ANNOTATED BIBLIOGRAPHY

APPLICATION OF SURGE-PROTECTIVE DEVICES

AND

COORDINATION OF CASCADES

Compiled by François D. Martzloff
September 1992

FOREWORD

In view of the emerging concerns on the likelihood of achieving a successful coordination of cascaded surge-protective devices, this bibliography has been compiled to provide as complete information as possible to the joint efforts underway within the US National Committee for the IEC, as well as within the transnational community, at the level of the Working Groups of cognizant Technical Committees.

This document is organized in two parts:

1. List of identified documents with retrieval information. Depending on the outcome of requests made to the various publishers, full copies of the documents might be made available to members of interested Working Groups.

2. For each document, a single-page digest showing the author's abstract, the author's conclusions, and brief annotations from the reviewer concerning the implications/applications of the document to the subject of cascade coordination.

Unless stated otherwise, abstracts or conclusions shown for each paper are verbatim transcripts (in toto or in part) of those provided by the author(s) of the papers.

The 'Reviewer's Annotations' have been added to focus on the issue of cascade coordination, and represent the reviewer's (Martzloff) point of view. As such, they are subject to discussion or even refutation; they were formulated with the objective of stimulating open discussion, not adversarial controversy.

Comments on this bibliography will be welcome, perhaps leading to periodic updates as necessary. One possibility might be that annotations contributed by other experts could be included in later issues of this bibliography, leading to a shared document of the Joint Working Group. Suggestions for listing additional documents are invited.

NOTE: This September 1992 issue has been prepared for the September, 1992 meeting of IEEE SPD WG 3.4.6 and the October 1992 Joint Working Group of IEC SC28A, SC37A, TC64, SC77B and TC81. The deadline for printing and distribution made it impossible to complete all the annotations; the selection of those citations that are annotated does not reflect a systematic intention of ranking papers by order of significance.

2002 REMARKS

As stated in the Foreword (on following Page 3), this Annotated Bibliography was compiled in 1992 in support of a Working Group of the IEEE Surge-Protective Devices Committee engaged in the development of an Application Guide on Low-Voltage Surge-Protective Devices, and an IEC project about to be launched, involving five Technical Committees or Subcommittees of the IEC for developing a "pilot" Technical Report or Standard on the application of low-voltage surge protective devices (SPDs), intended in particular to focus on the coordination of cascaded SPDs, an issue that was emerging at the time. To the author's knowledge, only few additional papers were published on the subject after 1992, see the file "Citations Part 8" that is included as Annex A of this Part 8.

Both documents IEC and IEEE eventually reached maturity and, ten years later, the IEC has published its document, and the IEEE has conducted a ballot on its document. They can be obtained from their respective sponsoring organizations:

IEEE PC62.72-2002 – *Guide for the application of surge protective devices for low-voltage AC power circuits*
Ballot in progress (December 2002, publication expected mid-2003)

Abstract: Information is provided to specifiers and users of ***surge protective devices*** (SPDs) about the application considerations of SPDs associated with power distribution systems within North America. This guide applies to SPDs to be connected to the load side of the service entrance main over current device of 50 or 60 Hz ac power circuits rated at 100-1000V rms. The effects and side effects on the presence and operation of SPDs in low-voltage power distribution systems are described. The coordination of multiple SPDs on the same circuit is described.

IEC/TR 62066 (2002-06) – *Surge overvoltages and surge protection in low-voltage a.c. power systems - General basic information*

Abstract: Presents a general overview on the different kinds of surge overvoltages that can occur on low-voltage installations. Typical surge magnitude and duration as well as frequency of occurrence are described. Information on overvoltages resulting from interactions between power system and communications system is also provided. Additionally, general guidelines are given concerning surge protection means and systems on the basis of availability and risk considerations, including interactions and the need for coordination and consideration of temporary overvoltages in the selection of surge-protective devices.

1992 ACKNOWLEDGMENT
Only the cooperation of many authors who made available hard copies of their papers, or of their colleagues' papers, made this compilation possible. Their help in this venture has been essential. My hope is that in providing this review, I have not misrepresented their ideas. If I did, I take full responsibility for an unintentional error and offer my apologies.

ALPHABETICAL - CHRONOLOGICAL LISTING OF DOCUMENTS

ANSI/IEEE C62.41-1991 - *Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.*

ANSI C84.1-1989 - *American National Standard for electric Power Systems and Equipment - Voltage Ratings (60 Hertz).*

Anderson, L.M. and Bowes, K.B. - The Effects of Power-Line Disturbances on Consumer Electronic Equipment. *IEEE Transactions PWRD-5*, No.2, April 1990, pp 1062-1065.

Benda, S. - *Interference-free Electronics - Design and Applications.* Chartwell-Bratt Ltd., Bromley, U.K., 1991.

Bird, A.O. - The Effects of Installation Practices on the Performance of Transient Voltage Surge Suppressors. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 105-116.

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Crouch, K.E and Martzloff, F.D. - Lightning Protection of Residential AC Wiring. Declassified *Memo Report MOR-78-095, GE Company*, 1978. (Available from FD Martzloff)

Davidson, R. - Suppression Voltage ratings on UL Listed Transient Voltage Suppressors. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 89-92.

Dugan, R.C. and Smith, S.D. - Low-Voltage-Side Current-Surge Phenomena in Single-Phase Distribution Transformer Systems. *Preprint T&D 553-2, IEEE T&D Conference*, 1986.

Dugan, R.C., Kershaw, S.S., and Smith, S.D. - Protecting Distribution Transformers from Low-Side Current Surges. *Preprint TD 401-1 PWRD, IEEE T&D Conference*, 1989.

Dugan, R.C. - Conduction of Lightning Stroke Currents From the Utility System to Load Devices. *Conference Proceedings, Power Quality*, October 1989.

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Hasse, P., Wiesiger, J., and Zischank, W. - Isolations-koordination in Niederspannungsanlagen auch bei Blitzeinschlagen. *Electrotech. Zeitschrift*, Jan 1989, pp 64-66. (In German; English translation available from FD Martzloff)

Hasse, P. - *Overvoltage Protection of Low-Voltage Systems.* IEE Power Series, Peter Peregrinus Ltd. London, 1992. (Original German edition in 1987) Available in the U.S. from IEEE.

Hostfet, O.T. et al. - Coordination of surge protective devices in power supply systems: Needs for secondary protection. *Proceedings, International Conference on Lightning Protection*, Berlin, September 1992.

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IEC 28A(USA/Las Vegas)09 - (Draft) *Explanation for over-voltage categories*. December 1984, Amended August 1987.

IEC 28A(Norway) - *Comments of the Norwegian National Committee on Document 28A(Secretariat)47.*

IEC 37A/WG3(Convenor)1 - *Draft Application Guide*, 1992.

IEC 64/WG3 138A - Explanation of interfaces for overvoltage categories. Supplement to *Appendix B of Report 664*, November 1990.

IEC 77(CO)118 *Classification of Electromagnetic Environments*

Lai, J.S. and Martzloff, F.D. - Coordinating Cascaded Surge-Protective Devices. *Proceedings, IEEE/IAS Annual Meeting*, October 1991.

Lagergren, E.S., Martzloff, F.D., Parker, M.E., and Schiller, S.B. - The effect of repetitive swells on metal-oxide varistors. *Proceedings, PQA 92 Conference*, September 1992, pp xx-xx.

Lai, J.S. - Performance Criteria for Cascading Surge-Protective Devices. *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, August 1991, pp 147-160.

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Martzloff, F.D. - Coordination of Surge Protectors in Low-Voltage AC Power Circuits. *IEEE Transactions PAS-99*, January/February 1980, pp 129-133.

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Martzloff, F.D. - Coupling, Propagation, and Side Effects of Surges in an Industrial Building Wiring System. *IEEE Transactions IA-26*, March/April 1990, pp. 193-203.

Martzloff, F.D. and Lai, J.S. - Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase. *Proceedings, PQA 91 Conference*, pp 191-198.

Martzloff, F.D. - On the Propagation of Old and New Surges. *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, August 1991, pp 19-28.

Martzloff, F.D. and Lai, J.S. - Cascading surge-protective devices: Options for effective implementations. *Proceedings, PQA 92 Conference*, September 1992, pp xx-xx.

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Smith, S.B. and Standler, R.B. - The Effects of Surges on Electronic Appliances. *IEEE Transactions PWRD-7*, No.3, July 1992, pp 1275-1282.

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Standler, R.B. - Coordination of Surge Arresters and Suppressors for Use on Low-Voltage Mains. *Proceedings, 1991 Zürich EMC Symposium*, pp 517-524.

Standler, R.B. - Calculations of Lightning Surge Currents Inside Buildings. *Proceedings, IEEE International EMC Symposium*, August 1992, pp 195-199.

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Stringfellow, M.F. - Fire Hazard of Surge Suppressors. *Proceedings, Power Quality Conference*, Anaheim Ca, September 1992.

Anderson, L.M. and Bowes, K.B. - The Effects of Power-Line Disturbances on Consumer Electronic Equipment. *IEEE Transactions PWRD-5*, No.2, April 1990, pp 1062-1065.

