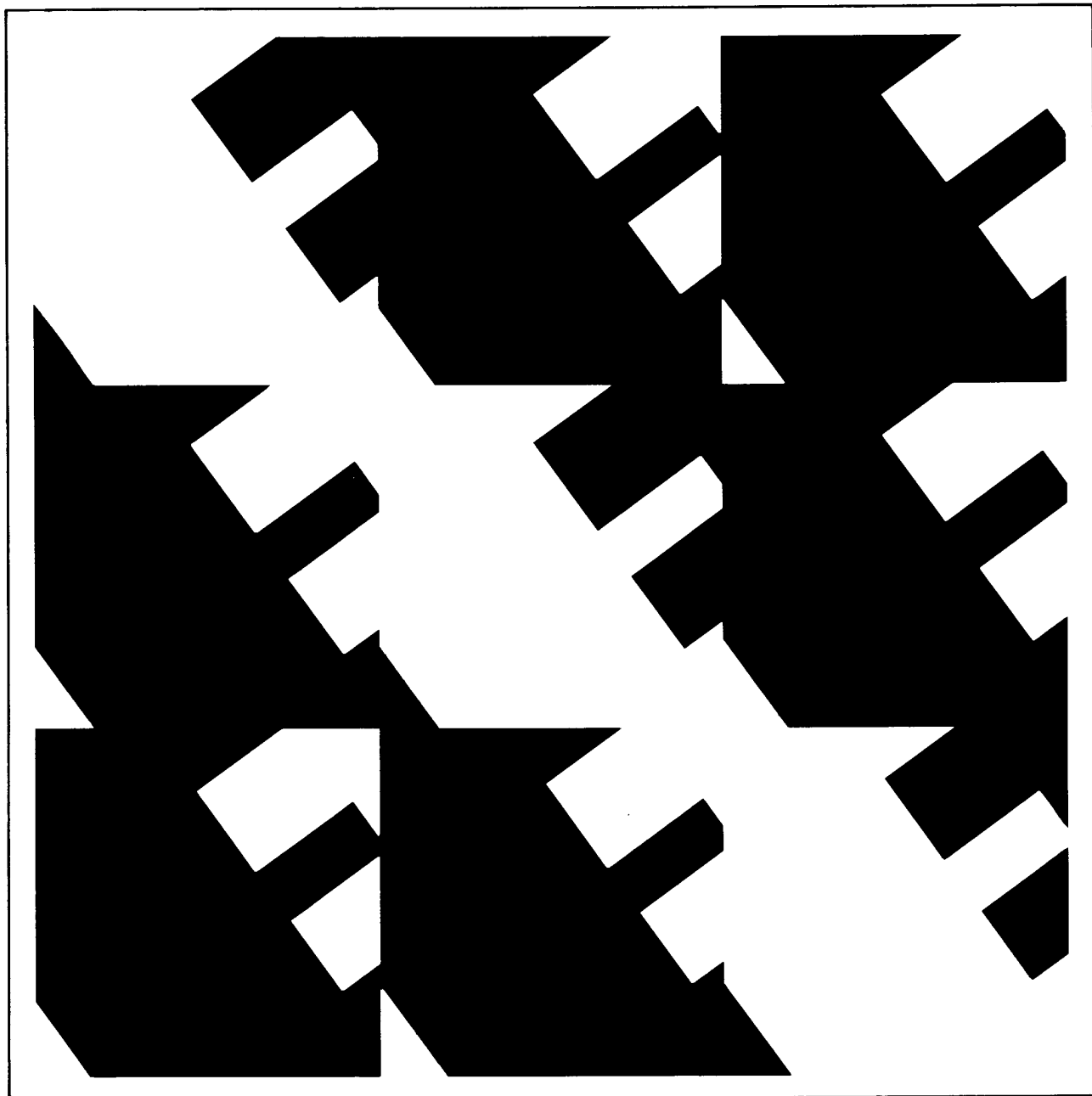


IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits



ANSI/IEEE C62.41-1980



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1. Scope

This guide primarily addresses ac power circuits with rated voltages up to 277 V line to ground, 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 ANSI/IEEE C37.90a-1974, Guide for Surge Withstand Capability (SWC) Tests, intended for the special case of high-voltage substation environments, and ANSI/IEEE Std 28-1974, Standard for Surge Arresters for AC Power Circuits, covering primarily the utilities environment. This guide intends to complement, not conflict with, existing standards, and to present a practical basis for the selection of voltage and current tests to be applied in evaluating the surge withstand capability of equipment connected to these power circuits, primarily in residential, commercial, and light industrial applications. Although the data have been recorded primarily on 120, 220/380, or 277/480 V systems, the general conclusions may be valid for 600 V systems, but more data are needed for the higher voltages.

While the major purpose of this guide is to describe the environment, a secondary purpose is to lead toward standard tests and the preparation of an application guide. Standard tests will provide a realistic evaluation of the surge withstand capability of equipment connected to the power circuits suitable for most installations. Of necessity, the complex real situation must be simplified to produce a manageable set of standards. Proper application, or coordination of equipment capacity and environmental characteristics, of course remains the responsibility of manufacturers and users.

The surge voltages (see 8.1) considered in this guide are those exceeding 2 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 2 per unit are not covered here, nor are transients of longer duration resulting from power equipment operation and failure modes. Because such low-amplitude and long-duration surges are generally not amenable to suppression by conventional surge protective devices, they require different protection techniques from those discussed in this guide.

2. References

2.1 Standards Publications

ANSI C62.2-1969, Guide for Application of Valve Type Lightning Arresters for Alternating Current Systems¹

ANSI/IEEE C37.90a-1974, Guide for Surge Withstand Capability (SWC) Tests

ANSI/IEEE Std 28-1974, Standard for Surge Arresters for AC Power Circuits

IEC No 664 (1980), Insulation Coordination within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment²

ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms

¹ANSI documents are available from The American National Standards Institute, 1430 Broadway, New York, NY 10018.

