The Development of a Guideline on Surge Voltages in Low-Voltage AC Power Circuits

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Significance:
Part 2 Development of standards – Reality checks

Progress report to the IEEE PES community on the development of what became IEEE Std 587-1980.
Explains the proposition that a Ring Wave should be added to the traditional unidirectional impulses
NOTE Parallel presentation of the subject made to the European EMC community under the title "*A Guideline on Surge Voltages in AC Power circuits rated up to 600 V*"

A 79 428-4

THE DEVELOPMENT OF A GUIDELINE ON SURGE VOLTAGES IN LOW-VOLTAGE AC POWER CIRCUITS

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Abstract - Surge voltages in ac power circuits become more significant with the increased application of miniaturized electronics in consumer and industrial products. A Working Group of IEEE is preparing a Guideline describing the nature of these surges in ac power circuits up to 600 V.

The paper describes the data base and approach used by the Working Group and the recommendations proposed to represent typical surges, in order to obtain feedback before the final writing of the Guideline.

Two waveforms are proposed, one oscillatory, the other unidirectional, depending on the location within the power system. Recommendations for source impedance or short-circuit current are also included.

INTRODUCTION

Surge voltages occurring in ac power circuits can be the cause of misoperation or product failure for residential as well as industrial systems. The problem has received increased attention in recent years because miniaturized solid state devices are more sensitive to voltage surges (spikes and transients) than were their predecessors.

Although surge voltage amplitudes and their frequency of occurrence on unprotected circuits are well known, their waveshapes and energy content are less well known. On the basis of measurements, statistics, and theoretical considerations, a practical guideline for outlining the environment for use in predicting extreme waveshapes and energy content can nevertheless be established. A Working Group of the Surge Protective Devices Committee is currently developing such a guideline; this paper reports the status of the Guideline, presents the considerations which led to the approach chosen, and provides a possible vehicle for discussion before the final writing and publication of the Guideline.

SCOPE

The Guideline primarily addresses ac power circuits with rated voltages up to 600 V, although some of the conclusions offered could apply to higher voltages and also to some dc power systems. Other standards have been established, such as IEEE 472, *Guide for Surge Withstand Capability (SWC) Tests*, intended for the special case of high-voltage substation environments, and IEEE 28, *Standard for Surge Arresters for ac Power Circuits*, covering primarily the utilities environment. The Guideline intends to complement, not conflict with, existing standards.

The surge voltages considered in the Guideline are those exceeding two per unit (or twice the peak operating voltage) and having durations ranging from a fraction of a microsecond to a millisecond. Overvoltages of less than two per unit are not covered, nor are transients of longer duration resulting from power equipment operation and failure modes. Because these low-amplitude and long-duration surges are generally not amenable to suppression by conventional surge protective devices, they require different protection techniques.

Definitions of terms used in the Guideline are consistent with IEEE Standard 100-1977, *Dictionary of Electrical and Electronic Terms*, 2nd ed.; however, some differences exist. For instance, IEEE Std 100-1977 defines a *surge* as a "transient wave of current, potential or power in the electric circuit"—a definition broader than that used here. *Transient overvoltage* is defined as "the peak voltage during the transient condition resulting from the operation of a switching device"—a definition more restricted than that of the Guideline.

While the major purpose of the Guideline is to *describe the environment*, a secondary purpose is to lead toward standard tests, through an application guide that will be prepared in the future. These standard tests will provide a realistic evaluation of the surge withstand capability of equipment connected to these power circuits. Of necessity, the complex real situation must be simplified to produce a manageable set of standards. One must recognize the unavoidably arbitrary character of any standard and be prepared to accept an imperfect approach which can simplify matters, rather than demand a perfect but unattainable match between the actual situation and the standard.

THE ORIGIN OF SURGE VOLTAGES

Surge voltages occurring in low-voltage ac power circuits originate from two major sources: load switching transients and direct or indirect lightning effects on the power system. Load switching transients can be further divided into transients associated with (1) major power system switching disturbances, such as capacitor bank switching; (2) minor switching near the point of interest, such as an appliance turnoff in a household or the turnoff of other loads in an individual system; (3) resonating circuits associated with switching devices, such as thyristors; and (4) various system faults, such as short circuits and arcing faults. Measurements and calculations of lightning effects have been made to yield data on what levels can be produced, even if the exact mechanism of any particular surge is unknown. The major mechanisms by which lightning produces surge voltages are the following:

(a) A direct lightning strike to a primary circuit injects high currents into the primary circuit, producing voltages by either flowing through ground resistance or flowing through the surge impedance of the primary conductors.

(b) A lightning strike that misses the line but hits a nearby object sets up electromagnetic fields which can induce voltages on the conductors of the primary circuit.

(c) The rapid collapse of voltage that occurs when a primary arrester operates to limit the primary voltage couples effectively through the capacitance of the transformer and produces surge voltages in addition to those coupled into the secondary circuit by normal transformer action.

(d) Lightning strikes the secondary circuits directly. Very high currents can be involved, exceeding the capability of conventional devices.

(e) Lightning ground current flow resulting from nearby direct-to-ground discharges couples onto the common ground impedance paths of the grounding network.

