charger failures. Although most of the significant plant transients have been the result of inverter failures, it has been demonstrated that the inverter and the battery charger are closely coupled in nuclear plant applications, contain identical components, and are subjected to similar stresses.

From the information presented in Section 4, it is concluded that battery charger and inverter failures at many plants directly affect reactor safety. As cited by the NPRDS 1983 annual report, the inverter is the component with the highest failure contribution in both the Reactor Protection Systems and the Emergency Core Cooling Systems (ECCS) for PWRs and BWRs. Battery chargers (and batteries) rank third as a contributor to ECCS failures. The bus configuration, specifically the existence of a standby or redundant full capacity battery charger for dc systems, or an automatic throwover switch to an emergency ac regulated supply for vital ac systems, is a significant factor in assessing the consequences of equipment failure and will determine how systems are impacted. The loads being supplied by each bus are plant specific and will also determine plant response to a loss of vital ac or dc event. In general, however, the data confirm that plant safety system operation and availability are directly affected by inverter and charger performance, and therefore this equipment warrants considerable attention.

Other conclusions developed as far as plant operation and system interactions are concerned include the following:

- Emergency diesel generator testing requirements could result in stresses being placed on chargers and inverters because of the wide frequency and voltage variations permitted by the diesel output. This is particularly evident in ferroresonant type inverters where phase unbalances can cause circulating currents within the transformer, which produces heat and accelerates component failures.

- Addition of a standby charger or a second full capacity charger on a dc bus dramatically reduces the number of LERs associated with battery charger failures, which implies an increased reliability for maintaining the batteries in a fully charged condition.

- Inverter performance is best on those units that employ a manual transfer switch, but no rectifier. The small number of plants included in the survey with automatic throwover switch capability make conclusions on this mode of operation difficult. Manufacturers report that the use of an automatic throwover scheme offers the highest system reliability and is typically required in military and computer industry applications.

6.1.3 Aging and Service Wear Characteristics

Perhaps the major goal of the research performed was to identify problems experienced (or which may be experienced) by inverters and battery chargers which are related to aging and service wear. This portion of the study concentrated on component level failure analysis including a close look at failure causes. As revealed by NPRDS data, the utilities considered at least 30% of the inverter and charger failures to be age related. Thus, mitigation of the effects of aging can significantly improve equipment performance. The aging and service wear characteristics identified in this report include the following:

- Increases in ambient or internal temperatures can have a dramatic effect on inverter and charger performance. Overheating is a major contributor to aging related failures and was especially noticeable in failures of capacitors, transformers, and semiconductors. See interim recommendations (Section 6.2) for possible improvements in this area.

- A number of weak links have been identified which could cause an inverter or battery charger, when aged, to fail under seismic loads. These include cabinet mountings, circuit board supports, wire and cable connectors, relays and circuit breakers, and oil filled capacitors.

- Chargers and inverters have a "wear out period" after four to six years of operation. That is, the failures, when plotted against the plant age at the time of failure (Figure 4-1), produced a curve similar to the classic bathtub curve with the wear out region occurring between years four and six.

6.1.4 Industry and Regulatory Criteria

Perhaps the most significant conclusions realized in the area of industry and regulatory recommendations is in the testing area. While much of the recommended industry testing deals with the manufacturing end of the business, sufficient inference to continued testing exists to conclude that periodic inverter and battery charger testing is not only desirable but necessary. Realizing that some of the industry standards reviewed were not solely dedicated to nuclear applications, the type of testing specified which would be related to ensuring the safety related application of inverters and chargers, is in the nature of capacity testing. Although some plants are required to perform periodic capacity tests of their battery chargers, this requirement is not universal. Evidence of required inverter capacity testing was not indicated.

Additional conclusions in this area include the following:

- The number of failures whose causes are unknown lead us to conclude that investigations following an equipment failure are inadequate. This may be due to either equipment unfamiliarity or time constraints. Because of the potential impact on plant safety and availability, this approach is not justifiable.

- Personnel errors in the design, manufacture, operation, and maintenance of battery chargers and inverters account for a large percentage of documented failures (~15%). It may be concluded that improvements in maintenance and operating personnel training would improve overall performance levels considerably.

- Classification of inverters as safety related equipment is not consistent, as evidenced by a review of 15 BWRs which have inverters supplying their vital bus but do not consider this equipment to be safety related. Since the inverter failures at these plants could affect safety system operation, it is concluded that this equipment should be reclassified.