²IEC documents are available from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

2.2 Other References

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- [2] JOHNSON, I. B. IEEE Tutorial Course: Surge Protection in Power Systems, IEEE Power Engineering Society 79EH0144-6-PWR, 1978.
- [3] BODLE, D. W., GHAZI, A. J., SYED, M., and WOODSIDE, R. L. *Characterization of the Electrical Environment*, Toronto and Buffalo, NY: University of Toronto Press, 1976.
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- [5] LENZ, J. E. Basic Impulse Insulation Levels of Mercury Lamp Ballast for Outdoor Applications, *Illuminating Engineering*, Feb 1964, pp 133-140.
- [6] MARTZLOFF, F. D., and CROUCH, K. E. Coordination de la protection contre les surtensions dans les réseaux basse tension résidentiels, *Proceedings 1978 IEEE Canadian Conference on Communications and Power*, 78CH1373-0, pp 451-454.
- [7] MARTZLOFF, F. D. Surge Voltage Suppression in Residential Power Circuits, Corporate Research and Development, General Electric Company, Schenectady, NY, 1976, Report 76CRD092.
- [8] BULL, J. H. Impedance of the Supply Mains at Radio Frequencies, *Proceedings of the 1st Symposium on EMC*, Montreux, May 1975, 75CH1012-4 Mont.

3. The Origin of Surge Voltages

3.1 General. Surge voltages occurring in low-voltage ac power circuits originate from two major sources, system switching transients and direct or indirect lightning effects on the power system.

3.2 Lightning Transients. Measurements and calculations of lightning effects have been made to yield data on the levels that 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:

(1) 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.

(2) 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.

(3) The rapid change of voltage that may occur when a primary arrester operates at low discharge currents 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.

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

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

3.3 Switching Transients. System switching transients can be 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. One switching transient, for example, results from fast-acting current protective devices such as current-limiting fuses and circuit breakers capable of arcing times of less than 2 μ s. These devices leave trapped inductive energy in the circuit upstream; upon collapse of the field, high voltages are generated.

Transient overvoltages (see 8.1) associated with the switching of power factor correction capacitors, on the other hand, have lower frequencies than the high-frequency spikes with which this guide is concerned. Their levels, at least in the case of restriking-free switching operations, are generally less than twice normal voltage. Nevertheless they should not be disregarded.

A switching operation involving restriking is

another example. 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 most visible effect is generally found on the load side of the switch and involves the device that is being switched as well as the switching device. In the case of the device being switched, the prime responsibility for protection rests with either the manufacturer or the user of the device in question. 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.

4. Rate of Occurrence and Voltage Levels in Unprotected Circuits

4.1 General. The rate of occurrence of surges varies over wide limits, depending upon the particular power system. Prediction of the rate for a particular system is always difficult and frequently impossible. The rate is related to the level of the surges; low-level surges are more prevalent than high-level surges (see 8.2).

It is essential to recognize that a surge voltage observed in a power system can be either the driving voltage or the voltage limited by the sparkover of some clearance in the system. Hence the term *unprotected circuit* must be understood to be a circuit in which no low-voltage protective device has been installed, but in which clearance sparkover will eventually limit the maximum voltage (see 8.3). The distribution of surge levels, therefore, is influenced by the surge-producing mechanisms as well as by the sparkover level of clearances in the system. This distinction between actual driving voltage and voltage limited by sparkover is particularly important at the interface between outdoor equipment and indoor equipment. Outdoor equipment has generally higher clearances, hence higher sparkover levels: 10 kV may be typical, but 20 kV is possible. In contrast, most indoor wiring devices used in 120-240 V systems have sparkover levels of about 6 kV; this 6 kV level, therefore, can be selected as a typical cutoff for the occurrence of surges in indoor power systems.

4.2 Rate of Occurrence versus Voltage Level. Data collected from many sources (see Appendix A) 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 in terms of low, medium, or high exposure. These exposure levels can be defined in general terms as follows:

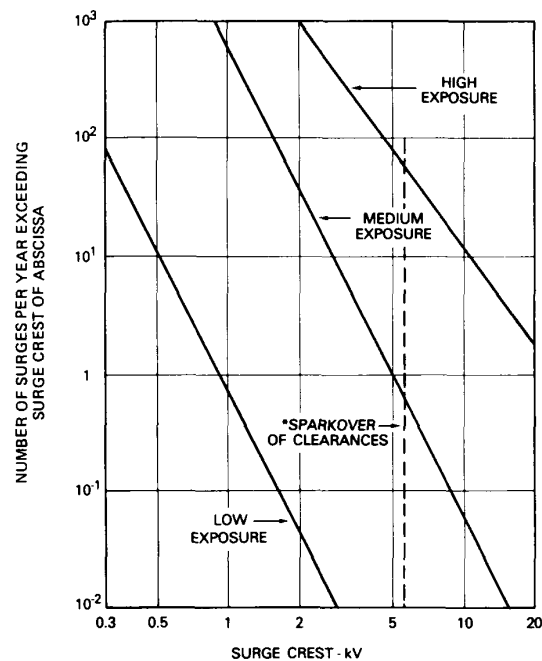
(1) **Low Exposure.** Systems in geographical areas known for low lightning activity, with little load switching activity.

(2) **Medium Exposure.** Systems in geographical areas known for high lightning activity, with frequent and severe switching transients.

(3) **High Exposure.** Rare but real systems supplied by long overhead lines and subject to reflections at line ends, where the characteristics of the installation produce high sparkover levels of the clearances.

The two lower lines in Fig 1 have been drawn at the same slope, since the data base shows reasonable agreement among several sources on that slope. All lines may be truncated by sparkover of the clearances, at levels depending on the withstand voltage of these clearances. The high-exposure line needs to be recognized, but it should not be indiscriminately applied to all

Fig 1
Rate of Surge Occurrences versus Voltage Level at Unprotected Locations



*In some locations, sparkover of clearances may limit the overvoltages (see 8.3).

systems. Such application would penalize the majority of installations, where the exposure is lower (see 8.4).

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

4.3 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. Furthermore, the timing of the surge with respect to the power frequency may affect the level at which failure occurs (see 8.5). Consequently when the failure mode is likely to be affected, surge testing should be done with the line voltage applied to the test piece.

5. Waveshapes of Representative Surge Voltages

5.1 General. This section presents the rationale of representative waveshapes independent of specific energy levels; the choice of waveshape, nevertheless, was influenced by a general consideration of the energy associated with specific waveforms. (Section 6 addresses the question of energy.)

