EPRI

UPS Maintenance and Application Guide

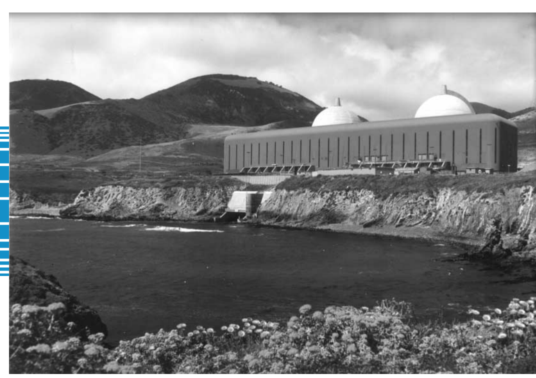
Revision of TR-100491

Technical Report

Plant Maintenance Support

Reduced Cost

Equipment Reliability



NMAC

UPS Maintenance and Application Guide

Revision of TR-100491

1003466

Final Report, December 2002

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REPORT SUMMARY

This guide provides maintenance recommendations to plant personnel involved in the reliable operation of uninterruptible power supply (UPS) systems. It identifies potential failure modes, basic troubleshooting techniques, and preventive measures, as well as a basic background description of UPS systems.

Background
Maintenance practices for UPS systems in nuclear power plants vary from nominal maintenance to involved preventive maintenance programs that replace primary components based on industry life estimations. Therefore, a need exists for a uniform set of preventive maintenance and condition monitoring practices to limit the potential for common cause failures of UPS systems in power plants.

Objectives
- To review current industry practices and procedures related to the application and maintenance of UPS systems
- To improve inspection, test guidance, and programmatic recommendations for improved UPS maintenance and performance

Approach
A project team reviewed current types and specific applications of UPS systems in power generating stations. Data were gathered from industry databases, power generating stations, and manufacturers to provide a basis for recommended practices. The team also consulted vendors and equipment users to ensure that needs in the areas of applications, maintenance, and testing practices for UPS systems and battery chargers were well understood.

Results
This guide familiarizes readers with the key components and subassemblies used in UPS systems and battery chargers. It also reviews fundamental operating principles. The guide discusses UPS design and construction features, the various types that have been used in power plants, and some design and application concepts.

The guide presents UPS and battery charger degradation, reliability, and failure information so as to establish a baseline from which recommended maintenance practices can be linked to a degradation mechanism or failure mode. Also provided is an overview of recommended maintenance practices related to mechanical inspection, electrical tests, and calibrations.

This guide discusses approaches to ensure continued performance of UPS systems and battery chargers through evaluating condition monitoring, periodic component replacement, and

surveillance testing. Recommended inspections and tests are provided in a format that facilitates implementation into existing plant maintenance and testing programs.

EPRI Perspective

The maintenance practices provided in this guide relate mainly to static UPS systems and battery chargers. However, general recommendations for control and auxiliary equipment are applicable to similar components in any UPS system.

UPS systems have experienced a decrease in primary failures over the last few years. This decrease can be attributed to improved manufacturing and better maintenance programs. Although this is the case in the industry as a whole, there are still aging and performance issues that will become apparent only with time. Nuclear plants are encouraged to review the performance of their UPS systems, evaluate the inspection and test intervals, and make adjustments when appropriate.

In order to optimize maintenance, recommendations must provide a balance between reliability and expenditures. Related EPRI research includes:

Maintenance and Application Guide for Control Relays and Timers, TR-102067

Protective Relay Maintenance and Application Guide, NP-7216

Stationary Battery Guide: Design, Application, and Maintenance, 1006757

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ABSTRACT

Industry experience to date points to a need for a uniform set of preventive maintenance and condition monitoring practices to eliminate the potential for common cause failures from aging degradation and to extend the service life of uninterruptible power supply (UPS) systems. The Nuclear Maintenance Applications Center (NMAC) of EPRI sponsored RP2814-77 to respond to this need by developing a guide that provides information for establishing an effective maintenance program and promotes uniformity of maintenance and testing practices for UPS systems. The guidelines and recommended maintenance practices presented in this guide apply to UPS systems that include the inverter, rectifier/battery charger, and static transfer switch.

The recommended practices in this maintenance guide have been developed from a perspective of ensuring reliability of UPS systems through a better understanding of the mechanisms that cause them to age and ultimately fail. By understanding the fundamentals of UPS system design, application, aging processes, and failure modes, maintenance staff can develop and implement a successful maintenance program and thus ensure a high degree of confidence that the systems can fulfill their intended design functions. Application and specification aspects are discussed in this guide only if they relate to maintenance.

Recommended periodic inspections and tests are described in detail. Further, a basis for each recommended test, inspection, or maintenance is provided so the user can understand why it is important. Inspections and tests are presented in a format that facilitates a comparison with existing plant maintenance and testing procedures.

The maintenance practices recommended in this guide were developed through a review of current nuclear industry practices and procedures, industry standards, regulatory research publications, manufacturers' recommendations, and technical papers. Experts and users were consulted throughout the project to ensure that the bases for the recommended practices were thoroughly understood. The collective information from this review was used to develop programmatic recommendations, and detailed inspection and test guidance.

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INTRODUCTION

In a nuclear plant, uninterruptible power supply (UPS) systems are used to provide an uninterruptible source of power to the control, protection, and safety systems. Depending upon the system design configuration, it consists of some or all of the following subsystems/components:

1. Inverters
2. Battery charger
3. Rectifier
4. Static transfer switch
5. Maintenance bypass switch
6. Battery power source
7. Line regulating transformer

The scope of this guide includes items one to four above. Proper maintenance of these components is essential to the reliable and successful operation of all safety and control systems. By understanding the fundamentals of UPS system design, component selection, application considerations, aging process, failure modes, and degradation mechanisms, maintenance staff can develop and implement an effective maintenance program.

1.1 Purpose

The purpose of this guide is to provide recommendations on surveillance, inspection, test, maintenance, condition monitoring, and trending practices. Maintenance tasks are approached from a reliability standpoint through an understanding of the mechanisms that can affect UPS system performance.

1.2 Organization

This guide is divided into seven sections and several appendices:

- Section 2 provides a general description of UPS systems and an explanation of the types of inverters and chargers used in the industry and covered in this guide.

- Section 3 presents the UPS application considerations.
- Section 4 discusses the degradation mechanisms and failure modes associated with the components of the UPS systems.
- Section 5 highlights the operating experience, including a discussion of the industry experience on UPS systems and component level failures.
- Section 6 covers the overall maintenance programmatic recommendations.
- Section 7 discusses the personnel and equipment safety precautions and training needs for personnel performing UPS system maintenance.
- Section 8 covers the recommended surveillance, inspection, maintenance, condition monitoring, and trending activities, including the frequencies for such activities.

The appendices include a listing of pertinent references, a glossary of UPS terms, background information, a detailed discussion of some of the UPS system failure experience, and a list of acronyms used.

1.3 Pop Outs

Throughout this guide, key information is summarized in *Pop Outs*. Pop outs are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the key points easier to locate.

The primary intent of a pop out is to emphasize information that will allow individuals to take action for the benefit of their plant.

The pop outs are organized according to three categories: O&M Cost, Technical, and Human Performance. Each category has an identifying icon as shown below to draw attention to it when quickly reviewing the guide.

Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Key Technical Point

Targets information that will lead to improved equipment reliability.

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Appendix E contains a listing of all the key points in each category. The listing restates each key point and provides a reference to its location in the body of the report. By reviewing this listing, users of this guide can determine if they have taken advantage of key information that the authors believe would benefit their plants.

2
UPS TECHNICAL DESCRIPTION AND USE

Systems that supply power to the instrumentation and control system and to other vital loads in a power plant are designed to be as reliable and disturbance free as possible. Even in the most well-designed system, there will be times when an interruption or disturbance to the power system cannot be avoided. While total system outage is less likely, power system transients are bound to occur with some frequency. Transients introduced onto the power supply system by some loads can have an adverse effect on other loads connected to the system. Disturbances can originate from within the system (that is, during load switching) or from an external source such as lightning and thunderstorms. Electronic devices can add contamination to an electric system in the course of their normal operation.

Many critical applications, particularly digital instrumentation and microprocessor-based systems, cannot tolerate unanticipated power system disturbances. Without pure, clean power, data and control signals could be corrupted, resulting in unreliable signals, equipment malfunctions, and possible loss of vital data. The protection and control systems at nuclear power plants require a clean, uninterruptible source of power to perform vital plant functions. When there is a loss of normal power for whatever reason, there are systems and parameters that must be monitored and controlled to bring the plant to an orderly shutdown. Even after a shutdown has been achieved, the systems must be monitored and controlled to maintain the plant in a stable condition. These instruments and other vital equipment are normally fed from one or more UPS systems that ensure a reliable source of clean power.

2.1 UPS Building Blocks

A UPS system consists of the following major components:

- Battery charger
- Inverter
- Battery
- Static transfer switch
- Manual bypass switch
- Regulating transformer

Figure 2-1 shows a typical UPS system configuration used in a nuclear power plant. It shows a double conversion system. In a double conversion system, the ac from the utility system is first converted to dc using a battery charger and then converted back to ac using an inverter. The charger supplies dc power to the batteries and the inverter. The ac output from the inverter is fed to the load through a static transfer switch and a manual bypass switch. Under normal conditions, power from the inverter feeds the load. If the output from the inverter is lost or degraded, the static transfer switch transfers the load to the alternate source. The manual bypass switch, which is a mechanical make-before-break switch, is provided to facilitate UPS system maintenance. When ac power to the battery charger is lost, the batteries supply the load through the inverter. The configuration shown in Figure 2-1 is called a *float configuration;* that is, the battery floats on the dc bus.

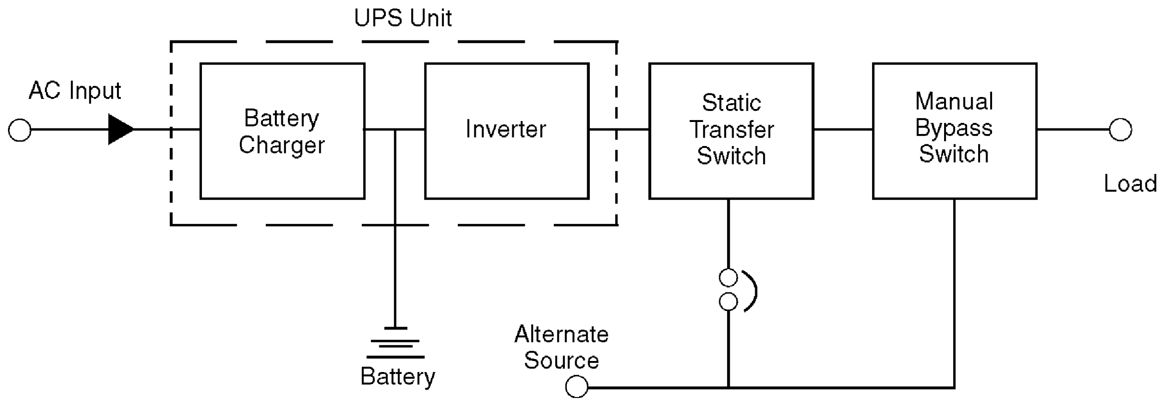


Figure 2-1
Single Unit Float Configuration UPS System

Since the battery is floating, there is no switching involved. A regulating transformer may be used in the feed from the alternate source to provide some voltage regulation.

Depending upon the specific application for which it is used, some UPS systems may not have one or more of the above components. For example, some systems may not have a manual bypass switch and/or a static transfer switch. In cases where only clean power is needed, a dedicated battery backup, as shown in Figure 2-1, may be substituted with a tie to the station battery bus. The system configurations used in nuclear power plants, and their advantages and limitations if any, are discussed in Section 2.2.

Figure 2-2 shows a second type of UPS system configuration used in nuclear power plants. This configuration is called the *Rectifier Configuration*. It is also a double conversion system, but instead of the battery charger, a rectifier feeds the inverter. The battery charger serves only to charge the battery. The rectifier functions much like a battery charger except that some rectifiers do not have current limiting capabilities or selectable output voltage. A blocking diode prevents the rectifier from charging the battery. Its output is regulated internally; once set, it should not vary. A rectifier configuration is generally used in UPS systems supplied from the main station battery. If a UPS system is provided with a dedicated battery, a battery charger is also required.

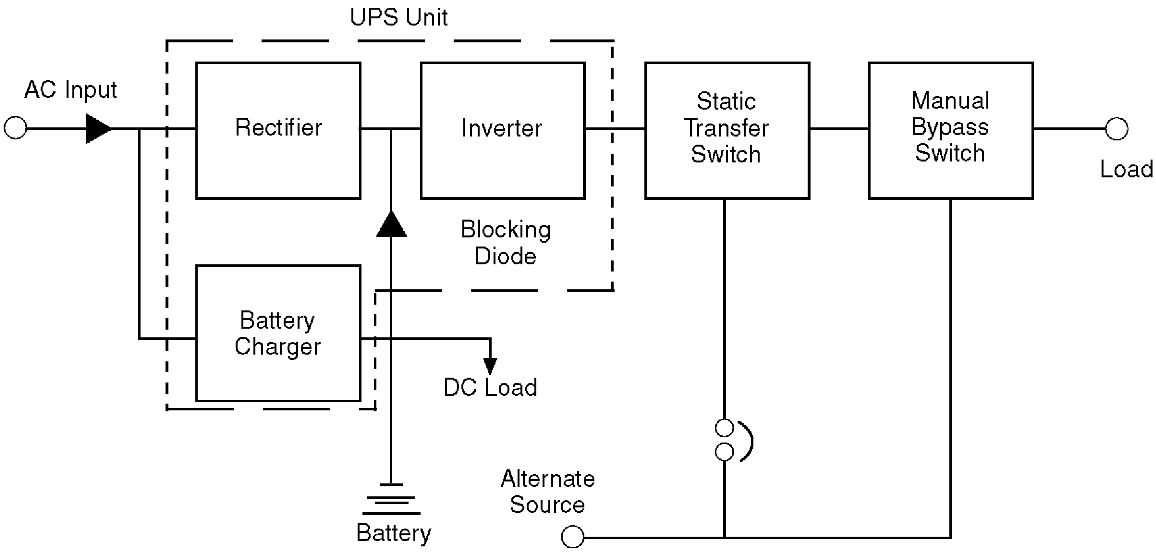


Figure 2-2
Single Unit Rectifier Configuration UPS System

This guide treats a UPS system as an assembly of the whole complement of components as shown in Figures 2-1 and 2-2, and discusses the application and maintenance aspects of the three major components (that is the charger/rectifier, inverter, and static transfer switch) so that the users may choose the portions that apply to their plant-specific configuration. For ease of reference, throughout this guide the following conventions are used:

- The term *UPS system* is used when the topic of discussion applies to the whole system.
- The term *inverter* is used to include the inverter and the static transfer switch.
- The term *charger* is used to include the charger and/or the rectifier.

The configurations discussed thus far employ batteries, chargers, and inverters. UPS systems that operate on the principle of using stored mechanical energy are beyond the scope of this guide.

2.1.1 Battery Charger/Rectifier

The heart of a battery charger or rectifier is a semiconductor bridge whose function is to rectify, that is, convert the ac to dc. The semiconductor may be a diode or a thyristor, also known as a *silicon-controlled rectifier* (SCR). The charger circuit consists of an input circuit breaker, an input transformer, fuses, control circuits, and a filter network. The circuit breaker is typically a molded-case breaker. This breaker provides some over-current protection to the overall unit, but its primary function is providing a means to isolate the unit from the ac source. An isolation transformer provided at the input side limits the effect of system noise and provides limited input voltage control to the rectifier. These transformers are built with special shielding between the primary and secondary windings. The function of the shield is to reduce the amplitude of the line noise and to retard the passage of noise through the transformer. The filter section will be some sort of inductor and capacitor (IC) combination that will smooth the output ripples and the output waveform. This is a generic description of a charger/ rectifier circuit. The specific manufacturer's instruction manual should be consulted for specifics.

Chargers used in utility UPS systems may be divided into the following three types:

- Ferroresonant transformer controlled type
- Magnetic-amplifier type
- SCR bridge type

2.1.1.1 Ferroresonant Transformer ControlledType

This type of charger uses a ferroresonant transformer to provide a constant voltage level to the input of the rectifier circuit, as shown in Figure 2-3. The transformer has two secondary windings and a tuned circuit made up of discrete elements (inductors and capacitors) configured to provide feedback to the transformer secondary. This type of charger uses a simple output filter to limit voltage and current ripples. The transformer provides current limiting capability on the input side and maintains the input voltage to the charger bridge constant within its design limits. Once the limits are reached, the transformer will not supply any more output current, and the output voltage will drop dramatically.

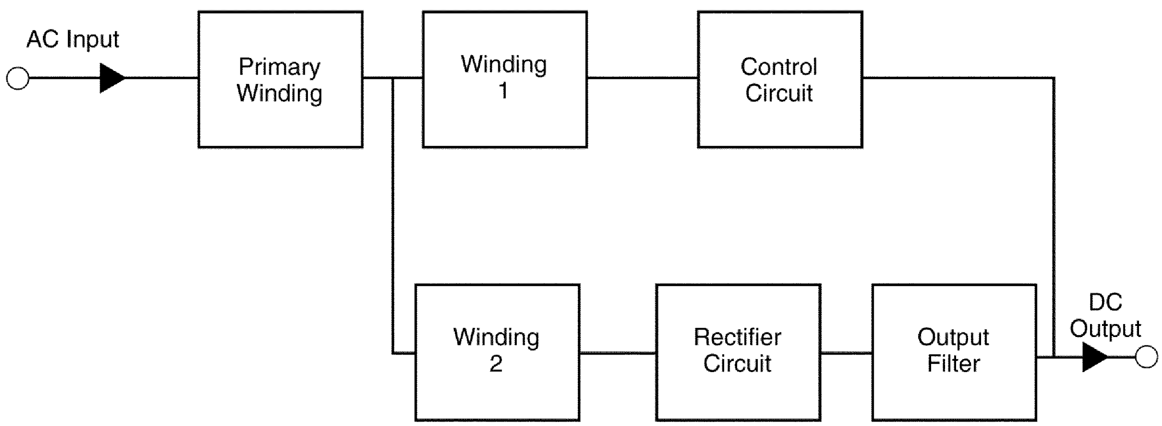


Figure 2-3
Ferroresonant Charger/Rectifier

2.1.1.2 Magnetic-Amplifier Type

The magnetic-amplifier (mag-amp) type charger, shown in Figure 2-4, consists of a rectifier type ac to dc converter with a mag-amp in the feedback loop providing the output regulation.

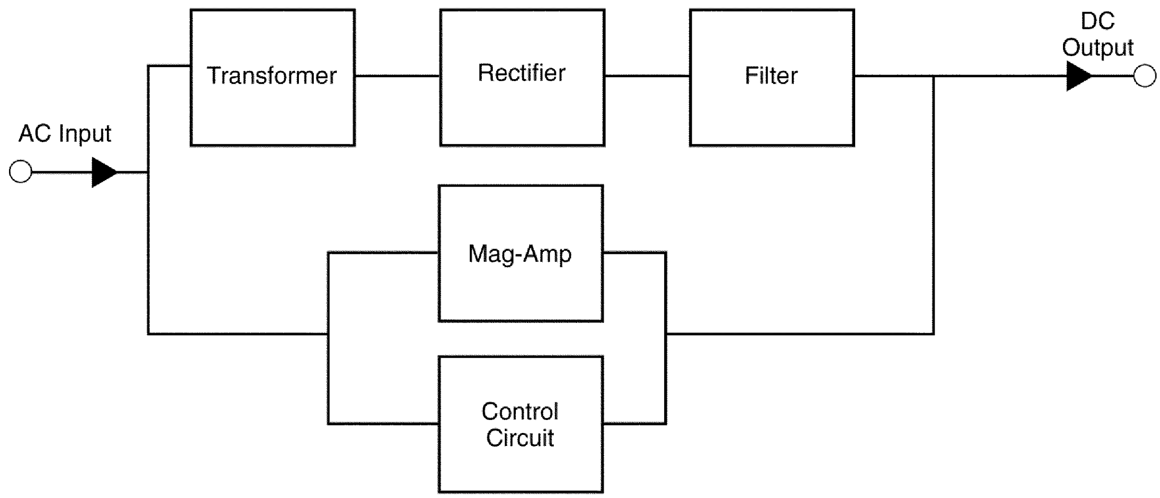


Figure 2-4
Magnetic-Amplifier Type Charger/Rectifier

The mag-amp is an adjustable inductor that causes the output voltage and current of the transformer to change by varying the magnetic circuit impedance. This provides ac input to the rectifier by moving the reactors in and out of saturation using a dc voltage feedback from the rectifier output.

2.1.1.3 SCR Bridge Type

In an SCR bridge type charger, rectification is performed using an SCR bridge in lieu of diodes. The firing order and sequence is controlled using an oscillator circuit. The dc output fed back to the control circuit through the oscillator circuit, as shown in Figure 2-5, enables full control of the voltage and current. The output filters serve to eliminate harmonic and ripple voltages.

