# TRANSIENT SURGE WITHSTAND CAPABILITY TEST STANDARDS, GENERATION, AND APPLICATIONS

Since early days of electronics, it has been necessary to protect equipment against detrimental effects of transient voltage surges. Widespread use of semiconductors and their susceptibility to damage by surges increases the importance of this protection. Products from consumer television sets to airborne systems need protection from catastrophic surge damage, including electronics systems in industrial and medical facilities.

Objectionable and destructive transient occur both from man-made and nature-caused phenomena. Some of the man-made transients are predictable, others are not (natural transients are almost non-predictable). A few examples of man-made transients include:

- Energizing and de-energizing transformers. Transients greater than ten times the voltage being switched can occur upon de-energizing transformers.
- Energizing and de-energizing inductive devices such as solenoids.
- Switch and circuit breaker arcing.
- Faults occurring in power transmission lines. For example, if a short develops somewhere in a power systems, parallel connected devices may be destroyed when the fuse breaks.
- Various combinations of switches and/or relays can cause severe arcing. This is not limited to mechanical switches, but also can be caused by solid-state switching elements.
- EMP(
- EMP (Electro-Magnetic Pulse) testing which subjects equipment to transients.

Frequently transient problems arise from outside a system, for example, from the source of power or load. It is these transients which create the greatest problems, as it is nearly impossible to predict their amplitudes. The transients can be caused by parallel loads on the same distribution system, but may also be caused by lightning, especially on communication lines, such as alarm and telephone systems.

For random transients, a statistical approach represents the only practical method of establishing test signal standards. An IEEE committee spent years collecting and studying data in order to arrive at the values (described in this article). Other groups are still collecting additional data, and other variations of the test signal may be developed at least for specific applications.

However, the existence of at least one standard represents a tremendous step forward (compared to having each concerned experimentor try to set his own test conditions, probably with extremely little data with which to establish the transient parameters).

Lightning surge protection is one part of the problem. Transients generated by other sources are more common than those generated by lightning, although the specification (and the equipment) described cover as complete a spectrum of transient sources as possible.

## COURSES OF ACTION

There are two courses of action that can be taken to avoid the detrimental effects of voltage surges. One is to prevent the surge from reaching the item that may be damaged; the second is to make the device capable of withstanding the surge without damage. Both, however, require a method of determining when the dangerous surge level has been reached. It therefore became necessary to agree upon and standardize a signal that would be most representative of what must be protected against. The signal need not (and should not) be a worst possible case, but it should represent a realistic case.

Several groups have been established to evaluate the surge transient problem and recommend solutions. Approximately eight years ago the Institute of Electrical and Electronic Engineers (IEEE) Power Systems Relaying Committee set up a Working Group on Static Relay Surge Protection. The International Electrotechnical Commission (IEC) also charged its Technical Committee Number 41 to study this problem and makes its recommendations regarding standardized tests. Other companies, groups and military establishments have also examined this matter and, in some cases, suggest somewhat different tests for their particular needs.

In 1974, the IEEE Standard 472-1974 (American National Standards Spec. ANSI C37.90a-1974) was issued, defining the "Surge Withstand Capability (SWC) Waveshape and Characteristics". This specification is presently included in many requirements of component, equipment, and system manufacturers.

## THE TEST WAVEFORM

Harmful voltage surges can originate either within the equipment under test or external to it. Since it is usually relatively easy to control those transients generated within the equipment, it is considered necessary to have a means of simulating the type of potentially harmful voltage surges that frequently originate external to the device or system being produced. It became necessary to determine the characteristics of the type of interference which most generally occurs.

The individual companies and industry committees that studied this question in detail arrived at the conclusion that the interferences of overwhelming importance consist of a single burst or repetitive bursts of damped sine waves. Some surge testing has been performed by use of unidirectional pulses because this can place a greater continuous stress for a longer period of time on the device or system under test. However, evidence indicated that most of the externally generated surges which were coupled into equipment under test were oscillatory, not unipolar.