5.2 Waveshapes in Actual Occurrences

5.2.1 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 (see 8.6). 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 30–100 kHz frequency is a realistic measurement of a “typical” surge for most resi-

dential and light industrial ac line networks.

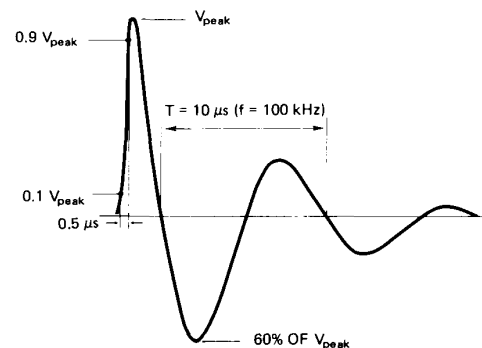
5.2.2 Outdoor and Service Entrance. Surges encountered in outdoor locations have also been recorded, some oscillatory (see 8.6), others unidirectional. Because the prime concern here is the energy associated with these surges, the waveshape to be selected must involve greater energy than that associated with the indoor environment. Secondary surge arresters have a long history of successful performance, meeting the specification of ANSI/IEEE Std 28-1974 as detailed below. Consequently these specifications can be adopted as a realistic representation of outdoor waveshapes.

5.3 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 tradeoff.

5.3.1 Indoor. Based on measurements conducted by several independent organizations in 120 and 240 V systems (Appendix A), the waveshape shown in Fig 2 is reasonably representative of surge voltages in these power circuits. Under the proposed description of a “0.5 μ s–100 kHz ring wave,” this waveshape rises from 10 to 90% in 0.5 μ s, then decays while oscillating at 100 kHz, each peak being 60% of the preceding peak.

Fig 2
Proposed 0.5 μ s–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 conducting states, or when a transient is applied during a particular portion of the 60 Hz supply cycle (Appendix B). 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 1 μ s. For this reason the first half-cycle of the test wave must have a sufficient duration.

5.3.2 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 $1.2 \times 50 \mu$ s for the open-circuit voltage or voltage applied to a high-impedance device, and $8 \times 20 \mu$ s for the discharge current or current in a low-impedance device. The numbers used to describe the impulse, 1.2×50 and $8 \times 20 \mu$ s,

are as defined in ANSI/IEEE Std 28-1974. Figure 3 presents the waveshape and a graphic description of the numbers.

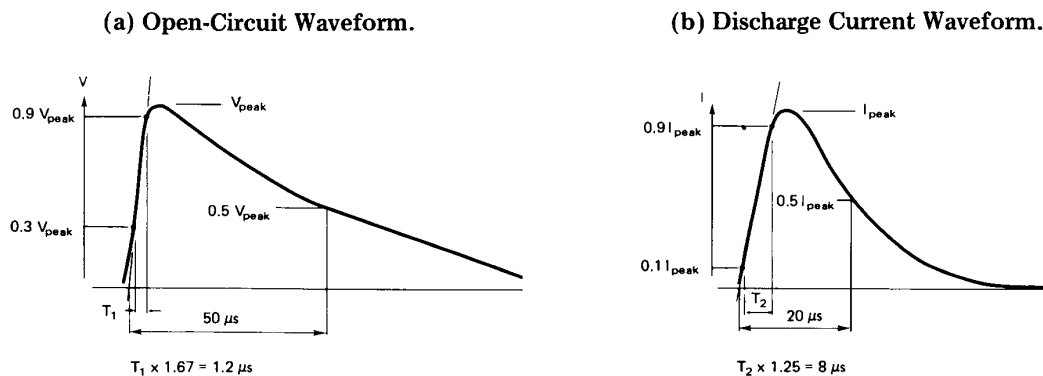
The waveshapes selected to represent the environment can be produced in the laboratory with conventional high-voltage impulse generators or with custom-made generators (Appendix C).

In the case of the oscillatory wave, the test circuit can deliver either the open-circuit voltage shown or the short-circuit current specified in Sec 6. (The short-circuit peak is specified in Sec 6, but the actual waveform will be influenced by the load circuit parameters.) In the case of the unidirectional wave, current practice in laboratories is to produce either a waveshape of voltage or a waveshape of current, depending on the nature of the test specimen: $1.2 \times 50 \mu$ s for insulation voltage withstand tests, $8 \times 20 \mu$ s for discharge current tests. For qualification or acceptance tests of a device whose characteristics are unknown, it would be desirable to have a single test generator capable of producing the open-circuit voltage wave shown, with a short-circuit current equal to the discharge current wave shown.

6. Energy and Source Impedance

6.1 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

Fig 3
Unidirectional Waveshapes (ANSI/IEEE Std 28-1974)



to be dissipated elsewhere; for instance, in a power-follow current-limiting resistor that has been added in series with the gap. 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 that 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 (see 8.7).

The degree to which source impedance is important depends largely on the types 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 a situation as unrealistic as an excessively high generator impedance.

6.2 Proposed Approach. Because of the wide range of possible source impedances and the difficulty of selecting a specific value, three broad categories of circuit locations are proposed to represent the vast majority of locations, from those near the service entrance to those remote from it. The source impedance and the load impedance increase from the outside to locations well within the building. Open-circuit voltages (high load impedance) show little variation within a building because the wiring provides little attenuation (see 8.8). Figure 4 illustrates the application of three categories to the wiring of a power system. These three categories are comparable to three of the four categories defined in IEC No 664 (1980), *Insulation Coordination within Low-*

Voltage Systems Including Clearances and Creepage Distances for Equipment (see 8.9), with the added specification of a source impedance or discharge current (see 8.10). Line-cord-connected equipment plugged into the outlets would correspond to IEC category I.

For the two most common location categories Table 1 shows the recommended surge voltages and currents, with the waveforms and amplitudes of the surges, and high- or low-impedance specimen. For the discharge current shown, the last two columns show the energy that would be deposited in a suppressor clamping at 500 and 1000 V in 120 and 240 V applications, respectively (see 8.11). For higher system voltages (assuming the same current values) the energy would increase in proportion to the clamping voltage of a suppressor suitable for that system voltage.

The values shown in Table 1 represent the maximum range and correspond to the medium-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 discharge currents.