AUTHOR'S ABSTRACT

This study quantified the effects of simulated power system transients, voltage fluctuations and momentary interruptions on household electronic equipment. Non-destructive testing was performed to determine the applicability of the CBEMA and IEEE susceptibility curves to consumer electronic equipment. As a results, graphs were developed which illustrate these effects.

AUTHOR'S CONCLUSIONS

(Excerpts)

Overvoltage/transient testing in this study failed to demonstrate any adverse effect on the equipment tested. [...] ***Any cumulative effects due to accelerated aging (loss of life) from either undervoltages or overvoltages were not considered in this study***. [authors' italics]

REVIEWER'S ANNOTATIONS

The researchers' objectives were primarily nondestructive tests an undervoltage effects. For transient testing, the ANSI/IEEE C62.41 tests were not used, "due to the destructive nature of the pulses." nor was any reference made to the IEEE Guide on surge testing. However, 'High-Energy' tests were applied with pulses of 100 and 300 μs width and 1000 V peak (presumably an open circuit voltage as the authors state "The equipment used was capable of supplying 1000 V peak impulses on the supply for the equipment tested ...") There is no statement on a back filter nor on the generator source impedance. Thus, the surge effectively applied to the test specimen terminals might have been less than 1000 V.

From the report that no adverse effects were found, one may draw a tentative conclusion (subject to revisiting the effects of loading the generator by the supply impedance and its internal impedance), parallel to that of Smith & Standler (1992), that appliances have more immunity than what seems to be postulated in offering Transient Voltage Surge Suppressors clamping at 330 or 400 V levels.

ANSI/IEEE C62.41-1991 - *Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.*

IEEE ABSTRACT

A practical basis is provided for the selection of voltage and current tests to be applied in evaluating the surge withstand capability of equipment connected to utility power circuits, primarily in residential, commercial, and light industrial applications. The recommended practice covers the origins of surge voltages, rate of occurrence and voltage levels in unprotected circuits, waveshapes of representative surge voltages, energy, and source impedance. Three location categories are defined according to their location relative to the building service entrance. For each category, representative waveforms of surge voltages and surge currents are described, organized in two recommended "standard waveforms" and three suggested "additional waveforms."

REVIEWER'S ANNOTATIONS

This is an update of ANSI/IEEE C62.41-1980 (previously known as IEEE Standard 587). It provides a description of surge sources and presents a database of previous surveys that have evaluated surge voltages in low voltage ac power circuits. Methods for design and protection of electronic circuits to achieve surge immunity are presented. This standard also includes information on probability of surges occurring and presents a new test waveform with a shorter wave front for testing of electronic equipment.

A surge voltage is regarded as having its origin in either a lightning or switching transient, and is therefore a high frequency phenomena. A graph based on test data is provided which shows the rate of surge occurrence based on surge crest voltage at unprotected locations. On an unprotected circuit, the surge voltage is limited by the sparkover of clearances, which for 120/240 volt systems is given as 6 kV or less. This level is considered as a cutoff level for transients on indoor power systems. The two recommended "standard waveforms" are the 100 kHz Ring wave and the 1.2/50 — 8/20 Combination Wave. The three suggested "additional waveforms" are the 5/50 ns EFT burst, the 10/1000 voltage/current wave, and the 5 kHz Ring Wave.

While providing a description of the surge environment that can be expected, the document emphasizes that it should not be construed as a surge-withstand requirement standard.

ANSI C84.1-1989 - *American National Standard for electric Power Systems and Equipment - Voltage Ratings (60 Hertz).*

1. Scope and Purpose

1.1 Scope. This standard establishes nominal voltage ratings and operating tolerances for 60-hertz electric power systems above 100 volts and through 230 kilovolts. It also makes recommendations to other standardizing groups with respect to voltage ratings for equipment used on power systems and for utilization devices connected to such systems.

NOTE: For completeness, information on extra-high voltage systems (345 kilovolts and higher) from American National Standard for Power Systems - Alternating-Current Electrical Systems and Equipment Operating at Voltages above 230 kV Nominal Preferred Voltage Ratings, ANSI C92.2-1987, is also included as a footnote to Table 1.

1.2 Purpose

The purposes of this standard are:

(1) To promote a better understanding of the voltages that are associated with power systems and utilization equipment in order to achieve overall practical and economical design and operation

(2) To establish uniform nomenclature in the field of voltages

(3) To promote standardization of nominal system voltages and ranges of voltage variations for operating systems

(4) To promote standardization of equipment voltage ratings and tolerances

(5) To promote coordination of relationships between system and equipment voltage ratings and tolerances

(6) To provide a guide for future development and design of equipment in order to achieve the best possible conformance with the needs of the users

(7) To provide a guide, with respect to choice of voltages, for new power system undertakings and for changes in old ones.

REVIEWER'S ANNOTATIONS

The document is essentially a steady-state voltage specification. It does not provide information on the magnitude or duration of abnormal temporary overvoltages, but only states that corrective action must be taken promptly when the system voltage exceeds the specified upper limit.

The group that developed this standard is currently considering developing a document that would address the issue of temporary overvoltages.

Benda, S. - *Interference-free electronics*. Chartwell Bratt Ltd. Bromley BR1 2NE, U.K.

Subtitle of the book:

Design and applications.
The design and use of interference-free systems and printed circuit boards within industrial process automation and the utilities industry.

Excerpts from back cover abstract:

Interference-free electronics teaches how to design circuit boards, electronic devices and systems with high immunity to interference. The book also deals with process adaptation, communication and power supply with immunity to interference. ....

... The book is intended for students at Technological Universities but also for designers of industrial electronics and for their customers.

Chapter headings:

Introduction
Interference sources, coupling factors
Grounding, earthing and screening
Standards for interference immunity tests
Supply system
Protecting components against transients and surges
Signal transmission ...
Field installation guidelines
Apparatus design
The design of interference-proof circuit boards ...
Communications
Mitigation methods ... in the field
Investigation disturbances ... Troubleshooting
Conclusion

Reviewer's annotations

The emphasis of the book is on equipment design rather than power systems and installation practices.
A limited scanning of the book and its index does not reveal the issue of cascade coordination as a topic.

Bird, A.O. - The Effects of Installation Practices on the Performance of Transient Voltage Surge Suppressors. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 105-116.

AUTHOR'S ABSTRACT

Packaged surge protection devices are generally installed on low voltage AC systems to provide a controlled transient environment, as opposed to an uncontrolled environment relying upon the unpredictable sparkover of some clearance within the distribution system.

The objective of effective surge protection devices or systems is to control transient overvoltages to a level below the vulnerability to damage and, in many cases, the susceptibility to interference of electronic equipment.

The achievement of this objective is dependent on the characteristics of the protection device, the length and configuration of connecting leads used, fusing and the coordination of protection devices.

The effects of differing installation techniques are investigated and, where possible, the optimum solution is proposed.

REVIEWER'S ANNOTATIONS

AUTHOR'S CONCLUSIONS

Correctly specified, correctly installed, transient voltage surge suppression can significantly reduce the incidence of disruption and damage of electronic equipment due to transient surge voltages.

The objective in specifying protection is to insure that transient overvoltages are controlled to a level below the Equipment Transient Design Level, achieving a reasonable safety margin.

In practice, this objective can only be achieved if the performance of the surge protection device is not compromised by poor installation practice and inappropriate device coordination.

Corbett, M.P. and Wolff, B.I. - Performance of MOV Suppressors in Low-Voltage AC Circuits. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 43-50.

AUTHORS' ABSTRACT

Surge voltages on indoor ac power distribution lines can arise from both external and internal sources. Service entrance arresters help to reduce the effects of lightning but do not eliminate a need for suppressors at the location of sensitive equipment. Protective characteristics are improved by cascaded stages of arresters and suppressors regardless of the strategy used for coordination.

AUTHORS' CONCLUSIONS

The surge-protective characteristics of MOVs are used to maximum advantage when surge arrester MOVs are combined with suppressor MOVs at distribution panels or branch locations serving sensitive equipment. This plan results in two or more stages of protection against lightning surges and achieves significantly lower clamping voltages.

Coordination of surge-protective devices involves many factors, technical and economic, and is a complex subject in the province of the MOV user. However, the presence of two stages does allow grader flexibility in grader of voltage ratings. Because protective levels are lower with two stages, a downward auction on ratings can be avoided. For the best suppression, MOVs are used in L-N, L-G, and N-G modes where consistent with other requirements

REVIEWER'S ANNOTATIONS

Crouch, K.E and Martzloff, F.D. - Lightning Protection of Residential AC Wiring. Declassified *Memo Report MOR-78-095, GE Company*, 1978. (Available from FD Martzloff)

AUTHORS' ABSTRACT

New transient suppressors using metal oxide varistors offer improved protection of appliances and consumer electronics against overvoltages. This improvement, however, could be at the risk of imposing excessive duty on the suppressor in case of a very severe lightning stroke near the house where these suppressors are installed.

