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Power Supply Maintenance and Application Guide

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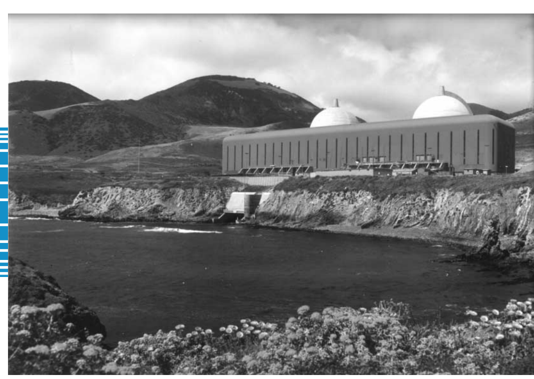

NMAC

Power Supply Maintenance and Application Guide

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Final Report, December 2001

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REPORT SUMMARY

Instrument power supplies are very reliable; however, there is limited information that ties together operating history, maintenance practices, and data associated with repairing versus replacing power supplies. Also, the issue of equipment obsolescence affects many of the considerations associated with making power supply maintenance decisions.

Background

Instrument power supplies play a crucial role in power generation stations because they support plant instrumentation loops. Most U.S. nuclear power plants utilize linear power supplies in their instrument applications, although there are a few applications that use switched mode power supplies.

EPRI published a tech note on instrument power supplies that provided good general information on the failures and maintenance practices related to power supplies used in a typical nuclear power plant. Since the publication of that work, EPRI has investigated the performance of capacitors, which are critical to most power supplies.

Objectives

- To develop guidance for instrument power supplies at nuclear power plants that provides insight into the principal components used to make up instrument power supplies
- To provide an overview of power supply operating principles
- To focus primarily on the maintenance and condition monitoring practices that will enable the plants to increase power supply reliability and to avoid unexpected failures

Approach

The investigators performed this study using plant visits, telephone interviews, and relevant document research. The research from the capacitor maintenance and capacitor performance guides was used as supporting information in this project. Several power supply repair facilities were interviewed and supplied data for this project.

Results

Although condition monitoring has been utilized to some extent to determine power supply degradation, the results have not been as definitive as had been desired. From this project, time-based replacement appears to be the most prudent approach for power supplies that are deemed critical.

EPRI Perspective

Current maintenance practices implemented at several utilities are discussed to inform the reader of potential options to enhance their current maintenance practices. Recommendations for troubleshooting, monitoring, repair, and replacement to ensure power supply reliability are presented.

Work has been done to identify phenomena associated with power supply failures, such as capacitor application and replacement information. In addition, there has been some limited work done to address condition-monitoring techniques for power supply components.

While all this work has brought more understanding to power supplies and the components that are used in power supply construction, detecting, tracking, and trending degradation in electronic equipment still present a challenge to the industry. Continued data collection and the evaluation of that data will eventually lead to methods that will allow for determining degradation of electronic equipment and components.

Keywords

Power supplies
Instrumentation
Controls
Maintenance

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1 INTRODUCTION

Instrument power supplies are associated with many vital systems that contribute to the reliability of plant operation. During the mid-1980s, studies showed that failure of power supplies affected power production [1]. In that time period, power supply failures demonstrated that significant attention was needed to establish a program to improve the reliability of instrument power supplies used in nuclear power plants. Many of the failures in the 1980s could be contributed to the learning curve of plant operators and maintenance personnel. Current data has shown that power supply failures have not caused significant power production impact.

The aging of United States (US) nuclear power plants raises the probability of higher failure rates for age-sensitive components in installed power supplies. A number of original power supply manufacturers are no longer in business. Based on these circumstances, it has become necessary to refurbish or replace original power supplies when technical support or replacement parts are no longer available.

The above issues complicate available options for a consistent routine maintenance practice. EPRI has been actively involved in the development of guidelines for troubleshooting and maintenance of instrument power supplies used in nuclear power plants [3,4]. However, these reports have not identified a consistent maintenance approach for these power supplies.

This report discusses maintenance considerations for several types of instrument power supplies and is limited to low-voltage process instrumentation power supplies. Emphasis is given to low-current level power supplies that could have single- or multi-loop designs with varying input and output voltages.

Power supply failures and the mechanisms that contribute to component degradation are addressed in this guide. Consideration is given to the subject of maintaining aging/obsolete power supplies through maintenance practices that will mitigate or pre-empt in-service failures.

Current maintenance practices implemented at several utilities are discussed to inform the reader of potential options to enhance their current maintenance practices. Recommendations for troubleshooting, monitoring, repair, and replacement to ensure power supply reliability are presented.

The purpose of this maintenance and application guide is to:

- Provide a description of typical power supplies used in nuclear power plants' applications and differences between them.
- Describe the differences in power supply design and how those differences affect application of maintenance.

- Identify typical systems that rely on power supplies.
- Describe typical failure modes of power supplies with emphasis on the failure modes of age-sensitive components used in power supplies.
- Determining frequency of and/or establishing periodic component replacement to enhance maintenance practices will be discussed. Methods of evaluating power supply performance, common repair practices, and troubleshooting tips will be explained.
- Discussion of current industry maintenance/repair practices and the impact of obsolescence with focus on methods used to enhance existing power supply maintenance/repair/replacement programs.
- Recommendations to enhance current maintenance practices for continued reliability of instrument power supplies.

2
POWER SUPPLY DESCRIPTION

Power supplies used in the power industry provide power to a variety of electromechanical equipment such as relays, actuators, sensors, and other electronic equipment. These devices rely on clean, reliable power to be delivered throughout the system in order to perform their functions properly. Electronic devices are used in many applications to control and monitor temperature, pressure, fluid levels, flow, machine operation, and other functions required to operate a system or plant.

Instrument power supplies used in nuclear power plants are actually the same types of power supplies used in other industries. There are two main types of power supplies: linear or switched-mode. The majority of power supplies used in nuclear power plants are the regulated linear type. Although, uninterruptible power supplies (UPS), and board-level power supplies (for example, servers, personal computers, etc.) are power supplies in the truest definition. They are not specifically addressed in this guide because they are not usually integral devices in an instrument loop.

2.1 Power Supply Circuit Description

For reliability and stability, alternating current (ac) source current is typically transformed and converted to direct current (dc) to provide power for control circuits in most industrial applications (see Figure 2-1). Typically, power supply circuits consist of three key building blocks:

- Rectification
- Regulation
- Filtering

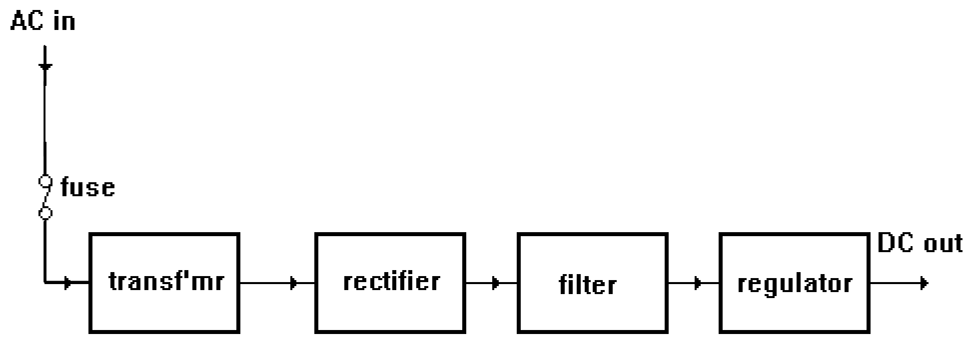


Figure 2-1
Power Supply Circuit Block Diagram

Typically, ac input power is transformed to a lower level by the use of an instrument transformer. The instrument transformer will be discussed along with rectification.

Filtering will be described in a stand-alone section because of the variations in component function based on power supply application.

2.1.1 Rectification

Rectification is the process by which an alternating current (ac) is converted to a direct current (dc). There are two key components that function together to achieve rectification of an ac input voltage: the instrument transformer and the semi-conductor diode or referred to a rectifier (see Figure 2-2).

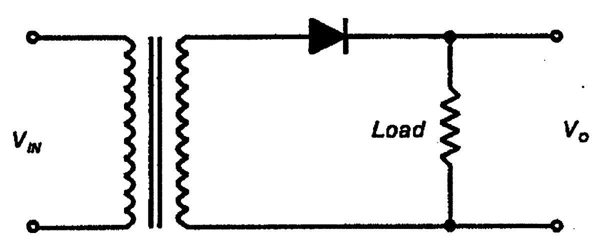


Figure 2-2
Typical Rectifier

An instrument transformer is constructed and performs in a similar fashion to any other type of transformer. A typical transformer consists of two or more coils of wire that are coupled inductively. When an alternating current is applied to one coil, then a voltage is induced in the other coil. The magnitude of the induced voltage is determined by the number of turns in each coil. When the coils are appropriately magnetically coupled, the relationship between the voltage in one coil related to the voltage in the other coil can be expressed as:

$$E_1/E_2 = N_1/N_2$$

Likewise the relationship between the current in one coil related to the current in the other coil can be expressed as:

$$I_2/I_1 = N_1/N_2$$

thus

$$E_1/E_2 = I_2/I_1$$

Power conversion from one voltage to another is the most popular application for transformers. This conversion happens at relatively low frequencies for transmission considerations and to reduce losses in the transformers and equipment. In aircraft applications, 400 Hz operating frequency is used to allow for the reduction in the size of equipment that use magnetic materials, such as motors, generators, and transformers.

In the application of electronic transformers, it has been found that they often perform many functions besides the basic changing of voltage and /or current values. The conversion of power from one voltage to another has many applications in the operation of ac equipment, but in electronics applications, conversion to direct current at various voltages is common. This is especially important for rectifier operation where the ripple frequency and magnitude are directly related to the number of phases, rectifier circuit, and primary frequency. The use of lower voltages means higher current for equivalent power.

Power transformers are used primarily to change the magnitude of the source voltage and current. Additional uses might be isolation of circuits for safety or insulation purposes, change in the number of phases, or change of phase angle.

Special-purpose transformers, such as current-limiting, constant-current, regulating or power-factor-correcting, can be classified as electronic power transformers.

Most electronic systems require a instrument transformer to provide the source voltage. The dc voltages are created either by direct conversion of the prime power to a dc voltage without any frequency conversion or by converting a dc voltage to a higher frequency alternating voltage with subsequent transformation, rectification, and regulation. The direct conversion to a dc voltage is typical of a linear power supply and the higher frequency conversion is typical of a switching power supply.

A semi-conductor diode conducts (allows current flow) when forward biased, and does not conduct (or conducts very poorly) when reverse biased. Current can only flow from the anode to the cathode or in the direction of the arrow. A diode (see Figure 2-3) has an actual forward voltage drop and this voltage drop varies according to the type of diode. Also, the voltage drop increases slightly across the diode as the current flows through the diode increases. The voltage drop is related to the type of diode:

- Silicon diode = 0.7V
- Schottky diode = 0.2V
- Germanium diode = 0.2V

Figure 2-3
Diode

A Zener diode allows current to flow in both directions (see Figure 2-4). In the “forward” direction, no current will flow until the voltage across the diode is about 0.7 volts. In the reverse direction, no current will flow until the voltage approaches the “zener” voltage at which time a tremendous current will flow and the diode must be protected by placing a resistor in series with the diode. Within a certain supply voltage range, the voltage across the zener will remain constant.

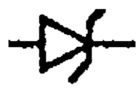


Figure 2-4
Zener Diode

Zener diodes are available in values up to about 33 volts. Voltage ranges from 2.4 to 30 volts are common. An “Avalanche” diode works in a similar manner as a zener diode and is rated for voltages between 100 volts and 300 volts. These diodes are often referred to as zener because their performance is similar.

Zener diodes are used to “clamp” a voltage in order to prevent it from rising higher than a given value. This might be done to protect a circuit from damage or to “chop off” part of an alternating waveform for various reasons. Zener diodes are also used to provide a fixed “reference voltage” from a voltage that varies. They are widely used in regulated power supply circuits.

Linear power supplies typically consist of a basic form of rectification (transformer and diode arrangement) and some form of electronic variable resistance, a voltage detector, and a reference voltage. A linear power supply takes the ac line voltage and transforms it to a lower level. The secondary voltage is converted to a pulsating dc.

For switch mode power supplies, the ac line voltage is applied to an input rectifier and filter circuit. The dc voltage output from the rectifier and filter circuit is switched to a higher frequency, typically 25 kHz to 100 kHz by the transistor switch in the high- frequency inverter circuit. The circuit contains either a high-frequency transformer or inductor depending on the output voltage required.

There are several types of rectification circuits:

- Half-wave
- Full-wave
- Bridge

2.1.1.1 Half-Wave

The simplest rectifier is a diode connected to the transformer as shown in Figure 2-5.

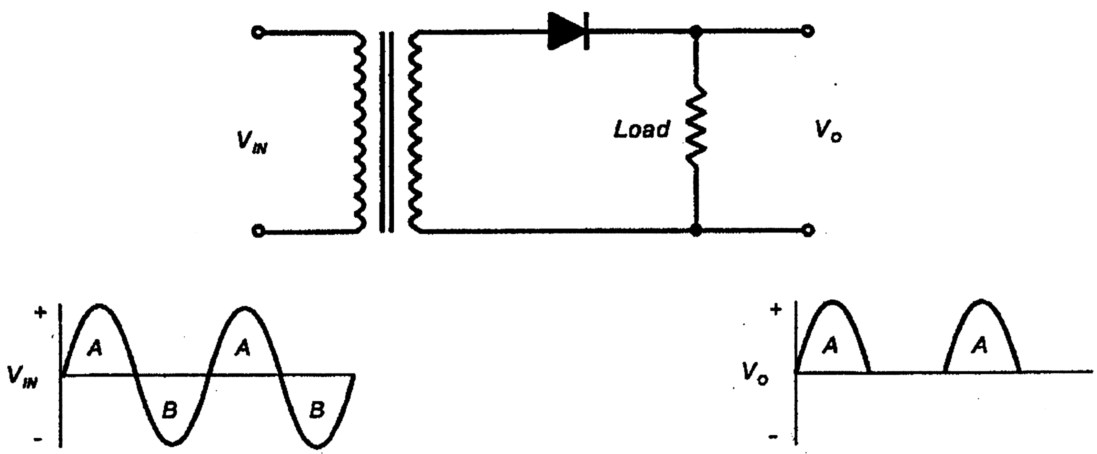


Figure 2-5
Half-Wave Rectifier Diagram

The alternating input voltage V_{in} is applied to the diode, the positive section of the wave is labeled A and the negative section is labeled B. When the positive section of the wave (A) is applied to the diode it conducts producing a wave section similar to the input at the output V_O. When the negative section of the wave is applied to the diode, it does not conduct, therefore there is no output voltage.

The value of the average half-wave output voltage is obtained by calculating the area under the half-cycle curve, and divides this value by the period of the rectified waveform. The result of this integration is:

$$V_{DC} = \frac{V_m}{\pi} = 0.318V_m$$

where

V_{DC} = average value of the rectified voltage

V_m = maximum (peak) value of ac input voltage

An important characteristic of the diode in a half-wave rectifier is the capability of the diode to withstand the maximum peak voltage when the diode is reverse biased. This is called the peak inverse voltage (PIV). The diode PIV rating must be larger than the dc voltage obtained using the circuit. The frequency of the output rectified pulsating voltage in a half-wave rectifier is 60 Hz.

It would be preferable to obtain a larger dc voltage compared to the maximum input voltage than that of 0.318 V_m for a half-wave rectified signal. In addition, note that although an average voltage is obtained using a half-wave rectifier, no voltage is developed for half of the cycle.

2.1.1.2 Full-Wave

Using two diodes, it is possible to rectify a sinusoidal signal to obtain one that has the same polarity for each of the half cycles of the input signal. A full-wave rectifier uses two diodes and a center tapped transformer, which is depicted in the following circuit (see Figure 2-6):

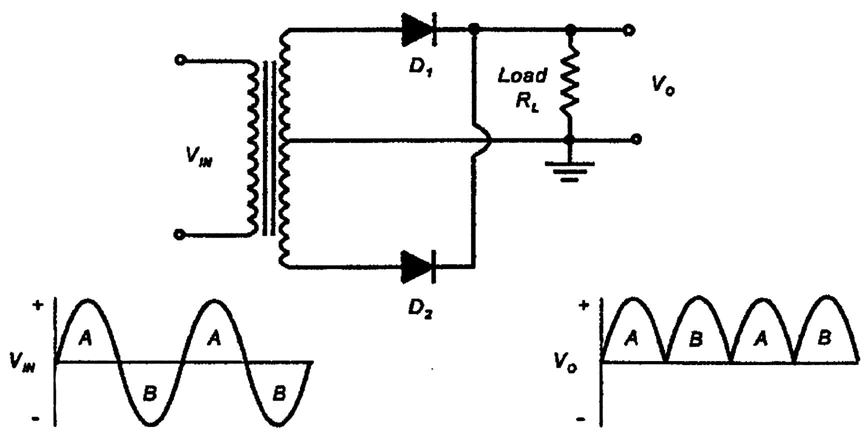


Figure 2-6
Full-Wave Rectifier Diagram

The transformer is center tapped and a peak voltage V_m is developed across each half of the transformer during the positive cycle.

During the entire positive half-cycle, the polarity of the signal across the upper half of the transformer is in a direction to forward-bias D_1 causing it to conduct. With diode D_1 conducting, a positive half-cycle of voltage is developed across the load R_L.

The polarity of the voltage developed across the lower half of the transformer results in diode D_2 to be reverse biased. In addition, the reverse biased voltage across the diode, which is maximum at the time of the maximum voltage V_m is present, is 2 V_m. This is because the voltage across the reverse-biased diode D_2 is equal to the sum of the voltages across the lower half of the transformer and the load R_L, since they are of the same polarity. The diodes in a full-wave rectifier circuit must be capable of handling a reversed-bias voltage equal to twice the value of the peak voltage developed across the output. The resulting output voltage for a full cycle of input voltage is two positive half cycles. The average voltage for a full-wave rectified signal is twice that for the half-wave rectified signal.

$$V_{DC} = 2(0.318\ V_m) = 0.636\ V_m$$

The frequency of the pulsating output voltage of a full-wave rectifier circuit is 120 Hz. The full-wave rectifier circuit has the advantage of developing a larger dc voltage for the same peak voltage rating. However, it has the disadvantage of requiring a diode rating of twice the peak inverse voltage and a center-tapped transformer having twice the overall voltage rating.

2.1.1.3 Bridge

Another type of full-wave rectification is accomplished by using an array of diodes. This circuit variation of a full-wave rectifier is a bridge circuit as shown in Figure 2-7.

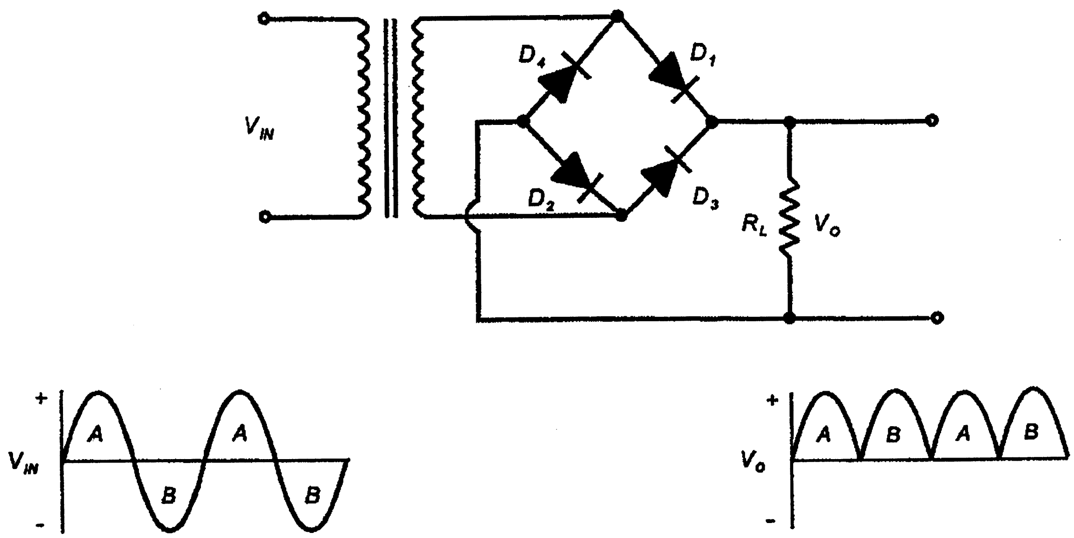


Figure 2-7
Bridge Rectifier Diagram

In considering how the circuit operates, one must understand how conduction and non-conduction paths are formed during each half of the dc cycle. During the positive half-cycle, the voltage across the transformer (measured from top to bottom) is positive and the conduction path is shown in Figure 2-8.

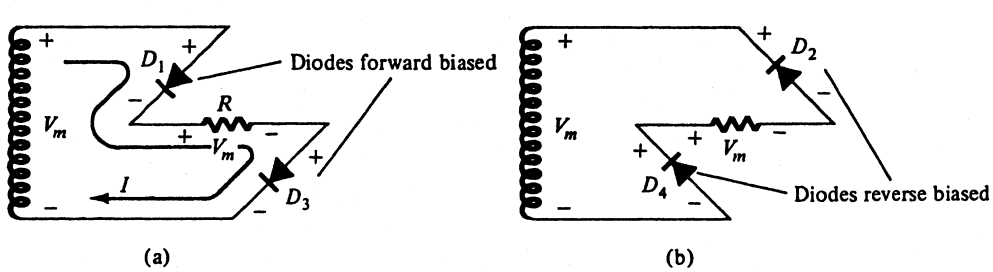


Figure 2-8
Positive Conduction Path of Bridge Rectifier Diagram

Figure 2-8 (a) shows the voltages at the peak of the positive voltage V_m. Since the diodes D_1 and D_3 shown are forward biased, the voltage drop across each diode is 0 V and the peak voltage from the transformer appears across R_L at this time. At the same time, the voltage polarity is such that diodes D_2 and D_4 are reverse biased as shown in Figure 2-8 (b). This represents the non-conduction path during the positive half cycle of the input ac signal. Resistor R_L has a voltage developed across it by the current in the conducting path of diodes D_1 and D_3. If the voltage drops around the non-conducting loop are summed, then the transformer voltage and the load voltage at the time of the peak voltage add up to 2 V_m. Since there are two diodes in the path, the voltage across each reverse-biased diode is V_m. This is half the developed peak inverse voltage in the full-wave rectifier circuit discussed earlier.

During the negative half cycle, the conduction and non-conduction path are depicted in Figure 2-9.

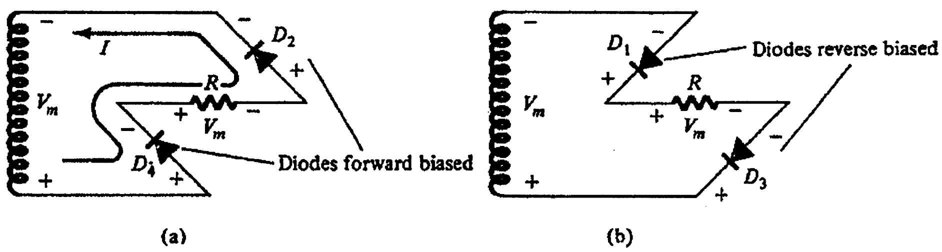


Figure 2-9
Negative Conductive Path of Bridge Rectifier Diagram

Figure 2-9 (a) shows that diodes D_4 and D_2 are forward biased. Note carefully that the current (*I*) goes through resistor R in the same direction as did the current on the previous half cycle. The voltage across resistor R is thus of the same polarity during each half cycle of the input signal. During the negative polarity half cycle the path of diodes D_1 and D_3 is non-conducting as shown in Figure 2-9 (b) and the peak inverse voltage developed across each of the diodes is V_m.

To summarize, the addition of two diodes above the number in the center–tapped full-wave circuit provides improvement of two factors. One, the transformer used need not to be center-tapped, requiring a maximum voltage across the transformer of V_m. Two, the peak inverse voltage (PIV) required of each diode is half that for the center-tapped full-wave circuit. For low values of secondary maximum voltage the center-tapped full-wave circuit will be acceptable, whereas for high values of maximum secondary voltage the use of the bridge rectifier to reduce the maximum transformer rating and diode PIV is usually necessary.

