Transient Control Levels:
A Better Way to Voltage Ratings in Power Converter Applications

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Significance
Part 6: Textbooks, tutorial, and reviews

A tutorial paper presented to the IEEE Industry Applications Society, as a complement to a parallel paper presented to the IEEE Power Engineering Society in 1976 (see the file "TCL Proposal") and to the international EMC community (see the file"TCL philosophy"). Includes a detailed description of the "Ring Wave" and possible generator circuits to produce this novel (at the time) waveform.

TRANSIENT CONTROL LEVELS
A BETTER WAY TO VOLTAGE RATINGS IN POWER CONVERTER APPLICATIONS

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Abstract

Failure and circuit upset of electronic equipment caused by transients has now been recognized as a significant obstacle to the development of new systems. While designers have recognized the problem and are taking steps to deal with it in their own systems, there is a lack of overall coordination beyond the confines of a given black box. The total environment must be considered in contrast to the present approach where electronic power and control equipment is all too often designed, built, and delivered before the transient threat is dealt with.

The authors transient control level (TCL) philosophy provides an approach toward coordination of the intrinsic capability of equipment to withstand overvoltages, the capability of existing or future protective devices for limiting overvoltages, and the known or assumed characteristics of surge voltages in power systems. Examples of this coordination, for general applications as well as for a specific power converter circuit, are given at the end of the paper. The paper also discusses the evolution of the TCL philosophy since its initial disclosure.

INTRODUCTION

Present standards do not offer sufficient guidance to designers and manufacturers of electronic equipment regarding what types of transients to consider and how to prove that equipment works in the presence of transients. This situation is perhaps under better control in the electric power field than it is in the fields of aerospace, general industry, housewares, and the military. For instance, the Working Group on Surge Voltages in AC Power Circuits Rated 600 Volts and Less, of the IEEE Surge Protective Devices Committee, has been collecting data on the occurrence of surges for several years. This group is now in the process of preparing a guideline document describing the transient environment [1]. The IEEE Power System Relaying Committee also has collected information on the surges found in power substations and has developed the Surge Withstand Capability (SWC) test [2]. Transient insulation coordination is well developed with regard to high voltage apparatus. Insulation structures are designed to meet specific industry standard transient levels, and the equipment is subjected to proof tests. The design levels are coordinated with the capabilities of existing surge protective devices. 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. In fact, there may not be a satisfactory answer to the problem posed by transients when retrofit situations are involved.

In an attempt to improve the situation, where existing standards do not offer sufficient guidance, the authors have proposed the concept of transient control levels [3], patterned after the basic insulation level (BIL) approach which has been utilized very successfully in the electric utility field to coordinate the withstand capability of equipment, the surge-limiting ability of suppressors (surge arresters), and the overvoltage/overcurrents encountered in power systems.

Therefore, it will be useful to briefly review the concept of insulation coordination, and the procedures developed to verify satisfactory performance, in the power/utility industry.

THE CONCEPT OF INSULATION COORDINATION

As a result of the mature philosophy of insulation coordination, power equipment achieves its resistance to lightning-induced transients not so much from being designed to the threat posed by lightning, but by the threat posed by acceptance test. This acceptance test does not subject the equipment to transients having the complex waveshapes produced by lightning. Instead, the equipment is subjected to transients which have elementary waveshapes that can be produced by basically simple test apparatus. Furthermore, the acceptance test does not subject the equipment to transients of the amplitude produced by lightning. However, it does subject the equipment to transients having an amplitude consistent with the capabilities of existing surge-protective devices. If it is intended that suppression devices be used to control the magnitude of the voltage transient, one should be sure there are suitable devices before the level is selected.

The basic concept, which needs to be mutually accepted by both manufacturers and users of equipment, is that it is impossible to simulate all of the possible transient overvoltages a given product line might experience. However, by designing the equipment to a certain standard and controlling the occurrence of overvoltages by suitable protection, a much greater chance of successful operation in the real world is obtained.

The challenge is to select a standard for the withstand capability of the equipment that will reflect the real world and yet be simple enough to be practical. The other difficulty is to trade off the specification of ultra-conservative standards that insure a very high reliability for the equipment, but impose on the manufacturer (and therefore on the user who pays for the equipment) unnecessary costs.

