# TRANSIENTS AND HARMONICS

## INDEX SHEET

## I. INTRODUCTION

How can one be sure that equipment is adequately protected from transients? There is no simple cookbook method, but one must start with an assessment of the transient environment. This may be based on overvoltage categories as defined in standards. Since past experience may not be sufficient because of changes in technology, actual measurement of the transient environment with monitoring equipment may be necessary in some cases.

Electrical equipment is designed to National and/or International standards which define the overvoltage categories or Basic Impulse Insulation Levels (BIL)[1]. In most cases this is for a "normal service" installation. A more severe transient environment may require a product with higher ratings or more protection. This protection can be internal or external devices offered as an option. The goal is to minimize the risk of damage or malfunction due to transients. In this way transient protection devices are analogous to the automotive seat belt for protection; the seat belt will offer a certain level of protection in a crash (transient). If additional protection is desired, an "air bag" may be installed as an option.

The purpose of this paper is to discuss the terminology of transient protection and the state-of-the-art devices. The references at the end of this paper provide additional information on the detailed application and characteristics of these devices.

(1) IEEE definition: Reference insulation levels expressed as the impulse crest value of withstand voltage of a specified full impulse voltage wave. Nominal 1.2 x 50 microsecond wave.

## II. DEFINITION OF TRANSIENT

The IEEE Dictionary of Electrical and Electronics Terms defines transient as follows:

"A change in the steady-state condition of voltage or current, or both... The frequency, damping factor, and magnitude of the transients are determined by resistance, inductance, and capacitance of the power and control circuits and the degree of coupling. ... Transients may be caused by a lightning stroke, a fault, or by switching operation..."

The word "surge" is frequently used as a synonynm for transient. In fact, the IEEE has a subcommittee on Surge Protective Devices (SPD) and many authors and manufacturers specify surge protection rather than transient protection.

### A. Repeatable Transients

A sudden change in the electrical conditions of any circuit will cause a transient voltage to be generated from the energy stored in circuit inductance and capacitance. The rate of change in current (dI/dT) in an inductor (L) will generate a voltage equal to L(dI/dT), and it will be of a polarity that causes current to continue flowing in the same direction.

It is this effect that accounts for most switching-induced transient overvoltages. It occurs as commutating spikes in power conversion circuits, when switching loads, and under fault conditions. ...However, the simple effect of a switching operation can be repeated several times during a switching sequence (consider arcing in the contact gap of a switch), so that cumulative effects can be significant.

### B. Random Transients

Frequently, transient problems arise from the power source feeding the circuit. These transients create the most consternation because it is difficult to define their amplitude, duration, and energy content. The transients are generally caused by switching parallel loads on the same branch of a distribution system, although they can also be caused by lightning. Communication lines, such as alarm and telephone systems, are also affected by lightning and power system faults.

The importance of the last sentence cannot be overemphasized because many installations have protection only on the incoming power lines. Equipment also needs transient protection on the communication, control and sensor lines connected to the assembly. This area only recently has received the attention it deserves with surge protection devices for industrial and commercial equipment.

## III. SOURCES OF TRANSIENTS

### A. Switching Transients

Energizing a motor can generate transients because inductive and capacitive circuits do not like to be interrupted instantly, while modern high speed switching equipment attempts to do so. NEMA suggests voltage limiting resistors across high speed breaker contacts to lower surge crest values.

Jogging motors, particularly when power factor correction capacitors are on the circuit, is another surge producer. Capacitor switching, which is much more common than it was years ago, can cause dangerous impulses.

Vacuum contactors, for highly corrosive environments and high duty cycle applications, accomplish current interruption within the bottle very rapidly. This minimizes the arcing energy and permits the use of relatively small, sealed devices. Unless properly controlled, the arc extinction can be too fast and the current interrupted, or chopped to zero, before natural current zero. This could cause undesirable voltage surges, as high as ten times rated voltage, when the chopped current is a few amps or greater.

While controlling chopped currents to less than an amp for motor controllers was a challenge in the past for vacuum bottle designs, the present state of the art has removed this problem for most manufacturers. It is necessary to coordinate the interrupting rating of the vacuum bottle with current limiting fuses for fault protection in motor controllers.