2.1.2 Filtering

The output voltage even from a full-wave rectifier and any form of regulation will require smoothing or filtering. Filtering will smooth out the pulses that are generated while the voltage changes direction and magnitude every cycle. Those cycles will vary depending on the method of rectification and regulation. Filtering is often required at the regulation and rectification portion of the power supply.

A section was devoted to filtering because of its importance and use in power supplies. Many of the current maintenance recommendations rely on monitoring power supply output voltage ripple as an indication of power supply degradation. The function of filters and the components that are used in designing filters are covered in this section of the report.

A capacitor connected in parallel with the output of a power supply is the simplest filter arrangement. The voltage pulses from the rectifier output will charge the capacitor to the peak voltage during the positive half-cycle. During the negative half-cycle, the capacitor will discharge its stored energy into the load, thus providing a fairly constant dc output to the load (see Figure 2-10).

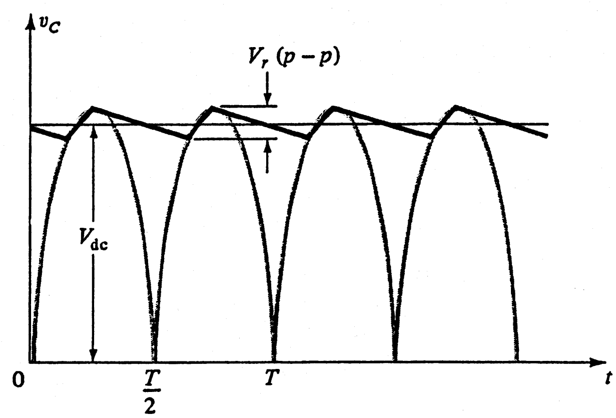


Figure 2-10
Voltage Ripple

Most modern power supplies also use a capacitive input filter (see Figure 2-11) when powered directly from an ac power line. These capacitive filters, many times, are not single capacitors but will be smaller capacitors mounted in parallel to provide the desired level of capacitance.

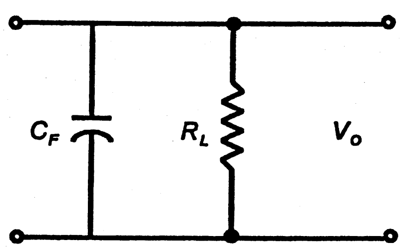


Figure 2-11
Capacitive Filter

An inductor, which is a magnetic coil with very low resistance, can be placed in series with the load to provide another form of simple filtering. The current flowing through the inductor builds up an electromagnetic field that induces a voltage in the inductor. This induced voltage acts as an energy reservoir to provide a constant dc output voltage to the attached load. An inductor will allow steady state current to flow (that is, dc) but it will oppose the change in that current flow or not allow the current flow to change abruptly or routinely (that is, ac).

Lumped element filters are used across the frequency range from Very Low Frequency (VLF) to Ultra High Frequency (UHF). Filters containing individual resistors, capacitors, and inductors are used in dc power supply applications for ripple reduction. These types of filters are called low pass filters and typically are made up of resistors and capacitor (RC) [see Figure 2-12 (a)] combinations. Electromagnetic interference (EMI) filters are commonly available as LC [see Figure 2-12 (b)] combinations. The majority of lumped element filters are the LC type.

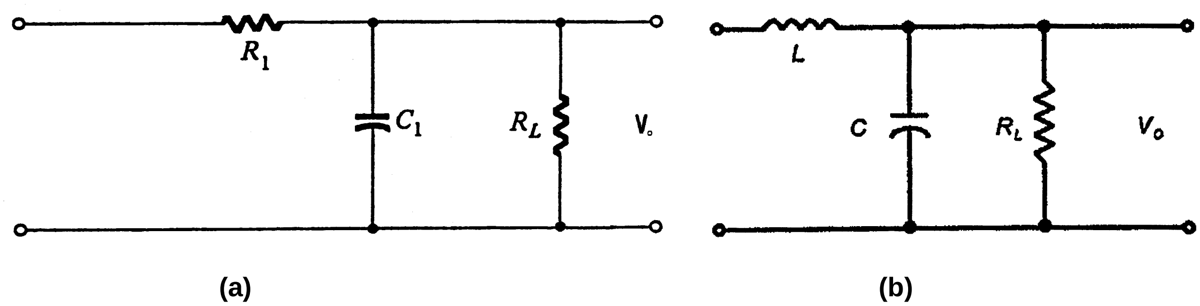


Figure 2-12
RC and LC Filters

Low frequency filters normally require capacitors and inductors with high discrete values and are physically large. In low frequency filters where the inductors contain many turns of wire warped in or around an iron core, the circuit can be tuned or affected by adjusting the number of turns.

The advent of high frequency rectification has allowed the use of very small capacitor and inductor values even down to the chip level. In the high frequency type filters, the circuit can be tuned by physically spreading or closing the distance between turns or physically cutting a pair of twisted wires, which might represent the capacitance of one of the filter elements.

2.1.3 Regulation

Almost all instrument loop devices require a stable input in order to operate, no matter what the load demand. In order to obtain stable supply voltage and flawless operation of the device(s), adding a voltage "regulator" to the unregulated power supply reduces fluctuations in the supply voltage. In the case of a dc/ac power source (line), the voltage regulator has to be connected between the dc/ac line voltage of the unregulated power supply and the load. Voltage regulators may be classified into:

- Linear operation
- Switching or switched-mode regulators

Thus, a regulated power supply consists of inserting a regulator circuit between the rectifier portion of the circuit and the load. By adding this circuit to the power supply design, load demands are constantly met as the regulator circuit varies the voltage across itself to maintain consistent output voltage. This design gives the regulated power supply an advantage over unregulated types of power supplies by distributing a constant supply voltage to all devices in line, no matter what the demand.

The voltage regulation control circuit defines the type of power supply design. Power supply regulation circuits consist of various combinations of components, such as resistors, diodes, transistors, capacitors and others, configured to maintain stable voltage and current to an attached load.

The following sections will describe the two chief types of regulation circuits used in power supply construction.

2.1.3.1 Linear Power Supply Description (Operational/Functional)

Linear Power Supplies are the most commonly used power supplies in nuclear stations in critical systems; therefore, basic linear power supply operation is discussed in detail.

The position of the regulation element in the linear power supply circuit distinguishes voltage regulators employing:

- Series (series pass)
- Parallel (shunt) voltage regulation

The most common linear regulating configuration is the series regulator. The series regulator is essentially variable impedance, usually a circuit containing a transistor (or a bank of them) placed between the unregulated input and the regulated output. By varying this impedance, the output voltage (or current) is maintained constant.

Another frequently used regulation system is the shunt regulator, where fixed-source impedance is placed between the unregulated input and the regulated output. This shunt or parallel impedance varies to maintain the output voltage or current constant. The EPRI/NMAC *Instrument Power Supply Tech Note* document TR-107044 describes in detail the linear power supplies mentioned above. This guide will expand on the control system (circuit) basics of linear power supplies.

A feedback control system derives the name from the fact that the control quantity is continually being measured to determine how closely it matches the desired value. The difference between the desired and the actual value is the *error.* This error is used by the control circuitry to alter the controlled quantity until the latter equals the desired value, at which time the error becomes zero or acceptably small.

There are two general categories of feedback control systems, one is the *on-off* system in which some constant action takes place until the controlled quantity reaches the desired value, at which time the action ceases. Here the feedback/error mechanism is some form of switch, like a thermostat or limit switch, which simply changes state when the controlled quantity has reached the desired level. The error information is simply the fact that the desired level has or has not been reached, with the action continuing at full throttle until the error suddenly becomes zero, at which time the action stops completely. As might be expected, there is often an overshoot due to the mass of the system or its equivalent. Overshoot is considered a transient due to the increase of voltage or current over the regulated value caused by a change in the load or the input level, or by turning the input power on or off.

The second and more complex category is the proportional control. Here the error signal will be larger or smaller depending on how closely the controlled quantity matches the desired value. The control circuitry will respond in proportion to the size of the error signal in an attempt to keep the error reduced to a near-zero level. If the error is large, the controls will react forcefully, while if the error is small, they will react more gently, but always in such a way as to approach near zero error.

The result of a well-designed proportional control system is a steady-state error signal that hovers near zero; only departing when some abrupt change is called by the system's load.

The modern regulated linear power supply is a good example of the proportional control category. Figure 2-13 shows the elements of a linear power supply in a block diagram.

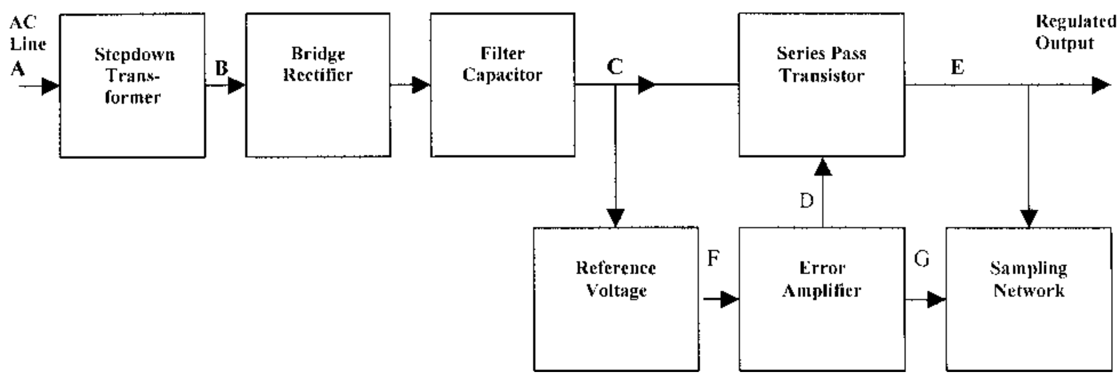


Figure 2-13
Block Diagram of Linear Power Supply

From A to C on Figure 2-13, these are the components of an *unregulated* power supply, consisting of a transformer to step down the line voltage to an acceptable level, a full-wave rectifier and a filter capacitor. The serial pass, or shunt transistor, is the actual control "valve" that accepts the varying capacitor voltage at C, and reduces it to a constant output voltage at E. The error amplifier, whose output at D must always be the correct value to change the transistor's voltage drop to accomplish this goal, controls the transistor. The error amplifier gets its error information by comparing a constant reference voltage F with a sample of the output voltage G.

A simplified diagram of a regulated series pass linear power supply is shown in Figure 2-14.

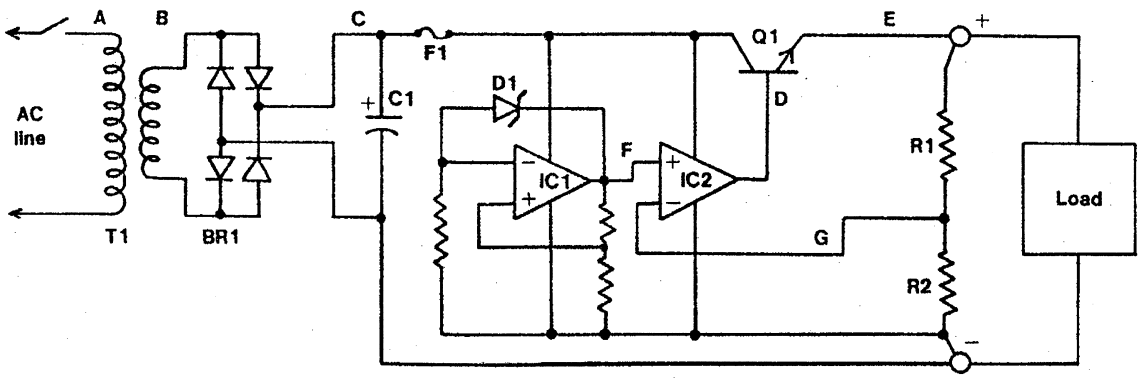


Figure 2-14
Regulated Linear Power Supply Circuit Diagram

The capacitor voltage at C contains a considerable amount of ripple and must always exceed the desired output voltage at E by some margin that permits the regulating circuit to perform its task of subtracting exactly the correct amount to leave a constant result. The subtraction is produced by the V_{ce} of Q1, the series transistor which must fulfill KVL (Kirchhoff's Voltage Law) around the loop from C1 to the output. This is a very dynamic system because the capacitor voltage is continuously changing, thus requiring the pass transistor's voltage drop to change continually along with it.

Regulating circuits are readily available in integrated circuit (IC) form. There are other circuits in regulated power supplies, which are not shown on the diagram, but are very important in the design of the power supplies. They are basically protecting circuits; referred to as current limiting circuits, which are included in some of the IC regulators and the over voltage protecting circuits known as the 'crowbar" circuit that protects the power supply from over voltage fluctuations.

There are some additional components added to the regulated power supply that deserve to be mentioned [for example, output capacitor(s)]. They are a small compensating capacitor (usually 100 pF) required because the error amplifier is not internally compensated so the capacitor is connected across the output. This capacitor acts as a short circuit to high frequencies, thus freeing the transistors from the necessity to respond to these frequencies. Its size would be a fraction of a picofarad for this purpose. In addition, a capacitor at the output provides momentary surge current protection and if used for this purpose, the capacitor should be an electrolytic of a few hundred microfarads. Normally, power supplies use a parallel combination of these capacitors at the output.

Another point worth mentioning concerning the regulation circuit is the placement of sensing leads. This is very important for best regulation, because the sensing leads must be placed as close to the load as possible. If they are placed at some point before the output, regulation will suffer, because some number of millivolts will drop in the sensing lines when high currents flow.

Regulation will be best if sensing leads are placed at the actual output terminals. Some manufacturers of power supplies include a set of removable straps joining the sensing leads to the output terminals. This permits unstrapping the sense leads and connecting them across the load itself, eliminating the drops in any wiring between supply and load. This rather subtle point is one of the least understood in power supply applications.

The advantages of the linear power supplies is that they feature ultra low noise levels and can offer virtually ripple free precision outputs. The disadvantage is that their efficiency is very low (40% to 60%) and their power range is limited to several hundred watts.

2.1.3.2 Switch Mode Description (Operational/Designs)

The basic design and operation of typical switching power supplies consist of four basic circuits: input rectifier and filter, high frequency inverter, output rectifier and filter, and the control circuit (regulator). Figure 2-15 shows a block diagram of the basic circuits.

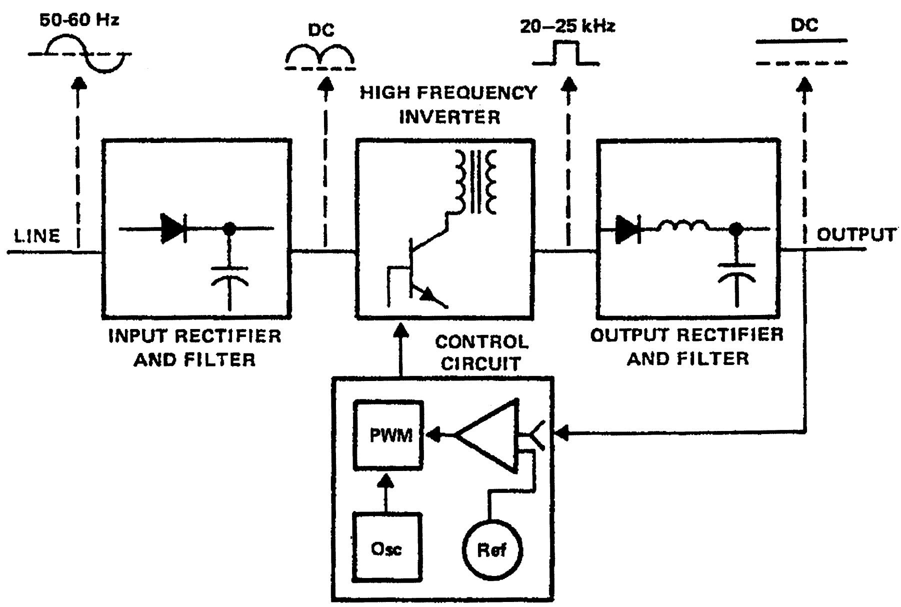


Figure 2-15
Basic Switching Regulator Block Diagram

The ac line voltage is applied to an input rectifier and filter circuit. The transistor switch in the high frequency inverter circuit switches the dc voltage output from the rectifier and filter circuit to a higher frequency, typically 25 kHz to 100 kHz. The circuit contains either a high frequency transformer or inductor depending on the output voltage required.

The output from the high frequency inverter circuit is applied to the output rectifier and filter circuit. The circuit is monitored and controlled by the control circuit, which attempts to keep the output at a constant level.

The control circuit consists of an oscillator driving a pulse-width modulator, an error amplifier and a precision voltage reference. The error amplifier compares the input reference voltage with a sample of the voltage from the output rectifier and filter circuit. As the load increases the output voltage drops. The error amplifier senses this drop and causes the pulse-width modulator to remain on for a longer period of time, delivering wider control pulses to the transistor switch.

The width of the pulse determines how long the transistor switch allows current to flow through the high frequency transformer and ultimately, how much voltage is available at the output. If the load decreases, narrower control pulses are delivered to the switching transistor until the output voltage remains at a constant value.

The primary advantages of switching regulators are higher efficiency (typically, 60% to 90%) and smaller in size. Switching regulators achieve their higher efficiency as a result of three factors:

1. The power transistor switch is always turned completely on or off, except when it is switching between the two states, resulting in either low voltage or low current during most of its operations.

2. Good regulation can be achieved over a wide range of input voltage.

3. High efficiency can be maintained over wide ranges in load current.

Switching regulators use the on-off duty cycle of the transistor switch to regulate the output voltage and current. By using a frequency much higher than the line frequency, typically 20 kHz to 500 kHz, the transformers, chokes, capacitors and other filter elements can be made smaller, lighter and less costly. The smaller elements used in switching regulators result in smaller power losses.

The highest cost elements of the switching power supplies are the transistor switches. The remaining costs in descending order are due to the magnetic components, capacitors, and rectifiers.

The disadvantages of a switching regulator are that switching regulation can generate some electromagnetic and radio frequency interference (EMI/RFI) noise due to the high switching currents and short rise and fall times. The noise can not be totally filtered and as a result, the output of the power supply exhibits higher noise and ripple.

The basic switching regulator architecture (topology) consist of three basic switching regulator configurations from which the majority of present day circuits are derived:

1. The Step-Down, or “Buck” regulator

2. Step-Up, or “ Boost” regulator

3. Inverting, or “Flyback” regulator (which is a variation of the “boost” regulator)

The Step-Down Regulator is shown in the Figure 2-16. The output voltage of this configuration is always less than the input voltage.

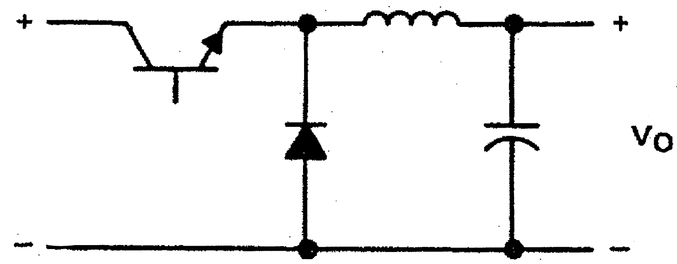


Figure 2-16
Step-Down or "Buck" Switching Regulator Diagram

In the buck circuit, a semiconductor switch (transistor) is placed in series with the dc input from the input rectifier/filter network. The switch interrupts the dc input voltage providing a variable width pulse to a simple averaging LC filter. When the switch is closed, the dc input voltage is applied across the filter and current flows through the inductor to the load. When the switch is open, the energy stored in the field of the inductor maintains the current through the load.

In the buck circuit, peak switching current is proportional to the load current. The output voltage is equal to the input voltage times the duty cycle.

$$V_O = V_I \text{ x Duty Cycle}$$

The Step-Up or "Boost" regulator is depicted in Figure 2-17. In this type of circuit, the output voltage is always greater than the input voltage.

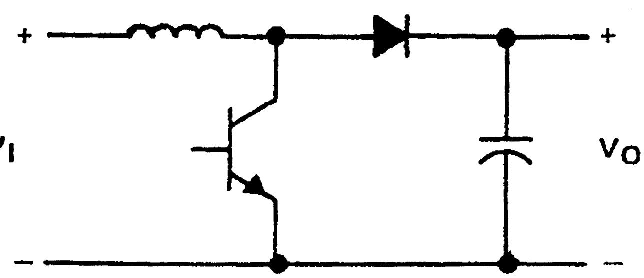


Figure 2-17
Step-Up or "Boost" Switching Regulating Circuit Diagram

The boost circuit first stores energy in the inductor and then delivers this stored energy along with the energy from the dc input voltage to the load. When the switch is closed, current flows through the inductor and the switch, charging the inductor but delivering no current to the load. When the switch is open, the voltage across the load equals the dc input voltage plus the charge stored in the inductor. The inductor discharges, delivering current to the load.

The peak switching current in the boost circuit is not related to the load current. The power output of a boost regulator can be determined by the following equation:

$$P_{OUT} = \frac{LI^2 f}{2}$$

Where: P_{OUT} = power output
L = inductance
I = peak current
f = operating frequency

The Inverting Regulator or "Flyback" is a variation of the Step-Up or "Boost" circuit. Figure 2-18 represents an inverting regulator circuit.

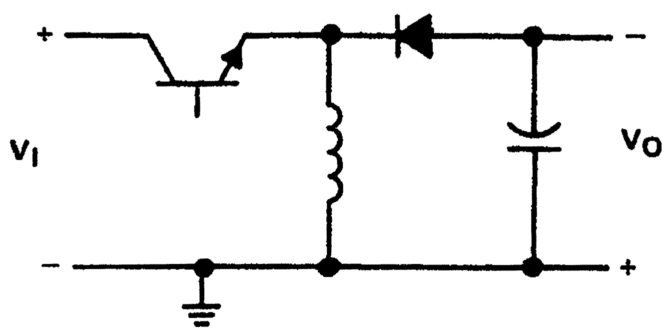


Figure 2-18
Inverting or "Flyback" Switching Regulator Circuit Diagram

Flyback regulators, which evolved from the "boost" regulators, deliver only the energy stored by the inductor to the load. This type of circuit can step the input voltage up or down. When the switch is closed the inductor is charged, but no current is delivered to the load because the diode is reverse biased. When the switch is open the blocking diode is forward biased and the energy stored in the inductor is transferred to the load.

The flyback circuit delivers a fixed amount of power to the load regardless of load impedance. It is widely used in photo-flash, capacitor-discharge ignition circuits and battery chargers.

To determine the output voltage of a flyback power supply, the load R_L must be known. If the load is known, the output may be calculated using the following equation:

$$Vo = \sqrt{P_o R_L} = I\sqrt{\frac{LfR_L}{2}}$$

Where: V_O = voltage output

P_O = power out

R_L = load resistance

I = Inductor current

f = operating frequency

The inductor current is proportional to the “on time” (duty cycle) of the switch and regulation is obtained by varying the duty cycle. However, the output also depends on the load resistance (which was not true with the step-down circuit).

Transient response to abrupt changes in the load is difficult to analyze. Practical solutions include limiting the minimum load and using the proper amount of filter capacitance to give the regulator time to respond to this change. Flyback-type circuits are used at power levels of up to 100 W.

The Forward Converter family, which include the push-pull and half bridge circuits, evolved from the step-down or the “buck” type regulator. Figure 2-19 shows a basic diagram of a forward converter:

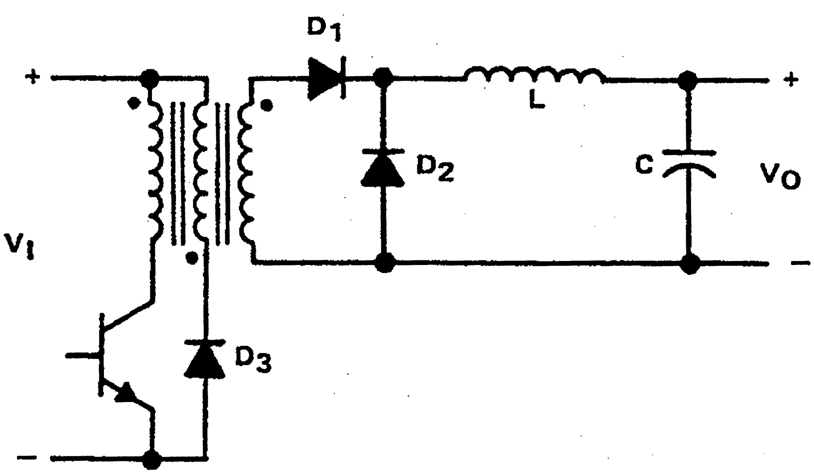


Figure 2-19
Forward Converting Switching Regulator Circuit Diagram

When the transistor switch is turned on the transformer delivers power to the load through diode D1 and the LC filter. When the switch is turned off diode D2 is forward biased and maintains current to the load.

