3

Power Quality

Power quality is one issue we are hearing more about since poor power quality costs money. Let's look at some direct and indirect costs attributed to power quality.

Direct cost is the loss of production due to a voltage problem, which trips a motor or other device and stops the manufacturing process. It is the loss of the items not produced, the cost of removing any damaged materials and the labor charges paid to employees waiting for the process to restart.

Indirect cost is the replacement of equipment that was stressed by changing electrical voltages. For example, a solid-state motor drive failed because of voltage spikes. These are commonly caused by power factor capacitors switching on and off the line to correct varying power factors. However, the failure and subsequent damage to the machine is not caused by any one spike but by numerous spikes occurring over a period of time.

What is power quality?

Power quality is the measurement of how close to perfect an electrical voltage is at any given time or point. High quality electrical voltage is a sine wave that measures exactly what is expected in both voltage and frequency. A high quality electrical source is one that can deliver all the electrical energy needed without any change in the voltage. In the past, responsibility for power quality was thought to be the power companies problem but that isn't really true. In almost every case, the circumstances that impact power quality are outside of the power companies' control.

Historically, most power quality problems were considered to be those things that affected the distribution of power. Lightning, line or transformer failures and/or very high electrical demands (brown outs) on the electrical network are just a few. Today, however, most power quality problems are due to technology changes and the way the electricity is now used.

In the 1990's, we in the Power Conditioning and Power Quality industries have if not a new set of challenges, at least an expanded set of problems to deal with. The expanded role of computers and the dependency on electrical equipment, which is subject to power quality problems for productivity improvement and cost reduction, has forced those of us specializing in large critical power protection systems to look into the demands placed upon us by the users of our equipment and services. From our prospective, we see several facts that will force changes in the technology/topology of power protection systems.

The role of power conditioning systems in the past was to protect our customer's equipment from power quality problems that occurred external to their facility. Today we must also deal with power quality problems caused by their own equipment.

While power requirements are decreasing for individual pieces of equipment, the electrical distortion caused by the newer, more efficient power supplies degrade the performance of the electrical system both inside and outside the facility. Utilities are unable to provide the high quality and reliability in electrical power required to meet the ever increasing power quality standards of newer equipment.

In the 1970's and 1980's, the problems were most felt in large data centers using sensitive computers. Power quality problems were addressed with Uninterruptible Power Systems (UPS), Power Distribution Units (PDU) and on site Power Generation (APS). In the 1990's, these problems have increased and moved into factories, offices and anywhere solid-state devices are used. The question now is "Can these systems deal with the new types of critical load?" In many cases the answer is, "Not without minor, and in some cases, major design changes."

The issues are becoming more technical and much harder to explain to the non-engineer. In this chapter we will explain the problems associated with harmonics.

Nonlinear Loads

Nonlinear loads cause harmonic distortion, which is the newest problem and the most difficult to explain. Before we begin, let's establish some background on electrical power.

Electrical power in the United States is supplied at 60 hertz (Hz) and is produced by rotating generators. The prime mover for these generators can be hydro (water), steam from coal, oil or nuclear. In all cases, the prime mover changes one type of energy into rotational energy (torque). This rotational energy is then applied to the generator, which turns a magnet in an electrical field. The speeds that the magnet turns determine the frequency of the electrical voltage produced. In the U.S., it is 60 turns each second or 60 Hz. In other countries it may be 50 turns a second (50 Hz).

Each cycle or turn produces a voltage that starts at zero volts and increases to some maximum positive value at ¼ of a revolution (90°) and then decreases back to zero volts at ½ a revolution (180°). It then increases in a negative direction to a maximum value of ¾ revolution (270°), then decreases back to zero one complete revolution. This is one cycle and is repeated 60 times each second. The voltage waveform is a sine wave (see figure 1) and contains 360 electrical degrees (a circle).

With a linear load, the current drawn by the load is dependent on the voltage. A linear load is also known as a resistive load. Some examples of resistive loads are heaters and lights.