Fast-acting protection devices, such as current-limiting fuses and circuit breakers capable of clearing or beginning to part contacts in less than 2 ms, leave trapped inductive energy in the circuit upstream; upon collapse of the field, very high voltages are generated.

Transient overvoltages associated with the switching of power factor correction capacitors [1] have lower frequencies than the high-frequency spikes with which this document is concerned. Their levels, at least in the case of restrike-free switching operations, are generally less than twice normal voltage and therefore are not of substantial concern here, but should not be overlooked.

On the other hand, switching operations involving restrikes, such as those produced by air contactors or mercury switches, can produce, through escalation, surge voltages of complex waveshapes and of amplitudes several times greater than the normal system voltage. The severest case is generally found on the load side of the switch and involves only the device that is being switched. While this situation should certainly not be ignored, in such a case the prime responsibility for protection rests with the local user of the device in question. However, switching transients can also appear on the line side across devices connected to the line. The presence and source of transients may be unknown to the users of those devices. This potentially harmful situation occurs often enough to command attention.

While the data have been recorded primarily on 120, 220/380, or 277/480 V systems, the general conclusions should be valid for 600 V systems. To the extent that surge voltages are produced by a discrete amount of energy being dumped into a power system, low-impedance, heavy industrial systems can be expected to experience lower peaks from surge voltages than 120 V residential systems, but comparable, or greater, amounts of energy potentially available for deposition in a surge suppressor.

A 79 428-4 A paper recommended and approved by the IEEE Surge Protective Devices Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Summer Meeting, Vancouver, British Columbia, Canada, July 15-20, 1979. Manuscript submitted February 6, 1979; made available for printing April 3, 1979.

OCCURRENCE AND VOLTAGE LEVELS IN UNPROTECTED CIRCUITS

Rate of Occurrence Versus Voltage Level

The rate of occurrence of surges varies over wide limits, depending on the particular system. Prediction of the rate for a particular system is always difficult and frequently impossible. Rate is related to the level of the surges; low-level surges are more prevalent than high-level surges. The relationship between the level and the rate of occurrence of surges is partly caused by the attenuation of the surges as they propagate away from the source of the surge and divide among paths beyond branching points. Equipment at a given point will be subjected to a relatively small number of high-level surges from nearby sources, but to a larger number of surges from more remote sources.

Data collected from many sources have led to the plot shown in Fig. 1. This prediction shows with certainty only a *relative* frequency of occurrence, while the absolute number of occurrences can be described only for an "average location." The "high exposure" and "low exposure" limits of the band are shown as a guide, not as absolute limits, to reflect both the location exposure (lightning activity in the area and the nature of the system) and the exposure to switching surges created by other loads.

The literature describes the frequency of occurrence vs amplitude of lightning strikes, from the low levels of a few kiloamperes, through the median values of about 20 kA, to the exceptional values in excess of 100 kA [2]. Clearly, a secondary arrester rated for 10 kA can protect adequately in case of a mild direct strike, or of a more severe strike divided among several paths to ground. However, a very high and direct strike will exceed the capability of an ANSI-rated secondary arrester [3].

The voltage and current amplitudes presented in the Guideline attempt to provide for the vast majority of lightning strikes but should not be considered as "worst case," since this concept cannot be determined realistically. One should think in terms of the statistical distribution of strikes, accepting a reasonable upper limit for most cases. Where the consequences of a failure are not catastrophic but merely represent an annoying economic loss, it is appropriate to make a trade-off of the cost of protection against the likelihood of a failure caused by a high but rare surge. For instance, a manufacturer may be concerned with nation-wide failure rates, those at the upper limits of the distribution curve, while the user of a specific system may be concerned with a single failure occurring at a specific location under "worst-case conditions." Rates can be estimated for average systems, however, and even if imprecise, they provide manufacturers and users with guidance. Of equal importance is the observation that surges in the range of 1 to 2 kV are fairly common in residential circuits.

From the relative values of Fig. 1, two typical levels can be cited for practical applications. First, the expectation of a 3 kV transient occurrence on a 120 V circuit ranges from 0.01 to 1 per year at a given location - a number sufficiently high to justify the recommendation of a minimum 3 kV withstand capability. Second, the wiring flashover limits indicate that a 6 kV withstand capability may be sufficient to ensure device survival indoors, but a 10 kV withstand capability may be required outdoors.

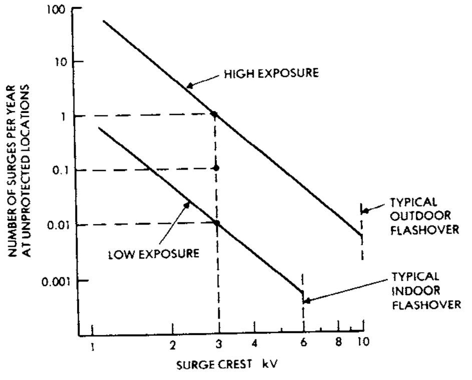

Fig. 1. Rate of surge occurrence vs voltage level.

Timing of Occurrence

Surges occur at random times with respect to the power frequency, and the failure mode of equipment may be affected by the power frequency follow current or by the timing. Consequently, surge testing must be done with the ac voltage applied to the test piece.

