Transient Control Levels: A Proposal for Insulation Coordination in Low-Voltage Systems

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Significance:
Part 2 Development of standards – Reality checks
Part 6 Textbooks and tutorial reviews

One of the first papers addressing the issues of surge protection in low-voltage AC power circuits, making a proposal for a departure from the traditional unidirectional and separate 1.2/50 and 8/20 waveforms, on the basis of the results of monitoring the occurrence of surges in these circuits. Nevertheless, the concept is emphasized that surge test waveforms should not attempt to duplicate the environment, but only to apply "representative" waveforms and levels that will demonstrate the equipment withstand capability.

The proposal also included the concept of establishing ***first*** a level of surges that will not be exceeded, thanks to the application of appropriate SPDs, and ***only then*** designing equipment that will withstand level higher than the allowable level of surges. This was nothing new, having been applied successfully in the high-voltage utility environment. However, the proposal was new for the low-voltage community.

Unfortunately, the *fait accompli* of equipment being designed and placed on the market without such coordination prevented application of that proposal. Thus, industry is left with the situation where equipment failures under surge conditions can occur, after which remedies must be found as retrofits.

In 1975, the following statement appeared in the paper and should be kept in mind when questions arise on the selection of "representative waveforms" in IEEE Std C62.41.2:
These BIL amplitudes, while assigned somewhat arbitrarily, were (and are) kept in touch with reality by the fact that equipment designed in accordance with standards do not fail when exposed to surges produced by lightning, in contrast to equipment designed prior to the development of the philosophy of insulation coordination and the establishment of standard BILs.

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ABSTRACT

Failure and circuit upset of electronic equipment due to transients is a problem now and is one which has promise of becoming more of a problem in the future as trends continue toward miniaturization and circuit complexity. Protection methods are used more or less extensively and often haphazardly.

At present, there does not appear to be a clear approach toward achieving compatibility between the transient withstand capability of devices and the transients to which such devices are exposed. A more scientific approach is needed to guide manufacturers and users of equipment.

The purpose of this paper is to promote a concept of transient coordination for electronic and other low-voltage equipment through the establishment of a system of Transient Control Levels, similar to the concept of Basic Insulation Levels so successfully used for many.years in the electric power industry. Specific suggestions for possible Transient Control Levels and standard test wave shapes are made, in order to promote wide discussion as to whether these waveforms and levels are the best that can be developed toward good transient coordination for the electronic industry.

INTRODUCTION

Failure and circuit upset of electronic equipment due to transients is a problem now and is one which has promise of becoming more of a problem in the future as trends continue toward miniaturization and circuit complexity. At present, there does not appear to be a clear approach toward achieving compatibility between the transient withstand capability of devices and the transients to which such devices are exposed. This situation appears somewhat as illustrated on Figure 1. A similar situation prevailed many years ago in the electric power industry. Transients produced by lightning frequently caused failure of such vital and expensive power equipment as transformers and generators. Those transient problems were solved by engineering design guided by the concept of insulation coordination and the establishment of a series of Basic Insulation Levels (BIL's).

Paper F 75 466-3, recommended and approved by the IEEE Surge Protective Devices Committee of the IEEE Power Engineering Society for presentation at IEEE PES Summer Meeting, San Francisco, Calif., July 20-25, 1975. Manuscript submitted February 3, 1975; made available for printing April 28, 1975.

The purpose of this paper is to promote a concept of transient coordination for electronic and other low-voltage equipment through the establishment of a system of Transient Control Levels (TCL's), similar to the concept of BIL's so successfully used for many years in the electric power industry. In the following sections, specific suggestions for possible standard Transient Control Levels and standard test wave shapes will be made. While the waveforms here suggested are chosen somewhat arbitrarily, they are well grounded in physical reality. The purpose of making such suggestions is to promote wide discussion as to whether these waveforms and levels are the best that can be developed, or if indeed the establishment of such standards is the best way to promote good transient coordination for the electronics industry. The ultimate purpose of any system of transient coordination would be to achieve greater product reliability at minimum cost to the user.

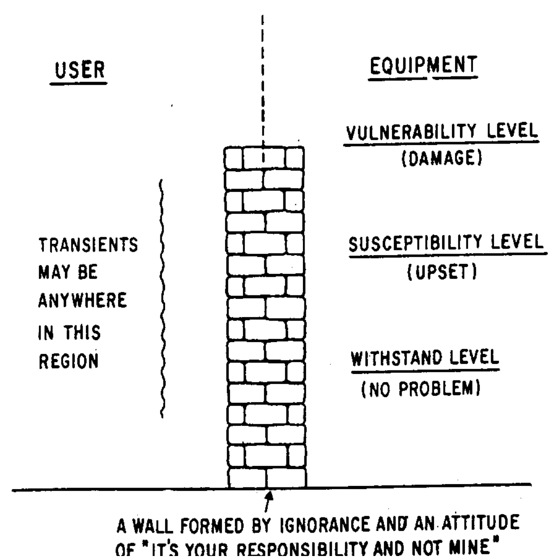

Fig. 1. The present situation.

AN EXAMPLE OF THE PROBLEM

TCL concepts would be of benefit to all users of electronic and other low voltage equipment, such as railroad, telephone, power, oil industry, aircraft, and high frequency communications. The source of transients to which equipment is exposed may be either external (lightning and power system switching) or internal (switching of inductive loads, contactor restrikes or cross talk from adjacent circuits). While the concept of TCL's is intended to apply to the full spectrum of frequencies and voltages (DC, 120 V, 60 Hz AC, 400 Hz) the problem of transient coordination will here be illustrated by discussion of 120 volt AC systems intended for consumer and residential use. During the introduction of electronic equipment into consumer appliances and other residential use, the importance of *transient* coordination was not always sufficiently recognized. In some cases, excessive failure rates occurred as a result of transients having amplitudes greater than the *withstand* level of the equipment.