A simulated house wiring system (actual wire, not computer simulation) was subjected to three levels of lightning currents injected into the ground wires, with various combinations of suppressors installed alone or in a coordinated combination.

Test results show that an effective and safe combination of devices can be specified for full protection of the loads in the house.

AUTHOR'S CONCLUSIONS

Installation of a varistor protector at the load center, if incorporated with very short leads, effectively protects all of the wiring in the house. However, this installation is difficult to implement in existing systems and will continue to be difficult until a package is developed to allow connection to the load center bus bars with very short leads.

Until such an integral package is marketed for new systems, a coordinated protection scheme can be implemented, as a retrofit, that would still provide reliable protection for millions of sensitive appliances in existing systems.

Thus, a coordinated protection scheme is technically feasible. The cost should be acceptable to do-it-yourself homeowners, although it might be a deterrent to those owners who have to call in an electrician to install a protector at the load center. Based on increasing awareness in the technical and regulatory agencies community of overvoltage protection, the incorporation of protection to load centers offers the best approach to new installations.

REVIEWER'S ANNOTATIONS

The paper shows the effect of large currents flowing in the neutral/grounding conductor of the service drop to a building, and explores options for placing an arrester at the service entrance or at the end of branch circuits, or both.

The many oscillograms reproduced in the paper also show how a unidirectional stimulation (8/20 μs current flowing only in the grounding conductors) result in oscillatory transients in the differential mode.

Davidson, R. - Suppression Voltage ratings on UL Listed Transient Voltage Suppressors. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 89-92.

AUTHOR'S ABSTRACT

Some manufacturers and purchasers of UL Listed Transient Voltage Surge Suppressors (TVSS) have expressed concern to UL about certain types of advertising claims that have been made with respect to the suppression voltage ratings marked on UL Listed TVSS.

Examples are claims that the minimum 330 volt suppression rating in UL's 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 (or protection it provides)".

The purpose of this brief paper is to clarify the meaning and limitations of the suppression voltage ratings that are marked on UL Listed TVSS products in association with the UL Listed Mark.

AUTHOR'S CONCLUSIONS

The suppression voltage ratings marked on UL Listed TVSS provides the purchaser with independently generated information on how a TVSS performs when subjected to a specified impulse surge. On the other hand, 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.

To the extent that the above mentioned factors are known, the suppression voltage ratings on UL Listed TVSS can contribute useful information to an overall assessment of the adequacy of surge protection. When these factors are not known, claims that one TVSS provides better protection than another, solely on the basis of the UN 1449 suppression voltage rating, may be misleading.

REVIEWER'S ANNOTATIONS

The paper provides the position of UL concerning the issue or clamping voltage selection for TVSSs.

Dugan, R.C. and Smith, S.D. - Low-Voltage-Side Current-Surge Phenomena in Single-Phase Distribution Transformer Systems. *Preprint T&D 553-2, IEEE T&D Conference*, 1986.

AUTHORS' ABSTRACT

Lightning current surges entering the secondary windings of distribution transformers can be a cause of transformer failure. Proposed solutions have included interlacing the secondary windings and applying low-voltage arresters. Tests have been proposed to verify the ability of a transformer to withstand these surges. This paper shows that the amount of current varies significantly for different sizes and designs of transformers, loads, and secondary cables. It is also shown that the entire secondary circuit must be treated as a system. Measures taken to protect the transformer generally increase the surge voltage stress on the load equipment. The source of the problem is the voltage drop along the secondary cable. Minimizing that voltage can effectively alleviate the problem at both the transformer and the load. These facts must be taken into consideration before developing transformer test standards to address the low-voltage-side current surge problem.

AUTHORS' CONCLUSIONS
(Excerpts)

Concerning proposed test levels for low-voltage current surges in distribution transformers, it would appear to be inappropriate to specify a single current magnitude for all transformers. The amount of surge current that passes through the transformer varies significantly with the design and k VA rating of the transformer. The current that flows is not a constant, but is determined, primarily, by the net differential mode voltage drop across the secondary cable and, also, by the impedances of the transformer, cable, load, and ground.

Smaller-sized transformers with interlaced secondaries of low-voltage arresters will typically pass twice as much surge current as conventional, non-interlaced designs of the same rating.

The 10-kVA transformer described in this paper would typically see less than 7 percent of the lightning stroke current in each half of the secondary winding (14 percent total in the secondary) when the secondary windings are not interlaced. In the interlaced connection, the same transformer would be expected to see nearly 16 percent of the lightning stroke current in each half (33 percent total). The latter figure is the theoretical limiting value assuming equal division of the stroke current in the secondary cable and between pole and house grounds.

25-kVA and 50-kVA non-interlaced transformers will allow more current to flow than the 10-kVA non-interlaced transformer because of their low impedances. In fact, the impedance of a 50-kVA transformer is relatively insignificant when compared to the cable impedance and the surge current in the transformer approaches the theoretical limit. This fact, in combination with different distributions of the turns in larger kVA transformers may explain why researchers have reported that transformers that are 50-kVA or larger, are essentially immune to failure from low-voltage-side current surge phenomena. Another factor might be that these transformers are generally connected to more than one secondary load, which our studies indicate would decrease the voltages induced within the transformers.

The system consisting of the distribution transformer and load has a complex response to lightning surges and very sensitive to changes in the characteristics of the components of the system. Changes to the transformer cannot be considered without also considering the effects of the changes on the rest of the system. For example, protecting the transformer insulation by interlacing the transformer secondaries or by applying low-voltage arresters will approximately double the voltage stress on the load for the smaller transformer sizes. The only solution found that minimizes the problem in all areas of the system is to use shielded secondary cable that has adequate mutual coupling between the neutral and phase conductors. This minimizes the surge currents by reducing the net differential voltage induced by the lightning surge currents flowing in the cable neutral.

REVIEWER'S ANNOTATIONS

Dugan, R.C., Kershaw, S.S., and Smith, S.D. - Protecting Distribution Transformers from Low-Side Current Surges. *Preprint TD 401-1 PWRD, IEEE T&D Conference*, 1989.

AUTHORS' ABSTRACT

Abstract - In geographical regions where severe lightning is accompanied by poor pole grounds, the secondary distribution system is subjected to high voltage surges due to lightning current seeking alternate ground paths through the low-voltage circuits. Complete protection of the low-voltage circuits must be coordinated because applying surge protection at one location will frequently increase the stress at other locations. Distribution transformers are subjected to high stress in the primary winding layer-to-layer insulation due to induction from the secondary side. The internal voltage distribution is such that primary arresters are generally ineffective in controlling this stress. Interlacing the secondary windings will reduce the primary winding stress when the surge current is nearly balanced in the two secondary winding halves, but is ineffective when the surge current is not balanced. Either MOV or gapped arresters across the secondary terminals provide more complete protection for the transformer. Transformers with interlaced secondaries and those with low-voltage arresters can place greater stress on the load insulation. Arresters applied at the service entrance do not protect all insulation throughout the structure, but do not appear to worsen any insulation stress. Arresters applied at the transformer or at the service entrance should have about one-half of the current surge capacity of distribution class arresters. Arresters should have a protective level of 2 k V for the service entrance while 4-6 k V appears adequate for the transformer.

REVIEWER'S ANNOTATIONS

AUTHORS' CONCLUSIONS

In areas where low-side current surges are a problem, all distribution transformers, with or without interlaced secondaries, are susceptible to failure from low-side current surges. Interlaced secondaries are effective in reducing the transformer failures from secondary surges, but are still susceptible to surges that are not balanced. Low-voltage arresters can significantly reduce the failure rate of non-interlaced transformers and offer protection against both balanced and unbalanced surges.

Both MOV-type arresters and a simple gapped arrester are effective in protecting transformers. It would appear from the literature that MOV arresters would be required for protecting loads.

Arresters applied in the pole environment should have a current discharge capability of at least half of that for a standard distribution class arrester. Arresters applied at the service entrance should have the same capability because they see the same currents. The minimum conduction level should be high enough to coordinate with the primary arrester.

Because the surge originates from a surge voltage drop in the service drop cable, clamping or limiting the voltage at one end increases the voltage at the other end. This implies that the service entrance ought to be protected as well to coordinate with the transformer protection. This arrester should be similar in rating to the transformer arrester and have a discharge voltage of less than 2 k V to coordinate with load insulation. This arrester seems to be only partly effective in protecting the house load if there are other ground paths. However, the addition of a service entrance arrester is not likely to worsen surge problems within the house such as might occur if the transformer is protected without protecting any part of the load circuit.

Dugan, R.C. - Conduction of Lightning Stroke Currents From the Utility System to Load Devices. *Conference Proceedings, Power Quality*, October 1989.

AUTHOR'S ABSTRACT

Recent research into distribution transformer failures has suggested that the frequency of lightning surges entering loads from the utility system may be higher than previously believed. Protective devices must be carefully applied to be effective. Multiple grounds, which are frequently found in load circuits, can defeat protective efforts. This paper describes how surges can enter load circuits through utility system neutral paths. Surges may come from overhead and underground (UD) systems alike. The surges follow ground paths into the load, inducing high differential voltages as they pass through unshielded cables. Sensitive appliances should be protected. Appliances connected to multiple ground paths should have the ground conductors of all paths bonded at a single point of connection. Arrester voltage discharge levels and current discharge capacities should be coordinated from the utility system all the way to load point.

