Surge Protection in Low-Voltage AC Power Circuits - An Anthology
Part 1 - Annotated Bibliography

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FOREWORD

This is the first part of a multi-part anthology, offered to promote better understanding of surge protection techniques through a historical perspective and easy access to relevant papers on the fundamental principles and application of surge-protective devices. It might also serve as a refresher to avoid reinventing surge-protective devices or techniques.

This first part, Annotated Bibliography, provides a list of papers, standards, and textbooks written by many contributors to the development of surge protection technology. Subsequent parts of this anthology will be compiled to include reprints of the public-domain papers by the author as cited in this Bibliography. Those published after 1985 under the umbrella of NIST are in the public domain. Those written before 1985 will be reprinted in by permission of the copyright holders or with declassification of proprietary reports; these releases are gratefully acknowledged.

This bibliography is provided to give the interested reader a source of reference material with a few lines of comments on content or comments on the significance of the cited document. The compilation is divided into eight categories, as listed below. Publications relevant to more than one category are listed in each category of interest to allow browsing only through a particular category and still find the listing. The listing is arranged by alphabetical order and chronology of the lead author in each category. The following are the categories for the listing:

1. Standards relevant to surge protection
2. Development of standards — Reality checks
3. Recorded surge occurrences, surveys and staged tests
4. Propagation and coupling of surges (Experiments and numerical simulations)
5. Monitoring instruments, laboratory measurements, and test methods
6. Textbooks and tutorial reviews
7. Mitigation techniques
8. Coordination of cascaded surge-protective devices

Each of the categories 2 through 8 will be compiled in installments and issued as separate booklets. In addition to the printed booklets available from the U.S. Superintendent of Documents, this Anthology will also be available on the Web, thus opening the door for suggestions of additional entries for periodic updates of the listing. The site URL is: http://www.eeel.nist.gov/811/spd-anthology/

This bibliography was initially compiled by the author as a contribution to the IEEE “Trilogy” of the Surge-Protective Devices Committee (a set of three standards on the surge environment). This initial compilation is now complemented with additional relevant papers and reports written by the author. Undertaking a listing of “relevant papers” entails the risk of offending researchers whose papers might have been overlooked in the compilation. Sincere apologies are offered in such cases, as the omission was not a deliberate act of rejection, but an unfortunate accident in an imperfect literature search that was initially focused on the Trilogy development rather than aiming to be a comprehensive and exhaustive project. Nevertheless, the volume of this Bibliography is testimony to the contributions from all the listed authors to a data base for the Trilogy. Members of the IEEE working group that developed the Trilogy also contributed suggestions for entries in the listing. All these contributions are gratefully acknowledged.

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1. Published standards related to surges

1.1 The IEEE C62 Series

A bound-book collection of all ANSI and ANSI/IEEE C62 standards that were compiled periodically by the IEEE. The last such collection was published in 1995 and included all published IEEE standards applicable to Low-Voltage Surge-Protective Devices at the time of the edition. More recent updates of individual standards are listed after the following contents of the 1995 edition:

C62.11-1993 IEEE Standard for Metal-Oxide Arresters for AC Power Circuits
C62.22-1991 IEEE Guide for the Application of Metal Oxide Surge Arresters for AC Systems
C62.92.x (A series of IEEE Guides on neutral grounding practices)

1.2 Additional C62 Standards

Additional C62 Standards, or major revisions published since the 1995 collection include:

C62.11-1999 IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (>1kV)
C62.22-1997 IEEE Guide for Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
C62.22.1-1996 IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems
C62.43-1999 IEEE Guide for the Application of Surge Protectors Used in Low-Voltage (Equal to or less than 1000 Vrms or 1200 Vdc) Data, Communications and Signaling Circuits
C62.64-1997 IEEE Standard Specifications for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits

1.3 Other Standards

[1] The IEEE SPD “Trilogy” – Pending approval by the IEEE Standards Board expected in early 2002, includes three documents:
- C62.41.1 Guide on the surge environment in low-voltage ac power circuits
- C62.41.2 Recommended practice on characterization of surges in low-voltage ac power circuits
- C62.45 Recommended practice on surge testing for equipment connected to low-voltage ac power circuits
1. Published standards related to surges – Continued

- Rules for the protection of persons during installation, operation and maintenance of power and communications lines and equipment for utilities and for systems under the control of qualified persons.
- For building utilization wiring, refer to ANSI/NFPA 70 (National Electrical Code).
- 257 pages, 77 reference documents

- Defines steady-state limits of system voltages for the United States.
- Addresses only steady-state voltages or short-term departures from nominal conditions.
- Provides list of related standards.

- A fundamental document providing minimum requirements for safe installation practices (USA)
- A companion handbook provides explanations for application of the code.
- Specifies minimum requirements for safety, not necessarily optimum surge protection.
- Allows connection of SPDs between any pair of conductors.
- Updated every three years.

- A conversion of parts of the IEC International Electrotechnical Vocabulary (IEV) into a dictionary

- Defines parameters of impulse waveforms.

- Earthing systems and arrangements in transformer substations.
- Earthing arrangements and earthing systems in low-voltage installations.
- Stress voltages in cases of lost neutral (TN and TT), accidental earthing (IT), and line-to-neutral short.

- Superseded, but significant historical document. See IEC 60664 below.
- Introduced the staircase concept of surge voltage reduction.

- Major revision and update of IEC 664 (above).
- No longer shows a descending staircase of voltages.
- Does not discuss surge source impedance considerations as it is concerned with insulation withstand.

- Basic EMC publication (Technical Report)
- Not a test or performance specification, but a guide to what levels of disturbances might be expected.
- Proposes and arrangement with five classes of locations and corresponding characterized by levels.

- Specifies interference immunity test with bursts of fast-transient pulses applied to EUT in "common mode" by a coupling clamp or in selective mode by capacitor coupling.

- Specifies the Combination Wave (1.2/50 –8/20) only for power circuits (no mention of Ring Wave)
- Line-to-earth test voltage levels are twice the levels specified for line-to-line.

- Presents the IEC TC81 perception of "requirements" for service-entrance SPDs.
- Approved according to the IEC operating procedures, but with only 68% of the votes.
- Defines three classes of tests, I, II, and III with specific energy and charge stress levels.
- Does not relate the test levels to the location of application.

- A tutorial technical report describing the origins, propagation, and mitigation of surges.
- Bibliography with 58 citations, similar to the present bibliography.

- A document developed for the environment of high-voltage substation equipment. Its fast transient requirement, with a rise time of less than 10 ns, is similar to the IEC EFT burst requirement.
- Calls for a 1 MHz to 1.5 MHz ring wave and a 4 kV to 5 kV peak impulse, < 10 ns rise time.
- 14 references

- Defines impulse parameters.