Lightning surges are completely random in their timing with respect to the power frequency. Switching surges are likely to occur near or after current zero, but variable load power factors will produce a quasi-random distribution. Some semiconductors, as shown in Appendix II, exhibit failure levels that depend on the timing of the surge with respect to the conduction of power frequency current. Gaps or other devices involving a power-follow current may withstand this power follow with success, depending upon the fraction of the half-cycle remaining after the surge before current zero. Therefore, it is important to consider the timing of the surge with respect to the power frequency. In performing tests, either complete randomization of the timing or controlled timing should be specified, with a sufficient number of timing conditions to reveal the most critical timing.

WAVESHAPE OF REPRESENTATIVE SURGE VOLTAGES

Waveshapes in Actual Occurrences

Indoor - Measurements in the field, measurements in the laboratory, and theoretical calculations indicate that most surge voltages in indoor low-voltage systems have oscillatory waveshapes, unlike the well-known and generally accepted unidirectional waves specified in high-voltage insulation standards. A surge impinging on the system excites the natural resonant frequencies of the conductor system. As a result, not only are the surges typically oscillatory, but surges may have different amplitudes and waveshapes at different places in the system. These oscillatory frequencies of surges range from 5 kHz to more than 500 kHz. A 30 to 100 kHz frequency is a realistic measure of a "typical" surge for most residential and light industrial ac line networks.

Outdoor - Surges encountered in outdoor locations have also been recorded, some being oscillatory, others being unidirectional. The "classical lightning surge" has been established as 1.2 x 50 µs for a voltage wave and 8 x 20 µs for a current wave. Evidence has been collected, however, to show that oscillations can also occur. Lenz [4] reports 50 lightning surges recorded in two locations, the highest at 5.6 kV, with frequencies ranging from 100 to 500 kHz. Martzloff [5] reports oscillatory lightning surges in a house during a multiple-stroke flash.

Because the overriding concern here is the energy associated with these surges, a conservative but realistic description of the surges can be derived from the long-established specified duty of a secondary arrester, as detailed below. While this specification is arbitrary, it has the strength of experience and successful usage.

Selection of Representative Waveshapes

The definition of a waveshape to be used as representative of the environment is important for the design of candidate protective devices, since unrealistic requirements, such as excessive duration of the voltage or very low source impedance, place a high energy requirement on the suppressor, with a resulting cost penalty to the end user. The two requirements defined below reflect this trade-off.

Indoor - Based on measurements conducted by several independent organizations in 120 and 240 V systems (Appendix I), the waveshape shown in Fig. 2 is reasonably representative of surge voltages in these power circuits. Under the proposed description of a "0.5 µs - 100 kHz ring wave," this waveshape rises in 0.5 µs, then decays while oscillating at 100 kHz, each peak being about 60% of the preceding peak.

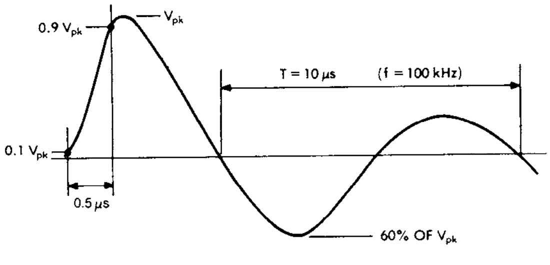

Fig. 2. The proposed 0.5 µs - 100 Hz ring wave (open-circuit voltage).

The fast rise can produce the effects associated with nonlinear voltage distribution in windings and the dv/dt effects on semiconductors. Shorter rise times are found in many transients, but, as those transients propagate into the wiring or are reflected from discontinuities in the wiring, the rise time becomes longer.

The oscillating and decaying tail produces the effects of voltage polarity reversals in surge suppressors or other devices that may be sensitive to polarity changes. Some semiconductors are particularly sensitive to damage when being forced into or out of a conducting state, or when the transient is applied during a particular portion of the 60 Hz supply cycle (Appendix II). The response of a surge suppressor can also be affected by reversals in the polarity, as in the case of RC attenuation before a rectifier circuit in a dc power supply. The pulse withstand capability of many semiconductors tends to improve if the surge duration is much shorter than one microsecond. For this reason, the first half-cycle of the test wave must have a sufficient duration.

Outdoor - In the outdoor and service entrance environment, as well as in locations close to the service entrance, substantial energy, or current, is still available. For these locations, the unidirectional impulses long established for secondary arresters are more appropriate than the oscillatory wave.

Accordingly, the recommended waveshape is 1.2 x 50 µs for open-circuit voltages and 8 x 20 µs for short-circuit current (impulse discharge current) or current in a low-impedance device. The numbers used to describe the impulse, 1.2 x 50 and 8 x 20, are as defined in IEEE Standard 28 - ANSI Standard C62.1; Fig. 3 presents the waveshape and a graphic description of the numbers.