The 6 kV open-circuit voltage derives from two facts; the limiting action of wiring device sparkover and the unattenuated propagation of voltages in unloaded systems. The 3 kA discharge current in category B derives from experimental results: field experience in suppressor performance and simulated lightning tests (Appendix A2). The two levels of discharge currents for the 0.5 μ s-100 kHz wave derive from the increasing impedance expected in moving from category B to category A.

Location category C (comparable to category IV of IEC No 664) is likely to be exposed to substantially higher voltages than location category B because the limiting effect of sparkover is not available. The high-exposure rates of Fig 1 could apply, with voltage in excess of 10 kV and discharge currents of 10 kA or more. Installing unprotected load equipment in location category C is not recommended; the installation of secondary arresters, however, can provide the necessary protection. Secondary arresters having 10 kA ratings have been applied successfully for many years in location category C (ANSI/IEEE Std 28-1974 and ANSI C62.2-1969, *Guide for Application of Valve Type Lightning Arresters for Alternating-Current Systems*).

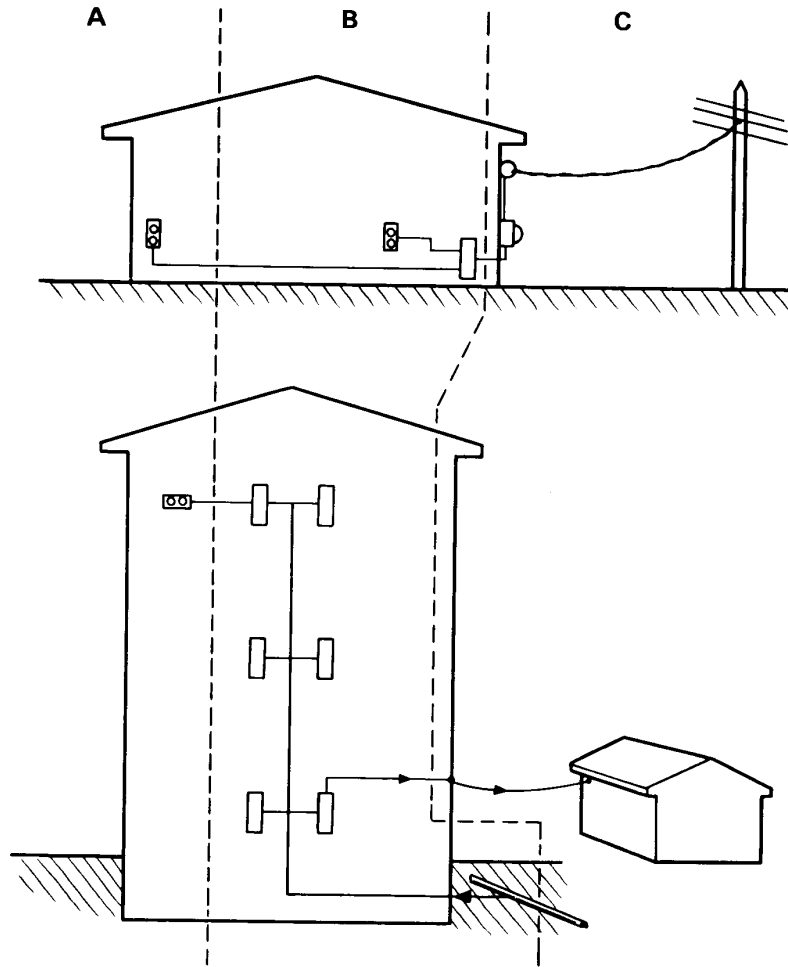


Fig 4
Location Categories

A. Outlets and Long Branch Circuits

All outlets at more than 10 m (30 ft) from
Category B with wires #14-10

All outlets at more than 20 m (60 ft) from
Category C with wires #14-10

B. Major Feeders and Short Branch Circuits

Distribution panel devices

Bus and feeder systems in industrial plants

Heavy appliance outlets with "short" con-
nections to the service entrance

Lightning systems in commercial buildings

C. Outside and Service Entrance

Service drop from pole to building entrance

Run between meter and distribution panel

Overhead line to detached bu'ldings

Underground lines to well pumps

Table 1
Surge Voltages and Currents Deemed to Represent the Indoor Environment
and Recommended for Use in Designing Protective Systems

Location Category	Comparable to IEC No 664 Category	Impulse		Type of Specimen or Load Circuit	Energy (joules) Deposited in a Suppressor* with Clamping Voltage of	
		Waveform	Medium Exposure Amplitude		500V (120 V System)	1000V (240 V System)
A Long branch Circuits and outlets	II	0.5 μ s-100 kHz	6 kV	High impedance [†]	—	—
			200 A	Low impedance ^{‡, §}	0.8	1.6
B Major feeders, short branch circuits, and load center	III	1.2 \times 50 μ s 8 \times 20 μ s 0.5 μ s-100 kHz	6 kV	High impedance [†]	—	—
			3 kA	Low impedance [‡]	40	80
			6 kV	High impedance [†]	—	—
			500 A	Low impedance ^{‡, §}	2	4

*Other suppressors having different clamping voltages would receive different energy levels.
[†]For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.
[‡]For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.
[§]The maximum amplitude (200 or 500 A) is specified, but the exact waveform will be influenced by the load characteristics.

7. Conclusion

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. Simple test circuits can be used (Appendix C).

Field measurements, laboratory experiments, and calculations indicate that two basic waves, of various open-circuit voltages and short-circuit current values, can represent the majority of surges occurring in residential, commercial, and light industrial low-voltage power systems.

Exceptions will be found to the simplification of a broad guide; however, these exceptions 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; the specifications of this guide should not be imposed where they are not applicable.

8. Notes

8.1 Surge Voltage. Definitions of terms used in this guide are consistent with ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms. However, some differences exist. For instance, ANSI/IEEE Std 100-1977 defines a *surge* as a “transient wave of current, potential or power in the electric circuit” — a defini-

tion 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 present guide, which deals only with surge voltages.

8.2 Level versus Rate of Occurrence. 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.

8.3 Sparkover of Clearances. Sparkover, as defined in ANSI/IEEE Std 100-1977, has both a general meaning and a meaning that pertains to surge arresters. In the context of this guide, sparkover is to be understood as a controlled, desirable function (“preset electrode,” “protective function”) as well as the unplanned arcing between live parts that is not intended but that performs a voltage-limiting function when it does occur. When sparkover of the clearance occurs, there are three possible results:

- (1) A power-follow current occurs, with destructive effects on the components.
- (2) A power-follow current occurs, but over-current protection (circuit breaker or fuse)

limits the damage. The system can be restored to operation after a mere nuisance interruption.