Circuit breaker vacuum bottles require a high interrupting rating to clear branch circuit faults. The chop current will be relatively high. Consequently, surge protection is usually required to limit voltage transients within the circuit breaker. New design techniques are also lowering the chop current of the vacuum bottles for circuit breakers.

Current limiting fuses, because of their speed of operation, can produce very high voltage spikes. When a current limiting fuse is called upon to operate under a high fault current condition, the fusible element will be transformed quickly from a metallic conductor of low impedance to a long highly restricted arc of very high resistance. This produces a current forcing action to reduce the current to a much lower value than what would occur if the fuse were not in the circuit. The sudden change of current in this circuit inductance produces an arc voltage across the fuse of a magnitude greater than the circuit voltage.

System switching transients can be divided into four categories.

1. Transients associated with major power system switching disturbances, such as capacitor bank switching.
2. Transients associated with minor switching near the point of interest, such as turnoffs of an appliance in a household or of other loads in an individual system.
3. Transients associated with resonating circuits associated with switching devices, such as thyristors.
4. Transients associated with various system faults, such as short circuits and arcing faults.

An example that could cause a switching transient would be a fast acting current protection device such as a current limiting fuse or circuit breaker capable of arcing times of less than 2 microseconds. These devices leave trapped inductive energy in the circuit upstream. When the field collapses, high voltages are generated.

Transient overvoltages associated with the switching of power factor correction capacitors have lower frequencies than the high frequency spikes described above. Their levels, at least in the case of restrike free switching operations, generally are less than twice normal voltage. They should not be disregarded.

Switching operations involving restrikes are another example. Air contactors or mercury switches can produce, through escalation, surge voltages of complex wave shapes and of amplitudes several times greater than the normal system voltage. The most visible effect generally is found on the load side of the switch and involves both the device that is being switched and the switching device. In the case of the device being switched, the prime responsibility for protection rests with either the manufacturer or the user of the device in question. The presence and source of transients may be unknown to the users of these devices. This potentially harmful situation occurs often enough to command attention. The above information was taken from IEEE Standard 587-1980.

Very little is known as to how frequently a winding can withstand a given impulse. Impulses are destructive, and the fact that a winding withstands the first impulses does not necessarily mean that it will withstand the second or third impulses. These transient impulses eventually can puncture the insulation of the conductor.

### B. Lightning Transients

A direct lightning strike to a primary circuit injects high currents into a primary circuit, producing voltages by either flowing through ground resistance or flowing through the surge impedance of the primary conductors. A lightning strike that misses the line but hits a nearby object sets up electromagnetic fields which can induce voltages on the conductors of the primary circuit.

The rapid change of voltage that may occur when a primary surge arrester operates at low discharge currents to limit the primary voltage couples effectively through the capacitance of the transformer and produces surge voltages in addition to those coupled into the secondary circuit by normal transformer action.

When lightning strikes the secondary circuits directly, very high currents can be involved, exceeding the capability of conventional devices. Lightning ground current flow resulting from nearby direct-to-ground discharges couples onto the common ground impedance paths of the grounding network.

## IV. VULNERABILITY VERSUS SUSCEPTIBILITY

Vulnerability can be defined as the characteristic of a device capable of being damaged by an external influence such as a surge. The damage can either be an insulation type failure or a component failure.

Susceptibility can be defined as the characteristic of a device capable of having its operation upset by an external influence such as a surge.

### A. Vulnerability

In case of damage, a device should be designed such that no danger to human safety due to either shock or fire hazards exists. Testing for this is one of the major roles of third party organizations such as Underwriters Laboratories. However, just meeting a UL Standard does not necessarily mean that the product has adequate susceptibility characteristics.

### B. Susceptibility

Testing to a performance standard is necessary to ascertain that the equipment operates properly under the transient test conditions. (If the equipment does malfunction, it should do so in a safe or known state.)

Transients can give rise to very fast rates of change of voltage and/or current resulting in electromagnetic interference (EMI). This is another subject, but transient protection can provide some degree of immunity to certain types of EMI.

## V. TRANSIENT ENVIRONMENT

Recent national and international standards define a range of installation parameters which establish degrees of severity of transients together with the classification of the pollution environment, i.e., the temperature, humidity, contaminants, etc. As indicated in Section II, there are two major divisions of transient environment: power lines and sensor, control and communication lines.