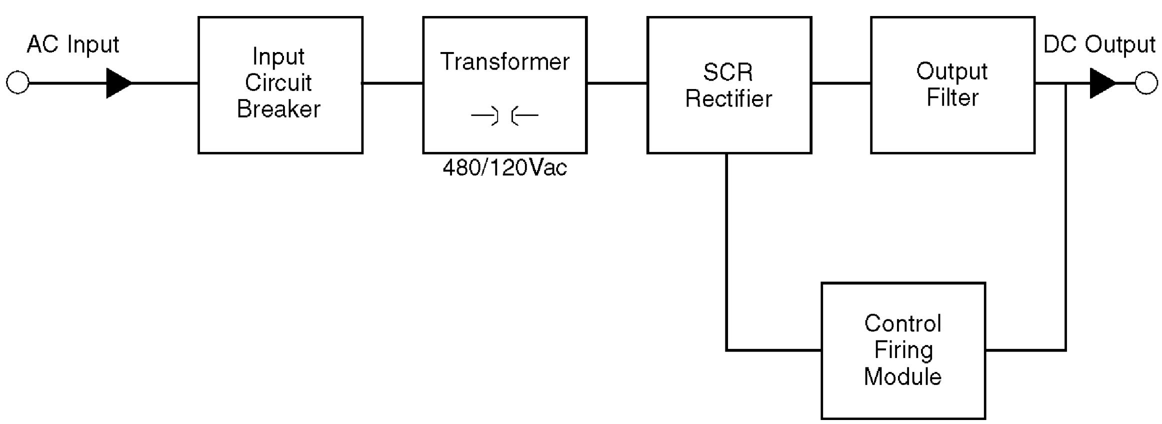


Figure 2-5
SCR Bridge Type Charger/Rectifier

2.1.2 Inverter

The heart of an inverter is also a semiconductor bridge whose function is to invert, that is, to convert the dc to ac. The semiconductor is usually a SCR because of the ability to control their firing order and duration. Unlike the rectifier, which has only to switch from one device to another when the voltage changes direction, the inverter must force the associated semiconductors to turn on and off in the correct order, at the correct time interval, and for the correct duration to produce a sinusoidal ac output waveform and carry the current continuously. This means that the currents must be commutated reliably from one device to another. In addition, the inverter must provide output voltage regulation. The four types of inverters used nuclear plant UPS systems are:

- Quasi-square wave
- Step wave
- Ferroresonant
- Pulse-width modulation (PWM) or control

The last two are the most popular types in UPS systems installed after the 1970s. Regardless of the type, an inverter consists of an input circuit breaker, a semiconductor bridge, a set of fuses, control circuits, and input and output filters to limit the ripples.

2.1.2.1 Quasi-Square Wave Type

The quasi-square wave type inverter uses a thyristor bridge and regulates the output voltage and current through a feedback control circuit that controls the firing time (Figure 2-6). The two offset square wave output from the bridge is transformed to the desired voltage level and then added in series to produce a quasi-square wave. The output filter, composed of inductors and capacitors, eliminates/reduces the harmonics. This type of inverter requires a complex filtering network to filter out the low-order harmonics. These do have the advantage of being able to handle short-term overload (that is, the inrush from motor start) without going into current limit mode.

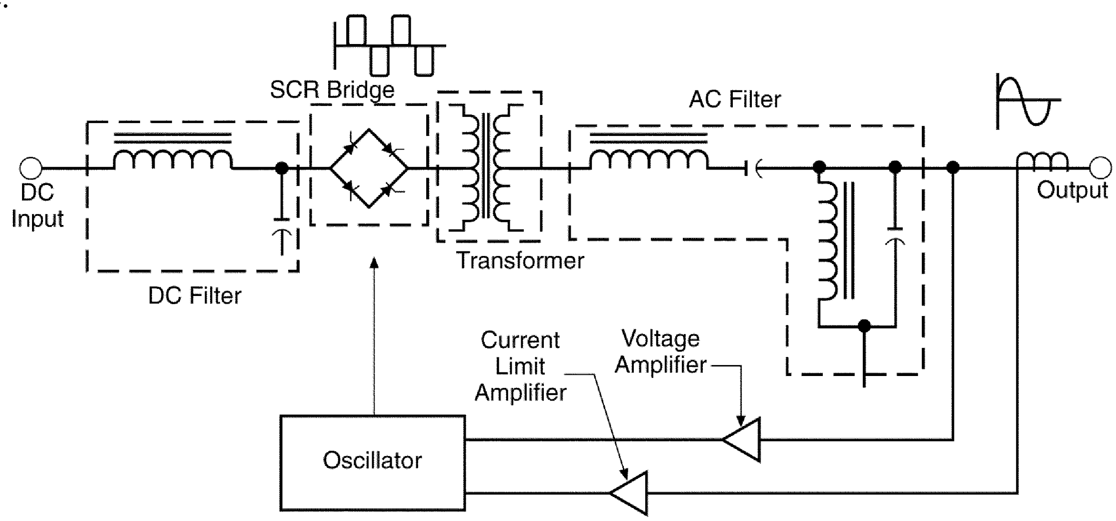


Figure 2-6
Quasi-Square Wave Inverter

2.1.2.2 Step Wave Type

The step wave type inverter is a variation of the quasi-square wave type. It preserves the advantages of the quasi-square wave type while eliminating the need for a complex filtering network. By using a multiple-bridge switching scheme to produce a series of step square waves to approximate the sine wave pattern (Figure 2-7), the need for a large filter network is eliminated. The increased number of bridges used makes this type of inverter better suited for large load applications.

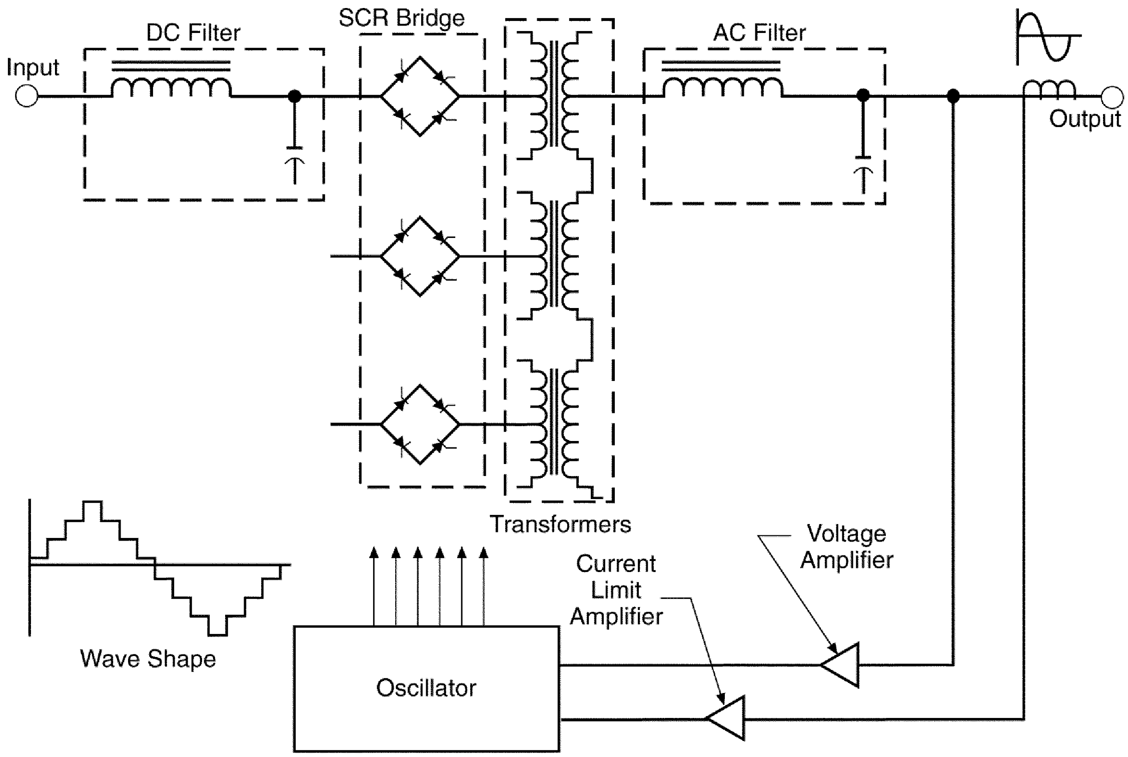


Figure 2-7
Step Wave Inverter

2.1.2.3 Ferroresonant Type

Ferroresonant inverters, shown in Figure 2-8, use a bridge and oscillator setup similar to that in the quasi-square wave inverter.

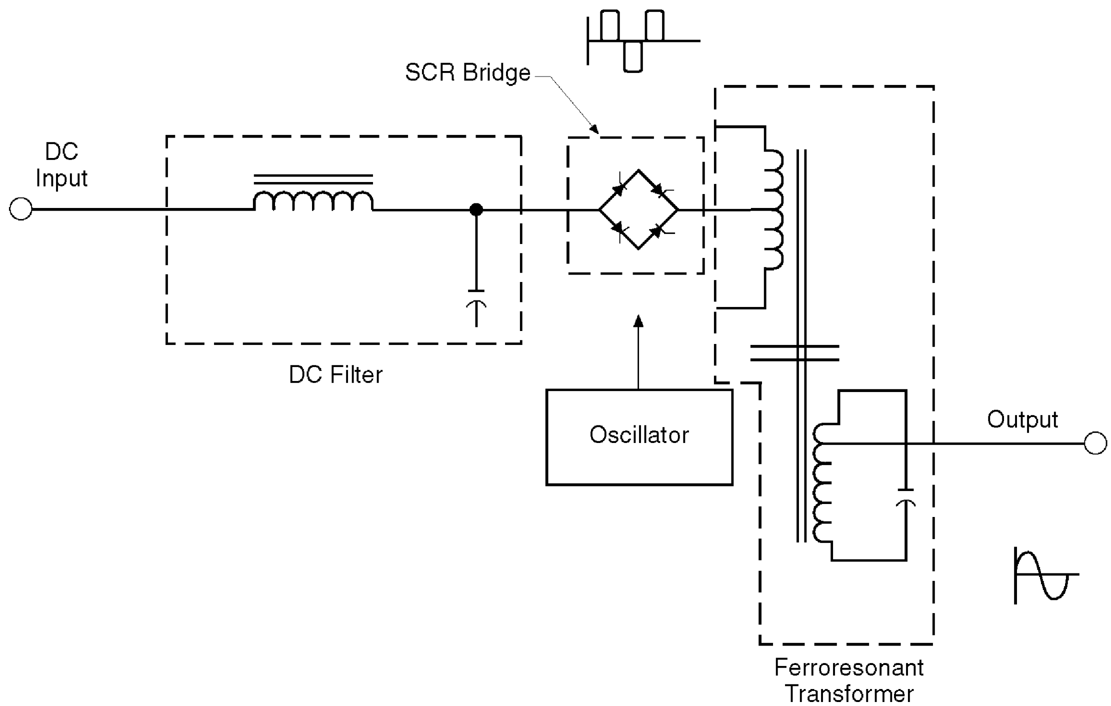


Figure 2-8
Ferroresonant Type Inverter

The primary difference is in the output filter that is a ferroresonant transformer, also known as a *constant voltage transformer* (CVT). The CVT provides harmonic filtering, voltage regulation, and current limiting. The output is controlled without any feedback circuitry to the input bridge. The output voltage and current are regulated within the design limits of the ferroresonant transformer. The size of the output ferroresonant transformer will determine the total space required for the inverter cabinets, for example, the larger the unit's kVA rating, the larger the transformer and thus the cabinet.

The CVT is a current limiting device in that it can provide an output only equal to its design capability. At constant frequency, it is also a voltage regulating circuit. Therefore, regulation is totally magnetic, requiring no electronics. Hence, this type of inverter contains less complex electronic control circuits and circuit boards. Two main limitations of this type of inverter are that at sizes greater than 50 kVA, their initial cost becomes high and they are slow to respond to transients. Other limitations are:

- Inability to adjust the output voltage in the field.
- Higher total harmonic output waveform distortion (> 5%).

- Efficiency decreases as load decreases.
- Sometimes, the footprint may be larger than those of comparably rated units of other types.

Approximately 50% of all inverters used in safety-related applications in the nuclear industry are of the ferroresonant type.

2.1.2.4 PWM Type

PWM inverters use multiple rectifier bridges to produce a series of square wave pulses of varying widths, but the same height. The square wave frequency is either 600 or 1200 Hz. A complex feedback circuit controls the output, which is a series of square waves of varying pulse width approximating a sine wave (Figure 2-9). An oscillator controls the inverter frequency. The oscillator controls the timing and duration of the thyristor's conduction. The bridges are turned on and off many times in each half-cycle.

By controlling the pulse repetition rate, it is possible to limit the harmonics produced to high orders only, that is the 20th harmonic and above for a repetition rate of 10 times per half-cycle. Therefore, this type of inverter requires a smaller filter than other types. The optimal design represents a trade-off between several factors such as filter size, efficiency that is a function of the commutation rate, and the SCR operating parameters (that is, the turn-on and turn-off times). An important characteristic of power electronics switching devices is that they have a limited over-current capability. Therefore, the feedback control system automatically limits the inverter output current to a safe value, under overload or faulted condition, by reducing the inverter output voltage.

With many bridges, this type of inverter can be designed for very high-rated power capacities. Another advantage is its fast transient response. The main limitation is that it is very complex in design and has many electronic control circuits and cards; thus, there are many components to maintain.

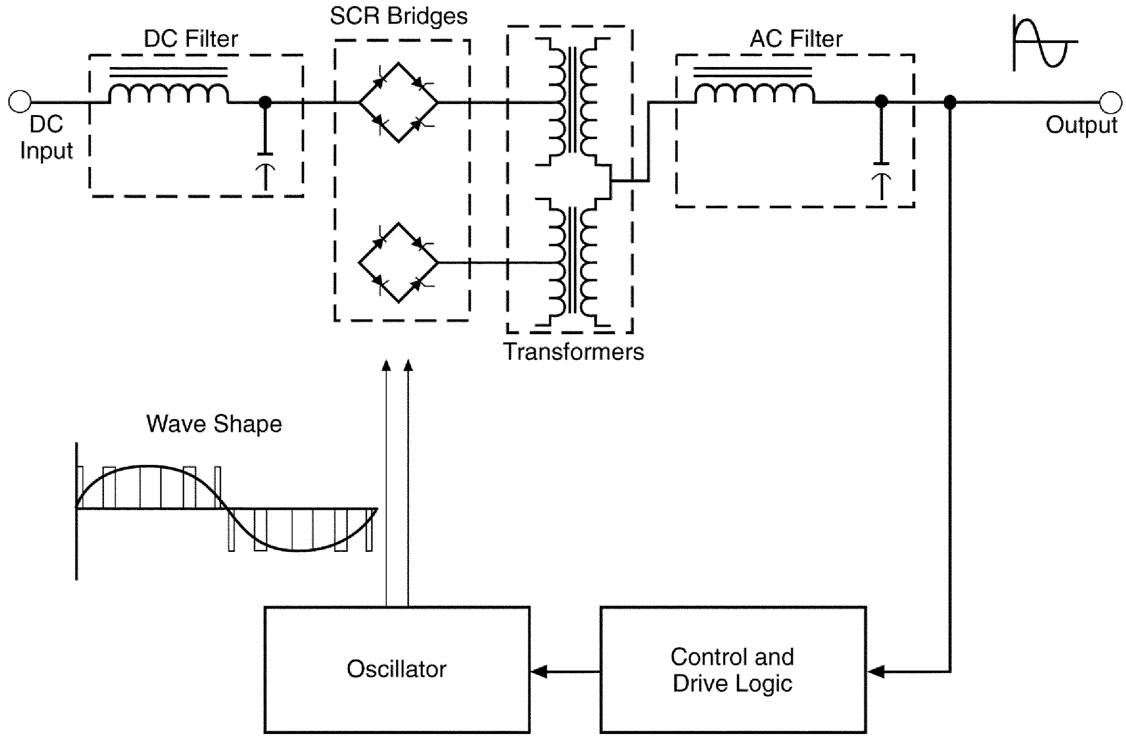


Figure 2-9
PWM Type Inverter

2.1.3 Transfer Switch

Modern UPS systems include a static type bypass switch. Its purpose is to provide an uninterrupted power source to the loads by transferring the loads seamlessly from one source to another. Load transfer may be required due to inverter or rectifier failure or for system maintenance. In situations where a large amount of current may be required, for example, during motor starting or a load fault, the transfer switch can momentarily connect to the alternate source to prevent the inverter from going into current limit mode.

As shown in Figure 2-10, a typical static transfer switch is an electronic version of a make-before-break switch, and is made up of two thyristors in parallel. The firing of the thyristors is controlled to ensure that current from the alternate source is supplied to the load before the inverter output is lost. The static switch contains circuitry that monitors the load current, voltage, and bridge output waveform, usually at the bridge output. If the load current becomes excessive (instantaneously or continuously), if the load voltage is too high or too low, or if the bridge output square wave deteriorates, then the static switch transfers the load from the preferred source to the alternate source (reverse transfer). The speed of such transfer is of the order of 4 ms (~ ¼ quarter of a cycle). To avoid phase rotation problems at the load side, these switches are designed to ensure that the transfer to and from the alternate source takes place only if the two sources are displaced less than 5 degrees. When the output conditions of the inverter returns to acceptable values, the loads are again transferred back to the inverter (forward transfer) seamlessly.

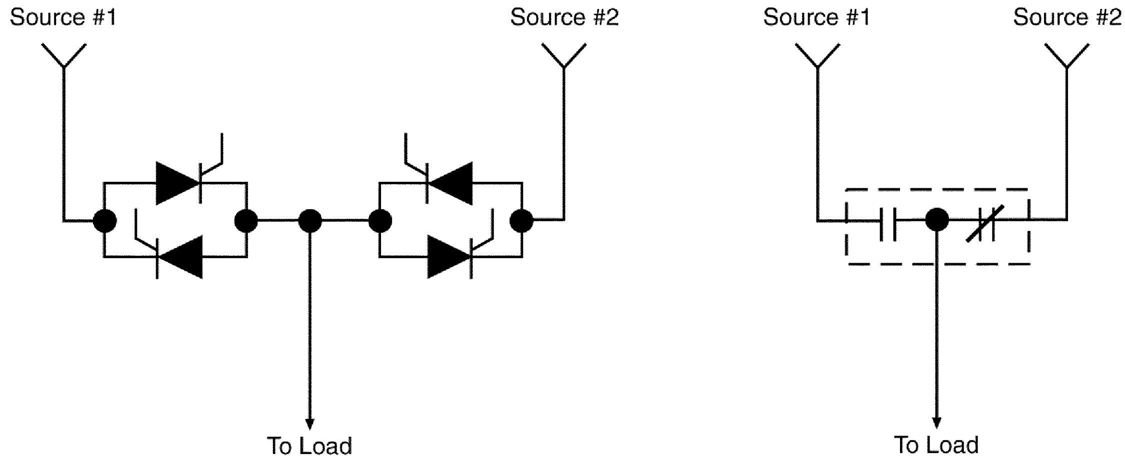


Figure 2-10
Thyristor Arrangement in a Static Transfer Switch

Besides the improvements in overall system reliability, another important benefit of using a static transfer switch is that the alternate source can be used as a storage tank to feed momentary high-current demands. This feature allows the inverter and the charger/rectifier to be sized without excessive safety factors and permits UPS system operation at better efficiencies.

2.1.4 Regulating Transformer

A regulating transformer is normally used with the alternate source to provide voltage regulation. It is a specially designed transformer with two compensating windings. One compensating winding aids the input voltage while the other opposes it. Similar to the ferroresonant transformer, the regulating transformer has a specially constructed iron core. The core saturation level can be controlled through an electronic feedback control circuit. By controlling the core saturation level and with the aid of the compensating windings, the regulating transformer compensates for input voltage variations and produces a near constant output voltage. However, the regulating transformer cannot control the supply frequency, and its output is interrupted during input voltage interruptions.

2.2 Comparison of UPS System Configurations

2.2.1 Float Configuration UPS System

This configuration, an inverter connected to a dc bus that is backed up by the station battery or a dedicated battery, represents the simplest UPS system (Figure 2-11). This basic configuration is used in a number of small safety-related and non-safety UPS system applications in nuclear power plants, for example, reactor protection systems (RPS), emergency safety feature actuation systems (ESFAS), and security systems.

The inverter converts the dc power from the battery to ac and supplies regulated voltage and frequency to the loads. The battery charger or eliminator normally supplies the inverter, and the battery floats on the dc bus, always ready to pick up the load when the charger fails. This configuration is called uninterruptible because the dc source (bus) is designed to be available at all times. It has the following limitations:

- An inverter failure results in the loss of ac power supply to the connected loads.
- The inverter limits the total current available to the loads since no alternate source or transfer capability to an alternate source exists.
- Load faults or high motor inrush demands can cause the inverter to go into current limit mode leading to output voltage drop that further aggravates the situation.

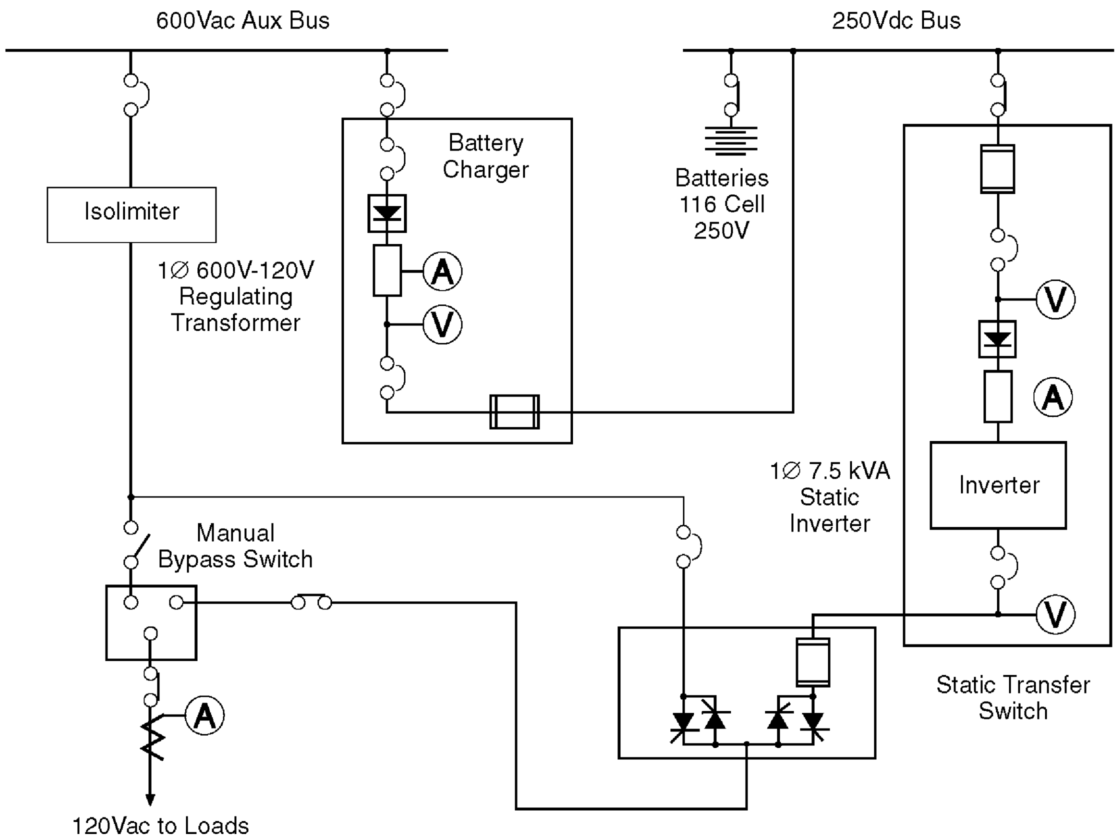


Figure 2-11
One-Line Diagram of a Float Configuration Single Source UPS

2.2.2 Rectifier Configuration

In a rectifier configuration, the battery charger in the float configuration (see Figure 2-12) is split into a charger and a rectifier. The battery charger is sized to handle only the battery charging duty plus any dc loads connected directly to the battery bus. A rectifier, also connected to the plant ac bus, feeds the inverter and the battery (dedicated or station battery) bus serves as a backup dc source. A blocking diode between the rectifier output and the battery bus prevents the power flow from the rectifier to the battery bus. The inverter supplies regulated ac power to the loads. Upon loss of the rectifier output due to ac input power interruption or a rectifier failure, the battery supplies dc power to the inverter without the need for any switching.