(3) No power-follow current takes place; the overvoltage protective function of the system can be considered as accomplished.

8.4 Amplitudes of Strikes, Worst Case. The surge voltages described in this guide include lightning effects on power systems, mostly strikes in the vicinity of a power line or at a remote point of the power system. The literature describes the frequency of occurrence versus amplitude of lightning strikes, from the low levels of a few kiloamperes through the median values of 20 kA [1] to 45 kA [2]³ (see also ANSI C62.2-1969), to the exceptional values in excess of 100 kA. 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.

The voltage and current amplitudes presented in this guide attempt to provide for the 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 [3], [4]. Where the consequences of a failure are not catastrophic but merely represent an annoying economic loss, it is appropriate to make a tradeoff 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 nationwide 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 "worse case conditions." Rates can be estimated for average systems, however, and even if imprecise, they provide manufacturers and users with guidance.

8.5 Timing of Surges with Respect to Power Frequency. 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 B, 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.

8.6 Low-Voltage System Oscillatory Surges during Lightning. For the evaluation of power system equipment against lightning surges encompassing a wide spectrum of waveshapes, two standard test waves have evolved over the years: a $1.2 \times 50 \mu\text{s}$ voltage wave and an $8 \times 20 \mu\text{s}$ current wave for surge arrester discharge voltages. Evidence has been collected, however, to show that oscillations will occur in low-voltage power systems as a result of lightning discharges. Lenz reports 50 lightning surges recorded in two locations, the highest at 5.6 kV, with frequencies ranging from 100 to 500 kHz [5]. Martzloff reports oscillatory lightning surges in a house during a multiple-stroke flash [4].

8.7 Surge Impedance and Source Impedance. 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 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 150–300 Ω , but because the durations of the waves being discussed (50–20 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" (ANSI/IEEE Std 100-1977), 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)

³The numbers in brackets correspond to the references listed in Section 2 of this standard.

are sufficient to calculate the short-circuit current, as well as any current for a specified suppressor impedance.

8.8 Open-Circuit Voltages and Wiring Sparkover. Surges propagate with very little attenuation in a low-voltage power system with no substantial connected loads. Measurements made in an actual residential system as well as in a laboratory simulation [6] have shown that the most significant limitation is produced by wiring sparkover, not by attenuation along the wires [7]. Ironically, a carefully insulated installation is likely to experience higher surge voltages than an installation where wiring sparkover 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, the reason for maintaining the 6 kV surge specification when going from the B location to the A location.

8.9 Installation Categories. Subcommittee 28A of the International Electrotechnical Commission has prepared a report in which installation categories are defined (see IEC No 664). These installation categories divide the power systems according to the location in the building, in a manner similar to the location categories defined in this guide. 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. Source impedances, in contrast to this

guide, have not been defined in the IEC report. Further discussion and work toward the application guides of both documents should eventually produce a consistent set of recommendations.

8.10 Power System Source 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 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 [8]. Attempts were made to combine the observed 6 kV open-circuit voltage with the assumption of a 50 Ω , 50 μH impedance. 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 associated with unidirectional waves. It also led to a deeper understanding of the significance of clearance sparkover in limiting the observed voltages that result from current source surges.

8.11 Multiple Strokes and Total Energy. The literature reports (see Appendix D; D6, D7, D8, D10) that lightning flashes may consist of multiple strokes, with a total energy substantially larger than that of a single stroke. The current levels of the successive impulses of a multiple stroke are generally lower than the first. The distribution of Fig 1 remains valid for the voltage levels of each strike of a multiple stroke. However, to apply a surge protective device, one must consider the cumulative energy deposition of multiple strokes.

Appendixes

(These appendixes are not a part of IEEE Std 587-1981, IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits.)

Appendix A Data Base

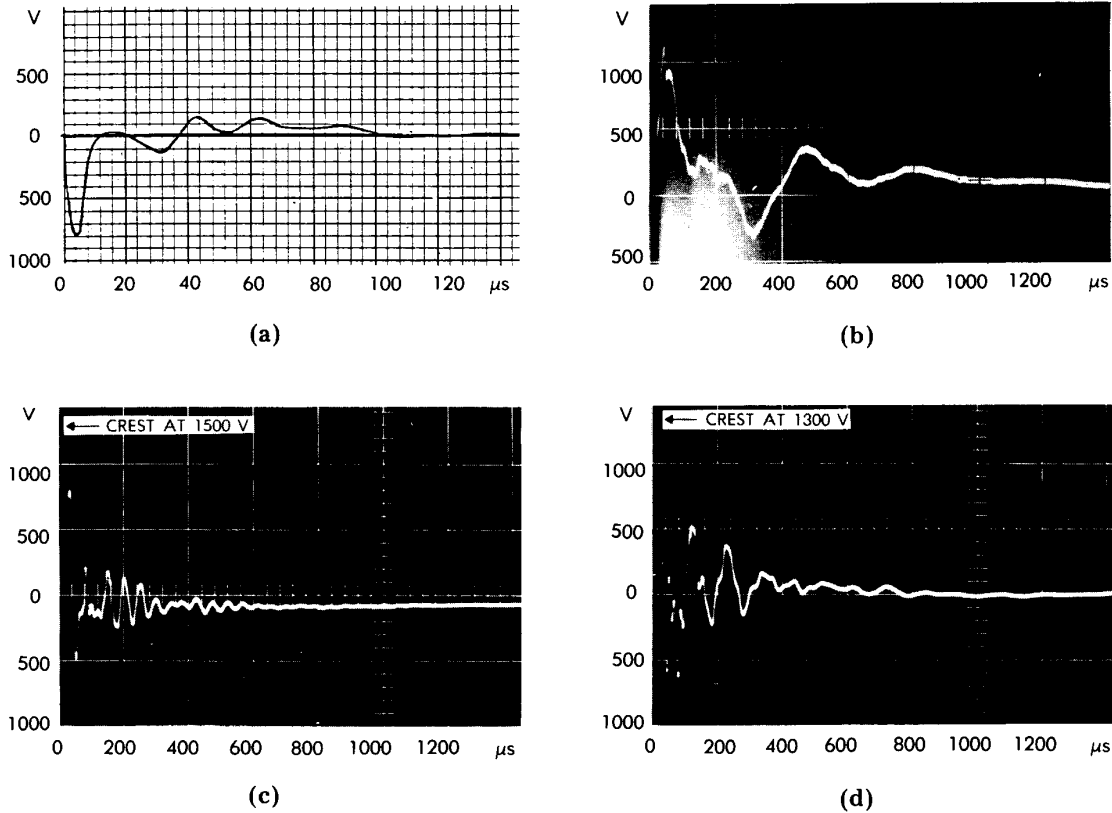


Fig A1
Typical Oscillograms

(a) 120 V Outlet, Laboratory Bench (b) 277/480 V Service Entrance
(c) 277/480 V Service Entrance (d) 277/480 V Service Entrance