Having agreed that the damped sine wave was the most representative form of interference of concern, it became necessary to define its characteristics. These parameters are not as clear cut as the waveform itself, and some differences will still exist between authorities in defining these parameters.

## FREQUENCY

Let us first discuss the basic oscillatory frequency. Values from less than 5 kHz up to 100 MHz have been suggested. Field measurements of high voltage switching operations are reported to result in transients which cluster approximately in the 100 kHz to 5 MHz range (however, in testing of some military airborne systems, frequencies up to 100 MHz may be of importance). Reviewing the available information from various domestic and European sources indicates complete accord on the necessity of testing at approximately one MHz, although there does not appear to be complete accord on whether additional testing at lower and/or higher frequencies is also required.

## AMPLITUDE AND DECAY RATE

The question of the peak voltage of the first half-cycle appears to be agreed upon by the various groups studying this problem: The IEEE group set this value between 2.5 and 3.0 kV. Some data reported that voltage magnitudes somewhat greater than 3 kV were observed; but since this did not seem common and since the voltage ratings on most relay insulation systems are rarely set above 3 kV, it was agreed that to test above this value would not be meaningful and may result in other problems. For some testing modes, considerably lower crest values are specified, 500 volts being the lowest desired test voltage.

The decay rate of the sine wave burst is a problem because the value most widely specified as being representative is difficult to achieve using techniques that are not prohibitively costly (see discussion of methods of achieving the test waveform). The decay rate is sometimes specified in terms of the envelope value at a designated time interval following the first peak, and sometimes in terms of the number of cycles following the first peak. The decay is always specified in terms of open-circuit conditions. It is the opinion of the writer that further studies should be made to determine whether this should be specified when working into a defined load value.

The IEEE specification states that the envelope decay (open-circuit) should reach 50 percent of its initial peak value in not less than 6 $\mu$ seconds from the start of the wave. The IEC proposed specification calls for from three to six cycles to have occurred by the time the 50 percent envelope decay point is reached. One proposed Italian specification calls for the one-half voltage response point to be reached in 22.5 $\mu$ seconds. Another approach has been to specify a formula that takes into account the frequency of the sine wave in the burst, namely:

$$E_{\text{open-circuit}} = E_{\text{initial E}}{}^{-\omega t/48} \sin \omega t$$

where E is the instantaneous voltage of the burst. If we let e = the amplitude of the envelope of the peaks of the burst, it is seen that

$$e_{\text{open-circuit}} = e_{\text{initial}} \omega^{-\omega t/48}$$

where $e_{\text{open-circuit}}$ is the instantaneous value of the decay envelope at time $t = 0$, $e_{\text{initial}}$ is the initial crest value, $\omega$ is $2\pi$ times the oscillation frequency, and t is the time (in cycles) after the start of the burst. Substituting 6 complete cycles in the above formula results in:

$$e_{\text{open-circuit}} = e_{\text{initial E}}{}^{\pi/4} = 0.45\, e_{\text{initial}}$$

or an amplitude of approximately 50 percent of the initial peak (the response generally specified) at the time of the sixth cycle.

## OTHER PARAMETERS

The IEEE specification requires a source impedance of 150 ohms; other suggested values have included 7.5, 25, 50, 200, 300 ohms, and even a variable source impedance starting at 1,500 ohms at 100 kHz then decreasing to 150 ohms at 800 kHz to 2 MHz and then increasing to 500 ohms.

The rise time from zero to the peak of the first sine wave is not clearly defined in most specifications. The references that are made to it in the studies that a rise time (from 10% to 90% of the initial crest value) of 100 ns (or at a rate of 20 kV/$\mu$ second) is desired. A sine wave at 1.0 MHz would take 250 ns from zero to peak; therefore, the desired rise time is substantially faster than the equivalent portion of the period at the operating frequency.