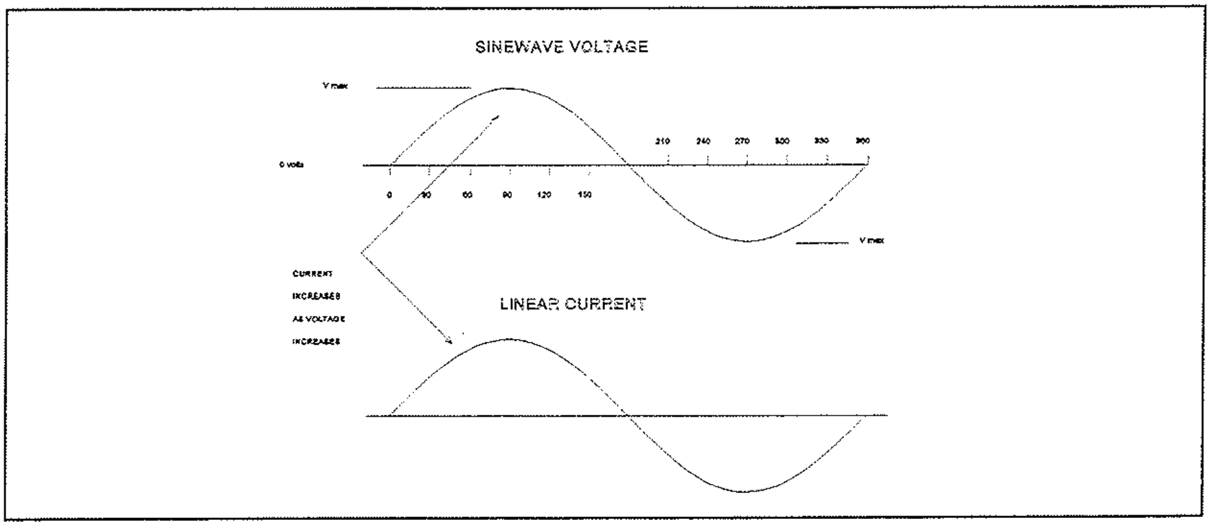

Figure 1 Linear Utility Sine Wave

Each cycle of the generator produces a voltage that varies from zero to maximum. As the voltage increases, the current increases. Think of a dimmer. As you turn the dimmer up, you are increasing the voltages to the light. The increase in voltage causes more current to flow and the light to brighten. If you turn the dimmer the other way, the voltage and current decrease and the light dims. This is a linear response, which is another way of saying the current (light) is a direct response to the amount of voltage.

In the past, most electrical loads were linear loads. This is what made "brownouts" attractive to utilities. If the power company reduced the voltage, the current would decrease as would the total power they demand.

This brings us to *nonlinear loads*. A nonlinear load is when the amount of current the equipment draws from the utility is not dependent on the utility voltage. One of the very first large nonlinear loads in common use was the static UPS.

The job of the UPS was to provide regulated output voltage to the critical load. When the utility decreased the voltage, the UPS had to compensate. This was accomplished by demanding more current as the utility lowered the voltage. This type of operation is known as a constant kW. One of the key elements of a UPS is to make sure the load never sees a brownout.

The way a UPS compensates for low voltage is to place a very high speed switch between itself and the utility. In large systems, the switch is a SCR, which turns on when the available power is equal to the power required by the load. If the input voltage decreases, the SCR turns on earlier for longer and draws the same amount of power. If there is not enough power, then the UPS uses a battery to make up the difference. In smaller systems, transistors are used in place of SCR's but work the same way.

The nonlinear response just means that the power varies with the load and not the voltage. In a UPS system, and many other high powered nonlinear loads, the switching of the SCR only happens once each voltage cycle.