- The earliest publication of the “CBEMA Curve” (updated as “ITIC Curve”) occurred in the 1980 edition of this standard.

- Discusses the sources of electrical noise; provides an example of the “showering arc” leading to the EFT concept.
- Provides guidance on noise reduction (not suppression) and installation practices.

- Recommended engineering principles and practices for powering and grounding electronic equipment in commercial and industrial applications.
- 400 pages, 120 bibliographic citations

- Provides definitions of power systems disturbances.
- Makes recommendations on deployment of surge monitoring instruments.
- Makes recommendations on interpretation of power quality surveys.

- First proposal to industry of what became the 100 kHz Ring Wave.

- The second edition which became effective in 1998, features a new set of failure mode tests.
- Specifies safety aspects of suppressor design, with some performance implications.
- Requires citation of limiting voltage level, from a tabulation of values starting at 330 V.
2 Development of Standards — Reality checks

- Experimental study of the immunity of typical electronic equipment to sags and surges.
- Surges applied were not the ANSI C62.41, but a 100 µs or 300 µs pulse, presumably open-circuit voltage.
- Surges of 1000 V (open-circuit voltage of generator) did not cause any failure of PCs.

- Shows failure mechanisms and levels, by electrical measurements, with high-speed video recording.
- 120-V lamps can fail in the range of 800 V to 1200 V, depending on waveform and phase angle.
- Makes the point that surges are unlikely to occur frequently at levels above the failure level of lamps.
- 5 references

- Simulation of varistor behavior under current pulses of various magnitudes and duration.
- Comparison with experimental results.
- Demonstrates that energy-handling capability is not a constant, but depends on intensity and duration.
- 14 references, 1 discussion

- Numerical computations of the energy deposition associated with a proposed IEC standard indicate that massive failure of ubiquitous metal-oxide varistors should occur – but they do not.
- The proposed test was eventually removed from the menu of IEC EMC test methods.
- 10 references

- Computer modeling of the resulting current and energy deposition into typical varistors subjected to the proposed 10/1300 µs waveform.
- Yields a prediction of failure for the small varistors and survival for the larger varistors.
- Because small varistors do not fail in the field at the rate that is predicted by the model, the conclusion is that stresses associated with this proposed waveform make it unrealistic.
- 15 references

- Describes field experience of arresters designed in accordance with IEEE Std C62.11-1999.
- Concludes that tests with a 10/350 µs waveform are not necessary.
- 11 references

- Progress report on the development of a tutorial on surge protection.
- Presents the need for “intersystem bonding” at the entrance of power and communications utilities.
- Brief discussion of the need for surge reference equalizers.
- 6 references

- Field experience of EDF on 700 000 arresters.
- Failure rate lower (1/4) than calculated in [44] Rousseau, 1989 (CIRED).
2. Development of standards – Reality checks – Continued

- Shrinking surge recordings vs. proliferation of SPDs.
- Applying equipment failure rates to assess the surge environment.
- Limits to pushing surges into branch circuits.
- 19 references

- Measurements and modeling, validating each other, show the physical impossibility for large surge currents to propagate very far into the branch circuits of a building, because flashover will occur at the service entrance.
- Demonstrates the importance of considering the maximum rate of rise (early in the surge) rather than the peak value and overall rise time.
- 13 references

- Compares the TN and TT for dispersion of lightning current in several scenarios.
- Shows the need for careful review of grounding practices in effect at service entrances.
- Questions the applicability of high amplitude, long duration requirement for service entrance SPDs.
- 20 references

- Three examples of temporary overvoltage conditions that can produce failure of SPDs.
- The significance of available fault current and the need for more explicit standards.
- 17 references

- Experimental measurements of effective mitigation by multiple SPDs.
- Numerical simulation of the effect of proliferating SPDs and PCs.
- Calls for an industry-wide reassessment of surge monitoring parameters.
- 20 references

- Presents the concept of testing low-voltage equipment patterned on the high-voltage BIL concept.
- Techniques and equipment for making TCL tests.
- 10 references

- Staged test of capacitor switching on remote MV side produces ring waves on low-voltage load.
- Coordination between 3 kV and 480 V varistor-based SPDs.
- 5 references, 1 discussion

- Reports tests performed with a prototype 100/1300 surge generator, resulting in failure of the ubiquitous 20-mm diameter varistors, hence demonstrating that the proposed standard is unrealistic.
- 9 references

- Reports measurements on the propagation of oscillatory waves in typical low-voltage circuits, as opposed to the unidirectional waves initially defines for high-voltage power systems.
- Shows how impinging unidirectional surges can produce oscillatory waves responses.
- 17 references
2. Development of standards – Reality checks – Continued

   - Computer modeling of the current dispersion among available paths to ground.
   - Comparison between proposed SPD ratings based on computer modeling and field experience.
   - 9 references

   - The seminal paper proposing a long waveform with extremely high energy-deposition capability, leading to the development of German Standard DIN 0160.

   - Points out ambiguities in the test procedures.

   - Design of ZnO MV arresters based on statistics of lightning current magnitude and tail.
   - Sharing of current between many arresters as well as number of lightning strike per year and per km of overhead line are used in calculations.
   - Design based on an energy requirement converted in lab into a 4/10 standard waveshape.
   - 13 references

   - Clocks, TV receivers, and switching power supplies were subjected to surges from 0.5 kV to 6 kV.
   - The switching power supplies and television receivers were damaged with surges from 4 kV to 6 kV.
   - Three of five models of digital clocks were upset with surges from 1.6 kV to 6 kV.
   - The conventional wisdom that electronic appliances are easily damaged by surges with a peak voltage of a few kilovolts greatly exaggerates the effect of surges on modern consumer appliances.
   - 15 references

   - Some critical issues in the development of a performance standard for surge arresters and suppressors for use on low-voltage mains are discussed.
   - A series of electrical tests to determine the safety and adequacy of surge protective devices is described.
   - 4 references

   - Shows that using the integral of $V^2/50\Omega \cdot dt$ to compute energy in a surge is invalid.
   - A quantitative error analysis is presented that uses an artificial AC line network to simulate a long branch circuit and to give the impedance of the AC line as a function of frequency.
   - A method for measuring energy dissipated in a varistor is advocated for use in future experiments.
   - 18 references

   - A review major standards in the USA for low-voltage AC power surge-protective devices prepared for presentation at a European based forum.
   - Since it is clear that international standards are greatly preferable for both manufacturers and users, the US position [in 1992] on the IEC SC37A drafts is also briefly reviewed.
   - 9 references

   - Describes the need for dual capability of a test generator to adapt inherently to the impedance of the EUT, even during the surge event.
3 Recorded surge occurrences, surveys, and staged tests

   - Reports surge monitoring performed in Germany.