In residential circuits, transients can occur from two main sources: internally, from the switching of appliances, and externally, most typically from the effects of lightning. One study of internally generated transients[1] has indicated that in about three percent of U.S. households transients greater than 1200 volts occur one or more times per week. Several studies have been made of externally generated transients. One such study[2] indicates two percent of recorded transients exceed 1500 volts. The data also indicate that at the location studied, approximately two surges per year would exceed 1000 volts. Field experience[1] indicated that a 100:1 drop occurred in the failure rate of clock motors when the withstand level was increased from 2000 to 6000 volts. These data indicate that the exposure rate to surges of 2000-volt amplitude was sufficient to be of concern, but that surges exceeding 6000 volts were quite rare, at least on a national basis. Another study[3] showed that during two weeks of monitoring in a lightning-prone area, several surges exceeding 2000 volts were recorded, with the maximum recorded being 5600 volts. Experience with field trials of Ground Fault Circuit Interrupters sponsored by NEMA and the Underwriters' Laboratory[4], when correlated with the known nuisance trip level of the devices and the observed number of trips[5], would indicate an occurrence frequency of perhaps one surge per 7 years above 2000 volts per household.

Most residential wiring systems are constructed in such a manner that the various wiring boxes will flash over if they are exposed to surges greater than 5 to 10 kV. This means that the amplitude distribution will be chopped at 5 to 10 kV.

Based on these admittedly scattered and tentative numbers, it appears that the typical residential circuit will be exposed to surges of magnitude and frequency of occurrence as illustrated in Figure 2.

The magnitude of the transients produced on 120 volt power lines, however, is not of importance except as it relates to the vulnerability level of the equipment connected to such lines. "Vulnerability" is defined here as the level that causes an irreversible and undesirable change (usually failure) in a device. A corollary term is susceptibility, or that level which causes temporary malfunction of the device. The susceptibility level cannot, by definition, be higher than the vulnerability level. Rectifier diodes and similar semiconductors do not have any particular susceptibility level; they either fail or do not fail when exposed to transients. Active semiconductor devices or a control system operated by a mini-computer system might be a different story. It is quite possible

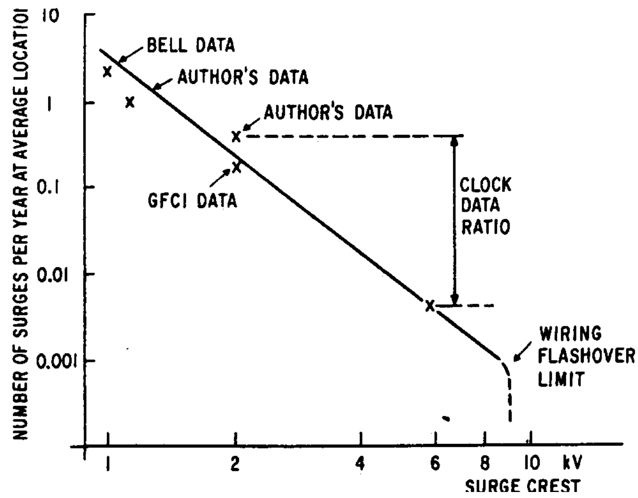

Fig. 2. Exposure of residential circuits to surge (Number of surges vs highest surge at any one location)

that transients of a low level interfere with the operation of the mini-computer, causing it to give incorrect results without causing permanent physical damage. The vulnerability level of such a mini-computer will be higher than the susceptibility level. Both levels must be higher than the normal operating level of the computer logic elements or input/output terminals.

The transient breakdown level or vulnerability of semiconductors is not presently a part of any industry accepted rating system. The vulnerability level is furthermore not inherently related to the normal operating voltage or peak inverse voltage (PIV) level. As examples, consider the data of Table I. During this investigation, power diodes were subjected to unidirectional transient voltages cresting in a few microseconds. The voltages at which failure occurred are seen to have little correlation to the nominal PIV rating.

Similar data have been accumulated for many semiconductors, particularly when semiconductors are exposed to very short transients, characteristic of those produced by nuclear weapons (NEMP). Such information has not been widely reported.

TABLE I
Transient Vulnerability Levels
Typical 1A Silicon Diodes

Diode Number	PIV Rating Volts	Failure Level Under Reverse Impulse* Volts
1	200	1100 – 1500
2	400	1400 – 1500
3	600	1400 – 1600

*Breakdown observed when exposed to a unidirectional surge rising at 1000 volts per microsecond.

Clearly, surges occur with amplitudes greater than the vulnerability of the indicated semiconductors. The frequency of occurrence of such damaging surges, while small on an individual basis, may be unacceptably high on a product line. The transient amplitudes, of course, could be reduced by the use of suitable protective devices. Likewise, the vulnerability levels of the diodes to transients could be raised. Some questions now present themselves, all having to do with the question of who should assume what part of the job of providing transient coordination.

a) Should it be the responsibility of the user to control transients to levels that do not damage equipment supplied by vendors?

b) Should it be the responsibility of the manufacturer to provide equipment that will not be damaged by the naturally occurring transients?

c) If it is the responsibility of the user to control transients, to what level should he control them — the published operating levels (in this case the published PIV levels) or some other level higher than the operating level but below the vulnerability level?

d) If it is the responsibility of the vendor to provide surge-proof equipment, what level of transient voltage and transient energy must he anticipate?

Similar questions can be asked for all product lines: consumer, industrial, and military, and at all levels of operating voltage.

INSULATION COORDINATION IN THE ELECTRIC POWER INDUSIRY

Similar questions occurred many years ago during the development of the electric power industry at a time when the art of designing equipment to withstand the effects of lightning was in its infancy. The nature of the transients, the level of insulation to be used, or what should be expected of the designers of transmission lines and lightning arresters was not clear.