6.2 Interim Recommendations

On the basis of a detailed review and analysis of operating experiences as provided by a number of varied data sources including LERs, NPRDS, IPRDS, NPE, and plant maintenance records, and supplemented by information from vendor instruction manuals and industry standards, a number of interim recommendations are made which may improve battery charger and inverter reliability and thereby increase the performance level of nuclear safety systems. Further research into these recommendations will be completed as part of the Phase 2 study which will evaluate the cost/benefit value and the practical applicability.

Plant maintenance records support the conclusion that significantly improved battery charger and inverter performance could be obtained through implementation of a comprehensive preventive maintenance (PM) program supported by personnel training, both in operations and maintenance (See Fig. 4-15). It is expected that much of the PM would be checks of connection tightness, structural support integrity, and cleanliness, as well as examination of parts for evidence of overheating and wear. In addition, a review of some of the key subcomponents employed in both battery chargers and inverters reveals that certain performance indicators may be effective in predicting failure due to aging of the equipment; several of which may be performed while the equipment is supplying station loads.

These performance indicators are illustrated in Figures 6-1 through 6-3 and exhibit the specific parameters that can be monitored to verify proper charger and inverter operation and anticipate equipment degradation. Phase 2 of the NPAR program strategy requires further evaluation of the performance indicators through testing and analysis. Monitoring the output waveform may provide the best on-line indication of capacitor and semiconductor degradation. Changes in wave shape could alert personnel to potential problems as well as to provide guidance for troubleshooting. Note that resistance value changes (a fairly simple measurement) can also signify capacitor and semiconductor degradation, but would generally require the equipment to be deenergized.