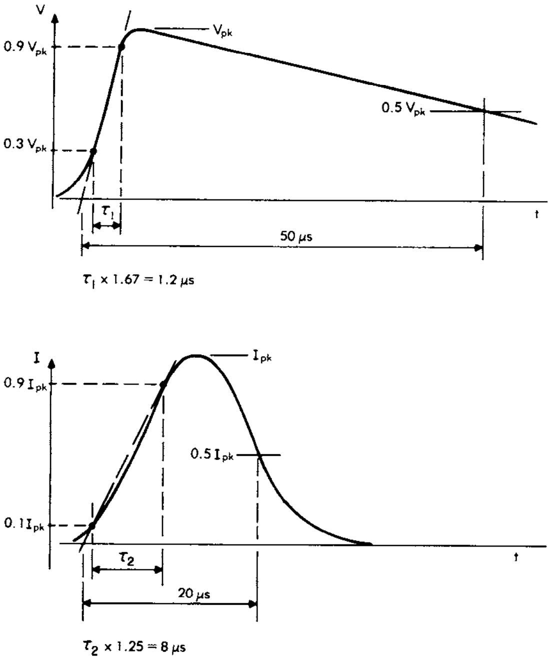

Fig. 3. Waveshapes for outdoor locations.

ENERGY AND SOURCE IMPEDANCE

General

The energy involved in the interaction of a power system with a surge source and a surge suppressor will divide between the source and the suppressor in accordance with the characteristics of the two impedances. In a gap-type suppressor, the low impedance of the arc after sparkover forces most of the energy to be dissipated elsewhere: for instance, in a resistor added in series with the gap for limiting the power-follow current. In an energy-absorber suppressor, by its very nature, a substantial share of the surge energy is dissipated in the suppressor, but its clamping action does not involve the power-follow energy resulting from the short-circuit action of a gap. It is therefore essential to the effective use of suppression devices that a realistic assumption be made about the source impedance of the surge whose effects are to be duplicated.

The voltage wave shown in Fig. 2 is intended to represent the waveshape a surge source would produce across an open circuit. The waveshape will be different when the source is connected to a load having a lower impedance, and the degree to which it is lower is a function of the impedance of the source.

To prevent misunderstanding, a distinction between *source impedance* and *surge impedance* needs to be made. Surge impedance, also called *characteristic impedance*, is a concept relating the parameters of a long line to the propagation of traveling waves. For the wiring practices of the ac power circuits discussed here, this characteristic impedance would be in the range of 150 to 300 Ω, but because the durations of the waves being discussed (50 to 20 µs) are much longer than the travel times in the wiring systems being considered, traveling wave analyses are not useful here.

Source impedance, defined as "the impedance presented by a source of energy to the input terminals of a device, or network" (IEEE Standard 100), is a more useful concept here. In the conventional Thevenin's description, the open-circuit voltage (at the terminals of the network or test generator) and the source impedance (of the surge source or test generator) are sufficient to calculate the short-circuit current, as well as any current for a specified suppressor impedance.

The measurements from which Fig. 1 was derived were of voltage only. Little was known about the impedance of the circuits upon which the measurements were made. Since then, measurements have been reported on the impedance of power systems. Bull [6] reports that the impedance of a power system, seen from the outlets, exhibits the characteristics of a 50 Ω resistor with 50 µH in parallel. Attempts were made to combine the observed 6 kV open-circuit voltage with the assumption of a 50 Ω/50 µH impedance [7]. This combination resulted in low energy deposition capability, which was contradicted by field experience of suppressor performance. The problem led to the proposed definition of oscillatory waves as well as high-energy unidirectional waves, in order to provide both the effects of an oscillatory wave and the high-energy deposition capability.

The degree to which source impedance is important depends largely on the type of surge suppressors that are used. The surge suppressors must be able to withstand the current passed through them by the surge source. A test generator of too high an impedance may not subject the device under test to sufficient stresses, while a generator of too low an impedance may subject protective devices to unrealistically severe stresses. A test voltage wave specified without reference to source impedance could imply zero source impedance - one capable of producing that voltage across any impedance, even a short circuit. That would imply an infinite surge current, clearly an unrealistic situation.

Because of the wide range of possible source impedances and the difficulty of selecting a specific value, three broad categories of building locations are proposed to represent the vast majority of locations, from those near the service entrance to those remote from it. The source impedance of the surge increases from the outside to locations well within the building. Open-circuit voltages, on the other hand, show little variation within a building because the wiring provides little attenuation. Figure 4 illustrates the application of the three categories to the wiring of a building.

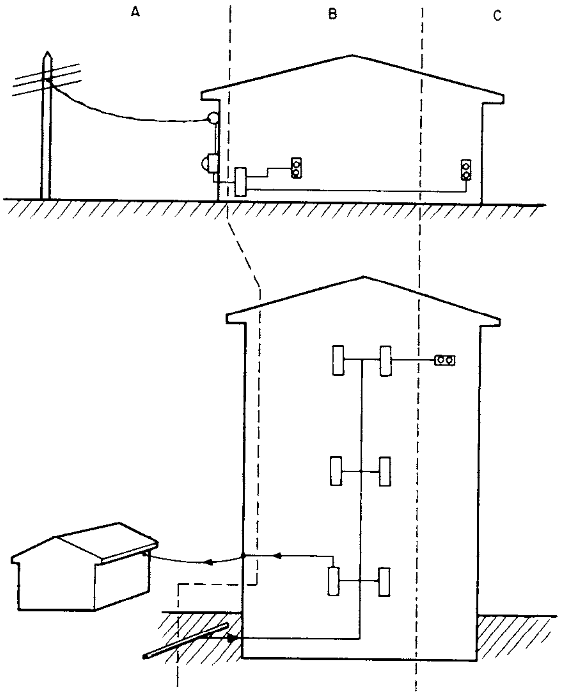

Fig. 4. Location categories.