Those transient problems have largely been eliminated today by proper engineering design on a system-wide basis. The evolution of insulation coordination in the electric power industry, while it can be only very briefly described here, may be of benefit to the electronic industry.

First, the type of transients produced by lightning on transmission lines, their magnitude and wave shape were measured. This was not easy in the days of cold-cathode oscilloscopes employing 50 kV accelerating voltages. Even today with vastly improved instrumentation, such investigations are expensive and time-consuming to make.[6] Yet, on the basis of very limited testdata, a standard voltage test wave was derived, the familiar 1.5×40 μs wave. Similar investigations in other countries led to the establishment in Europe of the 1×50 μs impulse wave. International standardizing activities have now produced the 1.2×50 μs impulse wave, a test wave used throughout the world for coordination of insulation protection. It was never pretended, however, that naturally occurring surges were of this type, only that the rise and fall times of the natural surges were in the vicinity of the above values.

The next stage in the process of insulation coordination was the establishment of a series of standard test and design levels, BIL's. For example, equipment designed for operation on 115-kV systems was assigned a BIL of 550 kV. The designer of equipment to be used on 115 kV systems then was required to provide an insulation structure that would withstand 550 kV. The level of 550 kV was derived on the premise that existing lightning arresters could be used to control the transients applied to that apparatus to less than 550 kV. The proper design of the insulation system was next demonstrated by subjecting the apparatus in the laboratory to a surge of 1.5×40 μs wave shape and a peak amplitude of 550 kV . Frequently it was part of the purchase agreement that the equipment had to successfully pass the laboratory test. If the equipment failed, it had to be rebuilt or redesigned. Conversely, it became the responsibility of the user to insure that no surge greater than 550 kV was ever applied to the apparatus.

As a result, power equipment achieves its resistance to lightning-induced transients not so much by being designed to the threat that might be posed by lightning, but by the threat that will be posed by an acceptance test. This acceptance test does not subject the equipment to transients having the complex wave shapes produced by lightning, but instead to transients having elementary wave shapes that can be produced by basically simple test apparatus. Neither does the acceptance test subject the equipment to transients of the amplitude produced by lightning. However, it subjects the equipment to transients of amplitude consistent with the capabilities of existing surge-protective devices.

These amplitudes, the BIL's while assigned somewhat arbitrarily, were (and are) kept in touch with reality by the fact that equipment designed in accordance with standards does not fail when exposed to surges produced by lightning, in contrast to equipment designed prior to the development of the philosophy of insulation coordination and the establishment of standard BIL's.

The test and design levels, the BIL's, are not necessarily fixed. As better protective devices are developed, the levels may be lowered so that reliable equipment can be built at lower cost.

Electronic and control equipment, on the other hand, is all too often designed, built, and delivered before the existence of a transient threat is recognized. If transients turn out to endanger the equipment, there may be no adequate surge protective devices. There may, in fact, not be any satisfactory answer to the problem posed by transients.

THE TRANSIENT CONTROL LEVEL CONCEPT

One way in which transient compatibility might be achieved in the electronics industry is to establish a transient coordination system similar in concept to the BIL system, but of a nature more adapted to the requirements of electronic and control equipment.

In this paper, such a concept is called the Transient Control Level (TCL)* concept. Specifically, it is hereby proposed:

a) That there be defined for electronic equipment (and other low-voltage equipment) a standard transient voltage similar in concept to, but different in wave shape from the 1.2 × 50 μs wave used in coordination of insulation in high-voltage power apparatus.

b) That there be defined for electronic (and other low-voltage) equipment a series of TCL's similar in concept to the BIL's.

c) That a start be made on assigning one of these standard levels to individual electronic components and electronic devices.

d) That individual protective devices be rated in terms of their ability to control transients to levels no greater than, and preferably lower than, one of the above levels.

e) That equipment and procedures be developed by which equipment may be tested by vendors to determine which TCL is appropriate to assign to individual components and equipment.

f) That TCL's begin to be used in purchase specifications.

g) That such equipment and procedures be used by purchasers to evaluate vendor-supplied equipment to determine its compliance with such purchase specifications.

h) That such TCL's begin to appear in regulatory specifications for consumer apparatus in which the consumers cannot make the appropriate tests or prepare appropriate specifications.

Suggested TCL Voltage Wave Shape

The wave shape suggested for the TCL concept (with the understanding that discussion and presentation of alternatives is actively encouraged) is shown on Figure 3. Shown are both proposed open-circuit voltage and short-circuit current waveforms, since the question of the impedance of the source from which voltage surges derive must ultimately be considered. These shapes are different from the long-established 1.2 × 50 μs wave employed in the BIL rating system for electric power apparatus because none of the recorded transients exhibited this type of wave shape on 120-volt AC circuits. The type of transient most frequently recorded appeared of an oscillatory nature, very strongly damped, and in a frequency range between 100 and 500 kHz.

Independent work on the resonant frequency of power systems previously indicated a range of 150 to 500 kHz as being the natural frequency of typical residenial sytems.[7] Other investigations indicate that a lower limit of 5 kHz might be more typical.[8] Thus, it appears that the observed transients are not at all typical of lightning surges propagated directly into the system but are rather the response of the power system to an initial excitation caused by a nearby lightning stroke. The internally generated transients due to switching operations typically are of the same basic type as those produced by the indirect effects of lightning. The observed transients are in each case more nearly the result of the natural oscillatory response of the local wiring system, in this case the wiring system of typical residences. Similar surge wave shapes have been encountered in a wide variety of other systems, ranging from airplanes to space booster rockets.[9, 10] Typical examples of recorded transient wave shapes are given in the Appendix. The great bulk of the recorded transients exhibit a faster front time and shorter decay time than do the transients produced by lightning on high-voltage power lines, the 1.2 × 50 μs type of wave.

