Power Line Aberrations and Their Effects on Health Care Facility Microprocessor Equipment

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1 Introduction

1.1 Introduction

You are working on a project and suddenly the lights go out. Just as suddenly, the lights return and the phone/beeper begins ringing off the hook with reports of equipment that is down. Another scenario, suddenly the lights dim for an extended period of time. As the lights return to normal intensity or even before the lights return to normal intensity, the phone/beeper begins ringing. There are countless scenarios, the causes numerous, and the solutions many and varying.

Since 1975, technology has led to the invasion of microelectronic and computer- controlled medical equipment. This invasion comes as a blessing, because better patient care is possible, and as a curse trying to keep these electrical gadgets operating. The invasion of technologically advanced equipment has greatly increased capabilities in radiology (examples : Digital Subtraction, High Frequency Generators, Anatomical Programmed Generators, improved Cardiovascular image systems), Magnetic Resonance (MR), Computerized tomography (CT) X-ray, Ultrasound, patient history data base systems, patient diagnostic systems, improved Clinical laboratory equipment, and lasers to mention only a few areas. [11:2] When the utility power lines deviate from the norm, (typically values 110, 220, or 277/440 volts line to ground) the problem(s) begins.

Various individuals and organizations have studied power system aberrations. A two year study conducted by Bell laboratories in several geographic locations within the United States demonstrated the average location experiences approximately 25 power line aberrations per year and of these, 87% were sags below 96 volts. In 1970, Martzloff and Hahn performed a two year study on power aberrations for The Institute of Electrical and Electronics Engineers (IEEE). Their study revealed the average residence or light industry experiences two spikes or surges per hour. The typical values measured were 1500 to 2500 volts (peak values) although 5600 volts were measured during lightning storms. In 29 different geographic locations within the United States, International Business Machine (IBM ®) conducted a power aberrations study. Again, spikes were the most common problem occurring with an average of 62.2 spikes per month. [21:145] Figure 1 displays the results of the 1974 IEEE test. 48.8% of the power aberrations were spikes. [11:10] Recently, James D. Vail conducted a study on what happens electrically

Incidence Rate of Harmful Power Line Disturbances

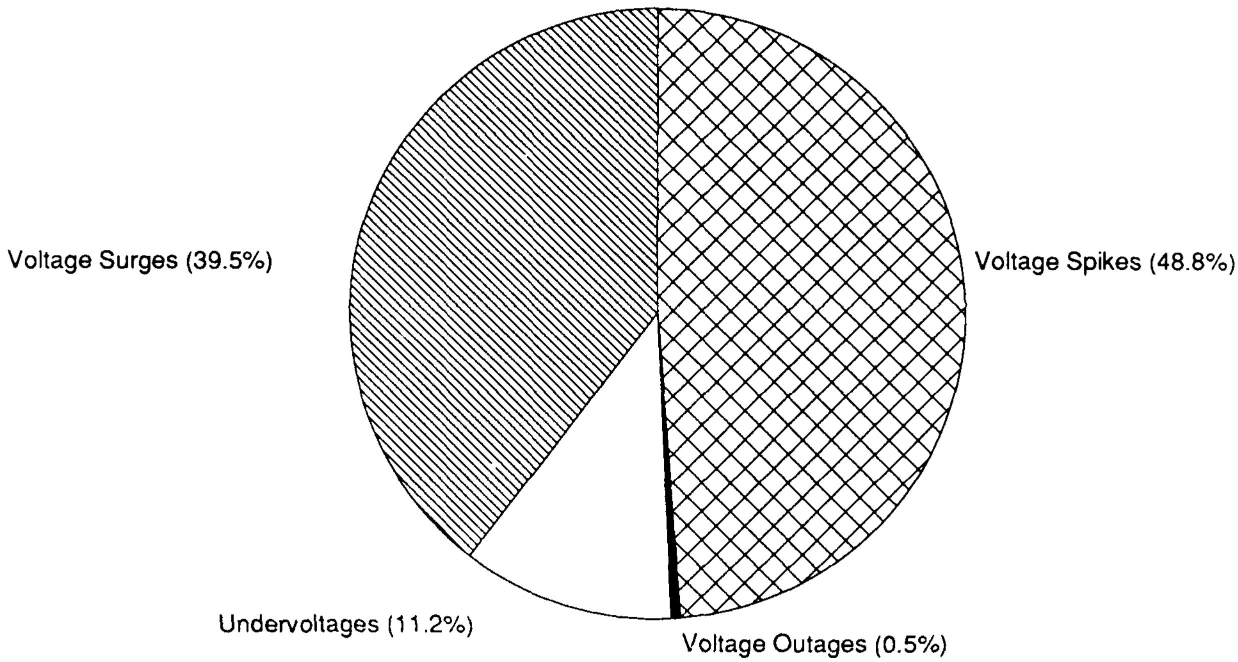


Figure 1

Reprinted from Howard C. Cooper, "Power Conditioning to protect computers and Electronic Equipment", American Society for Hospital Engineering of the American Hospital Association, June 1984, p. 10.

during an emergency-generator test. The test revealed voltage deviations (sags) along with normal-mode and common-mode spikes or impulses occurred during the transfer to generator or the transfer back to utility power. The most significant factors affecting voltage deviations were type of generator, age of facility, and type of transfer switch utilized. [45:22-25] These studies differ on the quantity and the determination of the most significant problem(s) (spikes, surges, or sags), but they all conclude power line aberrations are a significant problem particularly for microprocessors and computer-controlled equipment. [21:145]

1.2 Goals of Power Protection/Condition Systems

The ultimate goal of a power protection system is to neutralize undesireable voltages and currents. If the protection system is unable to totally neutralize the power aberrations the protection system must alter the aberrations to an acceptable level. People, buildings, equipment, software and assorted other items are protected by these protection systems. National Electrical Code (NEC ®), Underwriters Laboratories (UL ®), The Institute of Electrical and Electronics Engineers (IEEE ®), Joint Commission on Accreditation of Health Care Organizations (JCAH ®), National Fire Protection Association (NFPA ®) and various Federal organizations have developed codes and guidance for the protection system. Table 10 shows the human body's response to various sizes of electrical currents. [14:x] This paper is directed to protection systems for buildings, equipment, software and assorted equipment items.

Norman H. Haskell, Jr. defines power protection as one simple principle "*equalization of potential*". [14:xii] Power conditioning and power protection are the two principle power protection systems. The goal of power conditioning is to take commercial *ac* (raw) utility power with its power aberrations (transients, surges, sags, noise, spikes, etc.) and smooth or stabilize the power into "*computer*" grade *ac* power. Power conditioning does not deal with blackouts or brownouts but with power aberrations by regulation or suppression. [11:2-3]

The goal of power protection is to take the same commercial *ac* power, smooth or stabilize the power into "*computer*" grade power and at the same time provide coverage for power deficiency conditions such as blackouts and brownouts. Blackouts, even those lasting only a thousandth of a second, can interrupt the routine of microprocessor controlled equipment. The average blackout lasts less than six (6) seconds. Most power companies do not consider a power outage as a blackout until at least three (3) minutes have passed. At other times, line voltage can sag (low voltage or brownout) resulting in malfunction of the microprocessor's power supplies and in turn affect the performance of the equipment if the sag lasts long enough or drops low enough. Regulation procedures cannot deal with these types of power deficiency conditions. [5:84] Power conditioning deals with power fluctuations by employing a combination of regulation and/or suppression and a backup power source to overcome power fluctuations including blackout or brownout conditions.

1.3 Purpose of Paper

The purpose of this paper is to provide a practical technical guide to power conditioning/protection for the health care facility's equipment environment. The following main items will be considered:

a) define the various power aberration problems,

b) cost effective power conditioning/protection systems,

c) methods to reduce/eliminate equipment malfunction due to power aberrations,

d) reduce maintenance contracts and overhead costs,

e) reduce/eliminate crisis situations due to equipment down time because of power aberrations.

2 Discussion

2.1 Definition of Power Terms

Acceptable power standards for computer operation have been defined by numerous organizations. American National Standard Institute (ANSI ®) Utility Power Profile considers power to be reasonably clean when the steady-state voltage is between + 6 percent to - 13 percent of nominal line voltage. The standard requires voltage variations of three (3) to thirty (30) cycles in duration to be between + 15 percent and - 20 percent and + 20 percent and - 30 percent for voltage variations lasting 1/2 cycle to 3 cycles. To meet this standard, a utility company must provide a steady-state voltage at the meter of ± 10 percent of nominal. This standard does not address transients, noise content, wave shape or frequency factors. The Computer Business Equipment Manufacturers Association (CBEMA) establishes guidelines for computer power systems. For disturbances above 30 cycles duration, the guideline is very similar to ANSI standards. Disturbances below 30 cycles in duration, the CBEMA guidelines are more strict. [31:3-4] There is no single standard for manufacturers, utility companies, or users to follow that defines acceptable power for computer operations.

The terms used to define power aberrations are frequently used to mean more than one thing. For example, the terms ***transient*** and ***surge*** are frequently used to describe all types of overvoltage power line disturbances. [6:143] The two main categories of power aberrations are ***surges*** (surges, spikes, transients, or noise) and ***sags*** (brownouts, or blackouts). Surges are a condition of excessive power or periods of overvoltage. [11:3] From this point on, the term transient will be used to describe a particular type of overvoltage condition lasting longer than one cycle. A surge excites the system's natural resonant frequency. [18:10] Sags are the opposite condition, a deficiency of power or a period of undervoltage. [11:5] The primary factors to consider for categorizing power line disturbances are the amplitude, duration, and frequency (if able to predict) of the disturbance. [7:34,41:70] The amplitude and duration of the disturbance will determine the energy of the disturbance. See Figure 2.

Categories of Power Aberrations

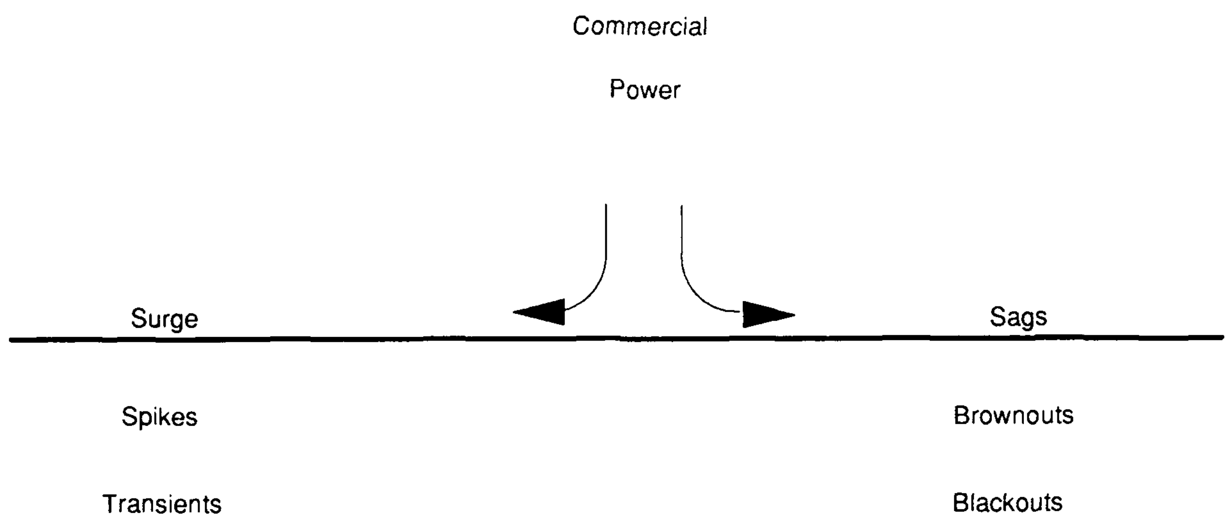


Figure 2

The term ***surge*** covers broad categories of overvoltage conditions modulating on the normal voltage sine wave. IEEE Std 587-1980 defines a surge as a "*transient wave of current, potential or power in the electric circuit*". [18:14] This definition includes "*slow*" (lasting up to several cycles down to a few milliseconds) overvoltage conditions. Norman H. Haskell, Jr. defines an impulse as a transient spike lasting less than a quarter cycle, while a surge lasts at least one cycle. [14:14] In this paper, a surge condition that lasts greater than one (1) cycle is called a ***surge*** while a surge condition of less than one (1) cycle is treated as a category divided into the following groups: 1) Spikes (sometimes referred to as impulses), 2) transients (sometimes referred to as impulses), and 3) noise. The height of the voltage rise and duration of the overvoltage condition determines the group of the surge condition. A spike is defined as a singular or several short bursts of energy riding on the normal power voltage sine wave. These additional burst(s) of energy modulating on the normal voltage sine wave cause the line voltage to rise sharply from normal voltage to several thousand volts. Typically, the voltage returns to normal within eight (8) milliseconds (8×10^{-3}). [7:34,11:3,41:70] See Figure 3 for an example.

Transients modulated on the normal voltage sine wave cause the line voltage to rise within several nanoseconds to several thousand volts and return to normal within microseconds. Before 1974, transients were unknown although they existed all along. Development of faster monitoring equipment enabled the detection of these high-speed power aberrations. The extremely high voltage coupled with the extremely short duration limits the energy within a transient. Transients contain sufficient energy to affect (destroy or disrupt microprocessor routines) integrated circuits (IC), and to a limited extent, transistors. Transients occur more frequently than spikes. [11:3-4,41:70] See Figure 3 for an example.

Noise is referred to as hash by radio and communication people. Noise covers a broad spectrum of high frequency signals ranging from 5 kHz to 800 kHz, modulating on the normal voltage sine wave. Howard C. Cooper described noise as "*a caterpillar crawling up and down the sine wave*". [11:4-5] The technical terms for noise are electromagnetic interference (EMI) and radio frequency interference (RFI). Electromagnetic interference involves the electromagnetic flux lines from a source crossing a conductor (power line), which in turn induces a current within the conductor (current modulated on the normal power sine wave). The EMI

Sample Electrical Disturbances

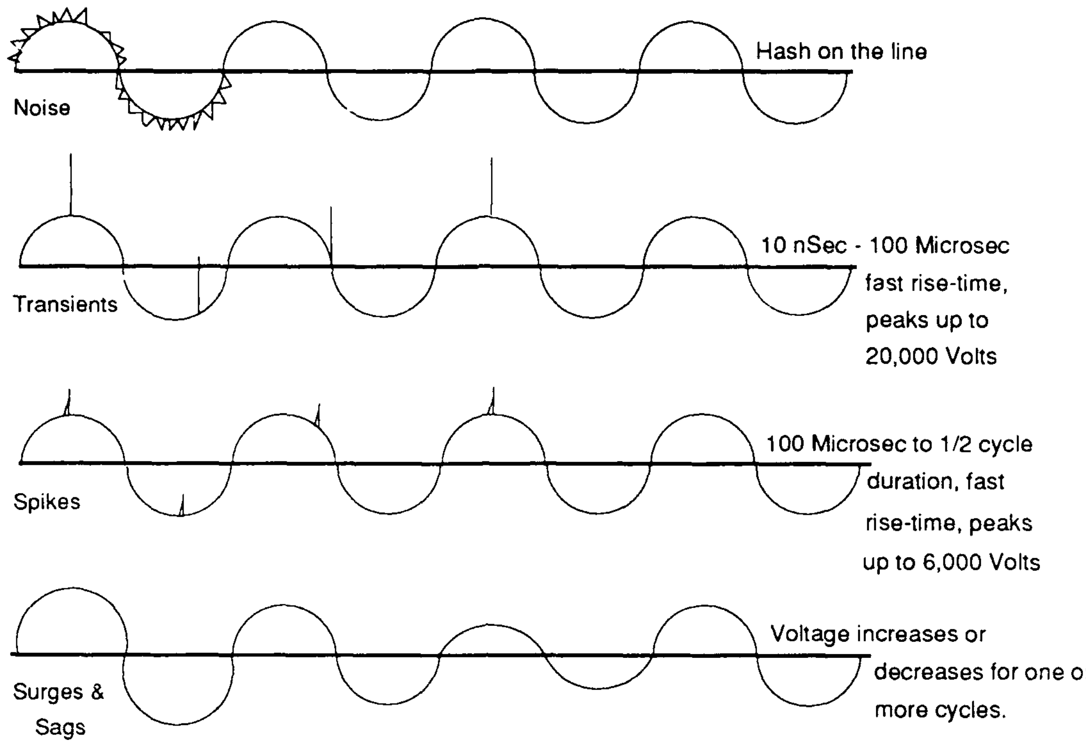


Figure 3

Reprinted from Howard C. Cooper, Power Conditioning to Protect Computers and Electronic Equipment, American Society for Hospital Engineering of the American Hospital Association, June 1984, p. 11.

can either be in the form of radiating or conducting energy. Many of today's power supplies for computers and other microprocessor driven items can introduce noise into the building's (utility) power system. In particular, the switcher power supply and the microprocessor equipment they power produce significant levels of EMI. The problem is not with the equipment producing the

EMI, but with the electrical system and other equipment items connected to the electrical distribution system. [39:124-126] Radio frequency interference is created in a similar manner as EMI. The fact the interference is RFI suggests the source of the noise as radio signals and a typical frequency of radio signals. [11:5] See Figure 3 for an example.

The term ***sag*** covers a broad category of undervoltage conditions lasting from 2-3 cycles to an undeterminable time length. A ***sag*** can starve a *dc* power supply if it lasts long enough (push-through) and/or the undervoltage condition is severe enough. Sags are frequently associated with other power aberrations. The recovery of power from an undervoltage condition is seldom "*clean*" but instead overshoots in the form of a transient. Transients are destructive while sags are not destructive in nature to electronic equipment except for the loss of data in volatile memory (Read only memory, RAM). The sag category is divided into two groups 1) brownouts, and 2) blackouts. [11:5] Brownouts are the reduction of voltage sine wave amplitude (typically below 96 volts and frequently intentionally) while blackouts are the total loss of power (voltage sine wave amplitude goes to zero) for a period of time. 50% of all blackouts last six (6) seconds or less. An utility company defines a blackout as a period without power (zero voltage) for three (3) minutes. [5:84,41:70] See Figure 3 for an example.