A. Outside and Service Entrance
- Service drop from pole to building entrance
- Run between meter and distribution panel
- Overhead line to detached buildings
- Underground lines to well pumps

B. Major Feeders and Short Branch Circuits
- Distribution panel devices
- Bus and feeder systems in industrial plants
- Heavy appliance outlets with "short" connections to the service entrance
- Lighting systems in commercial buildings

C. Outlets and Long Branch Circuits
- All outlets at more than 10 m (30 ft) from Category B with wires #14-10

Subcommittee 28A of the International Electrotechnical Commission has prepared a Report [8], in which installation categories are defined. These installation categories divide the power systems according to the location in the building, in a manner similar to the location categories defined in the Guideline. However, there are some significant differences between the two concepts. First, the IEC categories are defined for a "controlled voltage situation," a phrase that implies the presence of some surge suppression device or surge attenuation mechanism to reduce the voltage levels from one category to the next. Second, the IEC report is more concerned with insulation coordination than with the application of surge protective devices; therefore it does not address the question of the coordination of the protectors but, rather, the coordination of insulation levels – that is, voltages.

Surges propagate with very little attenuation in a power system with no substantial connected loads. Measurements made in an actual residential system as well as in a laboratory simulation have shown that the most significant limitation is produced by wiring flashover, not by attenuation along the wires. Ironically, a carefully insulated installation is likely to experience higher surge voltages than an installation where wiring flashover occurs at low levels. Therefore, the open-circuit voltage specified at the origin of a power system must be assumed to propagate unattenuated far into the system, which is the reason for maintaining the 6 kV surge specification when going from one category to an adjacent category farther into the building.

Furthermore, source impedances are not defined in the IEC report. The Guideline attempts to fill this need by specifying several levels of source impedance, or of short-circuit current, for the various categories.

PROPOSED REPRESENTATION OF THE ENVIRONMENT

On the basis of the preceding discussions, the Guideline proposes to reduce the infinite variety of actual conditions to three categories, from the outside service drops to the long branch circuits and outlets.

For each category the most appropriate waveshape is indicated, an open-circuit voltage for high-impedance loads, or a short-circuit current for low-impedance loads. The tabulation that follows shows open-circuit voltages and short-circuit currents for each of the three categories. The energy deposited in a 500 V suppressor has been computed and is shown for each of the categories.

The values shown in the table represent the maximum range, corresponding to the "High Exposure" situation of Fig. 1. For less exposed systems, or when the prospect of a failure is not highly objectionable, one could specify lower values of open-circuit voltages with corresponding reductions in the currents. IEC Category I, not represented in the Guideline, would correspond to line cord-connected devices in this context.

CONCLUSIONS

The broad range of surge voltages occurring in low-voltage ac power circuits can be simulated by a limited set of test waves, for the purpose of evaluating their effects on equipment.

Field measurements, laboratory experiments, and calculations indicate that two basic waves, at various open-circuit voltages and short-circuit current values, can represent the majority of surges occurring in residential, commercial, and light industrial power systems rated up to 600 V rms.

Exceptions will be found to the simplification of a broad guideline; however, these should not detract from the benefits that can be expected from a reasonably valid uniformity in defining the environment. Other test waves of different shapes may be appropriate for other purposes, and the present guideline should not be imposed where it is not applicable.

The Working Group is approaching the final phases of preparation of the Guideline document; comments are solicited from the engineering and user communities. However, readers must recognize the unavoidably arbitrary character of any standard and be prepared to accept an imperfect approach, which can simplify matters and clarify the issues as well as provide uniform evaluations of performances, rather than demand a perfect but unattainable match between the actual situation and the standard.

ACKNOWLEDGMENTS

The concepts presented in this paper have greatly benefited from the informed questions and discussions by members of the Working Group on Surge Voltage in AC Power Circuits Rated 600 V or Less, and from interested reviewers; particular appreciation for effective critiques from Catharine Fisher and Peter Richman is acknowledged. The data base presented in Appendix I has been broadened by the contributions of the Bell Telephone Laboratories and Landis & Gyr, Inc.