This configuration has the same limitations as the float configuration UPS system. In addition, this configuration also demands an improved input filter because the tank capacity from the battery to smooth out ripples is lost. Two main advantages of this configuration are:

- The battery charger size is significantly reduced.
- It has better capability to isolate the charger or the rectifier for maintenance without affecting the loads.

This system is commonly used in plants designed with common station batteries feeding dc buses. From an overall UPS system reliability view point, equally convincing arguments can be made for and against either of the two (that is float or rectifier) configurations. Available data on system failures do not permit a meaningful evaluation of the reliability of these systems.

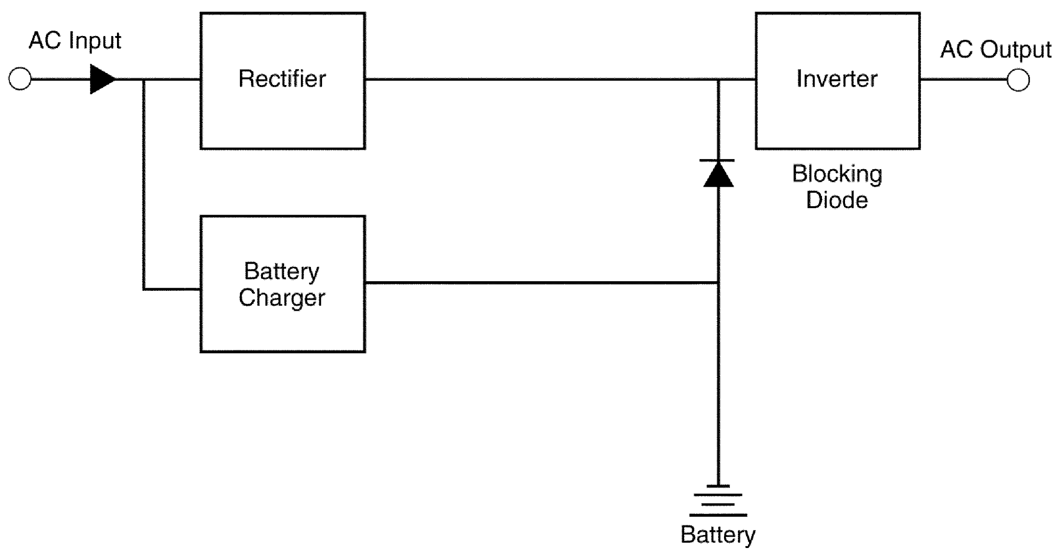


Figure 2-12
Block Diagram of a Rectifier Configuration UPS

2.2.3 UPS System with a Bypass

A static transfer switch and a tie to an alternate source (Figure 2-13) can be used to improve the overall reliability of a UPS system. In this configuration, the load is normally connected through the static transfer switch to the inverter.

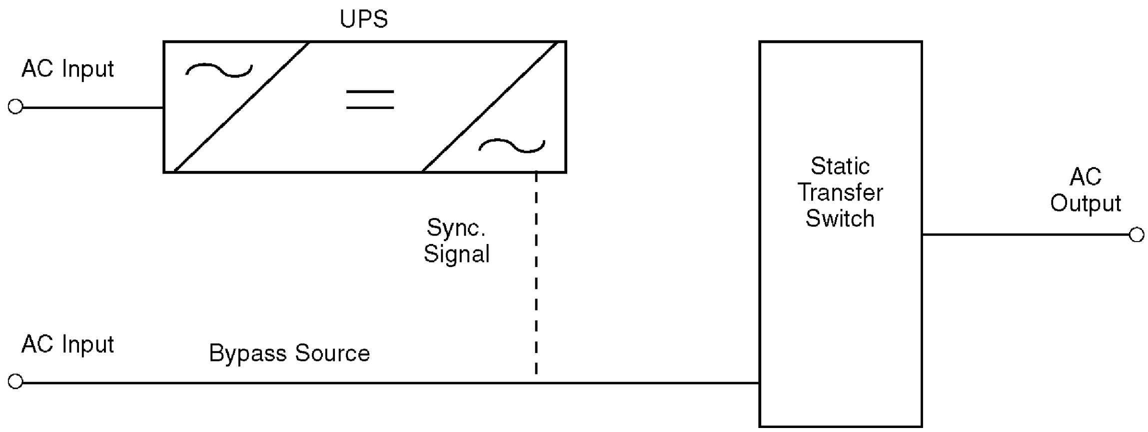


Figure 2-13
Block Diagram of a UPS System with Bypass Capability

The static transfer switch automatically transfers the load to the alternate source during the following events:

- Loss of inverter output
- Deviation of the inverter output voltage beyond preset limits due to inverter malfunctions
- Deviation of the inverter output parameters (that is voltage and current) beyond preset limits during switching of loads with high inrush currents or due to a fault at any of the connected loads

Including a manually operated bypass switch in this scheme will have the added benefit of isolation of the preferred source components for maintenance purposes. The static transfer switch control logic is normally programmed to automatically retransfer the load back to the inverter output following a transfer caused by high load inrush current. Retransfers following other events can be programmed to take place either automatically or manually.

A regulating transformer is usually included with the alternate source to regulate the voltage within an acceptable tolerance band. However, the power supply through the regulating transformer is subject to interruptions, and its voltage will fluctuate during *wide swings* in the input voltage. Therefore, the load should be supplied from the alternate source only when necessary. Also, transfer to the alternate source should be permitted only when the alternate source is available.

To minimize voltage disturbances during transfers, the inverter is synchronized to the alternate source such that its output voltage is in phase with, and has the same frequency as, the alternate source voltage. However, when the alternate source frequency deviates beyond a preset tolerance, the synchronizing circuit is automatically disabled, and the inverter reverts to its own regulated frequency.

2.3 UPS System/Component Population

Table 2-1 lists the manufacturer and typical rating ranges of the inverters and chargers used in nuclear plants. This list was compiled using information collected from a survey of utilities conducted during this project, from the Nuclear Power Reliability Data System (NPRDS), and by plant visits or telephone conversations with utilities and manufacturers. It is emphasized that the list contains only those manufacturers and products that are widely used; it is not intended to be a complete listing of all inverters and chargers used in the industry.

Table 2-1
Manufacturer and Rating for Commonly Used UPS and Chargers

Manufacturer	Equipment Type and Commonly Used Rating
C&D	Battery Chargers - 25 to 300 kVA
Cyberex	UPS Inverters - 5 to 50 kVA
Elgar	UPS Inverters - 5 to 50 kVA
Exide	Battery Chargers - 25 to 300 kVA
Exide	UPS Inverters - 5 to 150 kVA
Power Conversion	Battery Chargers - 25 to 300 kVA
Solid State Controls	UPS Inverters - 5 to 50 kVA
Westinghouse	UPS Inverters - 5 to 15 kVA

A survey was performed during the development of this guide. Thirty-seven plants representing a total of 124 UPS systems responded. The survey shows that:

- Inverter and charger/rectifier systems used in the currently operating U.S. nuclear plants fall into the following types, listed in decreasing order of the respective population:
  - Inverter

    -Ferroresonant transformer inverter

    -PWM inverter

    -Quasi-square wave inverter

    -Step wave inverter

– Charger/Rectifier

-SCR solid-state type

-Controlled ferroresonant type

-Magnetic amplifier type

- Generally, single-phase systems are used for the small sizes (< 50 kVA) in many of the safety-related applications in nuclear power plants. Three-phase systems are used in larger UPS systems (about 50 kVA and larger), such as those used to supply non-safety loads. Single-phase systems accounted for more than 75% of the population and so did systems rated 25 kVA or less.
- Safety-related and non-safety-related applications usually share a common station battery with its own charger. Some UPS systems for safety-related applications are provided with a dedicated battery and associated battery charger.
- The majority (> 70%) of the UPS systems in the U.S. nuclear industry are configured in the rectifier configuration, and others have the float configuration. One Canadian plant reported using a redundant inverter configuration, where two equal-sized inverters are connected in parallel.

Approximately 80% of the systems have a static transfer switch. Systems installed after the late 1970s generally have a static transfer switch. For systems installed before then, it was not common practice to install a static transfer switch or a maintenance bypass switch, but many inverters have since been retrofitted with these switches.

3
APPLICATION CONSIDERATIONS

The performance and life of a piece of equipment or system relies on its intended function and application. The requirements spelled out in the designer's equipment specification govern the intended function(s) and application-specific considerations. The following discussion highlights the salient application and specification considerations that relate to the maintenance of UPS system components. It is intended to assist the user of this guide in gaining a better insight into the application of the equipment so that an effective maintenance program can be designed.

Note: Throughout this section, typical specification values, where provided, are generic. They are intended to provide a frame of reference for discussion of the associated topic. Users of this guide should consult the plant-specific equipment instruction manual or specification as appropriate for the values pertinent to their equipment.

3.1 Charging Methods

Several charging techniques can be used to charge or recharge a battery. A battery can be charged using a constant current or a constant voltage method.

3.1.1 Constant Current Charging

Constant current charging of a battery requires that a charger provide the same amount of current to a battery at various voltage levels. The amount of the current being provided to the battery is dependent upon the difference between the system voltage and the battery voltage (open circuit). When charging a battery at constant current, the voltage impressed across the battery terminals must increase in order to maintain a constant value of charging current. Although the normal process of constant current charging results in increased voltage, the value of the voltage has to be limited to some upper limit. For example, the charging voltage for lead-acid cells should not exceed 2.5 V per cell.

Constant current charging causes excessive gassing in the cell. It is typically used by manufacturers for initial battery charging. Constant current charging is used to help complete the plate forming process. This method might also be used to bring a battery back from a sulphated condition (an undercharged condition).

3.1.2 Constant Voltage Charging

Chargers used for utility applications are of the constant voltage type. They charge a battery by holding the voltage constant while varying the current from the maximum allowed by the charger to the minimum amount needed to maintain a battery in a fully charged state. During the charging process, the voltage of the battery gradually rises as the current falls. Charging a battery at constant voltage provides a larger amount of current during initial recharge. The current limit setting of the charger may limit the maximum current available. For lead calcium batteries, constant voltage charging systems are typically set at 2.33 V per cell when equalizing and 2.25 V when floating. At these voltage levels, the batteries will charge without experiencing excessive gassing. The voltage settings vary depending upon the battery type. See Appendix A for useful references.

3.2 Design Conditions That Influence Performance in the Field

3.2.1 Service Conditions

The makeup of a piece of equipment and its performance will be influenced by the environment in which the equipment is located. The equipment should not be subjected to excessive temperatures, moisture (through direct contact or humidity), dust, or abnormal vibrational forces. The equipment should be located in areas where proper airflow to the equipment is available for cooling. However, conditions in the field may not be fully consistent with the original specification of the equipment. Therefore, it is a good idea to review the location of equipment and the original specification if there are recurring problems.

3.2.2 Equipment Rating

Chargers are sized based on their intended application. For example, chargers used in a float configuration UPS system in safety-related applications are sized to have sufficient capacity to feed the worst-case connected inverter load plus recharge the battery from a deep discharged condition within a specified time plus some safety margin. Whereas, chargers used in a rectifier configuration need only be sized to handle the charging duty plus any loads connected directly to the dc bus plus some safety margin.

Inverters are generally sized to provide the worst-case loading expected plus some margin to handle momentary overloads and some room for expansion. Inverter systems originally installed without a static transfer switch were very likely sized with sufficient short circuit capacity to handle a load fault without tripping the main system output breaker. Such sizing would have resulted in a system that is normally lightly loaded. For a ferroresonant transformer-based system, continuous operation at lightly loaded condition results in a higher operating temperature and thus enhanced insulation degradation. In addition, other components such as electrolytic capacitors and SCRs within the cabinet may also be operating at a higher temperature because of the increased transformer heat dissipation.

Recurring component failures from overheating or during load switching may be indicative of a sizing problem. Plant modifications resulting in gradual increase in load over time could lead to such a sizing problem.

3.2.3 Output Ripple

Manufacturers design chargers and rectifiers to limit the output voltage ripple to a specified limit, usually from 2% rms for a standard unit down to 100 mv rms for special units. The energy from the excessive ripples could cause overheating of the battery connected to the dc bus and overheating and reduced life of the inverter input filter capacitors. For chargers used in a float configuration, if the original specification did not specify the need to operate the system for extended periods in a battery eliminator mode, that is, with the associated battery disconnected, it is likely that the unit does not include the additional filtering required to operate the unit in this mode. If the original equipment specification did not specify the output ripple requirements, the unit supplied is very likely a standard unit with minimal filtering, and the batteries were assumed to act as a supplementary ripple sink.

3.2.4 Output Regulation

Manufacturer's design of the output voltage regulation circuits for a charger/rectifier is based on the input voltage and frequency variation contained in the equipment specification. Typical output voltage regulation specification is ± 1% for input voltage variations of ± 10% over no load to full load, and input frequency change of ± 3 Hz. When recurring regulation problems are encountered, it would be a good idea to verify the corresponding input parameters to make sure that the problem is not external to the equipment or component.

3.2.5 Fusing

Fuses are used in chargers and inverters to protect semiconductors, control circuits, and power circuits. The manufacturer, based on the specific protection function involved, selects the fuses for the specific application. Fuses installed in the cathode of the SCRs provide overload protection. If a fault occurs when an SCR is conducting, the device may be subject to extreme overloads and, thus, a very rapid rise in the junction operating temperature. For overloads lasting more than one half of one cycle, SCR manufacturers specify an I^2t rating. The SCR fuses are selected based on this rating. Replacement fuses must be identical. Fuse equivalency technical evaluation for replacement fuses must address this factor. A change in the operating characteristics of this fuse can affect the surge withstand capability of the UPS and jeopardize device protection.

3.2.6 Surge Voltage Withstand Capability

Utility electric power sources are vulnerable to voltage surges and sags at all times during any 24-hour period. They may be caused by sources within (for example, starting a large motor, a feeder trip, operation electric igniters) and/or outside the plant boundary (for example, lightning). Sensitive analog, digital, and computer-based instrumentation require power that is essentially free of voltage surges and sags. A function of the UPS system is to provide just that.

UPS systems are designed to ensure that surges and sags do not *walk through* the system down to the loads. This is achieved by providing an input isolation/regulating transformer for the charger/rectifier, careful selection of fuses, and appropriate filtering at various input and output stages throughout the system. Some manufacturers also use a surge arrestor such as a metal oxide varistor or selenium surge suppressor to enhance the surge withstand capability of the unit. Therefore, it would be a good idea to examine this aspect of the system if recurring failure of power semiconductors or filter capacitors or repeated blown fuses occur.

4
DEGRADATION AND FAILURE MODES

Developing and implementing a maintenance program that will result in high reliability of the UPS systems requires an understanding of the degradation modes, their underlying physical processes, and stressors. To that end, this section provides a description of the components that make up the UPS systems, their degradation modes, mechanisms, and stressors.

4.1 Component Failure Modes, Mechanisms, and Stressors

For purposes of discussing the failure/degradation modes and their underlying mechanisms and stressors, we can break down the UPS systems, including the inverter, battery charger, and rectifier types mentioned above, into the following component categories:

- Power semiconductors - diodes, SCRs
- Magnetic components - ferroresonant transformers, chokes, power transformers
- Capacitors - filtering and commutating type
- Circuit boards and circuit components such as integrated circuits, resistors, capacitors
- Miscellaneous electrical hardware such as circuit breakers, relays, fuses, switches, timers, wires, terminal blocks

The subsections that follow present a description of the principal materials of construction, failure/degradation modes, underlying failure mechanisms, and the stressors for power semiconductors, magnetic components, capacitors, circuit boards, and fuses.

4.1.1 Materials of Construction

In order to understand what goes wrong with any of these components with time in service, it is necessary to study the components, their design, and materials of construction. Table 4-1 lists the age-degradable materials of construction used in the components listed earlier.

Table 4-1
Typical Materials of Construction for UPS/Charger Components

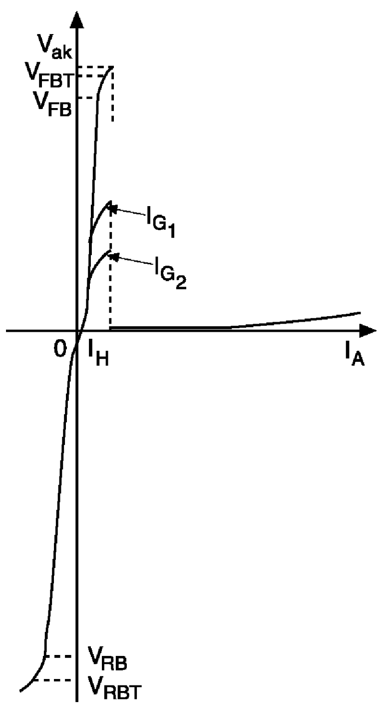
Components	Material of Construction	Age Degradable?	Comments
Power Semiconductors – Diodes and SCRs			
Diodes and SCRs	Silicon oxide Ceramic Teflon or XLPE wire insulation	Yes Yes Yes	Function of junction operating temperature
Magnetic Components – Transformer and Inductors			
Coil wire	Coil wire, polyamide-imide insulated copper magnet wire	Yes	Insulation degrades with time in service
Coil spool or box	Nomex, Kraft paper	Yes	
Coil covering	Varnish, epoxy	Yes	
Layer-to-layer insulation	NOMEX or Kraft paper	Yes	
Coil assembly	Epoxy impregnated steel	Yes	Heat, vibration
Capacitors – Electrolytic and Oil-Filled Types Used in Filter and Commutating Applications			
Electrolyte	Aluminum oxide Synthetic oil	Yes	Function of operating voltage, ripple current, and temperature
Electrodes	Aluminum foil Polypropelyne film	Yes	Function of heating, voltage, and frequency
Terminals	Polypropelyne film	Yes	Oxidation, corrosion
Fuses			
Fuse link	Metal (silver or gold) alloy Solder	Yes Yes	Thermal fatigue Thermal fatigue and vibration

4.1.2 Power Semiconductors

Power semiconductors are used in battery chargers, inverters, and rectifiers in circuits that perform *rectification* (convert ac to dc) or *inversion* (convert dc to ac). These devices include diodes, power transistors, and thyristors, also called SCRs.

A *diode* is a semiconductor device that has a two-layer p-n structure and thus one junction. It has two terminals: an anode and a cathode. An ideal diode has zero resistance in the forward (anode to cathode) direction, and infinite resistance in the reverse direction. Hence, the diode conducts; the current flows from anode to cathode when the anode is positive with respect to the cathode. The current flow stops when the cathode voltage is reversed.

An *SCR* is a semiconductor device that has a four layer p-n-p-n structure and thus three junctions. This device combines the properties of a diode and a switch. It has external cathode, anode, and gate terminals. In an SCR, the current flows from the anode to cathode as long as the anode is positive with respect to the cathode and only when the cathode to gate current is given a positive value. In other words, the solid-state switch is turned on. Once initiated by this positive bias, the current continues to flow, even when the gate current is reduced to zero, until the cathode voltage is reversed. The magnitude of the gate current will determine the forward blocking voltage at which conduction begins. The magnitude of the current following from the anode to the cathode is limited only by the external load. The conduction will continue until either the current flow between the anode and the cathode falls below a minimum value called the *holding current* or the anode is made negative with respect to the cathode. Once turned off, the switch will continue to stay off until the anode is made positive with respect to the cathode and the gate pulse is applied. Figure 4-1 shows a typical SCR current vs. voltage characteristic.



V_{ak} = Anode to Cathode Voltage
V_{FB} = Repetitive Peak Forward Voltage
V_{RB} = Repetitive Peak Reverse Voltage
V_{FBT} = Non-Repetitive Peak Transient Forward Voltage
V_{RBT} = Non-Repetitive Transient Peak Reverse Voltage
I_A = Anode Current
I_{GX} = Gate Current
I_H = Threshold Current

Figure 4-1
Current-Voltage Characteristics of an SCR

There are two types of diodes and SCRs commonly used: the stud type and the disk type. The *stud* type is called that because it has a threaded part at the bottom that forms the cathode terminal. For a diode, the braided cable at the top forms the anode. In a stud type SCR, the stud forms the anode, the braided terminal forms the cathode, and the gate lead is a small wire adjacent to the cathode wire. An additional thin cathode (white) lead is often provided for use in the gate circuit. This is intended to ensure that the operation of the gate circuit is not affected by the significant voltage drop that may take place in the cathode lead at high loads. In a *disk* type SCR, also known as a *press-pak* or *hockey-puck*, the round flat faces of the top and bottom of the disk form the anode and cathode terminals. Circuit contacts are made by clamping against the faces. The disk type also contains red and white leads.