THE TRANSIENT CONTROL LEVEL CONCEPT

Three basic parameters that relate to the amplitude of the surge, the waveshape of the surge, and the energy content of the surge must be considered. The amplitude and energy content depend, to some degree, on the nominal operating voltage of the system on which the surge may appear. Higher amplitude and higher energy surges are found on higher voltage systems. The waveshape and amplitude of the surge depend, to some extent, on the origin of the surge and how far away the point of observation is from the origin. Surges produced by arcing contacts tend to involve faster rates of change than surges produced by lightning. The latter, in turn, tend to have slower rates of change than surges produced by arcless switching of highly inductive circuits. Surges originating remote from an observation point tend to have slower rates of change than surges originating close to the point of observation. There is no "typical" surge.

On the premise that even an imperfect approach to transient coordination is better than none, two of the authors of this paper recently proposed the transient control level philosophy. In the paper [3] in which the philosophy was presented, a request was made for feedback about some of the details of the philosophy. Some of the feedback indicates that modifications to the test waveshapes and levels originally presented might be in order. The essential elements of the philosophy remain the same and are reiterated below.

The amplitude and energy content of the surge are defined in terms of the voltage produced by the surge across an open circuit and the current produced by the surge through a short circuit. A specified open circuit voltage and short circuit implies a definite impedance of the source from which the surge originates. This impedance is usually reactive. Observations by Bull [4] and others suggest that a reasonable impedance for 115-VAC circuits is 50Ω paralleled by 50 μH (Figure 1). In the absence of other information, the authors suggest that a TCL philosophy be built around this impedance. This combination of elements has a breakpoint (ωL = R) at 159 kHz, which may be difficult to implement in a simple surge generator. The important points about the source impedance are that the impedance should be in the order of 50Ω resistive at high frequencies and 50 μH inductive at low frequencies.

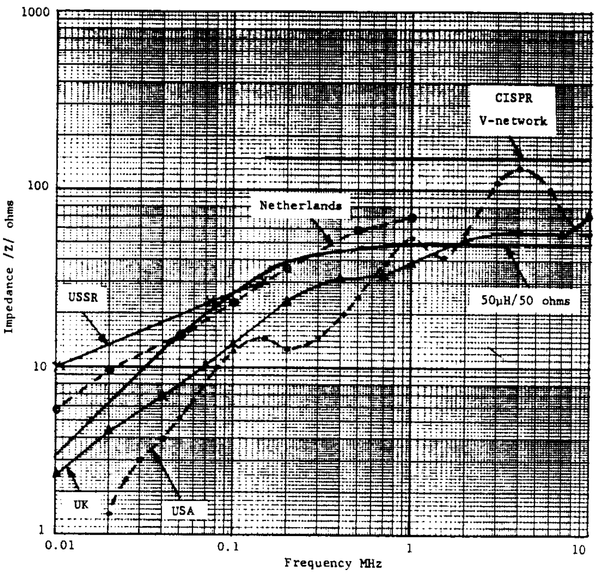


Figure 1. Impedance of Low Voltage Circuits (From reference 4)

Consideration of waveshapes is of great importance. Two types of waveshapes enjoy some prominence. The first is the 1.2 × 50 μs unidirectional voltage which is the basis of the BIL system of insulation coordination and whose historical origin comes from studies of the effects of lightning on high voltage power lines. The second is the highly oscillatory (1.5 MHz) SWC voltage waveform. The latter waveshape has its origins in the transients produced by switching operations in high voltage substations. Experience has proven that neither of these types of waveforms is a good representation of the types of transients found in 115-VAC circuits and other circuits of similar physical construction. The typical surge is oscillatory, but of a frequency lower than that specified for the SWC test.

In the previous paper [3], the authors suggested a voltage test wave of the characteristics shown in Figure 2. That particular test wave had its origins in the Space Shuttle program and was originally viewed as a short duration surge predominantly unidirectional. It was not intended that the surge be oscillatory; but some degree of oscillation was considered allowable. If treated as a damped oscillatory surge, Figure 2 implies an oscillatory frequency of about 50 kHz. After considering other studies and feedback from readers of the original paper [3], it seems more appropriate to emphasize the oscillatory nature of the surge, rather than to downplay it, and to specify the surge in terms of its oscillatory frequency rather than in terms of the duration of the first quarter cycle. A specification that may more nearly meet the requirements of the industry is shown in Figure 3.

The important characteristics include an initial rate of change sufficient to stimulate the dv/dt effects in semiconductors and inductive components with an oscillatory decay, a decrement typical of that observed in low voltage circuits, and a duration comparable with clock cycles in digital equipment. The duration of the original and revised waveforms have also been chosen after consideration of the failure modes of semiconductors. Failure characteristics tend to be different if the semiconductors are exposed to much shorter duration. Finally, the waveforms can be produced with simple test equipment. An example of a test circuit is shown in Figure 4. An example of the open circuit voltage and short circuit current produced by this circuit is shown in Figure 5.