### A. AC Power Lines

1. Low Voltage.

The standards for AC power lines arbitrarily are divided into two categories: high-voltage and low-voltage systems. Two very new surge standards indicate wide agreement on power line surges for low voltages:

a. In the United States, the IEEE Guide for Surge Voltages in Low-Voltage Power Circuits ANSI/IEEE Std. C62.41-1980 describes power circuit surges for Class A, B and C uncontrolled location categories. This document was originally released as IEEE 587-1980.

**THE ANSI/IEEE STD C62.41 — 1980 CONCEPT OF LOCATION CATEGORIES IN UNPROTECTED CIRCUITS**

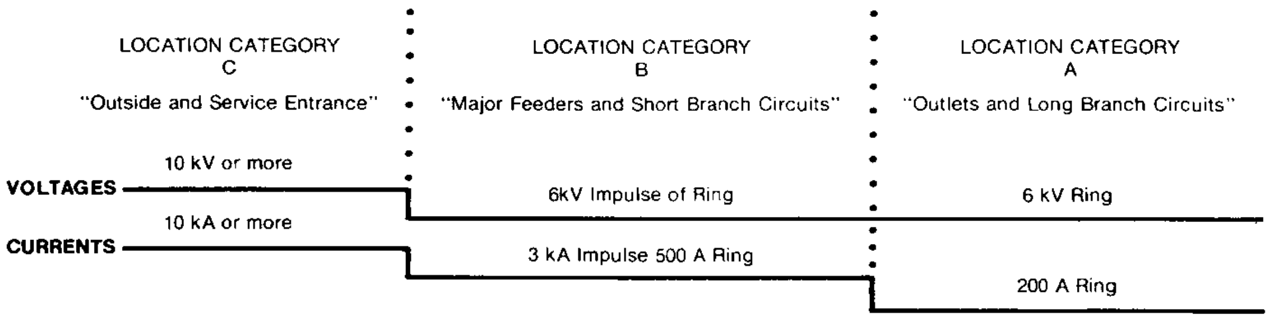


**Figure 1**

b. Internationally, the International Electrotechnical Commission (IEC) 664 occupies a similar position and is likely to have a similar far reaching influence for world-wide products. The document uses the concept of four controlled overvoltage categories.

**THE IEC REPORT 664 — 1980 CONCEPT OF CONTROLLED VOLTAGES**

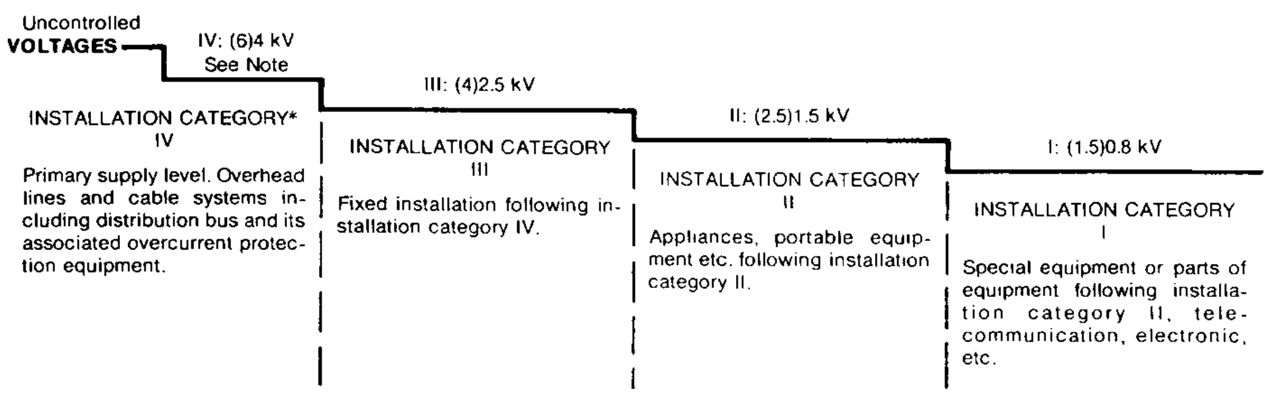


**Figure 2**

Note: Voltage levels following the designation of Overvoltage Categories (IV, III, II, I) are shown in parentheses for a system with 300V phase-to-ground voltage, and next for 150V phase-to-ground voltage. The voltages shown are implied as 1.2x50 $\mu$s impulses.
*The term "overvoltage category" will replace "installation category" in subsequent IEC recommendations.