Without the third winding and diode D3, the converter would lose efficiency at higher frequencies. The function of the winding is to return energy stored in the transformer to the line and reset the transformer core after each cycle of operation.

The forward converter is a popular low power (up to about 200 W) converter and is almost immune to transformer saturation problems.

The Push-Pull converter is probably one of the oldest switching regulators type circuits. It was first used in the 1930s with mechanical vibrators functioning as a switch. When transistors became available, push-pull converters were used as free-running oscillators in the primary of many automobile communication converters.

Some recreational vehicles still use this free-running type of oscillator converter in dc to dc converters. A typical push-pull converter circuit is shown in Figure 2-20.

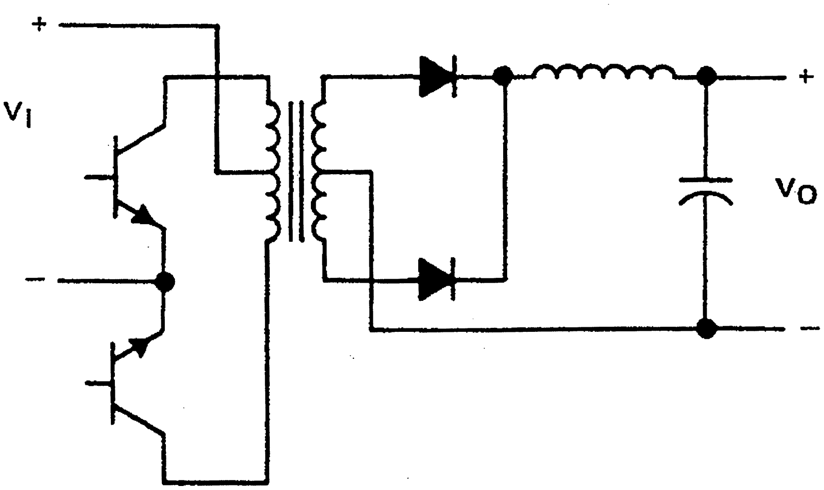


Figure 2-20
Push-Pull Converter Circuit Diagram

The most popular type of high power converter is the Half-Bridge circuit. This converter has several advantages over the push-pull circuit. First, the midpoint between the capacitor (point A in diagram) can be changed to $V_I / 2$. This allows the use of transistors with lower breakdown voltage.

Second, because the primary is driven in both directions (push-pull), a full wave rectifier and filter are used which allows the transformer core to be more effectively utilized.

Figure 2-21 shows a diagram of a half bridge converter.

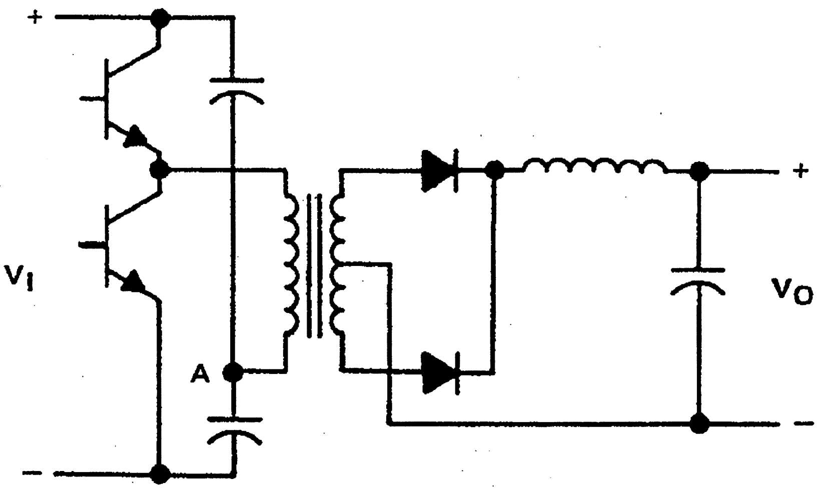


Figure 2-21
Half-Bridge Converter Circuit Diagram

In contrast to the Half Bridge, the Full Bridge (or H-Bridge) converter uses four transistors. In a Full Bridge circuit (see Figure 2-22) the diagonally opposite transistors (Q1/Q2 or Q3/Q4) are turned on during alternate life cycles. The highest voltage any transistor is subjected to is V_I, rather than 2 X V_I as is the case in the push–pull converter circuit. The full bridge circuit offers increased reliability because less voltage and current stress is placed on the transistors. The disadvantage of this circuit is the space required by the four transistors and the cost of the two additional transistors.

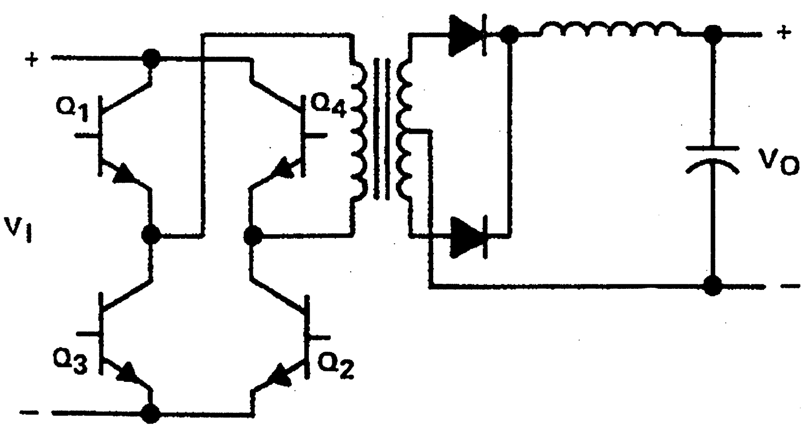


Figure 2-22
Full Bridge Converter Circuit Diagram

A newer form of switching technique, called soft switching allows higher frequency operation in switched mode power supplies by effectively reducing power device switching losses to near zero.

When coupled with new magnetic components designs, this allows an increase in the switching frequency by a factor of 2 to 3, having substantial impact on the power density of the converter. This approach also results in generally lower levels of electromagnetic interference. In all other respects, the soft switching converters are similar to their hard switching counterparts. It is anticipated that soft switching switched-mode dc power supplies will become the dominant technology in the near future for power levels up to several hundred watts.

2.2 Power Supply Application and Selection

Both the linear and switch mode power supply perform the same function of providing a regulated constant supply power to a load. The functional differences of “how” they do this is primarily in the differences of design as discussed earlier in this section. Even though a linear, and switched-mode power supply operate differently, they contain the same basic circuit design of a transformer circuit, a voltage modification circuit, and a filtering circuit. Linear power supplies however, utilize larger, bulkier internal components, whereas most switched-mode power supplies use a “miniaturized” version making them lightweight and smaller in size.

There are advantages and disadvantages with either type of power supply and the most common will be addressed in this section. Linear power supplies will be addressed first as they are the most common power supplies found in use in power generation stations.

2.2.1 Linear Power Supplies

Linear power supplies provide good regulation with very low ripple on the output, thus is often used where very clean power is required. It is a commonly accepted concept that analog circuits require cleaner power than logic circuits. Linear power supplies tend to provide more stable and “clean” dc output voltage as required for analog circuits. At the time of construction for most US nuclear power plants, analog controls were chosen because of their proven capability and availability in general industry.

Linear power supplies usually employ series regulation or shunt regulation, with either design providing a constant output to the load.

The linear power supply is relatively inexpensive (unless obsolete), has a reliable history and is easy to understand from an operational standpoint. This means that skilled and knowledgeable maintenance personnel or technicians will find the linear power supply relatively easy to troubleshoot and repair. The main advantages of a linear power supply can be summed up as:

- They contain a smaller number of internal components
- Higher reliability
- Well-known technology
- Particularly low output ripple and noise
- Absence of electromagnetic interference
- Low cost (in most cases)

- Simplicity of field troubleshooting and testing
- Easy access to components

The major drawbacks to the linear power supply are its:

- Size—due to their design age they require larger heavier components. To obtain the needed cooling capabilities to the components, most designs incorporated a large surface area to dissipate the heat generated by the components, with some having self-contained cooling fans.
- Weight—heavy by design limitations of the internal components
- Low efficiency—related to the high dissipation, which limits the output capabilities. (A significant amount of power may be lost in the regulator especially under high line voltage/high load conditions)
- Ripple voltages of 50 Hz to 100 Hz in the audible frequency range and stray magnetic components generated by the transformer might interfere with some applications
- Narrow tolerance range of permissible input voltage
- Low “holdup” capacity (with respect to the output voltage) and a low energy storage capacity

The term “output voltage holdup” refers to the capability of the power supply to maintain the output voltage within the specified limits even when the input supply voltage fails fully or partly for a definite length of time. Some equipment cannot withstand a departure of the supply voltage from the specified range even for a short time. A linear power supply is only rarely capable of complying with a voltage failure over 10 ms or a voltage drop beyond 15 percent.

2.2.2 Switch-Mode Power Supplies

Switch-Mode or switching power supplies have gained in popularity because of their size and capability. Because of the ability to operate at higher switching frequencies, components can be physically reduced in size. These power supplies offer higher efficiencies (70 % to 90 %) regardless of input voltage.

Switch mode or switching power supplies have been used for sometime in the military, space, and industry due to smaller size and higher efficiency. Nuclear power applications can have these types of power supplies systems such as Solid State Protection System, Turbine Electro-Hydraulic System, as well as the majority of computers and servers used at the sites.

Because switching power supplies have been integrated in many applications, the cost of these types of power supplies have been driven downward, which makes them an attractive choice for output power greater than 10 Watts or where multiple outputs are desired.

Filtering for switching power supplies is much more complex and critical. The output voltage of switching power supplies is difficult to filter; however, logic circuits can tolerate more ripple than analog circuits.

However, switched-mode power supplies are particularly suitable in applications with poor voltage stability. Their output voltage holdup is considerable with some models ensuring the specified output voltage with voltage fluctuations as wide as140 V to 270 V. Other advantages of the switched-mode power supply are:

- High efficiency with very low losses
- Smaller size due to less required surface cooling area
- Weighs less than linear design; due to smaller components and surface area
- High operational frequency enabling the dimensions of the transformer and filter components in the secondary circuit to be small
- Operates over a wide range of input voltages by varying the pulse duty cycle to meet demands
- High “holdup” capacity

Although design has produced many advantages for switched-mode power supplies there are drawbacks as well. Summarized they are:

- More complex circuit arrangement requiring greater skill and knowledge base for maintenance personnel or technicians
- Increased noise rejection requirements
- Slower response to abrupt changes in load
- Difficulty filtering output voltage (ripple)

Within the switch-mode “family,” there are characteristic differences as well. A comparison of these differences is given in Table 2-1.

Table 2-1
Comparison of Switching Power Supply Topology

Topology	Advantage	Disadvantage
Flyback	Simple topology, lowest parts count, and multiple outputs possible	Transformer core utilization poor, transformer design critical, leakage inductance high large core gap can increase core loss. Output ripple high.
Feed Forward	Simple topology, multiple outputs possible, and low output ripple	Transformer core utilization poor, poor transient response, and low output ripple
Series Resonant	Low switching losses, leakage inductance and capacitance are part of the resonating circuit, good transformer core utilization	Transformer design is critical

2.2.3 Plant Application

Power generation systems that rely on power supplies are numerous and varied. Many perform a critical function to ensure plant operability. The power supplies can be found in the following:

- Annunciator systems
- Auxiliary Power Systems
- Area Radiation Monitoring Systems
- Containment Monitoring Systems
- Computer Systems
- Diesel Generator Systems
- Battery and Distribution Systems
- Turbine Electro Hydraulic Control System
- Fuel Handling System
- Feedwater System
- Leakage Detection System
- Nuclear Boiler System
- Neutron Monitoring and Traversing In-Core Probe Systems

The type of power supply selected for any application is inherent to system design requirements. Most utilities purchase power supplies from published manufacturer product specifications (considered “off-the-shelf”) and do not request manufacturers to create special designs to meet system design requirements. Exceptions to this are power supplies manufactured by industry to exact design specifications directed by NSSS suppliers.

Selection of the appropriate power supply for the application is based on many factors, which can include the type of load it will be supplying, whether it will see continuous or intermittent duty, the operating environment, size, and seismic considerations are only a few.

Table 2-2 discusses the advantages and drawbacks for each power supply design. This information merely provides the reader with basic design comparisons and is not intended for design basis selection. Selection of a new or replacement power supply must always be based on plant specific critical design parameters.

Table 2-2
Comparison of Linear and Switched-Mode Power Supplies

Type Characteristics	Linear Power Supplies	Switched-Mode Regulated Power Supplies
Efficiency (percent, at nominal input voltage and under nominal load)	Acceptable	Outstanding
1. V_I = 220 V; V_o = 5 V; P_o = 400 to 1000W	25 to 40 percent	75 to 86 percent
2. V_I = 220 V; V_o = 15 V; P_o = 500 to 1000W	30 to 45 percent	80 to 90 percent
Required total (relative) cooling area of the power regulation element(s)	High (1)	Very Small (0.1 to 0.2)
Total (relative)		
1. Loss	High (1)	Very Low (0.1 to 0.2)
2. Peak Current load (of the power regulating element/s)	Low	High
Overall dimension (Relative cubic capacity)	Large	Very Small
Overall Weight (Relative)	Very Heavy	Very Light
Circuit Arrangement	Simple	Complex
Capacitance of Output Capacitor Required	Low–Medium	Very High
Regulation Parameters	Outstanding	Good
Transient Behavior	Outstanding 5 to 50 µs	Poor 100 to 1000 µs
Noise and ripple voltage suppression: (Value of noise and ripple voltage u_{pp})	Outstanding 0.2 to 2 mV_{pp}	Poor 10 to 60 mV_{pp}
Output Voltage Hold-Up (Carryover time t_c) In the event of a short-duration supply voltage failure	Poor 1 to 10 ms	Outstanding 20 to 50 ms at I_{Lmax} 80 to 400 ms at 0.5 I_{Lmax}
MTBF (Mean Time Between Failures)*	*20,000 to 60,000 hours (2.2 to 6.8 years)	*30,000 to 50,000 hours (3.4 to 5.7 years)
Failure Free Operation	50,000 to 100,000 hours (5.7 to 11.4 years)	50,000 hours (5.7 years)
Temperature of Unit (°C)	~80…85	~35…40
Permissible variations of nominal input voltage(by design)	+ 10% - 15 %	+ 20% - 40%
Costs of Operation Derived from Efficiency	High	Low
Serviceability	Problem-Free (Less skill required)	Difficult (Greater skill required)

3
POWER SUPPLY FAILURE DISCUSSION

Power supplies, in general, will perform well and provide a reasonable service life if the application where they are used is within its designed limitation. However, no power supply was designed to operate indefinitely and all will fail eventually, either by gradual degradation or catastrophic failure. The length of time before a power supply presents signs of degradation vary and are based on numerous factors including, equipment age, transient voltages, load demands, operating environment, and internal component reliability.

The most common power supply commercially available at the time of construction (1970s to 1980s) for the majority of plants was the linear power supply. This topology met the design requirements needed for support of many instrument loops and are still in use today. Design engineers from three of the most commonly used power supply manufacturers were contacted to determine what method was used to establish service life for power supplies. Surprisingly, the response from all was "*confidence in their design.*" Each stated that neither an Empirical Model (from field data), or a Physics-of-Failure Model (detailed fabrication information/encompasses reliability parameters) or other model was used to determine expected service life; therefore, no service life was given then or now. They do warranty the power supply for five years based on the most limited life component installed in the power supply—the capacitor(s).

Prior to further discussion about failure modes of power supplies, is it important to distinguish the difference between power supply reliability and component reliability. Power supply reliability is related to its ability to perform without failure over an established period of time. Likewise, each component's reliability is its ability to perform to its' design specifications over an established period of time. The component's reliability has a relationship to the power supply reliability in that the component's Mean-Time-Between-Failure (MTBF) rate can be used to determine which component will be used in the design to improve the power supply performance.

This is not to say that the power supply reliability is limited to the component with the lowest MTBF. The power supply reliability is based on how all those components work together, each encountering different operational stresses and each entering a possible failure mode at different times.

The following section will focus on these failure modes as they relate to components and potential effects on power supply behavior.

3.1 Common Power Supply Failure Modes (From Industry Data)

INPO's EPIX database was searched for reported power supply failures and failure modes to ascertain any commonalties between reporting stations. Information in EPIX from January 1997 to July 2001 was used to determine the type of failure modes reported, the number of times a specific failure mode was reported, and if an internal component was responsible for the failure. A total of 510 reports were analyzed during this time frame with the results shown in Table 3-1.

Table 3-1
Reported Industry Failures

Reported Failure Mode	Part Causing Failure & Number Reported	Number of Times Failure Mode Reported
Blown Fuse	1 – Fuse	1
Circuit Defect	1 – Unknown	1
Degraded Output Voltage	1 – NONE	1
Erratic Actuation	1 – Circuit Card	1
Erratic Output	5 – Capacitor 1 – Transistor 1 – Diode 4 – Circuit Board 60 – NONE	71
Failed Open Coil	1 – Transformer	1
Failed Output	11– Capacitor 2 – Circuit Board 2 – Converter 3 – Diode 4 – Fuse 1 – Lug/Connector 3 – Thyristors 3 – Transformer 1 – Transistor 1 – Multiplexing Relay 4 – Potentiometer 2 – Voltage Regulator 254 – NONE	291
High Output	1 – Transistor 2 – Capacitor 15 – NONE	18
High Ripple	2 – NONE	2
Inaccurate Output	1 – NONE	1
Infant Mortality	1 – NONE	1
Leakage	5 – Capacitor	5
Loss of Display	1 – NONE	1

Table 3-1 (cont.)
Reported Industry Failures

Reported Failure Mode	Part Causing Failure & Number Reported	Number of Times Failure Mode Reported
Low Output	8 – Capacitor 1 – Fuse 1 – Voltage Regulator 62 – NONE	72
Open	1 – Resistor 1 – NONE 4 – Capacitor 4 – Fuse 1 – Potentiometer 1 – Rectifier	12
Not Determined	1 – NONE	1
Out of Calibration	1 – NONE	1
Out of Tolerance	1 – Voltage Regulator	1
Short	2 – Diode 1 – Capacitor 1 – Transistor 1 – Light Bulb 1 – NONE	6
Unavailable	35 – NONE	35

3.1.1 Failed Output—Possible Causes

Excessive voltage or current (transient) can damage or initiate a failure to any component within a power supply. The top four components identified as the part that caused the failure (capacitor, fuse, potentiometer, and transformer) were probably damaged by such a transient occurrence. If a transient occurs causing a component to fail, check all surrounding components for possible degraded parameters.

This is the most difficult failure mode to analyze because the supply voltage or any circuit component within the power supply might be at fault requiring time consuming troubleshooting.

Failed output is normally caused by:

- Primary electrolytic capacitor(s) greatly reduced or entirely open
- Open fuseable resistor
- Blown fuse
- Shorted power transistor or other semiconductors
- No input to the power supply
- Defective power cord connection

As shown in Table 3-1, "failed output" was the most reported failure mode at 47 utilities in the past five years with 37 reports citing the failure was directly related to a part. There were 11 instances in which the capacitor was determined to be the root cause of failure. Out of 291 reports of "failed output," 254 reports did not identify a component as the specific cause of failure.

All 37 component types reported as the cause of failure are consistent with possible causes of failed output. The 254 reports that did not specifically identify a component as the cause of failure had 53 various reported categories as the specific cause of failure, including 103 reports identified as "normal equipment aging." This implies the utilities expected some type of failure due to the age of the power supply.

3.1.2 Erratic Output—Possible Causes

Erratic output is a failure mode that is fairly simple to isolate. Troubleshooting the power supply for a defective voltage adjustment control might be all that is needed to rectify the problem. There is usually indication that this device is malfunctioning prior to failure by previous "drift" readings. If this device is determined not to be the problem, check for defective components in the regulation circuit. Transistors and resistors will still operate, but if degraded will sometimes conduct sporadically.

Normal causes of erratic output:

- Damaged voltage adjustment control
- Demand supply (load) is operating as constant current source at current limiting value of the power supply
- Defective components in the regulation circuit (transistors, resistors, silicon control rectifier (SCR), integrated circuit (IC), capacitors other than electrolytic)

Erratic output was reported in 71 instances as the failure mode of a power supply. Of those 71 reports, the largest reported component failure (5 reports) was the capacitor. Sixty (60) reports did not indicate that an internal component was responsible for the Erratic Output.

Not all of the components identified in Table 3-1 are consistent with erratic output behavior. For example, the diode is not a part of the regulation circuit, and its failure would normally cause high output readings.

3.1.3 Open Circuit—Possible Causes

An open circuit is caused by a variety of possible causes. In the case of a newer power supply, manufacturing processes could be at fault (improper component soldering, component lead too long or short, and/or component lead fatigue). For older power supplies that have never been repaired, continued vibration could have broken a component lead. For power supplies that have been repaired poor workmanship might be at fault. And, any component within the power supply could fail "open" due to normal aging, accelerated aging, or transient damage.

Possible causes of a power supply to exhibit an open circuit are:

- Any open component within power supply
- Failed soldered connection of any component
- Blown fuse
- Broken component lead

Twelve reports indicated that the power supply failure mode was an open circuit directly related to component failure. The capacitor and fuse each were identified in four instances as the part causing the failure. Again, the components identified are consistent with the possible cause of failure.

3.1.4 High Output—Possible Causes

There are numerous causes for a component to fail open, the most common being age due to normal stresses. For example, when two or more filter capacitors are connected in parallel, one may have dissipated its' electrolytes at a faster rate causing it to fail, but the other capacitor(s) are still operational. This change causes greater stresses to the remaining capacitors (which will accelerate their potential to fail) and reduces their ability to provide a constant dc output to the load normally causing a high output reading.

Possible causes of high output from the power supply are:

- Open circuit on one or more of the rectifier diodes (voltage will continue through other diodes in circuit)
- Shorted turns in the primary or secondary transformer winding
- Open circuit on filter capacitor (when two or more are connected in parallel)

High output was reported 18 times, but only 3 reports identified the component as causing the failure. The three reports indicated that a (1) transistor and (2) capacitor were the components responsible. Fifteen reports did not determine if a component was responsible for the failure.

3.1.5 Low Output—Possible Causes

The most probable cause of low output is the capability of the power supply is not well matched with the requirements of the attached load. The load resistance is improper with the unit rating (load is greater than intended power supply design).

Depending on the design of the regulating circuit, a degraded component such as resistor, clamping diode, or lumped filter could affect the output of the power supply. A low reading in both directions usually indicates a bad diode. Sometimes diodes will actually test ok but fail under load or at operating voltage.

Possible causes of low output:

- Load demands greater than power supply specifications
- Degraded components in regulation circuit
- Failed diodes

Low output was reported the failure mode in 72 power supply failures. However, only 10 utilities reported the actual cause of failure to be related to a component failure.

3.1.6 Short—Possible Causes

Again, a transient voltage could cause damage to components such as capacitors, inductors, or transformer, which could cascade and cause further damage to the power supply. Many times it is difficult to determine the true cause if the failure is catastrophic because of the level of damage caused by the short.

Possible causes of shorted component:

- Transient voltage causing damage to any internal component
- Component degradation—loss of dielectric properties (transformer windings shorted and capacitor loss of dielectric)
- Shorted turns in the primary or secondary transformer winding

There were only 6 reports of a short being the primary failure mode for power supplies with the diode being reported the most often.

3.1.7 High Ripple—Possible Causes

If readings indicate one or more outputs are out of tolerance, and have excessive ripple at the line frequency (50/60 Hz) or twice the line frequency (100/120 Hz), the main filter capacitor(s) on the rectification circuit are degraded.

In switch-mode power supplies if one or more outputs are out of tolerance or readings indicate excessive ripple at the switching frequency (10s of kHz typical)—degraded output filter capacitors might be the problem.

In either case, this is the one reading that is indicative of component (mainly capacitor) degradation and the power supply should be removed for troubleshooting and/or repair.