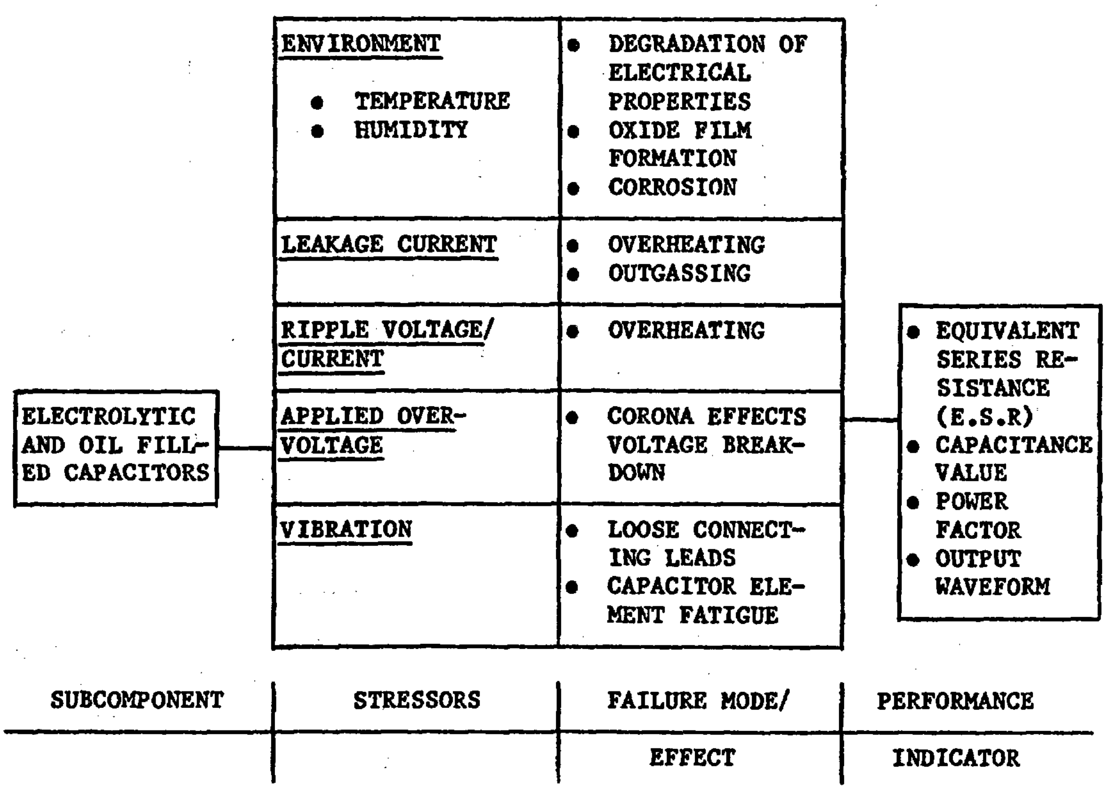


Figure 6-1: Performance Indicators for Electrolytic And Oil Filled Capacitors

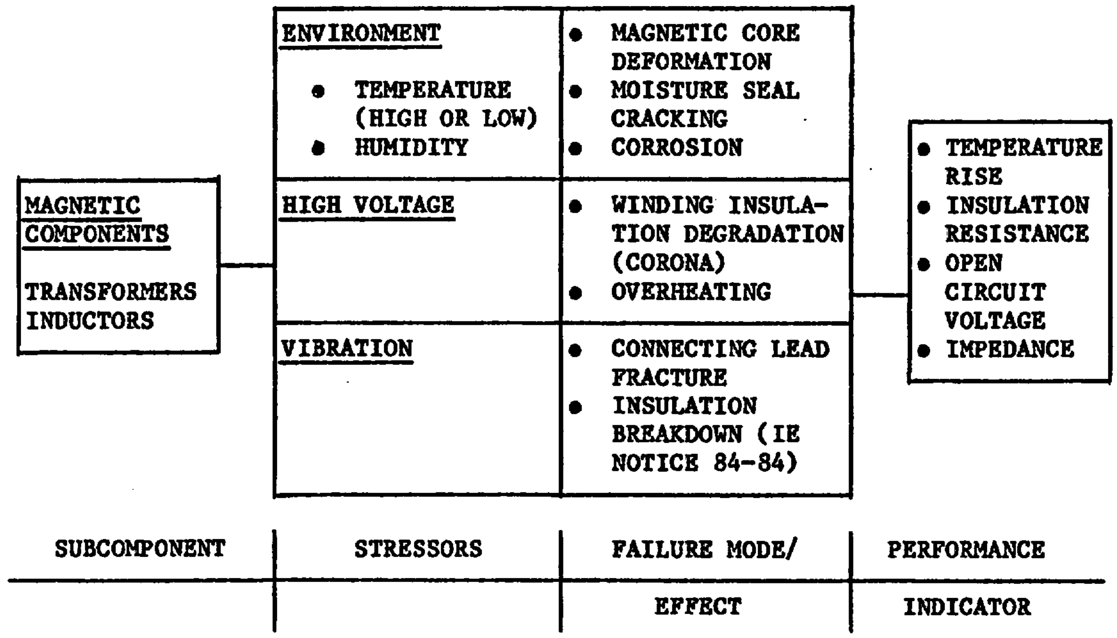


Figure 6-2: Performance Indicators for Magnetic Components

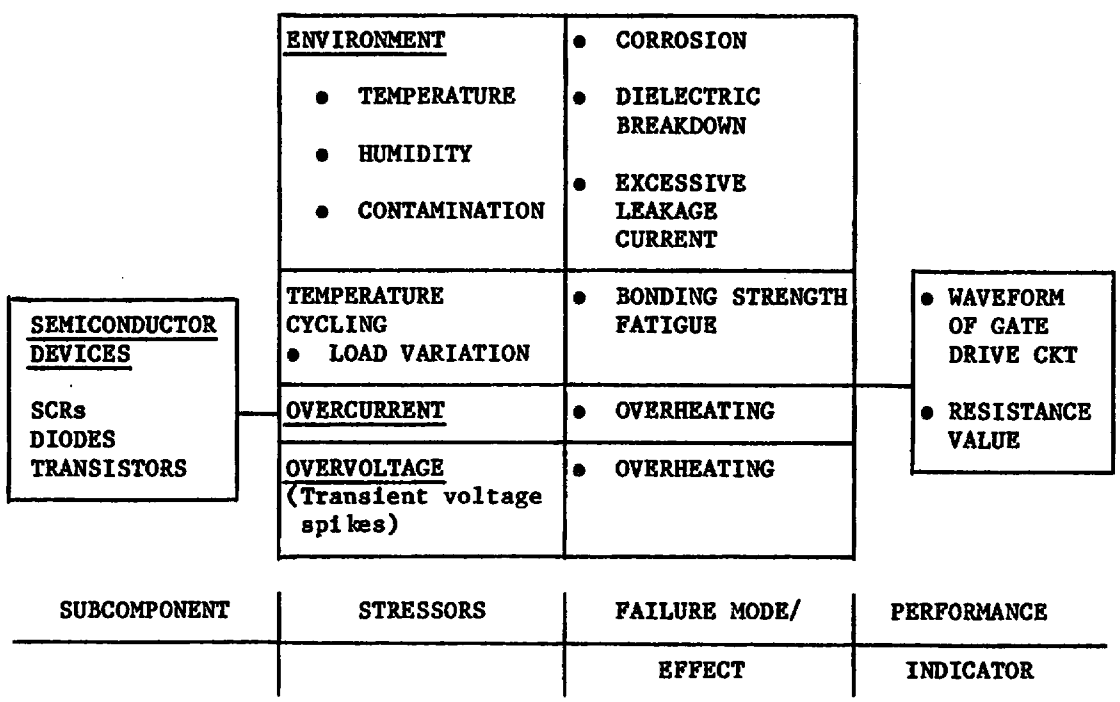


Figure 6-3: Performance Indicators for Semiconductor Devices

Other interim recommendations which will be pursued in Phase II include the following:

- Because of the obvious detrimental impact of high ambient and internal temperatures, forced air cooling of certain sized units may be warranted. Convection cooling is typically used in units up to 50 KVA.

- Additional attention to inverters and battery chargers is required during the final plant construction phase and initial plant operation to minimize stresses on the equipment that could accelerate aging and cause premature failures. This includes frequent inspection for cleanliness during construction and additional protection for the equipment (i.e., surge suppression) during startup testing.

- Each plant is unique in its bus configuration and load distribution. Despite redundancies of supply, however, inverter and charger failures can result in extensive plant interactions. Procedures should be in place at each plant to respond to charger and inverter failures as far as total plant response is concerned. Alerting operators to safety system operational changes or instrument indication unreliability is an important feature of the procedures.

- The operation of fast acting fuses typically used in battery chargers and inverters has resulted in a large number of inverter and battery charger failures. While designed to protect sensitive subcomponents from damage due to electrical transients which frequently occur in a power plant environment, indication of fuse failures due to thermal fatigue makes it necessary to pursue this failure mechanism in a future study. Because of the extensive application of fuses throughout the power plant, fuse failures due to aging could have a dramatic impact on plant safety system operations.

- For components such as capacitors and transformers, actual operating data support equipment qualification recommendations obtained through artificial aging techniques or analyses as specified in IEEE 650-1979. Adherence to the manufacturer's equipment qualification recommendations should be enforced in these cases, even though the equipment is located in a mild environment (10CFR50.49 currently excludes equipment located in mild environments).