   - Reports surge measurements in Germany that include “energy content” in Ws (watts x seconds).
   - 10 references

   - Comprehensive report, 1961 vintage, of the subject.
   - 84 references, 10 discussions

   - Reports occurrence rates at computer sites, recorded with CRT memory scopes.
   - Possible artifact of insufficient writing speed discussed but not appended to conference preprint. See IEEE Std C62.41.1-2002 data base for that discussion.
   - 7 references

   - Probability of occurrence of lightning flashes.
   - Peak current amplitude and waveshape parameters.
   - 55 references.

   - Survey with digital-output disturbance monitors.
   - Did not consider the effect of SPDs integrated in the instrument power supply that limited observed surges.
   - 28 references, 2 discussions

   - Surge recordings with storage oscilloscope and disturbance analyzers.

   - Recording of 1309 lightning surges at four sites of distribution systems.
   - Uses a modified MOV arrester as transducer to bring signals down to low-voltage input of recorder.
   - 23 references

   - Injection of triggered lightning current into a runway lighting system at Camp Blanding.
   - Measurements of the dispersion of lightning current among ground rods and counterpoise.
   - 3 references

   - Investigates the influence of load, capacitive compensation, machine parameters on resulting overvoltages.
   - Presents results of simulation of a distribution network.
   - 11 references
3. Recorded occurrences, surveys, and staged tests – Continued

- The seminal paper on lightning parameters.
- Statistical distribution of 10 parameters, including peak current, charge, and waveshape.
- 8 references

- Book initially written from the communications point of view but applicable to AC power circuits.
- 124 references, 320 pages

- Field tests and computer analysis for overvoltages on transformers and arresters, with corrective measures.
- 15 references, 11 discussions

- Peak-reading recordings at substations, bus-bars, and point-of use.
- 5 references

- Oscilloscope recordings and histograms.
- 18 references

- Computation of flashover rates as a function of BIL.
- 18 references, 1 discussion

- Comprehensive statistics on the characteristics of lightning.
- 108 references, 136 pages

- Summarizes the development and upgrade of the U.S. National Lightning Detection Network.
- Provides examples of the cumulative distribution of peak current.
- 36 references

- Statistics on the occurrence of lightning.
- 14 references

- Presents results of four years of monitoring at 112 North American locations.
- Cites relatively low rate of occurrence of surges above 500 volts, suggesting that the proliferation of SPDs can be the cause of this low incidence.
- Other Power Quality statistics include sags, swells, and outages.
- 17 references

- Injection of triggered lightning current into several configurations at Camp Blanding.
- Review of tests reported in earlier papers and preview of forthcoming test reports.
- 3 references
3. Recorded occurrences, surveys, and staged tests – Continued

- Opportunistic natural flash events at the triggered lightning facility of Camp Blanding.
- One flash struck earth away from the line: electromagnetic coupling and injection via ground connections.
- One flash event struck the directly the overhead distribution line, equipped with MOV arresters at the time.
- 4 references

- Citation of long duration current in arresters.
- 8 references

- Shows rates of rise up to 30 kV/μs, peaks exceeding 3 kV.
- Contains extensive analysis of data.
- Avoids the use of ‘energy in the surge’ but defines ‘energy measure’ based on integral of $v^2dt$.
- 13 references

- Low-side surges are known to cause failures of low voltage distribution transformers.
- Tests on low-side surges were found to consist of two basic components:
  - The natural frequency of the system, responsible for corona discharge spots at secondary bushings.
  - The inductive response of the system to the stroke current, responsible for transformer failures.
- 11 references

- Monitoring with Dranetz 606-3 at Bell Telephone sites.
- Statistical discussion of relative percentages of disturbances based on arbitrary thresholds.

- Discussion of capacitor switching transients and magnification effects.
- Provides several examples of recordings with the “PQNode” instrument.
- Points out the need to evaluate energy considerations if MOVs are applied for mitigation.
- 6 references


- The survey logged 22 201 monitor-days at 25 IBM computer sites.
- Frequency-distribution tables, Weibull profiles, histories of monthly events, and chronologies of vents.
- The composite results of the survey are compared with those of the 1972 and 1982 IBM surveys.
- 93 pages, 5 references

- Reports submicrosecond rise times of lightning current and differences in winter and summer lightning in Japan.
- 7 references

- Monitoring with a digital system show ring waves and nanosecond rise times near switching devices.
- 1 reference (in German)
3. Recorded occurrences, surveys, and staged tests – Continued

- Reports results of monitoring surge occurrences (only as part of a power quality survey).
- Three-year period at 550 sites classified as industrial, commercial, and residential, each for one month.
- 8 references

- Records of disturbances and general discussion.
- Early version of the computer susceptibility curve that became "The CBEMA Curve."
- 10 references

- Reports (in the discussion) oscilloscope recordings at pole-mounted transformers with 5.6 kV peaks, the maximum surge recording in 120 V circuits found in the literature.

- Lightning strike density computed from aviation stations observations, presented as maps and tables.
- 16 references

- Injection of surges and their propagation in a residential power system.
- Examples of suppression achieved by selenium cells before the advent of metal-oxide varistors.
- 2 references

- Oscilloscope recordings showing ring waves; peak detector recordings yield statistics.
- Documents the anecdotal story of clock motor failure rates.
- 9 references

- Capsule summary of data collected in the survey over the period of 1963-1970.
- Large-size, first generation reproductions of original oscillograms contributed to IEEE Std C62.41.
- 6 references

- Staged test of capacitor switching on remote MV side produces ring waves on low-voltage load.
- Coordination between 3 kV and 480 V varistor-based SPDs.
- 5 references, 1 discussion

- Reports generic types of disturbances.
- Procedures on conducting a site survey.

- The seminal paper proposing long waveform with extremely high energy-deposition capability (leading to the development of German Standard DIN 0160, but no longer acknowledged by the IEC TC77).
- Documents the effects of fuse blowing in industrial environments.

- Shows field and laboratory recordings of bursts such as those involved in the IEC EFT specifications.
- 11 references
3. Recorded occurrences, surveys, and staged tests – Continued

- Reports measurement in megahertz range of contact opening sequences.
- 11 references

- Reports mostly long-duration surges (1000 μs).
- 5 references, 2 discussions

- Statistics and maps of lightning ground flashes for Eastern United States.
- 13 references

- Recordings of atmospheric overvoltages on MV/LV stations and rural distribution lines.
- Statistical analysis of the recordings.

- Reports measurements conducted in Germany in the late eighties.

- Statistics of the recording of lightning-induced surges in an overhead line.