The polarity of the initial peak appears to have been of little (if any) concern to the IEEE group, although some users have specified this as + or −. In at least one instance, the requirement for selectable polarity has been included.

The test burst repetition rate is specified by the IEEE as not less than 50 bursts per second. The IEC proposal specifies 400 bursts per second. While producing 400 bursts per second is not difficult to achieve, the generator required to produce such a signal must handle eight times the average power required for 50 bursts per second to fulfill this need.

A test duration of 2 seconds appears widely accepted.

Output isolation is not specified, per se; however, since the application of this signal requires that under some test conditions it be applied directly across the power lines, the system should be protected for at least 120 VRMS and in many cases, 240 or 480 VRMS. It is also implicit that both "high" and "low" signal outputs must be floating with respect to system ground.

## GENERATING THE SWC SIGNAL

Although generation of the required signal may appear simple, the required high output power level severely complicates the problem. After examining a variety of approaches, four basic methods were given serious consideration. These are:

1. Complementary unipolar pulse approach.
2. Low-level generation-linear-power-amplifier approach.
3. Switched tuned-circuit with electro-mechanical or spark gap switching.
4. Switched tuned-circuit with electronic switching.

After considering the four above approaches, the choice quickly reduced to only two—the linear-amplifier and the electronically switched tuned-circuit. The choice between these two clearly depends on the application and on the available funding to construct the test equipment. The only advantage of spark gap or electro-mechanical switching is a modest savings in cost. This cost difference appears negligible compared to the advantages of a solid-state switched tuned-circuit technique. A spark gap device relies upon an arc between two electrodes in a gas filled enclosure. At the frequency and current levels required in this application, rapid wear of the electrodes must be expected. Further, the inconsistencies of breakdown timing between one "switching" and the next cause tremendous jitter and instabilities. A technique also has been utilized with a motor driven mechanical switch in a vacuum enclosure. Such a technique has all the inherent disadvantages of mechanically moving contacts, especially when the contacts make and break high voltage and must carry very high currents. The savings in test generator life span, reduced maintenance, and the existence of a fully repeatable and jitter-free signal make avoidance of spark gaps or mechanical switches extremely desirable.

It is felt that a surge generator using the tuned-circuit solid-state switching technique is the best approach, except for those applications that require the use of linear amplifiers. Several points regarding the design of the tuned-circuit surge generator are worthy of particular mention. Presently known techniques make design of a high-Q tuned-circuit difficult. Losses are introduced in the tuned circuit from the series resistance of the coil, losses in the capacitor, losses in the switching mechanism, and losses caused by external loading. Since the Q is specified into open-circuit conditions, the last item is not a factor. Extreme care must be exercised in the design of the resonant

TABLE I. SPECIFICATION REQUIREMENTS OF VARIOUS ORGANIZATIONS

| PARAMETER | IEEE SPECIFICATION | INTERNATIONAL PROPOSAL OF IEC | FRANCE (EDF) | ITALY (ENEL) |
|---|---|---|---|---|
| COMMON MODE SUSCEPTIBILITY TESTING | | | | |
| FREQUENCY | 1.0 MHz TO 1.5 MHz | 1.0 MHz | 1.0 KHz TO 1.0 MHz | 1.0 MHz |
| DECAY TO ONE-HALF CREST VALUE | $\geqslant$ 6 $\mu$s | 3 TO 6 PERIODS | 3 TO 6 PERIODS | 22.5 $\mu$s |
| CREST AMPLITUDE | 2.5 KV TO 3.0 KV | 1.0 KV TO 2.5 KV | 500 V | 2.5 KV |
| BURST FREQUENCY | $\geqslant$ 50 Hz | 400 Hz | 40 Hz TO 300 Hz | 200 Hz |
| DURATION | 2.0 sec | 2.0 sec | * | 2.0 sec |
| INTERNAL GENERATOR IMPEDANCE | 150 Ω | 200 Ω | 50 Ω | * |
| SERIES MODE SUSCEPTIBILITY TESTING | | | | |
| FREQUENCY | 1.0 KV TO 1.5 MHz | 1.0 MHz | 100 KHz TO 1.0 MHz | 1.0 MHz |
| DECAY TO ONE-HALF CREST VALUE | $\geqslant$ 6 $\mu$s | 3 TO 6 PERIODS | 3 TO 6 PERIODS | 22.5 $\mu$s |
| CREST AMPLITUDE | 2.5 KV TO 3.0 KV | 500 V TO 1.0 KV | 500 V | 1.0 KV |
| BURST FREQUENCY | $\geqslant$ 50 Hz | 400 Hz | 40 Hz TO 300 Hz | 200 Hz |
| DURATION | 2.0 sec | 2.0 sec | * | 2.0 sec |
| INTERNAL GENERATOR IMPEDANCE | 150 Ω | 200 Ω | 50 Ω | * |