AUTHOR'S CONCLUSIONS

One thing that should be obvious from this article is the "ground" is not always at zero potential, especially under lightning surge conditions. Surge currents can be very high and have a high rate of rise, which develop large voltage in inductive elements as well as resistive elements. The surges become a problem basically because there are multiple grounds in the system and the surge currents flow between them. This can result in insulation failure due to potential differences between grounds.

The basic protection principle is to clamp voltages and bond all ground conductors at the point of connection to the power supply.

Surges can enter the load structure quite easily on the system neutral conductors. Surge current is conducted to the neutral nearly every time a utility primary distribution line is struck by lightning. Because these lines are struck many times in lightning-prone areas, surges may be entering load circuits more frequently than believed. There seems to be little that can be practically done to reduce the frequency of these surges. In fact, efforts by utilities to protect their own equipment may increase the magnitude of the surges entering the load. Therefore, load device protection that is carefully coordinated with other elements of the system seems prudent.

REVIEWER'S ANNOTATIONS

Dugan, R.C., Goedde, G., and Henry, C. - Conduction of Lightning Stroke Currents From the Utility System to Load Devices. *Conference Proceedings, Power Quality For End-Use Applications*, March 1990.

AUTHORS' ABSTRACT

Recent research into distribution transformer failures has suggested that the frequency of lightning surges entering loads from the utility system may be higher than previously believed. Lightning does not have to strike the secondary system directly on order to generate spikes in loads. In fact, many spikes are the result of lightning currents being conducted on the load on the so-called "neutral" or "ground" paths: the normal paths designed to conduct these currents. Protective devices must have the proper rating and be carefully applied to be effective. Multiple grounds, which are frequently found in load circuits, can defeat protective efforts. This paper describes how surges can enter load circuits through utility system neutral paths.

Surges may come from overhead and underground (UD) systems alike. The surges follow ground paths into the load, inducing high differential voltages as they pass through unshielded cables. Generally, both ends of the cables must be protected. Secondary arresters in the service drop environment may see as much as 1/3 to 1/2 of the utility's primary arrester discharge current. Arresters in the service entrance should have similar current discharge ratings as a secondary arrester on a distribution transformer. Service entrance arresters offer protection to load circuits that do not have other ground paths. Sensitive appliances and appliances connected to circuits with multiple ground paths should have special protection. Arrester voltage discharge levels and current discharge capacities should be coordinated from the utility system all the way to load point.

REVIEWER'S ANNOTATIONS

AUTHORS' CONCLUSIONS

One thing that should be obvious from the article is the "ground" is not always at zero potential, especially under lightning surge conditions. Surge currents can be very high and have a high rate of rise, which develop large voltage in inductive elements as well as resistive elements. The surges become a problem basically because there are multiple grounds in the system and the surge currents flow between them. This can result in insulation failure due to potential differences between grounds.

The basic protection principle is to clamp voltages and bond all ground conductors at the point of connection to the power supply.

Surges can enter the load structure quite easily on the system neutral conductors. Surge current is conducted to the neutral nearly every time a utility primary distribution line is struck by lightning. Because these lines are struck many times in lightning-prone areas, surges may be entering load circuits more frequently than believed. There seems to be little that can be practically done to reduce the frequency of these surges. In fact, efforts by utilities to protect their own equipment may increase the magnitude of the surges entering the load. Therefore, load device protection that is carefully coordinated with other elements of the system seems prudent.

Dugan, R.C. - Low-Side Surges: Answers to Common Questions. *Cooper Power Systems Bulletin SE9001*, April 1992.

AUTHOR'S ABSTRACT

The power industry is beginning to come to grips with the problem of low-side surges, also referred to as low-side *current* surges. However, the interjection of *current* may be inappropriate because there are voltage issues as well, so we will refer to the phenomena generically as "low-side surges."

The extent of the problem is very significant to the utilities, whether they realize it or not. Cooper Power System's recent Utility Power Quality Survey (1990) indicates that only about 10% of all utilities understand the problem. Our continuing research indicates that approximately 50% - 70% of all distribution transformer failures in regions with any significant lightning are due to low-side surges in one way or another.

REVIEWER'S ANNOTATIONS

Answers are provided to the following questions:

What is the origin of the surges ?
Are interlaced transformers immune to low-side surges ?
Why protect both sides ?
What do low-side surge voltages look like ?
Can a service entrance arrester protect the entire house ?

AUTHOR'S CONCLUSIONS

"It's a Complex Systems Problem"

Goedde, G.L., Dugan, R.C., and Rowe, L.D. - Full Scale Lightning Surge Tests of Distribution Transformers and Secondary Systems. (Place of publication unknown)

AUTHORS' ABSTRACT

Low-side surges are known to cause failures of distribution transformers. They also subject load devices to overvoltages. A full-scale model of a residential service has been set up in a laboratory and subjected to impulses approximating lightning strokes. The tests were made to determine the impulse characteristics of the secondary system and to test the validity of previous analyses. Among the variables investigated were stroke location, the balance of the surges in the service cable, and the effectiveness of arrester protection. Low-side surges were found to consist of two basic components: the natural frequency of the system and the inductive response of the system to the stroke current. The latter component is responsible for transformer failures while the former may be responsible for discharge spots often found around secondary bushings. Arresters at the service entrance are effective in diverting most of the energy from a lightning strike, but may not protect sensitive loads. Additional local protection is also needed. The tests affirmed previous simulations and uncovered additional phenomena as well.

AUTHORS' CONCLUSIONS

Low-side surges typically consist of two major components: a component ranging in frequency from 0.8 to 3 MHz and a slower-changing component that represents the inductive response of the system to the rate of change of the lightning stroke current in the triplex cable. The tests confirmed earlier analyses of low-side surge phenomena in transformers and verified that the phenomena affecting the transformer can be analyzed by simply considering the inductances in the secondary system, neglecting the cable capacitances.

The higher-frequency component is probably responsible for the low-energy discharge "spots" observed around the secondary bushings in some transformers. However, its greatest impact is likely to be on load equipment.

Arresters at the service entrance are useful for forcing low-side surges to be balanced and for diverting most of the surge energy away from outlet protectors with less energy-handling capability. Unbalanced surges were found to generate much higher surge voltages in the secondary system and are, therefore, undesirable. Balancing the surges between the two 120-volt side also aids in the protection of transformers with interlaced secondary windings. Non-interlaced transformers subject to low-side surge failure should be protected with arresters in accordance with previous analyses.

The service entrance arrester in all ratings studied (175V to 650V) appears to be quite effective in protecting conventional insulation against the lower-frequency component of low-side surges. However, it should not be relied upon to protect the entire load circuit, especially sensitive loads, against the higher frequency component of the surges. The appropriate local protection of devices sensitive to that type of surge is still required even if there is an arrester in the service entrance. It would appear that most practical lengths of secondary circuit feeder cable would be sufficient to force most of the energy from a low-side surge through the service entrance arrester and, thus, help prevent the failure of the local protective device. One area that remains open to investigation is the effect of the turnoff transient of MOV-type arresters in load circuits on the transformer. Another is the switching surge and power frequency coordination of arresters in the secondary circuit.

REVIEWER'S ANNOTATIONS

Goedde, G.L., Marz, M.B., and Henry, D.C. - Coordinating Lightning Stroke Protection From the Utility System to Load Devices. *Proceedings, Second International Power Quality/ASD Conference*, October 1990, Philadelphia.

AUTHORS' ABSTRACT

Distribution transformers and end user loads can be damaged by lightning strokes which pass through transformer primary winding arresters and are coupled to secondary circuits through grounding leads, as well as by lightning strokes directly to secondary circuits. This damage can be avoided if properly coordinated arresters are added at the transformer secondary, service entrance and load. This paper 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 also described and recommended.

AUTHORS' CONCLUSIONS

There are more paths for lightning surges to reach customer loads through utility systems than is generally believed. Multiple grounds at different potentials, especially under lightning surge conditions, prevent distribution transformer primary arresters from protecting secondary circuits. Two principles in using surge arresters to protect distribution loads and equipment are (1) prevent the surge current from flowing through the load or equipment to ground and (2) place the arresters as close to the load or equipment as possible. No arrester can guarantee the protection of a remote device.

In most distribution systems, transformer secondary circuit protection is rarely used and when used it is often miscoordinated. Many 175 and 650 volt arresters do not have the current carrying capability to survive the 34 kA surges that can be expected at transformer secondaries and service entrances. 175 volt arresters can also miscoordinate with transformer primary arrester SSPLs. 650 volt arresters will coordinate, but may provide inadequate voltage protection. Both current and voltage coordination can be improved by a 480 volt arrester with a 40 kA rating. Properly coordinated protection using the 480 volt high current arrester should become standard practice to protect both the utility's distribution transformers and end user's loads.