Switch Mode Power Supplies

One of the major advances in power supply design is the switch mode power supply. These new devices cost less, use less power and cause problems. To understand why switch mode power supplies are a problem where older supplies are not, some background on power supplies is necessary. In this section we will explain the differences in the older power supplies as it compares to the power supplies in use today.

The first generations of power supplies were linear. The basic schematic is shown below. A power supply has one purpose, which is to convert the alternating current (AC) furnished by the utility to a direct current (DC) used by the system in which it is installed. A linear supply had four major sections. The first section is the transformer, which will step down (change) the supply voltage to a lower voltage for the computer logic. Typical transformers reduced the 120 VAC supply voltage to 24 volts AC.

The transformed voltage is then sent to rectifiers (diodes) in the second section to convert AC to DC. The DC voltage still had an AC ripple. The rectified voltage was then filtered by the third section to make it usable by the logic. The final filtering of the raw DC voltage was accomplished by the capacitor shown above. The capacitor smoothed the rectified utility voltage to logic grade DC voltage. Logic will not operate correctly without a stable regulated DC supply voltage.

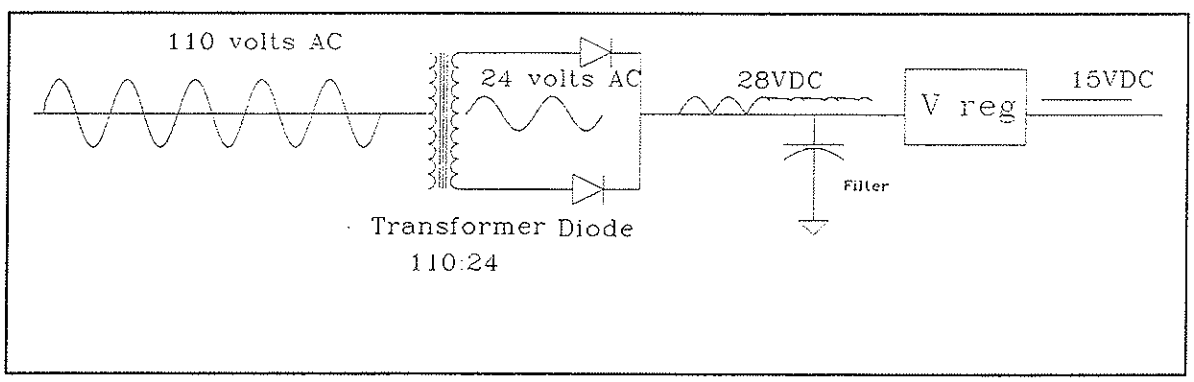

Figure 2 Linear Power Supply

The forth section of the power supply is the voltage regulator. The voltage regulator is a device that compensates for varying supply voltages from the utility. The power tolerance of early computers allowed correct operation from a voltage source, which varied from 8% low to 6% high. These variations were common due to changing demands on the utility. Peak loads during air conditioning and heating seasons will cause voltage sags and surges.

The voltage regulator can be looked at the same way as an air regulator on a diver's tank. The diver carries high pressure air in a tank on his back and the regulator reduces the pressure to a level that the diver can breathe. If there were no regulator, the high pressure would cause the diver to explode. The voltage regulator operates the same way. The high DC output from the rectifiers is reduced to a comfortable level for use by the logic. If unregulated DC voltage were given to the computer's logic, it would fail.

The term *linear* refers to the response of the power supply during input voltage changes. When the input voltage changes, the DC output of the rectifiers will increase or decrease the same percentage as the supply voltage. If the supply voltage increases too much, the raw DC voltage at the input to the regulator can exceed the ability of the regulator to protect the logic from high voltages.