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 level and oscillatory wave proposals.

⁴Data contributed by P. Speranza, internal report.

A1. Recordings by Bell Telephone Laboratories⁴

Typical surge counter statistics for a 120 V line at the BTL facility in Chester, New Jersey, during 42 months of monitoring were:

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

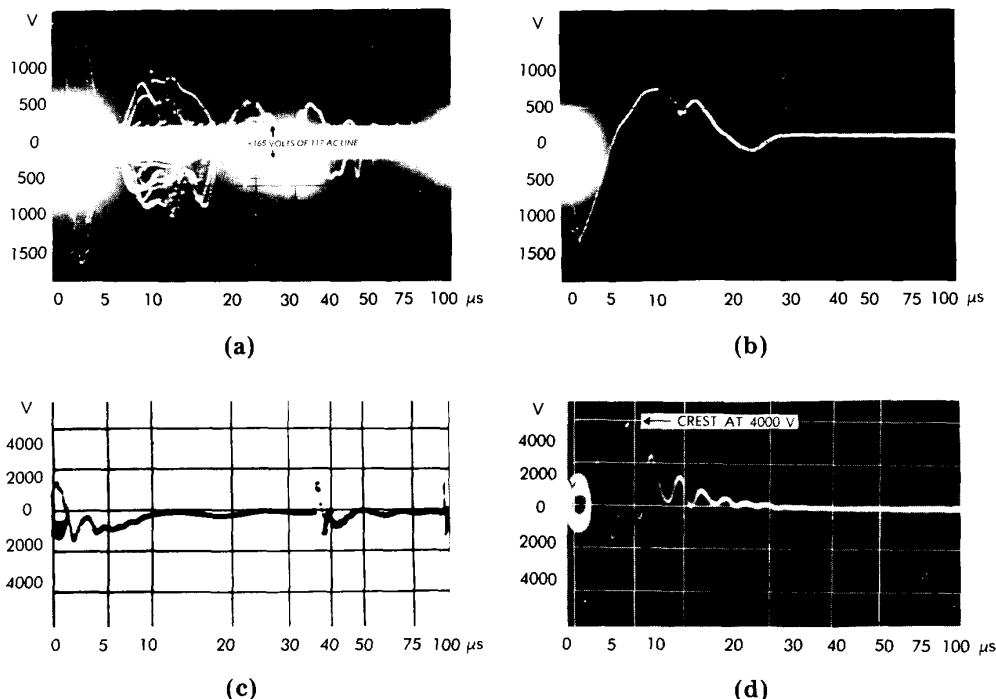


Fig A2
Typical Oscillograms
(a) Furnace Ignition, 24 h Period (b) Furnace Ignition, Single Recording
(c) Service Entrance, Lightning Storm (d) Street Pole, Lightning Storm

A2. Recordings by General Electric Company⁵

The surge counter results are given in Tables A1 and A2 (see Appendix D, Ref [D15]⁶). It was found that:

(1) 3% of the U.S. locations surveyed experience frequent occurrences (one per week or more) above 1200 V.

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

Typical oscillograms are shown in Fig A2.

Simulated lightning strokes on a residential power circuit (laboratory model of system) are shown in Figs A3-A6 (see Appendix D, Refs

[D12], [D14]). A 1.5 kA current impulse (approximately $8 \times 20 \mu s$) is injected in the *ground wire only* of a service drop (Fig A3). Higher currents produce flashover of wiring. The open-circuit voltage at a branch circuit outlet during the 1.5 kA impulse was found to be 2200 V peak, 500 kHz oscillations (Fig A4). By connecting a 130Ω load at the same outlet (1 A load) the voltage is reduced to 1400 V peak, with more damping (Fig A5). For a 30 kA injection (corresponding to an assumed 100 kA lightning strike on the distribution system), the discharge current passing through an arrester installed at the service entrance is 3.5 kA (Fig A6).

The following conclusions can be drawn from this test series:

(1) A current of 1.5 kA (moderate for a lightning discharge injected into the ground system) raises the wiring system of the house 2.2 kV above ground. In the case of 4 kA (still a mod-

⁵Data contributed by F. D. Martzloff.

⁶The numbers in brackets in the Appendixes correspond to the references listed in Appendix D of this standard.

Table A1
Number of Houses with Repetitive Surge Activity above 1200 V

Location	Number of Homes Surveyed	Recording Period (weeks)	Houses with Repetitive Surges
Providence, RI	4	2-6	None
Cleveland, OH	28	2-4	None
Auburn, NY	12	2-3	None
Lynchburg, VA	3	2-3	None
Syracuse, NY	8	1-2	1
Chicago, IL	23	1-6	None
Ashland, MA	24	1-2	1
Holland, MI	6	2-10	None
Louisville, KY	10	2-6	None
Somersworth, NH	50	1-2	1
Plainville, CT	5	10	None
Ashboro, NC	24	1-2	None
Fort Wayne, IN	38	1-4	3
DeKalb, IL	14	3-12	None

Table A2
Surge Counter Recordings above 1200 V (Spring, Summer, and Fall)

Location	Number of Homes	Total Homes x Weeks	Number of Surges
Providence, RI	6	60	1
Ashboro, NC	13	85	None
DeKalb, IL	11	60	2
Somersworth, NH	3	48	1
Chicago, IL	12	58	None
Cleveland, OH	8	106	1
Decatur, IL	12	72	2
Holland, MI	7	56	None
Auburn, NY	3	70	None
Springfield PA	1	24	None
Ashland, MA	6	72	None
Pittsfield, MA	3	60	1
Plainville, CT	3	60	None
Lynchburg, VA	3	15	None
Total	91	846	8 in 8 homes

erate value) this voltage would reach 6 kV, the typical sparkover value of the wiring.