* NOT SPECIFIED

coil, and selection of a low-pass capacitor is essential.

The switching circuit is designed to keep its losses during the "on time" to an absolute minimum. If six cycles of oscillation are required until the envelope decay reaches 50 percent of the crest value, it is easier to design the tuned circuit as the frequency of oscillation is reduced; conversely, as the frequency is increased, the problem becomes more difficult. This means that providing generator(s) to reach the suggested 100 kHz poses no problem. However, it is unlikely at the present state-of-the-art that surge generators using a switched tuned-circuit technique are feasible for frequencies above 1.5 MHz. Either the complementary or the linear amplifier would probably be required if a higher test frequency is desired.

## APPLICATIONS

Surge transient generators providing the damped sine wave described in this article have been utilized in a wide variety of applications. Amongst others these include testing computers, power utility control and distribution circuits, equipment used in process industries, semiconductor devices, medical equipment, communications systems, scientific instrumentation, and microprocessors used in a variety of applications. Although the IEEE standardized signal has been used only a relatively short period of time in testing, it appears that the type of failure which occurs most frequently does not involve catastrophic destruction of components, but more often causes equipment malfunction when the interference is present. Some typical types of malfunctions include destruction of information held within memory banks of computers or garbling of input or output data in a computer. Other frequent types of failure are those which cause logic circuits to malfunction. Such occurrences can be extremely costly and/or dangerous. For example, in the food process industry a malfunction of devices which regulate amounts of food additives could conceivably be quite disastrous.

Various specifications call for superimposing the damped sine wave burst signal between various equipment points. Typically, these include between phases of the input power lines, between all phases of the power line in parallel and system ground, at various signal input terminals, across signal outputs, and on various power supply busses and other points, depending on the system configuration. Early limited data indicates that frequently more malfunctions and/or failures are caused in the common mode power connection; that is, when the burst signal is applied between system ground and the power lines.

Methods of eliminating the detrimental effects of these transient signals are beyond the scope of this article; however, since so much of such elimination relies on empirical measurements, the use of the standardized burst signal has proven extremely valuable in evaluating means to reduce effects of interference and to effect cures.

## SUMMARY AND FUTURE TRENDS OF SWC TESTING

SWC testing has become recognized on a worldwide basis as essential. Major steps forward have been made by the IEEE and IEC in moving toward standardization. It is expected that agreement will be reached so that test requirements will be universal. Obviously, as experience is gained with equipment now coming to the market, refinements in requirements will emerge. It is likely that the new equipment will include multi-oscillation frequencies (through probably not continuously variable), higher burst rates, and more fully defined signals when operating into specified loads. As new devices for consumer, industrial and medical products are developed that are even more sensitive to damage or malfunction by transient voltage surges, the greater will be the testing requirements.

As a result of now having standards based upon realistic conditions and methods of testing, engineers will be able to provide Surge Withstand Capability (SWC) in their designs.

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