2.2 Frequent Sources of Power line Aberrations

Power line aberrations are caused by natural and human sources. Nature in the forms of lightning, magnetic storms, wind, and snow affect the utility's power system. Although static electrical discharges can damage dielectric components they are not introduced into the utility system. Man introduces power line aberrations by many methods. The common methods are grid switching, contact faults, and load variations. [11:2-3,14:8 and 19] Ironically, the high-frequency power supplies found in today's microprocessor equipment can cause power aberrations. [31:1] Power conditioning/protection provides a bridge between "*commercial*" grade utility power and "*computer*" grade power.

Lightning strikes can affect a power system in two primary ways: 1) ground potential rise (GPR), and 2) direct hit of a power line (hot), transformer, capacitors, substation, or other power system equipment (induction). [14:14-16] In the first case, lightning strikes a grounded item. The grounded item could be a "*neutral*" wire (NEC requires neutral line grounded every quarter mile but power companies attempt to ground more frequently [14:12]) or grounded support structure. Soil in the area of the ground has a finite resistance to the current flow from the lightning strike. The area immediately around the ground spike will raise in potential with respect to an area farther removed from the grounding spike. The difference in potential will equalize and indirectly cause sags or surges. Little can be done to prevent this type of power aberration. [14:14-16]

Protection systems can be installed to attempt to minimize the effect of a direct lightning strike. A power line waving up in the air 25 to 30 feet, a metal transformer, or a metal capacitor provides an excellent path to ground for lightning. A lightning strike causes the potential of the item to raise in respect to the power system. A lightning arrestor momentarily connects the line directly to ground (low impedance, best path for the extra potential to ground). Even though the main source of the lightning's energy has been dissipated to ground, surges and sags have been introduced into the power system. [14:14-16]

Solar flares can affect the earth's magnetic field (geomagnetic field). A magnetic storm or geomagnetic field fluctuation can introduce quasi-dc currents into an utility power system. The disturbance can raise the *Earth-Surface-Potential* (ESP) three to six volts/km. This increase in ESP can induce currents into the utility power system through grounding points. These currents (called *Solar-Induce-Currents* SIC) can cause half-cycle saturation of power transformers. The primary factors affecting the magnitude of SIC are latitude and amount of igneous rock present. Thus, during a magnetic storm, the farther north and the larger the amount of igneous rock present in the soil content determines the effects of SIC on the utility power system. [1:1031-1033]

An accumulation or the lack of electrons on a surface that is usually a poor conductor or insulators can lead to a static electricity discharge. When two materials (either both poor conductors or insulators) come into contact, the friction between the items leads to electron transfer. Upon separation, the difference in potential (due to electron transfer) is equalized by a discharge between the two items. A second example of static electricity is when a charged object comes into close proximity (or contact) with an object of different potential. Given the correct conditions, a static discharge occurs. 2500 volts is the threshold for human feeling. Static electricity can develop charges as high as 20,000 to 30,000 volts. [14:19-21] Many of today's modern technological devices are very susceptible to electrical discharge (static). Table 1 provides susceptibility ranges of electronic devices exposed to electrical discharges.

To regulate power distribution, power companies perform an operation called grid switching. During this operation, an utility company attempts to balance the load demanded by the customer's equipment. Switching of the loads causes changes in the steady-state voltage or power aberrations. This operation can and frequently does introduce aberrations into the power system. [11:2,31:4]

The utility company "*sees*" an infinite number of loads attached to the utility power system. The loads cannot be treated as individual loads but Norman H. Haskell, Jr. recommends classifying the loads according to the type and effect on the power system: 1) unbalanced loads, 2) loads that switch or are switched, and 3) harmonic generators. A balanced load(s) operating on three phase power produce little if any residual current. If a load on one of the "*legs*" is suddenly and drastically reduced, then sags and/or surges are created in the short term and increase the residual current in the long run. The changes caused by these disturbances affect not only the local premises but can be transmitted into the utility power system. [14:16-17]

Reported Susceptibility Ranges of Various Devices Exposed to Electronic Discharge from a person or Electronic Equivalent	
Device Type	Range of ESD Susceptibility (Volts)
VMOS	30 - 1,800
MOSFET	100 - 200
GaAsFET	100 - 300
EPROM	100
JFET	140 - 7,000
SAW	150 - 500
OP-AMP	190 - 2,500
CMOS	250 - 3,000
Schottky Diodes	300 - 2,500
Film Resistors (Thick, Thin)	300 - 3,000
Bipolar Transistors	380 - 7,000
ECL	500 - 1,500
SCR	680 - 1,000
Schottky TTL	1,000 - 2,500

Table 1

Reprinted from Norman H. Haskell, Jr., P. E., Surge Protection of Electronics, (South Carolina: Continuing Engineering Education College of Engineering) p. 10.

Inductive motors start by the closing of starter contacts. Upon closing, the inductive motor (as a load) is added to the power system. During this addition, an initial voltage sag occurs followed by an overvoltage condition (spikes or transients). Typically short sags do not affect microprocessor equipment while spikes or transients can affect microprocessor equipment. [31:4-5]

An inductive load that is switched off can "*pump backs*" several cycles of power as the inductive fields collapse. The stored energy within the induction motor's magnified fields decay exponentially as the switch contacts open creating sags and/or surges. Like the balanced load problem, these disturbances affect not only the local premises (health care facility) but also are able to be transmitted into the utility power system. [14:17, 31:5]

An emergency generator can introduce harmonic load disturbances (sags and/or surges) during switching. [14:17] JCAH, NFPA 99 and NEC require health care facilities to have an alternate (emergency) power source. This power source must be inspected weekly and operated under load conditions at operating temperature for at least thirty (30) minutes each month. [28:1023, 33:8] The scenario begins with a commercial power failure. The generator starts and comes up to operating speed. Once the generator is at operating speed, the transfer switch transfers the load to the generator. At the instant of transfer, the load has unique resistive, capacitance, and inductive properties. Due to these unique properties, the generator sends an initial surge of energy until a steady state condition is obtained. Over the entire scenario the loads experience a sag followed by a surge and eventually a steady state condition returns. Similar scenarios occur upon return to commercial power or during normal monthly testing of the generator. The disturbances created by generator switching generally affect only the local premises. [14:17] See Figure 4.

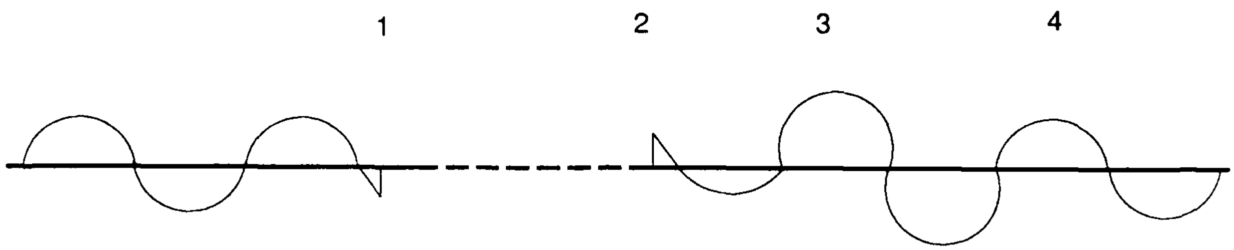
2.3 Definition IEEE Standards for Surge Voltages in Low-Voltage *ac* power circuits

IEEE Std 587-1980, IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits, provides guidance for selection of voltage and current specifications for testing the capability of equipment to withstand surges. The standard deals primarily with indoor power systems. IEEE Std 28-1974, Standard for Surge Arresters for AC Power Circuits, and ANSI/IEEE C37.90a-1974, Guide for Surge Withstand Capability (SWC) Tests, deal primarily with outdoor power systems. IEEE Std 587-1980 is directed for equipment that operate on voltages up to 277 volts line to ground (120, 220/380, or 277/480 volts systems) which includes most equipment used in the residential, commercial and light industrial environment. The standard defines a surge as a voltage condition of at least twice the normal operating voltage and with a duration of a microsecond up to a millisecond. The standard does not address surges of less than twice operating voltages, nor a surge of longer duration. [18:7]

IEEE developed IEEE 587-1980 based on twenty (20) years of statistical data of overvoltage conditions. During the development of the standard, two primary schools of thought emerged: 1) design for worst case (lightning) or 2) design for the "*norm*" and not the exception. The second group felt lightning induced overvoltage conditions were the exceptional case (unlikely or significantly unimportant). Protection devices should be designed for the "*typical*" overvoltage condition rather than the exceptional case. Including protection for lightning is not required and only significantly raises the cost of protection devices unnecessarily. [4:147]

On the other hand, protection devices that can handle lightning induced overvoltage conditions could certainly handle the lesser more common power line disturbances. [4:147] One's view on the significance or insignificance of lightning could well be determined by where you are located geographically. Most of the entire western part of the United States has an average of ten to thirty (10 - 30) thunderstorm days per year. The southeastern part of Colorado, northern part of New Mexico and the southeastern part of the United States experience above fifty (50) thunderstorm days per year. In particular, most of Florida and the southern part of Louisiana experience eighty or ninety (80 - 90) thunderstorm days per year. [14:5] If the equipment you are protecting is in an area that receives above 50 thunderstorm days per year, lightning induced overvoltage conditions may not be insignificant events.

Typical Voltage Waveforms during Power Transfer



1. Power failure and generator starts
2. Transfer switch operates
3. High Current demand
4. Steady state condition reached

Figure 4

Reprinted from Norman H. Haskell, Jr., P. E., Surge Protection of Electronics, (South Carolina: Continuing Engineering Education College of Engineering) p. 18.

Predicting the rate of occurrence and/or the level of surges (amplitude) is difficult, if not impossible. [18:9] The studies cited in section 1.1 demonstrate the vast variance in types of surges and sags seen and the frequency of the problem. The timing of the surge with respect to power frequency occurs randomly. The force of a surge is attenuated as one moves away from the source and divides at branch points. Typically the transient(s) or spike (s) condition wavelength is shorter compared to the length of the power line. Thus, the rise time decreases (due to line impedance) giving the condition a more gradual slope while the amplitude of the condition decreases. Hence, the greater length of transmission line, line-to-ground capacitance or series inductance, the greater the attenuation effect. On the average, equipment is exposed to a relatively small number of high-level surges and a considerably larger number of low-level surges. [18:14-15, 31:7] In designing a surge suppressor, an engineer must deal with relative values as the major factors of a surge frequency, amplitude, and timing occurs randomly.

IEEE Std 587-1980 recognizes surge voltages as either the result of a driving voltage or of voltage limited by the sparkover. The standard defines an "*unprotected circuit*" as a circuit with no low-voltage protective device installed, but with a clearance sparkover that will limit the maximum voltage. The sparkover level for outdoor equipment is typically set for 10 kV (20 kV is possible) while the indoor level is usually set at 6 kV. This lower level for sparkover on indoor equipment is used as a cutoff for surges. [18:9]

Combining measurements and theoretical calculations, IEEE Std 587-1980 defines the "*typical*" surge voltage waveform as oscillatory with varying amplitudes and waveshapes depending on its location within the power system and distance from the surge source. The voltage or current surge waveform is described by three parameters: 1) rise time, 2) decay time, and 3) amplitude. Rise time is defined as the time required for the waveform to rise from 10% of peak amplitude to 90% of peak amplitude. [14:76-77, 37:278] Decay time is the elapse time required for the voltage or current to decrease to 50% of the peak value. Amplitude is the crest height. [14:76-77] The range of oscillations during the decaying tail is from 5 kHz to in excess of 500 kHz with a "*typical*" range of 30 - 100 kHz found within residential and light industrial power systems. The standard recommends 0.5 μsec-100 kHz ring wave as a test wave. The wave rises from 10% to 90% in 5 μsec (rise time) then decays at a frequency of 100 kHz. [18:10] The area under the waveform represents the energy content of the disturbance. The longer the pulse or greater the amplitude, the greater the energy content of the disturbance. The decay time of the disturbance will affect the energy content of the disturbance. [14:77-78] This test wave is specifically designed for a surge applied across an open circuit. [18:12] See Figure 5.

IEEE Std 587-1980 states three reasons for using a test wave of the above description. First, the rapid rise time of the test wave provides a nonlinear voltage effect on windings and the d*v*/dt effect on semiconductors. Transients typically have faster rise times but as the transient travels the rise time increases. The wave provides an oscillating and decaying tail. This area of the test wave provides frequent voltage polarity changes. Because of the frequent voltage polarity changes, the semiconductors are forced in and out of the conducting state (forward and reverse biasing) and this action can be particularly damaging to certain semiconductors. Last, as surge durations decrease (duration less than 1 μsec), the capability of many semiconductors to withstand surges improves. Thus, the test wave (at least the first half-cycle) must have adequate duration in order to test the system's capability to withstand a surge. [18:11]

The energy of a surge will divide in accordance with many factors. One factor, in particular, is determined by the source's and the suppressor's impedances. Surge impedance is the ratio of voltage and current wave traveling a power line of infinite length. Source impedance is defined as the impedance at an input of a device or network. [17:904] To design an effective surge suppression device, one must make realistic assumptions on the voltage surge source impedance. The test voltage wave specified by IEEE Std 587-1980 (Figure 5) is intended to be used across an open circuit. Connecting any load to the circuit will lower impedance and thus affect the shape of the test voltage wave. The assumptions on voltage surge source impedance will be tempered by the type of surge suppressor used. Two primary types are 1) gap-type, and 2) energy-absorber suppressor. The gap-type suppressor has low impedance after sparkover, therefore, has a power-follow current-limiting resistor in series to assist in the dissipating of the surge's energy. The second type, energy-absorber suppressor, has a high impedance and can dissipate a substantial portion of the surge's energy and does not require a power-follow current-limiting resistor in series. [18:11-12]

The combinations of source and load impedances is infinite, thus IEEE Std 587-1980 recommends three broad categories of circuit locations. [18:12] These three categories correspond to three (3) of the four (4) categories used in IEC Number 664 (1980), Insulation Coordination within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment. [19:1-6] The three IEEE categories are A) Outlets and Long Branch Circuits, B) Major feeders and short branch circuits, and C) Outside and Service Entrances. [18:13] Table 2 provides specific details on the two most common categories, A and B. The table expresses the maximum range and medium-exposure situation. The 6 kV open-circuit voltage was obtained due to the sparkover limiting action for indoor wiring systems and the attenuation propagation properties of voltages within an unloaded system. Category C (compares with Category IV of IEC No. 664) deals with a portion of the outdoor wiring system. Substantially higher voltages and higher sparkover levels will be seen in this category. [18:12-13]

Figure 6 provides examples of location categories in residence and/or light industrial environments. The test waves 1.2 x 50 μsec and 8 x 20 μsec are for evaluating power equipment against lightning surges. [18:15] See Figure 7.

The test circuits in Figure 8 are provided by IEEE Std 587-1980 to generate the three different surge test wave patterns seen in Figure 5 and Figure 7. [18:23]

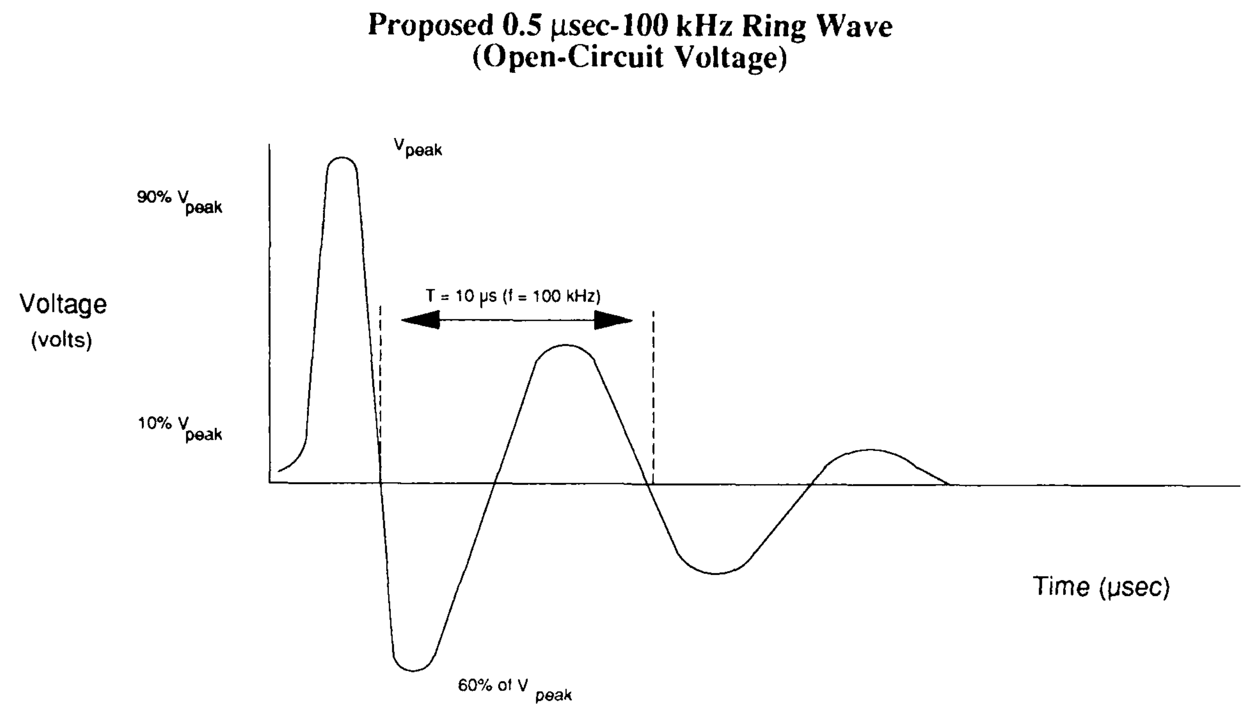


Figure 5

Reprinted from The Institute of Electrical and Electronics Engineers, Inc., IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (IEEE Std 587-1980), (New York: The Institute of Electrical and Electronics Engineers, Inc.) p. 10.