- Electric field measurements and TV records of multiple strokes.
- Time intervals between two stroke can be less than one millisecond.
- 25 references

- Measurements at Camp Blanding of electric and magnetic fields at distances of tens to hundreds of meters from point of strike.
- Comparisons with data from Kennedy Space Center and Fort McClelland.
- 9 references

- Transients associated with UPS operation and CRT flashover.
- 5 references

- Comprehensive statistical data base of power quality measurements collected during the EPRI Distribution Power Quality (DPQ) Project.
- 15 references

- Generic report of recordings and statistical discussion.
3. Recorded occurrences, surveys, and staged tests – Continued

- Measurement by digital oscilloscope of transients on the single-phase 120 V mains of a residential environment.
- Waveforms are shown for transient overvoltages on the mains caused by three nearby lightning strikes and one unknown source. Statistical summaries are presented for all naturally occurring transients.
- Waveforms are presented for the transient caused by switching on various loads, resulting in rates of rise ranging from 6 kV/μs to 17 kV/μs.
- 6 references

- Presents the concept of “stroke factor”.

- Shows rise times in the range of 60 ns to 600 ns.
- Contains a graph of number of occurrences versus peaks.
- 12 references

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4. Propagation and coupling of surges
(Experiments and numerical simulations)

- Presents simulations of direct lightning strikes to the building for TN, TT, and IT power distribution systems.
- Makes the statement “Coordination must be done on a basis of lightning currents with the 10/350 waveform.”
- 31 references

- Considers first stroke, subsequent stroke, and continuing current.
- Impact on surge arresters.
- 5 references


- Effect of large currents flowing in the neutral/grounding conductor of the service drop to a building.
- A unidirectional 8/20 μs current flowing only in the grounding conductors induces oscillatory transients in the differential mode. (Test results contributed to the data base of IEEE Std C62.41.)
- 5 references

- Describes the scenario of a lightning strike to the service drop and resulting surges in the transformer.
- Simulations show the effects of placing surge arresters at the transformer secondary terminals.
- 7 references

- Coupling of surges between grounding conductors, etc., and the line conductors during lightning current.
- Describes solutions.
- 4 references

- Discusses effects of the type of windings of the transformer on the resulting surges at the service entrance.
- Recommends installation of SPDs at both transformer secondary and service entrance.
- 7 references

- Describes how lightning surges can enter load circuits through utility system neutral paths.
- Offers comments on protection schemes within the building.
- 4 references

- Discusses low side surges and effects on distribution transformers.
- Discusses effect of secondary arresters on distribution transformer failures.
- 11 references
4. Propagation and coupling of surges – Continued

- Tutorial presentation of the subject of low-side surges
- Laboratory test results from injection of 4/10 strokes at the transformer primary and at the service entrance.
- 9 references


- Description of the public domain version of the original EMTP program, adapted for PC use.

- Measurement of voltages induced into an 11-kV line, 10-km long, by nearby and far lightning strikes.
- Model for computing induced voltages.
- 24 references, 2 discussions

- Camp Blanding, Florida facility for rocket-triggered lightning.
- Direct lightning strikes to overhead line and to a simulated house ground.
- 25 references

- Summary of power quality related concerns associated with the application of utility distribution system capacitor banks.
- 7 references

- Computer analysis of nuisance tripping of adjustable speed drives caused by capacitor switching.
- 8 references

- Computer and parametric analysis of secondary transient overvoltages caused by utility capacitor switching.
- 5 references

- Transient Network Analyzer study.
- 4 references

- Describes a test bed for the propagation and mitigation of surges.
- Illustrates the differences of voltage references developed across multiple ports of appliances.
- 8 references

- Theoretical treatment of the subject.
- 5 references
- Presents several calculation methods for temporary overvoltages and an evaluation of these methods.
- Defines limits of applicability of the methods.
- 8 references

- Tests the two most commonly used lightning return stroke models, Bruce-Golde and transmission line, against subsequent stroke electric and magnetic field measured simultaneously at near and distant stations and shows that these models are inadequate to describe the experimental data.
- A new return stroke model is proposed that is physically plausible and that yields good approximations to the measured two-station fields.
- 38 references

- Measurements and modeling show the physical impossibility for large surge currents to propagate very far into the branch circuits of a building, because flashover will occur at the service entrance.
- Demonstrates the importance of considering the maximum rate of rise (early in the surge) rather than the peak value and overall rise time.
- 13 references

- Compares the TN and TT for dispersion of lightning current in several scenarios.
- Shows the need for careful review of grounding practices in effect at service entrances.
- Questions the applicability of high amplitude, long duration requirement for service entrance SPDs.
- 20 references

- Injection of voltage surges and their propagation in a residential power system.
- 2 references

- Reports laboratory injection of lightning current in house wiring.
- Illustrates conversion of unidirectional surges into oscillatory surges.
- 4 references

- Coordination between gap-type (“voltage switching”) and clamp-type (“voltage limiting”) protectors.
- Coupling between grounding conductor and phase wires.
- 7 references

- Propagation and attenuation of 1.2/50 μs and 100 kHz Ring Wave.
- Coupling of differential mode through isolation transformers.
- 9 references, 1 discussion

- Propagation of 100 kHz Ring Wave in steel conduit lines.
- Options for coupling one, two, or three surge diverters at line end; resulting mode conversion.
- 8 references
4. Propagation and coupling of surges – Continued

- Propagation of low-frequency, capacitor switching ring waves from distant substation to low-voltage load.
- Coordination between 3 kV and 480 V varistor-based SPDs.
- 5 references, 1 discussion

- Measurement and modeling of attenuation of pulses with nanosecond rise time in steel conduit lines.
- 8 references

- Measurement and modeling of attenuation of the EFT 5/50 ns pulse in conduit and nonmetallic jacket lines.
- Shows the decrease in pulse front steepness occurring for a relatively short length of line.
- Suggests that the EFT test should be required only when exposure to this type of environment is likely.
- 9 references

- Propagation and attenuation in multi-branch systems.
- Surges in power lines can cause failures of data port components when ground loops exist between pieces of equipment powered by separate branch circuits and connected by a data link.
- Findings promoted the concept of a surge reference equalizer.
- 11 references

- Measurements on the propagation of the Ring Wave, the Combination Wave, and the 10/1000 µs Wave.
- The lack of effect of wire diameter is documented by a simple experiment.
- 14 references

- Comparison of the performance of filter-type vs. voltage-limiting type surge-protective devices.
- Experimental demonstration of voltages induced in branch circuit conductors by the flow of surge currents diverted by the action of the two types of SPDs.
- 9 references

- Describes a test bed for studying the propagation of surges in low-voltage installations.
- Test and computer modeling on appliances connected to different systems show reference voltage shifts.
- 4 references

- A review of simulation examples and anecdotal case history.
- 9 references

- Detailed calculations of lightning return stroke electric and magnetic fields above ground are presented.
- 16 references

- A 200-page report on the results of triggered lightning experiments.
- 43 references
4. Propagation and coupling of surges – Continued

- Modeling of the Camp Blanding overhead distribution line subjected to injection of lightning current.
- Model elements include transmission line, MOV arresters, grounding leads, and ground rods.
- 9 references

- Results of Transient Network Analyzer study evaluating switched capacitor banks.
- Includes normal energizing, voltage magnification, phase-to-phase transients, inrush, outrush, and restrikes.
- 14 references, 2 discussions

- Transient Network Analyzer study.
- 9 references, 4 discussions

- Method for determination of relative value of common-mode and normal-mode noise, with modeling of candidate mitigation methods.
- 5 references

- A review of the propagation of surge voltages (in German).