Possible causes of high ripple:

- Filter capacitor degradation (low frequency ripple)
- Lumped element filter components such as inductor and/or capacitor could be degraded
- Degradation and aging of components in the regulation circuit (high frequency/noise)

High ripple was only reported in 2 instances as the failure mode. Even though this is the one failure mode that would indicate capacitor degradation or failure, no reports identified the capacitor as a "failed part."

3.2 Common Component Failures (Aging Mechanisms—Degradation—Failure Mechanisms)

The life of the power supply is a function of the aging components within the power supply. The component with the lowest life will normally dictate the life of the power supply. Component "aging" is the actual property changes of a material or device over time. In most cases, the life of an electrical component is limited by the aging of the insulating material. This is due to the degradation of dielectric strength as a function of time. Also, the time variation of parameters of electronic components (diodes and transistors) such as leakage current or dc gain could lead to aging of these components. Many physical stresses can lead to aging of a component. Internal or operational stresses, such as current, voltage or ohmic heating in electrical components are an inherent phenomenon. External stresses, such as ambient temperature, radiation, vibration, shock, or other mechanical and chemical stresses all contribute to the aging of the component. However, it is known that the failure of a component is not always related to aging, but due to other reasons, such as component quality (manufacturing) or circuit design of the power supply.

The aging of components is a factor used in determining its overall reliability that is determined, in part, by establishing its Mean-Time-Between-Failure (MTBF). MTBF is based on either actual testing of a component or use of a statistical model.

MTBF: *The average time (usually expressed in hours) that a component works without failure. It is calculated by dividing the total number of failures into the total number of operating hours observed. Also, the term can mean the length of time a user might reasonably expect a device or system to work before an incapacitating fault occurs.*

The power supply has its own MTBF, which is related to the reliability of the components, but the design as well. The selection of a component used in a specific power supply is contingent upon the function of the component in the circuit to meet overall design parameters. There are no manufacturing standards requiring product design engineers to select a more reliable component over a lesser one (except power supplies manufactured to government standards), and selection can be driven by a limit on production costs. The operational life, reliability, and the MTBF of the power supply is dependent upon all of these factors and are rarely tracked by the end user.

Certain components within a power supply have limited life; therefore, the manner in which a component degrades and/or fails is an important piece of information that should be coupled with the expected operating life. Knowing what component might fail, when it might fail, and in what order can be useful in a preventive maintenance program. The key components that make up a typical power supply and their failure modes are discussed in the following sections.

3.2.1 Transformer

The typical failure mechanisms for instrument transformers will be related to the windings of the transformer or the heating of the core material.

Typically a transformer will have at least two windings—a primary and secondary winding. But instrument transformer can have multiple windings and also center-tapped secondary windings depending on transformer design. The windings can have turns that will short together to the loss of insulation on turns of wire that make up the transformer winding. A loss of a turn or set(s) of turns will affect the voltage seen by the regulation circuit and the output voltage of the power supply.

Transformers and inductors generally develop an open circuit, although a shorted turn does sometimes occur. For transformers, an open circuit can occur in either the primary or the secondary winding. If a shorted turn exists, the DC resistance changes from its normal value. More importantly, the inductance decreases because the field in the winding is partially canceled by the current induced in the shorted turn. With a reduced inductance, the ac current will be higher, causing the transformer to operate hotter.

The core of these instrument transformers are affected by the heat generated by current flowing in them but also by magnetic effects or saturation of the core. The heat can eventually cause the core to breakdown and affect the ability of the transformer to supply voltage to the power supply.

The cause of many of the operating issues is heat and/or voltage transients. The design of the power supply, its application, and its ambient conditions will greatly affect the performance this component.

Although this component can be affected by operating condition, proper application and selection of a transformer by the design should provide trouble-free service.

EPRI NP-1558 reviews the failure mechanisms of the typical electrical components listed above. Field experience in operating transformers has shown that they are robust and have performed well over an extended period (over 20 years or more). Life characteristics of power and audio transformers were evaluated based on extensive life tests on these components. The results of these tests showed no failures of these components tested up to 560,000 hours. The environment to which these components were exposed had little effect upon the performance. The life test included 210 power transformers and 335 audio transformers. These transformers of which 40 percent of the units were energized for 5000 hours at an ambient temperature of 125°C and included measurements of electrical characteristics, insulation resistance, and dielectric strength at intervals of 100, 250, 500, 1000, 2000, 3000, 4000 and 5000 hours. All units met the requirements of electrical characteristics by maintaining the insulation resistance and dielectric strength. This high stability of the insulation properties of transformers along with its insignificant failure track record indicates that transformers are relatively age insensitive. Therefore, one can eliminate the transformer from the list of weakest component that determines the life of the power supply.

3.2.2 Resistors

Most resistors are used in the power supply to drop voltage to be used by other circuit components such as transistors and diodes. Since these components have voltage to drop across them, the energy is dissipated in the form of heat. When a resistor degrades or fails, it will tend to fail open. Resistors can change in value or completely open in the circuit because of excessive current flow through them. Long-term aging can also contribute to resistance changes.

Resistors are generally the most stable electronic components due to its simplicity and robustness in the materials that it is comprised of. Historically, resistors have performed well compared to the failures of other electronic components. The limited number of power supplies failures has confirmed this where resistors were known to have caused the failures of the power supplies. EPRI NP-1558 discusses failure rates of various types of resistors. A failure rate of $0.14x10^{-6}$ failures/hour (resulting into a mean time between failure of over 40 years) was reported in this reference for wire wound resistors. This failure rate was found to be high compared to others resistors in this reference. Again, test results indicate that the resistor is not the weakest component in the power supply. Therefore, resistors can be considered age insensitive compared to other electrical components in the power supply.

3.2.3 Capacitors

Capacitors are the only component used in power supplies with an established life expectancy, making them the most limited life component in a power supply. Capacitors are designed with a maximum operational temperature, voltage stress, capacitance range, and tolerance to ripple current, which relates to its reliability.

Capacitors usually experience one of three faults:

- Excessive leakage current and/or reduced capacitance
- Short circuit, indicating zero ohms if checked by an ohmmeter
- Open circuit, exhibiting little or no capacitance and no meter deflection if checked by an ohmmeter

In the case of either a short circuit or an open circuit, the capacitor is broken because it can no longer store a charge. A capacitor with high leakage current has a weakened dielectric, causing a lower-than-normal resistance. Electrolytic capacitors can dry out (lose electrolyte) as they age, causing a decrease in capacitance. This leads to an increase in capacitive reactance and can affect circuit operation through increased ripple current and greater instability of the equipment relying on the power supply.

Capacitors can be checked with a capacitance tester or with an ohmmeter. If using an ohmmeter, a good capacitor should initially indicate a low resistance as the capacitor charges with the resistance slowly increasing towards infinity. The final resistance represents the insulation resistance of the capacitor. The insulation resistance of electrolytic capacitors varies, but greater than 1 megohm is common.

Dielectric breakdown, terminal lead trouble, and seal or container failure are some of the chief failure mechanisms for capacitors. Temperature (ambient and operational), voltage, and ripple are some of the operational stressors that contribute to capacitor failure by overworking the capacitor and accelerating electrolyte evaporation.

A capacitor will fail shorted in normal circuit applications. A short will develop after a substantial loss of electrolytes within the capacitor case. When the electrolyte dissipates to the point that rectification voltage (or the line voltage in the case of a switching power supply) is moving directly across the plates an internal short occurs. Capacitor failure can be manifested as an open circuit, too.

The Reliability Analysis Center (RAC) evaluated Failure Rate data on hundreds of capacitors based on specific applications used by the military with results published in *"Reliable Application of Capacitors."* This study utilized a combination of field failure data and mathematical models to arrive at its findings, which is measured in units of failures per million operating hours. This document is targeted at electromechanical design manufacturers to assist in the capacitor selection process to improve overall product reliability. Using this data, the Mean-Time-Between-Failure can be calculated by using the formula:

$$\frac{\text{Operating Hours (Found in RAC)}}{\text{Total Number of Failures}}$$

Using the figures in RAC for commercial grade fixed aluminum electrolytic capacitors and the formula above, we get a MTBF of 1.101×10^{8} hrs for aluminum electrolytic capacitors. The same capacitors manufactured to military grade specifications had so few failures that their MTBF was almost equivalent to zero.

There is evidence within industry that shows power supplies have operated as long as twenty three years without the capacitor failing. Capacitor manufacturers are extremely conservative when publishing expected capacitor life, which was proven during performance of EPRI/NMAC Report 1001257, *"Capacitor Performance Monitoring Project."*

Manufacturers normally give a capacitor an expected life of 1,000 hours if operated at its maximum voltage and temperature range. Experience alone tells us the capacitors are operating longer than this and EPRI/NMAC Report 1001257 found little to no changes to capacitors after 1,000 hours of maximum temperature and voltage stress, and an additional 750 hours beyond specified voltage (+10) and temperature ratings (+10°C). In fact, there were no changes to the output ripple readings of the power supplies until the capacitance was only 13% of the rated value of the capacitor. As evidenced by this test, capacitors were able to take a lot of punishment and still operate within their parameters. Based on this report, we can safely state that the manufacturer stated expected life is extremely conservative.

EPRI NP-4483 *"Improved Reliability for Analog Instrument and Control Systems, Vol. 2 Guidelines for Component Selection and Replacement"* demonstrates that the failure of capacitors depended on the initial quality level of capacitors. Capacitors with lower failure rates as a function of stress and temperature are those that are of higher quality level (for example, military grade parts). Therefore, it should be noted that higher quality capacitors such as MIL-STD and hermetically sealed capacitors have comparatively higher reliability than commercially manufactured capacitors as evidenced by the RAC study indicating near zero failure rates for these types.

Methodology presented in Appendix E of EPRI TR-112175, "*Capacitor Maintenance and Application Guide,*" provides three methods used to estimate operational life for capacitors. Based on the methods shown in the Appendix, each plant can calculate an expected life for their in-service capacitors based on certain parameters.

The shelf life for aluminum electrolytic capacitors can be shown to be about 20 years or better using life estimation guidance based on storage temperature. This information is conservative because power supplies have lasted in service at nuclear power plants more than 20 years without capacitors failing.

3.2.4 Semi-Conductors (Transistors, Diodes, etc.)

Transistors and diodes can experience the same types of problems. Typical problems include:

- Short-circuited junction, caused by a high-voltage surge
- Open-circuited junction, usually caused by excessive current
- High-leakage current, usually accompanied by low gain or a high noise level

When checking transistors, observe proper polarity for PNP or NPN to avoid measurement error. The forward resistance is low, but never zero for a good transistor. Backward resistance is always higher than the forward resistance.

Diodes are semi-conductor devices that can be damaged by current surges. Three types of faults can be encountered in diodes:

- Open circuit
- Short circuit
- High resistance

Excessive current can cause any of the previously mentioned conditions. An open circuit exists when the diode PN junction has been blown apart; the diode measures infinite resistance in both directions. A short circuit exists when the PN junction is fused together; the diode measures zero ohms in either direction. High resistance can be measured if the PN junction has been partially damaged. In this case, the diode will have a higher than normal voltage drop in the forward direction because of the higher resistance. In the forward direction, a small resistance should be observed; the reading will vary depending on the type of diode. During operation with the diode properly biased, the forward resistance will be much less. With the diode reversed, the diode resistance should indicate infinity.

The manufacturers of semiconductor components have performed tests to determine failure rates. The time-temperature effects on the aging of semiconductors are reported in EPRI NP-1558 and "*Determination and Application of Aging Mechanism Data in Accelerated Testing of Selected Semiconductors, Capacitors and Resistors,*" *General Electric Company.* Arrhenius model relates the variable time and temperature through the knowledge of activation energy. Numerous references exist to review the theory that applies to thermal aging processes and application of Arrhenius model in the evaluation of thermal degradation of materials. The reader is advised to review EPRI NP-1558 as one useful reference for further review of this topic. It discusses the screening of semiconductor components based on its activation energies associated with the generally known failure modes. The generally known failure modes and their activation energies are shown below:

Failure Modes	Activation Energy (eV)
Electromigration of Aluminum	0.5
Degradation of Aluminum Silicon Contact	0.8
Surface Degradation	1.0
Aluminum-Gold Bonds	1.0

A graph based on the Arrhenius equation is shown in Figure 2-1 [7]. The Arrhenius equation is given by [7]:

Failure Rate = A exp (-ϕ/kT)

Where:

A is constant determined through experiments

ϕ is the activation energy in eV

k is the Boltzmann constant = 8.62×10^{-5} $eV/°K$

T is aging Temperature in $°K$

This relationship can be used to estimate a failure rate. The lowest activation energy can be used to conservatively estimate a failure rate for the semiconductor components. For an activation energy of 0.5eV and 125°C aging temperature, Figure 2-1 from the available reference yields a failure rate of 0.1%/1000 hours. This failure rate results approximately 114 years of mean time between failure (MTBF). Such a failure rate demonstrates that the semiconductors are age insensitive in terms of thermal aging. A review of WYLE Material Aging Data [9] also shows that a number of semiconductors (diode and transistors) are age insensitive.

The semiconductor components are sensitive to operational stresses, such as voltage, internal temperature rise due to inadequate design, etc. The failure rates can be reduced if the operating voltage of the device is reduced below the rating. Similarly, the failure rates can be increased if the operating voltage is increased above the rating. The most common Failure Mode for these components is short-circuit.

Establishing Mean-Time-Between-Failure rates for semi-conductors was also undertaken by the Reliability Analysis Center (RAC) in a document titled EPRD-97 (Electronic Parts Reliability Database—1997). This document is extremely detailed and encompasses many types of semi-conductors each with failure rates listed to calculate MTBF. This would be an excellent resource for engineers when looking for a better quality component for replacement.

3.2.5 Printed Circuit Boards

The known failure modes of the printed circuit board assembly is cracking of solder joints as a consequence of temperature variations that results in the fatigue of the materials and eventually open the solder joints. This can be avoided if the solder joints are provided with adequate stress relief in the packaging design.

Power supplies are typically used in mild temperature environment at nuclear power plants and are not exposed to frequent temperature variations. Therefore, this failure mode is of limited concern for the printed circuit boards in power supplies. However, vibration or mechanical shock can tend to cause solder joints to crack and produce intermittent connections.

3.2.6 Fuses

Fuses are made of wire and are not sensitive to aging when exposed to mild temperatures. However, they are subject to voltage and current stresses and will eventually fail. The historical failures of fuses in the power supplies are either related to material fatigue or under sizing of the rating. Fuses are not considered to be a component that degrades the performance of a working power supply, however if a fuse blows it could be a signal that there was a transient in the circuit and attention should be paid to that section of the power supply circuit.

3.3 Industry Case Studies on Failures

INPO's EPIX Database was searched for reported failures of power supplies from January 1997 to July 2001 to identify any common failure modes or specific internal component failures contributing to catastrophic failure. A total of 510 power supply failures were entered by utilities into EPIX with specific data points during this time frame. Each of these categories was entered into a spreadsheet format to search the data for any significant information leading to singular cause/s of failures. Key data points reviewed were:

- Utility
- Manufacturer
- Model Number
- Failed Part
- Failure Mode
- General Cause
- Specific Cause
- Date Failure Reported

The result of the analysis is summarized Table 3-2.

3.3.1 Number of Power Supply Failures in Past Four Years

During the selected time period fifty (50) utilities reported power supply failures from a total of seventy-six units as shown in Table 3-2:

Table 3-2
Power Supply Failures Reported per Year

Year Failure Reported	Number of Utilities Reporting Failures	Number of Reported Power Supply Failures
1997	34	135
1998	35	140
1999	37	122
2000	34	96
2001	7	17

This data indicates that the average number of power supply failures reported per year is 35 for all reporting utilities (leaving out 2001 as an incomplete year). None of the reports indicated power generation loss directly related to power supply failure, which significantly differs from power supply failures analyzed through 1979-1982 where reported loss of power generation was directly due to power supply failure.

The above data also indicates that there is an average of 3 (actual 2.96) failures per utility per year. This is supported by responses from utility members reporting an annual power supply failure rate of four. Respondents also identified that 600 to 1,000 power supplies are installed at their plants indicating a total failure rate of power supplies per utility to be less than .01% of the total installed power supplies.

3.3.2 Greatest Reported Cause of Failures

Sixteen components types were entered into EPIX as a Failed Part with the capacitor identified the most often. The capacitor was reported in 37 out of 510 records as “Failed Part” reflecting the capacitor as 0.07% overall as the reason for power supply failure.

Fifty-nine percent (59%) of the reported capacitor failure in the General Cause and Specific Cause categories was reported as Equipment Age and Normal Expected Aging respectively. Other specific causes for capacitor failure are listed in Table 3-3.

Table 3-3
Capacitor Failure Cause

Specific Cause of Capacitor Failure	No. of Times Reported
Accelerated Aging	1
Capacitor Shorted	1
Defective Circuit	2
Excessive Temperature	1
Heat Degradation	1
Inadequate Preventive Maintenance	3
Investigation Inconclusive	1
Leakage	2
Material Deficiency	1
No Preventive Maintenance	1
Normal Expected Aging	22
Short/Ground	1

Because the capacitor has been the suspected culprit of power supply failure for years, the specific causes above were scrutinized a little more closely for possible reasons the capacitors failed.

Capacitor shorted and short/ground could be the only specific causes listed that are directly related to the capacitor being the root cause of failure. In either of these cases the short may have been internal after a total loss of electrolytes within the case. The electrolytes in a capacitor will dissipate with use over time. Dissipation of electrolytes is a normal expected characteristic of aluminum electrolytic capacitors. If loss of electrolyte was the case in these two events, detection and replacement of the capacitor prior to failure would have prevented total failure of the power supply.

Excessive temperature, heat degradation and accelerated aging to the capacitor could be contributed to several causes.

1. Location of the capacitors in the circuit in relationship to other heat producing components

2. Ambient temperatures of equipment installed near power supply

3. Poor quality capacitors (not hermetically sealed) were used

Capacitors are designed with a maximum operational temperature to reduce the amount of electrolyte loss, which relates to its reliability. If the actual design of the power supply is at fault, a higher temperature rated, (or higher quality) capacitor that performs the same function can be substituted. This will change the internal design, but not the system design as long as the power supply operates to its design parameters.

Leakage was an interesting “cause of failure” as this is normal behavior for a capacitor, if “electrolyte leakage” was what the utility meant. Leakage is the dissipation of electrolytes as discussed previously. If the “electrolyte leakage” was to the point that the capacitor/s caused the failure, then the capacitor, when tested, would have been out of manufacturer specified tolerances, or completely shorted. If the utility meant “leakage current” the capacitor was not totally reformed to the rated level for the capacitor to perform its filtering function or the capacitor did not have enough electrolyte to reform but was placed in service anyway. In either of these cases, the capacitor is damaged to some degree and should not have been put in, or left in the power supply.

Material deficiency cannot be addressed due to a lack of information. It is assumed that the root cause analysis performed by the utility found a poorly manufactured capacitor. If this was the case, replacement with a higher quality capacitor may mitigate future failures.

Inadequate preventive maintenance, no preventive maintenance and normal expected aging are lumped into the same category here because they are essentially the same. If the capacitor failed due to normal expected aging and was the direct cause of failure for the power supply, inadequate or no maintenance was performed to mitigate the failure. Inadequate or no preventive maintenance means that the capacitor was allowed to run-to-failure (that is, normal expected life) causing the power supply to fail before being replaced.

When reviewing the actual causes of capacitor failure as the root cause of power supply failure, the capacitor, when held up to the light, does not appear to be the cause of 37 reported failures. The actual culprit is time. Knowing what “time” to change the capacitors may have prevented 36 of the 37 failures reported. EPRI Project *“Capacitor Performance Monitoring Project” Document 1001257* can give further guidance on establishing a monitoring method for capacitors to enhance maintenance activities.

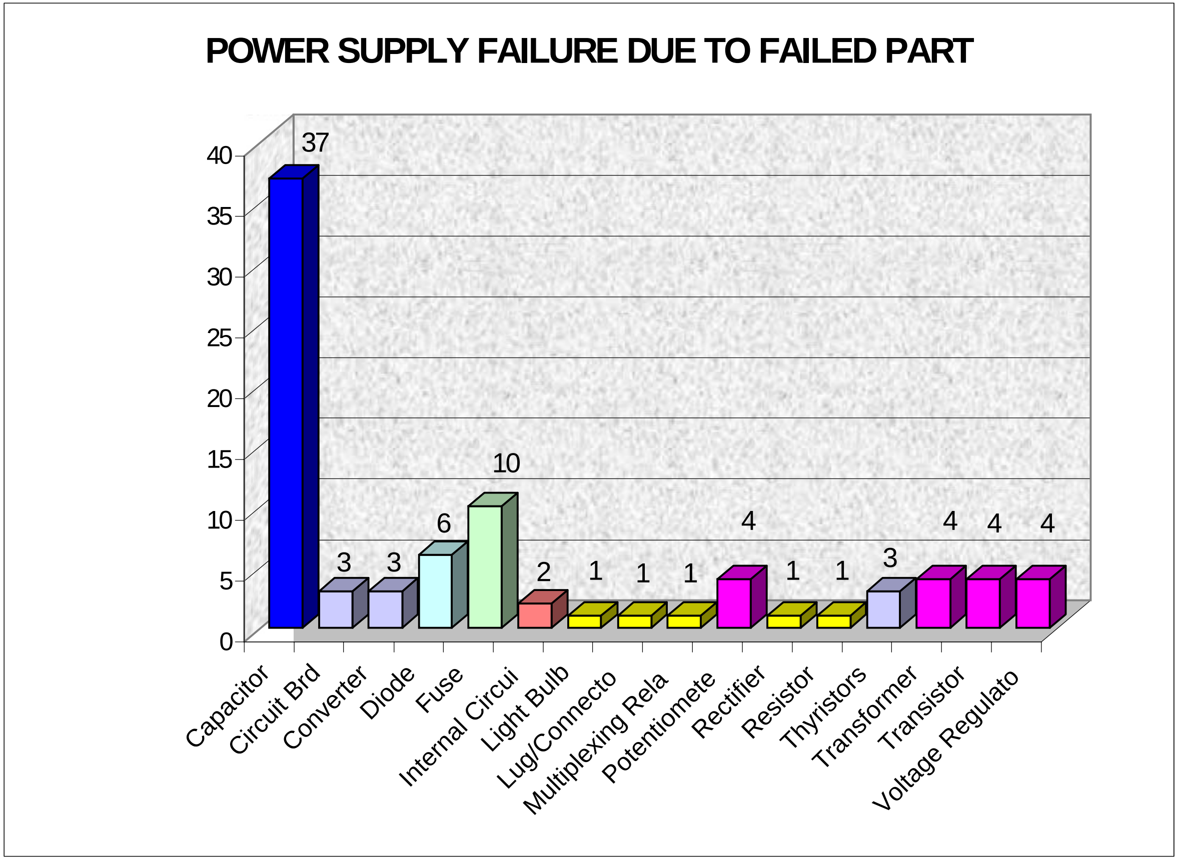
The next most reported component responsible for power supply failure was the fuse, which had ten (10) records in NPRDS, making the failure rate for the fuse overall 0.01% and other reported components < 0.01%. All reported component types and the number of times reported are reflected in Table 3-4.

3.3.3 Reported Component Failures

From 510 records, a total of 87 records reported a power supply failed due to a “failed part”. This means that only 5.86% of reported power supply failures were actually attributed to internal components.

Sixteen component types directly contributed to failure of the power supply, either catastrophic or fluctuations in operational parameters. The following chart indicates the component type and the number of failures reported.

Table 3-4
Failed Power Supply Components



When reviewing the chart above it is interesting to note that the capacitors are downstream from the fuse, diode, transformer, and voltage regulator in a linear power supply design. A failure of any of these components could cause a transient voltage that could damage the capacitors. This is not a literal interpretation of the chart data, only that in a single power supply this could be one failure sequence, which would effect the performance of the power supply. Also, during performance of a failure analysis of the power supply this would normally be the sequence used to check individual components for failure.

3.4 Conclusion of Failure Data

From the overall failure information reviewed for power supplies, the actual annual failure rate for power supplies is very low (for example, 0.3%) on per plant basis. The majority of failures reported were related to specific power supply vendors but even when that information was reviewed further, it became apparent that many of the power supplies that failed had been in service greater than 15 years on average. The in-service time does not begin to address the actual age of each power supply.

Based on the limited data for actual power supply failure causes, power supply failures appear to be fairly random. This conclusion is based on the information gleaned. When trying to determine a root cause from the available information, it becomes clear that it is difficult to tie down a specific component or series of components although, the capacitor has been highlighted as the most likely component.