Surge Voltages and Currents Deemed to Represent the Indoor Environment and Recommended for use in Designing Protective Systems				
Location Category	Comparable to IEC No. 664 Category	Waveform	Medium Exposure Amplitude	Type of Specimen or Load Circuit
A Long Branch Circuits and Outlets	II	0.5 μs-100 kHz	6 kV 200 A	High impedance § Low impedance ¥, ¤
B Major Feeders, short branch circuits, and load center	III	1.2 x 50 μsec 8 x 20 μsec 0.5 μs-100 kHz	6 kV 3 kA 6 kV 500 A	High impedance § Low impedance ¥ High impedance § Low impedance ¥, ¤

§ For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.

¥ For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.

¤ The maximum amplitude (200 or 500 A) is specified, but the exact waveform will be influenced by the load characteristics.

Table 2

Reprinted from The Institute of Electrical and Electronics Engineers, Inc., IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (IEEE Std 587-1980), (New York: The Institute of Electrical and Electronics Engineers, Inc.) p. 14.

Location Categories of IEEE Std 587-1980

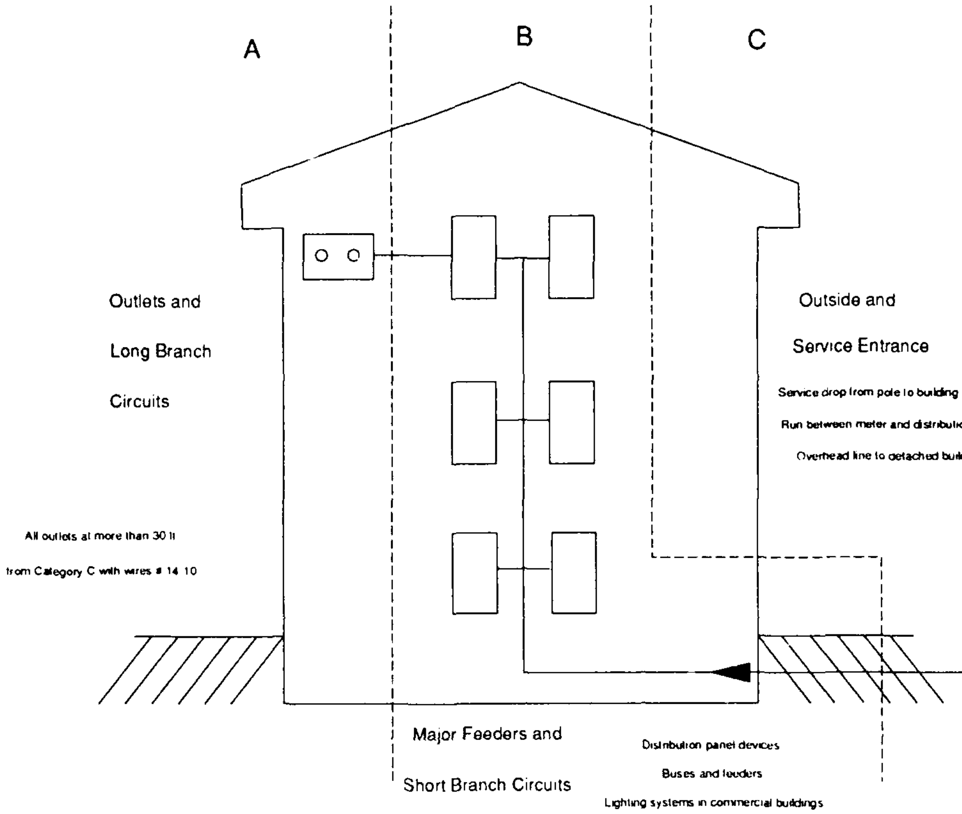


Figure 6

Reprinted from The Institute of Electrical and Electronics Engineers, Inc., IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (IEEE Std 587-1980), (New York: The Institute of Electrical and Electronics Engineers, Inc.) p. 13 and Bob Pospisil and Clayton Bennett, "New Chips Transform Power Conversion." Machine Design, September 7, 1989, volume 61, number 18, p. 137.

2.4 Power Supply Design

Electrical power must be in the correct form (*ac* or *dc* / power conversion), frequency (60 Hz, etc. / frequency changers), and stay within certain voltage and current tolerances (line regulation) to be used by a load. There are numerous ways to convert the input power to the required output form. Power conversion encompasses four general categories: 1) Frequency changers, 2) Inverters, 3) Converters, and 4) Power supply. Frequency changers take an input *ac* power of one frequency and provide an *ac* power of a different frequency. Inverters input source is *dc* and output is an *ac* of the required frequency and amplitude. A converter takes *dc* and

Unidirectional Waveshapes IEEE Std 587-1980

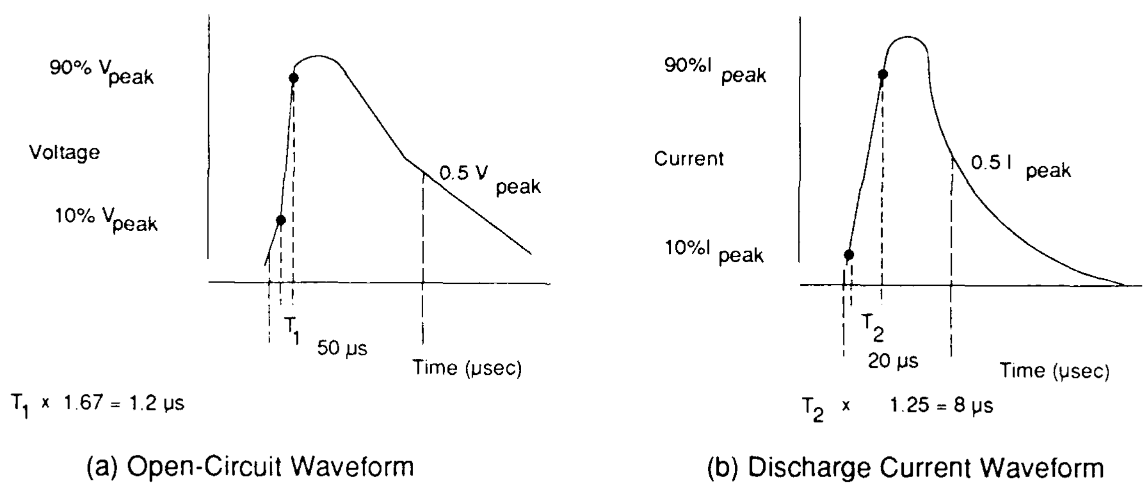


Figure 7

Reprinted from The Institute of Electrical and Electronics Engineers, Inc., <u>IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (IEEE Std 587-1980)</u>, (New York: The Institute of Electrical and Electronics Engineers, Inc.) p. 11.

Test Circuits from IEEE Std 587-1980

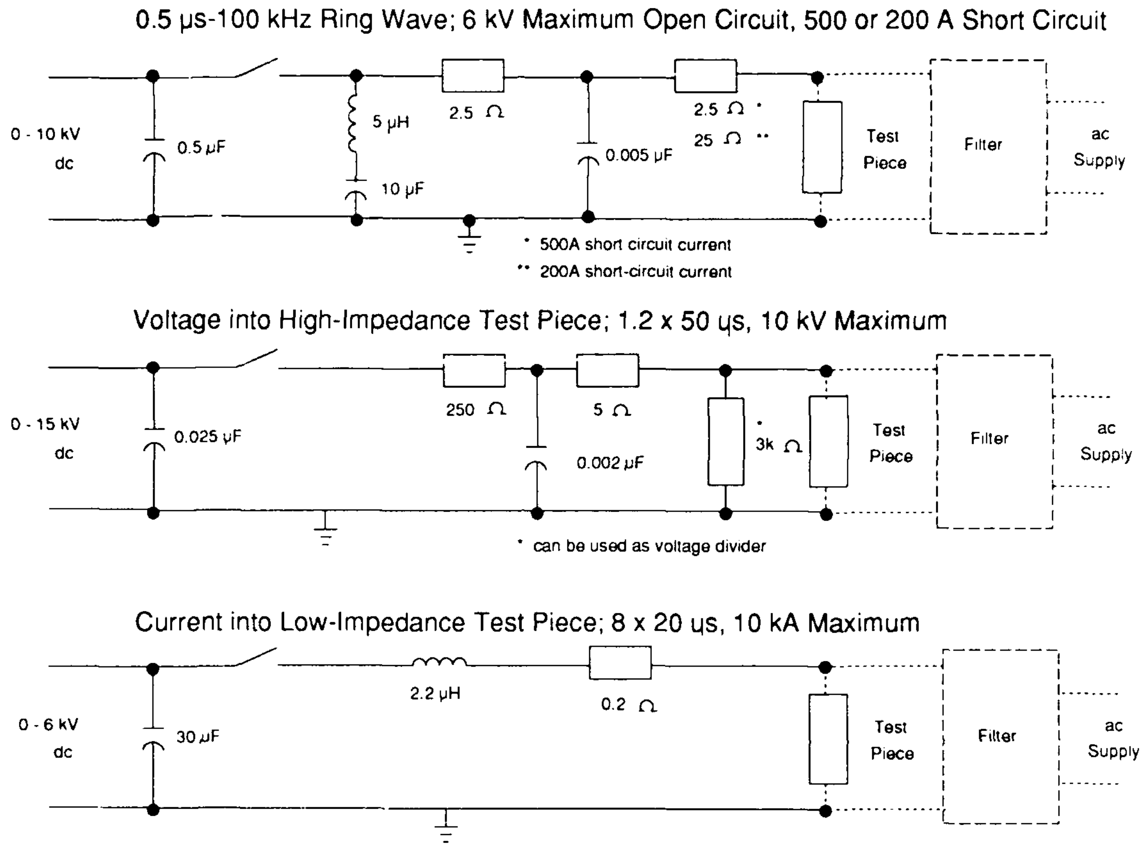


Figure 8

Reprinted from The Institute of Electrical and Electronics Engineers, Inc., IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (IEEE Std 587-1980), (New York: The Institute of Electrical and Electronics Engineers, Inc.) p. 23.

converts it into a different *dc* level (higher or lower). Today's solid state electronic systems require regulated *dc* voltages that are produced by a power supply. The input to the power supply is *ac* while the power supply output is *dc* voltage at required levels. [39:6]

The typical unregulated power supply is composed of two stages: 1) power transformer, and 2) rectifier while the typical regulated power supply is composed of four stages: 1) power transformer, 2) rectifier, 3) filter, and 4) regulation stage. The most basic power supply is the brute-force supply. The rectifier stage can be accomplished by the following methods: 1) half-wave, 2) full-wave, and 3) bridge. The half-wave system places a single diode in series with the load which will conduct (when forward biased) every other cycle. The drawbacks of this system are dead time (only half of the time is used) and difficulty in filtering output. See Figure 9. The addition of a second diode and a center-tapped transformer allows full-wave rectification. This system is efficient and reliable. The drawback of this system is the cost and size of the center-tapped transformer. See Figure 10. A bridge rectifier eliminates the need for a center-tapped transformer and includes two additional diodes. At low power, the bridge rectifier

Brute-Force Half-Wave Rectification

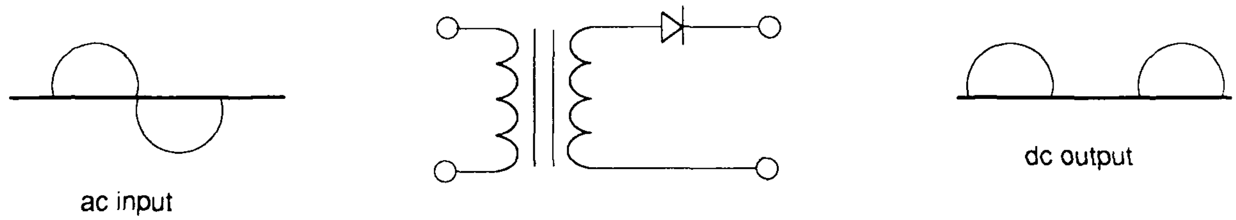


Figure 9

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 7.

Brute-Force Full-Wave Rectification

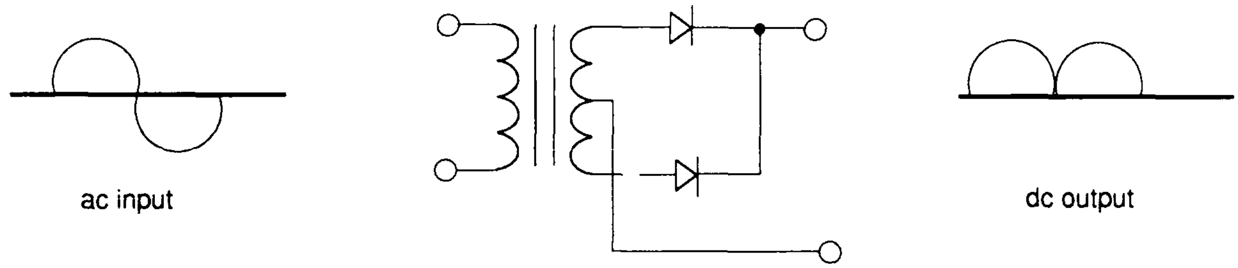


Figure 10

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Brute-Force Bridge Rectification

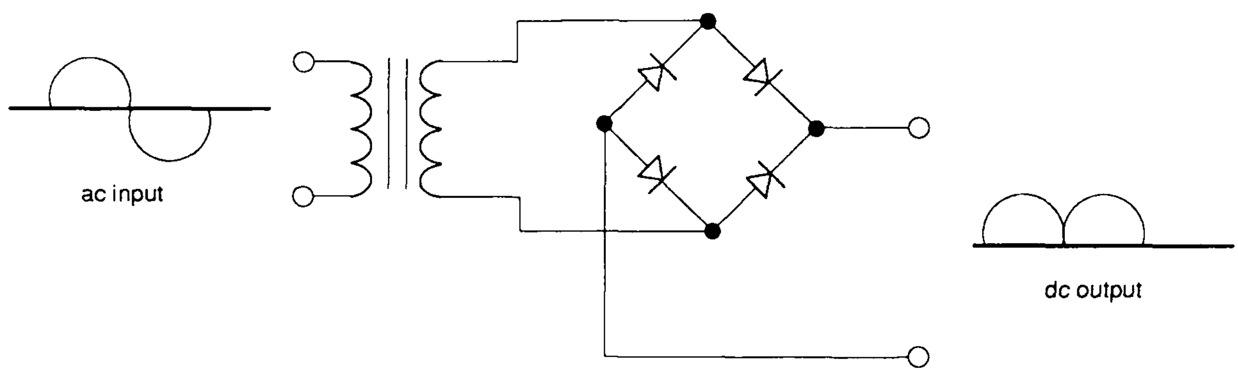

Figure 11

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 9.

system is as efficient and is less costly to construct than the center-tapped transformer. High power diodes are expensive and have a decreased reliability making the center-tapped transformer more effective at higher power. See Figure 11. The brute-force approach provides an unregulated *dc* output. Power aberrations in the *ac* input are directly reflected in the *dc* output. [39:7-9]

Today's sophisticated electronic systems require a regulated *dc* power supply. The brute-force supply must be regulated and filtered to provide a regulated constant *dc* output. The basic regulation techniques are 1) ferroresonance, 2) linear and 3) switching. [39:9-14]

Ferroresonance regulation provides the simplest approach to voltage regulation. The transformer contains an iron core divided into two magnetic circuits (primary windings, and secondary windings output) and a magnetic shunt (located within the secondary windings). The transformer's design dictates the power supply method of operation. The transformer configuration allows the secondary windings to operate in saturation. Because the secondary operates in saturation, the secondary's flux density is saturated and the output voltage remains relatively constant. Changes in the input voltage (± 15%) have little affect on the output voltage because the secondary windings are saturated. [39:9-10] Load regulation is less accurate because of the tank's long time constant. The magnetic shunt circuit within the secondary contains a tank circuit. This circuit is "*tuned*" to the power source frequency (USA 60 Hz or Europe 50 Hz), thus creating a resonance between the capacitor and secondary windings. This form of resonance is called ferromagnetization and thus the reason for the term. [39:9-10] See Figure 12.