2. High Voltage.

An acceptable system of transient protection will be influenced by a number of factors. Of prime importance is a knowledge of the Basic Insulation Impulse Level (BIL). See ANSI/IEEE Standard C57.12.01-1979, Table 3 Page 12 for Dry Type Transformers and ANSI/IEEE Standard C57.12.00-1980, Table 3, Page 14 for Liquid Filled Transformers.

Insulation standards have been developed which recognize the need to meet a limited amount of temporary excess voltage stress over and beyond the normal operating voltage. The ability of the equipment insulation system to withstand these stresses is certified by excess voltage tests applied to the electrical products.

The appropriate application of surge protective devices such as surge arresters will lessen the magnitude and duration. Thus, a margin can be established between the surge protective device operating voltage and the BIL.

### B. Communication Lines, Analog and Digital Signal Lines, and Other Input/Output Lines

Less data is available to identify the types of transients on this low level wiring. In many installations they are even more susceptible to the transient environment, and require lower level surge protection devices. There are Federal Communications Commission (FCC) standards and Consultative Committee, International Telegraph and Telephone (CCITT) standards. Fortunately, more and more products are receiving protection for the signal lines as well as the power lines.

## VI. TRANSIENT TESTING

A wide variety of transient test waves exist in the standards and guides of today for simulating the real world transient environments. However, there is an effort by many organizations to reduce the number of several generally accepted transient test waves. These include waves for both AC power lines and communication lines. While specialized areas may require variations in these waves, many can be generated using the same test equipment with different plug-in modules.

It is important to realize that these standard transient test waves were selected so that they could be generated accurately and repeatedly. Although they are not necessarily true reproductions of the real world transients, they can produce similar vulnerability or susceptibility results in equipment and can thus evaluate the effectiveness of transient protection.

A manufacturer of transient wave generators is KeyTek Instrument Corporation. KeyTek Application Note AN 103/3 October, 1981 identifies at least four basic types of transient test waves:

### A. Impulse Voltage and Current:

An oversimplified explanation for a 1.2 x 50 voltage impulse wave means that it has a 1.2 microsecond rise time with a decay to half-amplitude of 50 microseconds. An 8 x 20 current impulse wave is usually available from the same test equipment. KeyTek makes a major point of offering an impulse transient test generator that can switch automatically from the 1.2 x 50 high impedance voltage source to an 8 x 20 low impedance current source. This is important if during transient testing the load suddenly changes due to either insulation or component failure or by the natural action of surge protection devices.

### B. Chopped Impulse Wave:

A transient wave derived from a full 1.2 x 50 voltage impulse wave that is interrupted by a disruptive discharge. The collapse can occur on the front, at the peak, or on the tail.

### C. Ring Wave:

This is an oscillatory wave of decaying amplitude.

### D. Fast Transient Impulse Wave:

This test wave has an extremely fast rise time, simulating a breakover type transient, i.e. nanoseconds.

Where installation circumstances are conducive to exposure to large-magnitude, extremely steep-front transient waves, a surge capacitor protective device should be installed. This will reduce the rise time and facilitate application of surge protective devices.

## VII. SURGE PROTECTIVE DEVICES (SPD)

In some parts of the world surge protectors are called surge diverters. This is probably better technical terminology since the purpose is to divert surge current away from the equipment while limiting the peak surge voltage. The term surge arrester is still used, particularly for high voltage installation, but it is also a diverter function rather than "arrester." Diverting the surge can be accomplished with two basic types of protection: voltage-clamping devices and crow-bars.

### A. Voltage-clamping

A voltage-clamping device is a component having a variable impedance depending upon the current flowing through the device or on the voltage across its terminals.