4.1.2.1 Application Considerations

A power semiconductor will give satisfactory performance only if it is protected from excessive heating of its parts, particularly the semiconductor junction. Correct application and operation of power semiconductors depend upon the following:

- Observing the proper voltage limitations for the forward and reverse blocking voltage
- Maintaining the load current at values that will operate the junction at a temperature lower than its continuous maximum operating limit
- Protecting them from prolonged surge voltages in either the forward or the reverse direction
- For SCRs, ensuring that the turn-on, turn-off, and conducting times are controlled in accordance with the design specification

4.1.2.2 Degradation/Failure Modes

Typical failure modes for power semiconductors are open circuit, short circuit, or unacceptably high leakage current. The stresses that lead to these modes of failure are thermal stress, electrical stress, or mechanical stress.

4.1.2.2.1 Thermal Stresses

The major source of heating is from the forward conduction loss at the junction. Typical design maximum junction operating temperature for SCRs and diodes fall in the range of 105°C–135°C. In the conducting state, the anode to cathode resistance of a diode or a thyristor is very low but not zero. As the load current flows through the junction, this resistance, albeit very small, produces a large amount of heat, which will destroy the device if not removed quickly. Heat sinks are provided to remove heat from the device. Heat is transferred from the junction to the case of the device and from the case to the heat sink, from which it is transferred to the atmosphere by radiative and conductive transfers.

To ensure fast heat transfer, the heat sinks are mounted vertically, and the device is mounted to the heat sink with a coating of grease with high thermal conductivity (for example, Copper Shield from Thomas & Betts) at a specified torque. For the disk type devices, torquing down also ensures that the anode and cathode terminals faces make full contact within the devices. If it is not properly torqued down, the device is likely to fail from overheating caused by a few localized conduction areas carrying the full load current.

Gradual or immediate changes in thermal impedance of the device and heat sink system can enhance aging degradation of power semiconductors. Factors that might contribute to significant changes in thermal impedance of the device include the following:

- Improper torquing of the device to the heat sink
- Improper aligning of the SCR in its heat sink (that is, the hockey puck is out of center)
- Cleanliness of the heat sink
- Improper selection and/or application of thermal grease
- Gradual drying out of the conductive grease

Key Technical Point

To minimize the thermal stress on an SCR, ensure that the heat sink is clean, the proper conductive grease is applied, the SCR is aligned in the heat sink, and the correct torque is applied.

4.1.2.2.2 Electrical Stresses

Surge voltage increases the current through the device and thus the power dissipation at the junction that produces heat. The rate at which the junction temperature increases will exceed the rate of heat removal because of the difference in time constants of the sink and the junction. This results in junction overheating and device failure if the surge is prolonged. Repeated application of surge voltages over its service life can lead to device failure due to thermal cycling and dielectric breakdown. Manufacturers specify an I^2t rating for overloads lasting less than one-half of one cycle. This rating is used in the selection of fusing for the SCRs. It is therefore important to ensure that the SCR fuses are properly selected, especially as they are replaced in the field.

In some designs, a surge arrestor such as a metal oxide varistor (MOV) or a selenium surge suppressor is employed on the input ac side to preclude input voltage surges.

Note: It is important to ensure that the operating voltages of the SCR and MOV are properly matched.

Rate of load current variation can affect both short-term and long-term performance of the power semiconductors. The design of the power semiconductors ensures that the conduction area spreads quickly. When the load current variation is great, a local hot spot will be formed in the neighborhood of the gate connection due to the high current density in that part of the junction that has started conduction. The result will be local overheating and device failure. Recent advances in manufacturing technology have minimized this effect by spreading the physical connection over a larger area.

The oscillator board, also called *gate trigger board* or *firing module*, controls turn-on time, conduction length, and turn-off time. Once turned on, a thyristor cannot recover its forward resistance unless the current is reduced to zero and held there for a minimum time, called the *turn-off time*. Proper control of turn-off time is important; otherwise, the output waveform and frequency will be affected. The method employed to achieve this is called *commutation*. Forced commutation systems, normally used in the design of inverters and chargers, employ components such as diodes, inductors, and capacitors. Changes in the value of capacitors or inductors or forward leakage currents of diodes caused by aging effects can affect turn-on and turn-off times; conduction length; and thus the output voltage, waveform, and frequency.

4.1.3 Magnetic Components

Magnetic components used in UPS systems can be divided into the following three categories:

- Power transformers, including the ferroresonant type output transformers
- Instrument transformers
- Chokes or inductors used in filtering and commutation applications

When properly designed and applied, very little can go wrong with the magnetic components

4.1.3.1 Degradation/Failure Modes

Operation within the rated operating temperature limits should not result in failures of magnetic components before their estimated design life. Manufacturers have projected a design life of 40 years for inverter and charger systems. In some cases, qualified life estimates have been established, again in excess of 40 years, through aging evaluation. The failure modes for these components are open circuit and short circuit. The primary mechanism that leads to either of these failure modes is oxidative degradation of the coil wire insulation. Heat, humidity, electrical, and vibration stresses promote or enhance this mechanism.

4.1.3.1.1 Thermal Stresses

Overheating can cause turn-to-turn shorts or open circuit. Overheating generally occurs as a result of prolonged operation outside the design limits of voltage, current, or ambient temperature. Prolonged operation of ferroresonant transformers under lightly loaded (< 50% of rated capacity) conditions can lead to overheating. It is worth noting that many UPS systems in the nuclear plants in operation operate lightly loaded; some at less than 25% of their rated capacity. Review of the industry failure data confirm that failure of magnetic components is quite low. With few exceptions, where failures have occurred, they reportedly have been caused by either overheating or electrical surges.

4.1.3.1.2 Electrical Stresses

Electrical stresses that can lead to failure of transformers or chokes include prolonged and/or frequent exposure to surge voltages/currents. Besides causing overheating, such surges can also destroy the coil insulation through dielectric breakdown. Properly designed and applied magnetic components experience only a gradual degradation of electrical insulation properties from electrical stresses, leading eventually to catastrophic failure from dielectric breakdown.

4.1.3.1.3 Mechanical Stresses

Vibration can loosen electrical terminations and magnetic core and cause dielectric breakdown of embrittled insulation. Industry operating experience shows that this is not of great concern. Few reported cases of vibration-induced failures leading to loose terminations and resultant ground faults or blown fuses were the result of either manufacturing or installation deficiencies.

4.1.4 Capacitors

Aluminum dc electrolytic and ac polypropylene film capacitors used in filtering and commutating applications account for most of the capacitor failures in inverters, rectifiers, and chargers. Depending upon the specific manufacturer and circuit design, filter capacitors are used in banks of 10 to 18 capacitors (~ 5,000 µfd).

The commutating capacitors are usually 2 to 4 ac capacitors of ~10 to 50 µfds. The value of the commutating capacitors varies with rating of the unit. Commutating capacitors are designed to withstand high levels of surge. The output filter capacitors in inverters may have harder duty cycles than those in chargers because of the demand placed on them by the high levels of harmonics and the need to smooth square wave outputs from the bridge circuits. Hence, capacitors used in charger filter applications may be expected to last a little longer than those in inverters.

4.1.4.1 Degradation/Failure Modes

When properly selected, applied, and operated within design specifications, capacitors should provide satisfactory service for up to 10 years. Aluminum dc electrolytic capacitors used in filtering applications have design life limitations ranging from 5 to 10 years. Some manufacturers have established a qualified life and hence replacement intervals ranging from 3 to 7 years for dc electrolytic capacitors based on aging evaluations. AC metallized film capacitors generally can be expected to last about 15 to 20 years. Table 4-2 provides a listing of the failure modes, mechanisms, and the underlying stressors for capacitors.

As seen from this table, thermal and electrical stresses are of primary concern in determining capacitor reliability. The failure mechanisms are generally vaporization of electrolyte and/or electrode degradation from corrosion or mechanical damage. Electrolyte loss is a function of the operating or storage temperature. It is relatively insensitive to operating voltage provided the operating voltage does not exceed the rated voltage. Open circuit failure mode can also result from corrosive attack of the aluminum foils and terminal tabs by halogenated hydrocarbon cleaning solvents absorbed through the capacitor end seal.

Key Technical Point

Establish a replacement frequency for capacitors based upon the manufacture and style of capacitors installed.

Table 4-2
Failure Modes, Mechanisms, and Stressors for Capacitors

Failure Mode	Mechanism	Stressors
Catastrophic Failure		
Short circuit	Electrode degradation, corona effects	Overvoltage and electrical cycling
Open circuit	Separation or corrosion of electrode to terminal connections	Vibration, chemical reaction
Incipient Failure		
Reduction in capacitance Increase in equivalent series resistance (ESR) Increase in dissipation factor (DF) (tan σ) Weight loss	Gradual degradation of electrodes and/or loss of electrolyte Vaporization caused by operation or storage	Heat
	Increase in leakage current Gradual electrode degradation Corona effects	Overvoltage Excessive ripple current for dc capacitors Excessive frequency variation for ac capacitors
Vent open	Internal pressure buildup	Overheating, overvoltage
Blistering, seepage, or leakage of electrolyte	Internal pressure buildup, seal degradation	Overheating, overvoltage, chemical reaction

Generally, dc electrolytic capacitors used for filtering applications are aluminum electrolytics with values ranging from 5,000 to 10,000 μfd, rated at 350 V, and 85°C. The ac capacitors used for filtering and commutating applications are of the polypropylene film type with values ranging from 5 to 10 μfds, rated at 250 V and 85°C.

Review of the industry failure experience indicates that capacitor failures have been predominantly dc aluminum electrolytics and the failures have been detected only after they have catastrophically failed. Most of them were of the open circuit or short circuit type. In a few cases vent-out (that is the loss of electrolyte through the pressure vent) type failure has also occurred. Incipient failure detections have been rare. This may be due to the absence of any predictive maintenance directed at measurement of parameters indicative of such conditions. With a few exceptions, most of the failures were attributed to the normal end-of-life aging. The few exceptions to this were attributed to excessive overvoltage or surge currents. End-of-life aging failures are usually caused by loss of electrolyte resulting from vaporization.

As a general rule, capacitor life for UPS and charger applications can be improved by providing additional (forced) cooling. Figure 4-2 shows the typical life expectancy versus operating temperature in °C for the large can aluminum electrolytics. As seen from these curves, if the operating temperature of the capacitors is reduced to 55°C, capacitor life can be nearly doubled. Typically, in nuclear plant applications, most of the chargers and UPS systems used in safety-related applications are operating at or below 50% of their rated capacity. Capacitors are typically rated for 85°C. The capacitor operating temperature, which is the sum of the ambient temperature and the core temperature rise, is estimated to be about 50 to 65°C. Capacitors rated for 105°C are available and may be used to prolong the capacitor's operating life. This would require a carefully documented engineering evaluation to justify their substitution to ensure that the critical design characteristics and qualification are preserved.

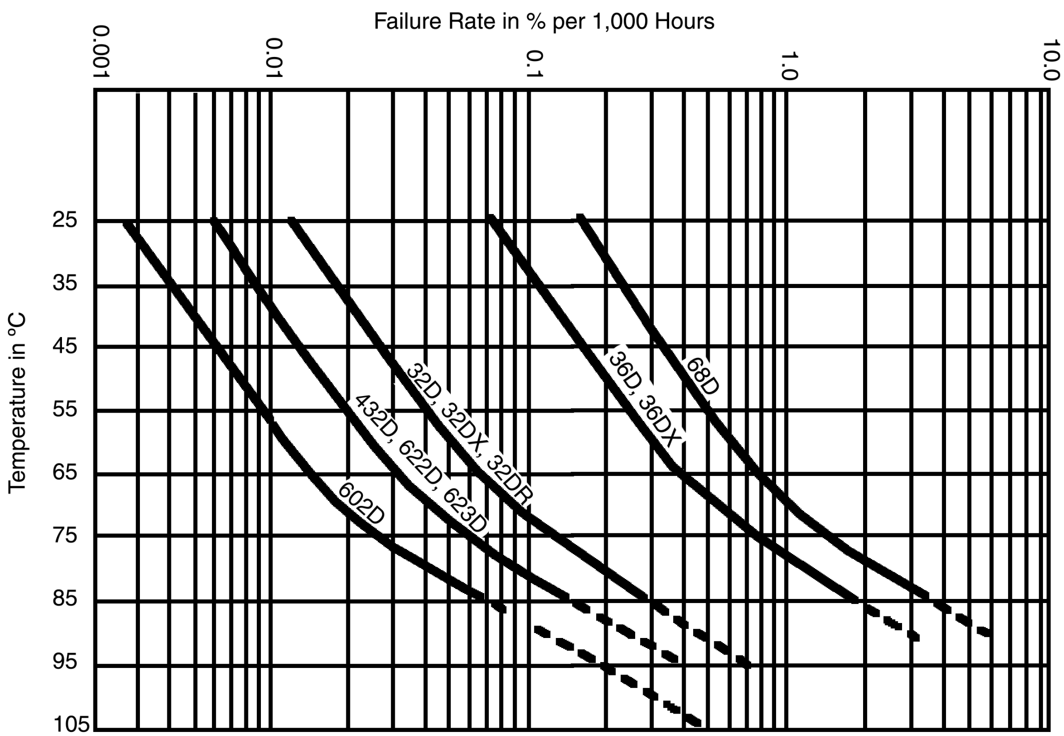


Figure 4-2
Operating Temperature vs. Failure Rate for Electrolytic Capacitors

4.1.4.1.1 Mechanical Stresses

Vibration can cause loosening of electrical terminations, internal shorting of electrodes, or open circuit at the point where the electrode connections to the terminal studs are made internally. Industry experience shows that vibration is not a significant concern. Few reported cases of vibration induced capacitor failures from loose terminations were the result of either manufacturing or installation deficiencies.

4.1.5 Circuit Boards

Circuit boards are the printed circuit cards used in control and signal processing applications. Examples include the gate firing modules used for controlling the firing sequence, timing, and length of SCRs, alarm logic, and synchronizing control; and the sensing modules used for sensing the input and output parameters such as voltage, current, and frequency. A circuit board consists of the board with the printed wiring, the components mounted thereon, and the solder joints.

A circuit board may fail in either a catastrophic (totally or partially nonfunctional) mode or incipient (performance below specification) mode. After their initial phase in, catastrophic failures of circuit boards are rare. A few cases have been reported, but they were the result of other external conditions such as water spray from inadvertent actuation of fire protection sprinkler or capacitor vent-out failure. Generally, circuit boards fail in an incipient mode resulting in performance below specification requirements. Such failures are the result of failure or degradation of circuit components such as capacitors, ICs, resistors, inductors, and potentiometers. Typically, such component degradation results from in-service aging caused by heat, leading to out-of-specification values. Sources of heat that could affect circuit boards include poor cabinet ventilation, improper location (mounting directly above heat generators like transformers), and voltage dropping resistors or power diodes on the board itself. Also, electrolytic capacitors on circuit boards may fail from aging caused by electrolyte loss, drying out, or both under in-service conditions or extended storage. Other stresses that could contribute to aging degradation of components are voltage or current surges, excessive dust, and corrosive or high humidity atmosphere. Ways to improve circuit board life expectancy include using components that have tighter tolerances and higher temperature stability and using them at low operating stress ratios, that is, to boost application margins for power dissipation.

Other circuit card failure modes of interest are wear-out of the card-edge connections from vibration and/or repeated insertion and removal, and high resistance and/or intermittent connections at solder joints caused by long-term oxidation.

4.2 Summary

The dominant stress that causes component failures in power semiconductors, magnetics, and capacitors used in UPS systems is thermal stress, which is additive in nature. Thermal stresses can originate from many sources including poor ventilation, continuous operation of ferroresonant transformers at significantly low loads, improper torquing of semiconductors, and certain electrical phenomena such as voltage and current surges or corona effects. The principal failure mechanisms associated with thermal degradation are listed in Table 4-3.

Key Technical Point

The dominant stress that causes component failures in power semiconductors, magnetics, and capacitors used in UPS systems is thermal stress, which is additive in nature. Thermal stresses can originate from many sources including poor ventilation, continuous operation of ferroresonant transformers at significantly low loads, improper torquing of semiconductors, and certain electrical phenomena.

Table 4-3
Component Failure Mechanisms Resulting from Thermal Degradation

Component	Mechanisms
Power semiconductors	Junction overheating, increase in leakage current
Magnetics	A cascading effect that is initiated in voids, bubbles, or other weakened portions of the insulation or impregnation in the coils
Capacitors	Loss of electrolyte and internal pressure buildup
Circuit board	Heat-induced changes in component physical properties

The next important stress is electrical stress resulting from overvoltage and surge currents. The principal failure mechanisms associated with electrical stresses are localized overheating and dielectric breakdown. In addition, corona effects caused by dielectric breakdown also result in capacitor degradation.

In either case, the resulting failure modes can be catastrophic or incipient in nature. While most of the catastrophic component failures will result in immediate and total system failure, the incipient failures quite often may not. Many of the incipient failures can be detected in a timely manner through enhanced surveillance, inspection, testing, and maintenance, as discussed in Section 8.

5
UPS SYSTEM OPERATING EXPERIENCE

This section presents a discussion of the experience with UPS system failures that are indicative of the stresses identified in Section 4. The sources of information on system level failures from 1976 to 1992 include the (INPO) Nuclear Power Reliability Data System (NPRDS), the licensing event report (LER) data system, and the Nuclear Operations and Maintenance Information Service (NOMIS) data system vendor advisories. At the component level, the data were provided by EPRI publication: *Preventive Maintenance Basis*, *Volume 22, Inverters*, TR-106857-V22.

5.1 System Level Failures and Effects

UPS systems are used in nuclear power plants to supply safety and non-safety loads. The effect of major component failures within the UPS system depends largely on the system configuration as discussed below.

UPS System with an Inverter Only

In this configuration, failure of the inverter results in a total loss of power to the loads.

UPS System with an Inverter and a Static-Transfer Switch

In this configuration, failure of the inverter causes the static-transfer switch to transfer the loads to the alternate source without interruption. However, the power supply from the alternate source is subject to disturbances. Therefore, the system may be operated in this mode only for a short duration.

Failure of the static-transfer switch without a coincidental inverter failure may not cause a system shutdown, but would result in degraded system capability because a transfer may not occur when required.

UPS System with an Inverter, Rectifier, and a Static-Transfer Switch

In this configuration, failure of the inverter or the static-transfer switch would have the same effect as described above. In this configuration, failure of the rectifier would not impact system operation provided the connected battery is capable of continuously supplying the inverter. Otherwise, the system will shut down at the end of the battery duty cycle.

In all of the above configurations, caution should be exercised when operating the inverter with the dc system feeder or battery failure. Unless the battery charger is specifically designed to work as a battery charger/eliminator, operating the inverter under this condition may result in severe overheating due to the increased ripple content of the rectifier/charger output.

Key Technical Point

Unless the battery charger is specifically designed to work as a battery charger/eliminator, operating the inverter with the dc system feeder or battery failure may result in severe overheating.

UPS system failures that result in a complete loss of vital ac can result in undesirable plant transients and/or challenges to the plant safety systems such as:

- Unnecessary actuation of safety systems
- Loss of control room indications that provide plant status information
- Primary coolant system transient
- Improper response of the feedwater and steam generator/reactor water level control systems
- Loss of some safety-related electrical equipment functions or control capability

Battery charger systems are used in nuclear power plants to supply the inverter that in turn supplies safety and non-safety loads and the charging current for the station batteries. Unlike the inverter, the battery charger system failures should not have any immediate and/or direct effect on the plant operation and safety because the vital power system is configured to preclude such effects.

A particular system/equipment design problem with respect to chargers may exist. In some older plants, a charger failure is apparently not annunciated in the control room, resulting in the detection of the failure only after a low voltage condition on the dc bus develops.