During an overload condition, the tank circuit ceases to operate and the output drops almost immediately to zero. Thus, this type of power supply has inherent capabilities to limit current draw and overvoltage protection. [39:11-12]

Ferroresonant Voltage Regulation System

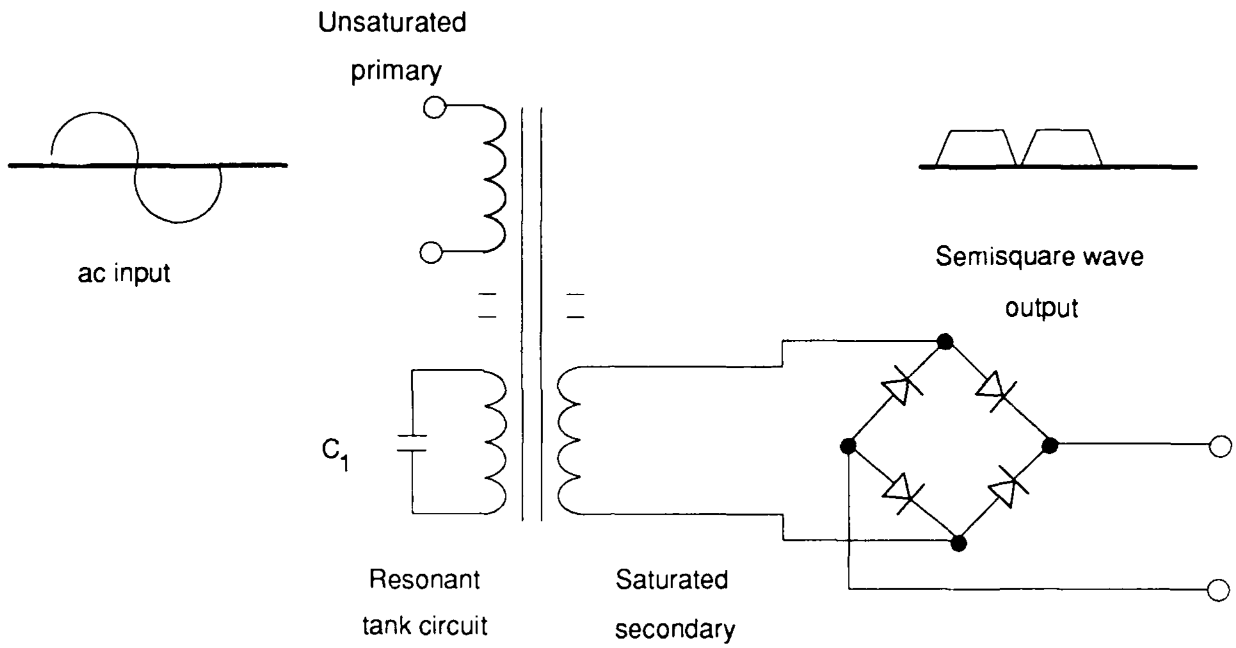

Figure 12

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 10 and 11.

With the cost of energy, efficiency is also a key factor. This supply operates nondissipative in nature and provides an 80% efficiency rating. But with all these advantages, this type of unit has significant disadvantages. The iron core transformer tends to be bulky and heavy. The tank circuit operation is very sensitive to changes in frequency (1% change yields a 1.5% voltage change). Typically the long time constant of the tank circuit yields long transient (impulse) response times. In all, the ferroresonant power supply output voltage will not change given a ± 15% change in the input voltage but is seldom used in today's electronics. [39:11-12]

While the ferroresonant power supply is slow to react to changing line conditions, the linear power supply can react to changes in 10 to 50 microseconds (μs). Unfortunately, the linear power supply is very inefficient (30% - 40%). For the power supply to provide a regulated five volts output, the transformer must provide a six to seven volts output. The difference between the transformer output and the power supply's regulated output is called "*head room*". The difference is required to ensure the power supply's full load operation even during a low input line voltage (maximum input line voltage ± 10%). [39:12-13]

Regulation in the linear power supply is accomplished after rectification. The output voltage is compared to a reference voltage. If the output voltage changes, either due to load condition or changes in input conditions, the change(s) is immediately detected (10 to 50 μsec) and the base current of the transistor is altered to compensate for the changed condition(s). [39:12-13] See Figure 13.

Switching regulation employs many of the superior qualities of the ferroresonant and linear power supplies. Like the ferroresonant system, the switching system is nondissipative with an efficiency typically in the neighborhood of 70% to 80%. The switching system uses an active feedback to control regulation like the linear system. For the ferroresonant system, regulation occurs within the transformer, while linear system regulation occurs after the secondary of the transformer and rectification. Regulation for the switching power supply can occur on the primary side of the transformer (Pulse-Width Modulation, PWM) or the secondary side of the transformer (Phase-Control Modulation, PCM). [39:13-15] These differences and similarities to the previously discussed power supplies make the switching power supply the preferred power supply choice for today's electronics.

Linear Power Supply System

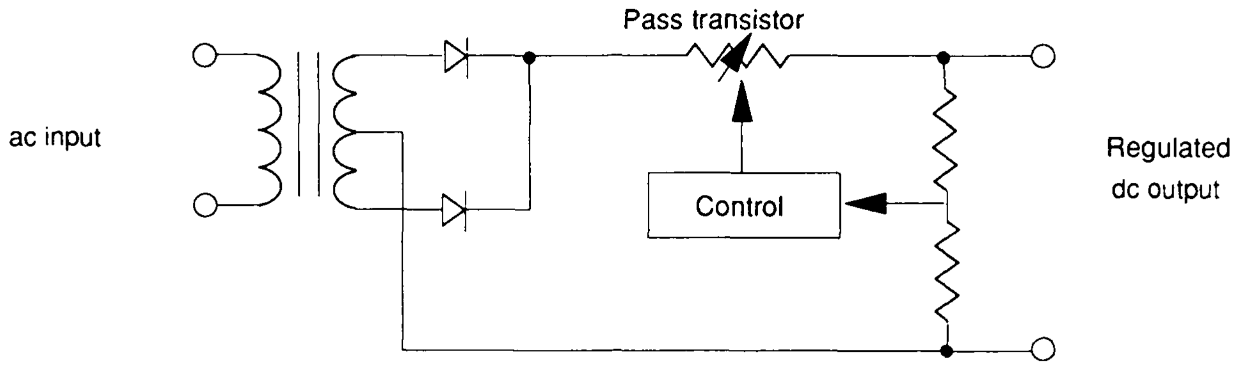

Figure 13

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 13.

The switching system, like the linear system, compares the *dc* output voltage with a reference voltage. In the switching case, the control system selects the amount of time the switching transistor (Pulse-width modulation) or the silicon-controlled rectifiers (SCR) (Phase-control modulation) are on or off. If ratio of on-time to off-time increases, the output voltage increases. The ratio of on-time to off-time can be varied by the controller to maintain a constant output with a varying input. Operation at frequencies between 20 and 50 kHz eliminates any possible audible noise and allows for the use of smaller transformer and filter systems (usually one-third to one-sixth the size of similar linear or ferroresonant power systems). However, operation of the switching power supply at these frequencies causes the unit to generate significant amounts of unwanted electromagnetic interference (EMI) that must be dealt with. [39:13-16]

The advantages of phase-control modulation are low cost, high efficiency and outstanding reliability. But, even with all of these advantages, the pulse-control modulation system is rarely used because of its disadvangtages. The disadvantages are less energy storage capacity than the pulse-width modulation switchers, higher noise (up to 500 millivolts peak to peak), and poor transient response and regulation characteristics (requires several *ac* line cycles to respond to input or output changes like the ferroresonant system). [39:14-15] See Figure 14 for an example of pulse-width modulation and Figure 15 for an example of phase-control modulation.

Switching Power Supply (Pulse-width modulation)

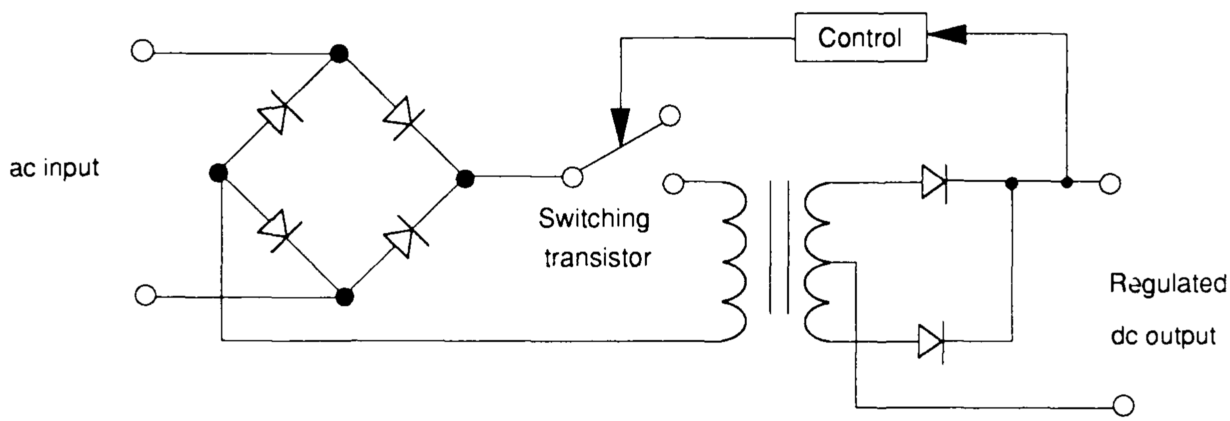

Figure 14

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 14.

2.5 Filters

No matter what form of regulation is used, brute force, ferroresonance, linear, or switching systems, the regulated source of power still experiences fluctuations. A filter stage can be placed between the load and the regulation/rectification power system to smooth the power fluctuations and provide a more constant *dc* output level. This filter is very important in the control of spikes and transients.

Switching Power Supply (Phase-control modulation)

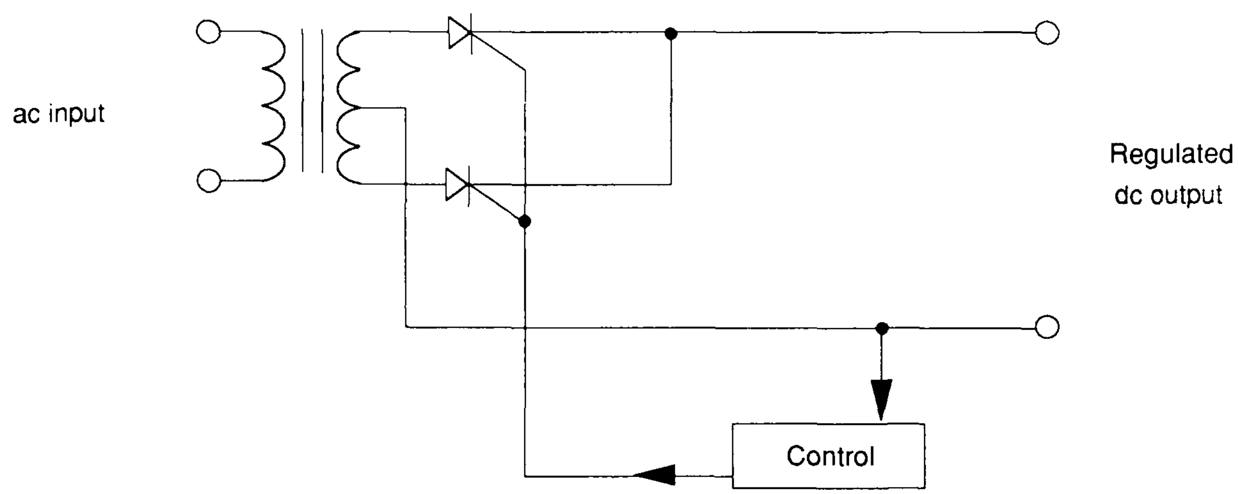

Figure 15

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 15.

The simplest filtering stage is to place a capacitor across the output of the regulation/ rectification power system (also in parallel with the load) or an inductor in series with the regulation/rectification power system and the load. In either case, the capacitor or inductor acts as a reservoir, absorbing or discharging energy with the net effect of a constant *dc* voltage applied across the load. [39:16-17] Inductors block high frequency changes while capacitors can shunt the high frequency changes from the load (the computer). [31:6] Figure 16 is an example of capacitive filtering and Figure 17 is an example of inductive filtering.

For today's microprocessor systems a single inductor (a magnetic coil with low *dc* resistance, voltage device) or capacitor (current device) cannot achieve a high quality *dc* output. By combining the qualities of the capacitor and the inductor, a LC filtering system can provide a high quality *dc* output. By adding a capacitor (in parallel with the load) or an inductor (in series with the load), the filtering network can be as complex as required to obtain the desired *dc* voltage output for load and input voltage sensitivity. [39:16-17] Inductors inherently experience capacitances between the windings. These capacitances allow very high frequency signals to pass through. On the other hand, foil capacitors have inherent series inductance. Since capacitors are placed in parallel with the load (computer), this would tend to block high frequency signals and pass the effects on to the load. Ceramic capacitors (low inductance pulse) do a better job of removing fast rise-time transients. [31:6-7] Figure 18 is an example of an inductive-capacitive (LC) filtering system.

Simple Capacitive Filtering System

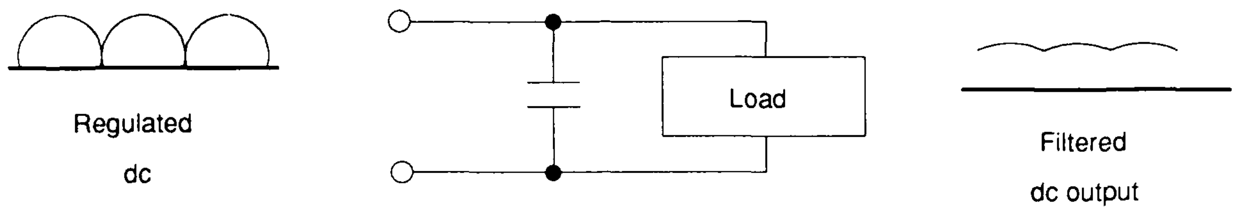

Figure 16

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Simple Inductor Filtering System

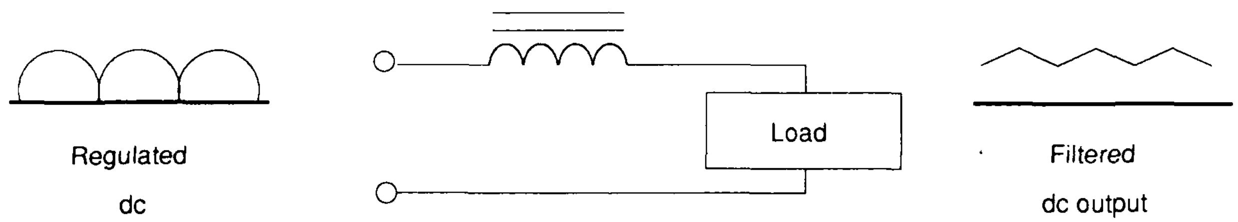


Figure 17

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 17.

Inductor-Capacitive (LC) Filtering System

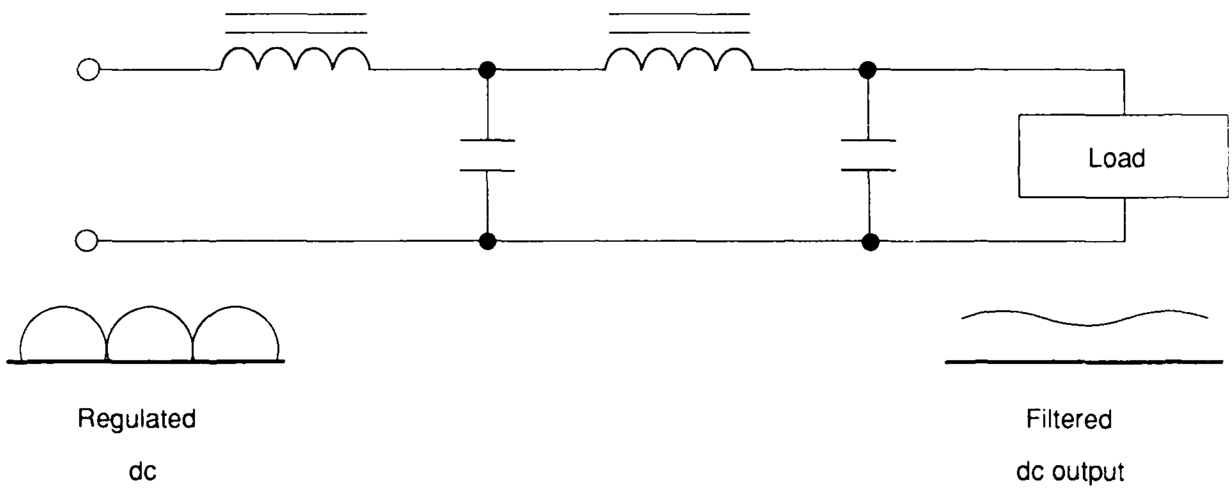


Figure 18

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 17.

3 Methods and Devices

3.1 Power Conditioning

Many factors must be considered to provide acceptable power for microprocessor equipment. Total power protection is impossible to obtain. Thus, the goal is to minimize, reduce, or increase power aberrations to an acceptable standard. James D. Vail pointed out the importance of the interface between the utility company, buildings, power-protection devices, and microprocessor load. These units must work in harmony or the goal to prevent damage and improve up time will not be met. James D. Vail provided the following four requirements that power-protection alternatives must meet to ensure appropriate interface between the electrical environment and microprocessor load;

> "1. ***Reduce all electrical noise*** levels to less than 10 volts of line noise (also referred to as normal-mode noise - between line and neutral), and less than 1/2 volt of ground noise (or common-mode noise - between line and neutral - in relation to ground). These are maximum levels tolerable to prevent disruption, degradation and destruction of medical electronic logic."
>
> "2. ***A clean, single-point ground.*** A noise-free ground reference prevents ground noise and ground loops which can occur when interconnected pieces of equipment are at different ground potentials."
>
> "3. ***A low-impedance source of power*** that will allow the switching power supply to effectively draw current from the line."
>
> "4. ***Low-leakage current*** specifications in order to maximize patient safety. Leakage current is any current which may be conveyed to the patient by the exposed metal parts of a product." [44:95]

The basic solution to power problems is divided into two areas, internal protection and external protection on a particular equipment item. Internal protection comes from the equipment's manufacturer. The user/operator has little or no control over this area. During the equipment design phase, the manufacturer designs or uses an "*off the shelf*" power supply that provides a particular minimal output, given various levels of input. As shown, a power supply is typically composed of transformer, rectifier, LC filter, and voltage regulator stages. These stages combine to provide an internal protection system for the microprocessor unit. [11:13, 14:145]

A LC filtering circuit can provide "*ride-through*" protection. A typical power supply can continue providing power for twenty (20) to twenty-five (25) milliseconds after total loss of power. The load at the time of power loss and the inherent characteristics of the filtering system determine the length of "*ride-through*". [31:5]

A properly designed power supply should have an input window of ± 10 percent (104 to 126 volts for 115 volts system). As long as the voltage remains within the input power window, the microprocessor system will operate correctly. If the voltage drops below the input power window for a period of time that exceeds the "*ride-through*" period, the power supply will not provide sufficient *dc* voltage and the microprocessor system will malfunction. [31:5] The internal protection system is primarily effective against short periods of sags or surge conditions. A well designed power supply system goes a long way in minimizing power aberration problems.