The voltage regulator reduces the unregulated or raw DC to the logic voltage by acting as a valve. For the regulator to operate correctly, the input voltages must always be several volts higher that the logic voltage. In this example, the logic voltage is fifteen volts and the raw DC voltage is 28 volts. For the regulator to work correctly, the input

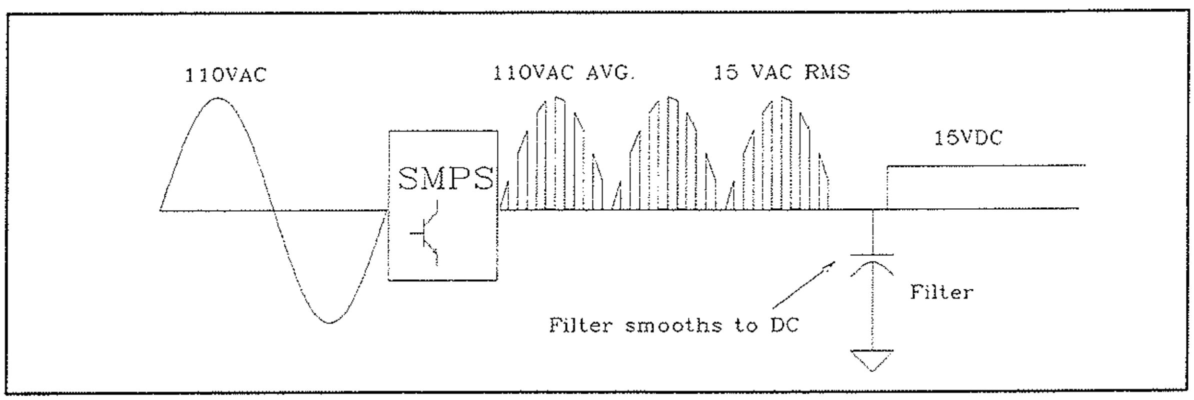

Figure 3 Nonlinear Power Supply

must never fall below 18 volts.

With a minimum DC input voltage of 18 VDC and a voltage tolerance from +6 to -8%, the power supply will operate with a voltage swing of 11%. This means that the 110 VAC nominal input can vary from 116 VAC to 101 VAC without a problem. If normal variations are greater than the 11%, a data center will have to install power conditioning. In the first computers, this was the typical power supply and there were problems. The linear supply produced heat and was slow responding to voltage changes. The transformer and voltage regulator both generate heat that could damage the computers' logic if the room was not kept cool.

Advances in voltage regulators and power switching devices made major improvements in the late 1970's and revolutionized the power supply field. As you see in Figure 3 above, the power supply was greatly simplified. The transformers were removed and the voltage regulator was combined with the rectifiers.

The operation was based on the principals that power and <u>not</u> voltage could be regulated. If you will accept that voltage is the same as pressure and current is the same as flow, then power can be looked at as volume. Power is the amount of energy that is used the same way as the amount of water is controlled by the water pressure and how long you open the valve. The higher the voltage (pressure), the more electrons flow (current) and the more energy used.
The new switch mode power supplies operate without a transformer by opening a valve (switch) and letting pluses of current enter the power supply. The switch will turn on several thousand times each second, which greatly improved the ability to respond to changing input voltages. The power supply switch now has many chances to correct the output voltage each cycle. The linear power supply could only react 60 times each second, or once each cycle. The time the switch is on is very short relative to the length