Since capacitors perform many key functions in power supplies such as clamping, chopping, blocking, and smoothing waveforms, they tend to see the majority of factors that cause voltage and/or current ripple. Also, electrolytic capacitor is probably the most life-limited part used in power supply construction but even this component has considerable operation capability.

Because linear power supplies tend to produce less ripple, it is expected that these types of power supplies should have long service lives because they tend to have very simple filters on the output of the rectification and the regulation circuits and a small number of parts in general.

Switch-mode power supplies tend to produce more output ripple and EMI/RFI effects, which tend to affect input and output filter life as well as contribute to possible transient effects that will snow-ball as components degrade. This type of power supply produces more ripple than a liner power supply therefore, it will have a more complex filtering scheme on both the rectification and regulation output circuits and these components experience more stress and will be the most likely components to fail.

4
CURRENT MAINTENANCE STRATEGIES

Nuclear power plants have taken various approaches to power supply maintenance. This section reviews these approaches and points out the pros and cons of the approaches.

4.1 Maintenance Practices

A number of utilities (16) were contacted directly, and surveys sent to others, to determine how, or if they were addressing Power Supply Maintenance. They were asked to describe: Current Maintenance Practices, Power Supply Failure Data, Repair/Refurbishment or Replacement Practices, and Obsolescence Practices of Power Supplies.

Overall response indicated the majority of utilities have implemented a power supply maintenance program. The degree to which it is implemented varies from responding only when alarms indicate a non-operational power supply, to replacing power supplies at a given interval irrespective of the condition of the power supplies. The majority of utilities are sending their power supplies out for repair on a regular basis during scheduled outages, or scheduled time intervals, regardless of power supply condition to ensure continued operability. Only one of the utilities responding indicated that minor repairs were performed in-house. Most utilities send power supplies to repair facilities or the original equipment manufacturer citing cost effectiveness and vendor knowledge as the reason for acquiring outside services.

4.1.1 Condition Monitoring

Several utilities indicated that they have taken various data points from hundreds of installed power supplies (Predictive Maintenance) for years in an effort to trend power supply behavior in order to:

1. Predict power supply degradation
2. Adjust existing maintenance schedules
3. Enhance troubleshooting practices
4. Improve operational life

Results of this effort allowed some of these utilities to improve their troubleshooting practices and adjust existing maintenance schedules, but failed to provide useful trending data that would allow them to predict power supply failure or determine remaining operational life.

There was and still is very little guidance on what parameters and/or values that indicate component or sub-component degradation. Output voltage ripple has been used by many but the level of ripple voltage, the change in the level, and the rate of that change has not been clearly defined in any literature nor established by vendors. Plants have however used ripple voltage as an indicator with less than stellar results.

It has been suggested that modifying existing power supplies by placing test leads at the rectifier output filter of the power supply may provide a better place for monitoring ripple voltage. The circuit components in this portion of the circuit see the largest amount of ripple and may well provide early warning to capacitor or other component degradation.

Because condition and operational monitoring has not proven to provide useful information, several utilities responding to the survey, indicated that time consuming monitoring is no longer done and have adopted other methods to maintain power supply "health." One such utility indicated that they have established a finite life for the power supplies based on capacitor life calculations. This maintenance method may provide the best insight into continued power supply operability to date and will be discussed further in the "Recommendations" section.

It is important to note that although most utilities are implementing maintenance programs for their power supplies and have operational data on installed power supplies, all are still experiencing the same issues for power supplies they had in the 1990s. Determining the frequency of monitoring, trending degradation, and repair/refurbishment/total replacement of a power supply are the same confusing issues today. The Recommended Best Practices Section will address this veil of confusion to enhance existing power supply maintenance programs.

Most utilities are measuring the input/output voltage and the regulation voltages (line & load), and fuses during scheduled surveillances or maintenance. The output ac ripple current is more difficult to properly check in the field, as the best instrument to use for measurement is an oscilloscope, which is somewhat large and cumbersome. However, a voltmeter is adequate to measure the RMS voltage. Visual inspection of the internal components is not frequently done in the field because the covers on most power supplies are difficult to remove due to location. This is usually done when a power supply is removed from the system for a "bench" check during scheduled PMs.

4.1.2 Case Study of One Utility's Maintenance Program

Manufacturers have always recommended a list of maintenance requirements in their vendor manual applicable to a specific model or series of models. It should be noted that manufacturer maintenance requirements be carefully reviewed before a preventive maintenance practice for the power supply is established. One utility that has established a maintenance program for its power supplies and provided their maintenance schedule, which shows how they schedule their preventive maintenance and the activities they perform. A list of the activities that this utility is performing are shown as follows:

- Perform visual inspection and cleaning
- Check auctioneering (only for circuits with redundant power supplies)

- Check over-voltage protection circuit
- Check Line & Load Regulation
- Energize spare power supplies
- Replace all electrolytic capacitors or entire power supply
- Replace input/output fuses

The actual frequencies of the tasks mentioned above are shown in the following table. The frequencies were established based on the failure data obtained from a number of nuclear power plants. Since the failure data was not statistically significant, the frequencies for the activities were considered at conservative intervals as represented in Table 4-1. As the experience with the failure data matures in the future, these frequencies can be extended with time. Also, the intervals should be adjusted based on the performance since the performance is a expected to change with age.

The following are some examples of current power supply maintenance practices implemented at several stations to protect and prolong their operability:

Due to the failure of 51 process instruments cards traced to voltage spikes from associated power supplies, one utility implemented the following practices:

1. Measures and trends AC ripple voltage
2. Installed plugs in power supply covers to facilitate testing
3. Daisy-chained power supplies for simple on-line replacement
4. Implemented in-storage maintenance program for spare power supplies

Several other utilities have installed redundant power supplies and have adjusted the primary and secondary power supplies so the load is equally shared between the two. This change was done to reduce secondary power supply failure when called upon to operate due to a failure in the primary power supply.

To protect a critical system from inductive voltage spikes, one utility added in-rush protection devices and metal oxide varistors. This method protects power supplies from transient voltage spikes when power is turned on or off to the device that could cause damage to internal components of the power supply.

Table 4-1
Power Supply Maintenance Schedule

POWER SUPPLIES

Component Classification Category		1	2	3	4	5	6	7	8		
Critical	Yes	x	x	x	x						
	No					x	x	x	x		
Environmental	Harsh	x	x			x	x				
	Mild			x	x			x	x		
Usage	Frequently	x		x		x		x			
	Seldom		x		x		x		x		
Condition Monitoring Task		**Frequency**								**Failure Causes**	**Comments**
Check output voltage and, if applicable, AC current ripple.		18M	18M	18M	18M	3Y	3Y	5Y	5Y	CD, OC, OP	Adjust output voltage as necessary. Replace power supply or output capacitors if ripple is out of specification. See Note 1.
Time Directed Task											
Perform visual inspection and cleaning		18M	18M	18M	18M	3Y	3Y	5Y	5Y	DA, MS	Look for damaged/loose connections, signs of overheating or corrosion. Fuseholders carrying input/output current should also be checked.
Check auctioneering (only for circuits with redundant power supplies)		18M	18M	18M	18M	3Y	3Y	5Y	5Y	CD	Either remove fuse or adjust power supply output such that the redundant power supply takes the load.
Check overvoltage protection circuit*		18M	18M	18M	18M	3Y	3Y	5Y	5Y	CD	Perform this step only if the power supply has a resetable overvoltage protection circuit.
Check Line & Load Regulation*		18M	18M	18M	18M	3Y	3Y	5Y	5Y	CD	Perform on power supplies that power more than one instrument loop
Energize spare power supplies			1Y		1Y		AR		AR	EL	Reforms electrolytic capacitor. Will prevent early failures when power supply is installed. AR - As Required (test before installing).
Replace all electrolytic capacitors or entire power supply		5Y	5Y	7.5Y	7.5Y	7.5Y	7.5Y	10Y	10Y	AG, EL	See Note 2
Replace input/output fuses*		5Y	5Y	7.5Y	7.5Y	7.5Y	7.5Y	10Y	10Y	AG	Applies to fuses that supply input power or power supply output. Inspect an replace fuseholders if indicated.

* Perform these tasks only on power supplies that, per plant records, have a history of this problem.

Note 1: If there is no visual indication or alarm to alert users that a power supply has failed, critical power supplies should be monitored more frequently.

Note 2: For auctioneered power supplies in mild environments, these frequencies may be extended by alternating which power supply carries the load. Set the ouput of one power supply (primary) slightly higher than the redundant supply (backup). At the next required maintenance check, adjust the voltage on the power supplies so that the output voltage on the power supply which was the backup for the previous cycle is slightly higher than the voltage on the power supply that was the primary for the previous cycle. During the cycle that a power supply is a backup, current is at a minimum and heating of the electrolytic capacitors is reduced. Since temperature is a major factor in capacitor degradation, the expected life of the capacitor should be increased.

4.2 Repair/Replacement Practices

Because repair is a critical factor in power supply operability utilities were asked to describe their current repair practices and what, if any, effects the repair had on the reliability of the power supply. Troubleshooting prior to repair is normally the first step in determining the root cause of a failure, so this topic was included in the repair discussion.

4.2.1 Utility Practices

Only one utility responded that repairs to power supplies are performed in-house, with the rest responding that repair/refurbishment was contracted out to either a repair facility or the manufacturer of the power supply. The cause of failure is identified by the utility, sometimes in conjunction with information received from the repair facility findings. Most utilities stated that the failure cause analysis is performed in-house and results are tracked and trended by them.

4.2.2 Repair Facilities (Manufacturer and Sub-Contracted)

As previously discussed, with few exceptions, utilities rely on the expertise of repair facilities or the original equipment manufacturer for repair of power supplies. Six repair facilities, including two OEMs, and those contracted with frequently in the nuclear industry were contacted to better understand how their role effects power supply operability. They were all asked to address:

1. When a power supply is repaired/refurbished at your facility, what percentage to the original condition is it considered repaired to? 100%, 50%, or other?

    All repair facilities responded that it was considered 100% "new" for the guaranteed warranty period because all characteristics are within manufacturer original specifications. The warranty period however was as short as three months with the longest warranty being one year.

2. Do they document failures, and if they do, have they found any repeated or singular cause that contributes to power supply failure?

    All repair facilities responded that they only document failures if requested by the customer. In depth root cause failure analysis was not routinely performed, nor requested, and the majority of facilities do not offer this service. The facilities that do, the cost is prohibitive. They do however send a failure report, which basically lists the replaced components.

None of the repair facilities appear to analyze failed components. Due to industry belief that the cause of failure is the capacitors, all facilities automatically replace the capacitors regardless of condition.

3. When replacing components do they offer an equal component of a greater quality than the one replaced?

   All repair facilities responded that due to the replacement requirements of the nuclear industry, if an exact replacement is not available (normally due to obsolescence) they notify the utility prior to installation for resolution. They do not routinely seek out higher quality replacement parts to improve the reliability of the power supply because of these restrictions.

4. What establishes your warranty period?

   Some of the repair facilities (OEMs) base their warranty period on standard business practices which support repair of equipment they manufactured, but not beyond 90 days due to the age of the equipment. Independent repair facilities give a one-year warranty based on the limited life of the capacitor and the fact that, if the power supply is going to fail based on the work they performed, it will fail within that period of time. Beyond one year they cannot guarantee that other factors once returned to the owner did not cause the failure.

4.2.3 Replacement Practices

Industry replacement practices of power supplies differed in that numerous variables come into the decision process. Almost all of the variables relate to the age of the plant and the age of components within those systems. Procurement of a replacement is regulated by licensing requirements which require original design parameters be maintained. The course of action with the least impact financially and to design basis is to replace a component with exactly the same component, with no change in form, fit or function.

It is these last three words that have caused some utilities to implement costly major design modifications for vital plant protection systems (including power supplies – analog vs. digital). They were unable to obtain replacement components of major system/s to the original design requirements so they changed the system design. The majority of these changes are due to obsolescence, which is addressed in a later section.

Some utilities are utilizing after-market suppliers to procure power supplies and other vital components. These companies specialize in buying surplus equipment from manufacturers and other utilities and sell to utilities needing such equipment. Some provide the component complete with Dedication so the component can be installed upon receipt. There are varying forms of this after-market business, including an alliance of utility members who have identified vital equipment that is common to all and share the costs of stocking unique, high cost equipment. This reduces each utilities inventory cost and provides “insurance” when/if the component is needed. Power supplies, however, do not fall into “capital equipment” category and are purchased on an individual basis when replacement is required.

Due to obsolescence of a number of power supplies, some procurement and design personnel have partnered with companies that specialize in component reverse-engineering. Utilities that have adopted this practice to ensure continued procurement of vital system power supplies have found there is a price for this practice, and not just financially. The cost for several utilities has been in substantial production delays. One utility was assured that the first power supply could be produced within six months. After eighteen months the vendor notified the utility it needed another six-month extension to produce the power supply. This one model of power supply is used in numerous systems critical to reactor protection. There are a limited number of spares on hand for this utility to utilize in case of failure. Should all spares be used prior to receipt of any contracted power supplies, this station could be facing a forced outage situation without an alternative plan.

Only one NSSS supplier has been identified as having implemented an approved replacement program for obsolete power supplies originally furnished by them. They have performed the necessary engineering analysis for the replacement, and once accepted by the utility, can be installed in lieu of the original without further engineering justification. Only one utility reported they are utilizing this service.

The majority of utilities are currently responding to power supply replacement needs on a reactionary level. The decision is made at that time to repair or replace, repair being the choice if a replacement cannot be procured, replacement if one is available. Most utilities currently do have not a long-term replacement plan for power supplies identified, much less implemented.

4.3 Obsolescence

The majority of nuclear power generating plants in operation today are of 1970s vintage or earlier and the majority were designed with analog instrument and control (I&C) equipment. The electronic industry has been very dynamic during the past 30 years and many vendors have moved from analog production to digital production of I&C equipment, or now produce only switched-mode power supplies. Nuclear utilities on the other hand have remained static in their use of analog equipment (mainly linear design) due to license requirements to maintain design basis. Because design modification costs involved in moving from an analog to a digital world are considerable in the nuclear industry, many utilities have decided to maintain their analog equipment.

No power supply should be expected to operate for the 30-40 year operating life of a power plant. The actual design life of a power supply, according to seven major manufacturers, is the actual warranted life of the power supply when purchased, which is about five years. The warranted life is usually based on the most restrictive limited life component of all installed components and in some part, the quality of the components purchased for use in the design. Installed power supplies have seen duty for as long as twenty-three years and have proved to have an average installed life of fifteen years (from NPRDS data). Power supply failures are being seen in greater numbers simply because they have reached, or are reaching, the end of their service life. Whether a maintenance program contributed to this longer operational life is indeterminate.

Many power supply manufacturers have either gone out of business, no longer manufacture the exact model, have changed designs to digital, or have no incentive to support spare and/or replacement parts for an obsolete power supply, now, or for another 10–20 years. Power supply obsolescence is a major challenge all utilities have been facing for the past ten years and continue to face in the future. Some manufacturers will no longer repair obsolete power supplies due to component obsolescence, they simply cannot procure the exact components installed during production of the power supply. The engineering costs involved to justify replacement component/s, testing, drawing and publication revisions to maintain obsolete equipment to the original design is cost prohibitive and not necessarily sound business practices for the manufacturer.

The importance of a well planned, cost effective maintenance program grows in direct proportion to the age of the power supply. Equipment Age was reported as 63% of the “Specific Cause of Failure” of power supplies from January 1997 to July 2001in EPIX. Continued operation of aging, obsolete power supplies have actually become an industry wide challenge of “life extension” since most of the installed power supplies have operated past their intended service life of five years. And most utilities have done an excellent job of extending the life of power supplies as evidenced by the average operating life of twelve years.

4.3.1 Obsolescence Assessment

The industry obsolescence gauntlet has been thrown and the challenge was accepted by a group titled Nuclear Obsolescence Utility Group, or NUOG. This organization was formed in November of 1999, with members from various North American utilities and all of Canada’s nuclear utilities. Membership is growing because utilities are beginning to realize just how large obsolescence issues are at their plant. With two years behind them, NUOG has addressed many procurement issues.

To understand how broad obsolescence issues are, and how/if it affects installed power supplies, an obsolescence self-assessment should be performed. NUOG’s Self Assessment guidelines address systems to determine the extent and potential impact of obsolescence. In this case we have taken the liberty of narrowing that scope to the component level. Most utilities have >600 power supplies installed, with the majority performing a critical function. An obsolescence assessment will enable a utility to determine:

- Exact number of obsolete power supplies
- Assess spare part levels
- Plan for procurement or replacement of obsolete equipment
- Perform cost analysis (design change vs. continued repair)
- Adjust budgets (maintenance, planning, procurement)
- Identify necessary training and other issues
- Become proactive instead of reactive to obsolescence issues

Once an obsolescence plan is completed, the utility will have a better understanding of its impact on power supply long-term operability. For those power supplies identified as obsolete, decisions can be made to extend their life through managed maintenance/repair, declare them a run-to-failure item with planned replacement upon failure, develop design modification for a different type of power supply and determine costs associated with their choice.

4.3.2 Reverse-Engineering

Reverse engineering is the process of developing a duplicate item by physically examining, measuring or testing the existing item, reviewing existing technical data, and/or performing engineering analysis in order to create an exact replica. Legal issues surround the decision to reverse engineer a component, which may have been patented, is considered proprietary or a trade secret and would have to be addressed by legal counsel prior to pursuing.

Nevertheless, reverse engineering is being utilized by some utilities to address power supply obsolescence. Three vendors were identified by utilities as reverse engineering obsolete linear/analog/board power supplies used in critical applications.

The positive side of the reverse-engineering coin is that utilities are partnering with a vendor in the design and manufacturer of specific types of power supplies. This allows the utility the ability to define design, determine immediate quantities, and establish long term relationships for future needs.

The negative side of the coin, for one utility, has been extreme long lead-time with continued increased cost amendments throughout the process. Original time for design and delivery was estimated at nine months with the vendor later requesting an extension of an additional 18 months before delivery.

4.3.3 Design Modification

Design Modification is the process of changing a system from the original approved design. The reasons for implementing a design change are varied and are usually reserved for major improvements to plant operation. Switching from analog to digital equipment would be considered a major design modification while changing out components that are compatible with the system (and perform the same function) may be considered a minor modification.

The costs associated with any design modification can be substantial and the review/approval process can be complex and lengthy. When considering changing out linear power supplies to switch-mode design to improve efficiency, effects on the system would have to be evaluated and may fall into the design modification category. The reasons a design modification is being considered for power supplies could include:

- The number of, and type of failures is impacting power generation or daily work schedules
- The cost of repair or continual repair is exorbitant and/or increasing
- The maintenance personnel are spending more time on power supply issues than seems necessary

It is these types of issues that utilities must address to determine if replacement of power supplies via a design modification would be cost effective in lieu of continued increasing maintenance costs.

4.4 Inventory

Once sent to the vendor for repair, a back-up power supply must be placed in service until the power supply is returned. This power supply is usually pulled out of spare inventory where prior to installation a bench check is performed to ensure it is operational. It is usually at this point that a utility becomes aware that replacement spares are low or completely depleted and that a replacement may not be available.

Several utilities reported that their number one concern today with power supplies is in the operability of stored power supplies. Many stored power supplies fail the operational bench check and are sent for repair. If spares have been completely depleted, a replacement is usually ordered. If a replacement is not available, the practice of cannibalization is sometimes performed if that option is available. The schedule in Table 4-1 addresses In-Storage PMs for one utility, which should be adequate for reforming capacitors. This schedule may even be a bit aggressive as the shelf life for electrolytic capacitors is defined as 15 to 16 years in EPRI NP-6408, "*Guidelines for Establishing, Maintaining, and Extending the Shelf Life Capability of Limited Life Items (NCIG-13)" and Mil-Std 1113B*.

Using methodology presented in EPRI TR-112175, "*Capacitor Maintenance and Application Guide,"* the shelf life for aluminum electrolytic capacitors can be shown to be around 20 years or better by applying the same guidance for determining operating life. But even this information is conservative because power supplies have lasted more than 20 years in service, with operational stresses, without capacitors failing.

One utility has modified their in-storage maintenance program for power supplies, in part due to the previously referenced EPRI TR-112175, "*Capacitor Maintenance and Application Guide."* Based on the shelf life of the capacitor as 20 years they have adopted a program, which only performs operational checks when the power supply is removed from storage prior to installation. Their procedures require a "soft start" of the power supply to reform the capacitors. If the power supply doesn't have the proper output at this time, further troubleshooting can be performed to identify the problem. A complete bench check is performed to ensure the power supply is operational. Because this utility has just recently implemented this program there was no data to determine how well this method addresses in-storage issues.

For those utilities without an In-Storage Maintenance Program for power supplies, the In-Storage schedule shown in Table 4-1 could be used as an example to establish a conservative program, or adjusted to implement a less aggressive schedule, or a third option such as the one just described could be adopted.

Currently there is one utility considering scrapping spare power supplies in their inventory due to age issues. They are grappling with capacitors that have expired in stored power supplies. One department has recommended a solution that all expired power supplies be scrapped and replaced with new power supplies. Another department believes this is an extreme action, and that other options must be available. This department is in the process of benchmarking practices at other utilities to determine what their future policy on expired capacitors in power supplies will be.

As previously discussed, capacitors have a limited life, but, like any other internal component, can be replaced when the need arises. The option of testing the capacitor for operability (and replacing it if needed) prior to replacement of the entire power supply would be more cost effective.

Other inventory issues concerning power supplies is adequate stocking of spares. Some power supplies because of their critical application have been designated as LCO (Limited Condition of Operation) items. This means that if an in service power supply so designated should fail in service that there is a defined time limit in which it must be repaired or replaced or plant generation may be effected. In this case an exact replacement spare power supply to replace the failed one would be the preferred choice. Defining individual power supply applications is critical in maintaining needed spares for continued plant operation.

4.5 Summary

From the information gathered during the project, power supply maintenance practices across the industry vary based on personnel knowledge of the issues and condition that actually affect power supplies and on current performance of their equipment (i.e., recent failures).

The knowledge of personnel related to the repair of power supplies is not the real issue because many plants have found it more cost effective to have their power supplies sent out to a repair facility for overhaul and repairs. However, there are some plants that do some on site repairs and maintain spare parts or "cannibalize" other power supplies to keep their equipment operating.

The majority of plants use off site repair facilities, either OEM or other vendors, to provide repair services. There is a repair specification that is prepared by the plant and supplied to the vendor. Plants should consider asking for more "detail" information regarding repairs performed on their power supply units. Information such as:

- Components replaced
- Why were the components replaced?
- What was the likely cause of the component failure?
- What parameters were checked on the failed component to confirm its condition?

If the power supply units are repaired on site, similar information should be collected.

Repair and failure information is important to obtain a more complete picture of power supply operating life. It is known that capacitors are the most limited part for power supplies; however, when power supplies failure data is reviewed, capacitors have not proven to be as temperamental as once thought. There are very few capacitor failures listed. This information was somewhat confirmed from a capacitor project that was undertaken to monitor capacitor ripple changes to develop condition monitoring guidance. For the period of time chosen, none of the capacitor's failed or even had operating parameters that were outside acceptable levels (see EPRI, *"Capacitor Performance Monitoring Project,"* Palo Alto 1001257).

Plant personnel should acquire knowledge in the area of component failure for their power supply units. Understanding how and when these components failed, will allow for more timely action related to component replacements.

Although condition monitoring has not proven to provide the anticipated benefits, it has allowed plant personnel to improve their trouble shooting skills. Condition monitoring should not be considered a completely lost cause, because there has not been enough repeatable data collected to establish life curves for power supplies by monitoring the change in output ripple voltage (at the rectifier output).

Plants should take advantage of the obsolescence work that has been done in the industry. The approach taken by one utility to use plant operating life as a limiting factor when selecting their repair/replacement opposition has shown some immediate benefits and has basis to show that it may prove to be a wise long term approach. Whether, a plant choose to replace (with different power supply units or reverse engineer existing units), there will be some design modification work and this should be figured into the decision process.

Power supply unit inventory is important especially for those power supplies that are in critical applications, reaching end of life, or have experienced increased failure rate. The power supply units that are in inventory should be ready to go into service and if they are routinely powered up, before placing them into service. They should undergo a soft-start (if applicable) and be operated a certain period of time (typically 24 hours) before being placed into service.