REVIEWER'S ANNOTATIONS

Same conclusions as Marz & Mendis, 1992

Hairabedian, B. - A survey of Power Line Disturbances at Typical IBM Computer Installations in the U.S. for the Period 1988-1992. *Document Number TR 21.1507*, International Business Machines Corporation, Kingston NY, June 1992.

AUTHORS' ABSTRACT

The results of a power-line-disturbance survey at 25 IBM computer installations are presented. Twenty-four (24) of the sites were in the US and one (1) was in Canada. The survey logged a total of 22,201 monitor-days and spanned the period 1988 to 1992. The results are given in the form of frequency-distribution tables, Weibull profiles, histories of monthly events, and chronologies of shared events. The data is given for individual sites and for composites of all the sites. The sites are compared in a Weibull parameter-ranking map. The composite results of the survey are compared with those of the 1972 and 1982 IBM surveys. Examples demonstrate the use of the Weibull parameters for defining and predicting site behavior and the sue of frequency distribution data for deriving relative susceptibilities of various load systems.

AUTHOR'S CONCLUSIONS
(Excerpts)

History of Events:
The monthly history data of sag/swell and surges show some patterns of Periodicity. The month-of-year data shows an increase in sags for the month of July, and modest increases for August and November. There is no obvious explanation for this pattern.

The hour-of-day data shows a much more obvious increase in sags during the daylight hours. It suggests that some of the sags are directly related to daily human activity.

REVIEWER'S ANNOTATIONS

A comprehensive report on the recording of disturbances at various computer sites.

THe detailed tables include statistics on several categories of disturbances. Most significant to the present context are the temporary overvoltages, with a classification bin of overvoltages above 35% of the nominal rms line voltage. A few occurrences of these are reported in some locations.

Hasse, P., Wiesiger, J., and Zischank, W. - Isolations-koordination in Niederspannungsanlagen auch bei Blitzeinschlagen. *Electrotech. Zeitschrift*, Jan 1989, pp 64-66. (In German; English translation available from FD Martzloff)

AUTHORS' ABSTRACT

This paper describes the principle of insulation coordination in low-voltage consumer systems for mains-carried overvoltages according to IEC Pub 664 and DIN VDE 0109. The required surge voltage levels can also be maintained during a direct lightning stroke. For mains-carried overvoltages and for the case of a direct stroke, distribution of the surge current between the two arresters in different application categories are determined.

AUTHORS' CONCLUSIONS

The authors do not label a particular part of the article as 'Conclusion' but the closing paragraph reads as follows:

Thus the spark gap will -largely independently from the impedance of the downstream system - only respond to surge currents having a higher rate of change of current than 1 kA/μs, which corresponds to a 8/20 μs wave, with a peak current of 5 kA. In more than 99% of the cases, direct lightning currents have a higher value than 1 kA/μs! So the circuit in Figure 3 makes it possible for the spark gap to distinguish between a distant stroke and either a near-by or direct stroke. This safety method is effective as well for partial lightning currents entering the structural system by the mains network (near-by stroke) as also in case of partial lightning currents that travel backwards into the mains from a building struck by lightning.

REVIEWER'S ANNOTATIONS

Cites 10/350 μs as a waveform to consider for simulation of near-by and direct stroke, in addition to the 8/20 μs waveform, which is considered appropriate for distant strokes.

Proposes to provide at the service entrance a two-stage surge arrester consisting of a gap on the utility side and a varistor on the load side, separated by a coordinating inductance. Clearing of power-follow in the gap is not discussed.

Hasse, P. - *Overvoltage Protection of Low-Voltage Systems*. IEE Power Series, Peter Peregrinus Ltd. London, 1992. (Original German edition in 1987) Available in the U.S. from IEEE.

Excerpts from back cover abstract:

... The author gives examples of overvoltage damage to electrical systems with electronic devices, such as measurement, control and regulating circuits and data processing systems. The book goes on to discuss causes .... The operation and application of proven overvoltage protection devices are considered and the author refers to relevant German and international standards.

Chapter headings:

Damage caused by overvoltages
Causes of harmful overvoltages
Protective measures
Components and devices ....
Practical examples of protection
Final remark

Reviewer's annotations

Sections 5.4.1.4, *Coordination of protective elements*, and 5.4.2, *Arresters for power systems* discuss the topic of cascades, with reference to a protection scheme that includes a gap, which may be of the "quenching gap" type also described in that chapter. Thus, the downstream device is spared the dissipation of large energy, following sparkover by the gap. No computations are presented in association with the discussion of the principle of this approach to coordination.

Examples are given, with schematics and device photographs, of the application of arresters in low-voltage TN and TT networks.

Hostfet, O.T., Hervland, T., Nansen, B., and Huse, J. - Coordination of surge protective devices in power supply systems: Needs for secondary protection. *Proceedings, International Conference on Lightning Protection*, Berlin, September 1992.

AUTHORS' ABSTRACT

Primary SPDs at the origin of an LV installation will not in general assure sufficient overvoltage protection. Voltage oscillations will occur within the installation depending on the circuit lengths, resonant frequencies, steepness of the surge impulses, etc. Therefore, there is a need for additional SPDs for sensitive apparatus/equipment within the installation.

To ensure safe coordination regarding the energy stresses on the SPDs, the protection level (clamping voltage) of the primary SPDs should generally be somewhat lower than for the additional SPDs (secondary protection) within the installation.

AUTHORS' CONCLUSIONS

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 analyses have shown that, generally, voltage oscillations will occur within an installation with surge protection. The amplitudes of these oscillations depends on several circuit parameters as well as the incoming surge voltages. In special cases, the maximum voltage may be more than twice the protection level on the primary surge protection devices. Accordingly, there might be a need for secondary protection, especially with respect to various sensitive equipment.

Furthermore, it is found that in an installation with two or more surge protective devices, the higher energy stresses will generally occur on the device with the lowest clamping voltage. Therefore, the protection level for the secondary protection should be selected somewhat higher than for the primary protection independent of the location. In this way the current flowing in the secondary devices will be lower than in the primary ones, and sufficient protection is obtained for sensitive equipment although the nominal clamping voltage is relatively high.

REVIEWER'S ANNOTATIONS

Huse, J.P. - Contributions to the revision of Doc 28A(Sec)47, *Internal document, IEC/SC28A WG01*, 1988.

AUTHOR'S ABSTRACT
('Introduction')

Calculation results are presented in order to give a contribution to the revision of the document [28A(sec)27 - 'Explanation of interfaces for overvoltage categories]. In the paper, only stresses on surges suppressors are dealt with.

AUTHOR'S CONCLUSIONS
(From concluding 'General comment')

From the analysis made in this paper, it is seen that the suppressor energy stresses occur on the suppressor with the lowest clamping voltage representing the lowest resistance to ground. Accordingly, it seems that concerning the stresses upon voltage limiters, suppressors, etc., it would be preferable to have one overvoltage category only. In that case several suppressors with the same clamping voltage could be applied and the stresses would be reasonable shared between the suppressors.

REVIEWER'S ANNOTATIONS

These comments on the simplifications made in the 28A approach (Table E) were the first submitted that provided computations of cascades. In particular, the assimilation of the wave *front* of an 8/28 μs current to a 1/4 sine wave of 30 kHz impulse was debated.

In support of the objections, the paper presented results of computations, but its was not until later that papers emerged that included both computations and actual tests, validating each other.

Noteworthy is the concluding statement that the device with lowest clamping level is subjected to the highest stress, in contrast to the underlying assumptions of the IEC 664-1980 staircase.

This contribution has appeared in several IEC documents, SC28A, TC64, and now SC37A.

IEC 28A(USA/Las Vegas)09 - (Draft) *Explanation for over-voltage categories*. December 1984, Amended August 1987.

REVIEWER'S ANNOTATIONS

The seminal IEC paper on cascade coordination - before the term was coined.

Based on assumed 8/20 μs waveforms and some separating inductive impedance, approximate computations were made by assuming that at each stage of a multiple-step cascade, the driving voltage is that established by the preceding surge-protective device.

Numerical simulations have made this paper obsolete.

IEC 28A(Norway) - *Comments of the Norwegian National Committee on Document 28A(Secretariat)47*

INTRODUCTION

In this document [28A(Secretariat)47] extensive simplifications are made in order to present simple explanations. It seems, however, that some of the simplifications and assumptions made are questionable. Accordingly, the results presented (Table E for instance) should be reconsidered. Furthermore, there are some statements in the document that should be revised.

CONCLUSIONS

As stated in the introduction, this document should be reconsidered and revised on several points. It is proposed that more realistic calculations be performed in order to analyze the stresses on interface suppressors. Representative crest values of 8/20 current impulses for testing purposes should be determined on the basis of results from these analyses.

The weaknesses pointed our in our comments are also of relevance to test generator impedance requirements. Accordingly, also these parts of the document should be reconsidered.

REVIEWER'S ANNOTATIONS

These comments on the simplifications made in the 28A approach (Table E) were the first submitted that provided computations of cascades. In particular, the assimilation of the wave *front* of an 8/28 μs current to a 1/4 sine wave of 30 kHz impulse was debated.