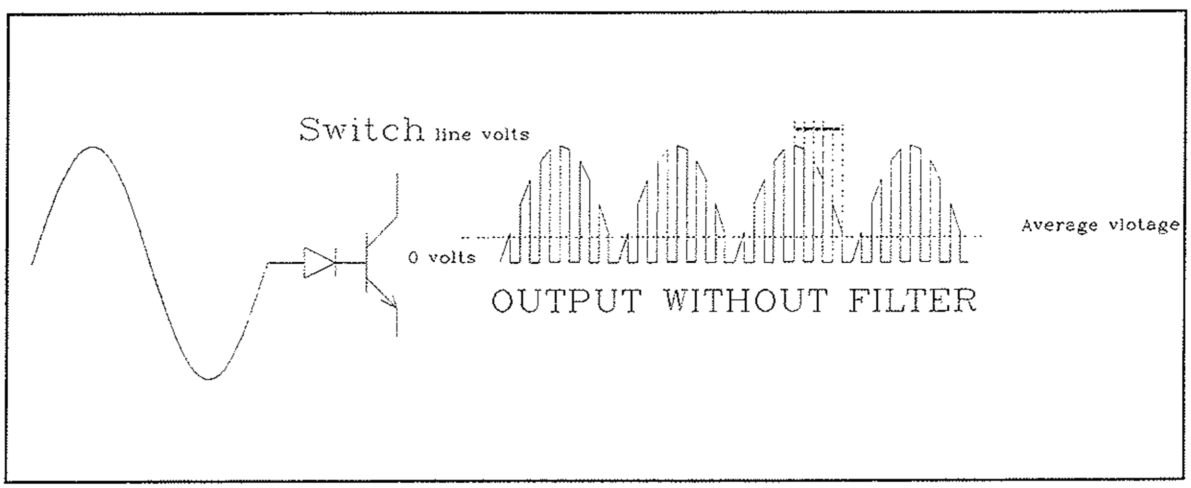

Figure 4 SMPS unfiltered output

of the cycle.

Figure 4 shows a typical output from the switch mode power supply without any filtering. When the switch is on, energy is taken from the source and the voltage increases to the line voltage. When the switch is off, the voltage drops to zero. The addition of a filter allows the power supply to averages out the on and off times to smooth DC voltage for use by the computer's logic. The end result is a power supply that does not need a transformer and can adapt to a wide range of input voltages. The

SMPS can adjust the "on" time of the switch to a longer period when the line voltage is low and a shorter "on" time when the line voltage is high.

Switch mode power supplies solved many of the problems that computers suffered with linear power supplies. However, there are problems with electrical systems and power conditioners associated with switching power supplies. The power taken from the electrical source is not drawn evenly. The pulses (on time) occur many times each cycle, at a higher frequency than electrical generators used by the power companies.

The number of "on" periods is known as the pulse repetition rate, and the time the switch is on is the pulse width. The repetition rate is normally at some multiple of the line frequency. This allows an even number of pulses each cycle. The term harmonic refers to the specific multiple of the line frequency that the current is drawn from the source. Figure 6 on the next page depicts how the third harmonic (180 Hz) has three cycles for every one cycle of the fundamental (60 Hz). The seventh harmonic (420 Hz) has seven cycles for every one of the fundamental. If the power supply turns its switch on seven times each cycle, the supply draws' currènt (power) at the seventh harmonic. The effect of high frequency power supplies is to strain the electrical system. Transformers, circuit breakers and other electrical devices are designed to operate at a specific frequency. If you look at any piece of equipment, it will have a voltage, frequency and power rating listed on the manufacturers' name plate. When transformers, circuit breakers, UPS and other systems are asked to supply nonlinear currents, their operation can be different from expected.

In the U.S., the National Electrical Code (NEC) defines the correct (safe) way that electrical systems should be installed. The Electrical Code Board and electrical engineers assume that the electrical systems we connect to the power system are linear and not high frequency. In the next few years there will be many changes in the code caused by the changes in power supplies, both in data centers and other areas with electronic systems.