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Recommended Surge Voltages and Currents Deemed to Represent the Environment

Location Category	Comparable to IEC SC28A Category	Impulse Waveform	Impulse Maximum* Amplitude	Type of Specimen or Load Circuit	Energy Deposited in a 500 V Suppressor (joules)
A. Outdoor and Service Entrance	IV	1.2 x 50 μs	10 kV o.c.	High Impedance	--
		8 x 20 μs	10 kA s.c.	Low Impedance	150
B. Major Feeders and Short Branch Circuits	III	1.2 x 50 μs	6 kV o.c.	High Impedance	--
		8 x 20 μs	3 kA s.c.	Low Impedance	40
		0.5 μs - 100 kHz	6 kV o.c.	High Impedance	--
			500 A s.c.	Low Impedance	2
C. Long Branch Circuits and Outlets	II	0.5 μs - 100 kHz	6 kV o.c.	High Impedance	--
			200 A s.c.	Low Impedance	0.8

*o.c.: open-circuit voltage s.c.: short-circuit current

APPENDIX I - DATA BASE

Recordings and surge counter data have been contributed from several sources, in addition to the surge counter data obtained by members of the Working Group. Representative oscillograms and summary statistics are reproduced in this appendix, in support of the voltage levels and oscillatory wave proposals.

1. Recordings by Bell Telephone Laboratories

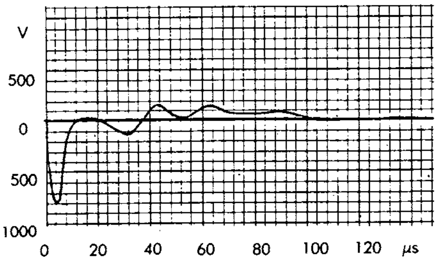
(Data contributed by P. Speranza, internal report, unpublished to date)

1.1 Typical Surge Counter Statistics

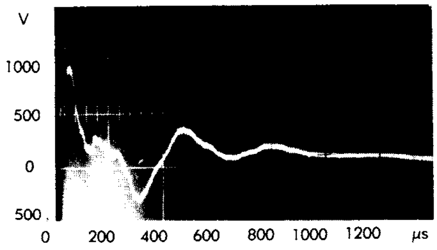
120 V line at BTL facility in Chester, New Jersey, during 42 months of monitoring:

146 counts at 300 to 500 V
14 counts at 500 to 1000 V
3 counts at 100 to 1500 V
3 counts above 1500 V

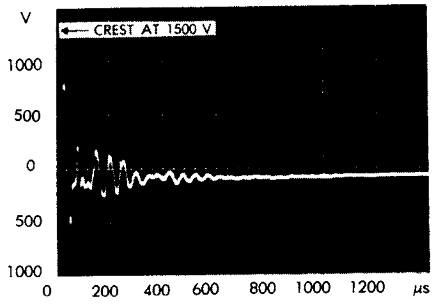
1.2 Typical Automatic Recording Oscilloscopes



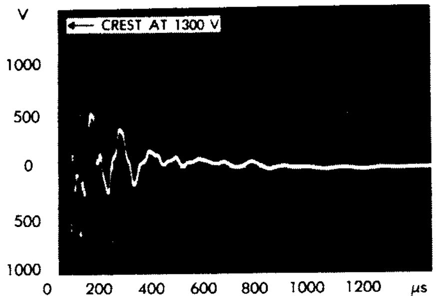
120 V OUTLET, LABORATORY BENCH



277/480 V SERVICE ENTRANCE



277/480 V SERVICE ENTRANCE



277/480 V SERVICE ENTRANCE

2. Recordings by General Electric Company

2.1 Surge Counter Statistics - Martzloff, F.D. and G.J. Hahn, "Surge Voltage in Residential and Industrial Power Circuits, *IEEE Pas-89*, 6, July/August 1970, 1049-1056.

a) Three percent of all U.S. residences experience frequent occurrences (one per week or more) above 1200 V.

b) There is a 100:1 reduction in the rate of device failure when the withstand level is raised from 2 kV to 6 kV.

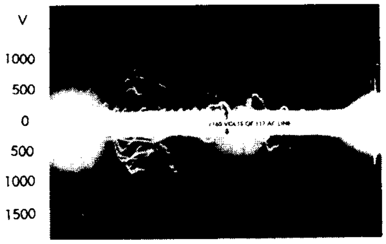
Number of Houses with Repetitive Surge Activity Above 1200 Volts

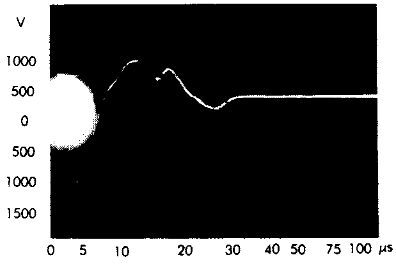
Location	Number of Homes Surveyed	Recording Period (weeks)	Houses with Repetitive Surges
Providence, R. I.	4	2-6	none
Cleveland, Ohio	28	2-4	none
Auburn, N. Y.	12	2-3	none
Lynchburg, Va.	3	2-3	none
Syracuse, N. Y.	8	1-2	1
Chicago, Ill.	23	1-6	none
Ashland, Mass.	24	1-2	1
Holland, Mich.	6	2-10	none
Louisville, Ky.	10	2-6	none
Somersworth, N. H.	50	1-2	1
Plainville, Conn.	5	10	none
Asheboro, N. C.	24	1-2	none
Fort Wayne, Ind.	38	1-4	3
DeKalb, Ill.	14	3-12	none

Surge Counter Recordings Above 1200 Volts (Spring, Summer, and Fall)