In support of the objections, the paper presented results of computations, but its was not until later that papers emerged that included both computations and actual tests, validating each other.

See the 1988 Huse citation for an expanded contribution of this subject.

IEC 37A/WG3(Convenor)1 - *Draft Application Guide,* 1992.

SCOPE

This application Guide gives indications regarding selection and installation of SPD to be connected to 50/60 Hz AC and to DC power circuits rated 50 to 1000 V.

AUTHOR'S CONCLUSIONS

None

REVIEWER'S ANNOTATIONS

A working document that has not yet reached maturity.

Annex 1, 'Two and three step protection efficiency' is the same as given in Clause 2.2 of IEC TC64 WG3 (Ad-Hoc WG Convenor)1 of February 1990.

Shows a graph of required Temporary Overvoltage levels of 1.7 per unit at 3 seconds and 3.0 per unit at 0.05 second. Such a requirement is likely to challenge the use of 130-V varistors on a 120-V system.

IEC 64/WG3 138A - Explanation of interfaces for overvoltage categories. Supplement to *Appendix B of Report 664*, November 1990.

ABSTRACT
(from 'General' Clause)

The framework of IEC publication 664 includes cases where the incoming supply to an installation can be considered inherently controlled and cases where protective control is used. This supplement deals with situations where protective control is used in the installation or within equipment connected to the installation. In this latter case the installation may have inherent or protective control.

It must be recognized that successive interface devices, such as surge suppressors, may interact detrimentally unless proper grader is provided in their selection. In this respect it is also noted that there is a fundamental difference in the behavior of surge suppressors based on air gaps as opposed to those based on solid-state monotonic devices (varistors or diodes). When a system includes both types of surge suppressors, it is necessary to take into consideration the impinging surge voltage as well as the corresponding available surge current.

CONCLUSIONS
(From Clause 2)

Three basic requirements determine the selection of an interface surge suppressors:

- The rated voltage of the surge suppressor is selected at a value above the working voltage of the system.
- The surge suppressor must be capable of discharging the maximum surge current and surge energy at its point of installation, without adverse effect on the expected life of the surge suppressor.
- Within the constraints of the first two conditions, the residual voltage of the surge suppressor should be selected according to the impulse withstand voltage of the equipment.

It is possible within a system to cascade a number of interface surge suppressors to achieve the various overvoltage categories. The number of overvoltage categories will be determined by the number of different surge suppressor residual voltages specified. However, it is also possible to achieve the lowest overvoltage category by the use of a suitably selected suppressor at the origin of the installation.

REVIEWER'S ANNOTATIONS

Note the continuation of the expectation that a cascade is possible, but the emergence of the idea that the lowest clamping voltage might be obtained by a service entrance arrester.

IEC 77(CO)118 *Classification of Electromagnetic Environments* (Committee Draft, 1992)

REVIEWER'S ANNOTATIONS

This document is an attempt at describing the total electromagnetic environment, both radiated and conducted. It starts by identifying the phenomena that produce disturbances, then proceeds to state what levels may be encountered at various categories of locations. The attempt is to have one single value for one location, but consensus in selecting these level has been a difficult process. Further revisions are likely before the document reaches recognition as a standard. Present plans at IEC is to publish it as a Report.

Lagergren, E.S., Martzloff, F.D., Parker, M.E., and Schiller, S.B., - The effect of repetitive swells on metal-oxide varistors. *Proceedings, PQA 92 Conference*, September 1992, pp xx-xx.

AUTHORS' ABSTRACT

Neither the effects of repetitive swells on metal-oxide varistors, nor the occurrence of swells have been documented in the literature. The paper briefly describes a laboratory system capable of generating arbitrary swells and applying them to test varistors. A statistical experiment on five lots of varistors has been performed and preliminary results are reported. Effects of amplitude, duration, and number of swell occurrences are assessed, using as a criterion the change in varistor nominal voltage from before to after the swell sequence.

AUTHORS' CONCLUSIONS

1. Applying swells produced by a computer-driven system is a practical method for subjecting varistors to repetitive swells under controlled conditions.

2. The factors that affect the varistor response are the amplitude of the swell, the duration of the swell, and the number of swells experienced in the life of the varistor.

3. It seems that failure by thermal runaway occurs quickly when amplitude or duration settings are large. Failure caused by gradual aging (the 10% limit quoted by industry) appears to require a larger number of swells than those applied so far in our experiments.

4. These results lead to an action items list, with an open invitation to all interested parties for contributing to shared information on the subject.

REVIEWER'S ANNOTATIONS

This paper is only a status report on an ongoing project aimed at characterizing the aging, if any, of generic MOVs under the effect of repeated swell over the service life of a varistor.

Two mechanisms have been encountered in the test series: a relatively small (less than 3%) change in varistor nominal voltage for limited cumulative stresses, and a failure by overheating when exposed to stresses of excessively long-duration (seconds) temporary overvoltages.

A more comprehensive paper should be presented at a future meeting.

Lai, J.S. and Martzloff, F.D. - Coordinating Cascaded Surge-Protective Devices. *Proceedings, IEEE/IAS Annual Meeting*, October 1991.

AUTHORS' ABSTRACT

Cascading surge protection devices located at the service entrance of a building and near the sensitive equipment is intended to ensure that each device shares the surge stress in a optimum manner to achieve reliable protection of equipment against surges impinging from the utility supply. However, depending upon the relative clamping voltages of the two devices, their separation distance, and the waveform of the impinging surges, the coordination may or may not be effective. The paper provides computations with experimental verification of the energy deposited in the devices for a matrix of combinations of these three parameters. Results show coordination to be effective for some combinations, and ineffective for some others, a finding that should reconcile contradictory conclusions reported by different authors making different assumptions. From these results, improved coordination can be developed by application standards writers and system designers.

AUTHORS' CONCLUSIONS

1. Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations will result in having a suppressor with low energy-handling capability called upon to divert the largest part of the surge energy. This uncoordinated situation can create adverse side effects when high current surges occur.

2. Significant parameters in achieving successful coordination involve three factors, over which the occupant of the premises has no control: the relative clamping voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges. This uncontrolled situation presents a challenge and obligation for standards-writing groups to address the problem and develop consensus on a trade-off of advantages and disadvantages of High-Low versus Low-High.

3. Coordinated schemes can be proposed by utilities to their customers, including a service entrance arrester and one or more plug-in devices to be installed for the dedicated protection of sensitive appliances. However, even such an engineered, coordinated arrangement could be defeated by the addition of a suppressor with a very low clamping voltage, not an insignificant likelihood in view of the present competition for lower clamping voltages.

REVIEWER'S ANNOTATIONS

The paper describes 72 combinations of 130 V, 150 V, and 250 V devices arranged in cascades, with separation distances ranging from 5 to 40 meters, and with 8/20 μs and 10/1000 μs impinging waveforms.

While the 8/20 μs waveform can still result in a contribution from both devices to sharing the surge 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, and for two different devices, the lowest rated take 90% or more of the total energy.

Lai, J.S. - Performance Criteria for Cascading Surge-Protective Devices. *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, August 1991, pp 147-160.

AUTHOR'S ABSTRACT

Cascaded surge-protective devices in a low-voltage power system interact each other under surge conditions. Coordination of cascaded devices may be achieved by manipulating the device clamping level and energy handling capability. However, as cascade condition may be effective for a certain surge source and distance between the devices but not effective for other cases. To develop the performance criteria for cascaded devices, all possible environments need to be taken into account. This paper uses the voltage clamping level of cascaded devices, their separation distance, and the surge waveform as parameters to study the energy deposited in the devices. All assumed cases were studied using computer simulation with necessary experimental verification. Results show reasonable agreement between simulation and experiment. A total of 72 case study results provide standards writers and application engineers with quantification information for the development of improved cascade coordination.

AUTHOR'S CONCLUSIONS

With study of a total of 72 cascade combinations using different parameters, this paper initiates a broader view of cascade coordination and a need for further consensus on real-life environments which involve the magnitude and waveshape of the high-energy impinging surges from utility lines, probability and severity of losing neutral, surge energy from switch-mode power conversion equipment, size of conductors, and the distance between the surge-protection devices.

Although the MOV model described in this paper successfully predicts the I-V characteristics and surge responses, especially the energy sharing of cascaded devices, more analytical studies are needed to reduce the deviation between simulation and experiment. These include:

- MOV stray inductance and capacitance if more accurate waveshape matching is necessary.
- Consensus of MOV characteristics for the same voltage level and size of the device but different manufacturers
- Modeling of a gap-type surge protection devices which would cause different surge responses when used as the arrester to replace MOVs.
- Well-defined impinging surge sources including voltage and current waveforms and the coupled source impedance network.

REVIEWER'S ANNOTATIONS

This paper contains a detailed report on the measurements and computations that were the basis for the two papers [Lai & Martzloff, 1991] and [Martzloff & Lai, 1991].