(2) A discharge current level in the order of 3 kA can be expected in an arrester installed at the service entrance when a very high current, 30 kA, is injected into the ground wire.

(3) A natural frequency of 500 kHz is excited by a unidirectional impulse.

(4) In this example the source of the transient (from the loading effect of 130 Ω) appears as

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

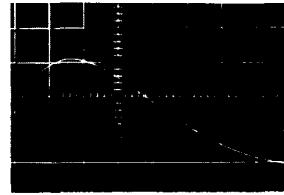


Fig A3
Injected Current Impulse: 500 A/div and 5 μs/div

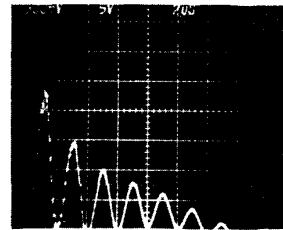


Fig A4
Open-Circuit Recording; 500 V/div and 2 μs/div

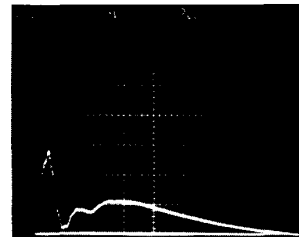


Fig A5
Recording with 130 Ω Load; 500 V/div and 2 μs/div

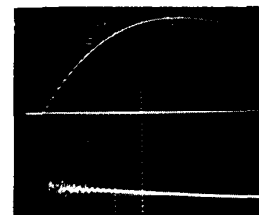


Fig A6
Discharge Current at Maximum Injection; 500 V/div and 2 μs/div

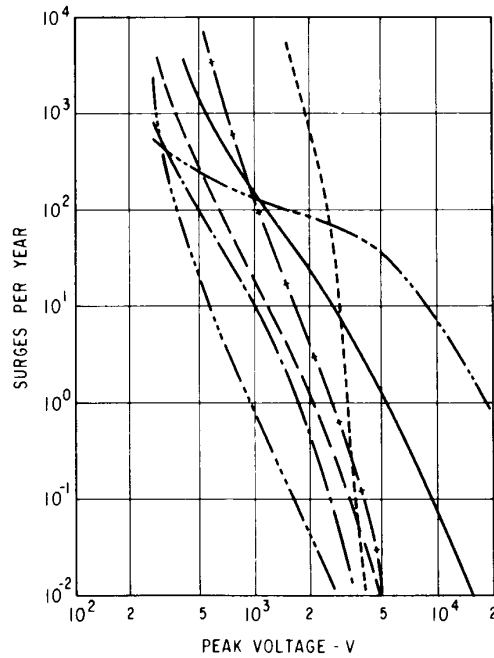
A3. Statistics by Landis and Gyr Company⁷

Surge recorders were installed at various locations of 220/380 V systems in Switzerland, monitoring the line to ground transients. Fig A7 shows a plot of the frequency of occurrence as a function of voltage level for locations including residential apartments, commercial and industrial buildings, and a rural location served by a long overhead line. These transients recording represent a composite of switching and lightning transients.

Switching transients measurements and calculations are the basis of the three curves shown in Fig A8, where the peak voltages reached for circuit interruptions at light load are plotted as a function of the system voltage. The fast tran-

sients (time to half-value $T_h = 5 \mu s$) reach higher peaks than the long transients ($T_h = 1000 \mu s$), but in all cases, the peaks increase slower than the system voltage.

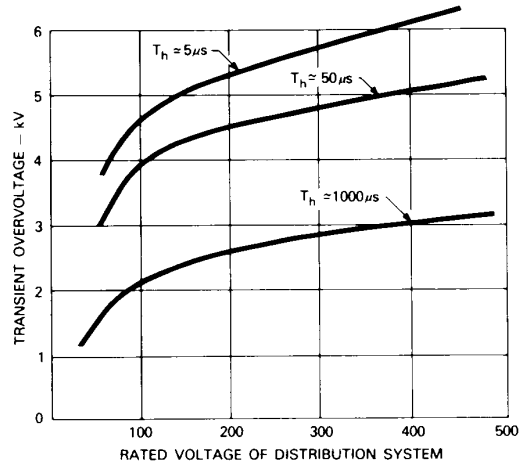
Fig A7
Rates of Surge Occurrence Recorded
in a 220 V System



- Service entrance, 16-family house, underground system
- Same house, outlet third floor living room
- · - · - Same house, outlet fifth floor living room
- Service entrance of bank building in Basel
- + — Landis and Gyr Plant, Zug, outlet in lab.
- x — Landis and Gyr, Zug, outlet in furnace room
- o — Farmhouse supplied by overhead lines

⁷Data contributed by L. Regez.

Fig A8
Effect of System Voltage on Transient
Overvoltages for Three Pulse Durations



A4. 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 them 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; and the 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 when establishing the low- and medium-exposure limits.

The statistics of these measurements can be summarized as follows:

(1) The data base was collected from 18 locations with a total recording time of 12 years spread over 4 calendar years, using six counters.

(2) The number of occurrences per year (weighted averages) at "average location" were:

- 350 V 22 occurrences
- 500 V 11 occurrences
- 1000 V 7 occurrences
- 1500 V 3 occurrences

(3) The following extremes were significant:

(a) One home with a large number of surges caused by washer operation.

(b) Four locations out of 18 never experienced a surge, perhaps due to the presence of continuous loads.

(c) One home experienced several occurrences above 1500 V, with none below that value

(d) 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 when compiling the average, but it is shown in the composite plot of Fig A9.

A5. Combined Results

From the data base described in this appendix, Fig A9 can be drawn together with the following information on voltage versus the frequency (rate) of occurrence:

(1) The Bell Telephone Laboratories data (BTL) yield a point of 1000 V at about two occurrences per year.

(2) The General Electric Company counter statistics (GE) yield a point of 1200 V at about one occurrence per year.

(3) The General Electric clock data indicate a ratio of 100:1 in the rate of occurrence from 2 to 6 kV.