When UPS system failures involve plant transients, they will very likely have plant safety and/or operational implications. Such events are reported in the LER data system. Review of the LER data indicate that between 1976 and 1992, 171 UPS events with plant transient impacts have been reported. Of these, 42% resulted in reactor trips. It should be noted that 145 of these 171 events occurred before 1986. As a result, improvements have been made in system design, manufacturing, application, operation, and maintenance resulting in improvements in their overall reliability. Data from NPRDS illustrate the improvements in:

- Number of inverter failures that resulted in a plant full trip or power reduction (Figure 5-1)
- Total number of inverter failures (Figure 5-2)
- Total number of charger failures (Figure 5-3)

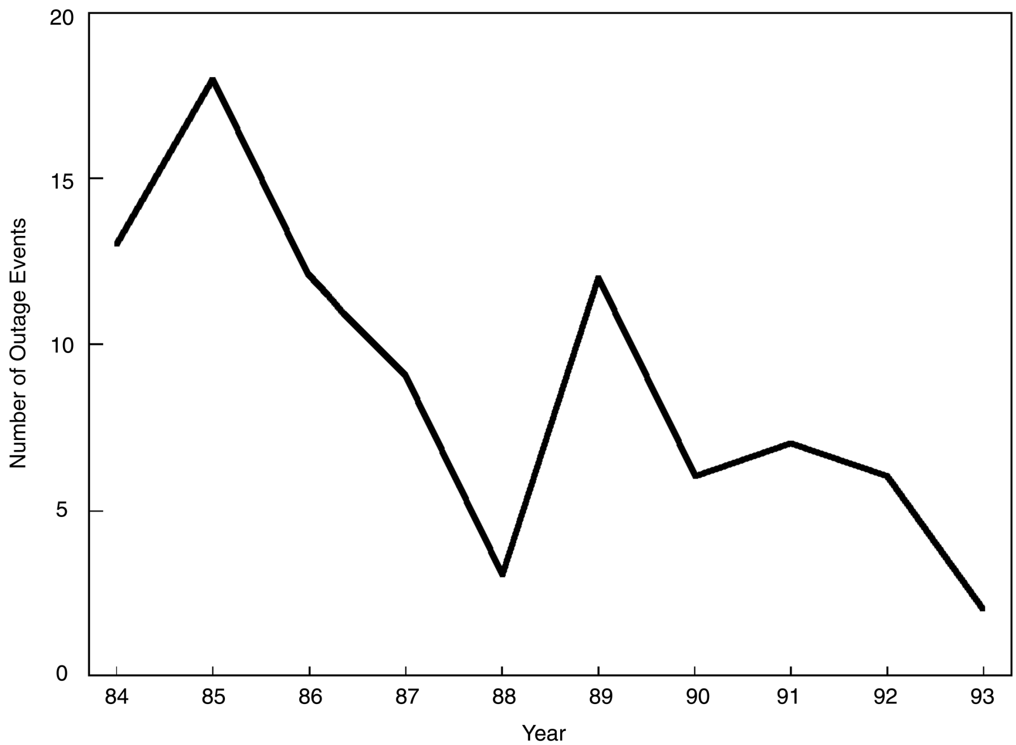


Figure 5-1
History of Full/Partial Plant Outages from Inverter Failure

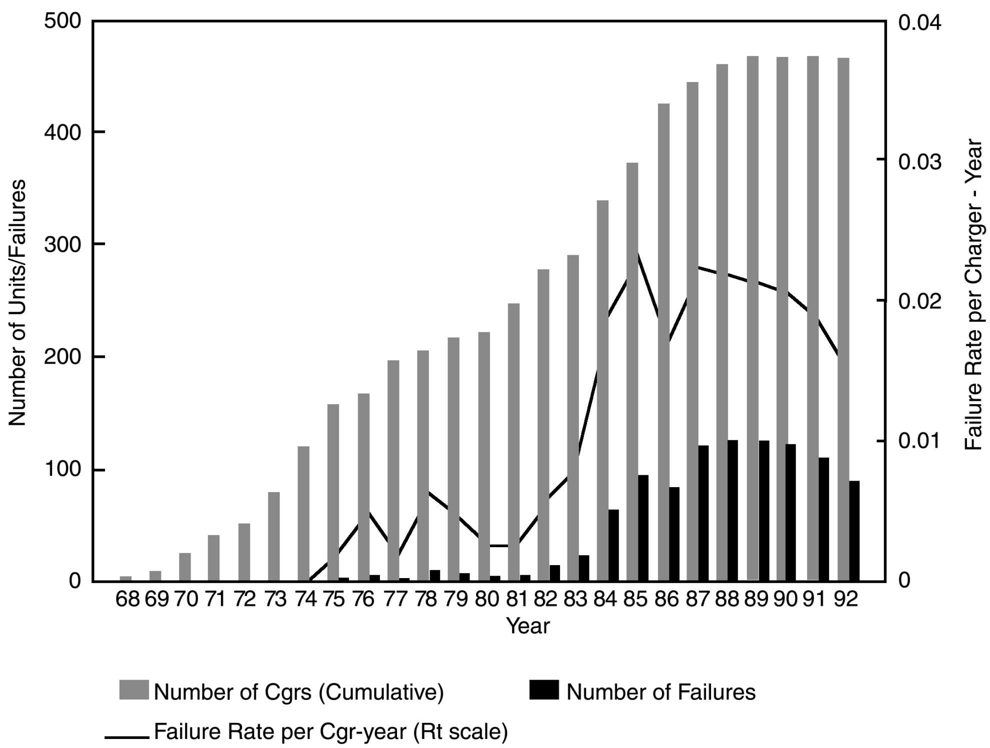


Figure 5-2
Failure Count/Rate History of Battery Chargers

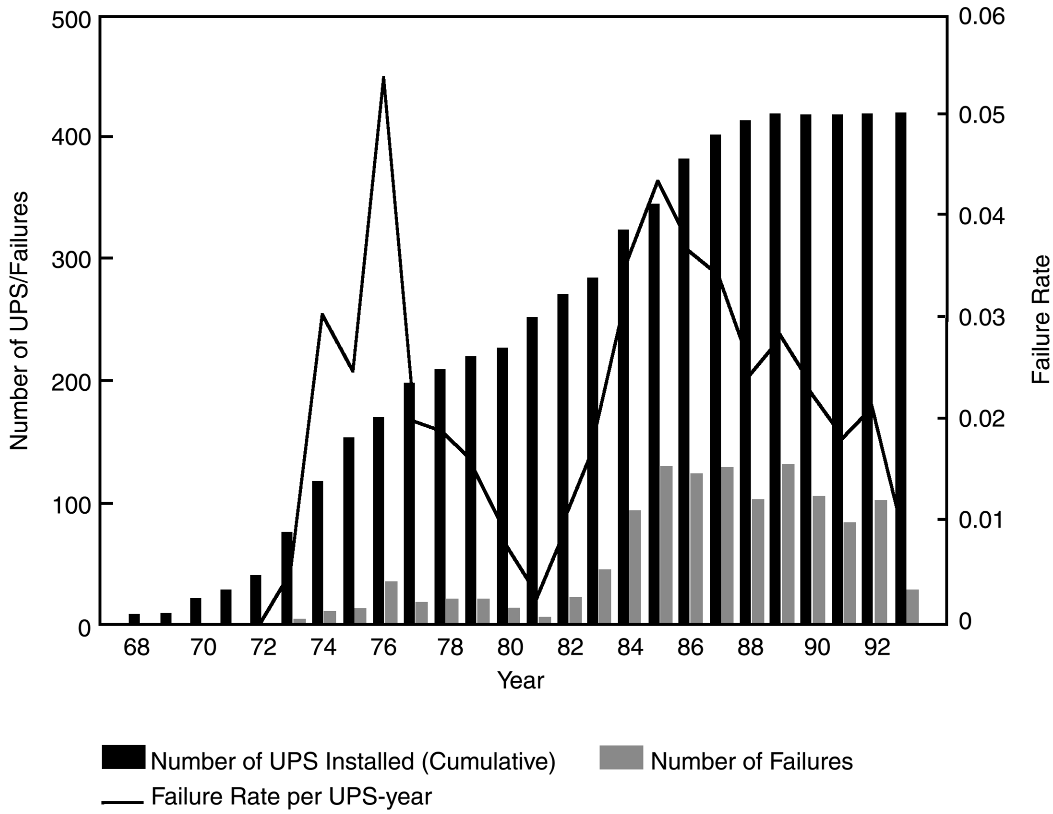


Figure 5-3
Failure Count/Rate History of Inverters

5.2 Component Level Failures and Effects

UPS system failures are generally the result of random component/subsystem failures. *Component failure* refers to the failure of discrete circuit components such as resistors, fuses, SCRs, connectors, inductors, and transformers. *Subsystem failure* refers to the failure of critical portions of the system such as the synchronization control, current limiter, load share control, and gate firing control circuitry caused mainly by the failure of the associated circuit boards. For purposes of this report, *component failure* refers to either or both.

Generally, component failures may not lead to total loss of the inverter but rather to the system functioning outside the specification limits. Table 5-1 identifies the degradation mechanism and the time progression of the degradation.

Table 5-1
Failure Locations, Degradation Mechanisms, and PM Strategies

Failure Location	Degradation mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery Opportunity	PM Strategy
Electrolytic capacitors	Dielectric breakdown	-Overvoltage -Temperature from ac ripple and environment -Aging	-Random -Continuous -Continuous, includes shelf life	-Random -Half the life for every 10°C above rated insulation system design life (nominally 10 years) -Failure free for 5 to 10 years	-Operation out of specification -System failure or alarm -Trend bank capacitance -Schedule component replacement	-Clean and reset -Component replacement -Operator rounds
	Leaking dielectric	-Mechanical damage -Manufacturing defect	Random	-Random -Random but rapid	-Visual inspection -Operation out of specification -System failure -Trend bank capacitance	-Clean and inspect -Component replacement -Operator rounds
Input/output filter choke and commutating chokes	Shorted, will eventual lead to an open circuit of the choke windings	-High temperature -Overvoltage -Foreign material damage	-Continuous -Random	-Half the life for every 10° above rated design life (20 to 40 years depending on insulation class) -Random	-Visual inspection -Thermography (only on large chokes) -Operation out of specification, will cause an unstable output voltage -System failure to alarm -Transfer to the standby power supply	-Operator rounds -Clean and inspect -Thermography

**Table 5-1 (cont.)
Failure Locations, Degradation Mechanisms, and PM Strategies**

Failure Location	Degradation mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery Opportunity	PM Strategy
Input breakers	Refer to PM Basis Report TR-106857, Vol. 4, on motor control centers					
Input fuse	Open circuit	-Age -High temperature	Continuous	Failure free for > 10 years	-System failure or alarm -Transfer to alternate power supply -Schedule replacement	-Clean and inspect -Component replacement -Operator rounds
Power semiconductor components	-Shorted -Open circuit	-High temperature from cooling fan failure or filters blocked -Overvoltage -Manufacturing defect (found after field replacement) -Improper assemble of heat sink: no thermal compound or improper torque	Random	Random and rapid	-System failure or alarm -Transfer to alternate power supply -Scheduled replacement -Post maintenance test	-Clean and inspect -Operator rounds

Table 5-1 (cont.)
Failure Locations, Degradation Mechanisms, and PM Strategies

Failure Location	Degradation mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery Opportunity	PM Strategy
Commutation and other filled capacitors	Dielectric breakdown	-Temperature -Aging -Overvoltage	-Continuous -Continuous (has no shelf-life aging component) -Random	-Half the life for every 10°C above rated temperature -Failure free for up to 20 years -Random	-System failure to alarm -Transfer to the alternate power supply	-No recommended PM strategy for commutation capacitors -Component replacement -Operator rounds
	Leaking dielectric	-Mechanical damage -Manufacturing defect	Random	-Random -Random but rapid	-Visual inspection -System failure or alarm	-Clean and inspect -Operator rounds
Transformer	Insulation degradation	-Elevated temperature -Restricted air flow -Circulating current from constant voltage transformer (CVT), capacitor changes, or failures -Insufficient loading (primarily Westinghouse and GE) -Mechanical damage -Aging	-Random -Continuous (application error) -Random -Continuous	-Random -Random, dependent on kVA size of the inverter -Can be as short as a few days, manufacturer dependent -Random -Failure free for 20 to 40 years	-Thermography -Visual inspection -Smell	-Thermography -Clean and inspect -Operator rounds
	Loose connections	Improper installation	Random	Random	-Thermography -Inspection	-Thermography -Clean and inspect
	Mechanical degradation	-Temperature -Aging	Continuous	Failure free for >10 years	-Audible noise -Visual inspection -Thermography	-Thermography -Clean and inspect -Operator rounds

Table 5-1 (cont.)
Failure Locations, Degradation Mechanisms, and PM Strategies

Failure Location	Degradation mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery Opportunity	PM Strategy
Printed circuit boards **-Firing circuit** **-Oscillator** **-Alarm** **-Sync** **-Metering circuits**	Failure	-Failed electroytic capacitors -Relay failure (coil or contaminated contacts) -Temperature -Overvoltage -Electromagnetic interference -Off-gassing from near by lead acid batteries	-Continuous -Random -Continuous	-Failure free for 5 to 10 years -Half the life for every 10°C above rated temperature -Random -Random on a scale of 10 years or greater	-System failure or alarm -Transfer to the alternate power supply -Erratic output -Intermittent transfer -Inspection -Scheduled replacement of critical boards only	-Clean and inspect
	Drift	-Temperature -Aging	Continuous	Failure free for 1 to 5 years	Calibration check	-Clean and inspect
Metering Instruments (that is voltmeter, frequency meter, status lights)	Drift	-Temperature -Aging	Continuous	Random on a scale of 3 to 5 years	-Calibration check -Visual inspection -Lamp test	-Clean and inspect -Operator rounds
Static switch	Slow or fails to operate	Stuck reed relay contacts	Continuous	Random on a scale of years	Periodic operation	-Clean and inspect
	Burned contactor contacts (where present)	-Number of operations -Load	Continuous	Random on a scale of 3 to 5 years	-Slow transfer -Failure to transfer -Contact chatter -Timing test	-Clean and inspect

Table 5-1 (cont.)
Failure Locations, Degradation Mechanisms, and PM Strategies

Failure Location	Degradation mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery Opportunity	PM Strategy
Maintenance bypass switch	Aging	-Temperature -Aging -Out of phase transfers	Continuous	Expect to be failure free for 15 to 20 years	Periodic operation, usually fails during operation	-Clean and inspect
Muffin fans	Failure of the motor or motor bearing	Age	Continuous	Expect to be failure free for 10 years	-Audible noise -Visual inspection -Alarms -Scheduled replacement of critical fans	-Clean and inspect -Operator rounds -Component replacement
Regulated rectifier (if installed)	Refer to PM Basis Report TR-106857, Vol. 23, on battery chargers					

The periodicities in Table 5-1 apply to those inverters and chargers that have been evaluated and determined by the plant to be included in a preventive maintenance program.

5.3 Summary

Experience gained in the operation of UPS systems and the enhanced planned maintenance programs implemented recently have led to improved overall reliability of UPS systems. At present, UPS system failures are mainly from component failures caused by aging effects. Failure trends point to a possible increase in aging-related failures. It appears that a major overhaul (see Section 8.3) through which the system could be returned to its *like-new* condition can help in slowing, if not in arresting, this trend.

6 TROUBLESHOOTING

6.1 Troubleshooting an Inverter and Rectifier

The following tables present potential problems, their possible causes, and suggested remedies for UPSs. The following is provided as basic guidance. Manufacturer's (vendor's) troubleshooting guidance and literature on your plant's specific equipment should be referenced.

Table 6-1
Inverter Problems, Possible Causes, and Corrective Actions

Problem	Possible Cause	Corrective Action
Inverter will not start, and the fuse blows.	Diodes D2, 3, 4, and 5 have failed.	Using an ohmmeter, check each diode. A good diode has a small resistance in the forward direction and is open circuit in reverse.
	SCRs 1, 2, 3, and 4 have failed.	Using an ohmmeter, check the forward and reverse bias. Both directions should be open circuit.
	Commutator capacitor has failed.	Disconnect the wires from one side of the capacitor, and using an ohmmeter, verify that the capacitor has not shorted.
	Replace any components that were found to have failed and restart the inverter. If the fuse blows again, proceed with the following steps.	
	Bridge has failed.	Lift wire from the oscillator board. Start the inverter, and if fuses blow, this confirms the bridge has failed.
	CVT is saturated.	Roll the gate leads on the oscillator board, and restart the inverter. This will desaturate the CVT. If fuses blow after 5 seconds, the SCR shorting assembly (SSA) has failed. Replace the SSA.
	Oscillator board has failed.	With the gate leads on the oscillator board still rolled and if the fuses continue to blow, then the oscillator board has failed. Replace the board. If fuses do not blow, then return the oscillator gate leads to their normal configuration.
	Restart the inverter, and if fuses do not blow and the inverter continues to run, then the problem was a saturated CVT. If fuses blow, proceed as directed below.	
	Gate transformer board has failed.	Replace the gate transformer board. If the problem still exists: 1 Lift wires from the CVT. 2 Connect a 60- or 100-watt light bulb to the wires as a load on the inverter bridge output. 3 Start the inverter and run for 15 minutes. If the fuses blow, the problem is in the inverter logic. If the fuses do not blow, the problem was with the CVT.
	CVT has failed.	Disconnect the input and output wires and megger between the primary windings, secondary windings, and primary and secondary windings to core.

Table 6-1 (cont.)
Inverter Problems, Possible Causes, and Corrective Actions

Problem	Possible Cause	Corrective Action
Inverter will not start, and the fuse does not blow.	Oscillator board has failed.	1. Test for dc voltage across the capacitor. 2. Test for a dc voltage across the fuse. 3. Test that start-up dc voltage is available to the oscillator board. If the above tests are satisfactory, then the oscillator board has failed.
Inverter starts but the output voltage is low, unstable, or not available.	Low inverter frequency.	Adjust the oscillator board.
	The CVT is current limited.	Check for an overloaded condition. No load should be indicated on the ammeter.
	The CVT capacitors have failed.	1. Check for swollen appearance or shorted condition resulting in a reduced capacitance. 2. Verify the capacitor currents, and ensure that each capacitor is providing approximately the same current. 3. Check for the correct choke current.
	Shorting board relay is energized.	Check if the CVT's current limiting current is being passed through the shorting board.
The in sync light is off.	Light burned out.	Check for voltage across the bulb.
	The output frequency is incorrect.	Check the frequency, and adjust the frequency control potentiometer on the oscillator board if necessary.
	Shorting board relay has failed.	Check the relay, and replace it if necessary.
	Sync board is not firmly plugged in.	Verify that sync board relays are securely installed.
	If all the above conditions are met, measure the voltage difference on the sync board terminals. If the voltage is stable and within 20 V or less, the inverter is in sync. Replace the sync board.	

Table 6-2
Rectifier Problems, Possible Causes, and Corrective Actions

Problem	Possible Cause	Corrective Action
Rectifier does not start, and input fuses have blown.	Diodes D2, 3, 4, and 5 have failed.	Isolate the rectifier. Using an ohmmeter, check each diode. A good diode has a small resistance in the forward direction and is open circuit in reverse.
	SCRs 1, 2, 3, and 4 have failed.	Using an ohmmeter, check the forward and reverse bias. Both directions should be open circuit.
	Open circuit on the resistance-capacitance (RC) network.	Verify continuity of the RC network.
	DC output voltage may have deviated high or low.	Test the rectifier output adjustment potentiometer for dead spots. Verify that the contacts are not bad.
Rectifier does not start, currents are imbalanced, and fuses are not blown.	Input voltages are imbalanced.	Verify that the input voltages are balanced.
	SCR has failed.	Measure the SCR gate-to-cathode resistance. It should be greater than 10 ohms.
	Misalignment of the regulated rectifier board	See manufacturer's instructions.
Rectifier does not start, and output voltage is unstable.	No input voltage.	Verify input voltage.
	Output breaker has failed.	Verify proper operation of the output breaker.
	High ripple on output voltage.	Capacitors are aging. Check date code, and replace it if it is 8 to 10 years old.

7 PERSONNEL AND EQUIPMENT SAFETY PRECAUTIONS

Working on inverters and charger systems involves various levels of dc and ac voltages. As a general rule, to the extent practical, work should be performed only with the equipment de-energized. Yet, work may have to be performed with some or all portions of the circuits energized.

The electrical shock hazards associated with dc power can be more severe than those associated with ac power for equivalent voltages and currents. A short circuit between the live terminals can result in electrical shock hazards and unwanted or undesirable equipment operation.

Only authorized personnel who have been familiarized and trained on the equipment fundamentals and maintenance procedures should be allowed to perform maintenance activities.

Generally, inverter and charger maintenance and/or testing procedures may be performed with the plant in any operating mode. Such test inspection and maintenance procedures often involve an infrequent activity. Therefore, depending upon the plant condition at the time of the activity, potential is great for reduced margins of safety, the introduction of unwarranted transients, or accidents if the activity is performed incorrectly. The manufacturer's literature should be reviewed for applicable personnel and equipment safety precautions.

Key Human Performance Point

Maintenance activities may be performed with the plant in any operating mode. Such activities are infrequent and create a potential for reduced safety margins. Therefore, the manufacturer's literature should be reviewed for applicable personnel and equipment safety precautions.

7.1 Personnel Safety Precautions

The following additional basic safety precautions should be exercised for working with UPS systems and associated circuits:

- Care should be exercised to prevent electric shock and/or equipment damage. Generally, a minor accidental shock or burn may cause an involuntary movement of a person's arm or body that can damage the equipment and injure personnel.

- Use only insulated tools to prevent accidental shorting across live connections or to grounds. As a general rule, the length of the exposed metal for any tool should be as short as practical. Never lay tools or other metal objects on components within the system cabinet. Shorting, fire, or personal injury could result.
- Always review the associated wiring diagrams to make sure that all related circuits are properly identified, de-energized if practical, and properly separated if hot.

7.2 Equipment Safety and General Precautions

The following additional basic equipment safety and general precautions should be exercised for working on UPS systems and associated circuits:

- Never use spray solvents to clean components. They may be incompatible with the nonmetallics.
- Solvents can attack and even crack the plastic and other nonmetallic parts.
- Use only approved lubricants. Unapproved lubricants may be incompatible and can attack plastic materials or solidify and cause improper operation of the item being lubricated.
- Do not use an emery cloth, sandpaper, or metal file to clean contacts. These tools can damage the plating on the contacts.
- Use only a burnishing tool or other approved means for contact cleaning.
- Use a capacitor-shorting device for discharging capacitors.
- Use only calibrated torque wrenches to tighten nuts or studs, particularly for installing SCRs and capacitor terminations. Do not use pliers or adjustable wrenches. Use properly sized socket or open-end wrenches.
- Provide proper wire lay for wires inside the cabinet or component covers to prevent excessive strain on the insulation, or wires causing binding of movable parts, or obstruction of proper airflow to facilitate heat removal.
- High voltage and current levels are associated with semi-conductor power electronic devices. Insulated tools should be used during maintenance to avoid accidental shocks and short circuits that cause further damage.
- Tools and test equipment lead wire insulation should be checked to ensure that it is fully rated for the operating voltage under test and is in a good condition.
- Properly tag any leads lifted.
- Follow plant procedures.

The following should be reviewed for inclusion of appropriate safety precautions in the UPS system maintenance procedures:

- The system is de-energized by removing the dc input power from the battery, the ac input power to the rectifier/charger, and the alternate ac input power to the bypass switch, as applicable.