Lat, M.V. - Determining Temporary Overvoltage Levels for Application of Metal-Oxide Surge Arresters on Multigrounded Distribution Systems. *IEEE Transactions PWRD-5*, April 1990, pp 936-946.

AUTHOR'S ABSTRACT

Abstract: This paper provides an evaluation of different analytical methods that may be used to calculate values of temporary overvoltage on multigrounded distribution systems as a result of single line-to-ground faults. The methods are evaluated in terms of their general accuracy, their ability to account for changes of earth resistivity, ground electrode resistances and grounding frequency, and also in terms of the overall impact of such changes on the calculated overvoltage level. Recommendations are provided for the use of these methods under different sets of system conditions.

AUTHOR'S CONCLUSIONS

The objective of this study was to evaluate the impact of the overvoltage calculation methods on the selection of metal oxide arrester ratings for multigrounded distribution systems in the presence of variable system grounding parameters. Accurate arresters are extremely sensitive to overvoltages. The results of the study indicate that presently used ratings, derived on the basis of the commonly assumed value of 1.25 p.u., are sufficiently conservative only for well grounded systems. Overvoltages on systems where the grounding parameters depart significantly from the nominal values should be calculated using the methods recommended in this paper. In many cases revision of ratings to be used on such systems may be required.

Based on a comprehensive evaluation of different methods for calculation of overvoltages on multigrounded distribution systems, it has been concluded that the commonly used method bases on symmetrical components is inadequate for anything but the simplest calculation for a system with near ideal grounding parameters.

For systems where poor grounding conditions are known to prevail, the best method of analysis is to neglect the ground effects altogether.

The best overall results are provided by a sophisticated, matrix algebra bases method, which analyzes the ladder network cells of the multigrounded distribution neutral individually.

REVIEWER'S ANNOTATIONS

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*, pp 451-454. (In French; English translation available from FD Martzloff: Coordination of overvoltage protection in low-voltage residential systems)

AUTHORS' ABSTRACT

The development of metal-oxide varistors has made possible a substantial improvement in the mitigation of overvoltages in residential, commercial or light industrial power systems. For instance, transient suppressors are now available that can be plugged into a wall receptacle, thus making possible the protection of appliances or electronic devices that might be damaged by overvoltages occurring in power systems.

However, due to economic considerations, these suppressors have only a limited capability for absorbing high current surges that may be associated with lightning strikes occurring nearby. Thus, one may ask whether the installation of a suppressor with limited capability might not pose a risk of failure or create a false sense of security.

It is then worthwhile to examine what occurs in a building provided with suppressors having different capability, located at different points of the building. as a function of the surge current intensity imposed by the lightning strike. Furthermore, the combination of several suppressors may allow a coordinated protection for reliable operation, which it would be worthwhile to demonstrate.

AUTHORS' CONCLUSIONS

1. It is sufficient to inject, in the ground conductor of the service drop, a surge current corresponding to a moderate lightning stroke to reach hazardous voltages between the phase and neutral conductors within the building.

2. Commercially available protective devices are capable of limiting overvoltages to acceptable limits; even in the case of an injection corresponding to extreme values, several arrangements may be considered:

a) A lightning arrester consisting of a spark gap and silicon carbide varistors can limit the overvoltages to about 2000 V, eliminating the risk of breakdown in the wiring and the attendant fire hazard. This 2000 V limit provides protection for conventional appliances but may be inadequate to protect electronic devices that tend to be more sensitive.

b) A metal-oxide varistor, presently available only as an industrial component package, correctly installed in the service panel (short connections) would be sufficient to limit overvoltages for all the building, even for high amplitude lightning strokes.

c) A varistor with limited capability, the VSP-1, installed at a particular receptacle, will limit overvoltages at that point to values that are acceptable for electronic devices, without being itself exposed to hazardous stress, if its distance from a panel — not equipped with protection — is greater than about 10 meters. For shorter distances, the stress applied to the VSP-1 might exceed the expected reliability, with failure of the varistor. This failure would still provide protection during the surge, but lead to a trip of the panel breaker. Of course, if a protection according to (b) were provided, it would not be necessary to install a VSP-1. If the protection provided at the service panel is less than ideal (HLP), the addition of a VSP-1 at the receptacles that supply sensitive devices would provide protection for these devices, while the HLP would provide diversion of high currents.

REVIEWER'S ANNOTATIONS

The conclusion presented in this paper, that coordination can be achieved, is based upon two premises:

1. The impinging surge (into the ground system, not in the phase conductors) is coupled into the phase conductors of the service drop and appears as a L-N mode at the service entrance, but still with a short rise time.

2. The service entrance is a gap-varistor combination, so that as soon as the gap has sparked-over (during the ascending front of the wave), all current ks transferred to the arrester, away from the suppressor at the end of the branch circuit.

Martzloff, F.D. - Coordination of Surge Protectors in Low-Voltage AC Power Circuits. *IEEE Transactions PAS-99*, January/February 1980, pp 129-133.

AUTHOR'S ABSTRACT

Surge protectors can be installed in low-voltage ac power systems to limit overvoltages imposed on sensitive loads. Available devices offer a range of voltage-clamping levels and energy-handling capability, with the usual economic trade-off limitations. Coordination is possible between low-clamping-voltage devices having limited energy capability and high-clamping-voltage devices having high energy capability. The paper gives two examples of coordination, as well as additional experimental results on surge propagation.

AUTHOR'S CONCLUSIONS

Coordination of surge protectors is feasible with existing devices, even if device characteristics vary. The experiments reported in the paper show three facts from which conclusions can be drawn:

Fact 1: Where an unidirectional current is injected into the ground system only, the response of the system is an oscillating voltage, at 500 kHz for the system described.

Fact 2: The equivalent source impedance, as determined by loading the system, is in the range of 50 to 100 Ω for the particular system investigated.

Fact 3: 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.

Con. 4: Coordination of surge suppressors requires a finite impedance to separate the two devices, enabling the lower voltage device to perform its voltage-clamping function while the higher voltage device performs the energy-diverting function.

Con. 5: The concept that surge voltages decrease from the service entrance to the outlets is misleading for a lightly loaded system. Rather, the protection scheme must be based on the propagation of unattenuated voltages.

Con. 6: Indiscriminate application of surge protectors may, at best, fail to provide the intended protection and, at worst, cause disruptive operation of the suppressors. What is needed is a coordinated approach based on the recognition of the essential factors governing devices and surge propagation.

REVIEWER'S ANNOTATIONS

A condensed version and archival publication of the information initially developed in the proprietary (now declassified) 1978 Crouch & Martzloff report.

Martzloff, F.D. and Leedy, T.F. - Selecting Varistor Clamping Voltage: Lower is not Better! *Proceedings, 1989 EMC Zurich Symposium*, pp 137-142.

AUTHORS' ABSTRACT

Surge protective devices, such as varistors, are applied to protect sensitive load equipment against power-line surges. The need to provide low clamping voltage for protection of equipment with low inherent immunity must be balanced against the risk of premature aging of the protective device. Lower clamping voltage causes more frequent interventions of the protective device, accelerating its aging. The paper describes four possible causes of such premature aging, calling for a more careful and thus more reliable application of protective devices.

AUTHORS' CONCLUSIONS

Several mechanisms involving surges or momentary overvoltages can cause accelerated, or premature aging of varistors, if the clamping voltage is selected at too low a level without appropriate consideration of all factors.

The first aging mechanlsm, repeated surge diversion interventions, has been well documented by the manufacturers. A low clamping level will invite more frequent interventions, but information is readily available on this mechanism. Careful designers can use the information to ensure reliability for specific environments and desired useful life.

A second mechanism, fortunately not occurring too frequently, involves fuse blowing and can produce immediate destruction of the varistor at the first occurrence if the clamping level is selected at too low a level. The implications of this situation needs greater recognition among varistor users.

A third mechanism, decreased thresholds of thermal runaway in the long term, is directly related to the selected clamping level, with aging accelerated by a low clamping level selection. This situation is well recognized by high-voltage arrester designers, but not by low-voltage electronic circuit designers.

A fourth mechanism, repeated conduction of currents associated with momentary system overvoltages ('swells"), has not been documented but is now being investigated. The results of exploratory investigations will be published when completed, to act as a catalyst for further investigations at NIST as well as by other varistor users.

The obvious, but difficult remedy to this situation is to design equipment with a reasonably high surge withstand capability so that retrofit using protective devices with very low clamping voltage will not be necessary. For those situations where a close protection would be required, a very careful consideration of all factors becomes imperative, rather than cookbook application of protective devices.

In the absence of a demanding retrofit challenge, there is no advantage and a considerable penalty in providing a too narrow protection margin by specifying needlessly low clamping levels. Such low voltages are counterproductive to total system reliability. Thoughtful design can provide good performance with good reliability; short-term perspective and quick fixes can only compromise long-term reliability.

REVIEWER'S ANNOTATIONS

The title is the theme.

Martzloff, F.D. - Coupling, Propagation, and Side Effects of Surges in an Industrial Building Wiring System. *IEEE Transactions IA-26*, March/April 1990, pp. 193-203.