It should be understood that the TCL philosophy is not written around any particular test circuit. Any circuit that produces open circuit voltage and short circuit current of the characteristics shown in Figure 3 and has an internal impedance similar to that of

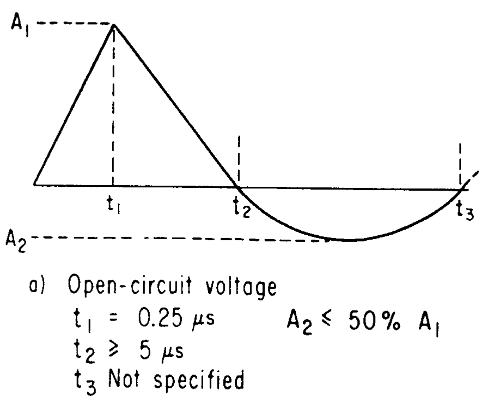


Figure 2. First Proposal for TCL Wave Shape

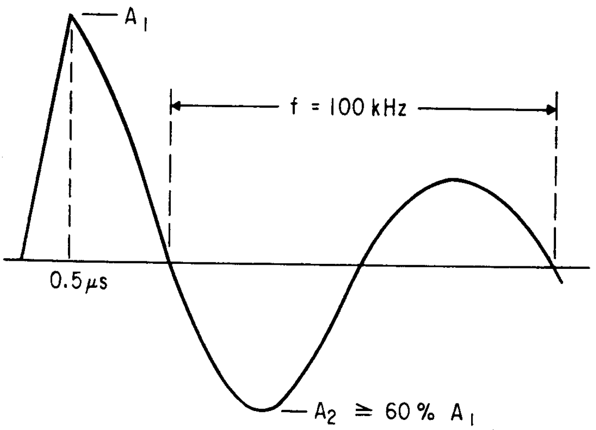


Figure 3. Alternative Proposal for TCL Wave Shape

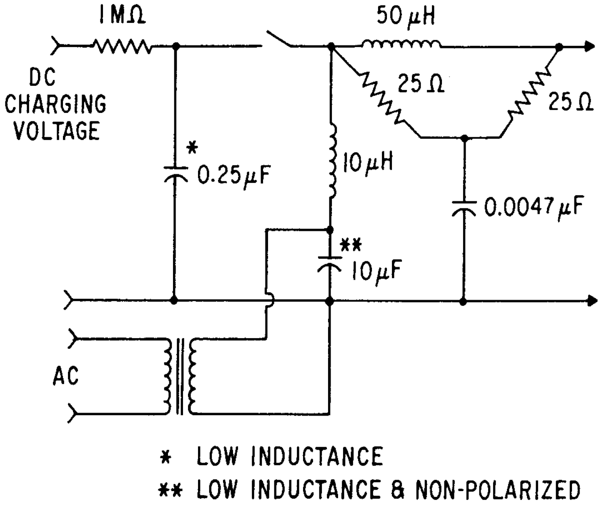
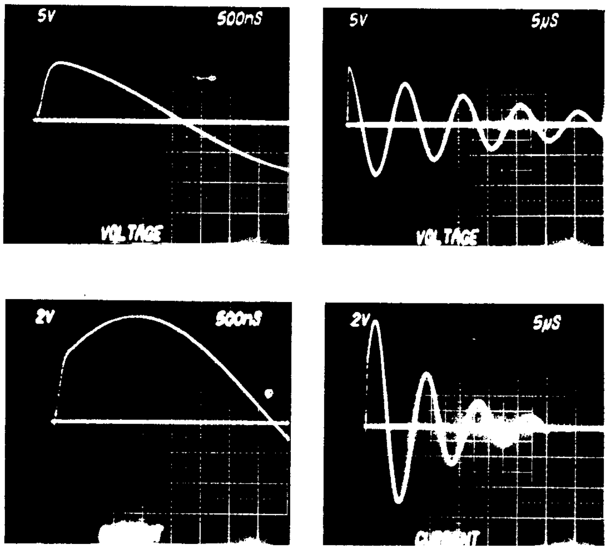


Figure 4. One Example of TCL Generator

Figure 1 would be equally satisfactory. The calculated impedance characteristics of the circuit shown in Figure 4 are shown in Figure 6. If losses had been considered in the calculations, the height of the resonance peak would have been reduced to 100 or 200Ω.



Voltage - 1000 V/major div.
Current - 40 A/major div.