External solutions to power aberration problems provide after the fact solutions. Power aberrations travel in the utility system at close to the speed of light. All electronic devices have a reaction time called delay time. Delay time in semiconductors is frequently the time required to create a depletion region (develop a capacitance charge) and the time for charged particles to cross the depletion region. In other words, it is the time required for the device to turn on. For a Metal-Oxide Varister (MOV), this time is typically 5 nanoseconds (5×10^{-9} seconds). During this 5 nanoseconds time period, a power aberration can travel four (4) to five (5) feet. By placing protective devices externally on the equipment, the protective devices have time to turn on and react to the disturbance. By placing the protective devices before the equipment, at the outlet or service panel, the intervening wire and typically six (6) foot power cord provides time for the protective device to react. Externally applied protective devices work better than if the same device was applied internally because of the reaction time provided by the intervening wire. [21:145]

3.1.1 Types of Power Conditioning

Howard C. Cooper recommends the following steps for selecting appropriate power conditioning:

> "1. Consider amount and type of conditioning already built into both the electrical system and into the electronic or computer devices."
>
> "2. Select the device or devices that will most cost-effectively remove or condition the remaining problem..." [11:5-6]

The primary means of accomplishing power conditioning are to ensure proper grounding and the use of a suppression network, or voltage stabilizer, and voltage regulating transformers. An isolation transformer can reject common-mode problems, but can do little against normal-mode problems. A surge suppressor is effective against common-mode and normal-mode problems to a maximum peak level and is ineffective after the peak level. Line and noise regulation, and to a limited extent, common-mode is provided by ferroresonant systems. At the same time, ferroresonant systems can aggravate sag and short power failure problems. A Radio Frequency Interference (RFI) filter is effective against normal-mode, common-mode and low frequency noise but has little affect against spikes or transients. [6:143] Figure 1 illustrates that spikes are the most common power aberrations encountered. A suppression network (crowbar - virtually short to ground or Transient Voltage Surge Suppressor (TVSSs) - removes spikes or transients above a certain threshold level) can protect (limit damage) equipment from circuit board failure, software glitching and system lock-up. Power conditioning techniques smooth the distortions riding on the sine wave. Suppression does not smooth the distortions but clamps the transient(s) or spike(s) at a preset peak voltage. The suppression device can deal with the excess energy from the transient(s) or spike(s) in several ways. The energy can be shunted to ground or clamp the voltage between the "*hot*" and "*neutral*" to stay within a preset limit. With the preset limit case, the excess energy is dissipated as heat within the suppressor and along the neutral side of the power line. Examples of simple suppression devices are constant-voltage devices (Metal-Oxide Varister's (MOV's), zeners and avalanche diodes, Silicon Control Rectifiers (SCR's), Triac's and Switching Darlingtons) and crowbar or short current devices (Arc Gaps, Gas tubes, and Thyristors). [11:6-7;15]

The next step up in suppression devices is networks. Howard C. Cooper compares suppression networks to car shock absorbers. Suppression networks average or smooth the power aberrations an equipment unit experiences. Howard C. Cooper provides the following key capabilities or specifications for suppression networks:

> "1. Speed or response time should be less than 1 nanosecond. Slower suppression devices will allow transient energy to pass by before they are able to respond".
>
> "2. Energy absorbing capability for maximum transient current should be 15,000 amps for 20 microseconds."
>
> "3. Clamping voltage should be 10 to 20 percent above nominal peak voltage (140 V RMS or 200 V Peak for nominal 120 V.A.C.)."
>
> "4. RF traps and voltage smoothing filters should be incorporated into the network of high speed and high energy suppressors to kill harmonic ringing that is sometimes generated as the transient is clipped off to a low amplitude square wave." [11:7]

Zeners and avalanche diodes pass a predictable current and voltage in the forward direction. High energy spikes or transients contain sufficient energy in the form of heat to destroy the diode. Initially, the diode fails as a *short* and then burns *open*. The reaction time of diodes to power aberrations is in the nanosecond range. [6:144]

Metal-oxide varistors (MOV's) are symmetrical (bipolar) semiconductor devices. These devices are voltage dependent with a nonlinear resistance variable. When a low voltage is applied across the metal-oxide varistor, the device displays a high resistance and thus passes little to no current. During an overvoltage condition, the metal-oxide varistor resistance decreases greatly and shunts the current from the load. Metal-oxide varistors can handle up to 300 joules with response in the nanosecond range. [4:147, 6:144]

Gas tubes are high-energy devices but with slow response times. With each spike, transient or surge, a portion of the gas with the tube is consumed. Frequent spikes, transients, or surges (above maximum continuous operating voltage) will significantly shorten the tube's life expectancy. [22:303, 40:S-14]

Hugh O. Nash, Jr. recommends health care facilities use silicon avalanche diodes that can pass IEEE (ANSI C62.41) 6KV pulse with 1.2 microsecond rise time for transient voltage surge suppressors. Where the exposure to lightning surges is high Hugh O. Nash, Jr., recommends using metal oxide varisters (MOV) at the service entrance(s) to handle the increased energy of the power aberrations. The suppressor includes a filter that removes the remnants of the oscillatory *ring* wave after clipping. [31:7-8]

The Transient Voltage Surge suppressor comes in two types: 1) series or 2) parallel. Series connected suppressors are more effective but are significantly more expensive. The inductor(s) of the series suppressors must be capable of handling 2,000 amps service for a typical 200-bed health care facility. Because of the high current rating required for series suppressors, they are seldom used on service entrances or large feeder lines. Series suppressors are very effective in controlling the power aberrations created by the health care facilities' solid state controllers and computer switching mode power supplies. [31:7-8]

Ferroresonant transformer systems have been the old standby for voltage regulated transformers. The ferroresonant transformer provides excellent normal-mode and common-mode rejection while correcting voltage irregularities of ± 15% of nominal line voltage to within ± 3% of the nominal line voltage. The switching power supplies frequently used in today's medical equipment provide excellent voltage regulation. In fact, a switching and ferroresonant transformer system can interfere with each other's operations unless they are compatible. Ferroresonant transformers tend to be unstable (oscillate) if the medical system equipment exhibits substantial load changes and/or variations. Line notches (can be experienced during test of the emergency generator) affect the ferroresonant system's ability to deliver power. A ferroresonant transformer must recharge the tank following the notch which extends the recovery time. The recovery time can extend through the microprocessor's "*ride-through*" power supply specification leading to a system crash. [44:97-98]

3.1.2 Sequence of Power Conditioning Steps

Frequently manufacturers require certain electronic or microprocessor equipment be installed on a dedicated line. A dedicated line is a separate line directly from a distribution panel to the site of the electronic or microprocessor equipment. No other piece of equipment is on tnis linc. A dedicated line is neither a power conditioning or power protection device. Any power aberration the distribution panel experiences will be transmitted to the dedicated line also. The primary advantage of a dedicated line is the dedicated ground from the distribution panel (source) to the equipment item (load). This improved ground helps to avoid common-mode problems and improve operation of power and/or conditioning devices. The load experiences a stable voltage level because of the absence of other loads. Long dedicated runs increase the probability of noise on the line. The increased wire length increases the wire's impedance which in turn increases the probability the computer's power supply will generate noise on the dedicated line. [5:84, 11:7, 44:95-96] This noise could be transmitted to other loads connected to the same distribution panel.

A dedicated power line improves grounding. A second approach to grounding problems is the Power Distribution System (PDS). This distribution system replaces the entire computer's power system, (wire, circuit breakers, transformer, etc). The system provides a quality ground and limited spike/transient suppression. The primary advantages are improved computer operation by quality ground, enhanced ability to interface with the building's power system, and increased flexibility to change. The power connections under the Power Distribution System are not in rigid conduit with conventional wiring but are flexible and will allow movement (to a limited extent) of the computer. [7:35]

Before a health care facility installs power conditioning devices they should consider the following factors. The FCC requires electrical power companies to regulate power within five (5) percent high and ten (10) percent low of nominal line voltage. Step down transformers used to convert power to the required user levels also reduce the effects of power aberrations by fifty (50) to seventy (70) decibels. Electronic equipment *dc* power supplies contain power protection elements. [11:7-8] This built in power protection should be considered before purchasing additional power protection.

There are two primary approaches to selecting power conditioning equipment. The first approach follows the philosophy ***"if it ain't broke, don't fix it"***. This approach follows a wait and see attitude. If a power problem occurs, then fix it. The user(s) and the clinical engineering department must consider the cost and probability of physical damage to the equipment, loss of operating time, and the probability of catastrophic data loss. While you are experimenting, be sure the cost and risk is acceptable. [31:2]

The second approach selects power conditioning equipment based on the type of equipment to be protected and based on the history of power line aberrations. For example, if a history of frequent voltage changes occur and the new equipment is sensitive to voltage fluctuations, then a voltage regulator is in order. If the health care facility is located in an area of frequent lightning storms or spikes/transients, a transient suppressor would be advisable. [31:2-3]

A ***site survey*** conducted with a power line analyzer before installation of new equipment has become fairly common. Hugh O. Nash, Jr., recommends installing a high quality surge suppressor on the power line before the site survey. Even if the site survey indicates further power protection is required, the surge suppressor can help protect the new equipment and power condition/protection equipment. [31:2-3]

Howard C. Cooper recommends the following cost-effective implementation step for power protection devices:

> "1. Check electrical wiring and grounding for poor contacts, resistive breakers, and poor grounding..."
>
> "2. Install transient suppression networks at the circuit breaker cabinet and at the equipment *ac* power entrance (physically at 120 V.A.C. or 208 V.A.C. as it enters equipment *dc* power supplies)..."
>
> "3. Install a power conditioning, regulating transformer between the line and load transient suppressors. Make sure the kilowatt volts x amps rating is about 20 percent over the actual peak Kilowatt demand of the system..."
>
> "4. With a good power conditioning transformer between line and load transient suppressors, the only remaining disturbances that could cause problems would be long-duration brownouts or actual blackouts. These will never cause hardware or circuit board failure. However, if they happen frequently enough and actually cause disruptive failures or loss of data that are costly to system operation or liability, then an Uninterruptible Power Source, (U.P.S.) system, voltage synthesizer, or motor generator will have to be cost justified..."
>
> "5. Before going from step 2 to step 3, and before going from step 3 to step 4, a complete check should be made for loose circuits boards or loose cable connections. Loose or oxidized connections within systems can cause symptoms that look like power disturbances. Also, particular disruptions that occur every afternoon at about the same time, could be caused by transients from elevators, chillers, or large equipment switched on at that time, or the cause could be heat build-up, which is always worse in the afternoon." [11:8-9]

Howard C. Cooper's power protection sequence provides a cost effective sequence for reducing the effects of power aberrations. He suggests you do not overlook the other causes of electronic failure such as heat, vibration, oxidation, and dirt build up. Following these simple steps can reduce the cost of overhead and at the same time increase the system's reliability (up time). [11:9]

3.2 Power Protection

Power protection devices (Uninterruptible Power Supply System U.P.S.) are the only devices available to ensure continued operation (no-break power) even during a complete loss of power. As stated previously, power companies only consider a lack of power lasting over three (3) minutes as a power failure. An outage greater than 4 milliseconds can cause a computer system to "*crash*". [5:84-85] The loss of power (blackout/brownout condition) can cause loss of data, but is typically not destructive to the computer's hardware. The surge that accompanies the return of commercial *ac* power can and often times is destructive to the computer's hardware. [11:5]

The intent of an U.P.S. is to provide total power protection against both overvoltage and undervoltage conditions. The primary reasons for using an U.P.S. are 1) clean uninterrupted power (primarily for data processing), 2) safety and security (provides emergency lighting, maintains operation of life support equipment, and continues alarm-system operation), and 3) prevents loss of production time and materials (continues a manufacturing operation that cannot be restarted "*midstream*"). An U.P.S. has three basic applications: 1) bridge the gap for motor-generator (provides power to the load after commercial *ac* power failure and before the motor-generator has stabilized, 2) provides time for an orderly shutdown (sequence shutdown rather than a system "*crash*"), and 3) continue operation until commercial *ac* power returns.

[5:86-87]

The typical U.P.S. is called a reverse-transfer system. The system is composed of four basic components: 1) rectifier/charger, 2) battery bank, 3) inverter, and 4) bypass/transfer switch. Under normal conditions, commercial *ac* line power is provided to the first stage rectifier/charger which in turn maintains the battery bank charge and power to the inverter. The inverter provides power to the load (computer). In the event of a commercial *ac* power failure/interruption, the battery bank (continuously provides power to the inverter) provides power to the inverter and continues normal operation of the load (computer) without power interruption. To provide redundancy, the bypass/transfer switch (as long as commercial *ac* power is available) provides protection to the load in the event of an inverter failure or if the load demands a high influx of power. The bypass/transfer switch can automatically connect the load directly to commercial *ac* power. Once the inverter can provide acceptable power, the bypass/transfer switch can be manually reset restoring the load to U.P.S. power. [5:85-86, 26:44] See Figure 19.

Correct tolerance parameters are important for the adequate operation of an U.P.S. . For the rectifier/charger stage, the following parameters are important: 1) *ac* walk-in feature, 2) battery recovery time, 3) input filter systems, and 4) input voltage tolerance. *AC* walk-in feature considers the gradual application of commercial *ac* power to the load (computer) during periods of high power demand (load startup conditions or return of commercial *ac* power after a power failure). This feature limits current demand on the inverter stage and reduces the possibility of blowing line fuses or tripping other protective devices. [5:87]

After a power failure, the rectifier must provide power to the load and recharge the battery bank. The time required to recharge the batteries is frequently expressed relative to the discharge time but, in some cases, manufacturers' specifications call for a minimum recharge time (typically 8 hours). [5:84 and 87] Remember, 50% of power failures last six (6) seconds or less. [5:84] A recharge time of eight (8) hours for a two (2) minute power failure could lead to problems if a series of short term power failures occur. Most manufacturers specify an eight (8) to fifteen (15) factor times the discharge period is required to recover the battery bank. [5:84 and 87]

Block Diagram of an Uninterruptible Power Supply System (U.P.S.)

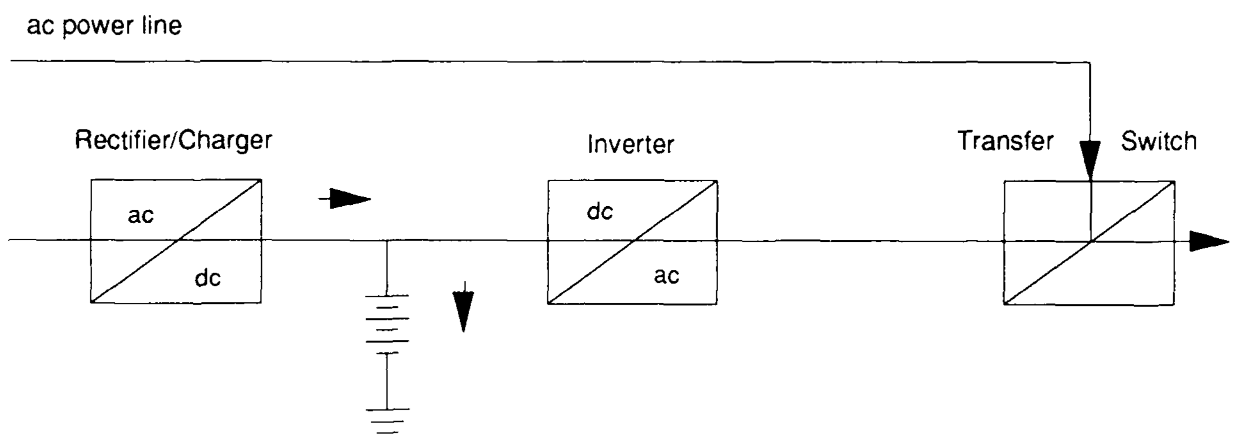


Figure 19

Reprinted from Richard Caprigno and Gurcharn Dang, "Uninterruptible Power Supply Systems." Medical Electronics, October, 1983, p. 85.