- In UPS systems with a bypass switch, it is common practice during maintenance to remove the dc input power from the battery and the ac input power to the rectifier and to supply the load from the alternate ac source by placing the bypass switch in the maintenance bypass position. With this configuration, an ac potential exists at some of the UPS system components. Such components should be identified, and appropriate precautions for working on energized equipment should be called out.
- After de-energizing a UPS or charger system, the stored energy in capacitors should be discharged to prevent accidental shocks. The stored energy can be discharged to ground or preferably by a capacitor-shorting device. Such capacitors should be identified and appropriate precautions taken.
- In a de-energized system, parts such as resistors, transformers, and heat sinks may remain extremely hot for some time after power has been removed. These components should be identified and appropriate precautions taken.
- Procedures should include the plant impact statement and cautions for lifted leads and de-energized circuits.

Key Human Performance Point

After de-energizing a UPS or charger system, the stored energy in capacitors should be discharged to prevent accidental shocks. The stored energy can be discharged to ground or preferably by a capacitor-shorting device.

Key Human Performance Point

In a de-energized system, parts such as resistors, transformers, and heat sinks may remain extremely hot for some time after power has been removed.

Key Human Performance Point

With the bypass switch in the maintenance bypass position, ac voltage exists at some components. These components should be identified and appropriate precautions taken.

8
RECOMMENDED MAINTENANCE PRACTICES

Inverters and chargers, like all electrical equipment, age and deteriorate with time. The aging and deterioration process starts when the system is installed. This process can lead to changes in the system performance, malfunctions, and random failures. A systematic program of surveillance, inspection, and maintenance that includes preventive and predictive maintenance activities can help in identifying performance changes and minimize malfunctions and failures. However, note that for some inverters and chargers, a well-developed corrective maintenance program supplemented by failure trending and/or scheduled replacement may be sufficient.

This section presents recommendations on what constitutes surveillance, inspections, and PM for UPS systems. For each recommended item, this section also presents:

- The purpose
- Degradation and/or failure that may be detected
- Key considerations in performing the item
- Recommended periodicity including the rationale
- Precautions and limitations

The recommendations presented in this section are based on a review of:

- The operating experience
- The system/component failure modes, their underlying mechanisms, and stressors
- The information collected from a utility survey conducted during this project and from discussions with utility maintenance staff
- The current industry maintenance practices and procedures
- Manufacturers' maintenance instruction manuals and service advisories
- The guidance available from EPRI and NRC research reports

Users of this guide should supplement the guidance herein with that from the specific system manufacturer's literature.

Note: The recommended surveillance, inspection, and maintenance activities and their frequencies should not be treated as requirements. They should be reviewed in the context of the plant-specific equipment operating experience and outage schedules and adjusted accordingly.

The central objectives of recommendations presented in this section are:

- To ensure a high level of UPS system reliability, especially as they age
- To preclude unwarranted plant transients and trips
- To enhance plant safety and availability

To this end, this guide avoids drawing any strict boundary between UPS systems used in safety and non-safety applications.

Figure 8-1 shows the recommended periodicity and schedule for surveillance, inspection, maintenance, and condition monitoring activities over a 10-year service period. This is based on an 18-month refueling cycle. These recommendations will vary depending on the plant's refueling cycle and operating experience.

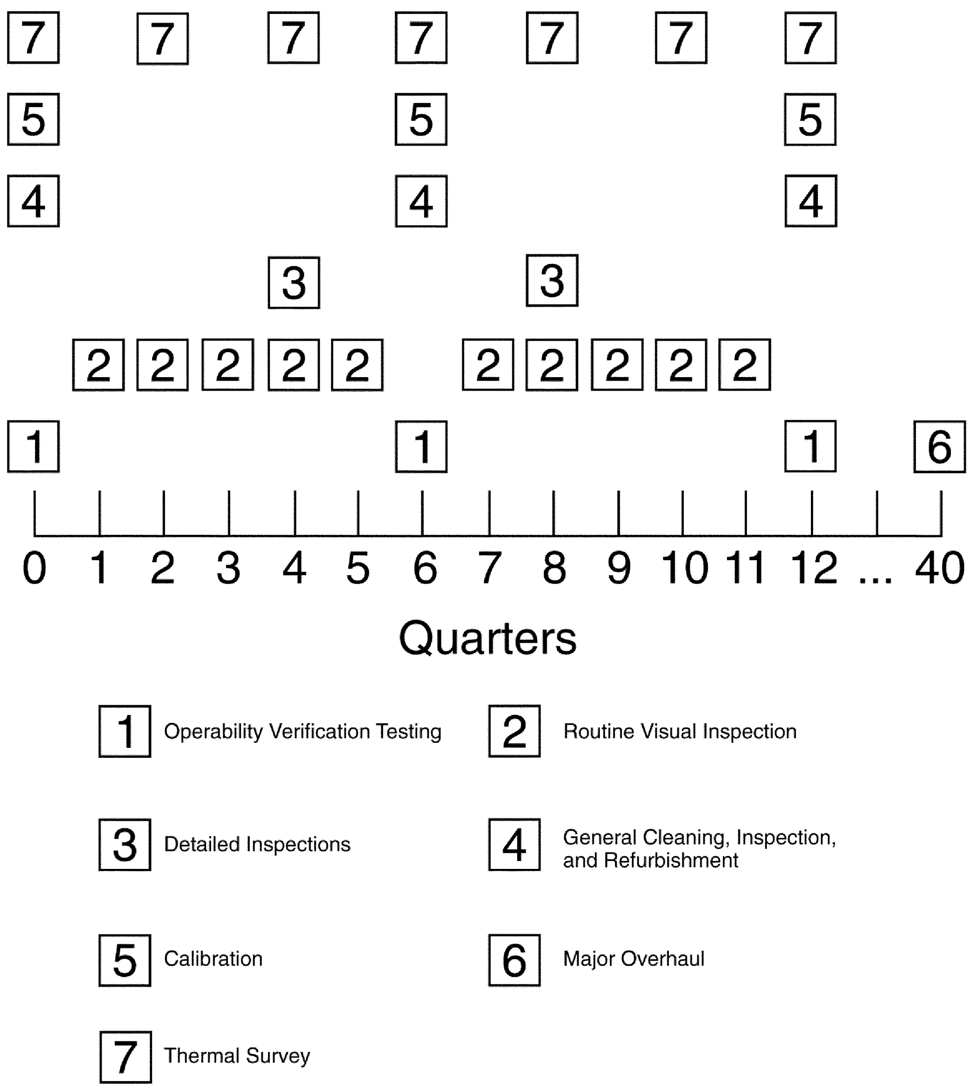


Figure 8-1
Interval Diagram for Recommended Surveillance, Inspection, and Monitoring

8.1 Surveillance

8.1.1 Battery Chargers

Surveillance in the form of operability verification testing is defined in plant technical specifications for battery chargers used in certain safety-related applications. Capacity testing is performed once every refueling cycle by applying the specified ampere loading (not necessarily full rated capacity) for a specified duration. The ampere loading and duration specified in the technical specification are based on meeting the design basis requirements for the chargers. The purpose of this operability verification test includes the following:

- To verify the capability of the chargers to recharge their associated batteries while feeding the connected normal dc bus loads
- To identify and correct any failures/deficiencies that may exist and can potentially affect the safety functional capability of the systems.

The test interval is established to ensure a high probability that the chargers will operate as required between two successive tests.

The degradation and failure modes that can be identified by this operability verification are:

- Defective circuit boards, such as the firing boards, and current and voltage sense boards that are likely to be challenged to their design stress capacity during the test
- Open or shorted electronic components such as diodes and SCRs
- To a limited extent, degraded transformers, inductors, fuses, and capacitors

Proven and time-tested procedures for conducting operability verification tests have been integrated into the respective system level test procedures. Therefore, descriptive steps for performing such tests are not included in this guide. However, one key item worth considering for improving these tests is temperature monitoring.

As discussed in earlier sections, heat is the principal stress that contributes to aging degradation and component failures. A thermal survey is an effective condition monitoring method to address the effects of this principal stressor. It can identify components that are subject to high thermal stresses. It can also pinpoint loose terminations that can lead to intermittent operation or continuously arcing contacts that can lead to reduced component life. Temperature monitoring should include measuring of the cabinet temperature rise and the following critical component operating temperatures:

- Electrolytic capacitors
- Power semiconductors, such as SCRs and rectifier diodes
- Transformers, chokes, power fuses, and fuse blocks.

A probe type, hand-held thermometer may measure the cabinet temperature. Component operating temperatures can be measured using an infrared gun. Trending these temperatures each time a capacity test is performed can help identify incipient failures that might otherwise be undetected until a catastrophic failure occurs. It is believed that the additional time and resources invested in performing these measurements and trend evaluations will be insignificant compared to the potential benefits of avoiding unplanned outages and/or transients caused by unexpected system failures.

8.1.2 Inverters

For the inverters, plant technical specifications contain requirements for restoring the inoperable inverter within a specified time (for example, 8 hours). They do not generally include special surveillance testing requirements. Therefore, with few exceptions, performing inverter capacity tests similar to that for battery chargers is not a common practice in the industry.

As discussed in Section 4, inverters are more likely to experience failures when a rapid change in load occurs than when they are operating at a steady load. Such would likely be the case during a DBE. Further, some incipient failures such as a degraded SCR, capacitor, or transformer are not likely to be detected unless they are challenged to a higher stress level. Such incipient failures are likely to result in catastrophic failures (possible common cause failure) during rapid load changes. Therefore, it is recommended that a 1-hour operability verification testing be considered for the safety-related inverters once every refueling cycle. The criteria in Table 8-1 may be used to determine the need for this separate operability testing and the load at which such test should be performed.

Table 8-1
Criteria for Determining the Need for Separate Operability Testing

Normal Load on the Inverter	DBE Load on the Inverter	Separate OperabilityTest Needed	Recommended Test Load
< 75% of rated capacity	Comparable to normal load	No	Not applicable
> 75% of rated capacity	Significantly below normal load	No	Not applicable
< 75% of rated capacity	< 75% of rated capacity and significantly higher than the normal load	Yes	DBE load +10%
> 75% of rated capacity	> 75% of rated capacity	Yes	Rated capacity

The rationale behind the criteria proposed above is that the system should be able to handle voltage surges, inrush from inductive loads, switching transients, and at least one load circuit fault at a time in conjunction with the DBE loads. The testing, as proposed above, would very likely drive the weak links in the system to their failure point, thus providing early identification of incipient failures and the need for corrective action.

In order to ensure that the static switch works properly, it is recommended that verification of its operation also be included as a part of an operability verification test. This is important since, in some cases, the system is designed to ensure that the fast-acting static transfer switch provides the first level of protection against a load circuit fault. Also, normally a static switch failure will very likely reveal itself only when it is challenged to transfer.

8.2 Inspection

This section covers the inspection activities for inverters and chargers. The inspection activities recommended are intended to provide a general assessment of the condition of the systems and guide decisions related to repair, component replacement, and/or refurbishment.

8.2.1 Routine Visual Inspections

This is a general visual inspection of the internals in the cabinets. The objective is to look for the obvious such as:

- Smoky deposits
- Odor
- Charred parts
- Arcing contacts or connections
- Loose connections
- Noisy cooling fan motor
- Leaky or blistered capacitors

This inspection is intended as a stand-alone activity to be performed by cognizant maintenance personnel. Routine system engineer walkdowns may replace this inspection. The degradation mechanisms addressed by these inspections are: overheating, vibration-induced mechanical degradation, and other visible electrical or mechanical damage. The recommended frequency for performing this inspection is quarterly.

8.2.2 Detailed Inspections

Detailed visual inspection is intended to identify conditions indicative of impending failure. Such inspections should be performed at least once every 12 months by cognizant maintenance personnel. They may be performed with the system energized.

The inspection activities discussed herein are generic in nature and apply to most UPS system makes and designs. They were compiled from a review of several manufacturers' recommendations and utility maintenance procedures. Although, the detailed inspection may be covered as a part of the preventive maintenance activities, it would be preferable to do it between PMs. This will ensure timely identification of potentially detrimental conditions (see Figure 8-1).

Detailed inspections should include the following items, preferably included in a checklist:

- Evidence of thermal degradation that may manifest itself in one or more of the following ways:
  - Cracked discolored coil forms on the magnetics
  - Smoky odor
  - Loose coil or wire insulation flakes or particles
  - Bulging or blistering of capacitor cans
  - Electrolyte or oil leakage or seepage from capacitors
  - Cracked or deformed pressure vent caps on electrolytic capacitors
  - Browning or charring of portions of circuit boards
  - Hardened or deformed insulation on wiring or terminal lugs
- Evidence of mechanical damage as indicated by:
  - Loose parts inside the cabinet
  - Arcing termination
  - Cracked cases or insulator on switches, terminal blocks, relays, or meters
  - Missing or loose mounting screws on terminals or components
  - Broken or about-to-break wiring connections on terminals
  - Excessively noisy fans, chattering of relays, other loud hums as would emanate from a loose transformer or inductor core
- Evidence of insulation or dielectric damage as indicated by:
  - Corona arcing at capacitor terminals or power wiring
  - Arcing contacts
- Evidence of damage from environmental stresses as indicated by:
  - Misty windows (mostly in meters and sealed relays)
  - Corrosion products on contact surfaces or other mechanical parts
  - Excessive dust accumulation on terminals, heat sinks, or transformers
- Evidence of fan cooler filter clogging
- Evidence of circuit/component misalignments or malfunctioning:
  - Measure total harmonic distortion (typically $< 5\%$). It should be noted that a high harmonic distortion might be load induced and not necessarily a problem with the inverter. High harmonic distortion from the inverter output is usually indicative of a problem with the filter components or the source itself, for example, magnetics.
  - Measure ac ripple on the dc link.

The results of the detailed inspections should be documented and reviewed to identify the need for replacement or refurbishment of parts. In addition, the information collected can be used to identify potential misapplication or design deficiencies that could be corrected through appropriate equipment or operating procedure modifications.

8.3 Preventive Maintenance

Preventive maintenance is performed on a planned or scheduled interval as a deterrent measure. Corrective maintenance responds to a failure or malfunction, and repairs the item. For UPS systems, preventive maintenance refers to a collection of activities such as cleaning, inspection, refurbishment, and calibration. They may be performed either singly or in combination, depending upon the specific item and its application.

This section provides recommendations for preventive maintenance activities. Whether they are performed on a planned interval or as a part of corrective maintenance, they require performance in a certain manner with appropriate precautions. Recommended preventive maintenance activities include the following:

- Cleaning, inspection, and refurbishment
- Calibration
  - Meter calibration
  - Set point verification and adjustment

8.3.1 Cleaning, Inspection, and Refurbishment

Cleaning, inspection, and refurbishment of UPS systems can be performed only with the system de-energized and will require a system outage for 8-hours or longer. Although these activities can be performed while the plant is in operation, prudence may suggest performing them only during refueling outages. Thus, the recommended schedule ranges from 18 to 36 months.

Cleaning and dust removal from the UPS system cabinet are essential for reducing the chances of flashover and to avoid overheating of components due to blocked ventilation passages. The purpose of inspection is to detect component overheating and discoloration, increased noise, and

loose connections, which may not immediately interfere with the system performance but may lead to failures later. Items to clean, inspect, and refurbish, include the following:

1. Clean all air filters and replace as needed.

2. Clean dust, dirt, and particles using a lint-free cloth.

3. Vacuum the system cabinet and exteriors of components such as diode/SCR heat sinks, capacitors, transformers, wire-wound potentiometer, and voltage dropping resistors.

Caution: Blowing out dust and debris using dry air is not recommended. It will result in moving the dirt and debris from one location to another and lodge it there securely. This could result in causing contamination and open circuit between relay contacts and connectors.

Key Technical Point

Blowing out dust and debris using dry air is not recommended. It will result in moving the dirt and debris from one location to another and lodge it there securely. This could result in causing contamination and open circuit between relay contacts and connectors.

4. Visually inspect for damaged insulation of components such as power wiring, terminal lugs, coils, and coil forms.

5. Check for tightness of bolted connections and screwed terminal connections for power wiring. Tighten as necessary using the correct size calibrated torque wrench.

6. Check for corrosion of terminals, capacitor cans, holding clamps, fuse blocks, and other components susceptible to corrosion. Clean as necessary. Use only approved solvents for the specific application.

7. Check for electrolyte or oil leakage from capacitors, and replace any damaged capacitor.

8. Check for swelling or blistering of capacitor cans, and replace any damaged capacitor.

9. Check for bulging or deformation of pressure vents on capacitor cans. Replace any damaged capacitor.

10. Check for cleanliness of voltage dropping resistors, and clean as necessary.

11. Check for evidence of arcing damage of fuses and fuse holders. Replace suspect fuses.

12. Check for loose fuse holders. Tighten or replace as necessary.

13. Check for cracks on insulators for busses, power block fuse holders, and power terminals. Replace damaged items.

14. Check for cleanliness of space heaters, and clean as necessary.

15. Check for loose debris such as paper, rags, and cloth at the cabinet bottom. Remove as necessary.

16. Inspect sealed relays (also known as ice cube relays) on circuit cards, such as the Potter and Brumfield relays, for discoloration or cracking.

17. Check the multi-position switches, such as the equalize and float transfer switch, for evidence of mechanical damage. Check for smooth operation and proper positioning. Check electrical contacts using a multi-meter.

18. Check and adjust fan failure and cabinet overtemperature shutdown and/or alarm thermostats.

19. Check and adjust the equalizing timer.

20. Check the slider of all accessible wire-wound potentiometers for cleanliness and tightness. Clean and adjust as necessary.

21. Inspect the power semiconductors (that is, SCRs and diodes) including their braided wire connections for cleanliness and corrosion. Clean as necessary. Inspect the gate leads for insulation integrity. Ensure that they are mounted securely by checking the torque using a calibrated torque wrench.

22. Check circuit boards for evidence of overheating by inspecting the temperature dots on each card when provided. Look for discoloration (that is, browning or charring around wire wound resistors or power components), cracking, and embrittlement. Check the card-edge connections for cleanliness and integrity. If the temperature dots have changed color, follow specific manufacturer recommendations. Also, check the electrolytic capacitors on circuit boards for evidence of leakage or deformation.

23. Check plug-in type relays for proper seating.

8.3.1.1 Lubrication

1. Most of the cooling fans used in UPS and charger equipment have sealed bearings and, therefore, should not require lubrication. If not, add oil or grease to fan motors as needed.

Caution: Do not attempt to lubricate sealed bearings. The motor nameplate usually indicates which bearings are sealed and which bearings require lubrication. If not indicated on the motor nameplate, consult the vendor manual.

Note: Some manufacturers recommend periodic replacement of the fan cooler units as a whole.

2. Rotate the fans by hand to check the condition of the bearings. Check for free and smooth movement.

Note: Checking fan rotation should be done after the UPS system has been down long enough for the bearings to cool. Worn-out bearings will tend to bend when cool.

8.3.1.2 Component Replacement

Replace limited life components that are due for replacement at this time. Examples of limited-life components that need periodic replacement include:

- Capacitors
- Fuses
- Cooling fans
- Circuit boards
- Normally lit neon lights
- Relays
- SCRs
- Diodes

Generally, utilities have established periodic component replacement requirements based on manufacturer's qualification test information.

Tips on Component Replacement

- Several parts may look alike. Make sure to locate the correct item in the cabinet by using the manufacturer's cabinet layout drawing and bill of material.
- When replacing a capacitor that has failed in a bank, check all the capacitors in the bank for proper capacitance value. It may be prudent to replace the entire bank because a single capacitor failure may be indicative of aging.
- Before installing new capacitors, they should be checked for manufacture date, proper value of capacitance, and leakage current.
- Electrolytic capacitors that have been in storage for more than six months or longer may require reforming or reconditioning. Consult the capacitor supplier for the specifics. Generally, this is done by applying 100 to 110% of rated dc voltage to the capacitor connected to a series current limiting resistor for several hours (may be up to 4 hours) until the leakage current decreases. Several capacitors may be reconditioned at once by connecting the RC combination in parallel across a power supply. Be sure to discharge the capacitors after the reconditioning is complete.

When replacing electrolytic capacitors, consideration should be given to replacing them with ones rated for 105°C and 450 Vdc if the existing ones are rated for less than these values. Such substitution should only be done only after a documented engineering evaluation of the critical characteristics.

Verify proper mounting of the capacitors. Some capacitors are not suitable for horizontal mounting.

- When replacing ac capacitors used in commutating applications, make sure that the capacitors are correct for the application. Commutating capacitors are designed for a higher surge withstand capability than normal ac capacitors of the same value and voltage rating.
- When replacing power semiconductors (that is, SCRs and diodes), be sure to:
  - Clean both mounting surfaces thoroughly.
  - Apply the conductive grease evenly on both mating surfaces.
  - Torque the device down to the specified torque using the correct size calibrated torque wrench.
- One utility reported that checking the peak inverse voltage (PIV) of power semiconductors before installing them could ensure that they are correct for the application. This practice may be useful in eliminating installation of semiconductors that have low PIV, which can lead to premature failures. One manufacturer reported that their critical characteristic verification as part of dedication includes a check of the PIV (also known as a leakage test). The same manufacturer also stated that although they have not encountered any failures on this attribute, it is believed that additional confidence in the item can be gained by this easy-to-do test.
- Replace fuses only with those of identical rating unless justified otherwise by a documented engineering evaluation.
- When replacing any component, make sure that the item is the correct one for the application by comparing the manufacturer's drawing, bill of material, the procedure, and the part number on the item.

8.3.2 Calibration

This section describes the component calibration and adjustments required.

8.3.2.1 Meter Calibration

Indicating meters on the local system panel and in the control room should be calibrated, as a minimum, once every 24 to 36 months. It may be convenient to combine this with every other scheduled PM on the system. This calibration may be performed in place by applying a simulated signal to the meter.