These devices exhibit a non-linear impedance characteristic; that is, Ohm's law is applicable but the equation has a variable R. ... The apparent clamping of the voltage results from the increased voltage drop (IR) in the source impedance due to the increased current. It should be clearly understood that the device depends on the source impedance to produce the clamping. Examples of voltage clamping devices are:

1. Varistors. Until recently, the most common type of varistor was made from specially processed silicon carbide. This material has been and is still very successfully applied in high-power, high-voltage surge arresters. This varistor has been used as a current limiting resistor to assist some gaps in clearing power-follow current.
2. Metal-oxide-varistors (MOV) are a relatively new family of varistors made of sintered metal oxides, primarily zinc oxide with suitable additives. Metal oxide varistors have an operating life which is dependent upon temperature, voltage stress and most important, on the number of surges at certain energy levels. A complete description of these devices is found in a General Electric document entitled Transient Voltage Suppression, (4th Edition) Publication No. 400.3.
3. Silicon avalanche diodes are another more recent form of surge protective device. They offer faster response to surges than the MOV's and can clamp to lower operating voltages for protection of more sensitive electronic circuits. General Semiconductor Industries, Inc., a domestic Subsidiary of Square D Company, markets these devices under the registered trademark of Transzorb.® A complete description of these devices and their application can be found in Product Data Book - 1985 available from General Semiconductor Industries, Inc.

### B. Crow-Bar

Crow-bar type devices involve a switching action, either the breakdown of a gas between electrodes or the turn-on of a thyristor. After switching on, they offer a very low impedance path which diverts the transient away from the parallel connected load. Examples are gas tubes and carbon block arresters.

These crow-bar devices have two limitations. The first is their time delay, typically microseconds, which leaves the load unprotected during the initial rise. The second limitation is that a power current from the steady-state voltage source will follow the surge discharge (called follow-current or power-follow). In AC circuits, this power-follow current may or may not be cleared at a natural current zero; in DC circuits the clearing is even more uncertain. Therefore, if the crow-bar device is not designed to provide self-clearing action within specified limits of surge energy and system voltage and power-follow current, additional means must be provided to open the power circuit.

### C. Hybrid Modules

These modules are made up of combinations of coordinated crow-bar and voltage-clamping devices with proper interfacing impedances. They provide readily available transient protection devices for original equipment or as an option for more severe transient environments. General Semiconductor Industries Inc., offers hybrid modules which meet IEEE Standard 587-1980 categories A and B, in addition to components.

## VIII. SURGE ARRESTER

### A. Liquid Filled Transformers

On liquid filled transformers, the most widely used type of surge arrester is the valve-type arrester. The active elements of a valve-type arrester are the spark gap and the valve block. These are housed in a porcelain shell for atmospheric protection and external insulation.

The gap assembly consists of a number of in-series air gaps with sufficient dielectric strength to withstand the highest 50 or 60-Hz crest voltage on the system. During severe overvoltage conditions, the gap must always break down at a voltage level somewhat below the insulation withstand voltage level of the equipment it is protecting. The voltage level at which the arrester goes from the passive (insulating) to the active (conductive) state is called the spark-over voltage.

### B. High Voltage Dry-Type Transformers

Because of the proliferation of transients due to various causes on high voltage systems, it is recommended that metal oxide varistors (MOV) be used to protect dry-type transformers over 600 volts. These metallic oxide arresters should be specified as standard on all transformers. To maintain their effectiveness, arresters are mounted as close as possible to the transformer terminals. (The further the arrester is from the terminal, the less effectiveness of the arrester.)

### C. Overall Transformer Considerations

As will be discussed in Section XII., it cannot be over emphasized that a good ground is exceedingly important.

It should also be recognized that harmonics and transients developed in secondary loads can pass through and be amplified by the windings of the supplying transformer and pass out of the primary of the winding, effecting additional transformers in the same primary distribution system. Consequently, in multiple transformer installations it is extremely important that all high voltage transformers have this metallic oxide protection at the high voltage terminals. The voltage rating of the arrester should be as close to, but above, the line-to-ground voltage of the transformer as possible. (i.e. a 13,200 delta primary should use a 9 or 10 KV arrester.)

It is also important to know that the Basic Impulse Level of a transformer is measured without the use of an arrester. The arrester then enhances the capability of the transformer to withstand lightning and switching surges which generate transients. It is also important to remember that in high potential testing of transformers with arresters, the arresters should be disconnected prior to the test of the high voltage winding.

The quality of stress cones must be carefully controlled. If the stress cones are not properly formed, problems can develop resulting in phase-to-phase strikes and phase-to-ground strikes. Stress cones should be provided on the primary connections to medium and high voltage transformers. The absence of stress cones results in non-uniform electrical fields between phase bushings and to ground such that in the presence of high humidity (which is usually the worst case), flashovers between phases and phase-to-ground might occur. Close inspection of primary bushings may show small pock-marks which could eventually lead to bushing failure.