Line filter(s) are placed on the commercial *ac* power line prior to the rectifier/charger to reduce or minimize power aberrations (harmonic feedback) the U.P.S. may place on the commercial *ac* power line. This prevents the U.P.S. from interfering with the operation of other loads on the same *ac* line or distribution panel. [5:87]

The input voltage tolerance is a very significant tolerance. This specification reflects the range of commercial *ac* power inputs the U.P.S.'s rectifier can accept to power the load and still charge the battery bank. Small U.P.S.'s (below 15 kVA) can continue to accept commercial *ac* power to 20% of nominal commercial *ac* power line, while larger U.P.S.'s accept commercial *ac* power to 15% of nominal commercial *ac* power line. This tolerance is particularly important if an U.P.S. is called upon to provide power during a blackout condition when the blackout follows an extended brownout period. The lower nominal *ac* voltage during the brownout condition reduces the battery bank charge affecting its ability to deliver power during the blackout period. [5:87]

The battery bank provides the power during periods of low nominal line voltage or no voltage conditions. The battery bank is divided into two groups: 1) wet-cell, and 2) gelled-cell. The wet-cell group is divided into flooded and maintenance-free batteries. Flooded style batteries have removeable vented caps. This provides the ability to checked the electrolyte and make corrections as needed. Wet-cell batteries release noxious and explosive gases during charging. The vented cap allows the gases (oxygen and hydrogen) produced during charging to escape. Therefore, the air in the battery room must be changed at least daily. The batteries must be situated within the U.P.S.'s room to allow servicing. Maintenance-free batteries are high-pressure sealed. Thus the gases (oxygen and hydrogen) produced during charging are contained within the battery and allowed to form water. Nickel-cadmium and lead-acid batteries compose the wet-cell battery category. The lead-acid batteries can be lead-calcium or lead-antimony. Lead-calcium batteries are preferred because they require less water, lower maintenance, and a lower floating charge to maintain a full charge. [5:87-88, 26:44-46]

Gelled-cell batteries are considered nonmaintainable. The electrolyte is immobilized within a gel. The battery is a lead-acid design. This style of battery releases gases (oxygen and hydrogen) like the flooded battery style. No provision is made to add water to replenish the electrolyte. Therefore, the air in the battery room must be changed at least daily. This type of battery construction is best for use in tight or confining areas. [5:88, 26:44-46]

The following basic safety precautions must be exercised and safety equipment present for all battery rooms: posting and enforcing a no smoking policy, fire extinguisher, gloves, goggles, and eye wash station or shower. Batteries perform best at 26°C ambient temperature. Higher temperatures reduce battery life (increase rate of chemical reactions within cells which reduce useful service life) and lower temperatures reduce battery efficiency (increase internal resistance). [5:88, 26:47-48]

The inverter stage converts the *dc* power from the battery bank or rectifier back into regulated *ac* power for the load. The desired output tolerance of the inverter stage is voltage regulation of ± 5% or lower with a dynamic regulation of ± 10% or lower. This stage typically employs pulse-width modulation (single-pulse, multiple-pulse, sinusoidal-pulse, or true harmonic-reduction), impulse current-commutation, or ferroresonant-transformer techniques. Impulse current-commutation controls the modulation by controlling the "*on*" time of SCR's. This technique controls the output voltage and a dual phase-shifted transformer reduces the harmonic distortion (typically to less than 3%). This design provides excellent regulation, good overload capabilities, and low output impedance. [5:88-89]

For small U.P.S.'s (15-30kVA), a ferroresonant constant-voltage transformer (CVS) provides acceptable *ac* power output. The size and the low operating efficiency of a ferroresonant constant-voltage transformer system makes the system impractical for larger systems. [5:88-89]

The automatic bypass/transfer switch provides a measure of redundancy in the case of

U.P.S. failure and commercial *ac* power available. The automatic bypass/transfer switch is a solid-state switch that can accomplish a "*no-break*" power transition. Typically the switch can automaticlly transfer (or manually for testing) to commercial *ac* power upon failure of the U.P.S. and must be manually returned to U.P.S. power. It is important the inverter's output is synchronized (phase-locked) with the commercial *ac* power line to ensure smooth transfer of the load. [5:89] See section 5.2, Points to consider when purchasing an Uninterruptible Power System (U.P.S.), for a detailed checklist of items to consider during purchasing of an Uninterruptible Power System.

3.3 Electromagnetic Interference (EMI) protection

Today's microprocessor equipment can operate (speed) within radio frequency ranges (10 - 30 kHz). Cost efficiency has led to the replacement of steel cabinets with plastic cabinets to contain microprocessor equipment that affords little, if any, protection from EMI or RFI. The Federal Communication Commission (FCC) has developed EMI emission standards for microprocessor systems. Technically, a subsystem can emit any amount of EMI, but once generated the system must deal with the EMI produced and meet the standard as a system. [39:126]

The FCC created two classes for EMI emissions: 1) class A for commercial, industrial and business systems and 2) class B for residential or home system use. The FCC terms class A as a "*friendly*", EMI-tolerant area, while class B as an "unfriendly", EMI-sensitive area. Therefore, class B standard is more strict than class A requirements. [39:126] See Figure 20.

Verband Deutscher Elektrotechniker (VDE) is a West German organization responsible for the testing of equipment for public safety similar to the United States organization UL. [39:168] Currently, VDE's standards for EMI are more strict than the American Standards. Rather than separating by areas of use, VDE developed two equipment classes based on operating frequency. Microprocessor systems operating above 10 kHz can generate significant amounts of EMI and are covered by VDE 0871. VDE 0875 applies to equipment operating below 10 kHz. Jeffrey D. Shepard believes the United States will eventually adopt the West German standards. [39:127] See Figure 20.

The problems of EMI are divided into two basic groups: 1) conducting EMI and 2) radiating EMI. The conduction of EMI into the power system and/or into the equipment item must be dealt with. Filtering devices are able to remove sufficient amounts of EMI to prevent interference with the microprocessor unit itself and the building's (utility) power system. The two forms of conducting EMI are 1) differential-mode and 2) common-mode. Differential-mode EMI (line-to-line) is an electrical potential across the *ac* lines (hot and neutral). The *ac* currents produced by differential-mode EMI are 180 out of phase leading to the cancellation of the electromagnetic fields. Hence, the effects of differential-mode EMI are minor and attenuated rapidly. [39:128]

Common-mode EMI is an electrical potential on *ac* lines (neutral and ground) but with respect to ground. Because this form of EMI is with respect to ground, the radiating disturbance can be effectively and rapidly conducted through the microprocessor unit itself and the building's (utility) power system. Thus, this form of EMI disturbance is the primary source of the problem. [39:129]

AC line filters can effectively control the amount of conducting EMI. One must consider the following when evaluating a filter's performance: matching *ac* line impedance, matching equipment impedance, smallest possible amount of attenuation at 60 Hz, and largest possible amount of attenuation in the 10kHz to 30 MHz range. [39:131] Both the FCC and the VDE have developed a 50 ohms line impedance stabilization network (LISN) to represent line impedance. The significant difference between the FCC and the VDE standards is the receiver bandwidth within the LISN. The VDE standard calls for a 0.2 kHz bandwidth for frequencies between 10 and 150 kHz while the FCC standard requires a 1 kHz bandwidth for lower frequencies. The size of the bandwidth makes the FCC standard tougher. [39:129] See Figure 21.

The number of sections a filter (the greater the number the greater the attenuation) contains directly affects the filter's performance. A typical single section filter is able to attenuate 12 to 22 dB at 150 kHz and increases to 55 dB above 3 MHz. At the same time, a two section filter can provide 70 dB of attenuation at frequencies below 500 kHz. Multisectional filters provide greater attenuation than single or two section filters. [39:129] See Figure 22.

The best time to reduce the effects of radiating EMI is in the initial design stage of the instrument (board development and component placement stage). To reduce radiated EMI the designer should use a grounded metallic cover surrounding the entire device, ground all shielded cables, use a single point ground method, and avoid using the metallic covers as return lines. The case enclosing the device could also be constructed of a conductive composition material or coated with nonconductive plastics. The design of the enclosure must avoid deep holes and sharp corners. Sharp right angled corners could contain sparse amounts of protective coating which could act as antenna thus increasing the effect of radiating EMI. In addition, the electrical paths must be kept as short as possible. The less EMI emitted by the individual components (the system not individual components must meet EMI standards) the easier the designer's task. [39:129-131] An effective grounding system and properly shaped enclosures are essential to reduce radiating EMI.

U.S. and West German Standards for EMI

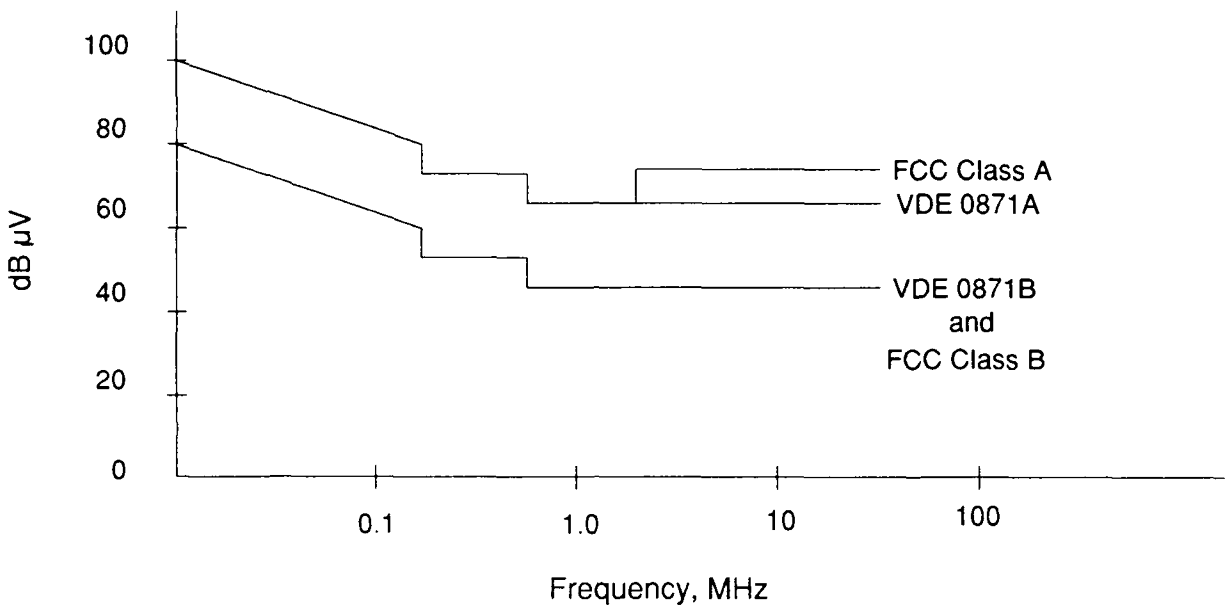


Figure 20

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 125.

Line Impedance Stabilization Network (LISN)

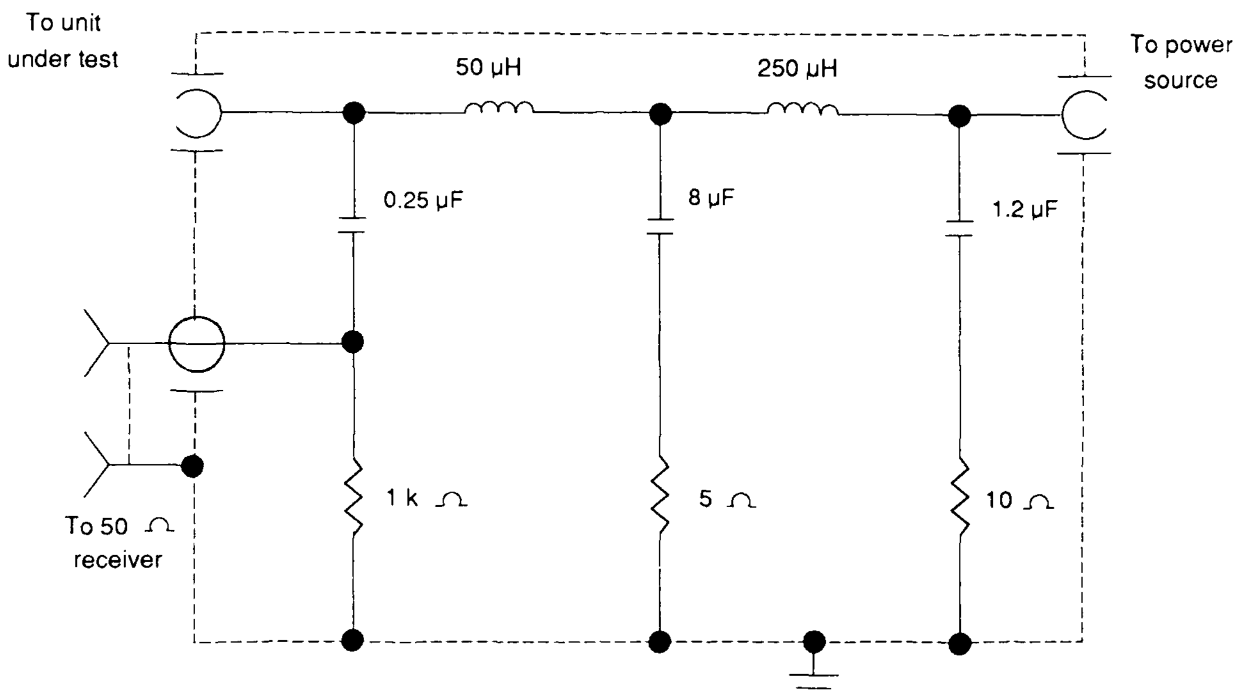
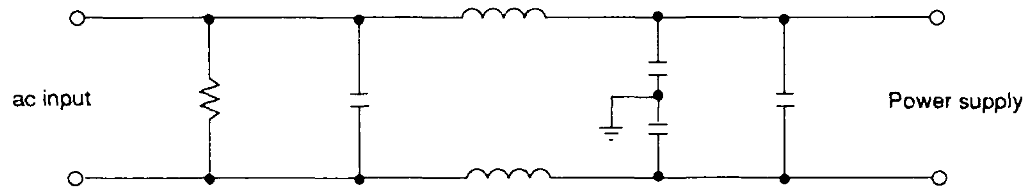


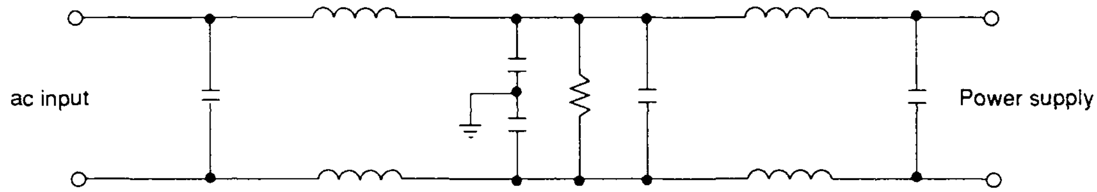
Figure 21

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 129.

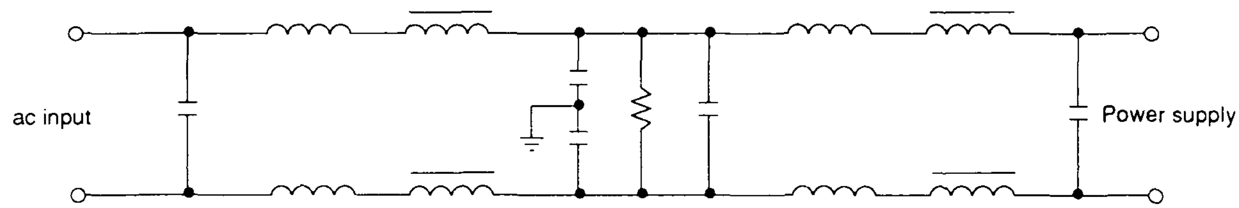
Sample filters that meet or exceed U. S. and West German standards for EMI



Single-section filter



Two-section filter



Multisection filter

Figure 22

Reprinted from Jeffrey D. Shepard, Power Supplies. (Reston, Virginia: Reston Publishing Company, Inc.) p. 130.

3.4 Generator Transfer Switches

Each month health care facilities must operate the alternate (emergency) generator system on load at operating temperature for thirty (30) minutes. [28:1023, 33:8] The horror stories are countless during this test period. Some personnel turn off or unplug all microprocessor equipment to avoid damage during generator testing. James D. Vail conducted a study at four Midwest health care facilities to determine what actually happens electrically during an emergency-generator test. His studies revealed a wide deviation in power quality during transfer and retransfer between the four health care facilities studied. But in all cases, a significant number of impulses (transients or spikes) (common-mode and normal-mode) were experienced. [45:22-25]

James D. Vail's study concluded the following three factors determine the amount of difficulties a health care facility experiences during emergency-generator testing: 1) age of facility, 2) age of generator, and 3) type of transfer switch (conventional versus make-before-break). The use of a make-before-break transfer switch generally resulted in no voltage drop upon transfer or retransfer while the conventional switch often caused the voltage to drop to zero. The best test results were obtained when the generator was brought up to speed, synchronized to the line, and then transferred using a make-before-break transfer switch. Typically, today's switching-powe' .pplies can handle the voltage deviations experienced during the emergency-generator test. If the microprocessor equipment cannot tolerate the voltage drop or frequency deviations then an uninterruptible power system (U.P.S.) is required. [45:25-29]

3.5 Bottom Line

Cost is an important consideration when dealing with power aberration problems. A clinical engineer must consider the opportunity costs when dealing with this type of problem. No matter what course of direction he/she takes, there is a cost involved. If the clinical engineer chooses not to add external power protection then he/she runs the risk that the equipment's internal power protection is insufficient to protect the unit's hardware. If the clinical engineer decides to use external power protection then he/she must consider the time value of money. The decision must consider the cost of spending money today versus the cost of spending money in the future. For example, to spend $50,000 for an U.P.S. to prevent a loss of $5,000 (patient safety not an overriding factor) woud not pass the test of time value of money. However, spending $100 to $500 for a surge suppressor to prevent hardware damage of several thousand dollars would pass the test of time value of money. [24:1-2]

Problem solving of power aberrations begins with the following steps:

1. Avoid problems in the beginning. Properly designed power supplies by the medical equipment manufacturers go a long way toward preventing power problems. If possible, review manufacturer's power supply specifications prior to purchase. Pay particular attention to the tolerance of input voltage, "*ride-through*" time, and response to IEEE surge waveforms. [21:145, 31:5]

2. Ensure metal-oxide varistors (MOVs) surge arrestors are installed at service entrance. [3:1033]

3. Establish a policy of installing a surge suppressor (series is best) at breaker box for sensitive computer equipment or computer equipment requiring extra surge/spike/transient protection. The policy should include installation of a surge suppressor prior to conducting a site survey. [31:3]

4) If power problems occur, then analyze the problems to determine the types, and if possible, the sources of the problems.

   a. Grounding problems. Consider the following possible solutions. See the following tables for advantages/disadvantages.

a. Dedicated line. See table 3.
b. Isolated Transformer. See table 5.
c. Power Distribution System (PDS). See table 6.
d. Ferroresonant Transformer. See table 7.
e. Low Impedance System. See table 8.

b. Transients/spikes/surges.

a. Suppressor or arrestors. See table 4.
b. Electronic Filtering System.
c. Regulation System. See table 7.
d. U.P.S. See table 9.

c. Sags/brownouts/blackouts.