- Model of electrical installation including power and telecom lines, water pipe, lightning rod and SPDs.
- Sharing of current between various paths including SPDs showing that neutral is more stressed in case of strike on lightning rod. Opposite in case of strike on power lines.
- In general 30 % of lightning current is shared among all power conductors.
- 8 references

- Injection of triggered lightning into a house replica at Camp Blanding.
- Measured data on dispersion of the lightning current among available paths to ground.
- Examples of current waveforms.
- 9 references

- Reports an investigation conducted by the French utility (in French).

- Mathematical model of high frequency lightning earth/ground.
- High frequency is just useful for overvoltages not for energy sharing between various paths.
- Equipment exist for measuring high frequency ground impedance and examples of good "lightning" ground are given based on real measurements.
- 5 references

- Laboratory measurements of propagation parameters on typical wiring practices
- Comparisons between gap-type and varistor SPDs.
- Recommendations on grounding practices and building construction.
- 8 references
4. Propagation and coupling of surges – Continued

- Provides mathematical equations for the 100 kHz Ring Wave and the Combination Wave.

- Makes computations with SPICE for a 10/350 µs, 20 kA impinging current.
- MOV arrester at the service entrance and varistors at the end of branch circuits of various lengths.
- Neglects inductance and considers only resistance, justified by the long tail of the surge.
- 11 references

- The distribution of surge currents between an arrester and suppressor separated by a transmission line is described for six different models of transmission lines.
- Two different surge waveforms are used in the simulation: the 1.2/50 µs wave, and the 10/350 µs wave.
- Conclusions on the relative accuracy of the various models of transmission lines.
- 14 references

- Computer simulations of surge suppressor circuits and propagation of surges on transmission lines show surge voltage waveshapes between the neutral and protective earth conductors inside buildings.
- Theoretical discussion is about the common error of approximating a transmission line as a single inductor.
- 13 references

- Experiments showing the effect of line length and surge waveform on sharing energy between service entrance arrester and surge suppressor inside building.
- Metal-oxide varistors were applied at service entrance, distribution panel and load.
- Removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection achieved with MOVs in all three locations.
- 4 references

- Reports conducted noise measurements from typical residential loads.
- 14 references

- Switching transients at the 41 kV level.
- 10 references, 2 discussions
5 Monitoring instruments, laboratory measurements and test methods

- Description of the instrumentation used by Allen and Segall in [53].
- 5 references

- Reports measurements and 50 Ω/50 μH equivalent circuit.
- 6 references

- Describes test methods and test circuits developed independently from standard approaches.
- 3 references

- Discusses the principle of lightning detection.
- Provides guidelines on the uncertainties of lightning parameters that are acceptable in the industry.
- 75 references

- Second part of a paper proposing a test protocol based on concepts derived from high-voltage BIL testing.
- General discussion of circuits for surge generators.

- Proposes to define a “steepness factor” to characterize the initial rate of rise of current.

- Describes a test bed for the propagation and mitigation of surges.
- Illustrates the differences of voltage references developed across multiple ports of appliances.
- 8 references

- Challenges the erroneous concept of characterizing “energy in the surge” from a simple voltage measurement.
- Lists surge parameters leading to failure of specific equipment.
- 15 references

- One chapter on planning and performing a power quality survey includes the topic of ‘impulses’.
- One chapter on waveforms shows examples of recorded surges.

- Challenges the erroneous concept of “energy in the surge” based on a simple voltage measurement.
- Lists surge parameters leading to failure of specific equipment.
- Proposes the approach for using existing power quality monitors to record available surge currents.
- 24 references
5. Monitoring instruments, laboratory measurements, test methods – Continued

- Experimental measurements of effective mitigation by multiple SPDs.
- Numerical simulation of the effect of proliferating SPDs and PCs.
- Calls for an industry-wide reassessment of surge monitoring parameters.
- 18 references

- Simplification of a system-wide survey through stratified random sampling.

- Injection of surges and their mitigation in a residential power system.
- Examples of suppression achieved by selenium cells before the advent of metal-oxide varistors.
- 2 references

- Early internal GE report addressing the emerging problem of semiconductor failures caused by surges.

- Steep front surges tend to increase the level at which 1960's diodes failed under surge conditions.
- Higher peak inverse voltage (PIV) do not result in higher levels for the surges that cause failure.

- Design of the surge counters used for the surge monitoring reported in [86] Martzloff & Hahn, 1970.

- For semiconductors of the late sixties vintage, there is no correlation between their peak inverse voltage rating (PIV) and the surge level at which failure occurs – most likely by edge flashover.
- Ageing by storage at elevated temperature changed the PIV but not the surge failure level.
- 8 references

- Development of a home-made Ring Wave generator used in the seventies and eighties.
- Two examples of circuits with identical open-circuit voltage waveforms, but different short-circuit current waveforms.
- 8 references

- Signals the fallacy of surge recordings from a monitoring instrument that included an internal SPD to protect its own power supply, inadvertently mitigating surges on the receptacle also used as power source to be monitored.