(4) The Regez data provide a band for the

majority of locations, with the exception of the rural location with a long overhead line, which has more occurrences.

(5) Working Group statistics (WG) indicate a more moderate slope, perhaps because of the influence of outdoor locations included in the sample (similar to the rural data of Regez). An extreme case of switching transients was also identified near a test rack (TR).

Three lines have been drawn. The medium-exposure and the low-exposure lines are parallel to the 100:1 reduction line. The high-exposure line, reflecting isolated cases, corresponds to locations where the higher voltages are not limited by clearance sparkover. These three lines are shown on the plot of Fig 1 in the text.

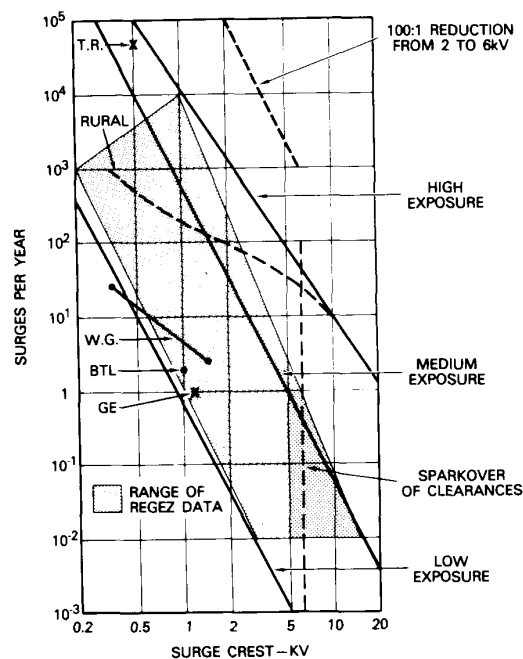


Fig A9
Combined Transient Recording Data

Appendix B

Effect of Transient Polarity Reversals
on Semiconductors

The sensitivity of semiconductors to the timing and polarity of a surge 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.

The breakdown of semiconductors under various conditions of load and transient over-voltage applications has been investigated (see

Appendix D, Refs [D5], [D13]). 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. They show statistically significant differences in the voltage levels.

Diode	Breakdown	Average Breakdown Voltage (V)	Reference
1N1190	Transient at no load	1973	From Chowdhuri (Appendix D, Ref [D5])
	Fast wave under load	830	
	Slow wave under load	1097	
1N2160	Transient at no load	2056	From Chowdhuri (Appendix D, Ref [D5])
	Fast wave under load	894	
	Slow wave under load	1106	
1N679	Transient applied at: peak of reverse voltage	1766	From Martzloff (unpublished report)
	25° after start of conduction	1181	
	90° after start of conduction	906	
	155° after start of conduction	1115	

Appendix C
Test Circuits

The test circuits shown in Figs C1-C3 can produce the three waveforms recommended as representative of the environment. Other test circuits capable of producing the recommended waveforms may also be used.

The circuits of Figs C1 and C2 are typical of the practice in routine testing of surge arresters, where the test piece impedance is known before the test. For test pieces of undefined impedance, tests are preferably performed in a circuit inherently capable of applying a $1.2 \times 50 \mu\text{s}$ voltage wave in a high-impedance test piece and

delivering an $8 \times 20 \mu\text{s}$ current wave in a low-impedance test piece. Tests conducted with line voltage applied require an isolating impedance (filter) to be inserted between the ac power supply and the test piece.

It is worthwhile to restate here that the impedance of the test piece, as well as the source impedance of the generator, must be selected properly. A voltage impulse cannot be imposed on a low-impedance test piece, nor can a current impulse be injected into a high-impedance test piece.

Fig C1
Current into Low-Impedance Test Piece; $8 \times 20 \mu\text{s}$, 10 kA Maximum

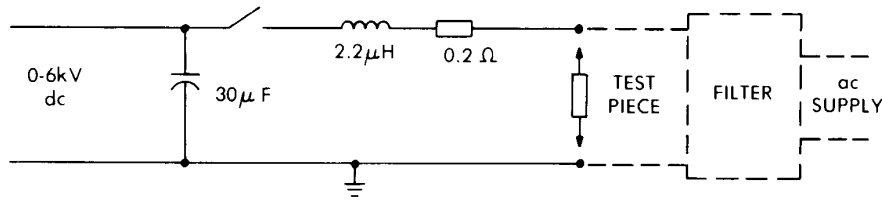


Fig C2
Voltage into High-Impedance Test Piece; $1.2 \times 50 \mu\text{s}$, 10 kV Maximum

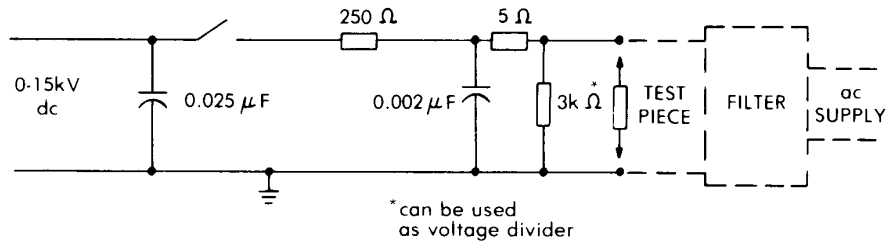
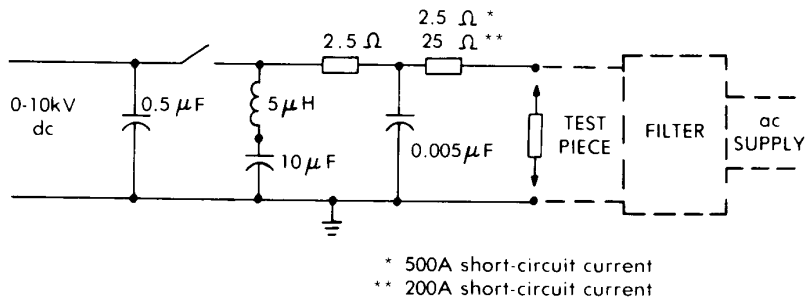


Fig C3
 $0.5 \mu\text{s}$ -100 kHz Ring Wave; 6 kV Maximum Open Circuit, 500 or 200 A Short Circuit



Appendix D Bibliography

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