U.P.S. See table 9.

d. Generator transfer.

Ensure transfer switch is a make-before-break type. [44:25-28]

e. Noise.

Add EMI or RFI filters depending on the type of noise and source.

Dedicated Power Line	
Method provides "*good power*" to sensitive equipment. Estimate Equipment and Installation Costs - varies Estimate Maintenance Costs - none Estimate Energy - none	
Advantages	**Disadvantages**
1) More stable voltage 2) Less chance other loads tripping CB 3) No other loads on feeder line 4) "*Good*" ground	1) Adds to electrical noise and feeds noise back to breaker panel 2) Longer the run the greater the electrical noise 3) Added installation cost 4) Can provide a false sense of protection 5) Must ensure dedicated line remains dedicated as changes occur to the electrical system

Table 3

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, pp. 95-96 and Howard C. Cooper, "Power Conditioning to Protect Computers and Electronic Equipment." American Society for Hospital Engineering of the American Hospital Association, June, 1984, p. 18.

Surge Suppressor	
Clips excessive voltages that might be present on the voltage sine wave. Estimate Equipment and Installation Costs (RC or LC filters) - $100 to $500 Estimate Maintenance Costs - none Estimate Energy - none	
Advantages	**Disadvantages**
1) Attenuates Noise 2) Clips excessive voltage 3) Low cost 4) Transfers power well 5) Effective against normal-mode problems	1) Allows spikes/transients to pass if they do not occur at the peak of the sine wave 2) Does little to reduce common-mode noise 3) Converts normal-mode noise into common-mode noise by diverting normal-mode to ground 4) Offer must sacrifice common-mode noise rejection to have acceptable leakage currents for patient safety

Table 4

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, pp. 96 and Howard C. Cooper, "Power Conditioning to Protect Computers and Electronic Equipment." American Society for Hospital Engineering of the American Hospital Association, June, 1984, p. 18.

Metal-oxide Varistor - Can handle high energy but degrades over time.

Silicon avalanche diode - Reacts quickly but cannot handle high energy.

Gas tube - Crow-bar suppression techniques. Causes notching that some power supplies cannot handle leading to a system crash. [44:96]

Isolated Transformer	
Offers isolation between the primary and secondary windings. Reduces leakage current thus reducing the chance of electrical shock to patient. Provides excellent common- mode and ground-mode rejection. Estimate Equipment and Installation Costs - $4,000 Estimate Maintenance Costs - none Estimate Energy - $600/year	
Advantages	**Disadvantages**
1) Reduces leakage current 2) Excellent common-mode and normal-mode noise rejection 3) Reliable 4) Relatively inexpensive to operate	1) High impedance forces switching power supplies to draw higher current and thus operate less efficiently 2) Allows components (one-point ground) to share noise due to high impedance of isolated transformer 3) High impedance leads to oversizing the isolation transformer relative to the load which increases costs of construction and operation

Table 5

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, pp. 96-97 and Howard C. Cooper, "Power Conditioning to Protect Computers and Electronic Equipment." American Society for Hospital Engineering of the American Hospital Association, June, 1984, p. 18.

Power Distribution System (PDS)	
Effective solution to complicated grounding requirements.	
Advantages	**Disadvantages**
1) Portable and flexible 2) Replaces all conventional wiring, conduit, and circuit breakers 3) Provides some attenuation of spikes, transients, and surges 4) Provides excellent single point ground for the computer system	1) ***"You get what you pay for"***. 2) An incorrectly installed unit can compromise the entire operation of the computer system

Table 6

Information obtained from Dennis M. Chambers, "An Overview of the Computer Power Problem", Proceeding of the 1982 Control of Power Systems Conference, The Institute of Electrical and Electronics Engineers, Inc., p. 35.

Ferroresonant Transformer	
Provides excellent common-mode and ground-mode rejection and voltage regulation. Must ensure the ferroresonant transformer system is compatible to the equipment system attached. Estimate Equipment and Installation Costs - $5,000 Estimate Maintenance Costs - $800/year Estimate Energy - $1,200/year	
Advantages	**Disadvantages**
1) Reduces leakage current 2) Excellent common-mode and normal-mode noise rejection	1) If the ferroresonant system is not compatible with equipment power supply can cause the entire system to oscillate 2) If the system has substantial load variation or changes, then the ferroresonant system will cause the entire system to be unstable. Peripherals that switch on and off frequently can cause substantial load variation and make the entire system unstable 3) Line notches (typically experienced when the health care facility transfers to generator or vice versa) force the tank circuit to recharge reducing power provided to the equipment item. If time exceeds the equipment item "*ride-through*" specification the entire system could crash 4) High impedance device that can lead to reflecting noise and cause switching power supplies to work harder 5) Low efficiency ratings

Table 7

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, pp. 97-98 and Howard C. Cooper, "Power Conditioning to Protect Computers and Electronic Equipment." American Society for Hospital Engineering of the American Hospital Association, June, 1984, p. 18.

Low-Impedance Technology	
Reduced impedance characteristics due to tightly coupling primary and secondary windings providing efficient interface with switching power supplies.	
Advantages	**Disadvantages**
1) Excellent normal-mode and common-mode rejection characteristics 2) Does not contain high-impedance conditioning products 3) Oversizing to ensure adequate voltage supply for the load is not required 4) Allows power supplies to draw required amounts of power and at the time required 5) Provides stable power during notch conditions 6) Provides stable power for dynamic loads 7) Excellent leakage current specifications 8) Less expensive than ferroresonant transformer system	1) Does not provide line regulation (Less of a problem if the load has a switching power supply) 2) More expensive than isolation transformers, surge suppressors, and surge arrestors

Table 8

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, p. 98.

U.P.S.
Used to prevent loss of data and hardware damage. Primarily used for blackout, brownout, or sag protection. Estimate Equipment and Installation Costs - $50,000 - $100,000 motor-generator add additional $25,000 - $40,00 Estimate Maintenance Costs - $6,000/year motor-generator add additional $900/year Estimate Energy - $5,000/year motor-generator add additional $3,000

Advantages	Disadvantages
1) Provides power to computer systems during blackout, brownout, or sag conditions thus preventing loss of data and hardware damage	1) Expensive to obtain, operate and maintain 2) Could actually reduce reliability of the computer system

Table 9

Information obtained from James D. Vail, "Protecting Digital Equipment from Power Line Disturbances, Part II-Power Protection Alternatives." Medical Electronics, February, 1988, pp. 98-99 and Howard C. Cooper, "Power Conditioning to Protect Computers and Electronic Equipment." American Society for Hospital Engineering of the American Hospital Association, June, 1984, p. 18.

3.6 Future or Not Too Distant Future

Chip manufacturers have developed integrated circuits that operate directly off *ac* power lines. These chips, particularly in the low-current versions, reduce the scope of the power supply required or eliminate the requirement totally. These chips can be connected anywhere without regard to the quality of the line power and provide three *dc* outputs with current supplied up to 50 mA. The chips do not use transformers or inductors. [38:131]

One example is the HV-1205™ made by Harris Semiconductor. This chip connects to any 120 volt *ac* line and functions as a transformer, rectifier, filter, and regulator. This chip can handle spikes/transients up to 6,000 volts and brownouts down to 30 volts *ac* (range of operation 30 to 132 volts rms). Input current can surge as high as 1.2 amps. This chip provides three regulated *dc* outputs in the range of 5 to 25 volts *dc* and up to 50 mA. A battery or capacitor provides power during sag/brownout/blackout conditions. [38:133-134] See Figure 23 for a block diagram of the chip.

Block Diagram of a Power Supply IC (HV-1205)™

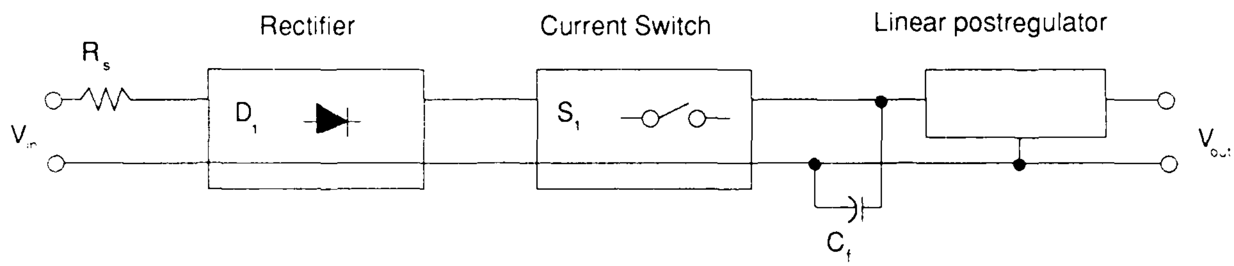


Figure 23

Reprinted from Bob Pospisil, and Clayton Bennett, "New Chips Transform Power Conversion." Machine Design, September 7, 1989, volume 61, number 18, p. 133.

The integrated circuit power supply design includes an *ac* input filter network, power supply IC HV-1205, energy storage network, and output conditioning network. The input filter network limits startup current, clamps surge (surges, spikes, and transients) voltages, and filters high frequency noise and spikes. The input network is an RC low-pass filter system. Circuit components can be sized for a particular application (ie. IEEE-587 category A and B 120 volts wall outlet and major branch circuits, see figure 6) but the resistive portion of the circuit remains at a constant 150 ohms series impedance. [38:134-135] See Figure 24.

The energy storage network receives energy directly from the *ac* input filter network. This power charges a storage capacitor (C_s) whose size is determined by the load current (I_o) and the incoming line frequency (f). A load current of 10 mA and a line frequency of 60 Hz would require a minimum 68 µF capacitor. Increasing the load current to 50 mA would require a minimum 280 µF capacitor. The manufacturer recommends using an oversized capacitor C_s. To provide the "*ride-through*" time during periods of low voltage, a 4,700 µF capacitor or rechargeable battery stores the required power during momentary power sags. This unit can provide 50 mA for 125 msec or up to 1 full second for lower current demands. During normal operations, power is supplied to the 4,700 µF capacitor or rechargeable battery through resistor R_s. The diode D_1 provides a low-resistance discharge path to HV-1205 during periods of low voltage. [38:136] See Figure 24.

The output network conditions and controls up to 3 different *dc* outputs. Typical voltages provided are 5 volts, 25 volts, and a regulated ground (0 volts). [38:136-137] See Figure 24.

Metal-oxide varistors (MOVs) provide excellent spike, transient and surge protection. Unfortunately, MOVs deteriorate over time because of the spikes, transients and surges. Eagle Electric Manufacturing Company Inc. manufactures the Surge Bloc™, a MOV technology surge (surge, transient, and spike) protected receptacle. To overcome the drawback, an audible alarm sounds indicating the MOV section requires replacement. The MOV section is removed and replaced restoring the protection capability of the receptacle. [23:74]

National Electronic Associate's Equalizer™ is the first surge suppressor to meet or exceed military standards for surges. Using metallized crystalline ceramic structures, the Equalizer™ appears to surges (spikes/transients/surges) as ground. The energy within the power aberration is absorbed within the crystalline structure for temporary storage and then dissipated. Power aberrations on the ground line are treated in a like manner. The unit switching time is 0.5 to 25 nanoseconds (nsec). [46:154]

For 120 V or 240 V single phase power systems, the Equalizer™ can handle a maximum surge energy of 240 joules with a maximum current of 19,500 amps. For 3 phase 600 V service these maximums increase to 1,620 joules and 38,750 amps. The unit has built in redundancy with two crystalline stages in parallel. If either (or both) crystalline stages fail, an audio alarm responds. [46:154]

Diagram of a Power Supply IC (HV-1205)™

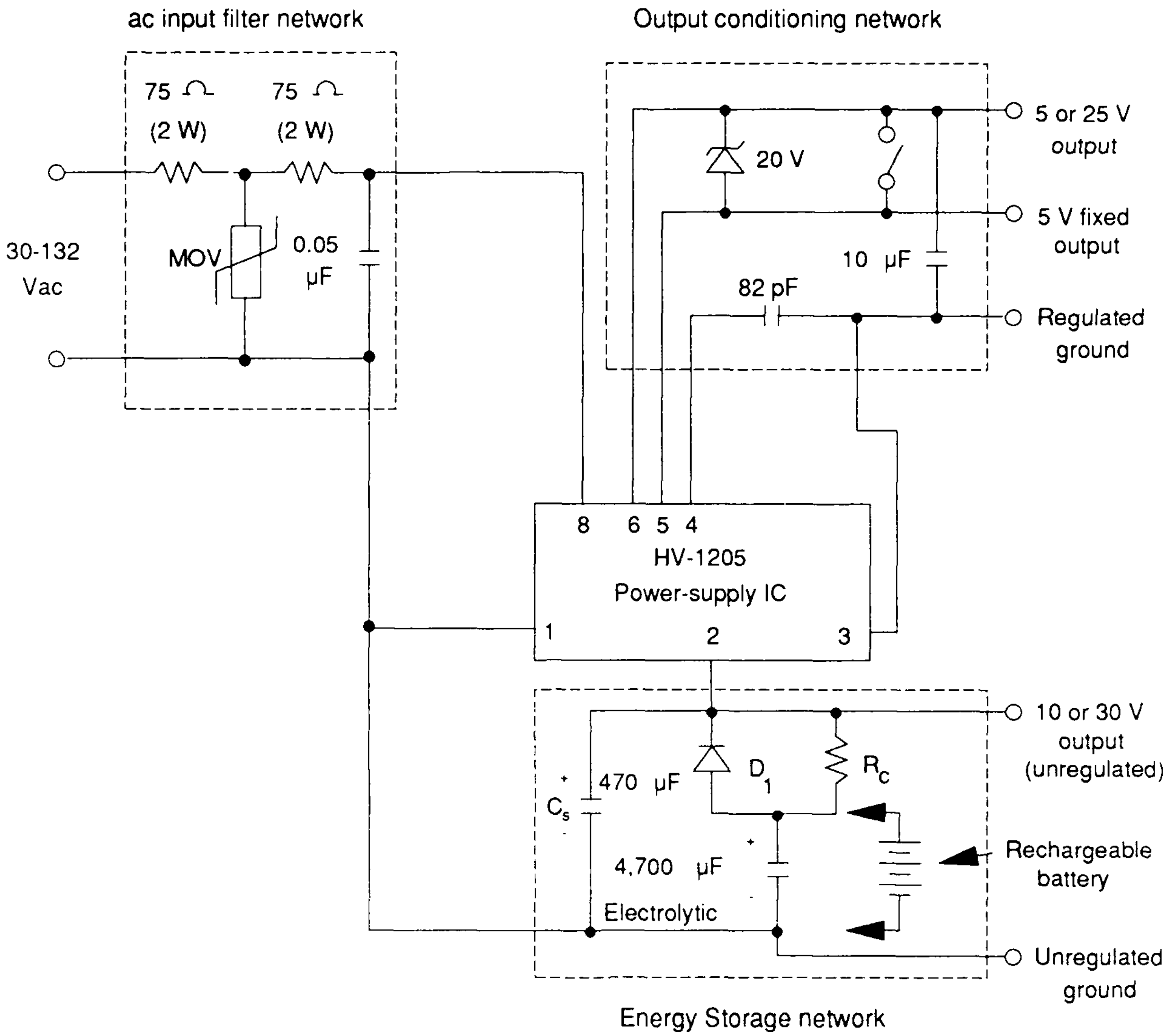


Figure 24

Reprinted from Bob Pospisil, and Clayton Bennett, "New Chips Transform Power Conversion." Machine Design, September 7, 1989, volume 61, number 18, p. 134.

4 Conclusion

Better power aberration term standardization would improve defining the problem. If everyone (user, medical equipment manufacturer, power conditioning/protection equipment manufacturer and utility company) used the same terminology it would improve communications in the field of power aberrations. IEEE has formed a working group to improve power aberration definitions and parameters. Cooperation among the various groups will go a long way toward improving communication and diagnosing the various power aberration problems. [6:143, 31:3-4]

In the past, power line monitors measured voltage threshold information about power aberrations. The monitors could provide the time of the occurance and the type of the event (sag or surge). If the duration and the rise time of the event could also be provided the possibility of locating the origin of the power aberrations would be enhanced. Newer power line monitors are beginning to provide rise time and duration of power aberrations. [31:3-4]

To achieve maximum effectiveness against power aberrations, one must match the solution with the particular type of problem. The clinical engineer should not totally discount the internal power protection within new microprocessor equipment. Remember, power aberrations travel near the speed of light. [21:145] A proper balance between internal and external power protection must be achieved. If the problem is grounding, a dedicated line or Power Distribution System (PDS) should be used. If the problem is regulation, the clinical engineer should consider using an U.P.S. or voltage regulation system. [7:35] Spikes, transients or surge problems can be handled by a surge suppressor.

The use of money now or in the future has a particular cost. The clinical engineer must consider the time value of money. A selected course of action has an opportunity cost and a risk associated with it. No action has the risk that the equipment will be damaged by power aberration problems. The opportunity cost when adding external power protection is the benefit or advantage lost by selecting external protection over another alternative. Engineering economic considerations are important. Both sound engineering practices and fundamental economic considerations are needed to develop a sound plan for power protection against power aberrations. [14:66, 24:1-2]

Dedicated power lines for microprocessor equipment have certain advantages/ disadvantages. If a clinical engineer has determined his/her particular power aberration is being caused by a grounding problem, then a dedicated power line with its dedicated ground line could just be the solution to the problem. Dedicated power lines are useful but a mandatory policy that all microprocessor equipment be on a dedicated line is not required.

A more important consideration is what other devices are on the feeder circuit with the microprocessor equipment. The placement of inductive motors on the same feeder circuit or very large inductive motors on the same circuit panel should be avoided. The use of low voltage starter circuits on inductive motors helps to reduce the effects of power aberration problems caused by these motors.

