TRANSIENT PROTECTION AND SURGE WITHSTAND CAPABILITY — A TEST STANDARD

Even in early days of electronics, it was necessary to protect equipment against detrimental effects of transient voltage surges. Because of semiconductor susceptibility to damage by surges, the importance of this protection is increased. Products from consumer television sets to airborne systems need protection from catastrophic surge damage, including electronics systems in industrial and medical facilities.

Objectional be and destructive transients occur both from man-made and nature made phenomena. Some of the man-made transients are predictable, others are not (nature-made transients are almost non-predictable). "Transient Voltage Supression Manual" published by the Semiconductor Products Department of General Electric quotes the following examples of man-made transients:

1. Energizing and de-energizing transformer primary windings. Transients greater than ten times the voltage being switched occur at times upon de-energizing transformer primaries.
2. Energizing and de-energizing inductive devices such as solenoids and auxiliary coils.
3. Switch and circuit breaker arcing.
4. Faults occurring in power transmission lines. For example, if a short develops somewhere in a power system, parallel connected devices may be destroyed when the fuse breaks.
5. 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.
6. EMP (ElectroMagnet Pulse) testing which subjects equipments to transients.

Transient ringing at frequencies greater than 2MHz are encountered in testing to perform Electro Magnetic Pulse (EMP) measurements.

Frequently, transient problems arise not from within the system, but from the source of power (or load). It is these transients which create the most consternation, as it is nearly impossible to predict their amplitude. The transients are generally caused by parallel loads on the same branch of the 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. The 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 existance of at least one standard represents a 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.)

Note that lightning surge protection is only a small part of the problem. In most instances, transients generated by other sources are far more common than those generated by lightning, although it is the intention of the specification (and the equipment) described to cover as complete a spectrum of transient sources as possible.

BASIC 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.

The first industry groups to seriously address themselves to this problem were those concerned with power relay systems and the associated required relay logic. The area of concern has grown to include the fields of communication links (such as wireline, powerline carrier, and microwave systems), computer and computer interface equipment, control systems, data acquisition systems, military equipment, a wide area of component testing (for example, semiconductors, varistors, circuit breakers and switches), and a variety of consumer products.

Manufacturers of surge protections devices also need standardized testing methods. In addition, many manufacturers of products to be incorporated in equipment either may be required or may choose to test their devices (e.g., power supplies, A/D converters, etc.) before they are delivered. All need test standards.

Several groups have been established to evaluate the surge transient problem and recommend solutions. Approximately five 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 make 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.

On July 15, 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 SURGE 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 havea 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 parametersare not as clear cut as the waveform itself and some differences still exist between authorities in defining these parameters.

FREQUENCY

Let us first discuss the basic oscillatory *frequency*. Values from less than 5kHz 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 megahertz, 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 3kV were observed but, since this did not seem common, and since the voltage ratings on most relay insulation systems are rarely set above 3kV, 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 μseconds 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 μseconds. Another approach has been to specify a formula that takes into account the frequency of the sine wave in the burst, namely:

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

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

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

where $e_{open\text{-}circuit}$ is the instantaneous value of the decay envelope at time t = 0, $e_{initial}$ is the initial crest value, ω is 2π 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:

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

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

The IEEE specification requires a *source impendance* 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 2MHz 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 a rate of rise of 20kV/μs) 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.

BURST RATE

The test *bursts repetition rate* is specified by the IEEE as not less than 50 burst per second. The IEC proposal specifies 400 bursts per second. While producing 400 burst 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 fulfull 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.

Table 1 indicates areas where several different groups have specified values (some tentative) required for SWC testing. It is known that groups in countries other than those shown are working on SWC specifications; however, meaningful data is not available at present.

GENERATING THE SWC SIGNAL

At first glance (or "on paper"), generation of the required signal is simple. Unfortunately, the required high output power level severely complicates the solution. After examining a variety of approaches, four basic methods were given serious consideration. These are:

1. Complementary unipolar pulse appreach.
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.

SWITCHED TUNED CIRCUIT WITH ELECTRONIC SWITCHING

Using the same high-Q switched-tuned-circuit approach as described above, but substituting electronic switching provides another approach. The switching elements tested in the laboratory for this purpose included hydrogen thyratrons and various networks of SCRs and diodes.

COMPARISONS OF SWC SIGNAL GENERATION METHODS

Table 2 lists the four techniques discussed and the various parameters of concern. An arbitrary scale of 1 (best) to 5 (worst) has been used to indicate approximately how each approach compares with the others.

After considering the four approaches discussed, 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 equipmnet.

The complementary unipolar approach was eliminated since it presents a poor compromise when considering that it requires two pulse generators and associated circuitry.

The only advantage of the spark-gap switching is some cost saving, but this is almost negligible when compared to the solid-state switching tuned-circuit approach. It should be remembered that a spark gap device relies upon an arc between two contacts (in a controlled gaseous 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. The savings in test-generator life span, reduced maintenance, and the existence of a signal which is fully repeatable and free from jitter make avoidance of the spark gap (or any mechanical switch) virtually essential.

Referring to Table 2, it will be observed that if one desires (a) a high-performance instrument operating at a fixed sine-wave frequency, and (b) does not require a decay significantly slower than six cycles to the one-half envelope response points, then the tuned-circuit solid-state switching approach is best. On the other hand, if high sine-wave frequencies are needed with low damping-rates, no practical method except the linear amplifier has been demonstrated. However, the linear amplifier is costly, large, high in power dissipation, and results in need for eliminating the heat generated. Further, when using the linear amplifier, the equipment to be tested (in most cases) must be taken to the SWC signal site rather than taking a piece of portable test equipment to the device to be tested. However, for testing large military systems, aircraft, etc., where the expenditure of money can be justified, the linear amplifier approach probably must be used.

A surge generator using the tuned-circuit solid-state switching technique seems 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 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 curcuit 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.

TABLE 1. 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

TABLE 2. COMPARISON OF GENERATOR TECHNIQUES

PARAMETER	GENERATOR TECHNIQUE			
	COMPLEMENTARY UNIPOLAR	LINEAR AMPLIFIER	TUNED CIRCUIT WITH SPARK GAP	TUNED CIRCUIT WITH SOLID STATE SWITCH
COST	3	5	1	1
SIZE	3	5	1	1
INPUT POWER	3	5	1	1
LIFE	1	2	5	1
REPEATABILITY OF SIGNAL (ABSENCE OF JITTER, ETC.)	2	1	5	1
FREQUENCY RANGE	3	1	5	5
DECAY RATE (HIGH Q)	1	1	5	5
SOURCE IMPEDANCE (ABILITY TO OBTAIN LOW SOURCE Z)	2	1	5	5
MAINTENANCE	2	3	5	1
PORTABILITY	3	5	1	1

1 = BEST 5 = WORST

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 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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