Figure 5. Output Characteristics of TCL Generator

For a standard to be practical, there must be a limited number of test levels reflecting system voltages and application requirements. The authors propose that the levels shown in Table 1 be defined. The table is based on a geometrical progression and deliberately includes, but is not limited to, levels having the magnitudes 600, 3000 and 6000 V specified in other standards [2,5, and 7]. Intermediate levels, if needed, should also be based on a geometric progression.

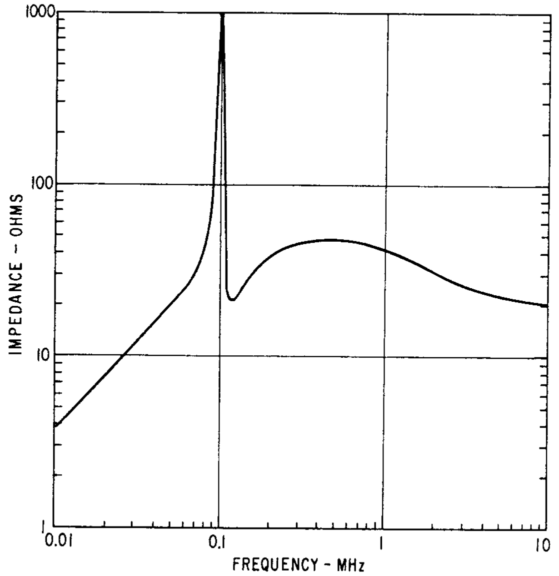


Figure 6. Calculated Impedance of TCL Generator

A concept requiring emphasis is that the definition of a series of levels from which a choice of a level may be made is a task separate and distinct from the task of choosing which level is appropriate for any particular application. This latter choice must reflect the nature of the application and the consequences of a failure, as well as the exposure of the power system. For instance, a low cost domestic appliance, produced under strong competitive pressure, cannot be expected to offer the same degree of transient withstand capability as a critical industrial system.

Table 1

POSSIBLE TRANSIENT CONTROL LEVELS

Level Number	Open Circuit Voltage Level (volts)	Short Circuit Current Level (amperes)
1	60	2.2
2	150	5.4
3	300	11
4	600	22
5	1500	54
6	3000	110
7	6000	220

It is unlikely that a single surge waveshape, such as that of Figure 3, can meet all of the needs of a mature TCL system any more than the 1.2 × 50 μs waveshape meets all of the needs of the BIL system. For many applications other waveshapes may be needed. The authors suggest that the 1.2 × 50 μs unidirectional and the SWC waveshapes be considered as part of the TCL family of waveshapes. The family would then consist of:

1. A relatively slow, low amplitude overvoltage, representing switching transients and some fault clearing transients. This may be the unidirectional 1.2 × 50 μs waveform from the BIL system.
2. A composite waveshape, including a fast rise time and oscillatory decaying tail. This will test some dv/dt effects as well as the energy handling capability of suppressors. This would be the waveshape shown in Figure 3.
3. A very fast burst-type oscillation, such as the current SWC test. This will test devices against dielectric failures as well as electromagnetic interference.

Depending upon the application, the degree of reliability required, and the available knowledge of the environment, one or more of these three tests could be specified for a particular system.

EXAMPLES OF TCL SELECTION

Two examples of TCL selection are presented: one leads to the selection of one of the proposed levels of Table 1 and the other does not. The first example deals with ground fault circuit interrupter (GFCI) devices. A combination of field experience, qualification testing [6], and *a priori* requirements has indicated that these devices should not functionally fail at 6 kV and should not experience nuisance tripping when exposed to 3 kV transients [7].

The type of transients to which these devices are most apt to be exposed are shown in Figure 5. A TCL of 6 kV (Level 7) would be appropriate for qualification testing of devices unprotected by circuit protection devices. However, protection devices that can clamp transients to 3 kV or less are available. A production test might be run at the 3 kV level on interrupters fitted with protective devices. The purpose of the test would be to demonstrate that the protective devices could withstand the current surge associated with a TCL of 6, rather than demonstrate that the GFCI could withstand 3 kV at its terminals.

An example of a specialized system in which the proposed subdivision of levels shown in Table 1 may be too coarse in the static power converter shown in Figure 7. In a static power converter, the voltage transients are best separated into three frequency ranges or transient durations. High frequency transients (tens of microseconds duration) are basically lightning-related transients and some load switching transients. Medium frequency transients (hundreds of microseconds duration) include power system switching surge transients as well as SCR commutating transients. Low frequency transients (milliseconds duration) are confined to 60-Hz overvoltages and leg fuse clearing voltages.