8.3.2.2 Set Point Verification and Adjustment

After cleaning, inspection, and refurbishment (as described in Section 8.3.1), the unit should be powered up according to the established startup procedure. Then the set points for the applicable control and alarm parameters listed below should be verified and adjusted as required:

- Rectifier/battery charger dc voltage level
- Low dc voltage
- Overload
- Output ac bus overvoltage
- Output ac bus undervoltage
- Inverter synchronization
- Inverter frequency setting
- Inverter output voltage setting
- Instantaneous overcurrent
- Current limiting function
- Charger failure
- Fan failure
- Cabinet overtemperature
- Ground detection
- Static switch transfer time

Some set point verification tests outlined below may be performed by testing components in-place or bench testing, or as part of a system level test using a load bank.

Note: The set point verification and adjustment tests described below are generic to many UPS systems in use today. The specific method of performing each test for any given plant system will depend upon the specific test objective and system configuration. Consult your plant-specific vendor manuals and system drawings to decide on the best method for your plant equipment.

Rectifier/Battery Charger dc Voltage Levels

This test is applicable to a rectifier/battery charger. It is intended to verify the accuracy of the voltage adjustment potentiometer and the functional performance of the dc-dc converters supplying the control and logic boards within the rectifier/battery charger.

Low/High Input dc Voltage

This test is applicable to a rectifier/battery charger and the battery bus section of the UPS. It is intended to verify the functional performance and settings of the inverter low dc voltage alarm and shutdown devices. The test for low dc voltage from the rectifier, if one is provided, is performed by varying the rectifier output voltage adjust potentiometer and monitoring the corresponding voltage sense board output. The test for low dc voltage from the battery is performed by applying a dc voltage to the corresponding voltage sense board using a variable dc source and checking the output contacts or alarm indications. Adjustments, if needed, are performed through the potentiometer on the respective voltage sense boards. Similarly, if so equipped, the high dc input voltage alarm should also be checked and adjusted.

Overload Alarm

This test is intended to verify the functional performance and setting of the inverter/charger/rectifier overload alarm device. It is performed using a load bank to gradually increase the load and verifying the load levels at which the overload alarm occurs.

Output ac Bus Overvoltage

This test is applicable to UPS systems with or without a static transfer switch. It is intended to verify the functional performance and setting of the inverter output overvoltage alarm, shutdown, and transfer features as applicable. The test is performed by increasing the inverter output voltage through the voltage adjustment potentiometer and monitoring the corresponding voltage sense board outputs. If a static transfer switch is used, then the voltage variation is continued until reverse transfer (that is, transfers to the alternate source) occurs. Then, the inverter output voltage is slowly decreased to verify the forward transfer (that is, transfer back the inverter) if the system is equipped with automatic retransfer feature.

Output ac Bus Undervoltage

This test is applicable to UPS systems with or without a static transfer switch. It is intended to verify the setting of the undervoltage alarm, shutdown, and transfer feature as applicable, and verify the operation of the transfer device if one is provided. The test is performed by reducing the inverter output voltage through the voltage adjustment potentiometer and monitoring the output of the undervoltage sense board. If a static transfer switch is used, then the voltage variation is continued until reverse transfer (that is, transfer to the alternate source) occurs. Then the inverter output voltage is slowly increased to verify the forward transfer (that is, transfer back the inverter) if the system is equipped with automatic retransfer feature. It is recommended that the manufacturer be consulted when establishing a procedure to perform this transfer time test.

Inverter Synchronization

This test is applicable to UPS systems with a static transfer switch. It is intended to verify that the inverter operates at the same frequency as the bypass source and that the output voltage is in phase with the bypass source voltage. The test is performed by monitoring the inverter output and the bypass voltage waveforms using an oscilloscope and adjusting the inverter output voltage phase on the phase control board when needed.

Inverter Frequency

This test is applicable to UPS systems with or without a transfer switch. It is intended to verify that the built-in oscillator controls the frequency within the required tolerance when the inverter is not synchronized to a bypass source. For UPS systems with a bypass source, this test can be performed after the bypass source input breaker is opened. Frequency adjustment, when required, is done through the frequency adjustment potentiometer on the frequency control board.

Inverter Output Voltage

This test is applicable to pulse width control or PWM type inverters. It is intended to verify the inverter output voltage potentiometer set point.

Instantaneous Overcurrent

This test is applicable to pulse width control or PWM type inverters. It is intended to verify the setting and functional performance of the inverter's instantaneous over-current shutdown device if one is provided. It is performed using a load bank to increase the load on the inverter and verifying the current level at which the inverter shuts down.

Current Limiting Function

This test is applicable to pulse width control or PWM type inverters. It is intended to verify the setting and functional performance of the inverter output current limiting device. It is performed using a load bank to increase the load on the inverter until the current limit is reached. A decreased output voltage followed by a rapid step decrease in current indicates the current limit.

Fan Failure and Cabinet Overtemperature

This test applies to systems equipped with features for alarming and/or shutdown interlocks based on either fan failure or cabinet high-temperature conditions or both. It is intended to verify the setting and functional performance of the respective sensors and circuits. The test is performed by manually exercising the paddle type flow switch or using a heat source to warm the thermostat while monitoring the output contacts.

Ground Detection

This test is applicable to UPS systems equipped with a ground fault alarm feature. It is intended to verify the setting and functional performance of the ground fault sensors and circuits. The test is performed by varying the resistance of a decade resistance box connected between the system output terminal(s) and ground to actuate the alarm.

8.3.2.3 Tips on Set Point Adjustment

- Obtain the correct set points including applicable tolerance from the set point list if one is not specified in the procedure.
- Ensure that the correct PC board and/or potentiometer are selected before making any adjustments. In addition to keeping the vendor manuals current, it may be useful to label them in the cabinet and the procedures using the vendor layout drawings. If configuration control practices and procedures preclude such item-specific labeling, consideration should be given to including detailed sketches with component location and identification in the procedures.
- When a load bank is used, ensure that the area is well ventilated and that the bank is set up away from other equipment and cables, cable trays, or conduits overhead.
- When using a decade resistance box for a ground detector check, ensure that the resistance selector switch is set to maximum resistance before connecting it to the system.
- In some cases, the manufacturer's instruction manual may caution against field adjustments. In such cases, before performing adjustments on circuit boards and potentiometers, consult the manufacturer.

8.3.3 Major Overhaul

By virtue of their circuit complexity, ensuring optimal and reliable performance of the UPS systems requires a careful alignment of the internal circuit parameters. Examples of such parameters include:

- Waveforms at different stages
- SCR or thyristor turn-on and turn-off times
- Firing duration
- Ferroresonant transformer tank circuit parameters
- Sensing speed for control parameters such as overvoltage, underfrequency, and overload

As originally installed, these adjustments were made by the original equipment manufacturer at the factory. They were probably adjusted again during the plant startup. Then the internal component characteristics were in their as-new condition. Over a course of time in service, the component characteristics change due to aging and piecemeal component replacements during corrective and preventive maintenance activities. After several years in service, the cumulative effect is a system that may be out of tune unless careful alignments were performed each time a component is replaced.

By design and application, UPS systems have a high inherent tolerance for a fair amount of misalignments of circuit parameters and thus do compensate for them. Therefore, a complete system retuning is not always required or desirable each time a component, such as a failed capacitor in a bank or a failed circuit board, is replaced. Prolonged operation under a misaligned condition will affect the performance of individual components over the long term and potentially cause an increase in system failures.

Review of the UPS failure experience suggests a higher rate of system failures as the system ages (see Section 5). A periodic major overhaul that restores the system to as near its like-new condition as practical could improve their operational reliability and extend the installed life. It is, therefore, recommended that a major overhaul once every 10 to 12 years be included in the utility's preventive maintenance program for UPS systems.

Key Technical Point

It is recommended that a major overhaul to restore the UPS to its like-new condition once every 10 to 12 years be included as part of the preventive maintenance program.

However, for the inverters and chargers purchased in the mid-1970s and with a poor performance history, it may be cost effective to replace them. The rationale here is that:

- There have been significant technology changes since the late 1970s.
- There have been significant changes in equipment qualification practices around the late 1970s that led to changes in equipment design configuration. Examples include upgraded temperature rating of magnetics to 220 from 160°C, and reduction in the circuit component design stress ratios to 60% or less.
- Replacement parts for older designs may become cost prohibitive or just unavailable.
- There has been a significant improvement in technology since the mid-1970s that has resulted in increased equipment reliability.

Key O&M Cost Point

There has been a significant improvement in technology since the mid-1970s that has increased equipment reliability. It would, therefore, be prudent to evaluate the cost benefits of installing replacement parts or replacing both inverters and chargers, especially if they have a poor performance history.

Also, the present loading on these systems may be significantly higher than the original plant design; thus, a capacity upgrade may be justified. However, the decision to replace should be made considering the failure experience, availability of spares, and vendor support.

A major overhaul should include the following:

- Replacement of certain vital circuit boards (for example, firing boards, some relay boards, high-voltage and current limit sense boards), fuses, capacitor banks, and SCRs.
- Retuning of the system.
- A set of before and after overhaul load tests at normal operating load and at rated load. Vital system performance (for example, output voltage, frequency, harmonic distortion, limit settings) and design (for example, component operating temperatures, waveform, SCR switching parameters) parameters should be measured during these tests. The post-overhaul

tests should be run for at least 1 hour before taking data. The results from these tests would form the basis for trending of system/component performance until the next test.

Key Technical Point

Ferroresonant type UPS units should be run for at least 1 hour prior to taking vital performance measurements.

Note: Ferroresonant type UPS units may require a continuous run of 12 to 24 hours prior to reaching a stable output. When cold, the output voltage of a ferroresonant transformer will be higher than when hot. However, the stabilization is complete after approximately 2 hours of being energized.

Such an overhaul is perhaps best done by the original equipment manufacturer because of the need for specialized knowledge and skills on the system, the use of sophisticated test equipment, and interpretation of waveform data.

8.4 Condition Monitoring

A well-developed, condition-monitoring program can be a useful adjunct to the PM in order to ensure the timely identification of problems that are indicative of impending failures. Based on the trend information from the condition-monitoring program, corrective actions can be initiated to ensure improved reliability and extended operating life of the systems. As discussed in earlier sections, heat is the principal stress that contributes to the aging degradation of many components.

This guide recommends that a thermal survey of selected critical components and set point trending form the core of this condition-monitoring program. Other condition monitoring techniques, such as trending of capacitance measurements, monitoring of SCR output, and bridge output waveforms, may provide additional information, but the results cannot be justified considering the time demands and complexity of the tests.

8.4.1 Thermal Survey

A thermal survey is an effective condition-monitoring method to address the principal stressor. This survey can identify components that are continuously subject to high thermal stress. It can also pinpoint more specific component degradations as discussed elsewhere in this section. Much of the thermal survey can be performed using contact probe or infrared thermography instruments. The monitored data and images can be stored on a computer for trending. Refer to the EPRI report *Infrared Thermography Guide*, NP-6973, Rev. 1.

The inverter and charger system components that should be considered for a thermal survey include the following:

- Ferroresonant transformer coils
- Electrolytic capacitors, including their termination studs

- SCRs and power diodes
- Power fuses, including the fuse holders
- Continuously energized dc relays
- Bus connections
- Power cable terminations

An initial survey should be conducted of these components while the systems are loaded at their normal and worst case design basis loads. If the margin between the worst case load and the rated load capacity of the system is less than 25%, then using the rated load instead of the worst case load is preferable. The rationale is that the system should be able to handle the expected transients, including low main feeder bus voltage, and load side surge and inrush. These conditions challenge the components more than the design basis load applied by itself. The surveys should be repeated once every 12 months.

The results from this initial survey should be compared with the rated component operating temperatures to identify components whose operating temperatures have insufficient margin. Such conditions may be indicative of impending component failures and may call for either frequent monitoring or outright replacement. Table 8-2 provides examples of typical component temperature rating and their expected operating temperature at rated load based on the equipment designers' selection criteria.

Table 8-2
Typical Component Temperature Rating

Component Type	Normal Operating Temperature with 30°C Ambient	Rated Temperature with 30°C Ambient
dc electrolytic capacitors	~ 55°C	85°C
ac capacitors	~ 55°C	85°C
SCRs	~ 100°C at the case	130°C at the junction
Ferroresonant transformer Newer systems (post-1980) Older systems (pre-1980)	 ~ 180°C ~ 150°C	 ~ 220°C ~ 180°C
Choke Newer systems (post-1980) Older systems (pre-1980)	 ~ 85°C ~ 85°C	 ~ 220°C ~ 160°C

Note: The ratings given in Table 8-2 are typical values. Component temperature ratings and selection criteria vary widely from manufacturer to manufacturer. Consult plant-specific documents to establish the ratings for the components used in your plant systems.

In addition to the initial survey, a semiannual thermal survey is recommended for critical components to trend their operating characteristics and identify incipient failures that might otherwise be undetected. Examples of incipient failure conditions include the following:

- Loose terminations
- Loose electrical connections (for example, misaligned relay contacts, improperly torqued SCR, poor slider contacts on potentiometer)
- Degraded electrolytic capacitors
- Degraded ferroresonant transformers and inductors
- Degraded fuses
- Degraded power semiconductors

The next two sections provide some tips for conducting a thermal survey. For additional guidance, consult the EPRI report *Infrared Thermography Guide*, NP-6973, Rev.1.

8.4.1.1 Tips on Performing Thermal Survey

- Make sure that the measured area completely fills the instantaneous field of view of the instrument.
- Take measurements at a perpendicular angle to minimize reflections.

- To ensure accuracy, determine the target emittance values for the different components, and use them consistently.
- Take the readings as close to the component as practical.
- For identical components, as far as practical use the same distance to the target and emittance settings.
- For each item, take at least three readings, one each looking in from front or top and at 45° from left and right. If the data show wide variation, additional readings may be required.
- Use a line diagram of the target, and document the positions and target distances from where the baseline readings were taken. Future readings should be taken from the same positions to ensure a valid comparison.
- Following an extended shutdown, the system should be stabilized by operating it for 2 to 3 hours before performing the thermal survey.

8.4.1.2 Tips on Using Thermal Survey Information

A gradually increasing temperature trend would indicate a problem. The exact nature of the problem would depend upon the specific component being monitored. Some examples are listed below:

- In an SCR, a gradually increasing temperature trend may be indicative of higher junction operating temperatures caused by:
  - Increased leakage
  - Poor heat dissipation
  - Improper torquing
- In an electrolytic capacitor, a gradually increasing temperature trend may be indicative of:
  - Increased leakage
  - Poor heat dissipation
  - High ripple current
  - Core shorting
  - Loss of electrolyte
- In a transformer, a gradually increasing core or winding temperature trend may be indicative of:
  - Poor heat dissipation
  - Degraded coil insulation
  - Loose core lamination
  - Bad tank circuit capacitor

Section 4 provides a detailed discussion of the possible causes for overheating of various components.

For components included in an ongoing thermal survey program, the action level classifications shown in Table 8-3 may be used.

Table 8-3
Recommended Action Level Classification for Thermal Survey

Action Level	Temperature Difference	Recommended Action
Advisory (Level 1)	~ 5°C	Item to watch. Perform a survey again within the next 3 months. If the temperature rise continues or shows an increasing trend, initiate a corrective maintenance work request to attend to the problem at the next available opportunity.
Serious (Level 2)	6 to 15°C	Item to watch. Initiate monthly survey. If the temperature rise continues or shows an increasing trend, initiate corrective maintenance to attend to the problem as soon as practical

The problem classification levels recommended above are more conservative than those general levels recommended in EPRI report *Infrared Thermography Guide*, NP-6973, Rev. 1. This conservatism is justified based on the operating characteristics and aging effects of the electrical components under consideration.

8.4.2 Set Point Trending

Trending the as-found and as-left set points from each calibration is an effective way to monitor drifts in electronic circuits caused by component tolerance changes or other incipient failures. A continuously increasing or decreasing trend suggests a set point drift problem that would likely require a change out of the associated circuit cards. The EPRI report *Guidelines for Instrument Calibration Extension/Reduction – Revision 1: Statistical Analysis of Instrument Calibration Data*, TR-103335-R1, provides additional discussion on evaluating set point trend data and data analysis.

8.5 Data Collection and Record Keeping

Data collection and record keeping for the maintenance and condition monitoring activities on UPS systems should include the following:

- Inverter output current
- Inverter output voltage
- Inverter frequency
- Status of indicating lights

- Battery input dc voltage
- Charger output dc voltage
- Rectifier output dc voltage
- Normal ac source voltages
- Alternate ac source voltages
- ac ripple on dc line
- Output total harmonic distortion
- Selected component operating temperatures at normal and design basis load conditions (see Section 8.4.1 for a list of components)
- As-found and as-left set points for all parameters that perform control and alarm functions
- Operability verification test data

8.6 Precautions

Maintenance procedures should include precautions, cautionary alerts, or specific warnings as appropriate to address the following:

- Exercise caution around large resistors and heat sinks because high temperature may be present.
- Care should be exercised when working on these systems as long as any potential is applied to the system. Even with the input circuit breakers turned off and with the manual maintenance bypass switch (when provided) in the off position, power potentials may be present at the breaker and/or switch terminals.
- Care should be exercised since ac power for space heaters may be on.
- Ferroresonant type inverters should not be operated at no load and/or high dc input voltage (that is, 140 Vdc on a 125 dc) for long durations. Operating the inverter in this mode for longer than 72 hours may cause overheating of the ferroresonant transformer and possible damage.
- Following an extended shutdown, the systems should be operated for at least 2 to 3 hours before recording data.
- Inverters are commonly ungrounded. When measuring voltage in an ungrounded inverter, the neutral should be used as the reference; power ground should not be used as the reference.
- Test equipment should be isolated from power ground using an isolator plug or a differential amplifier. Failure to isolate from power ground may result in severe damage to the UPS system.
- Exercise caution when working with ungrounded test equipment since the equipment case will be hot with respect to ground.

- Exercise caution when disconnecting and connecting wiring in a de-energized UPS system. High voltage may be present due to an existing capacitor charge. Capacitors should be discharged by using a capacitor discharge device such as connecting a 120 V, 10-watt light bulb across the capacitor terminals.

Key Human Performance Point

Caution should be exercised when disconnecting and connecting wiring in a de-energized UPS system. High voltage may be present due to a existing capacitor charge. Capacitors should be discharged by using a capacitor discharge device such as connecting a 120 V, 10-watt light bulb across the capacitor terminals.

- When using meggar for testing capacitors for breakdown under high voltage, select the proper voltage based on the capacitor rating. While some capacitors can be meggared at 1,000 Vdc, others can be meggared only at 250 Vdc. The procedure should specifically call out the voltage to be used whenever practical.
- All access panels, component covers, and hold-down clamps removed should be replaced securely with all screws properly tightened. Loose or missing covers and the like can jeopardize the heat removal and seismic functional capability of the system.

8.7 Summary

For PM tasks and their degradation mechanisms, see Table 8-4

In addition, perform routine visual inspections at least once a quarter with a major system overhaul once every 10 to 12 years.

A condition-monitoring program that includes a periodic thermal survey of selected components and set point trending should supplement any maintenance. Finally, after about 20 years of service, it may be prudent and cost effective to replace the inverters and chargers.

Table 8-4
PM Tasks and Their Degradation Mechanisms

		PM Task	**Operator Rounds**	**Thermography**	**Clean and Inspect**	**Component Replacement**
		Interval	**Shift**	**1 to 2 Years**	**2 to 3 Years**	**5 to 10 Years**
Failure Location	**Failure Time**	**Degradation Mechanism**				
Electrolytic Capacitors	Random, many years	Dielectric breakdown	X		X	X
	Random	Leaking dielectric	X		X	X
Input/output Filter Choke and Commutating Chokes	Expect to be failure free for > 10 years, some random	Shorted, will eventually lead to open circuit of the choke windings	X	X	X	
Input Breaker		Refer to *PM Basis Report,* TR-106857, Vol. 4, on motor control centers				
Input Fuse	Failure free for > 10 years	Open circuit	X		X	X
Power Semiconductor Components	Random and rapid	- Shorted - Open circuit	X		X	
Oil Filled Capacitors	Failure free for >10 years, some random	Dielectric breakdown	X			X
	Random, rapid	Leaking dielectric	X		X	

Table 8-4 (cont.)
PM Tasks and Their Degradation Mechanisms

		PM Task	Operator Rounds	Thermography	Clean and Inspect	Component Replacement
		Interval	**Shift**	**1 to 2 Years**	**2 to 3 Years**	**5 to 10 Years**
Failure Location	**Failure Time**	**Degradation Mechanism**				
Transformer	Failure free for >20 years, some random	Insulation degradation	X	X	X	
	Random	Loose connections		X	X	
	Failure free for >10 years	Mechanical degradation	X	X	X	
Printed Circuit Boards - Firing circuit - Alarm - Auxillary circuits - Current limit	Failure free for 5 to 10 years, some random	Failure			X	X
	Failure free for 1 to 5 years	Drift			X	
Metering Instruments (that is voltmeter, ammeter, status lights, ground detectors)	Random on a scale of 3 to 5 years	Drift	X		X	

Table 8-4 (cont.)
PM Tasks and Their Degradation Mechanisms

		PM Task	Operator Rounds	Thermography	Clean and Inspect	Component Replacement
		Interval	**Shift**	**1 to 2 Years**	**2 to 3 Years**	**5 to 10 Years**
Failure Location	**Failure Time**	**Degradation Mechanism**				
Timer	Random	Misadjusted or failed			X	
Float and Equalize Potentiometers and Switches	Failure free for 5 to 7 years	Wear				
Muffin Fans	Failure free for 10 years	Failure of the motor or motor bearing	X		X	X

A
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B
GLOSSARY

Blocking Diode - A diode used in a UPS system to prevent the flow of current from the rectifier to the battery.

Bridge Rectifier Circuit - A full-wave rectifier with four rectifying elements connected as the arms of a bridge circuit.

Calibration - Making adjustments necessary to bring operating characteristics into substantial agreement with standardized scales or marking.

Cathode - The electrode by which currents leave the thyristor when the thyristor is in the on state with the gate open-circuited.

Current Limiting - A control function that prevents a current from exceeding its prescribed limits.