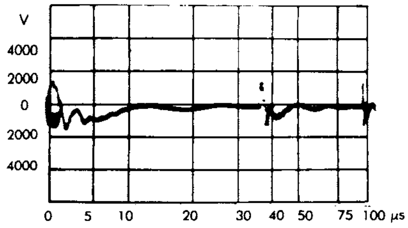
Location	Number of Homes	Total Homes × Weeks	Number of Surges
Providence, R. I.	6	60	1
Ashboro, N. C.	13	85	none
DeKalb, Ill.	11	60	2
Somersworth, N. H.	3	48	1
Chicago, Ill.	12	58	none
Cleveland, Ohio	8	106	1
Decatur, Ill.	12	72	2
Holland, Mich.	7	56	none
Auburn, N. Y.	3	70	none
Springfield, Pa.	1	24	none
Ashland, Mass.	6	72	none
Pittsfield, Mass.	3	60	1
Plainville, Conn.	3	60	none
Lynchburg, Va.	3	15	none
Total	91	846	8 in 8 homes

2.2 Typical Automatic Recording Oscilloscopes

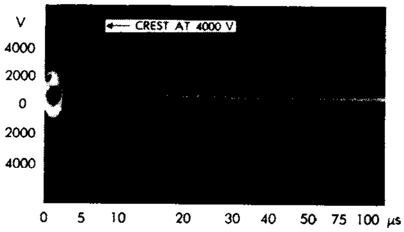




FURNACE IGNITION - SINGLE RECORDING.



SERVICE ENTRANCE, LIGHTNING STORM

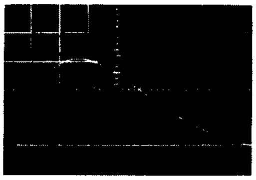


STREET POLE, LIGHTNING STORM

2.3 Simulated Lightning Strokes on a Residential Power Circuit (Laboratory Model of System) - Martzloff, F.D. and K.E. Crouch, "Coordination De La Protection Contre Less Surtensions Dans Les Réseaux Basse Tension Résidentiels," *Proceedings, 1978 IEEE Canadian Conference on Communications and Power, 78CH1373-0*, pp. 451–454.

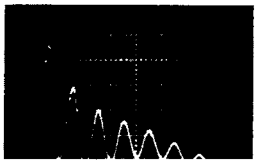
1.5 kA current impulse (8 x 20 μs approx.) is injected in ground wire only of service drop. (Higher currents produce flashover of wiring.)

500 A/div
5 μs/div



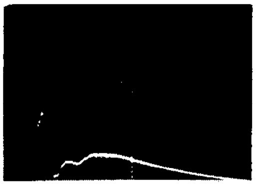
Recording of open-circuit voltage at a branch circuit outlet: 2200 V peak 500 kHz oscillations

500 V/div
2 μs/div



By connecting a 130 Ω load at the same outlet (1 A load) the voltage is reduced to 1400 V peak, with more damping.

500 V/div
2 μs/div



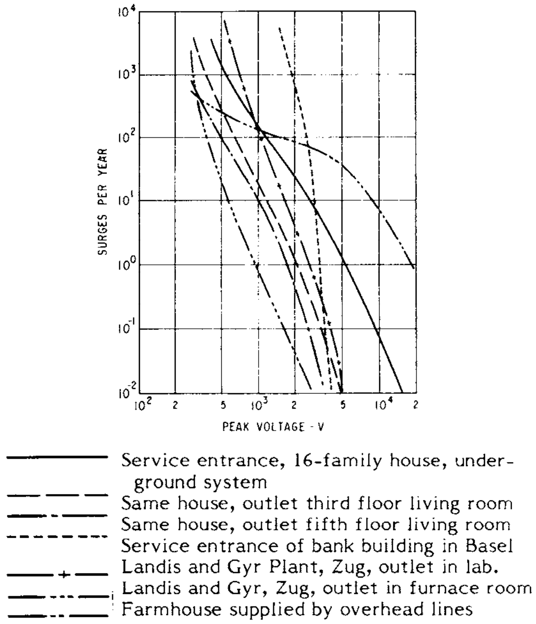
Conclusions from this test series

1. A current of 1.5 kA (moderate for a lightning discharge injected in the ground system) raises the wiring system of the house 2.2 kV above ground. Four kiloamperes (still a moderate value) will bring this voltage to 6 kV, the typical flashover value of the wiring.
2. A natural frequency of 500 kHz is excited by a unidirectional impulse.
3. In this example, the source of the transient (from the loading effect of 130 Ω) appears as

$$Z = 130\,\Omega\left[\frac{2200}{1400} - 1\right]$$
$$= 75\,\Omega$$

3. Statistics by Landis & Gyr, Inc.

Surge counter data on various locations in Swiss 220 V systems (Data contributed by L. Regez - unpublished to date)



Frequency of Voltage Transients per Year as a Function of the Peak Value of the Voltage Transient for a 220 V, 50 Hz Distribution System with Grounded Neutral

4. Working Group Surge Counter Statistics

Surge counters with four threshold levels (350, 500, 1000, and 1500 V) were made available to the Working Group by Joslyn Electronic Systems, for recording surge occurrences at various locations. Members of the Working Group installed these on 120 and 240 V systems of various types, including the following: outlets in urban, suburban, and rural residences; outlets in a hospital; secondary circuits on distribution system poles (recloser controls); secondary of pad-mounted distribution transformers; lighting circuits in an industrial plant; life test racks at an appliance manufacturer; bench power supply in a laboratory.