- Reports measurements on the propagation of oscillatory waves in typical low-voltage circuits, as opposed to the unidirectional waves initially defines for high-voltage power systems.
- Shows how impinging unidirectional surges can produce oscillatory waves responses.
- 17 references
5. Monitoring instruments, laboratory measurements, test methods – Continued

- Explains that monitoring voltage surges no longer makes sense because of the proliferation of SPDs.
- Rebutts the misconception of characterizing surges by their “energy content.”
- Proposes an IEEE-sponsored sharing of field failure data as an assessment of the surge environment.
- 15 references

- Makes the case that the proliferation of SPDs makes monitoring surge voltages debatable.
- Proposes an approach for using existing power quality monitors to record available surge currents.
- 18 references

- Techniques and equipment for making TCL tests.
- 10 references

- Reports generic types of disturbances with non-standard terminology.
- Calls a surge as defined by IEEE an ‘impulse’. Calls a swell as defined by IEEE a ‘surge’.
- Describes procedures on conducting a site survey.
- 287 pages

- Describes the design and characteristics of a probe that filters out the power-frequency component.
- 20 references

- Filter network removing the power-frequency voltage from the record.
- 5 references

- Proposal for systematic classification of disturbances.
- 17 references

- Discussion of common mode and differential mode from the point of view of frequency domain measurements.
- 5 references

- General review of surge generator technology.
- Detection of breakdown by monitoring both voltage and current waveforms in EUT.
- 11 references

- Presents the case for the Combination Wave rather than separate 1.2/50 µs and 8/20 µs impulses.
- 4 references

- Undershoot effects on unidirectional waves, the case for oscillatory waves.
- 5 references
5. Monitoring instruments, laboratory measurements, test methods – Continued

- Describes a differential probe with 10 kΩ input impedance, 2 ns rise time, 10 kV rating.
- 5 references

- Design, construction, and performance of a circuit that detects transients on low-voltage AC mains.
- The disturbance detector circuit can be used to trigger a digital waveform recorder or to operate a counter circuit to simply record the occurrence of a disturbance.
- 7 references

- Experiment to collect waveforms of mains disturbances and determine energy deposited in MOVs.
- 16 references

- Describes the design of an experiment to characterize disturbances on the mains, including the trigger criteria for waveform recorders.
- Definitions of some disturbances are provided.
- 16 references

- Simple equations are provided that satisfy the definitions of five of the most common transient overvoltage test waveforms: the Ring Wave specified in ANSI C62.41-1980, the fast transient specified in IEC 801, and the 8/20-μs 1.2/50-μs, and 10/1000-μs waveforms.
- 7 references

- Evaluates several commercial surge generators and proposes using equations to define nominal waveforms and tolerances of unipolar waves.
- 11 references

- Shows that using the integral of \( V^2/50Ω \cdot dt \) to compute energy in a surge is invalid.
- An artificial AC line network simulates a long branch circuit to give line impedance vs. frequency.
- 18 references

- Describes how electronic equipment and surge protective devices are surge tested in the USA, with emphasis on differences between the American and European practices.
- 11 references

- Description of rocket-triggered lightning at Camp Blanding, with examples of recordings.
- 6 references

- Endorses the concept of the Combination Wave in the European context.
6 Textbooks and tutorial reviews

- Book initially written from the communications point of view but applicable to AC power circuits.
- 124 references, 320 pages

- Overview on causes of temporary overvoltages on HV networks and impact on surge arresters.
- Equipment withstand capability and methods of temporary overvoltages control.
- 23 references

- A well published photograph purportedly of ball lightning has been critically examined.
- Evidence is stronger for interpreting the photograph as a street lamp rather than lightning ball.
- 7 references

- Comprehensive (44 pages) review of the subject.
- 102 references

- Tutorial presentation of the subject of low-side surges
- Laboratory test results from injection of 4/10 strokes at the transformer primary and at the service entrance.
- 9 references

- Injection of triggered lightning current into an overhead distribution line with MOV arresters at Camp Blanding.
- Measurements of the response of the arresters to the lightning current.
- 8 references, one discussion

- Proposes parallel with the BIL concept for high-voltage system.
- First published version of a test circuit for 100 kHz Ring Wave.
- 12 references, 3 discussions

- Second part of a paper proposing a test protocol based on concepts derived from high-voltage BIL testing.
- General discussion of circuits for surge generators.

- Vol 1: Physics of lightning
- Vol 2: Lightning protection
- Several hundred references

- Comprehensive textbook.
- Cites 2.1 per-unit overvoltage during ground fault clearing.
- 210 references, 540 pages
- The effect of arbitrary threshold selection on statistics.
- 2 references

- Examples of causes of overvoltages and damage to electrical systems with electronic devices.
- The operation and application of proven overvoltage protection devices are considered.
- Discusses coordination with a “quenching gap” as the upstream SPD.
- 355 pages, 83 references (many in German)

- Bibliography compiled by the original IEEE working group 3.6.4.
- 73 references

- Records of disturbances and general discussion.
- The seminal proposal of the computer susceptibility curve now known as “The CBEMA Curve”.
- 10 references

- General tutorial discussion of the subject.
- Proposed computer susceptibility curve.
- 19 references

- Summary of a comprehensive report developed by a team of experts, sponsored by EPRI.
- Presents three reports of case studies on lightning damage and post-mortem tests.
- 9 references

- First part of a paper proposing a test protocol based on concepts derived from high-voltage BIL testing.
- Equipment should be designed and rated to withstand a limited set of surge tests rather than attempting to emulate “real world” but ill-defined surge events.
- 10 references

- Signals the fallacy of surge recordings from a monitoring instrument that included an internal SPD to protect its power supply, inadvertently mitigating surges on the dual receptacle used for monitoring.

- Discussion of the background leading to testing for the propagation if the IEC “Electrical Fast Transient”.

- A summary of tests on the propagation of surges in a building and the side effects of installing SPDs.

- Review of instrumentation development, definition deficiencies, and past survey results.
- First proposal of the term “swell”.
- 33 references

- Condensation of Martzloff/Gruzs paper for power-quality context.
- 16 references
- Trade magazine version, in two successive articles, of the 1988 Martzloff/Gruzs IEEE paper.
- 14 references

- Overview on the issue of ageing metal-oxide varistors subjected to repetitive momentary overvoltages ("swells").
- Computations of temperature rise in the varistor body during a swell.
- Preliminary experiments on ageing (see later experiments under [259] Lagergren et al., 1992).
- 5 references

- Brief review of the origin of transients.
- Explanation of and remedy for interaction between power port and communications port.

- Trade magazine review of the revised and expanded C62.41 in its 1991 issue.
- 5 references

- Cites the ambiguity in the status indications of surge-protective devices.
- Describes two failure modes and conflicting indications.