Diode - A semiconductor device having two terminals that will conduct electric current in one direction and provide a high resistance in the other direction.

Equalizing Charge - An extended charge to a measured end point that is given to a storage battery to ensure the complete restoration of the active materials in all the plates of all the cells.

Filter - A network of inductors and capacitors designed to eliminate signals with selected frequencies.

Gate - An electrode connected to one of the thyristor semiconductor regions for introducing control current.

Infrared Thermography - A non-intrusive method of determining surface temperature by measurement of the radiated heat.

Isolation - The value of insulation resistance, dielectric strength, and capacitance measured between the input to case, output to case, inputs and outputs, and output to output as applicable.

Isolating Transformer - A transformer inserted in a system to separate one section of the system from undesired influences of the other sections.

Inverter - A system that changes direct-current (dc) power to alternating-current (ac) power.

Junction Operating Temperature - The temperature at which a semiconductor junction operates.

Oscillator - An electronic device for producing ac with maintained frequency that is determined by the characteristics of the device.

Qualified Life - The period of time for which satisfactory performance can be demonstrated for a specific set of service conditions.

Rectifier Assembly - A complete unit containing rectifying components, wiring, and mounting structure capable of converting ac power to dc power.

Regulating Transformer - A transformer used to vary the voltage of an output circuit controlling the output within specified limits, and compensating for fluctuations of load and input voltage within specified limits.

Ripple - The ac component from a dc power supply arising from sources within the power supply.

Set Point - A predetermined point within the range of an instrument where protective or control action is initiated.

Stressor – An agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation.

Surge Suppressor - A device operative in conformance with the rate of change of current, voltage, and power to prevent the rise of such quantity above a predetermined value.

Synchronism - The state where the UPS system operates at the same frequency as the bypass source and where the phase-angle displacement between their voltages is constant and kept at a predetermined level.

Synchronizing - The process whereby the UPS system, with its voltage and phase suitably adjusted, is paralleled with the bypass source.

Synchronizing Light - An indicating light that lights when the UPS system and the bypass source are within the desired limits of frequency, phase angle, and voltage.

Thyristor - A semiconductor device comprising three junctions that can be switched from the off state to the on state or vice versa.

Transfer Time - The time interval between opening the closed contact and closing the open contact of a break-make contact form.

Transfer Switch - A device for transferring one or more load conductor connections from one power source to another.

Troubleshoot - Action taken by operating or maintenance personnel, or both, to isolate a malfunctioned component of a system.

Triode AC Switch (TRIAC) - Refers to a gate controlled semiconductor device, usually called a thyristor triode, used to switch ac loads.

Turn-off Time - Defined as the time that must elapse after forward current through the device has ceased before the forward voltage may again be applied without turn-on.

Varistor - A two-terminal, resistive element composed of an electronic semiconductor and suitable contacts, which has a markedly nonlinear volt-ampere characteristic.

Zener Diode - A class of silicon diodes that exhibit in the avalanche-break-down region a large change in reverse current over a narrow range of reverse voltage.

C
OVERVIEW OF NRC RESEARCH AND VENDOR DOCUMENTS

This appendix presents a summary of:

- Selected regulatory requirements and guidelines governing the design, installation, maintenance, and testing of inverters and chargers.
    - It should be noted that not all regulatory requirements or recommended practices discussed here apply to every nuclear plant since the specific plant system design establishes the extent to which a UPS or a battery charger fulfills a safety function. Each facility must determine the applicability of these requirements to its specific configuration, as well as determine its level of commitment to regulatory documents such as Nuclear Regulatory Commission (NRC) Regulatory Guides. Also, the NRC Regulatory Guides are not always updated when the applicable Institute of Electrical and Electronic Engineers (IEEE) standards are revised. Consequently, some Regulatory Guides refer to superseded or withdrawn IEEE standards. The latest IEEE standards should be consulted and a judgment made regarding the applicability of a Regulatory Guide based on the plant licensing commitments.
- The results of the related research/testing sponsored by EPRI and the NRC.
- Inverter and charger problems identified by NRC Generic Communications (that is, Notice, Bulletin) and Vendor Advisories (for example, Westinghouse Technical Bulletin).

C.1 Regulatory Requirements and Guidance

C.1.1 Electric Power Systems, 10CFR 50, Appendix A, General Design Criterion 17

Criterion 17 specifies the requirements for the design of the on-site power systems, which include the UPS inverter and the battery charger. The requirements include single failure capability, independence, and redundancy.

C.1.2 Inspection and Testing of Electric Power Systems, 10CFR 50, Appendix A, General Design Criterion 18

Criterion 18 specifies the design requirements for testability of the on-site power systems, which include the UPS inverters and battery chargers.

C.1.3 Criteria for Safety-Related Electric Power Systems, Regulatory Guide 1.32

Regulatory Guide 1.32 provides guidance on acceptable methods for demonstrating compliance with the General Design Criteria 17 and 18. This guide endorses the requirements of the industry standard IEEE 308-74, subject to certain modifications. One such modification concerns the battery charger. It states that the battery charger capacity should be determined based on the largest combined demands of the various steady-state loads and the capacity to restore the battery to its fully charged condition from the design minimum charge, irrespective of the plant status when the such demand occurs.

C.1.4 Instrumentation for Light-Water Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident, Regulatory Guide 1.97

Regulatory Guide 1.97 provides guidance on acceptable methods for complying with General Design Criteria 13, 19, and 64. With respect to the UPS and the battery charger, this guide:

- Lists the variables (that is, voltages, currents) required to monitor the system status under type D post-accident monitoring variables
- Provides minimum design requirements that should be met for monitoring instrumentation.

C.1.5 Periodic Testing of Electric Power and Protection Systems, Regulatory Guide 1.118

This guide endorses the requirements of IEEE standard 338-1977 subject to certain modifications involving the test configurations and performance. Although they are not specific to inverters and chargers, this guidance should be reviewed when developing the technical specification surveillance test procedures for operability verification testing of inverters and chargers.

C.1.6 Criteria for Power, Instrumentation, and Control Portions of Safety Systems, Regulatory Guide 1.153

This guide endorses the industry standard IEEE-603-1980 subject to certain regulatory positions. The regulatory positions modify the IEEE-603 requirements regarding post-accident monitoring instrumentation and terminologies. It also states that the endorsement is limited only to IEEE-603 and excludes others referenced therein.

C.2 Industry and NRC Sponsored Research

C.2.1 Industry Sponsored Research

Investigation of Instrumentation and Control (I&C) Power Supply Failures

A 1981 study by EPRI and the Nuclear Safety Analysis Center (NSAC) investigated the failures of I&C power supply hardware and concluded that the biggest contributor to their failures was the inverter component failure. Capacitors and fuses were identified as the principal contributors. The most common causes of component failure were excessive temperature, currents, and voltages. Other factors that could also affect the life of the parts are humidity, temperature cycling, thermal, and mechanical shocks. The main causes of capacitor failures were ripple currents, current pulses, overvoltages, surge voltages, heat, vibration, and lack of ventilation. The main contributors to fuse failures were incorrect fuse application, improper branch circuit protection, and fatigue. This report also identified that the following measures can significantly improve inverter reliability:

- Use capacitors certified for higher temperatures, voltage, and currents encountered in I&C systems
- Undertake periodic capacitor replacement program
- Use high quality and high capacity components
- Monitor temperatures within inverter cabinets
- Improve protection coordination

C.2.2 NRC Sponsored Research

The Nuclear Plant Aging Research (NPAR) program was initiated by the NRC to investigate aging effects on installed equipment in nuclear power plants. The general objectives of the NPAR program, as explained in NUREG-1144, include the following:

- Identify and characterize the aging and service-wear effects associated with electrical and mechanical components, interfaces, and systems likely to impair plant safety.
- Identify and recommend methods of inspection, surveillance, and condition monitoring of electrical and mechanical components and systems that will be effective in detecting significant aging effects before loss of safety function so that timely maintenance and repair or replacement can be implemented.
- Identify and recommend acceptable maintenance practices that can mitigate the effects of aging and diminish the rate and extent of degradation caused by aging and service wear.

The NPAR program included a two-phased research and testing effort on the aging and reliability of inverters and battery chargers. The three NUREG documents listed below present the results from this effort.

- U.S. Nuclear Regulatory Commission. *Operating Experience and Agency-Seismic Assessment of Battery Chargers and Inverters*. NUREG/CR 4564, June 1986.
- U.S. Nuclear Regulatory Commission. *Detecting and Mitigating Battery Charger and Inverter Aging*. NUREG/CR 5051, August 1988.
- U.S. Nuclear Regulatory Commission. *Testing of a Naturally Aged Nuclear Power Plant Inverter and Battery Charger*. NUREG/CR 5192, September 1988.

The conclusions and recommendations presented in these documents are discussed in the following sections.

U.S. Nuclear Regulatory Commission. *Operating Experience and Aging-Seismic Assessment of Battery Chargers and Inverters*. NUREG/CR 4564, June 1986.

This report documents the results of an evaluation of aging effects and failures of inverters and battery chargers. The significant conclusions documented in this report are presented below:

- 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.
- Over a nine-year period, 42 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.
- Plant-specific configurations 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.
- 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.
- Reliance on convective cooling alone is inadequate for certain designs and installations.
- 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.
- For battery chargers and inverters, the aging and service wear of subcomponents have contributed significantly to equipment failures.
- The subcomponents most susceptible to aging are capacitors, transformers and inductors, silicon-controlled rectifiers, and 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.

- 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.
- Inverter design such as the PWM type, which requires smaller filter capacitors because of the high frequency harmonics associated with the output waveform, may not be as susceptible to capacitor failures experienced in other types.
- Diodes and SCRs can change characteristics with time because of impurities introduced during the manufacturing process.
- Surge suppression schemes on the input to the equipment, especially when used to protect the SCRs in the rectifier circuit, have been effective in minimizing susceptibility to damage from electrical transients.
- Investigations following an equipment failure are inadequate. Because of the potential impact on plant safety and availability, this approach is not justifiable.
- Personnel errors in design, manufacture, operation, and maintenance of battery chargers and inverters account for a large percentage of documented failures (~ 15%).
- Capacity testing, while performed by many plants for battery chargers, is not regularly conducted for inverters.
- 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.
- 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.
- Use of capacitors with higher voltage and temperature ratings would increase capacitor life and, therefore, improve equipment performance.
- Table 3-3 in this guide incorporates the aging mechanisms and failure modes for inverters and chargers identified in this document as appropriate.

U.S. Nuclear Regulatory Commission. *Detecting and Mitigating Battery Charger and Inverter Aging*. NUREG/CR 5051, August 1988.

This phase of the study involved testing a naturally aged inverter and battery charger in a laboratory. Tests were supplemented with evaluation of certain vendor-recommended and field maintenance and surveillance practices. The objectives of this phase included:

- Verifying the effectiveness of the current surveillance, maintenance, and test techniques to identify the condition of the equipment and potential approach to failures
- Demonstrating the feasibility of implementing improved inspection, surveillance, and monitoring methods to provide the data required for effective condition assessment.

In addition to reinforcing many of the conclusions stated in the Phase I report, this report presents the following additional conclusions and recommendations:

- Plant impact of inverter failures is more dramatic in PWRs than boiling water reactors (BWRs) because of their close association with feedwater and turbine-generator control systems.
- Degraded or overvoltage conditions in inverter output can result in extensive plant transients.
- Current limiting features in modern UPS systems should be avoided in nuclear plant applications. To provide the additional overload capability obtainable through current limiting, the output voltage must be reduced. Loads may malfunction as a result of the reduced voltage while the inverter is in the current limit mode.
- Individual capacitor fusing should be considered for inverters.
- An automatic transfer switch should be incorporated.
- An excessive amount of battery charger ripple voltage can result in battery degradation or even affect instrumentation and controls powered from the dc bus. Increased charger ripple could result from filter capacitor, inductor degradation, or rectifier circuit malfunction.
- Inverter failures attributable to aging have occurred during the first two years of operation, as well as during later years.
- A 40% increase in the reliability of inverters could potentially be achieved by increasing maintenance frequency from annual to quarterly. For battery chargers, an increase of 30% can be achieved from the same maintenance frequency change.
- Testing the inverter's capacity, especially for standby systems such as high-pressure core injection (HPCI) and reactor core isolation cooling (RCIC) in a BWR, would ensure that the inverter would perform its intended safety function when required.
- A functional check of the automatic transfer capability, where applicable, would help to ensure the operational readiness.
- Current industry practices, which include visual inspection, testing, and preventive and corrective maintenance, can be and should be improved.
- Improved inspection, surveillance, and monitoring methods that include a combination of visual inspection, cleaning, temperature monitoring, periodic component replacement, and full load testing can be effective in identifying aging-related degradation.
- Indicating meters and limit set relays and switches should be calibrated periodically.

U.S. Nuclear Regulatory Commission. *Testing of Naturally Aged Nuclear Power Plant Inverter and Battery Charger*. NUREG/CR 5192.

This report documents the test plan and the results of a test performed by the Brookhaven National Laboratory on an 11-year old inverter and charger removed from the Shippingport facility. Based on this test, the following conclusions and recommendations supplementing those documented in NUREGs 4564 and 5051 are presented:

- SCRs were found to be operating with case temperatures 20% higher than when the original acceptance test was performed. Even with this increase, substantial temperature margin to the maximum allowable temperature still exists.
- Periodic monitoring of semiconductor and SCR case temperatures will pinpoint many malfunctions before they cause catastrophic failures.
- The ability of the inverter to respond to transients has not been affected by operation.
- No apparent aging mechanism has developed to date that results in an increased winding temperature in the inductors and transformers.
- Transformer and inductor winding temperatures are responsive to load changes indicating that they would also be responsive to internal degradation such as high impedance turn-to-turn shorts.
- Circuit characteristics have not changed substantially due to age.
- Some filter capacitor degradation has possibly occurred as reflected by the increase in case temperature.
- Although it is feasible to monitor circuitry waveforms, using that information to assess equipment condition is difficult. For example, the inverter output voltage waveform may not be responsive to component degradation other than for electrolytic capacitors. The inverter's circuitry can usually compensate for large variations in a component's performance.

C.3 NRC Generic Communications and Vendor Advisories

Several NRC Generic Communications (that is, Notices and Bulletins) and a number of Vendor Advisories have been issued on inverter and charger problems. A complete listing of these documents is included in Appendix A. Significant problems addressed in these documents are discussed in this section.

C.3.1 Set Point Problems

Improper settings of the dc input and ac output undervoltage devices and associated time delay trip or transfer settings caused the loss of two of the four UPS systems at an operating nuclear plant. This resulted in the unwarranted actuation of the Engineered Safeguard Features (ESF). Review of the Nuclear Plant Reliability Data System (NPRDS) data on inverter and charger problems also indicates that approximately 15% of all the inverter and charger failures arose from set point problems.

C.3.2 Plant Transients Caused by Loss of UPS

The loss of the power supply from a UPS system to non-class 1E control and instrumentation systems resulted in reactor control system malfunction, turbine trip, and significant loss of and misleading information to the control room operators. The NRC bulletin issued as result of this event also required plants to take specific actions to preclude similar events.

Three events involving the failure of non-nuclear instrumentation power supply UPS inverters led to the failure of vital plant instrumentation, including nuclear instrumentation. Each case was accompanied by a plant trip and presented difficult challenges to the control room operators in mitigating the transients. NRC review of 145 UPS inverter-related events indicated that UPS inverter losses have in many cases led to unplanned plant transients and/or inoperability or improper functioning of safety-related equipment and other important plant equipment. The dominant cause of inverter losses was failure of components such as diodes, fuses, SCRs, capacitors, resistors, printed circuit boards, transformers, and inductors. High ambient temperature and/or humidity within the UPS system enclosure, voltage spikes and inadequate interconnections, and physical arrangement were identified as the causes of such component failures. An update of the Office of Analysis and Evaluation of Operational Data (AEOD) report published in 1994 concludes that as of the end of 1992, the number of inverter failures has decreased, but problems still exist. The significant findings of this publication are as follows:

- Inverter failure is still causing a large number of inadvertent ESFAs, reactor trips, and turbine runbacks.
- Component failures are still the number one root cause of the failure, followed by human error.
- Electrolytic capacitors are the most failed component followed by transformers, silicon-controlled rectifiers, and transfer switches.
- Following vendor recommendations of minor and major maintenance would reduce the number of failures.

NPRDS failure data reviewed during the development of this guide also confirm that component failure is the dominant cause of UPS inverter- and battery charger-related events. This same review also indicates that recent industry initiatives, such as implementing systematic preventive maintenance programs and root-cause analysis of failures of safety-related UPS inverter and battery chargers, have contributed to a significant reduction in the frequency of such events and thus the overall failure rate reduction (see Figure 5-1).

C.3.3 Inadequate or Improper Maintenance

One plant experienced recurring failure of SCRs. The root cause was identified as improper torquing of SCRs. The vendor instruction manuals may not have been clear, and the maintenance personnel may not have been aware of the need for using proper torque values when installing the SCRs.

A voltage transient resulted in the loss of power from five of eight non-safety-related UPS systems. This caused the loss of control room annunciation, control rod position indications, the core thermal limit computer, the process computer, the safety parameter display system computer, and the feedwater control system in addition to the balance of other plant instrumentation and indication systems. The failures were partly related to inadequate maintenance procedures for small rechargeable batteries that provide backup power to the UPS system control logic.

C.3.4 Manufacturing Deficiencies

Loose connections on the capacitor terminals caused by a changeover from ring-tongue to fast-on terminal connections were identified at two plants. The problem occurred in Westinghouse-supplied inverters employing a GE-manufactured ferroresonant transformer. In response, Westinghouse issued a technical bulletin advising recommended corrective actions.

D
DICTIONARY OF ACRONYMS AND ABBREVIATIONS

AEOD	Office of Analysis and Evaluation of Operational Data
ANSI	American National Standards Institute
Btu	British thermal unit
BWR	boiling water reactor
CVT	constant voltage transformer
DBE	design basis event
DF	dissipation factor
DG	diesel generator
ECCS	emergency core cooling system
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
ESFAS	emergency safety features actuation system
ESR	equivalent series resistance
HPCI	high-pressure core injection
I&C	instrumentation and control
IC	inductance-capacitance
IEEE	Institute of Electrical and Electronic Engineers
INPO	Institute of Nuclear Power Operations
IR	infrared

LER	licensing event report
LOCA	loss-of-coolant accident
LOOP	loss-of-offsite power
Mag-amp	magnetic amplifier
MOV	metal-oxide varistor
NARM	National Association of Relay Manufacturers
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NMAC	Nuclear Maintenance Application Center
NOMIS	Nuclear Operations and Maintenance Information Service
NPAR	Nuclear Plant Aging Research Program
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
NSAC	Nuclear Safety Analysis Center
NUREG	Nuclear Regulatory Commission document
O&M	operation and maintenance
PF	power factor
PIV	peak inverse voltage
PM	planned maintenance
PWM	pulse-width modulation
PWR	pressurized water reactor
RC	resistance-capacitance
RCIC	reactor core isolation cooling
rms	root mean squared

RPS	reactor protection system
SCR	silicon-controlled rectifier
SOER	Significant Operating Experience Report
SSA	SRC shorting assembly
TRIAC	triode ac switch
UPS	uninterruptible power supply

E
LISTING OF KEY INFORMATION

The following list provides the location of "Key Point" information in this report.

Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Section	Page Number	Key Point
8.3.3	8-16	There has been a significant improvement in technology since the mid-1970s that has increased equipment reliability. It would, therefore, be prudent to evaluate the cost benefits of installing replacement parts or replacing both inverters and chargers, especially if they have a poor performance history.

Key Technical Point

Targets information that will lead to improved equipment reliability.

Section	Page Number	Key Point
4.1.2.2.1	4-5	To minimize the thermal stress on an SCR, ensure that the heat sink is clean, the proper conductive grease is applied, the SCR is aligned in the heat sink, and the correct torque is applied.
4.1.4.1	4-7	Establish a replacement frequency for capacitors based upon the manufacture and style of capacitors installed.
4.2	4-10	The dominant stress that causes component failures in power semiconductors, magnetics, and capacitors used in UPS systems is thermal stress, which is additive in nature. Thermal stresses can originate from many sources including poor ventilation, continuous operation of ferroresonant transformers at significantly low loads, improper torquing of semiconductors, and certain electrical phenomena.
5.1	5-2	Unless the battery charger is specifically designed to work as a battery charger/eliminator, operating the inverter with the dc system feeder or battery failure may result in severe overheating.

Section	Page Number	Key Point
8.3.1	8-8	Blowing out dust and debris using dry air is not recommended. It will result in moving the dirt and debris from one location to another and lodge it there securely. This could result in causing contamination and open circuit between relay contacts and connectors.
8.3.3	8-16	It is recommended that a major overhaul to restore the UPS to its like-new condition once every 10 to 12 years be included as part of the preventive maintenance program.
8.3.3	8-17	Ferroresonant type UPS units should be run for at least 1 hour prior to taking vital performance measurements.

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Referenced	Page Number	Key Human Performance Points
7	7-1	Maintenance activities may be performed with the plant in any operating mode. Such activities are infrequent and create a potential for reduced safety margins. Therefore, the manufacturer’s literature should be reviewed for applicable personnel and equipment safety precautions.
7.2	7-3	After de-energizing a UPS or charger system, the stored energy in capacitors should be discharged to prevent accidental shocks. The stored energy can be discharged to ground or preferably by a capacitor-shorting device.
7.2	7-3	In a de-energized system, parts such as resistors, transformers, and heat sinks may remain extremely hot for some time after power has been removed.
7.2	7-3	With the bypass switch in the maintenance bypass position, ac voltage exists at some components. These components should be identified and appropriate precautions taken.
8.6	8-23	Caution should be exercised when disconnecting and connecting wiring in a de-energized UPS system. High voltage may be present due to a existing capacitor charge. Capacitors should be discharged by using a capacitor discharge device such as connecting a 120 V, 10-watt light bulb across the capacitor terminals.

Target:
Nuclear Power

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