Switching transients in air break contacts (internally generated transients) can produce rise times in the order of 10 to 100 ns. Although this steepness attenuates rapidly with distance, the typical front time is still less than 1.2 μs. For some types of devices (rectifier diodes) the wave shape is of secondary importance, with only the peak magnitude being important. For other types of apparatus (inductive devices such as motors), the front time, or more correctly the rate of change, is of importance equal to that of the peak magnitude. In still other types of devices (surge protective devices), the total energy content of the surge is of most importance.

Current Wave Shapes and Source Impedances

The characteristics of short-circuit current wave shapes are less well known than those of open-circuit voltage. The short-circuit current is of importance both for evaluation of surge protective devices and for equipment of low input impedance such as lower voltage semiconductor devices. In any discussion of test wave shapes and test levels, it is important to recognize the natural response of the device in the test. It is inappropriate to prepare a specification that implies that a specified voltage must be developed across a device of low input impedance, such as a spark gap after it has broken down, or to seemingly require that a specified short-circuit current be produced through a high input impedance, such as the line-to-ground insulation of a relay coil. The characteristics of short-circuit currents are poorly defined because the impedance of the circuits from which transients are produced is poorly defined or unknown.

For purposes of discussion, it is suggested that two different types of impedance be considered, one independent of frequency (resistive source impedance or classical surge impedance, $Z = \sqrt{L/C}$), and one of simple inductive source impedance. The waveform shown on Figure 3b assumes a source impedance of

* The TCL concept was first proposed by one of the authors (F. A. Fisher) in regard to electronic equipment on the Space Shuttle.[12]

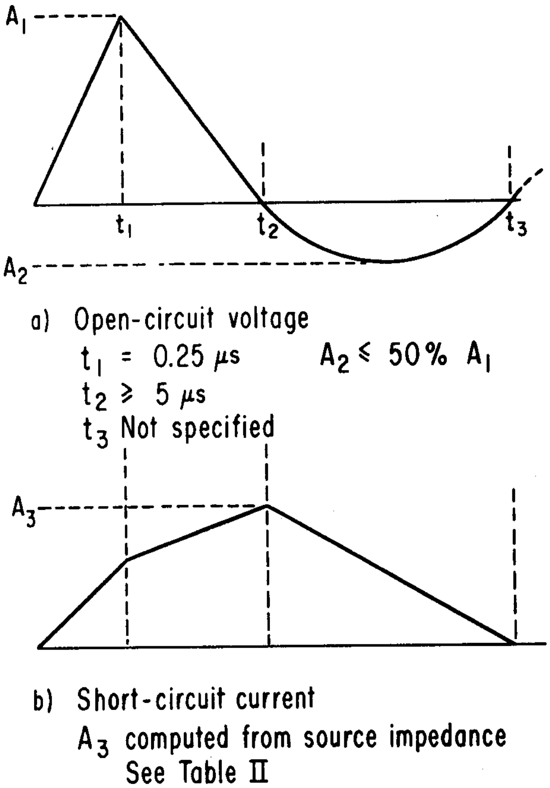

Fig. 3. Proposed TCL wave shapes.

10 μH. Again, for purposes of discussion, it is proposed that a resistive source have an impedance of 50 ohms, and an inductive source have an impedance of 10 mH.

Voltage and Current Levels

Central to the success of the BIL system of insulation coordination is the fact that only a limited number of BIL's were established, arranged in a generally geometric order of progression. For purposes of discussion, we therefore propose that there be established a series of TCL's progressing in the approximate ratio of $\sqrt[3]{10}$ or 3 values per decade. Such possible TCL's, as rounded to convenient voltages, then appear as shown on Table II.

The subject of source impedance and short-circuit current needs to be further discussed since the concept of constant surge impedance, and particularly constant inductive surge impedance, may not be valid. Transients of high voltage and large energy content tend to be produced by physically large systems, whose inductance tends to be larger than that of the systems producing lower voltage or lower energy transients.

Proof Test Techniques

The generation of surge voltages in the laboratory is well known to manufacturers and users of high power equipment. However, producing a test wave of the shape and levels proposed here may present some difftculty for the small equipment manufacturer. To answer this need, a previously developed circuit[11], as shown in Figure 4, may be applicable.

TABLE II
Possible Transients Control Levels

Level No.	Open Circuit Voltage (volts)	Short Circuit Current (amperes) Z = 50Ω	Z = 10µH
1	10	0.2	2.63
2	25	0.5	6.56
3	50	1	13.1
4	100	2	26.3
5	250	5	65.6
6	500	10	131
7	1000	20	263
8	2500	50	656
9	5000	100	1310
10	10000	200	2630

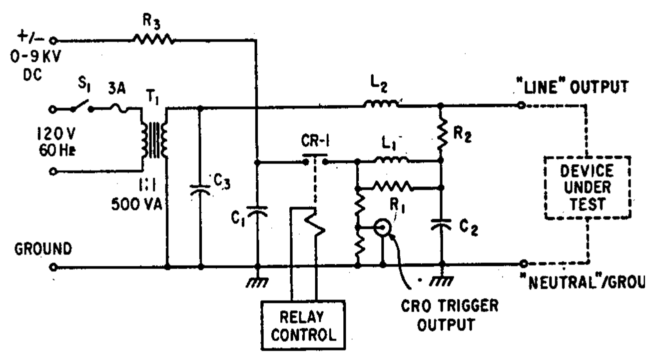

Fig. 4. Test circuit for applying spikes on 120-volt. AC lines.

The objective of this design was to super-impose on a 120-volt, 60-Hz power line a transient having a rise time to first peak of 0. 5 uus, followed by a damped ringing at 100 kHz in which each successive peak is 60% of the preceding peak amplitude. The amplitude of the first peak is adjustable f r o m 0 to 8000 volts. The source impedance for the high-voltage transient is 50 ohms.