- Consumer-oriented tutorial on the origins of surges and ways to mitigate them.
- Questions and answers, installation hints.
- 20 pages

- Measurements of lightning currents on tall towers and aircraft.
- Reports current rise times in the 50 ns to 100 ns range.
- 14 references

- Review of various models proposed to simulate lightning stroke events.
- Comparison of model predictions and measurements of electromagnetic fields.
- 34 references

- Review of measured characteristics of the electric and magnetic fields.
- Examples of different types of field waveforms are given.
- 12 references

- Discusses unprotected product input impedances, transient propagation modes and models, measured transient occurrences, and typical susceptibility.
- 9 references

- Class distinction of the various wide-range transients from arc to motor turn-on.
- Low product immunity to common-mode transients is shown to be caused by high energy-density spectrum.
- 18 references
6. Textbooks and tutorial reviews – Continued

- Review of transient types, standards, definitions, and cost considerations.
- 18 references

- Review of environment, statistics, measurements, and standards.
- 38 references

- Survey of the literature on surge occurrence, equipment design, and surge standards.
- 4 references

- Complete review of SPD specifications and characteristics for both telecom and power SPDs including important parameters for selection and comparison.
- Installation rules for SPDs including special case of TNC-S systems.
- 23 references

- Comprehensive review of the origin and propagation of surges, surge-protective devices and applications in circuits, and high-voltage laboratory testing techniques.
- 260 references, 434 pages

- Description of rocket-triggered lightning at Camp Blanding.
- Examples of recordings.
- 6 references

- Handbook addressing types of lightning and their parameters, electric and magnetic fields.
- Protected volume by intercepting devices, overvoltage protection, earthing systems.
- 154 pages, 83 references (German and English)

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7 Mitigation techniques

- The design and use of interference-free systems and printed circuit boards.
- The emphasis of the book is on equipment design.

- Review of issues such as length of connecting leads and provision of SPD disconnectors (fuses).
- Cascade coordination.
- 11 references

- Use of a secondary arrester on LV AC supply mains to prevent damage to electronic equipment is addressed.
- Some failure mechanisms of secondary arrester are described, and ways to minimize risks from possible failure of the arrester are suggested.
- 36 references

- Gives examples of connection configurations of MOVs and their coordination
- 8 references

- Reports differences noted between tests with single standard pulses and multiple closely-spaced pulses.
- Suggests that mechanisms other than mere total energy deposition might be involved.
- Proposes such a multiple test sequence in assessing SPD performance.
- 9 references

- Some advertising statements claim that the minimum 330 volt suppression rating in UL Standard for Transient Voltage Surge Suppressors, UL 1449, is “the best UL rating” or that 330 volts affords “the most protection possible” or that “the lower the suppression rating the better the TVSS product.
- The ability of a TVSS to protect connected equipment from both upset and damage may depend on a number of factors including knowledge of both the susceptibility and vulnerability of the particular equipment. When these factors are not known, claims that one TVSS provides better protection than another, solely on the basis of the UL 1449 suppression voltage rating, may be misleading.

- Discusses effects of the type of windings of the transformer on the resulting surges at the service entrance.
- Recommends installation of SPDs at both transformer secondary and service entrance.
- 7 references

- Describes how lightning surges can enter load circuits through utility system neutral paths.
- Offers comments on protection schemes within the building.
- 4 references

- Describes the overvoltages involved in commingling incidents of MV lines dropping on LV lines.
- Reports laboratory tests on distribution arresters.
- 4 references
7. Mitigation techniques – Continued

- Provides the results of a joint EPRI/NRECA effort to evaluate the state-of-the-art in distribution system capacitor switching transient overvoltage mitigation.
- 28 references

- Presents a summary of transient overvoltage mitigation techniques for transmission and distribution banks.
- 7 references

- Technical version of the market announcement of the new device technology.
- Brief description of structure, principle of operation, and planned applications.
- 6 references and 26 bibliographic citations

- Examples of causes of overvoltages and damage to electrical systems with electronic devices.
- The operation and application of proven overvoltage protection devices are considered.
- Discusses coordination with a “quenching gap” as the upstream SPD.
- 244 pages, 83 references (mostly in German)

- Background information on the family of System Compatibility test protocols.
- Reports the performance of generic surge-protective devices, not brand names.
- 21 references

- Case history on system interaction.
- Case history on damage to communications port, not power port.
- Case history on improper grounding practices.
- 6 references

- Effects of amplitude, duration, and number of swells, using change in varistor nominal voltage as criterion.
- A relatively small (less than 3%) change in varistor nominal voltage for limited cumulative stresses.
- Failure caused by gradual aging (the 10% limit quoted by industry) was not reached in this experiment.
- Failure by overheating occurs for stresses of long-duration (seconds) temporary overvoltages.
- 8 references

- Presents several calculation methods for temporary overvoltages and an evaluation of these methods.
- Defines limits of applicability of the methods.
- 8 references

- Three examples of temporary overvoltage conditions that can produce failure of SPDs.
- The significance of available fault current and the need for more explicit standards.
- 17 references

- Demonstrates the principle of a coordination scheme compatible with downstream SPDs having lower limiting voltage than the SPD at the service entrance.
- 23 references
Mitigation techniques – Continued

- Injection of surges and their mitigation in a residential power system.
- Examples of suppression achieved by selenium cells before the advent of metal-oxide varistors.
- 2 references

- Performance of nine commercial SPDs available before the advent of metal-oxide varistors.
- Tests include voltage-switching devices and voltage-limiting devices.

- Performance of mid-seventies vintage of service entrance SPD and simple MOV plug-in SPD.
- Introduction of the concept of cascade coordination achieved by the inductance of wiring.
- 4 references

- A glimpse at typical protective devices available in North America and Europe in the early 80's.
- Degradation of performance resulting from improper installation techniques.
- 10 references

- Performance and degradation of fuses subjected to repetitive surge currents.
- 10 references

- Summary of personal observations and experience on the subject circa 1985.
- Last Martzloff publication under the GE Logo.
- 39 references

- Staged tests of capacitor switching on remote MV side produces ring waves on low-voltage load.
- Coordination between 3 kV and 480 V varistor-based SPDs.
- 5 references, 1 discussion

- Occurrence, characteristics, and mitigation of surges.
- Varistor microstructure, conduction, and applications.
- 30 references

- Experimental and computed evaluation of heating effects from repetitive swells applied to MOVs.
- Four mechanisms are describe that can lead to premature failure.
- 11 references

- Overview on the issue of ageing metal-oxide varistors subjected to repetitive momentary overvoltages ("swells").
- Computations of temperature rise in the varistor body during a swell.
- Preliminary experiments on ageing (see later experiments under [259] Lagergren et al., 1992).
- 5 references

- Brief review of the origin of transients.
- Explanation of and remedy for interaction between power port and communications port.
- Comparison of the performance of filter-type vs. voltage-limiting type surge-protective devices.
- Experimental demonstration of voltages induced in branch circuit conductors by the flow of surge currents diverted by the action of the two types of SPDs.
- 9 references

- Explains the problem of interactions between power and communications systems during surge events.
- Describes the concept of a surge reference equalizer as possible remedy.
- 5 references

- Consumer-oriented tutorial on the origins of surges and ways to mitigate them.
- Questions and answers, installation hints.
- 20 pages