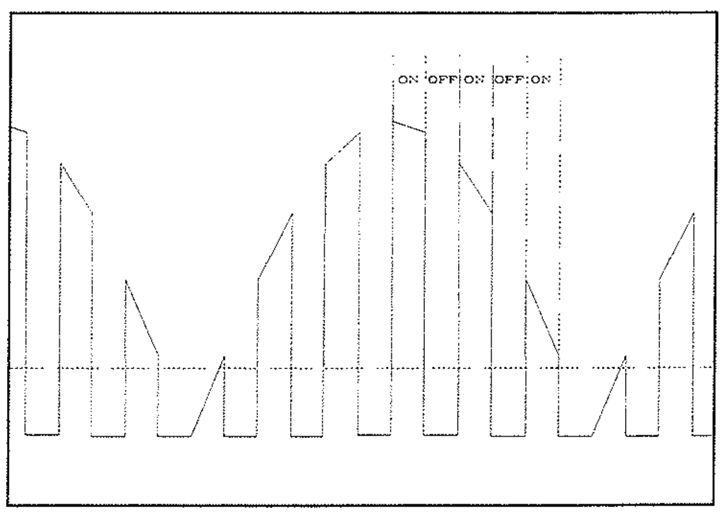

Figure 5 SMPS Output

The most noticed effect of the high frequencies is heating. The heating occurs in the wires, conduits, circuit breakers and transformers. In data centers, some of the more common problems have been neutral conductors failing, unexplained opening of circuit breakers and transformer failures.

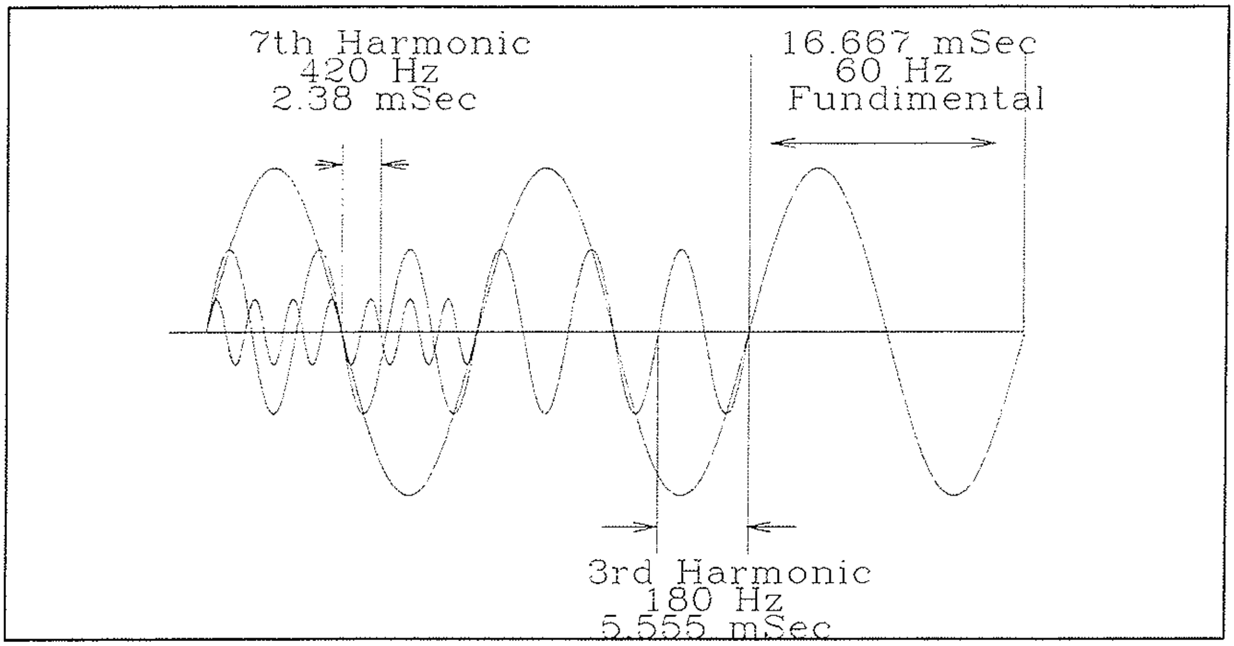

Figure 6 Harmonics

In the power conditioning industry, we have started to see a common problem. Data centers with power distribution units are running out of places to plug in additional systems. They are running out of pole positions. This shows that the new, smaller devices are filling the power system but not the computer room. This mean that the transformers are running at their design limit. The pulse currents cause a problem different problem than just the high frequency issue.