The 0.5 μs rise characteristic is obtained by the series resonance of L1 and the capacitance of C1 and C2 in series. Component values were selected to make $\sqrt{L/C}$ approximately 50 ohms, and R1 was selected to provide heavy damping for a smooth transition to the following wave.

The 100 kHz damped ring results from the parallel resonance of L2 with the parallel capacitance of C1 plus C2. Again, $\sqrt{L/C}$ is about 50 ohms. The series damping resistor R2 was selected to produce the decay to 60% amplitude between successive peaks.

CONCLUSIONS

1. The present lack of transient coordination methods in low-voltage systems does not allow the user of electronic equipment to obtain the best reliability at lowest cost.

2. Manufacturers, vendors, and users could benefit from a systematic approach to transient coordina-

tion similar in concept to the BIL used for many years in high-voltage systems. This is illustrated in Figure 5.

3. A concept of Transient Control Level (TCL) is proposed by the authors. This involves discrete steps of withstand level and proof tests based on the capability of available s urge protective devices and reflecting the occurrence of surges in the real world.

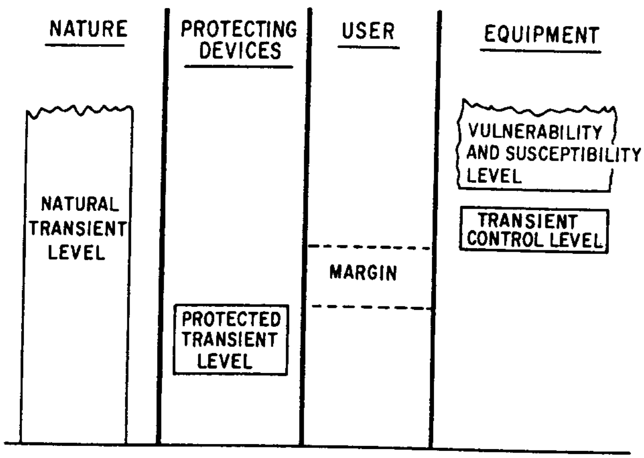

Fig. 5. Well-coordinated low voltage system.

4. Discussion is earnestly invited on the parameters to be considered in defining TCL's such as:

- voltage waveform of the transients
- source impedance of the transients
- current waveform of the transients
- levels to be assigned — current and voltage
- proof-test techniques.

Successful application of the TCL concept will require careful stud yof these factors, so as to develop a valid consensus among all interested parties.

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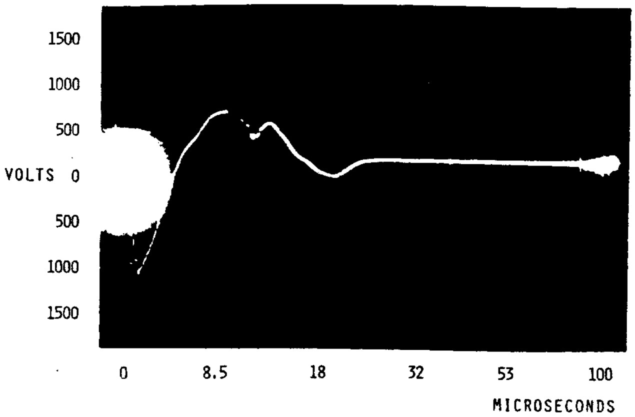

Fig. A1. Transient recorded during starting of a furnaceblower at service box.

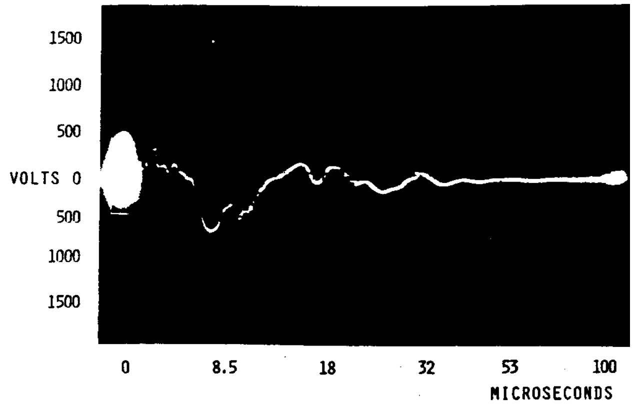

Fig. A3. Transient recorded during unidentified disturbance at service box.

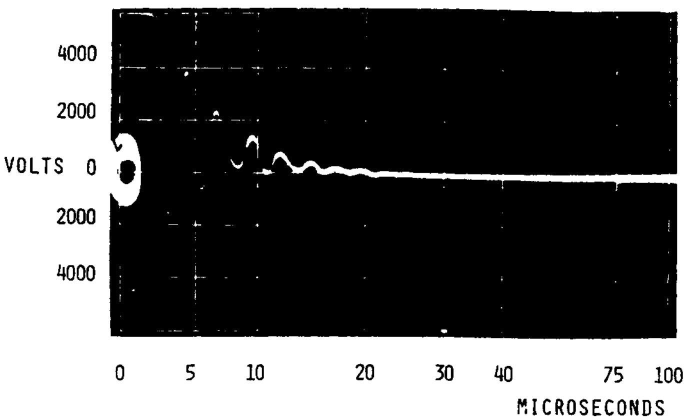

Fig. A2. Transient recorded during lightning storm on street pole.