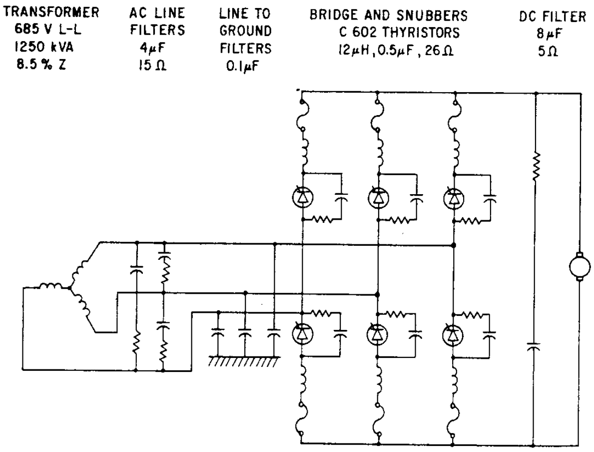
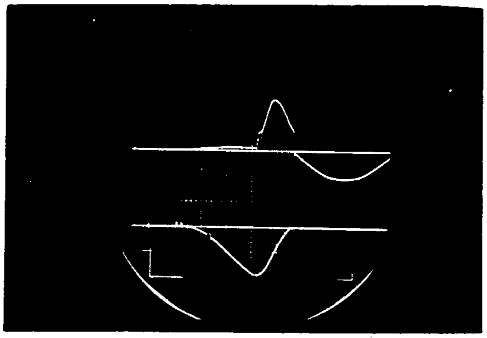


Figure 7. Converter Bridge circuit Used in Fuse-Clearing Transient Tests

The high frequency transients enter the system by capacitive coupling through the transformer and have relatively high source impedance (50 to 100Ω). The waveshape of Figure 3 is very appropriate for simulation of these effects. The medium and low frequency transients are inductively coupled or generated in the secondary winding and have fairly low source impedances (0.1 to 0.001Ω). Such waves primarily stress insulation and semiconductors. The 1.2 × 50 μs waveshape would be appropriate for simulation of these effects.

Basically, the TCL selected for the power converter will be an economic compromise between the cost of high transient withstand capability in the equipment and the cost of suppressor devices. Two limiting possibilities exist: 1) design the equipment (basically SCR reverse voltage ratings) to withstand the highest transient expected or; 2) design the equipment to withstand only the peak reverse operating voltage and clamp all transients to that level.

Nominal peak reverse voltage for the bridge is 1000 V. Commutating voltage spikes would normally reach 1300 V. If these spikes were suppressed to 1200 V with a nonlinear varistor material, the varistors would be subjected to transient currents of 10 to 20A, and there would be about 50W of continuous power released in the varistors. Single pulse transients, such as these generated when a leg fuse is called upon to interrupt a short circuit, can reach 1600 to 1800 V. (Figure 8). Suppressing these transients to a 1200 V level would require that the suppressors handle 10 to 20 kA. High frequency transients, such as those produced by lightning or arcing contacts on switches, can reach 5000 These transients can be easily suppressed to a 2000 V level with suppressors capable of handling about 100A.



Upper trace: Line-to-line voltage, 800 V/div
Lower trace: Line current, 9.6 kA/div
Sweep: 2 ms/div

Figure 8. Transient Produced by Fuse Blowing in Converter Circuit of Figure 7

The proposed standard TCL's of 1500, 3000, and 6000 (based on a $\sqrt[3]{10}$ progression) are not well adapted for this application. If SCR's of 1300 PIV were used, the transients associated with a 1500 V TCL would exceed the PIV and transients could only, with difficulty, be suppressed to 1500 V in the first place. Transients could easily be suppressed to a 3000 V level, but the cost of SCR's with a PIV of 3000 V would be very high. Silicon controlled rectifiers with a PIV of 1800 V are another possibility. These could be tied into a TCL progression based on $\sqrt[6]{10}$. Appropriate levels, rounded to convenient values, would be 600, 1000, 1500, 2000, 3000, and 4500 V. An economically appropriate TCL for the power converter might then be 2000 V.

ACKNOWLEDGMENTS

Helpful comments and suggestions on the TCL proposal have been received since the closing of the reference 3 paper. The feedback from Messrs. H.A. Gauper of Corporate Research and Development, General Electric Company, P. Richman of KeyTek Instrument Corp., A.W. Smoot of Underwriter's Laboratories, and P.D. Speranza of Bell Telephone Laboratories are gratefully acknowledged.

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