If shelf-life is established for components, be sure the basis for the shelf-life is understood and documented. Capacitors have been shown to be the life-limiting part, therefore, calculate the life using the only stressor for storage and that is temperature. The numbers of 16 to 20 years is based on the temperature effects, but with no other stressors, power supply units should exceed the expected shelf-life in controlled environments (moderate temperature and low humidity). The contributors to most premature failure are manufacturing errors, poor component selection by manufacturer, or misapplication in the field. Most of these contributors should have been worked through considering the maturity of linear power supplies that are used in nuclear power plants.

5
MAINTENANCE PROGRAM AND PRACTICES

From the information gathered during the research phase of this report, it was evident that some utilities may not be aware of options within maintenance programs. Several recommendations to improve power supply maintenance activities have been included in the following sections.

5.1 Maintenance Program Recommendations

Preventive Maintenance includes predictive (condition-based) and periodic (time-based) actions to improve equipment reliability and availability. The goal of predictive maintenance activities is to collect, trend, and analyze equipment operating data and process parameters to initiate maintenance activities for degrading equipment prior to failure thereby minimizing unplanned corrective maintenance activities.

5.1.1 Monitoring Program Recommendations

Condition Monitoring is the process of taking readings at different points (output voltage/current/ripple, input voltage/current, etc.) to determine potential degradation of a structure, system, or component (SSC).

Techniques such as voltage measurement, current measurements and thermography have been used as data points to determine overall degradation of the power supply.

According to EPRI/NMAC TR-107044 "*Instrument Power Supply Tech Note*" the condition of a power supply can be assessed by performing certain on-line tests as follows:

- Output voltage (DC)
- Output current (DC)
- Ripple voltage at the output
- Output voltage regulation
- Quality of the input voltage
- Temperature scanning (thermography)
- Visual inspection

The above parameters have been monitored as part of the periodic verification of the overall health of power supplies in most maintenance programs. However, in some instances this could be misleading, because, it really does not tell us what component in the power supply is failing in order to prevent failure.

For example, aluminum electrolytic capacitors have been considered the weakest link in the power supply by industry. When a power supply fails, with few exceptions, all the capacitors in the power supply are replaced. If the output ripple voltage increases, the capacitors are immediately declared as the cause for the increase. The output ripple voltage is a combination of noise produced by the regulation circuit as well as some ripple from the rectification network, usually 120 Hz or a harmonic thereof. The output ripple in linear power supplies is usually very low however, as the power supply ages the transistors in the regulation circuit get noisier and the output capacitors can not block all the ripple. The ripple that needs to be monitored is the ripple across the filter capacitor in the rectification network. This is recommended because in order to detect rectification ripple at the output of the power supply, the capacitance value of the filter capacitor would have to be so low that for all practical purposes the capacitor would already be damaged.

Consequently, seeing a high output ripple voltage means that other components are seeing higher stresses due to capacitor degradation, which, in turn is causing degradation to those components. As these components continue to degrade the power supply will experience higher failure rates in the form of out of tolerance readings and if left in operation will eventually experience a catastrophic failure.

There is no way known to detect individual component degradation in the power supply by any of the tests mentioned above. For example, condition monitoringtechniques which measure output ripple voltage to determine capacitor degradation have shown to be of little to no value for this purpose.

Voltage measurements at the output of the power supply can be a measurement of the power supply regulation (dc), or a measure of the ripple voltage at the output of the power supply (ac) using a voltmeter or an oscilloscope. These measurements can be of great help if they are taken when the power supply is first installed and after each repair or refurbishment. The first measurement can be used as a baseline measurement for comparison of future readings.

Measuring the ac ripple and comparing it to the manufacturer power supply specification will tell us that, if the reading is greater than the specified ripple some of the components in the regulation network may have started to age. This does not mean that the power supply is not performing well, because the high frequency ripple (noise), usually does not interfere with the load circuitry unless it is an extremely sensitive circuit. When the ripple is in low frequencies (60 Hz, 120 Hz, etc.) it means that the filter capacitors (s) in the rectification network have failed and the entire power supply will soon fail.

Measurements of the DC output voltage will be an indication of the power supply health if it stays constant, variation or erratic readings means that some components inside the power supply have degraded or failed. The same symptoms apply to the measuring of the output current. Measurements of current while the power supply is on line are not practical unless current shunts have been installed at the output and a millivolt drop measurement can be done.

Thermography maintenance methods to measure internal heat of the power supply is not practical and will not tell us what is wrong with the power supply unless we have some reference measurements of sections of the circuit in the power supply. This would be very difficult because the power supply thermal and internal components signatures will change depending on the load variations.

Utilization of the above mentioned techniques may indicate how the power supply is behaving during its service life, however, they are still not sophisticated enough methods to tell us which components inside the power supply are degraded or failing.

Several utilities have discontinued their condition-monitoring program because they determined that the data points taken were inconclusive for mitigating failure of specific internal components prior to failure of the power supply. They returned to a time-based maintenance schedule to ensure power supply operational specifications were being met freeing maintenance personnel schedules to support other plant priorities.

Existing condition monitoring programs should be reviewed to ensure they are meeting the intent of improving power supply reliability. If the collection of data has not proven useful in predicting equipment failure modes, a reassessment of the practice should be done. Specific data points could be used in conjunction with periodic maintenance to provide reasonable assurance of equipment operability. Benchmarking with utilities that have discontinued condition based monitoring power supplies is recommended.

5.1.2 Maintenance Intervals

Electronic equipment has proven to be difficult to monitor, trend, and analyze. The data has not produced definitive maintenance recommendations. Recommendations such as power supplies should be replaced every 2 years are difficult to defend from a cost as well as a performance position. Also, from the data that has been gathered, many of the recommended condition monitoring techniques do not show signs of degradation in time to make definitive operational decisions. One problem with monitoring items such as ripple voltage is that this parameter tends to be a lagging indicator since ripple current is the true culprit for capacitor degradation; however, ripple current is difficult to measure in the field by conventional means.

Until technology and basic understanding of the parametric changes that occur in power supplies can be measured, tracked, and trended, time-based replacements appear to be the most prudent approach to power supply maintenance. There should be some periodic inspections of the in-service units to detect any abnormal conditions such as degraded components. With that said, there must be some sanity applied to time-based replacements since the average nuclear power plant has more than 600 power supplies and some have as many as 1500 in service.

The first approach to applying time-based replacements is to identify which power supplies are critical – meaning a plant would not want these power supplies to fail in service. Also, if there are spares, can the spares be readily installed and perform reliably?

Power supply inspections intervals should correspond with times when it will be possible to take the power supply out of service. Many times this period is set by system or plant outage time.

Most US power plants operate on an 18 or 24 month fuel cycle. Based on guidance and industry data, most power should be capable of operating at one if not two operating cycle without problems unless they are in a degraded condition. However, it is important to inspect and clean the power supply on a routine basis to be sure that none of the components show signs of degradation and/or premature aging and to test associated circuits (i.e., circuit protection, etc.)

Power supplies should be refurbished/overhauled or replaced at the end of its expected operating life. In order to develop an expected operating life for power supplies, one must understand the effect that components have on power supply performance. Based on information in Section 3 of this report, using expected capacitor life would be a good rule of thumb on which to establish initial replacements intervals. Based on guidance in EPRI's Capacitor Maintenance and Application Guide and considering operating stresses, plants should be able to calculate an expected operating life for capacitors and use this number to set the replacement and/or major service interval for power supplies. Based on calculations done in Appendix E, capacitors were expected to provide a little more than 9 years of operating life. Operating life is not a hard and fast value but must be tendered by plant environment, operating conditions, and power supply duty cycle. Also, plants must use their own operating experience to adjust replacement intervals. If a plant has all aged power supplies and has not done any maintenance on their power supplies, then they should expect to have a shorter replacement interval when compared to a plant with non-aged or recently refurbished power supplies. Also, based on industry operating experience, the average service life for most power supplies has been between 12 to 15 years with some in service for as long as 20 years without failure and so with little to no maintenance.

For power supplies that are in storage, these units should be periodically powered up in order to maintain the oxide layer in aluminum electrolytic capacitors. This layer of oxide will settle out and leave the foil cathode or the actual can exposed to operating current and when this happens, the capacitor could fail open when current is applied. For this reason a "soft-start" is recommended prior to any power supply seeing full line voltage (in-storage or installed). This cannot be stressed enough in order to reduce potential damage to the power supply. Upon successful completion of the soft-start procedure, continue with all bench checks until power supply is determined to be operational. If this is unsuccessful, perform a failure cause analysis to determine the failure cause of. By determining the failure cause prior to corrective action, this data can be used to mitigate future failures by adjusting the in-storage maintenance schedule.

5.2 Trouble-Shooting Recommendations

Troubleshooting of failures is an art and is built around experience with the system and knowledge of various types of power supplies in the industry. Station specific procedures usually reflect the manufacturer instructions and are executed when required.

There are only few component types that fail in power supplies: transistors, capacitors, and diodes.

Transistors will short-circuit, causing excess current to be drawn across the transformer, thus blowing a fuse. The transistors can be tested using a multimeter. Typically, a transistor will fail short-circuit at the emitter collector junction. However, transistor failure is often caused by a degraded capacitor.

Electrolytic capacitor tend to degrade to due loss of electrolyte. Capacitors in this condition will appear to be swollen or in some extreme situations, leaking. Any capacitor that appears to be degraded should be tested and/or replaced. This replacement should extend the life of the power supply. Capacitors tend to fail short-circuit.

The input diodes will tend to be affected by other failures in the circuit. Diodes tend to fail short-circuit. When a diode fails, there will typically be an associated fuse operation. A multimeter check of the diode should reveal if the diode has failed.

Once repaired, maintenance does a check at different test points in the circuit as recommended by the manual. If all test point results are within parameters and the output of the power supply is within specification the power supply is returned to service. As mentioned before, when a component fails, for example a transistor in the regulating circuit, chances are that the adjacent components also were subjected to the same transient and were degraded to some extent. This does not mean that the downstream components have failed, but they may be operating in a degraded condition and may soon fail. Several options are available to technicians when they are repairing a failed power supply:

1. Test all the individual adjacent components to the failed component to make sure they are within design parameters

2. Replace all the components adjacent to the failed component

In the case of Option 1, a specific piece of testing equipment (LCR meter for capacitors and Inductors, a curve tracer for transistor and diodes etc.) maybe required in order to perform parametric tests on components. These components may also have to be removed from the associated circuit.

In the case of either Option, the utility must stock electronic components to replace the degraded items. The utilities must weigh the economic impact of the failures due to the amount of power supplies they have and make an appropriate decision.

A third option would be to contract with a repair facility to perform all the above functions if plant personnel are not trained, or do not have the required equipment to perform these functions.

5.3 Repair Recommendations

Equipment history records are vital in assessing power supply operational health. Record “as found” data prior to placing in service. (This information can be recorded during pre-installation bench check, or from repair facility “as left” data taken after repair.) The data set should be similar to condition monitoring data suggested in 5.1.1. This information will assist in determining power supply reliability between each repair.

When purchasing new power supplies or having power supplies repaired, “premium” or mil. spec. replacement parts should be required. Premium parts should provide more operating margin and some inherent design defects can be corrected during this process. For instance, capacitor with low ESR should be used when possible. The use of these types of capacitors will extend the operating life of the power supply.

Information such as date codes on all aluminum electrolytic capacitors should be requested. This information should be recorded with the equipment history records to assist in capacitor life calculations in order to improve preventive maintenance intervals.

5.4 Replacement Recommendations

There has been some guidance provided in previous sections of this report that should be useful when considering a replacement power supply.

First keep in mind that most likely there will need to be a basis established to defend any decision, replacement or otherwise. If the issues is obsolescence, then an obsolescence assessment such suggested by NUOG could be done to establish a basis for power supply replacement. Remaining plant life should also be considered, especially if there will be a large number of replacements needed.

One utility, after addressing all these questions, made the decision to replace all power supplies from one manufacturer. This brand of power supplies had experienced a number of failures requiring increasing attention by maintenance. The manufacturer no longer supported replacement parts or repair due to obsolescence and past history proved that any design line from this manufacturer was produced for only about fifteen years. This plant only had 20 years left on its current license. This meant three things to this utility if they purchased from this manufacture again:

1. Design modifications or equivalency evaluations would have to be performed to install non-original equipment.

2. Could this manufacturer produce a more reliable product than the ones being replaced?

3. In fifteen years they would probably have to go through the exercise again with only five years left on their license.

After researching the market for power supply manufacturers that met their design requirements, they found one that had manufactured the same line of power supplies for 22 years with no changes to design and planned no changes in the future. They repair, replace, and support spare parts for this line and foresaw this practice as unchanging for the duration of their business. The only drawback was this company lacked a recognized quality program. The utility responded by dedicating these power supplies for their use. The utilities cost for the original design modification, seismic qualification (done internally), and retro-fitting mounting was high, but not excessive. Their benefits have been no power supply failures in four years. Maintenance impact has been reduced and over-all power supply reliability has increased. If this change proves successful, the initial costs, when spread over the final twenty years of operation will probably prove to be less that the cost of maintenance “baby-sitting”.

This example of one utility's solution to replacement vs. repair was given as a potential solution for other utilities. Due to numerous variables in power supply applications each utility must decide an effective approach to replacement vs. repair.

Plants should consider standardizing to a single model where possible. This will reduce overall repair and maintenance costs and should lower spare part inventory. Spare component and/or parts adequate for the life of the power supply and the life of the plant should be considered, if obsolescence is a possibility.

5.5 Industry Challenges

The challenges for continued power supply reliability and adjustments to maintenance practices to ensure continued operability are many. A time based maintenance program is static and is the best plan when power supply history is known. But with no previous operational data, a mixture of equipment age, various operating parameters, numerous models, and random failures, a maintenance program must be more dynamic in addressing maintenance activities.

Utilities purchased power supplies during the construction phase with the expectation they would operate for the life of the plant and that manufacturer support would be available during that time frame. Times have changed, warranties have expired, designs are obsolete, and companies have gone out of business, pretty much leaving utilities to their own devices for power supply operability.

- Equipment Age – The expected operational life of a power supply was not normally asked for nor given by the manufacturer. However, enough information exists for each site to determine what that expected time frame might be (by model) based on failure data and equipment history records. Many utilities purchased the same power supplies and this information could be shared among common users. Knowing the operational life reduces unanticipated failures because the expected "End-of-Life" can be estimated. "Normal Expected Aging" should not be considered an expected failure mode unless the power supply is a Run-to-Failure item. By knowing how long the power supply has been installed and performing regular maintenance and/or repair (overhaul), power supplies (especially linear designs) should be expected to operate for the life of the plant (according to several manufacturers).
- Equipment Obsolescence – is an actually a subset of "Equipment Age." Since no one in the industry could predict the rapid changes in the electronic industry, most utilities were broad-sided with obsolescence issues when procuring replacement power supplies. Now that an obsolescence self-assessment guideline has been developed, there are no more excuses for not knowing if your plant is effected and to what extent. By performing this assessment utilities will be able to establish an:
- "End-Of-Life" Plan – Once the expected operational life is determined, a power supply can be placed in either a time-based maintenance schedule or surveillance schedule to ensure continued operation. As the power supply enters the final phase of its operational life and repair is no longer an option, a replacement would already in stock if a plan has been implemented properly.

- Maintenance Schedule – There is no data to support the position that maintenance activities were responsible for or contributed to power supplies operating more than twenty years.

The following recommendations are presented to encourage continued investigation of power supply reliability and offer the industry options for improved power supply maintenance issues.

5.5.1 Reliability Study of Repaired Obsolete Power Supplies

Industry data has shown that power supplies have performed in service for as long as twenty-three years; well beyond expected service life of ten years (100,000 hrs). However, there is no data to support how this unexpected life extension was accomplished. Data on the reliability of obsolete/aged power supplies between repairs has not been collected or analyzed to determine the reliability of repeated repairs to power supplies. If a plant has done a major overhaul/refurbishment of power supplies, tracking and trending the reliability of obsolete or aging power supplies though they have been repaired would be useful since the intent is to bring the power supplies back to "as new condition."

Repaired power supplies should be tracked to determine:

- What, if any characteristics could point to approaching failure
- Length of time between repairs vs. failures
- Potentially establish service life of aged analog power supplies

The outcome of this study could impact repair vs. replacement practices, ongoing maintenance/storage practices, obsolescence and overall power supply operability costs. If this is done on a limited basis, the data could be used to make further decisions on whether to continue to repair and overhaul or to scrape and select a new power supply type.

5.5.2 Reverse Engineering

Reverse engineering of special components such as power supplies has been undertaken by various power plants to address short and long term spare part issues. There are certain precautions that need to be addressed when taking this course of action.

First, the legal and ethical hurdles must be crossed in order to protect the plant and the interest of both companies (vendor and user). Typically, the reverse engineering approach has not been used unless the supplier has abandoned the product line, spare parts are difficult to obtain, and product substitution is not available or extremely costly.

Secondly, the operating parameters of the component and the system effects should be well understood. The tolerances and variations associated with the component should be identified and document through vendor data and/or testing. There have been situation when a particular power supply was reversed engineered to a specific voltage level but the system effects had not be accounted for and the voltage drop caused by the system affected the performance of the reversed engineered power supply.

5.5.3 Modifications (New/Different Power Supply Manufacturers)

If a new or different power supply must be obtained, most plants will make use of their design/modification and procurement process to ensure that the proper replacement equipment is obtained. However, the performance and maintenance history of the old power supply should be obtained.

Although most vendors develop and test their products before they are taken to market, some power supplies have a better performance history than others. These differences can be attributed to many considerations such as environment, operational stresses, and component selection but all things considered, a product's performance history, vendor support, spare part availability, long-term commitment to the product, and cost should be weighed before a new and/or different power supply manufacturer is considered.

6 CONCLUSIONS

This project built on previous EPRI projects that reviewed power supplies or components that are utilized in the construction of power supplies. Each of the projects addressed specific or general issues related to electronics or electronic components. Understanding, monitoring, and trending degradation of electronics and electronic components still remains one of the most difficult and least developed areas in maintenance and condition monitoring arena.

Shelf-life for electronic parts is difficult to determine. The shelf-life of power supplies is limited by the shelf-life of the most life-limited part and those are capacitors. However, by applying the guidance provided in EPRI's *"Capacitor Maintenance and Application Guide,"* TR-112175, and *"Capacitor Performance Monitoring Project,"* 1001257, aluminum electrolytic capacitor degradation is associated with the change of the dielectric layer on the capacitor plates and/or loss of electrolyte. If these failure mechanisms can be controlled, aluminum electrolytic capacitors should not see any change in there capability. These mechanisms are controlled for stored capacitors and power supplies by proper storage – limiting temperature and humidity. An ANSI B level storage or better should be used to store these electronic components. Also, before placing a stored component or power supply unit into service, it should be burned in to check its functional capability before being placed into service.

For capacitors in service, stressors are limited by applying the proper size of capacitor, limiting the ripple current and voltage transients, and controlling ambient temperature. These simple recommendations have held true for the majority of power supplies in use. The average life of power supplies in a nuclear power plant has been greater than 12 years with the average power supply lasting about 15 years in service.

With the average life of in-service power supplies being 10-15 years, power supply refurbishment or overhaul should be considered within this time period. This recommendation typically applies to linear power supplies since they are the most widely used in nuclear power plants and are typically represented in the industry data that was reviewed.

One other set of criteria that has fed into the recommended refurbishment timeframe is the review of MTBF information for electronic components and electronic modules. Using the observed failure rates of components to calculate the failure rate of the module it typically done. From one set of data, high quality linear power supplies should have a calculated operating life of 86,000 hours or 9 years, 10 months. Also for a switch-mode power supply of similar quality, the calculated operating life would be 64,000 hours or 7 years, 3 months. Now let's look at the operational life of the power supply and let's use the switch-mode because it tends to stress its capacitor even more than the linear and contain more components which leads to it lower MTBF calculation. The operational life for the switch-mode power supply was calculated to be 64,000 hours but actual power supply achieved 200,000 hours before failure, which is 22 years, 10 months. Note all of MTBF numbers and the actual failure numbers are based on using 8766 hours per year (24 hours per day, 365.25 days per year). It is not stated in the data whether the actual supplies were operated for full time or the tests were accelerated.

The actual operating life of most electronic assemblies, if properly design, sized, and applied should exceed the calculated MTBF numbers.

This summary of the findings, as they stand from this limited study, is not the last word on power supplies because there are still many unknowns and the conclusion are based on limited data provided by users. However, a solid approach to dealing with power supply issues is provided. The failure modes and mechanisms associated with the components that are used to make up power supplies is provided along with recommended maintenance practices that should help plants limit unexpected failures.

The key considerations are such:

- Shelf-life is not a hard and fast concept
- Storage is critical to maintain power supply unit materiel condition
  - Limit temperature
  - Limit humidity
- Track failures
  - Record key data: power supply type, manufacturer, time in service, system application, time in storage, input/output voltage
  - Identify failure causes by performing a “good” root cause evaluation
  - Require repair facilities to provide troubleshooting and component replacement report
- Establish program to do a time-based refurbishment or replacement of critical power supplies between 10-15 years (based on current industry data) by using sampling and failure data
- Consider modifying power supplies to add test points to monitor rectifier output ripple
- Check power supply output ripple initially and check on a periodic basis
- Track and trend, on a sample basis, to determine if degradation can be detected to allow adjustments to time-based refurbishment
- Consider reverse engineering for obsolete power supplies, if the product has been abandon by OEM and/or if suitable replacements can not be found
- Be careful to understand all power supply parameters when specifying replacement or reverse engineered parts or complete power supply
- Contact OEM technical department rather than marketing regarding replacement parts or replacement power supply units because it is possible that there is support for “vintage” products and equipment that are no longer in current production.

A
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B
GLOSSARY OF TERMS

Aluminum Electrolytic – A capacitor with two aluminum electrodes (one with an oxide film) separated by layers of absorbent paper and electrolyte, which acts as the cathode of the capacitor.

Amplifier - A circuit or element that provides gain.

Amplifier, Comparison - A dc amplifier which compares one output quantity to a stable reference, and amplifies the difference to create corrective drive to the power supply's power-control elements to effect stabilization.

Amplifier, dc - A direct coupled amplifier that can provide gain for zero-frequency signals.

Amplifier, Differential - An amplifier which has available both an inverting and noninverting input and which amplifies the difference between the two inputs.

Amplifier, Inverting - An amplifier whose output is 180° out of phase with its input. Such an amplifier can be used with regenerative feedback for stabilization purposes.

Amplifier, Noninverting - An amplifier whose output is in phase with its input.

Amplifier, Operational - A dc amplifier whose gain is sufficiently large that its characteristics and behavior are substantially determined by its input and feedback elements. Operational amplifiers are widely used for signal processing and computational work.

Automatic Crossover – The characteristic of a power supply that switches its operating mode automatically as a function of load or setting from the stabilization of voltage to the stabilization of current. The term is reserved for units having substantially equal stabilization for both voltage and current, not for voltage-limited current stabilizers or current-limited voltage stabilizers.

Bipolar - Having two poles, polarities, or directions.

Bipolar Power Supply - A power supply able to linearly pass through zero to produce outputs of either positive or negative polarity and able to function in all four quadrants as either source or sink.

Bounding - The process of providing a boundary or limit to various output quantities. Fuses, circuit breakers and current limiters, as well as overvoltage crowbars, spark gaps and voltage limiters, are all examples of bounding circuits.

Carry Through Time - Refers to the time interval between loss of source power and the generation of an indicator. This represents the time for which such source power loss is invisible. The interval is usually defined in terms of fractions of a cycle (half cycle or full cycle at the source frequency).

CC/VL - Constant Current, Voltage Limit. *(See Current Stabilization.)*

CIIL - A control language for instruments: Control Intermediate Interface Language. CIIL is based on the ATLAS programming language. It is implemented in many power supplies.

Common-Mode Output - That electrical output supplied to an impedance connected between the terminals of the ungrounded output of a power supply, amplifier, or line-operated device, and the ground point to which the source power is returned. Normal isolation makes the impedance of the common-mode output relatively high so that it may be expressed as a common-mode current.

Common Point - With respect to operationally programmable power supplies one output/sense terminal is designated "common", to which load, reference, and external programming signal all return.

Complementary Tracking - A system of interconnection of two voltage stabilizers by which one voltage (the slave) tracks the other (the master). By placing the two outputs in series opposing, a pair of complementary (+ and -) voltages are created.