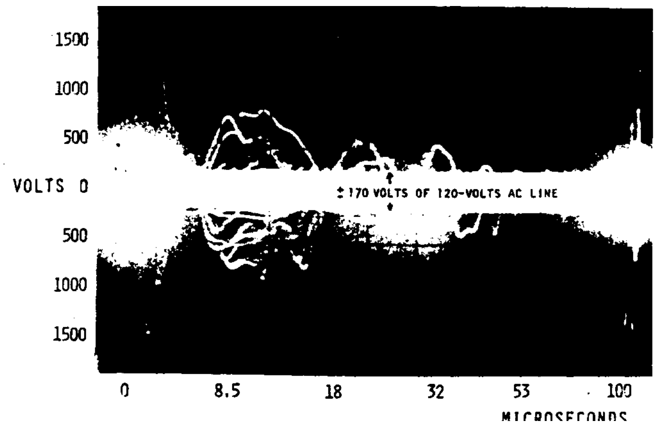

Fig. A4. Composite recording of furnace ignition transformer transients over 24 hours at service box.

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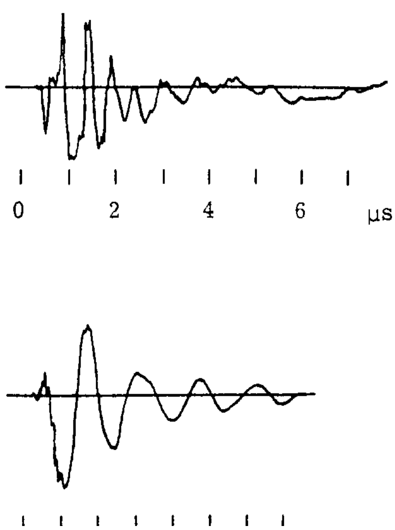

Fig. A5. Typical transients recorded during lightning injection tests on fighter-type aircraft (amplitudes are relative).

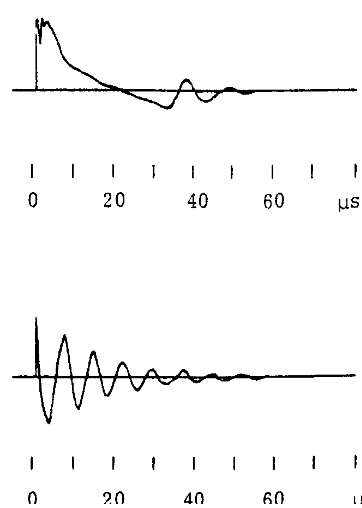

Fig. A6. Typical transients recorded during lightning injection tests on small general aviation aircraft (amplitudes are relative).

Discussion

S.M. Harvey (Ontario Hydro Research Division, Toronto, Canada): This paper provides a clear presentation of the case for a transient interference immunity standard applicable to residential and, presumably, light commercial electronic equipment. Designing transient or surge withstand compatibility into low-voltage equipment is not, of course, a new concept. The telephone companies have been doing it for years. However, the authors have commendably proposed their Transient Control Level concept in the context of a general and down to earth philosophy of testing that should encourage informed discussion.

Following the establishment of Basic Insulation Levels, the electric power industry has not been idle in the area of overvoltage testing of low-voltage equipment. A number of committees, including the Power System Relaying Committee of the IEEE Power Engineering Society and Technical Committee No 41 of the International Electrotechnical Commission have been working for years on the surge testing of static relays used for transmission line protection. The Swedish Electrical Commission has prepared a draft proposal for interference withstand capability testing of apparatus used in power stations and industrial installations. These committees have proposed a range of test waveforms including the familiar 1.2/50 impulse at peak voltages of 1, 3, and 5 kV, a moderately damped 1 MHz oscillatory wave at peak voltages of 0.5, 1, and 2.5-3.0 kV, and a high-frequency spark test at 2 - 4 and 4 - 8 kV.

In 1974, Ontario Hydro introduced a uniform transient immunity test specification for relays and other equipment intended for substation relay or control buildings. The test waveform is a moderately damped oscillatory transient whose frequency 'can be specified in the range of 100 kHz to 2 MHz. One of four test levels, specified in Table I, can be called for. The test is supervised by our Supply Division and manufacturers are encouraged to supply their own test equipment. However, it is still frequently necessary for Ontario Hydro to make its own test generators available.

Table I
Transient Test Levels

Test	Peak Amplitude (Volts)	Source Impedance (ohms)
A	5000	100-500
B	2500	100-150
C	1000	30-50
D	500	30-50

Note that these levels when specified at I 00 kHz are very similar to tests 6 and 9 in Table II of the present paper. Level B, incidentally, when specified at I MHz is equivalent to the IEEE Relay Test [1].

Our experience with the tests, although limited, suggests that minor circuit deficiencies leading to operational upsets are common but that damage is relatively rare. Probably the marginally greatest value of the tests at this time lies in their potential for creating an awareness of the transient problem.

A number of questions being considered at this stage of our transient test program can be rephrased to apply also to the proposals in this paper. Perhaps the authors could comment on the following:

1. What is the advisability of introducing a new test waveform or test procedure in addition to those already in circulation?
2. Would it be necessary to shield the test circuit of Fig. 4 or to locate it, say, 4-6 meters from the equipment under test? In the latter case, should the voltage and current waveforms be measured at the near end or the far end of the connecting cable?
3. Can the test circuit of Fig. 4 correctly simulate transient disturbances that occur when the white wire neutral and the green wire ground are connected together a quarter wavelength from the device under test?
4. Can a reliable certification procedure, particularly in terms of energy deliverable to a load, be established for test generators differing in design from the one shown?
5. Finally, what is the incidence of damage or significant upset to equipment now used in resident at or light commercial environments and does it justify the introduction of transient testing to this class o apparatus? If applied, in view of the data contained in Fig. 2 of the paper, what criterion would be used to select a test level of less than, say 500 volts?

REFERENCES

[1] ANSIC37.9Oa-1974(IEEE Std 472-1974)
Guide for Surge Withstand Capability (SWC) Tests.

Manuscript received August 13, 1975.

E.J. Cohen (U.S. Dept. of Agriculture, Washington, D.C.): We feel the concept expressed in this paper is long overdue in the field of electrical protection of electronic equipment. Experience within the telephone industry has already demonstrated that, with present trends to ever smaller equipment, protection problems can be severely aggravated. The over voltage and current tolerance of microelectric circuits has decreased to the point where protection should be major consideration in circuit design.