The clinical engineer should adopt a policy of placing surge suppression devices on feeder circuit at the distribution panel. The use of series surge suppression devices is more effective but more costly. By placing the surge suppression devices on microprocessor feeder circuit, the clinical engineer has developed an engineering practice that is effective against 88.3% of the typical power aberration problems experienced by a health care facility (See Figure 1). An U.P.S. is required when patient safety or the economic cost justifies the use. An U.P.S. is not a cure all solution to power aberration problems. They are very costly to purchase and maintain, and increase utility costs. The U.P.S. is the solution to particular power aberration problems.

The clinical engineer should review the health care facility's emergency power system.

He/she should ensure the unit(s) can provide adequate kVa and that the transfer switch is of the make-before-break type. A policy of synchronizing the generator with the commercial *ac* power line voltage is important. These considerations will help to reduce the power aberrations generated by the emergency power system.

The clinical engineer must understand that sound engineering practices along with proper consideration of the time value of money are the key ingredients for controlling (minimizing) power line aberrations. Knowing the source and type of power aberration allows for the proper corrective action and frequently at the least cost.

5 Appendix

5.1 List of Terms

Balance - A circuit is balanced when the current path to a common reference from a conductor is similar to the current path of the other conductor. The voltage drops are equal and opposite polarity thus, zero volts develop across the input signal and do not cause interference. Ratio of longitudinal voltage or current to the metallic voltage or current. [14:36-38]

Balance in Decibels (dB) - The balance/unbalance of equipment is often stated in decibels. By definition, dB is the level of power reference to one milliwatt across an impedance of 600 ohms. By definition, a decibel equals 10 log P_o/P_i where P_o equals output power and P_i equals input power. Decibels using voltages are 20 log V_o/V_i where V_o equals output voltage and V_i equals input voltage. [14:39-40]

Blackout - Any power outage, even if the condition lasts for only a thousandth of a second. Power companies consider this a power failure only when the condition lasts for at least three (3) minutes. 50% of all blackouts (total loss of power) last six (6) seconds or less. [5:84]

Bonding - permanent joining of metallic parts of a structure to form an electrically conductive path. The connection of the building assures electrical continuity of the building for ground purposes. [14:69]

Brownout - Condition when electric utilities reduce their nominal line voltage 10% to 15% because of demand during peak usage periods. [39:157] Also see Sags. See Figure 3.

Commercial grade power - Power as received from utility company power lines. [11:2]

Common-Mode signal - measurement of electrical disturbance between neutral and ground wires. [42:259,45:25] $V_{cm} = 1/2\ (V_1 + V_2)$ [15:382]

Dedicated Line - separate power line running from the main distribution box to a particular piece of equipment. This configuration avoids possible power aberrations caused by power equipment on the same power line but, does not affect power aberrations that the main distribution box experiences. An outstanding side effect provided by a dedicated line is a dedicated ground which avoids many common-mode problems. [11:7]

Electrical Protection - methods and devices used to control or reduce unwanted voltages and currents. Methods applied to the entire installation and the use of proven methods eliminate or reduce most undesireable longitudinal disturbances. Devices are considered supplements to the protection system [14:65]

Electromagnetic interference (EMI) - interference that travels electromagnetically through the air and when crossing the path of any conductor (power line), induces a current of like frequency and amplitude. [11:5] Typically, undesirable high-frequency noise (energy) created by switching transistors, output rectifiers, and zener diodes in switching power supplies. This high-frequency noise can radiate or conduct on electrical lines from the source to affect other electrical instruments. [39:159] Also see Radio Frequency Interference (RFI). See Figure 3.

Ground-fault protection system - on a three phase power system, current is measured on all phases and neutral conductor to ensure sum of currents provided to the load equals the sum of the currents leaving the load returning to the transformer. If the two sums are not equal (amount of current difference and time period of current difference is established by the values set by the user) an appropriate breaker is tripped to prevent arcing faults known as "*burn downs*". [30:6-7, 47:6]

Impedance - Real part of impedance is resistance while imaginary part is reactance. [17:426]

Line Regulation - The deviation of the output voltage as the input voltage varies, with all other factors held constant. Term is expressed as the maximum percentage change in output voltage as the input voltage is varied over its range. [39:162]

Load Regulation - Deviation of the output voltage as the output's load changes from no load to full load, with all other factors held constant. Expressed as a percent of the nominal *dc* output voltage. [39:162]

National Electrical Code (N.E.C.) - Code of rules and regulations as recommended by the National Fire Protection Association and approved by the American National Standards Institute (ANSI). This code is frequently accepted as minimum standard for electrical installations by many political entities as their official code, or has been incorporated in whole or in part in their official codes. [17:211]

National Electrical Safety Code - Rules prepared by the National Electrical Safety Code committee (secretariat held by the IEEE) and approved by the American National Standards Institute governing: (A) Methods of grounding, (B) Installation and maintenance of electric-supply stations and equipment, (C) Installation and maintenance of overhead supply and communication lines, (D) Installation and maintenance of underground and electric-supply and communication lines, (E) Operation of electric-supply and communication lines and equipment (Work Rules). [17:211-212]

Noise - Any high frequency signal modulating onto the voltage sine wave. FCC controls the amount of noise computer equipment can place onto power lines and into the environment. The noise is technically referred to as Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI). [11:4-5] Also see Electromagnetic Interference and Radio Frequency Interference. See Figure 3.

Normal-Mode - measurement of electrical disturbance between live and neutral wires. [45:25]

Opportunity Cost - The cost incurred in choosing a particular course of action. The cost is the loss in benefits and/or advantages of the choice not selected.

Overvoltages - last from a few to several *ac* cycles. (One *ac* cycle is 16.6 milliseconds, whereas a 20 microsecond transient is almost 1,000 times shorter.) During longer durations, the disturbance produces enough heat to blow fuses, trip circuit breakers, and tend to be destructive in nature. [11:5] See Figure 3.

Power Conditioning - All technologies and methods that help to clean and stabilize commercial *ac* power. [11:2] Power line aberrations are "*conditioned*" (corrected/ smoothed-out). Power conditioning does not provide uninterruptibility (no protection against blackouts, extended periods of brownouts, sags, or total failure of the utility power system). [36:89]

Power Failure (electric power system) - Variation in electric power supply which causes unacceptable performance of the user's equipment. [17:513]

Power Protection - protects (maintains) the quality and quantity of *ac* power line under all power aberrations, even blackouts. Power protection is a broad term that encompasses power conditioning. [36:89]

Power System, emergency - An independent reserve source of electric energy that upon failure or outage of the normal power source, automatically provides reliable electric power within a specified time to critical devices and equipment. The failure of critical devices and equipment to operate satisfactorily could jeopardize the health and safety of personnel or could result in damage to property. [17:520]

Power system, standby - An independent reserve source of electric energy that upon failure or outage of the normal source, provides electric power of acceptable quality and quantity. The system allows the user's facility to continue satisfactory operation. [17:520]

Radio Frequency interference (RFI) - frequency range and nature of this noise. Covers a spectrum, from a few thousand cycles per second (5 KHz) to several hundred million cycles per second (800 MHz). High frequency noise is induced onto the voltage sine wave by switching power supplies. [11:5, 39:159] See Figure 3.

Regulated Power Supply - constant output voltage maintained by sensing output and automatically compensating to minimize effects of input change. [39:9]

Risk (Expected Value) - Choosing a course of action involves risk. The future cannot be predicted with absolute certainty. The clinical engineer must weigh the advantages/disadvantages of each proposal and determine a probability of outcome. Based on a determination of risk, he/she makes a selection of action to obtain the greatest return of value. [24:2]

Sags - opposite of a surge. An undervoltage condition that lasts for approximately 2-3 cycles. Often called a "*brownout*" because it causes lights to dim for a half-second. Can cause disruptive malfunction if they are deep enough and long enough to starve *dc* power supplies. Malfunction is often associated with the transients generated by the same disturbance that caused the sag. As the power recovers, the voltage overshoots as a high-voltage transient. Brownouts are usually not destructive to hardware, but frequently cause loss of data. [11:5] See Figure 3.

Sneak Current - a small current that is insufficient to trip circuit breakers or open fuses but given sufficient time can cause damage to equipment. [14:72]

Source impedance - the impedance at an input of a device or network as presented by a source of energy. [17:428]

Sparkover - a discharge between electrodes of a measured gap, voltage control gap, or protective device. A general meaning referring to surge arrestors. [17:14 and 857]

Spikes - occur in short bursts, or even singularly. Causes line voltage to rise sharply from a few hundred to several thousand volts. Voltage frequently returns to normal in less than 8 milliseconds (8×10^{-3}). Spikes are frequently destructive to electronic equipment. Usually caused by extremely close lightning strikes or catastrophic disruptions within the power system. [11:3] See Figure 3.

Static Electric - excess or deficiency of electrons on a surface. Two materials that are typically poor conductors or insulators come in contact and separate. The contact (friction) allows a transfer of electrons between the objects which establishes a difference in potential. This difference in potential will attempt to equalize. [14:19-21]

Surge - This term is used to cover everything from overvoltage to transients. Typically refers to a broad spectrum of power disturbances. [11:5] The power aberration is superimposed on the normal sinusoidal wave form and reference to ground. [14:71] A transient wave of current, potential or power in an electrical circuit. [17:961] See Figure 3.

Time Value of Money - Concept takes into consideration the fact that the value of money changes over time. The use of money has a cost now and a different cost if used in the future. For example, the use of the money now prevents the same amount of money from earning interest in a bank account. The cost is the lost interest. The use of the money on a particular project prevents the use of the same money on a different project. The cost is the benefit of the project that is not funded. [24:1]

Transients - fast spikes that last only a few microseconds but can rise to peak amplitudes of several thousand volts within a few nanoseconds and decay away within several microseconds. Transients can force or find their way through *dc* power supplies and into electronic circuits. This has become a problem only in recent years because previous technologies such as vacuum tubes and even transistors were not as susceptible or vulnerable to transients as integrated circuit (IC) technologies. [14:3-4] See Figure 3.

Transverse-Mode Rejection - refers to radiation-induced interferences. Has no significant effect on power distribution aberrations within a building. [6:143]

Uninterruptible Power Supply System (U.P.S.) - fast acting emergency power system that provides no break in power. [21:145, 5:84] Isolates the critical load and supplies clean, reliable, uninterrupted power while protecting the load from commercial power aberrations. [36:89]

5.2 Points to consider when purchasing an Uninterruptible Power System (U.P.S.)

____ 1. General requirements:

a. Power Conditioning versus Power Protection.

1. Power conditioning protects (maintains) the quality and integrity of the power line. Power conditioning does not provide protection against blackouts, brownouts, sags or total failure of electric power systems. [36:89]

2. Power protection protects (maintains) the quality and integrity of the *ac* power line. Power protection does provide protection against blackouts, brownouts, sags, or total failure of electric power system. [36:89]

b. On-line versus off-line (standby) power system.

1. Off-line (or standby) power system is inappropriate to protect microprocessor type equipment. A time lag will occur between loss of power and the switch to back-up power system. [9:26] Off-line U.P.S. operate only during power failure (notch conditions or undervoltage periods). Once a power failure is detected, the U.P.S. begin to provide power to the load. The U.P.S. unit provides protection only during periods of undervoltage or notch conditions. [44:98-99]

2. On-line power system provides full-time power protection by isolating the dependent load from power fluctuations. During brownout and blackout conditions a constant flow of power continues to the dependent load. [9:26] On-line U.P.S. converts *ac* to *dc* (battery) and then back to *ac* by using an inverter or engine-generator. Theoretically, this type of U.P.S. eliminates all types of power aberrations (noise, undervoltages, and overvoltages). [44:98-99]

____ 2. How to choose between Power Conditioning versus Power Protection.

a. The worst possible power aberrations are total loss of power, insufficient power from utility company (brownout condition) or sustained sags when the equipment serviced by the *ac* line shuts down. [36:89] Ask yourself, what are the possible effects (safety/lost test results) on the patient? What are possible effects on the equipment hardware?

b. Call or if possible visit users of protection/condition equipment. Compare problems and review types of power processing (conditioning/protection) employed. [36:89]

c. Discuss power protection/conditioning methods with the manufacturer of the microprocessor medical equipment. Sometimes power conditioning techniques are not compatible with the protected equipment. [31:10]

____ 3. How to specify the size of an U.P.S. system.

a. Determine kVA size rating for the system to be protected. If the protected equipment includes computer equipment, be sure to include terminals, printer(s) and CPU for protection by the U.P.S. system. [5:89]

b. Consider start-up power requirements or possibly periods of high power demand rather than total normal operating power for kVA size rating. [5:89] This feature is called *ac walk-in*. Can the U.P.S. handle the start-up power requirements directly or must it temporarily use commercial *ac* line power directly? [5:87]

c. Emergency lighting should be considered in total kVA size rating. If the U.P.S. is intended to carry the load only until an orderly shutdown can by accomplished, then minimal lighting is required for safety. [5:89]

d. If possible, try to exclude air-conditioning or other things from the total kVA size rating that can wait until a generator can take over or commercial power is restored. This will reduce the cost of the U.P.S. system. [5:89]

e. For maximum efficiency, an U.P.S. system should operate at or near full-load rating. When operating at or near full-load rating the efficiency is approximately 80-90% while only 65-70% when operating at 50% load rating. The lighter load increases heat production by the U.P.S. system. Special consideration should be given to expandability of the U.P.S. system and user's future power protection demands. Oversize of the U.P.S. system would allow future expansion at a cost of increased operation in the near term. [36:91]

f. Battery Recovery time. Avoid manufacturers that require a set minimum recharging time (typically 8 hours). Instead, select manufacturers that specify a recharge factor (typically 8-15) times the discharge period. [5:84 and 87]

____ 4. How to specify the *ac* input service line.

a. The *ac* input service line should be sized for approximately one and one-half of the U.P.S. total kVA rating. Following a power failure (and the return to commercial /standby power), the U.P.S. system will draw power to satisfy the load and to recharge the batteries simultaneously. [5:89]

b. The following items/information are recommended to be placed in the contract:

1) User's service line voltage
2) User's service line amperage
3) User's service line frequency
4) User's service line wire configuration
5) Minimum power factors and harmonic feedback rectifier (U.P.S. 's) presents to operator's *ac* line [5:89]

____ 5. How to determine battery time requirements.

a. If required kVA reaches 50 and/or desired standby time required on batteries exceeds 30 minutes, consider cost tradeoff by using an engine-generator. [5:89]

b. If an engine-generator is used, recommend the following order of equipment along *ac* lines:

1) engine-generator
2) U.P.S. system
3) load

This configuration allows the U.P.S. system to provide power regulation regardless of type of power available. [5:89]

____ 6. How to select the input transfer switch to connect the generator output to *ac* line.

a. Numerous types of input transfer switches are available. This switch determines the length of time a blackout must last before the generator starts-up. Remember the average blackout lasts less than six (6) seconds. [5:89]

b. Make-before-break versus conventional transfer switch. Make-before-break transfer switch generally does not exhibit a voltage drop upon transfer or retransfer (during generator switching) while conventional switches often cause some type of drop. [45:25]

____ 7. Specifications to consider. Be sure to specify performance rather than design parameters. Try to use off-the-shelf equipment rather than modified equipment to meet your contract specifications. [36:89-90] Example of specifications:

a. Computer equipment contains high-frequency switching power supplies that exhibit a leading (capacitive) power factor. Will the U.P.S. equipment perform in all phase loading and unbalance line conditions? [36:90]

b. Consider the maximum ambient temperature limit of the U.P.S. system. Compactness of the U.P.S. system may increase the cost of serviceability and/or reduce the maximum ambient temperature limit. Depending on the maximum ambient temperature limit additional air conditioning for the U.P.S. system may be required thus reducing the efficiency of the U.P.S. system. [36:90]

c. After use of the standby batteries, how quickly do they fully recharge? Does the U.P.S. system allow for future expansion? [36:90]

d. Given IEEE conditions, an U.P.S. should reduce all electrical noise levels to less than 10 volts normal-mode and less than 1/2 volts common-mode.

e. If the equipment item to be protected has a switching power supply, ensure the U.P.S. will allow the equipment item to draw current as required.

f. Is the U.P.S. waveshape acceptable to the load? [44:99]

g. Ensure the system (U.P.S. and load) has a single-point ground. This will prevent a difference of potentials between different components. The single-point ground will prevent ground noise and ground loops. [7:35]

h. Ensure an automatic bypass/transfer switch is included. In the event of an U.P.S. failure, the load (computer) could be automatically connected directly to the commercial *ac* power line enabling continuous operation. Once the U.P.S. problem is corrected, the bypass/transfer switch will require manual activation to return the load (computer) to the U.P.S. . [5:86]

___ 8. Misconceptions to avoid.

a. The more the protection costs, the better the protection. **Wrong!** Increased cost does not mean a better chance of eliminating computer and electronic equipment problems. The goal is to achieve reliable equipment operation at the lowest cost (equipment and operation) without power conditioning/protection overkill. [11:3]

b. U.P.S. can provide a false sense of security. If power reliability is 99% and the U.P.S. has a 99% reliability, then the system's new reliability is 98%. A decrease of system reliability. [44:99]

5.3 Effects of 60 Hz Current on Humans

Current (mA)	Effect
1 - 7	Sensation of Shock Muscle Control not lost
8 - 15	Painful Shock Muscle Control not lost
16 - 50	Painful Shock Muscle Control lost Breathing becomes difficult
51 - 100	Very Painful Shock Possible ventricular fibrillation
101 - 200	Ventricular fibrillation (Heart loses its rhythm)
over 200	Heart stops beating and severe burns are possible

Table 10

Reprinted from Norman H. Haskell, Jr., P. E., Surge Protection of Electronics, (South Carolina: Continuing Engineering Education College of Engineering) p. xiii.

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