## IX. METHODS OF TRANSIENT PROTECTION

Transformer protection is covered by Section VIII., page 19, on Surge Arresters and High Voltage Transformers.

On oil-filled high voltage current transformers through the 345 KV class, a surge arrester is placed across the primary terminals which acts as a shorting device and tends to keep the transient on the primary side from entering the primary winding of the current transformer.

For low voltage circuit breakers, two times peak line voltage is the maximum theoretical voltage transient that could be generated during switching. However, the process of interruption attentuates the generated voltage transient. Even operation of the current limiting circuit breakers does not generate transients approaching the theoretical maximum.

GFCI circuit breakers use two methods of protection against transient voltages. The first method involves the use of a breaker tripping coil in series with the electronic power supply of the ground fault sensor. For any high spike type voltage, most of the voltage is dropped across the coil. Another version uses an MOV line-to-neutral on the input to the electronic module.

Silocon avalanche diodes and/or MOVs are used in power supplies and I/O when they are connected to AC power. Powerline filters are also used on most devices connected to the powerline. Silicon avalanche diodes are also used on certain serial communication lines and a "black box" containing silicon avalanche diodes, gas discharge surge arresters and series impedance is used on both ends of communication lines which run for long distance out of doors and may be subjected to lightning strikes.

An isolation transformer installed immediately ahead of an adjustable speed drive with SCRs will attentuate some of the voltage transients generated. Whether or not this will solve the problem will depend on other circuit conditions. Problems have arisen with SCR drives applied on elevator applications because there were no shielded isolation transformers ahead of the SCR drive.

## X. ISOLATION TRANSFORMER AND POWER CONDITIONER

Although primarily used for Electromagnetic Interference (EMI) rejection, an isolation transformer can provide a certain degree of transient attenuation (assuming that the transformer itself can withstand the transient condition). The common mode attenuation for transients, and particularly for EMI rejection, can be further improved by means of electrostatic shielding. However, an isolation transformer does not reduce significantly the magnitude of normal mode transients.

| | |
|---|---|
| Common Mode Interference | - A form of interference that appears between both signal leads and a common reference plane (ground) and causes the potential of both sides of the transmission path to be changed simultaneously and by the same amount relative to the common reference plane (ground). |
| Normal Mode Interference (differential mode) | - A form of interference that causes the potential of one side of the signal [or power] transmission path to be changed relative to the other side. |

An even more important function of an isolation transformer for transient protection is the ability to re-establish a new ground reference point at the secondary winding. This can facilitate the installation of additional surge protective devices.

A wide range of products for power conditioning in addition to power line regulation and uninterruptible power supplies (UPS) is available. Power Conditioners can provide transient protection through the use of three separate techinques:

1. Peak limiting circuits to remove high voltage transients at the input.
2. Resistor-capacitor snubber circuits for surges described by ANSI 3790 Surge Withstand Test.

3. Linear filters for attenuation of all signals above 1 kHz.

## XI. GROUNDING, BONDING, AND SHIELDING

This could be a complete subject in itself, for without proper grounding the surge protective devices may be ineffective.

The first and overriding requirement is that the installation conform to the National Electric Code ANSI/NFPA 70-1984. Many of the application problems associated with su:ge protective devices can be attributed to an improperly installed grounding system. Besides being dangerous it is unlawful.

It is imperative that the surge protective devices have the shortest possible leads; i.e., mounted as close as possible to the equipment to be protected. Also, all of the input and output ground references within an installation must have the same earth reference point. This is necessary so that in the event of the surge current all of the equipment will be raised to the same common mode potential.

While the manufacturer usually provides suitable low impedance connections to the case, the case-to-ground connection may be a relatively high impedance at the frequency of the surge current, say 5 ohms. A 30,000 ampere surge current could raise the entire system above earth by 150,000 volts. It is necessary to establish a low impedance path to ground for windings and arresters or to provide another surge arrester from the ground transformer connection to a separately established ground. The surge arresters should be connected directly to the ground connection of the transformer windings and not to the ground connection of the case. The bottom line is that surge protective devices must be properly selected, coordinated and installed with respect to grounding, bonding, and shielding. A more detailed explanation is beyond the scope of this paper.

A good reference on this subject is the IEEE Standard 142-1982, Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book).