Added to this increased equipment vulnerability, we have found a .,communications gap" between the manufacturers of electronic equipment, and the producers of protection devices. When a protection defect is uncovered, we frequently encounter disagreements between the equipment and arrester manufacturers. By establishing "Transient Control Levels," as proposed by this paper, much of this "finger pointing" could be eliminated. As both equipment and arrester manufacturers -should know precisely what the other adequate protection should be minimized.

It is felt that while the concept expressed here is valid, further consideration should be given to the levels and waveshapes involved in the tests. As these parameters may be critical to the workability of this proposal, every effort should be made to generate realistic values.

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Richard F. Hess (Sperry Flight Systems, Phoenix, Arizona): I agree that some form of action is needed to properly assess and overcome the adverse effects of power transients on military and commercial equipment. Assuming a consensus is reached concerning the need for transient control and the adoption of Transient Control Levels (TCL), the following comments are intended to complement the proposal for transient control in low voltage systems.

The voltage specification is based upon measurements which are appropriate to present and past equipment designs. For the most part these designs use devices which present a relatively high impedance to a source of transient energy.

Damage occurs during a power transient when the device breaks down and high to medium voltages are developed across the device while large to medium currents are flowing through it. Standard components are not normally tested under transient conditions, therefore it may be difficult to determine whether they would break down or to assign a confidence level that they would survive such a transient. When a device breaks down, either a voltage or a current viewpoint could be assumed when describing the threat of the power transient to the device.

If in order to conform to a specified TCL a device has been designed to withstand a specified voltage level, then the voltage specification is appropriate. However, a manufacturer designing equipment to meet a specific TCL could adopt an approach which calls for the use of transient power suppression devices (tranzorbs, metal oxide varistors, etc). In this case, transient power surges are manifested as large current surges into equipment (through the protection device) rather than a large voltage transient across the equipment. Even when passing large currents, the network impedances (suppression devices, etc.) will probably be significant enough to produce a natural mode current response within the total network. Thus, current measurement of such a network would contain a significant oscillatory component similar to that present in the voltage measurements.

Two types of TCL specifications should be provided:

1. Voltage
2. Current

Like the voltage specification, the waveform and magnitude of the current specification at each TCL would be based upon the measurement of the current response modes of networks containing power suppression devices and excited by a power transient.

With the two types of specifications, equipment could be designed and tested to withstand a power transient by safely withstanding specified voltage levels or by safely passing specified currents levels. The test equipment for, the voltage specification would be calibrated under open circuit conditions and would be designed to deliver current (in the event of device breakdown) at a level at least as large as that specified in the current specification. The test equipment for the current specification would be calibrated under short circuit conditions and would be designed to provide voltage (in the event of a high impedance) at a level at least as large as that specified in the voltage specification.

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Tests for semiconductor vulnerability (damage) levels using square pulse waveform are common practice with the military. The damage level of many discrete components has been determined an recorded. However, the damped sinusoid pulse is more appropriate to susceptibility testing (transient upset). Depending upon the type of equipment being tested and the frequency content of expected transients, it may be desirable to test using more than one waveform. lower frequency, high amplitude sinusoid (100 KHz) would be used to vulnerability testing and a higher frequency sinusoid (500 KHz, 1 MHz or 10 MHz depending upon the bandwidth of the equipment) would be used for susceptibility testing. At each frequency the equipment shoul be subjected to at least two pulses:

1. Maximum pulse is positive
2. Maximum pulse is negative

As a final observation, testing and test equipment should be kept a simple as possible to avoid adding inordinate costs to the equipment ideally, the degree of confidence obtained by such testing should result in a net reduction in equipment costs (manufacture plus maintenance).

F.A. Fisher and F. D. Martzloff: We appreciate the response of the discussors and will attempt to both respond to their questions and expan somewhat on the protection philosophy we propose. First of all, it should be pointed out that while this paper was written using household appliances as an example and presented before a group largely concerned with utility relaying, the problems of transients pervade the entire field of low voltage electrical and electronic apparatus, including the communication (telephone) industry. One of the areas where th authors have seen a great need for better transient compatibility is i the Aerospace field. Much of the background upon which the TCL concept is based comes from consideration of the transients induced in aerospace vehicles by lightning and other energetic discharges. Designers in the Aerospace community tend not to have had the problem of transients brought as forcibly to their attention as have the designers of relay devices intended to work in the harsh electrical environment of a utility substation. With reference to Mr. Harvey's first question, we feel that it is advisable to introduce new test procedures because th specialized test procedures adapted in the electric utility field may no meet the needs of users in other fields.

Each of the discussors mentions the subject of levels and waveshapes. We suggested the voltage waveshape of Figure 3 of the pape because measurements have indicated that most transients to which electronic equipment is exposed are oscillatory in nature and generally of faster front and tail times than the 1.2×50 microsecond test wave common in the electric power industry. Several other factors influence our choice. One was that the proposed wave is of long enough duratio that breakdown of semiconductor junctions would not be greatly influenced by deviations from the specified waveshape. With much shorter waveshapes, the resistance of semiconductor junctions to burn out becomes strongly influenced by waveshape. Another is that transients of this nature can be injected into wires by rather simple transformer-coupled pulse-injection generators, whereas transformer injection of higher frequency oscillatory voltages and currents is more difficult. Transformer injection of transients has not been discussed in this paper but is sometimes an appropriate means of evaluating the resistance of a device to circuit upset. Mr. Hess mentions the need for two types of TCL specifications: voltage and current. We agree. We have seen instances of groups worrying wastefully about specifications that call for a specific voltage transient to be developed at the terminals of a device when that device had properly been fitted with a low-pass filter, a low impedance suppressor, or transient suppression spark gap Specifications that do not recognize that one can neither develop a voltage across a short circuit nor circulate a current through an open circuit are not only incomplete but mischievous and counterproductive.