- Periodic capacity testing of chargers and inverters should be conducted to ensure the capability of this equipment to supply required loads for the required times. In conjunction with the above testing, this work should be performed to verify the failure mechanisms that would permit equipment operation under normal conditions, but would cause equipment failure when maximum rated conditions were applied.

6.3 Future Work

To determine the effectiveness of the recommendations presented, future work will be conducted consisting of a combination of testing and analyses. The testing area will include work with naturally aged battery chargers and inverters obtained from the Shippingport facility and will consist of monitoring the equipment under various conditions, including the application of seismic forces.

To achieve the goal of developing a cost effective preventive maintenance program, additional efforts will be focused on a cost/benefit evaluation for various inspection, surveillance, and monitoring techniques that are employed or that are developed through continued study. In addition to preventive maintenance recommendations, information on standards and regulation will be put into final form and technically justified.

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16. ABSTRACT (200 words or less)

This report provides an assessment of the aging of battery chargers and inverters which are vital components of the nuclear power plant electrical safety system, and was conducted under the auspices of the NRC Nuclear Aging Research (NPAR) Program.

Battery charger and inverter design and materials of construction are reviewed to identify age-sensitive components. Operational and accidental stressors are determined, and their effect on promoting aging degradation are assessed. Variations in plant electrical designs, and system and plant level impacts have been studied. Failure modes, mechanisms, and causes have been reviewed from operating experiences and existing data banks. The study has also considered the seismic correlation of age-degraded components within battery chargers and inverters.

The performance indicators that can be monitored to assess component deterioration due to aging or other accidental stressors are identified. Conforming with the NPAR strategy as outlined in the program plan, the study also includes a review of current standards and guides, maintenance programs, and research activities pertaining to nuclear power plant safety-related battery chargers and inverters.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Inverter
UPS
Aging
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Service Wear

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