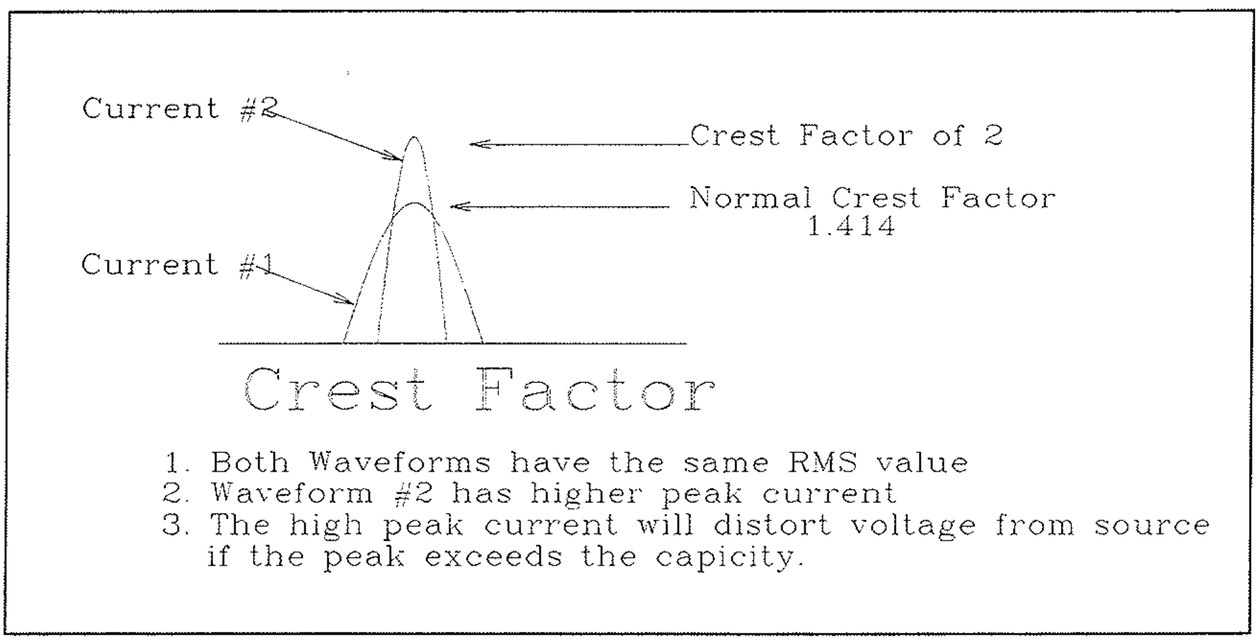

Figure 7 Crest Factor

When a switching power supply takes pulses of current and several power supplies all turn on at the same time, peak currents can be very large while the average current can be seen by standard metering as within the capability of the power system. The term that defines the peak current (power) is a crest factor.

Figure 7 shows two waveforms. The first is a normal current that most power systems expect, and the second is a pulse that is shorter in time (smaller at the base) but higher in peak. Both waveforms have the same amount of power but one stresses the electrical system more than the other.

Power Terms

Sine Wave	-	The normal waveshape of a generator produced voltage.
Peak	-	The maximum amplitude of the waveform.
Average	-	The average of the sum of the instantaneous peaks of the waveform.(0.637 x Peak in sine wave)
RMS	-	The effective or heating value of the waveform, the amount of work.(0.707 x peak in a sine wave)
Crest Factor	-	The ration of the peak to the RMS value of the waveform.(the peak or maximum current required)
Skin Effect	-	The tendency of electrons to travel on the surface of a conductor at high frequencies.
Impedance	-	The AC resistance to the flow of current.
Linear Load	-	A load that consumes power in an amount directly proportional to the voltage applied to the system.
Nonlinear Load	-	A load that consumes power independent of the voltage applied to the system.
Harmonic	-	A multiple of the line frequency
Harmonic Distortion	-	The distortion caused by currents drawn at frequencies higher that the line frequency.