Compliance Voltage - A term sometimes applied to the load voltage of a current stabilizer. The compliance voltage range is that range of voltage for which a current stabilizer can comply with the requirements of a load resistance. The corresponding term "compliance current", for voltage stabilizers, is not generally used.

Constant Current - As a prefix to the phrase power supply, the term describes a current stabilizer. *(See Current Stabilization.)*

Constant Voltage - As a prefix to the phrase power supply, the term describes a voltage stabilizer. *(See Voltage Stabilization.)*

Cooling - The process of removing heat, which in a power supply is generated by transformation, rectification, filtering, and the stabilization process that converts unwanted electrical energy to heat energy. Cooling means include convection and radiation, both "natural" and blower-aided, conduction to an external heat sink, and liquid cooling medium circulation.

Crossover Point - That point on the operating locus of a voltage/current automatic crossover power supply formed by the intersection of the voltage-stabilized and current-stabilized output lines. The resistance value (E/I) defined by this intersection is the matching impedance for the power supply, which will draw the maximum output power.

CSA - Canadian Standards Association. In Canada, a body that issues standards and specifications prepared by various voluntary committees of government and industry. CSA is coordinating its standards with those of UL in the USA and VDE and TUV in Germany to implement the recommendations of the IEC, International Electrotechnical Commission.

Current Limiting - A bounding circuit designed to prevent overload of a voltage stabilizer in which, for load resistances smaller than the crossover resistance, the current is limited to a preset value, while the output voltage diminishes in proportion to the load's resistance.

Current Stabilization - A process of stabilizing an output current so that the effect of various influence quantities is minimized. A current stabilized power supply contains means for controlling or setting the current, and will produce the load voltage (compliance voltage) required by the product of the set current and the load's resistance.

CV/CC - Constant Voltage, Constant Current. *(See Automatic Crossover.)*

CV/CL - Constant Voltage, Current Limit. *(See Current Limiting.)*

Effect, Coefficient - The maximum change of a stabilized output quantity per unit change of any one influence quantity, all other influence quantities maintained constant.

Effect, Combined - The maximum change of a stabilized output quantity produced by the concurrent change in two or more of the following influences: load, source voltage, source frequency, temperature. The combined effect excludes the time and settling effects.

Effects, Individual

- **Load Effect** -- The change in stabilized output produced by the specified change in the output load.
- **Source (voltage) Effect** - The change in stabilized output produced by a specified primary source voltage change.
- **Temperature Effect** - The change in stabilized output produced by a specified change in the environmental temperature. (This effect is usually reported as a coefficient).
- **Time Effect** - Unprogrammed output deviation; when observed in the frequency range d-c to 20Hz, it is classified as "drift"; in the 20Hz to 10MHz range, it is classified as "ripple" and "noise". Over a specified time period, usually an 8-hour day, drift is the residual output deviation that cannot be accounted for by a specific influence quantity. Unless specified separately, drift is understood to include the settling effects which follow a major change in an influence quantity affecting dissipation - except that drift does not include the turn-on transient settling effect; warm-up. NOTE: Drift cannot be extrapolated to longer time periods by simple multiplication. The expression of a maximum drift amplitude for an 8-hour period does not imply that direction at the same rate over a longer term. (See *Noise*).
- **Transient Effect** - A transient effect follows a step change in any influence quantity, consisting of a temporary excursion in the stabilized output quantity decaying to the effect band within the recovery time.

Effect, Interactive - A change in one stabilized output quantity produced by a specified change in another output quantity or its load.

Effect, Output - Typically, there are three time-separable responses to a step change in any influence quantity: the transient effect, output effect, and the settling effect. The output effect is considered to follow the transient effect by a time equal to five times the transient effect's recovery time plus 10 seconds.

Effect, Settling - The temperature effect coefficient multiplied by the change in equilibrium temperature. Unless specified separately, the settling effects are understood to be included in either the individual effect or the drift specification.

Electrolyte – The current-conduction solution (liquid or solid) between two electrodes of a device. A medium used to transport charged particles (electrons or ions) between conductors. Can also function as an electrode.

EMI, Conducted - Electromagnetic Interference reflected back into the source power connection by the action of switching circuits or other abrupt actions within a circuit connected to the source. the amount of noise that may be reflected is regulated by various agencies, the FCC, VDE, CISPR etc. Filters to reduce the noise to accepted limits are commonly included in switch-mode power supplies. The limits are tailored for expected applications, with higher conducted EMI permitted for industrial applications than for home or office applications.

EMI, Radiated - Consisting of broad band radio frequencies and narrow band emissions, the radiated noise generated by the action of a switching regulator is limited by standards set by various agencies such as FCC, VDE, CISPR etc. It is controlled by shielding.

Equivalent Series Resistance (ESR)– The sum of the resistance of the oxide film, electrolyte, separator, conductors, and lead wires of a capacitor.

Fast Programming - The operation of a power supply with reduced filtering and high frequency discrimination so as to allow it to be programmed at faster than normal rates. A power supply in fast programming mode is typically sensitive to load reactance and should be used with essentially resistive loads.

Fault Tolerant - A system configuration to ensure the integrity of operation in the event of a single point failure. For power supplies, the requirement is usually to ensure the maintenance of system power despite the loss of any single power module. The usual technique is to provide redundant power modules on an N+1 basis, with sufficient isolation that the failure of any one power module does not cause system failure. Additional systems redundancy may require multiple source power inputs.

Feedback - The process of returning a part of the output of a system to its input. Negative feedback (out-of-phase return) is used to effect the corrective action that is basic to the process of stabilization.

Ferroresonance - The principle used in a simple open-loop (nonfeedback), voltage-stabilizing power supply. The process consists of allowing a portion of the transformer's ison to be driven to saturation in a capacitor resonated "tank." Output is derived from the saturated part of the transformer so that its amplitude level is determined by core geometry and is relatively independent of the exciting source amplitude.

Flag Signal - An alarm signal generated by a power supply, indicating an abnormal situation.

Flyback Converter - A circuit used for low power ac to dc switching type power supplies. It is economical since the function of choke and transformer are combined in a single component.

Forced Current Sharing - When voltage stabilizers are paralleled, they will self-arrange their operation so that only one unit controls the voltage. The other units in the parallel group are forced to either shut off or go into current limit mode. This produces a natural unbalance in the way they share the load current. To restore a balance, circuits are employed to force paralleled voltage stabilizers to share the load current. With parallel operation used for redundancy and N+1 combinations, the concept of forced current sharing is increasing in importance.

Forward Converter - A circuit used in high-powered ac to dc switching type power supplies. Current flows in the output filter during both the on and off cycles, returning through a catch or flywheel diode. A separate choke is used to sustain the current during the off part of the cycle.

Frequency Response - The band of frequencies over which a control signal can effectively modulate the output. The usual frequency limits are taken to be the frequency points where the output response has diminished to 0.707 of the datum level.

Gain, Closed Loop - The gain measured after feedback is applied, designated "G" in the operational diagrams.

Heat Rise - The temperature increase caused by self-heating or absorption.

Heat Sink - A device designed to aid the transfer of heat by conduction, convection or radiation.

Hold Up Time - Refers to the time interval between detection of source power loss and the loss of a power supply's output stabilization.

Hot Swap - A phrase indicating the ability to insert and extract an electronic module from a larger assembly while it is powered (hot). In power supplies, it is used to describe a design which allows live power supplies to be attached to and removed from a powered set of rails without causing disturbance to the operation of the load.

IEC - International Electrotechnical Commission. A standards writing body headquartered in Geneva which produces safety recommendations that are incorporated by the various national standards organizations. Currently, power supplies are governed by IEC 60950 which has been widely adopted by national bodies.

Influence Quantities - Those items which have an effect on a stabilized output quantity. The list includes, but is not limited to:

- Source voltage
- Source frequency
- Load
- Temperature
- Time
- Control

Isolation Voltage - The amount by which the output terminals of a stabilizer may be operated off ground (chassis). *(See Common Mode Output.)*

Lag Network - Resistance capacitance combinations placed in an amplifier circuit to control the gain rolloff with increasing frequency. Lab networks are used to tailor the phase margin of a feedback loop for stability. The main effect of a lag network is the reduction of gain at high frequencies.

Large Signal Frequency Response - The frequency at which the closed loop gain (fully loaded output) reached 3% harmonic distortion.

Lead Network - Resistance capacitance combinations placed in an amplifier circuit to control the phase shift versus frequency. Lead networks are used to tailor the phase margin of a feedback loop for stability. The main effect of a lead network is the reduction of phase lag at low frequencies.

Leakage Current – The direct current that flows through the dielectric of a capacitor when voltage is impressed across its terminals.

Linearity - With respect to the control function, the correspondence between successive incremental changes in the control quantity and the consequent incremental changes in the controlled output quantity.

Linearity Error - Applied to digitally programmed power supplies it is the absolute deviation between the analog output and the digital input signals at any point of the output range.

Load - For a voltage stabilizer, the load is its current (load current); for a current stabilizer, the load is the voltage (compliance voltage). The loading means, the resistance or dissipator, is a sink.

MTBF - An acronym standing for Mean Time Before Failure. It is a rough gauge of reliability as it is computed by summing the reciprocal of the individual probabilities of failure associated with components under specified levels of stress. Many manufacturers use the MIL handbook 217 in its latest revision to compute MTBF.

Noise - One of the time effects, usually lumped together with ripple in assessing the unprogrammed output deviation. Noise is the aperiodic random component while ripple is the periodic component harmonically related to the source frequency. Generally, "noise" is distinguished from "signal" by its unwanted, unappreciated character.

Null Junction - *(also Summing Point)* - the inverting input terminal of the comparison amplifier to which reference and feedback are referred. With respect to common - or a non-inverting input, the null junction supports a virtual ground because of the voltage gain of the amplifier.

Offset Current - The net current flowing into or out of a closed-loop comparison amplifier's null junction. Normally zero (or nullable), its variations are tabulated for the major influences.

Offset Voltage - The residual voltage across the input terminals of a closed-loop comparison amplifier's input terminals. Normally zero (or nullable), the variations

Operational Power Supply - A power supply with sufficient open-loop gain, and provision for offset nulling such that its behavior is analogous to an operational amplifier

Output Impedance - The impedance that a power supply appears to present to its output terminals, and thus to its load's impedance. For a voltage stabilizer, this impedance is small, equal at d-c to the load effect ratio, increasing with the increasing load modulation frequency until the impedance is asymptotic to a characteristic series inductance. For a current stabilizer, this impedance is large, equal at d-c to the load effect ratio, decreasing with increasing load modulation frequency until the impedance is asymptotic to a characteristic shunt capacitance.

OVP - Over Voltage Protection. A sensing circuit that prevents a power supply's voltage from exceeding a preset limit. This limit can be fixed or programmable or may track the voltage setting of variable power supplies. For linear (series pass) power supplies, the action of the OVP is usually to short the output to discharge the energy stored in its capacitors. Sometimes this is called a "crowbar." For switch mode power supplies, the usual action of the OVP is to stop the transfer of energy by inhibiting the switch.

PARD - An acronym comprised of Periodic And Random Deviations. Recommended by the IEC as the specification term for "ripple and noise."

Pass Element - The active circuit element (commonly a transistor or a vacuum tube) which forms the output power stage of a power supply.

PFC - Acronym for Power Factor Correction. Better defined, however, as a technique for harmonic reduction in a power supply's source current. Off line rectifiers, un-corrected, draw large peaks of current from the source (mains) near the peak of the input sinusoid. The flattening, caused by the non-zero source impedance of the utility mains, causes harmonic distortion. Power Factor Correction may be of two types: Passive correction uses a choke input filter with the choke sized so that the rectifiers conduct continuously (critical choke value). Active correction uses a separate converter in front of the rectifier having the effect of causing conduction to occur over nearly the whole mains cycle. This produces near sinusoidal source current reducing harmonic generation and improving source power utilization.

Phase Margin - The amount of phase shift subtracted from 180° found in a feedback system at the frequency for which its gain reaches unity. The margin from 180° represents a measure of dynamic stability.

Power Factor - The ratio of real to reactive power. In sinusoidal circuits, it is the measure of the fraction of current in phase with the voltage and contributing to the average power.

Predictive Maintenance – The practice of collecting equipment operational parameters to detect early stages of equipment degradation. Theoretically this information is used to mitigate equipment failure.

Preventive Maintenance – Regularly scheduled inspections, tests, servicing, repairs, and replacements intended to reduce the frequency and impact of failures. Includes predictive (condition-based) and periodic (time-based) actions.

Programming - The control of a power supply's stabilized output quantity in accordance with a program of values usually by a remotely located, variable control quantity.

Programming Speed - A measure of a power supply's ability to respond to a varying command to change its output setting from one level to another. Can be measured in terms of programming time constant and a slewing rate.

Recovery Time - The time required by a transient overshoot in a stabilized output quantity to decay to within specified limits (usually within the individual effect band of the influence quantity whose step change initiated the transient).

Redundancy Power Systems - A configuration which combines fault tolerance, with fault detection, isolation and hot swap capability to improve overall system reliability.

Reference - A known, stable quantity to which an output quantity can be referred - via a comparison amplifier for the purpose of stabilizing that output quantity.

Regulation - The process of exercising control over an output quantity. A regulator devoted to stabilization, the maintenance of a constant output in the face of adverse influence quantities, has its degree of stabilization measured in terms of the effect individual influence quantities exercise on the output.

Remote Error Sensing - The means by which a power supply senses the potential at a remote point (usually the load) for the purpose of stabilizing that voltage. Remote error sensing is accomplished by a 4-wire connection to the load, in which one pair of wires is reserved for the voltage-sensing role and carry no load-related current.

Response Time - The response time for a transient disturbance with an exponential decay is the time corresponding to a single time constant. Response time is thus distinguished from recovery time for which the decay is timed to a specific error limit.

Resolution - The smallest level capable of being reliably changed. The resolution of a digital programmer is the number of bits used in the instruction. The resolution of an analog control is a function of the number of turns available and the fineness of the material used to produce the variable control signal.

Ripple - See Noise

SCPI - A control language for instruments: Standard Commands for Programmable Instruments. The SCPI command set conforms to all of the common commands declared mandatory by IEEE 488.2 Slewing Rate - The maximum rate of change that a power supply output can respond to when controlled (programmed) by an overdriving or forcing control quantity.

Slow Programming - The operation of a power supply with internal filtering to discriminate against high frequencies. The programming of such a power supply is characterized by a relatively narrow band-width and slow response to program inputs. Slow or conventionally filtered power supplies are generally independent of load reactance.

Soft Start - A system for controlling the rate of turn-on so as to reduce the surge current that starting power supply can impose on the source mains.

Stabilization - The function of a regulator devoted to maintaining a constant output quantity.

Step Change - An abrupt and sustained change in one of the influence of control quantities. When employed as a test means to observe transient behavior, a step change shall be complete in less than one-tenth the transient's response time.

Summing Point - See Null Junction.

Temperature, Ambient - The environmental temperature which exists unmodified by the operation of dissipative apparatus.

Temperature, Operating - The environmental temperature that prevails when the power supply is operating, reflecting, therefore, the effect a dissipative power supply has on its own environment. Measured at the air intake or - for convection-cooled supplies - below the equipment. Also the operating temperature range is the range of temperatures through which specified operation can be obtained.

(UL)Underwriters Laboratory - A laboratory established in the United States to test electrical apparatus mainly for fire safety. In recent years, UL has written standards that are (nearly) harmonized with the equivalent IEC standard. UL examines power supplies for recognition as a "listed component."

Under Voltage Protection - A circuit to detect and react to a prolonged output voltage that is below a threshold value. It is principally used to protect against prolonged short circuit faults.

Unipolar - Having but one pole, polarity or direction. Applied to power supplies, it means a single polarity output that operates in a single quadrant and therefore, has a dc component. Unipolar power supplies equipped with polarity changing relays have the appearance of operating in two quadrants.

Universal Input – See Wide Range Input.

Voltage Limiting - A bounding circuit designed to prevent overload of a current stabilizer. For load resistances larger than the crossover resistance, the voltage is limited to a preset value, while the output current diminishes in proportion to the load's resistance.

Voltage Stabilization - The process of stabilizing an output voltage so that the effects of various influence quantities are minimized. A voltage-stabilized power supply contains means for controlling or setting the voltage and will produce the load current required by the ratio of the set voltage to the load's resistance. See also Automatic Crossover.

VXI - VME eXtension for Instruments. A standard for test and measurement instruments that seeks to reduce the size of the instruments and the complexity of their interconnect by standardizing the size and shape, placing the functions on plug-in cards.

Wide Range Input - Refers to a power supply's ability to accept ac mains voltage through a wide range of voltage (typ: 85-264V ac) without manual selection. This may be accomplished in a variety of ways. In low powered models, it is achieved by simply sizing the components appropriately and requiring the regulator's control range to accommodate the voltages. In higher power models that use PFC, power factor correction, the preregulator that causes the input current to conduct over the whole of the mains cycle also accommodates the range of a-c input voltage. *Also called "Universal Input."*

C
OVERVIEW OF INDUSTRY STANDARDS

The following is a limited list of Industry Standards pertaining to Power Supplies and Components used in them. This list in not all encompassing but representative of the types of standards and the agencies who write them.

DSCC-DWG-87106 REV P

Title: CAPACITOR, CERAMIC, SWITCH MODE POWER SUPPLY
Document Type: Unknown document type
Preparing Activity: CC DEFENSE SUPPLY CENTER, COLUMBUS
Publication Date: 29 Feb 2000

Scope: This drawing and MIL-PRF-49470 describe the requirements for ceramic switch mode power supply capacitors.

Intended Use: These capacitors are primarily designed for use where a small physical size with comparatively large electrical capacitance and high insulation resistance is required. General purpose ceramic capacitors are not intended for frequency-determining or precision circuits but are suitable for use as by-pass, filter, and noncritical coupling elements in high-frequency circuits. All of these applications are of the type where dissipation factor is not critical and moderate changes due to temperature, voltage, and frequency variations do not affect the proper functioning of the circuit.

Capacitors covered by this specification are very susceptible to thermal shock damage due to their large ceramic mass. Temperature profiles used should provide adequate temperature rise and cool-down time to prevent damage from thermal shock. The capacitors should be preheated. The preheat and cool down should not exceed 4°C per second. The maximum preheat temperature should be within 50°C of the solder bath temperature. Consult manufacturers for further recommendation.

Capacitors covered by this specification have high mass and are susceptible to mechanical damage. Special mounting precaution may be necessary especially in high vibration environments. Consult manufacturers or recommendations.

The manufacturing complexity of the 480 parts on this drawing varies immensely. To determine whether to accept a certificate of compliance in lieu of performing group B inspections, appropriate data should be reviewed. Test data and/or reliability data from recent production lots consisting of parts with same case size, equal or greater capacitance, and equal or tighter tolerance should be reviewed.

DSCC-DWG-88011 REV C
Title: CAPACITOR, CERAMIC, SWITCH MODE POWER SUPPLY, CG

Preparing Activity: CC DEFENSE SUPPLY CENTER, COLUMBUS
Publication Date: 16 Nov 2000

Scope: This drawing and MIL-PRF-49470 describe the requirements for ceramic switch mode power supply capacitors.

Intended Use: These capacitors are primarily designed for use where a small physical size with comparatively large electrical capacitance and high insulation resistance is required. CG (BP) characteristic ceramic capacitors are for use in critical frequency determining applications, timing circuits, and other applications where absolute stability is required.

Capacitors covered by this specification are very susceptible to thermal shock damage due to their large ceramic mass. Temperature profiles used should provide adequate temperature rise and cool-down time to prevent damage from thermal shock. The capacitors should be preheated. The preheat should not exceed 4°C per second. The maximum preheat temperature should be within 50°C of the solder bath temperature. Consult manufacturers for further recommendation.

Capacitors covered by this specification have high mass and are susceptible to mechanical damage. Special mounting precaution may be necessary especially in high vibration environments. Consult manufacturers for recommendations.

The manufacturing complexity of the parts on this drawing varies immensely. To determine whether to accept a certificate of compliance in lieu of performing group B inspections, appropriate data should be reviewed. Test data and/or reliability data from recent production lots consisting of parts with same case size, equal or greater capacitance, and equal or tighter tolerance should be reviewed.

MIL-PRF-18546F

Title: RESISTORS, FIXED, WIRE-WOUND (POWER TYPE, CHASSIS MOUNTED)), GENERAL SPECIFICATION FOR
Document Type: Military Specifications
Preparing Activity: CC DEFENSE SUPPLY CENTER, COLUMBUS
Publication Date: 15 May 2001

Scope: This specification covers the general requirements for power type, wire wound, fixed resistors which utilize the principal of heat dissipation through a metal mounting surface. The resistors have an initial resistance tolerance of ±1 percent and a resistance temperature characteristic range from 30 ppm/°C to 200 ppm/°C depending upon the resistance value. They are not suitable for application when the alternating current (ac) characteristics are of critical importance; however, provisions have been made to minimize the inductance.

MIL-PRF-22D
Title: RESISTORS, VARIABLE, (WIRE WOUND, POWER TYPE)), GENERAL SPECIFICATION FOR
Document Type: Military Specifications
Preparing Activity: CC DEFENSE SUPPLY CENTER, COLUMBUS
Publication Date: 04 Aug 2000

Scope: This specification covers the general requirements for power type variable resistors having a resistance element of wire, wound linear on an insulating strip shaped in an arc, such that a contact bears uniformly on the resistance element when adjusted by a control shaft. The power ratings (see 3.1) cover a range from 6.25 watts to 1,000 watts, inclusive (see 6.2).

EIA 180
Title: Power Transformers for Electronic Equipment R(1982))
Document Type: Industry Standards
Preparing Activity: EIA1 Electronic Industries Association
Publication Date: 01 Jan 1957

EIA 197-A
Title: Power Filter Inductors for Electronic Equipment R(1986))
Document Type: Industry Standards
Preparing Activity: EIA1
Electronic Industries Association
Publication Date: 01 Jan 1973

IEEE 111
Title: Standard for Wide-Band (Greater Than 1 Decade)) Transformers
Document Type: Industry Standards
Preparing Activity: IEEE
Institute of Electrical & Electronics Engineers
Publication Date: 08 Mar 2000

IEEE 264
Title: STANDARD FOR HIGH-POWER WIDE-BAND TRANSFORMERS (100 WATTS AND ABOVE))
Historical
Document Type: Industry Standards
Preparing Activity: IEEE
Institute of Electrical & Electronics Engineers
Publication Date: 01 Jan 1977

IEEE 295
Title: Standard for Electronics Power Transformers
ANSI Approved Document: Yes
Document Type: Industry Standards
Preparing Activity: IEEE
Institute of Electrical & Electronics Engineers
Publication Date: 01 Jan 1969

UL 1012
Title: UL Standard for Safety Power Units Other Than Class 2 Sixth Edition; Reprint with Revisions Through and Including May 24,2000
DOD Adopted Document: Yes
ANSI Approved Document: Yes
Document Type: Industry Standards
Preparing Activity: UL
UNDERWRITERS LABORATORIES, INC.
Publication Date: 28 Jun 1994

D
OVERVIEW OF REGULATORY AND INDUSTRY ISSUES

NRC INFORMATION NOTICE 94-33: CAPACITOR FAILURES IN WESTINGHOUSE EAGLE 21 PLANT PROTECTION SYSTEMS

ABSTRACT: Two types of failures were identified, one involved electrolytic capacitors C2 and C7 failed, causing complete loss of dc power to the connected loads. Each rack contains two power supplies. One provides power to the tester subsystem, which is not essential for performing the system design safety function. The other power supply provides power for the loop processor subsystem, which includes reactor protection and engineered safety features channels and logic, and may include some control room indication channels. On loss of power, a loop processor channel fails to the de-energized state, which normally is the tripped state.

The other failure type involved time delay relays. Ceramic capacitor C2 failed, causing either repetitive cycling or complete loss of ac power to the connected loads. The time delay relays are used in the Eagle 21 ac power distribution panels to sequentially load the power supplies during protection system startup. The failure consequences are similar to those for the power supply capacitors described above.