## XII. HARMONICS

Power system harmonics have increased in recent years due to the increase of non-linear loads resulting from new technologies such as silicon-controlled rectifiers (SCRs), power transistors, and microprocessor controls which create load generated harmonics throughout the system.

In order to be more competitive, a few transformer companies, are designing their iron core devices to operate in the non-linear region. This causes a sharp rise in the harmonic content of the power system.

Because of the rising cost of electrical energy, and the fact that harmonics appreciably increase the losses of electrical devices, consideration should be given as to what factors produce harmonics and what can be done to minimize the effect of harmonics.

The IEEE Working Group on Power System Harmonics lists 11 areas where harmonics cause operating problems. Some of these major effects include:

1. Failure of capacitor bank due to dielectric breakdown or reactive power overload.
2. Interference with ripple control and power line carrier systems, causing misoperation of systems which accomplish remote switching, load control, and metering.
3. Excessive losses resulting in heating of induction and synchronous machines.
4. Overvoltages and excessive currents on the system from resonance to harmonic voltages or currents on the network.
5. Dielectric breakdown of insulated cables resulting from harmonic overvoltages on the system.
6. Inductive interference with telecommunications systems.
7. Errors in induction kWh meters.
8. Signal interference and relay malfunction, particularly in solid-state and microprocessor-controlled systems.
9. Interference with large motor controllers and powerplant excitation systems.
10. Mechanical oscillations of induction and synchronous machines.
11. Unstable operation of firing circuits based on zero voltage crossing detection or latching.

### A. Harmonic Sources

In addition to the established sources of harmonics that are present on a system, the power network is also affected by these possible harmonic sources:

1. Energy conservation measures using power semiconductor devices and switching for their operation often produce irregular voltage and current waveforms that are rich in harmonics.
2. Motor control devices such as speed controls for traction applications.
3. High-voltage direct-current power conversion and transmission.
4. Wind and solar power converters interconnected to the distribution systems.
5. Static-var compensators used as continuously variable-var sources.

6. Electric vehicles that require a significant amount of power rectification for battery charging.
7. Direct energy conversion devices, such as magneto-hydrodynamics, storage batteries, and fuel cells, that require dc/ac power converters.
8. Cycloconverters used for low-speed, high-torque machines.
9. Pulse-burst-modulated heating elements and saturable reactors for large electric furnace applications.

Conditions likely to cause problems from harmonic distortion are as follows:

1. Nonlinear loads.
2. Phase unbalance.
3. High input voltage.
4. High impedance (weak) power source.
5. Resonance.
6. Combination of two or more causes.

Problems with power factor capacitors can occur due to resonance when used with certain types of adjustable frequency drives or static rectifiers. These problems can occur when the power factor capacitors are installed near to the above devices.

### B. Possible Solutions to Harmonic Problems

1. It is recommended that transformers supplying rectifier loads be conservatively designed (i.e. 80°C rise and low core flux densities) as a preventive measure to guard against undetected partial failure of rectifier bridges. This results in a DC component flowing in the secondary winding of the transformer and can cause serious overheating of the primary winding due to the resultant high magnetizing current.
2. Require iron core devices to be designed with moderate flux densities.
3. Minimize the SCR load connected to any single load center.
4. Increase the number of pulses in an SCR control circuit.
5. Use isolation transformers on SCR circuits controlling drives.
6. Use a reactor in series with the power factor correcting capacitors to detune the feeder and allow capacitors to stay in service.
7. Design filters to shunt off harmonics from the system (very costly).
8. Reduce phase angle retard. As the phase angle increases, the magnitude of the harmonics increases.
9. Integral firing SCR controls on heater applications minimize the harmonic content and do not cause the large power factor reduction caused by phase angle controls.
10. Use dedicated services for sensitive equipment.

## XIII. CONCLUSIONS

Transients, harmonics and electromagnetic interference (EMI) are real world conditions that equipment will be subjected to in most installations. Electrical products are designed and tested to meet the "normal service" installation, including transient environments. Additional surge protective devices are available for more severe transient environments. Knowing how to identify the transient environment is probably the most difficult aspect of providing transient protection. Fortunately, there are standards and guides to assist in the application of transient protection.

The material in this paper is only an introduction to transient protection. More detailed information can be found in the references listed in Section XIV.

## XIV. REFERENCES

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