Limitations on the availability of personnel and communications made this sampling less than optimum from a statistical point of view. However, by computing weighted averages for each location, one can quote an acceptable overall average; this average has been included in the graph drawn to establish the low and high exposure limits.

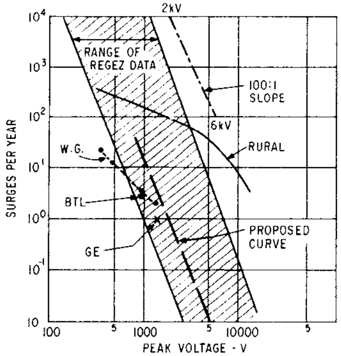
Summary Statistics of these measurements are as follows:

1. Data base from 18 locations with a total recording time of 12 years spread over 4 calendar years, using 6 counters.
2. Number of occurrences per year (weighted averages) at "average location."
    - 350 V: 22
    - 500 V: 11
    - 1000 V: 7
    - 1500 V: 3
3. Significant extremes
    - One home with large number of surges caused by washer operation
    - Four locations out of 18 never experienced a surge.
    - One home experienced several occurrences above 1500 V, with none below that value.
    - One industrial location (switching of a test rack) produced thousands of surges in the 350-500 V range, and several surges in excess of 1500 V. This location was left out of the average computation, but it exemplifies a significant extreme.

From the data base cited in the preceding pages, one can draw the chart below, including the following information on voltage vs frequency (rate) of occurrence:

1. The Bell Laboratories data yield a point of 1000 V at about 2 occurrences per year (●).
2. The General Electric counter statistics yield a point of 1200 V at about 1 occurrence per year (x).
3. The General Electric clock data indicate a *slope* of 100:1 from 2 kV to 6 kV (—·—).
4. The Regez data provide a band for the majority of locations (shown cross-hatched), with the exception of the rural location with long overhead line, which has more occurrences.
5. Working Group statistics (•—•—) indicate a less steep slope, perhaps because of the influence of outdoor locations included in the sample (similar to the rural data of Regez).

The proposed curve, which is the center of the ±10 range of Fig. 1 in the Guideline, is shown in bold dashed lines (— —). It has been drawn at the 100:1 slope, passing near the Bell and General Electric points and located within the band of the Regez data.

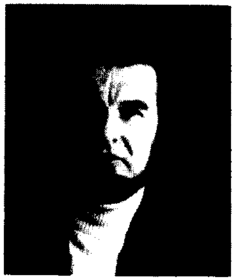


APPENDIX II - EFFECT OF TRANSIENT POLARITY REVERSALS ON SEMICONDUCTORS

Breakdown of semiconductors under various conditions of load and transient overvoltage applications has been investigated.*† Evidence is presented in the two investigations cited that a reverse voltage applied during the conduction period of the power frequency produces *lower* breakdown voltage than the application of the same transient with no load or during blocking. Examples are given below, taken from these two investigations, showing statistically significant differences in the voltage levels.

		Average Breakdown (V)
IN1190 Diode*	Transient at no load	1973
	Fast wave under load	830
	Slow wave under load	1097
IN2160 Diode*	Transient at no load	2056
	Fast wave under load	894
	Slow wave under load	1106
IN679 Diode †	Transient applied at:	
	- peak of reverse voltage	1766
	- 25° after start of conduction	1181
	- 90° after start of conduction	906
	-155° after start of conduction	1115

This effect is one of the reasons for selecting an oscillatory waveform to represent the environment: it will be more likely to induce semiconductor failures than a unidirectional wave. Also, it shows the significance of the timing of the transient application with respect to the power frequency cycle.



Francois D. Martzloff (M, 1956) was born in France and received his undergraduate degree at the Ecole Spéciale De Mécanique et d'Electricité in 1951; he received the MSEE degree from Georgia Tech in 1952 and the MSIA degree from Union College in 1971.

Since 1956 he has been with the General Electric Company, where he first gained experience in the Transformer and Switchgear Divisions. Upon joining General Electric Corporate Research and Development in 1961, he became involved in power semiconductor circuits and overvoltage protection. He has participated in the introduction and application of metal oxide varistors since 1971.

In IEEE Mr. Martzloff has been active on the Surge Protective Devices Committee and chairman of the Working Group on Surge Voltages in AC Power Circuits Rated 600 V or Less. He is also a member of the Ad Hoc Advisory Subcommittee of the USA Advisory Committee on IEC S/C 28A. He has been awarded 10 U.S. patents, primarily in the field of varistors and transient protection.

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*Chowduri, P., "Transient-Voltage Characteristics of Silicon Power Rectifiers." *IEEE IA-9, 5*, September/October 1973, p. 582.

†F.D. Martzloff, internal report, unpublished.