LER 263-99004 - 4/22/1999- FEEDWATER CONTROLLER POWER SUPPLY FAILURE CAUSES LOW REACTOR WATER LEVEL SCRAM AND GROUP 2 AND 3 ISOLATIONS; SUBSEQUENT EVENTS CAUSE HPCI TO BECOME INOPERABLE

ABSTRACT: Failure of a digital feedwater control system (DFCS) power supply caused one feedwater regulating valve to close and the other to lock-up in its pre-existing condition. The DFCS power supply failure was due to an oxidized connection in a plus 5 volt power supply. The overfill was caused by the failed level indications and misleading Safety Parameter Display System (SPDS) indications. Concern about using reactor water level indications led to bypassing the Reactor Feedwater Pump (RFP) high water level trip. Three power supplies were replaced and all associated connections cleaned. Several operating procedures were revised, temporary monitoring instrumentation was added and extensive testing was performed. Operator training was provided on several topics.

LER 220-97014 - 11/25/1997 - VENT AND PURGE SYSTEM ISOLATION DURING TROUBLESHOOTING DUE TO DEFECTIVE EQUIPMENT

ABSTRACT: On November 25, 1997, while performing troubleshooting on the stack gas radiation monitor (RAM-112-08A), an unexpected isolation of the containment vent and purge system was experienced. Equipment failure cause was the cause of this event. The 24 VDC power supply for RAM-112-08A was found to be defective due to an intermittent short to ground. The cause of the ESF actuation was verified, the signal was reset, and the drywell vent and purge valves were reopened. The defective power supply was replaced, and RAM-112-08A was tested and returned to service. A failure mode analysis will be performed on the defective power supply.

LER 529-97005 - 9/23/1997 - INADVERTANT TRAIN B ESFAS EQUIPMENT ACTUATIONS AND EMERGENCY DIESEL GENERATOR START DUE TO COMPONENT FAILURE

On September 23, 1997, Unit 2 was in its seventh refueling outage with the core offloaded to the spent fuel pool when an inadvertent actuation of the Train B Engineered Safety Feature Actuation System (ESFAS) 1-3 leg equipment (e.g., valves with power available, control room essential air filtration unit, and essential chiller), the Train B Diverse Auxiliary Feedwater Actuation System (DAFAS), and an automatic start of the Train B emergency diesel generator (EDG-B) occurred during planned outage maintenance activities. Initial troubleshooting identified that an apparently non-detectable failed power supply in the Train B ESFAS cabinet caused the inadvertent Train B ESFAS 1-3 leg equipment to actuate, and the subsequent EDG-B start when combined with the outage-related deenergization of power to an auctioneered power supply. As corrective action, the faulty power supply was replaced. No previous similar events have been reported pursuant to 10CFR50.73.

LER 456-95020 - 12/23/1995 - ENTRY INTO TECHNICAL SPECIFICATION 3.0.3 DUE TO HAVING TWO INOPERABLE POWER RANGE DETECTORS

On 12/23/95, Unit 1 was in Mode 1 at 60% power with Axial Flux Difference calibrations in progress. The initial indication was that Power Range N42 indication began swinging by 10% power, causing spurious rate trips. No other indications of changing reactor power were present. Power Range channel N42 was subsequently determined to have a failed power supply. The power supply was replaced and set. Calibrations were completed for channels N43 and N44.

LER 483-92011 - 10/17/1992 - A LOSS OF MAIN CONTROL BOARD ANNUNCIATORS CAUSED BY BLOWN POWER SUPPLY FUSES DURING MAINTENANCE WAS NOT DECLARED AN ALERT DUE TO LACK OF SYSTEM KNOWLEDGE

The plant was in Mode 1 - Power Operations at 100 percent reactor power at the time of the event. The cause of the initial failure of the power supply was a short in the power transformer internal to the field power supply. During restoration following replacement of this power supply, a short occurred while removing jumpers, causing the fuses to blow. The operators failed to declare an ALERT because inadequate knowledge of the RK system led them to believe that some annunciators remained operable. Training will be provided to personnel on the operation of the annunciator system. Actions to be taken in case of annunciator failures have been detailed in procedures. A modification will be evaluated to improve the reliability of field power supplies and provide detection of power supply failures to the operating crews.

LER 498-92012 - 9/3/1992 - ENTRY INTO TECHNICAL SPECIFICATION 3.0.3 DUE TO BOTH CHANNELS OF DRPI BECOMING INOPERABLE

The cause of this event was the failure of one of the Digital Rod Position Indication (DRPI) control module power supplies coupled with an apparent unknown failure of the redundant power supply. Corrective actions include replacing one of the two power supplies and returning DRPI to an operable status, replacing the remaining failed power supply during the upcoming Unit 1 outage, and developing testing for both units for the DRPI system that will include an assessment of the control system power supplies. The test will be implemented during the next Unit 2 refueling outage.

LER 528-92006 - 4/19/1992 - ESF ACTUATIONS DUE TO RADIATION MONITOR FAILURE

A spurious Train A Containment Purge Isolation Actuation System (CPIAS) actuation was initiated on the Balance of Plant Engineered Safety Features Actuation System (BOP ESFAS). The Train A CPIAS resulted in the designed cross trips of Train B CPIAS and Trains A and B Control Room Essential Filtration Actuation System (CREFAS). The cause of the CPIAS and CREFAS actuations and RU-37 dropping offline from the RMS minicomputer was due to a power supply failure in RU-37's remote indication and control (RIC) unit. The RIC unit's power supply was replaced. There have been no previous events reported pursuant to 10CFR50.73, which resulted from the same root cause.

LER 260-92001 - 2/21/1992 - AVERAGE POWER RANGE MONITORS (APRMS) FAILURE DUE TO DEGRADATION OF FLOW CONVERTER POWER SUPPLY WHICH CAUSED THE APRM OUTPUT TRIP RELAYS FAIL TO TRIP

The root cause of this event was an unexpected and unforeseen flow converter power supply failure. The degradation of the power supply resulted in APRM output trip relay failed to trip. The trip relay contacts were found to be welded closed. The degraded power supply and failed trip relays have been replaced and APRM A, C, and E were placed back into service. Utility will evaluate the current design of this trip system to determine if contact ratings are adequate.

LER 237-91020 - 7/23/1991 - REACTOR BUILDING VENTILATION ISOLATION AND AUTOMATIC STANDBY GAS TREATMENT INITIATION DUE TO RADIATION MONITOR POWER SUPPLY FAILURE

ABSTRACT: On July 23, 1991 at 1435 hours with Units 2 and 3 operating at 65% and 60% respectively, the power supply (2-1705-7A) for the Unit 2 Channel "A" Reactor Building Ventilation (RBV) and Channel "A" Fuel Pool Radiation Monitors failed. This caused these Radiation Monitors to initiate automatic isolation of the Unit 2 and 3 RBV systems and automatically initiated the Standby Gas Treatment (SBGT) system. Underlying causes of the Radiation Monitor signals were electronic in nature (power supply capacitor and Zener diode failures). The RBV systems remained isolated and SBGT was kept operating until 2220 hours when the power supply was replaced. The safety significance of this event is considered minimal because the automatic actuations that occurred were proper upon receipt of the Radiation Monitor signals and there was no affect on secondary containment integrity. A previous event involving automatic SBGT start due to a radiation monitor problem was reported by LER 88-019-0. Power supply problems of this type have e not been an adverse trend.

LER 389-91001 - 3/4/1991 - INADVERTENT ACTUATION OF AUXILIARY FEEDWATER COMPONENTS WHILE PERFORMING MONTHLY AUXILIARY FEEDWATER ACTUATION SYSTEM TEST DUE TO EQUIPMENT FAILURE

On March 4, 1991 at 1440, an inadvertent actuation of the Auxiliary Feedwater Actuation System (AFAS) Channel A occurred. The actuation occurred while Instrument and Control (I&C) technicians were performing a routine surveillance and had just finished balancing and adjusting power supplies 301A and 302B. The root cause of this event is equipment failure. One power supply was momentarily unable to pick up load from the other. Power supply 302B was found to be faulty and replaced. Other corrective actions include: checking other AFAS power supplies; replacing AFAS power supplies with an improved model; remove balancing and adjusting from the monthly surveillance to 18 month (performed when the unit is shut down). These actions will be taken on both units.

LER 324-90017-1 - 10/23/1990 - ESF ACTUATION CAUSED BY A BLOWN FUSE IN THE MAIN STEAM LINE " B " AND REACTOR BUILDING VENTILATION " B " RADIATION MONITORING POWER SUPPLY

On October 23, 1990, Unit 2 reactor was at 100% power, and the Emergency Core Cooling Systems were operable in standby readiness. At 1502, the "B" channel of the Reactor Protection System received an unexpected half scram signal. Also, the Primary Containment Isolation System received a half group isolation and a group 6 isolation. In addition, the Reactor Building Ventilation system automatically isolated and the Standby Gas Treatment trains started. The cause of the event was a blown line fuse in the power supply to the Unit 2 Main Steam Line (MSL) "B" and Reactor Building Ventilation "B" radiation monitors. The fuse is a Bussman MIN-5 (5 amp, non-time delay). The fuse was replaced at 1521, the isolation signals were reset and equipment was realigned. The MSL radiation monitor did not return to service as expected because its NUMAC Low Voltage Power Supply (LVPS) was not operating properly. The power supply was replaced. The original was sent to General Electric (GE) for a failure analysis. GE determined that the NUMAC LVPS experienced a random, internal, electrical short that would generate a fault current of approximately twelve (12) amps or greater. GE established that the external fuse would blow before the internal fuse with currents in excess of nine (9) amps. The cause of this event was the internal LVPS short. This event had minimal safety significance; equipment functioned as designed. This is considered to be an isolated event.

LER 317-90023-1 - 8/2/1990 - ENGINEERED SAFETY FEATURES ACTUATIONS DUE TO FAILED FUSE AND POWER SUPPLY

On August 2, 1990, Unit 1 experienced an actuation of subsystem ZA of the Engineered Safety Features Actuation System (ESFAS). The actuation occurred while power was being restored to subsystem ZA following maintenance and was caused by the operation of a fuse in the vital AC Distribution Panel. The fuse operated on over current but subsequent troubleshooting did not identify the cause. The system operated normally after the fuse was replaced. On August 7, 1990 prior to the restoration of ESFAS Subsystem ZA, Unit 1 experienced a partial actuation of subsystem ZB of the ESFAS which was caused by a degraded 15 VDC power supply in the Actuation Logic Cabinet. The power supply was returned to the ESFAS vendor for analysis. The vendor determined that the power supply voltage regulator had failed. In both cases, plant systems and components performed as required by the design, consistent with plant conditions and system lineups. Following the actuation on August 7, Containment Integrity was established in accordance with Technical Specifications because loss of the Undervoltage start signal associated with ESFAS required that the Unit 1 Emergency Diesels be declared inoperable.

LER 327-90003 - 2/4/1990 -TWO INADVERTENT CONTAINMENT VENTILATION ISOLATIONS CAUSED FROM POWER SUPPLY FAILURES OF THE UPPER CONTAINMENT AND CONTAINMENT PURGE RADIATION MONITORS

ABSTRACT: On February 26, 1990, with Unit 1 operating in Mode 1 at 98-percent power, an inadvertent containment ventilation isolation (CVI) occurred on Unit 1. On March 4, 1990, with Unit 2 operating in Mode 1 at 100-percent power, an inadvertent CVI occurred on Unit 2. An instrument malfunction alarm and high radiation alarm were present in the main control room on radiation monitors (RMs) 1-RM-90-112A and 2-RM-90-130 for the respective events. Operations personnel responded to the alarms and reset the high radiation alarm. The CVIs were caused from the failure of the power supplies to 1-RM-90-112A and 2-RM-90-130. After the cause of each CVI was determined, Operations personnel proceeded with recovery steps for the CVI. The power supplies were replaced and the RMs were returned to service.

LER 260-95007 - 8/19/1995 - REACTOR SCRAMMED ON A LOSS OF MAIN CONDENSER VACUUM AS A RESULT OF THE STEAM JET AIR EJECTORS ISOLATING ON A HIGH OFFGAS TEMPERATURE

On August 19, 1995, at 0124 hours, an offgas hold up volume high temperature alarm was received. This condition eventually resulted in isolating the steam jet air ejectors (SJAEs). When the SJAEs isolated, the main condenser began to lose vacuum resulting in a turbine trip. The turbine trip subsequently caused the reactor to scram at 0201 hours. The cause of this event was a faulty power supply resulting in an improper level control of the offgas condenser (OGC). The additional water in the OGC drastically reduced its heat removal capability. This caused the offgas holdup volume temperature to increase. Corrective actions were taken to restore the plant to a safe configuration. Additional corrective actions were to replace the faulty power supply, manually drain the OGC and clean the Raw Cooling Water (RCW) strainers filtering the RCW to the offgas dehumidifier chiller (OGDC). This event is reportable in accordance with 10 CFR 50.73(a)(2)(iv) as a condition that resulted in an automatic actuation of an Engineered Safety Feature system.

LER 269-94002 - 2/26/1994 - INAPPROPRIATE ACTION RESULTS IN FALSE HIGH STEAM GENERATOR LEVEL CAUSING LOSS OF MAIN FEEDWATER AND REACTOR TRIP

ABSTRACT: On February 26, 1994, at 0657 hours, Oconee Unit 1 tripped on loss of both Main Feedwater (MFDW) pumps, while operating at 100% Full Power. An Instrument and Electrical Supervisor (IES) was removing power from an Integrated Control System power supply that had failed and was smoking. The IES removed a neutral wire that is daisy chained with other devices. When the neutral (daisy chained) terminal was loosened, the 1B Steam Generator high level circuits were de-energized. This condition resulted in a trip of the Main Turbine/Reactor, of both MFDW pumps, and the initiation of the Emergency Feedwater system. The Unit was stabilized at Hot Shutdown conditions. The root cause of the Unit trip was Inappropriate action; Improper action (Response chosen was proper but proper execution failed because; a human factors deficiency existed). A contributing cause is Equipment Failure. Corrective actions included replacing the defective power supply and removing the daisy chain associated with this circuit.

LER 412-93002-1 - 1/30/1993 - REACTOR TRIP AND SAFETY INJECTION DUE TO COMPARATOR CARD FAILURE IN A MAIN STEAM PRESSURE CHANNEL

ABSTRACT: On 1/30/93, with the Unit at 92 percent power, the bistables for Loop "A" Channel II main steam pressure were in a tripped condition for transmitter replacement. At 0124 hours, the Loop "A" Channel III main steam pressure transmitter experienced a fuse failure, which tripped the bistables for that channel, generating a Low Steamline Pressure Safety Injection (SI) signal. The SI signal caused a reactor trip and SI flow to the reactor coolant system. Operations personnel entered Emergency operating Procedure E-0 and the plant was stabilized in Hot Shutdown. The emergency diesel generators started as designed, but did not load due to the availability of offsite power. The auxiliary feedwater pumps automatically started and supplied feedwater to the steam generators. All other SI equipment operated as designed. The cause for this event was a comparator card power supply failure in the "A" Channel III main steam pressure circuit. This tripped the bistables for that channel, which in conjunction with the tripped bistables for Loop "A" Channel II, resulted in a SI and reactor trip signal. There were no safety implications as a result of this event. The SI equipment including the emergency diesel generators, standby high head charging pump, auxiliary feedwater pumps, standby service water pump and the associated valves all actuated to their design positions.

E
SOFT START PROCEDURE

If a power supplies has been un-powered for extended periods, a soft start method may be recommended to allow electrolytic capacitors time to reform as voltage is applied. In this process, the voltage is slowly increased until the power supply reaches its rated voltage. A soft start might not be appropriate for all power supply types. Refer to manufacturer's data or the type of power supply before energizing.

The soft start process requires the voltage to be slowly increased until the power supply reaches its rated voltage. The steps for soft starting are given below:

1. Connect a voltage source to the power supply's input.
2. Starting from the minimum voltage, increase the voltage source's output slowly, in increments of 10 volts / minute until the rated voltage of the power supply has been reached.
3. After 24 hours of applied voltage, verify the output voltage is as specified by the manufacturer.

Only external measurements are made on the power supply. An oscilloscope or other conventional laboratory equipment is adequate for the measurements. The following characteristics should be checked:

- DC output voltage
- DC output current (measured with an ammeter or voltmeter across a current shunt)
- Ripple voltage amplitude at the output (measured with either an oscilloscope or with a digital volt meter)
- Load regulation from no-load to full-load operation
- Line regulation with rated input voltage variation

See the manufacturer's operating manual for acceptance criteria.

F
SURVEY OF INDUSTRY POWER SUPPLY MAINTENANCE PRACTICES

Appendix F presents the responses to an industry survey regarding the general practices of shelf life and in-storage maintenance of power supplies.

There were three questions asked in the survey. From the responses, it is easy to see that the maintenance practices for power supplies differ greatly.

The alphabet at the top row of the survey represents a different plant's response to the survey questions. For instance, if one wants to get the full response from plant A just read down the A column, then for plant B down the B column and so on.

Question	A	B	C	D	E
1. What sort of In-Maintenance does your facility conduct on spare Power Supplies?	No answer provided.	Task: Power supplies containing electrolytic capacitors are reformed/tested. If the capacitors fail the testing, the poser supplies are refurbished or scrapped. Frequency: 10 years	Task: None Frequency: N/A	Task: "Shelf life program". Frequency: According to the corporate procedure.	Task: None, if shelf life expires we will have caps replaced, or may consider reforming. Frequency: N/A
2. What shelf life do you assign to Power Supplies containing electrolytic capacitors?	Placing an item in the shelf life program or the in-storage maintenance program is based on manufacturer supplied information.	10 years based on capacitor manufacture code.	Power supplies are not shelf life items.	"The company shall provide a statement of shelf life for this item with shipment." If this information is missing, the shelf life will be calculated based on the EPRI guidelines.	10 years after receipt. Procurement document establishes acceptable manufacturing dates.
3. What is your basis for the shelf life assigned?	Manufacturer/engineering information.	Shelf life is set at 10 years for power supplies that contain electrolytic capacitors. Our shelf life procedure establishes the shelf life at 10 years based on analysis of industry data. Once the shelf life is reached, the shelf life procedure provides for reforming and testing the capacitors per MIL-STD-1131B.	Electrolytic capacitors, and items containing electrolytic capacitors, are reformed prior to installation.	Manufacturer's statement or EPRI guidelines.	EPRI Capacitor Maintenance and Application Guide EPRI Capacitor Performance Monitoring Project
Comments	Assigningshelf life and in-storage maintenance requirements has continued to be challenging since there are different opinions by the manufacturers.				

Question	F	G	H	I	J
1. What sort of In-Maintenance does your facility conduct on spare Power Supplies?	Task: Energize power supply to reform electrolytic capacitors. Alternately, may establish shelf life based on the internal components. When the shelf life expires, refurbishment would be required. Frequency: 18 months	Task: Reform capacitors through periodic energized testing of power supplies. Frequency: Initial is 5 years and 3 years for two cycles. After that, capacitors are replaced or power supply scrapped.	Task: Energize the supply, if a shelf life is specified for the item. Frequency: Dependent upon shelf life.	Task: None, power supplies are not in our in-storage maintenance program. Frequency: N/A	Task: Power Supplies are in the program, however, there are no specific maintenance activities while in storage. The recommendation to maintenance at issuance from storage is to perform a "soft start" as indicated by the "Instrument Power Supply Tech Note" (EPRI/NMAC TR-107044) after a long period of storage (5 years or more) to avoid any damage to capacitors from initial energization. Frequency: N/A
2. What shelf life do you assign to Power Supplies containing electrolytic capacitors?	16 years based on capacitor manufacturer code. Power supplies in the in-storage maintenance program are not shelf life items.	5 years initially, then 3 years for two subsequent testing cycles. Shelf life is based on capacitor manufacture code.	Varies as specified by manufacturer or guidance in EPRI NP-6408.	16 years based on capacitor manufacture code. If the date of manufacture, it is reduced to 8 years from the date of reciept.	Aluminum Electrolytic Capacitors have a shelf life of 20 years (refer to EPRI/NMAC TR-112175 "Capacitor Maintenance Guide"). Since these capacitors are the limiting life items of the power supplies, the shelf life should be 20 years and after that reform the capacitors in the power supply by energizing it with a "soft start" and leaving it energized for at least 24 hours until the output of the power supply is stable and within specifications.
3. What is your basis for the shelf life assigned?	EPRI NP-6408 and/or Arrhenius methods.	EPRI NP-6408 and MIL STD 1131B.	As specified by manufacturer, or using guidance in EPRI NP-6408.	EPRI NP-6408 and PNPS Supply Chain Management internal procedure SCM G2-2.	Studies performed by EPRI/NMAC like TR-112175 "Capacitor Maintenance Guide", and TR-1001257 "Capacitor Monitoring Project". Also studies published in the IEEE Transactions on Nuclear Science, and the "Capacitor and Resistor Technology Symposium" (CARTS).
Comments	We may also assign 16 years from the date of receipt if date codes of subcomponents are not readily available.				

Question	K	L	M	O
1. What sort of In-Maintenance does your facility conduct on spare Power Supplies?	Task: Soft start, power up and ripple check. Frequency: 18 months	Task: Power supplies to be stored in their original packing material, in an area that meets level B storage requirements. Each power supply shall be powered up, by connecting the power supply input to an appropriate voltage source. The power supply shall remain energized for a minimum of 1/2 hour. The output voltage shall be checked prior to de-energizing the power supply to verify proper operation. Frequency: 3 years Note: The minimum requirement for the Lambda power supply is 5 years, however this instruction recommends a 3 year interval for consistency.	Task: None Frequency: None	Task: Power up PM. Frequency: Annual
2. What shelf life do you assign to Power Supplies containing electrolytic capacitors?	16 years after receipt.	3 years based on capacitor manufacture code.	10 years after receipt.	Shelf life is set for one year after power-up and test. Each PM cycle resets the clock for another year provided successful test completion.
3. What is your basis for the shelf life assigned?	EPRI NP-6408, EPRI TR-112175, EPRI NP-6896, other information from Industry Technical Information Program.	Manufacturer's recommendation.	EPRI Guideline for shelf life of electrolytic capacitors.	Engineering evaluation based on original vendor recommendations.
Comments	The information provided is for those power supplies which have been determined to be essential for safe, reliable plant operation. Other power supplies may have slightly different requirements.	REFERENCES - (1) Vendor Manual N430-0159 Dual 20 Volt Power Supply Operations and Maintenance Manual for Acopian Power Supply Model S11262 (2) Trentec Certificate of Compliance #1T075.1 for Lambda Power Supply RWS-30A-48/A EPRI NMAC Tech Note (3) Instrument Power Supply Tech Note.	In our plant all safety related and non-safety related power supplies containing electrolytic capacitors are stored in Level "A" storage and assigned a 10 year shelf life.	

Question	P	Q	R	S
1. What sort of In-Maintenance does your facility conduct on spare Power Supplies?	No answer provided.	Task: N/A Frequency: N/A	Task: None, in-storage maintenance for power supplies is presently non-existent. A program is currently being developed. Frequency: None	Task: On spare power supplies that contain electrolytic capacitors the items are connected to a power source for 24 hours. Frequency: 18 months
2. What shelf life do you assign to Power Supplies containing electrolytic capacitors?	Electronic assemblies, including power supplies, are assigned an indefinite shelf life. However, these items are tagged with the following:" Electrolytic capacitors in this assembly must be replaced or evaluated to be acceptable prior to installation of this item, if the capacitor manufacture date is greater than 5 years."	Aluminum Electrolytic Capacitors - 10 years if it is stored per ANSI N45-2, Level A storage requirements and 5 years if it is stored per ANSI N45-2, Level B storage requirements.	We try to use manufacture guidelines when provided, otherwise we use 14 years knowing EPRI NP-6408 guidelines allow 16 years. However, experience is showing that this is too long. Preliminary development of an in-storage maintenance program seems to indicate the inclusion of electrolytic capacitors in an in-storage maintenance program would obviate the need for a shelf-life program for caps. However, it won't be cost effective to include all caps and equipment containing caps in an in-storage maintenance program so we'll be bouncing this against the critical spares list and anything that's not included in the in-storage maintenance program will remain in the shelf-life program.	12 years after receipt.
3. What is your basis for the shelf life assigned?	The limiting shelf life component of electronic assemblies is electrolytic capacitors. An indefinite shelf life can be assigned because the capacitors are replaced or evaluated to be acceptable prior to installation of the assembly. DAEC does not routinely replace electrolytic capacitors on stocked items. Capacitors are evaluated/replaced prior to installation of the item in the plant.	MIL-STD-1131B	Indeterminate at this time. EPRI guidelines are questionable at this time.	NPP Krsko procedure based on the EPRI report.

Target:
Nuclear Power

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