With reference to more of Mr. Harveys questions, we feel that any test circuit should be built in a sufficiently well-shielded cabinet so that there is no need to physically separate the test circuit from any device under test. If a test circuit must be located away from the device under test and an interconnecting cable be used, we would think that the generator open-circuit voltage and short-circuit current should be measured at end of the cable nearest the device under test.

We do not really know what would be the interaction between a white wire neutral and a green wire ground if the two were connected together a quarter wavelength away from the generator. We take refuge in the observation that transient coordination is more likely to be achieved through the successful passing of even an imperfect test than it is in the avoidance of all but perfect tests.

We hold no special faith in the virtues of the test circuit shown on Figure 4 of the paper and show it only as one example of various test circuits that might be produced. We feel that a reliable certification procedure not only can be, but must be, based on specifications that are not unique to any one test circuit. It is for this reason that we propose specifications be written in terms of open-circuit voltage and short-circuit currents; a concept that implies a fixed generator impedance. Care must be taken that the voltage and current specifications not be incompatible with the generator impedance. Since the writing of this paper another paper discussing the impedance of AC wiring circuits has been published [1]. Based on this paper, we would now propose that the internal impedance of a transient generator be 50 ohms paralleled by 50 microhenries. Figure 1, reproduced from the referenced paper with the permission of the author, shows how the impedance of the line ("the mains") can be closely approximated by the parallel combination of 50 ohms and 50 microhenries. Levels and waveshapes appropriate to such an impedance might then appear as shown in Figure 2 and Table 1.

As Messrs. Cohen, Harvey and Hess emphasize, the choice of appropriate levels is crucial to the successful implementation of a TCL philosophy. While a TCL of 5000 or 6000 volts might be appropriate to high reliability utility relays or a safety-oriented consumer product such as the Ground Fault Circuit Interrupter, it might impose an unnecessary economic hardship on a high volume item intended for routine household use. Likewise, while a TCL of 500 volts might be too low for residential purposes, it might be appropriate for the power inputs of electronic equipment used in aircraft, and excessively high for the signal inputs of data processing equipment intercommunicating through well-shielded signal wires.

Since of the major purposes of this paper is to promote discussion, it is appropriate to list some of the questions the authors have posed to themselves during the formulation of this proposal:

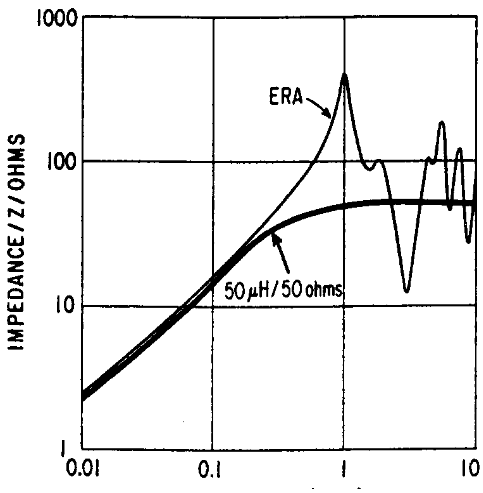

Fig. 1. Comparison of impedance measurements made by the Electrical Research Association (ERA) on the impedance of power systems with a network of 50 ohm & 50 μH in parallel

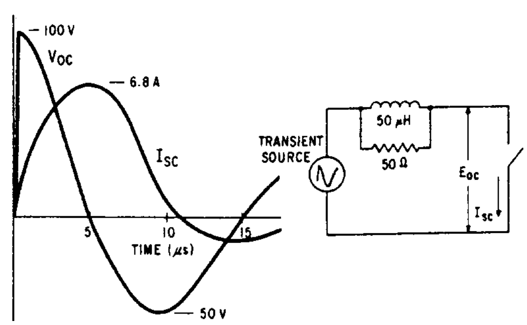

Fig. 2. Short-circuit current (I_{SC}) resulting from a transient source with V_{OC} open-circuit voltage and 50 Ω//50 μH source impedance.

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TABLE 1

Proposed Transient Control Level Number	Open-Circuit Voltage Level (volts)	Short-Circuit Current Level (amperes)
1	10	0.68
2	25	1.7
3	50	3.4
4	100	6.8
5	250	17
6	500	34
7	1000	68
8	2500	170
9	5000	340

— Are there sufficient problems relating to transient coordination to warrant an effort, likely to be major and long term, to achieve better coordination between the transients to which equipment is exposed, and the ability of equipment to withstand such transients?

— Would transient control level (or some other) specifications and standards help achieve successful transient coordination between equipment manufacturers, utilities and equipment users?

— Should there be a limited number of fixed levels? The authors feel that it is essential that the number of levels be limited, perhaps to 9-15 levels distributed in a geometric progression over the range 10-5000 volts. The assignment of the levels may have -to be done arbitrarily. This need not be cause for alarm. The electronic industry for years has worked successfully with resistor and capacitor values produced according to an arbitrarily selected geometric progression.

— Should these levels reflect the system voltage, the expected reliability of the equipment function, the environment?

— What kind of source impedance is appropriate? As mentioned above, an impedance of 50 ohms paralleled by 50 microhenries may be appropriate.

— Should open-circuit voltage and impedance be stated or, alternatively, should open-circuit voltage and short-circuit current be specified?

— Is one impedance value suitable for the majority of the systems?

— What waveshape is appropriate, for voltage as well as current? For damage, we are mostly concerned with energy and front-ofwave but if upset (interference) is to be included in TCL, then do we need to specify a frequency spectrum?

REFERENCE

[1] "Impedance of the Supply Mains at Radio Frequencies", J. H. Bull, Proceeding of 1st Symposium on EMC, Montreux, May 1975.