- Evaluation of MOV surge arresters for the overvoltage protection of shunt capacitor banks, including impact of lightning and switching transients.
- 10 references, 4 discussions

- Parametric analysis of the effects of capacitor switching.
- Shows high stresses on SPDs.
- Mitigation at the switched capacitor.
- 5 references

- Results of a Transient Network Analyzer study of switching 2500 MVAR 345 kV capacitor banks.
- Normal energizing, voltage magnification, phase-to-phase transients, inrush, outrush, and restrike events.
- 14 references, 2 discussions

- Laboratory measurements of propagation parameters on typical wiring practices
- Comparisons between gap-type and varistor SPDs.
- Recommendation on grounding practices and building construction.
- 8 references

- A total of 16 different clocks, television receivers, microwave ovens, and dc power supplies were subjected to three different surge waveforms with amplitudes between 0.5 kV and 6 kV.
- Switching power supplies and television receivers were damaged with surges between 4 kV and 6 kV.
- Three of five models of digital locks were upset (temporary malfunction) with surges between 1.5 kV and 6 kV.
- 19 references

- Simple rules for the protection of small computer system from disturbances on the mains.
- If a system operation is critical, the combination of varistors, line conditioner, and a standby UPS is recommended.
- Provides historical data on author’s computer protection experience.
- 12 references
7. Mitigation techniques – Continued

- Review of the design of commercial low-pass filter modules for equipment connected to the LV supply mains.
- Discusses problems of using these filters to protect electronic equipment from damage or upset by high-voltage transients on the mains.
- 12 references

- Discusses the use of a series spark gap with a metal oxide varistor to achieve both a small clamping voltage and a long life time for the surge-protective circuit.
- Extinguishing follow current in the gap and attenuating the remnant that propagates downstream prior to the conduction of the spark gap are discussed in detail.
- 5 references

- Tests on more than two dozen different models of commercially available surge suppressors during 1987-1990 showed that some types of suppressors perform much better than others.
- The manufacturer’s specifications and UL clamping voltage rating are often not consistent with laboratory measurements.
- 25 references

- Suppressors removed from service throughout the U.S. and Canada, contrary to popular myth, field data shows that surge suppressors containing metal oxide varistors do not degrade in service.
- All suppressors are, however, exposed to rare incidents of severe power-frequency overvoltage caused by power-line accidents, such as broken neutral conductors, which can cause suppressors to overheat internally.
- Products equipped with overcurrent fuses or magnetic circuit breakers might catch fire in rare cases. This is true for those having both plastic and metal housings and components rated for both 130 V and 150 V.
- A fire hazard test is proposed to be added to safety agency tests for surge suppressors and similar products.
- 3 references
8 Coordination of cascaded SPDs

- Describes secondary surge phenomena and the importance of transformer secondary circuit protection coordination to both utilities and end users.
- An effective MOV protection coordination scheme is described and recommended.
- Multiple grounds at different potentials, especially under lightning surge conditions, prevent distribution transformer primary arresters from protecting secondary circuits.
- 13 references

- Proposes a scheme where the performance of SPDs for any waveform is converted to an equivalent configuration referred to the performance under the Combination Wave.
- 7 references

- On the basis of observed failures on secondary surge protection devices, theoretical and experimental investigations are performed in order to clarify the need for such protection including the sharing of energy stresses in relation to the primary surge protection system.
- The higher energy stresses will generally occur on the device with the lowest limiting voltage. Therefore, the protection level for the secondary protection should be selected higher than for the primary protection.
- 5 references

- Voltage limiting level of cascaded devices, their separation distance, and surge waveform are used as parameters to compute the energy deposited in the devices.
- Experimental verification shows reasonable agreement between simulation and experiment.
- Contains details of the data base used for the Lai & Martzloff IEEE Transactions IA-24 1993 paper [291].
- 10 references

- Computations and experiments showing the effect of line length and impinging surge waveform on sharing energy between service entrance arrester and SPD inside building.
- While the 8/20 μs waveform can still result in a contribution from both devices to sharing the energy, the 10/1000 μs waveform does not produce any inductive separation of the devices past the rise time, so that energy is equally shared between devices of equal rating.
- 11 references

- Demonstrates the principle of a coordination scheme compatible with downstream SPDs having lower limiting voltage than the SPD at the service entrance.
- 23 references

- Performance of mid-seventies vintage of service entrance SPD and simple MOV plug-in SPD.
- Introduction of the concept of cascade coordination achieved by the inductance of wiring.
- 4 references
9. Coordination of cascaded SPDs – Continued

- Coordination between voltage-switching and voltage-limiting SPDs.
- Coupling between equipment grounding conductor and phase wires.
- Where an unidirectional current is injected into the ground system only, the response of the system is an oscillating voltage involving the phase conductors.
- Without substantial connected loads in the system, the open-circuit surges appearing at the service entrance propagate along the branch circuits with very little attenuation.
- 7 references

- Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations might leave the smaller device subjected to the highest stress.
- Significant parameters in achieving successful coordination involve three factors, over which the occupant of the premises has no control: the relative limiting voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges.
- 13 references

- Implications of the situation resulting from the present uncoordinated application of devices with low limiting voltage at the end of branch circuits and devices with higher limiting voltage at the service entrance.
- The reality of having many millions of 130-V rated varistors installed on 120-V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.
- As a compromise, a cascade with equal voltage ratings for the arrester and the suppressor can offer successful coordination, if the impinging surges are presumed to be relatively short.
- Tolerances on device characteristics might make the compromise ineffective.
- Bibliography with 32 citations

- Utilities are becoming aware of the low-side surge phenomenon and are applying secondary arresters to protect their distribution transformers. This practice can increase the voltage stress at the customer service entrance.
- If any ground paths exist on the customer side of the service entrance, these surges can penetrate further into the customer's system.
- Damage caused by low-side surges can be avoided if properly coordinated arresters are installed at the transformer secondary, service entrance, and load device.
- 15 references

- Results of both a theoretical analysis and laboratory experiments are reported on sharing of current between an arrester at the service entrance and a suppressor at receptacles during surges.
- Shows that it is better to design the arrester with a smaller conduction voltage than the suppressor, in order to obtain better coordination, better electromagnetic compatibility, and lower cost.
- Computations were made with only resistance of wire between cascaded devices, no inductance.
- 9 references

- Experiments showing the effect of line length and impinging surge waveform on sharing energy between service entrance arrester and surge suppressor inside building.
- Metal-oxide varistors were applied at three points on the system. These were at the service entrance, at the distribution panel and at the load.
- Removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection was achieved with MOVs in all three locations.
- 4 references
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