AUTHOR'S ABSTRACT

Measurements were made in an industrial building to determine the propagation characteristics of surges in the ac power wiring of the facility. The surges, of the unidirectional type or the ring wave type described in ANSI/IEEE Standard C62.41-1980, were injected at one point of the system and the resulting surges arriving at other points were measured. The results show how unidirectional surges couple through transformers and produce a ring wave component in the response of the system. An unexpected side effect of these surges, applied to the power lines only, was the apparent damage suffered by the data line input components of some computer-driven printers.

AUTHOR'S CONCLUSIONS

1) The response of the step down transformer and its associated bus wiring to stimulation by a 1.2/50-μs unidirectional surge contains two components:

- a unidirectional component matching the stimulation, and
- a ringing overshoot at a frequency dependent upon the circuit characteristics.

2) The unidirectional surge couples through the transformer according to the turns ratio, with negligible attenuation. The ringing overshoot frequency depends on the circuit parameters; its peak can exceed twice the peak of the stimulus.

3) The existence of multiple branch circuits in the building wiring reduces the overshoot and affects its frequency but does not change the unidirectional component.

4) A ring wave with a rise time shorter than the travel time in a simple point-to-point line produces the expected enhancement of the surge at an open-circuit receiving end. Adding loads at the end of the line reduces the amplitude of the surge at that point in a predictable manner, according to the classical transmission line theory.

5) Adding branch circuits and other circuit elements along the propagation path introduces mismatches in the line impedance, reducing the amplitude of the initial peak of the surge arriving at the receiving end. Subsequent parts of the surges, however, are less affected.

6) Providing protection against power line surges at the power line interface of devices linked by a data communication circuit does not guarantee that surges occurring in the power line environment will not cause damage to the devices. A more comprehensive protection scheme, coordinating both the power line and the data line, is required to ensure protection.

REVIEWER'S ANNOTATIONS

Martzloff, F.D. and Lai, J.S. - Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase. *Proceedings, PQA 91 Conference*, pp 191-198.

AUTHORS' ABSTRACT

Cascading two or more surge-protective devices located respectively at the service entrance of a building and near the sensitive equipment is intended to ensure that each device shares the surge stress in an manner commensurate with its rating, to achieve reliable protection of equipment against surges impinging from the utility supply as well as internally generated surges. However, depending upon the relative clamping voltages of the two devices, their separation distance, and the waveform of the impinging surge, coordination may or may not be effective. The paper reports computations confirmed by measurements of the energy deposited in the devices for combinations of these three parameters.

AUTHORS' CONCLUSIONS

1. Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations will result in having a suppressor with low energy-handling capability called upon to divert the largest part of the surge energy. This uncoordinated situation can create adverse side effects when high current surges occur.

2. Significant parameters in achieving successful coordination involve three factors, over which the occupant of the premises has no control: the relative clamping voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges. This uncontrolled situation presents a challenge and obligation for standards-writing groups to address the problem and develop consensus on a trade-off of advantages and disadvantages of High-Low versus Low-High.

3. Coordinated schemes can be proposed by utilities to their customers, including a service entrance arrester and one or more plug-in devices to be installed for the dedicated protection of sensitive appliances. However, even such an engineered, coordinated arrangement could be defeated by the addition of a suppressor with a very low clamping voltage, not an insignificant likelihood in view of the present competition for lower clamping voltages.

REVIEWER'S ANNOTATIONS

Martzloff, F.D. - On the Propagation of Old and New Surges. *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, August 1991, pp 19-28.

AUTHOR'S ABSTRACT

The revised IEEE Recommended Practice on Surge Voltages ANSI/IEEE C62.41 has introduced a new generation of surge waveforms; how they travel in low-voltage power systems will affect some of the earlier tenets on surge propagation characteristics. The recent emergence of cascaded surge-protective devices raises a new set of concerns in which propagation characteristics play an important role.

The objective of this paper is to review the propagation characteristics of the old and the new generation of surge waveforms. Measurements are reported and the effect (or, rather, the lack of effect) of wire diameter is documented by a simple experimental demonstration.

AUTHOR'S CONCLUSIONS

TABLE 1
MEASURED CURRENTS AND VOLTAGES, CALCULATED IMPEDANCE (10 m CABLE)
FOR THREE WIRE SIZES AND THREE WAVEFORMS

Nominal generator waveform	Ring Wave			Combination Wave			10/1000 μs Wave		
Peak current, I_p (A)	100			170			120		
Actual rise time of current (μs)	0.8			22			25		
Wire size (AWG)	10	12	14	10	12	14	10	12	14
Peak voltage during surge (V_p)	800	790	800	760	780	800	100	100	110
Effective impedance V_p/I_p (Ω)	8.0	7.9	8.0	4.5	4.6	4.7	0.8	0.8	0.9

REVIEWER'S ANNOTATIONS

Data for evaluating the effect of the inductance in separating two devices, as a function of waveform (major effect) and wire size (minor effect).

Martzloff, F.D. and Lai, J.S. - Cascading surge-protective devices: Options for effective implementations. *Proceedings, PQA 92 Conference*, September 1992, pp xx-xx.

AUTHORS' ABSTRACT

The basic and critical parameters for a successful coordination of cascaded surge-protective devices include the relative voltage clamping of the two devices, their electrical separation through wiring inductance, and the actual waveform of the impinging surge. The authors examine in detail the implications of the situation resulting from the present uncoordinated application of devices with low clamping voltage at the end of branch circuits and devices with higher clamping voltage at the service entrance. As an alternative, several options are offered for discussion, that might result in effective, reliable implementation of the cascaded protection concept.

AUTHORS' CONCLUSIONS

1. The reality of having many millions of 130-V rated varistors installed on 120-V systems, and 250-V rated varistors installed on 230-V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.

2. 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.

3. The coordination of a simple cascade of an arrester and a suppressor of equal voltage rating, both connected line-to-neutral, is slightly improved by the larger cross-section of the arrester. However, an unfavorable combination of tolerances for the two devices can wipe out the improvement.

4. The neutral grounding practice of the utility has a profound effect on the cascade behavior, and must be thoroughly understood for successful application of cascaded surge protection. Clearly, additional studies are required in this area.

5. The waveform of the impinging surge has also a large effect on the outcome. If more data were available on the frequency of occurrence of 'long surges', some of the uncertainty surrounding the success of a cascade would be lifted.

6. The idea of an expendable, one-shot arrester at the service entrance could offer a solution out of the dilemma and should be further investigated.

REVIEWER'S ANNOTATIONS

Marz, M.B. and Mendis, S.R. - Protecting Load Devices from the Effects of Low-Side Surges. *Proceedings, IEEE/ICPS Conference*, May 1992

AUTHORS' ABSTRACT

Wherever lightning and power systems grounds exist, distribution secondary systems are subjected to high voltage surges due to lightning current seeking ground through low-voltage circuits. Utilities are becoming aware of this 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.

This paper describes the secondary surge phenomena and the importance of protecting the service entrance and critical load devices properly, especially when secondary arresters are applied on distribution transformers. A properly coordinated and effective MOV protection scheme is described and recommended.

AUTHORS' CONCLUSIONS

There are more paths for lightning surges to reach loads through utility systems than is generally believed. Multiple grounds at different potentials prevent distribution transformer primary arresters from protecting secondary circuits, especially under lightning surge conditions. Two principles to follow when using surge arresters to protect distribution load devices are (1) prevent the surge current from flowing through the load or equipment to ground and (2) place the arresters as close to the load or equipment as possible. No arrester can guarantee the protection of a remote device.

In most distribution systems, transformer secondary circuit protection is rarely used and when used it is often miscoordinated. Many 175 and 650 volt arresters do not have the current carrying capability to survive the 33 kA surges that can be expected at transformer secondaries and service entrances. 175 volt arresters can also miscoordinate with transformer primary arresters SSPLs. 650 volt arresters will coordinate, but may provide inadequate voltage protection, Both current and voltage coordination can be improved by a 480 volt arrester with a 40 kA rating. Properly coordinated protection using the 480 volt class arrester should become standard practice to protect both distribution transformers and load devices.

REVIEWER'S ANNOTATIONS

Note the recommendation of a 480-V arrester at the service entrance. This recommendation proceeds from concerns about the current coordination of the arrester.

However, the coordination of energy sharing between service entrance and internal suppressor does not seem to be addressed.

A table shows current values in the range of 2 to 17 kA for 'Load Arrester' but this reviewer could not find the definition of the what this load arrester is -- is it a SPD at the end of a branch circuit ? Are we talking about 17 kA flowing in the branch circuits wiring ?

Meyer, J.P. - Parafoudres en Cascade. *Proceedings, UTE Workshop on Surge Arresters*, Paris, March 20, 1992 (In French).

AUTHOR'S INTRODUCTION
(Translated excerpts)

The purpose of this paper is to present a report on current standard activities. ...

A cascade is made necessary by the surge withstand levels of equipment in a 230/400 V installation:
- 6 kV at the point of common coupling
- 4 kV at the point of fixed switchgear
- 2.5 kV at the level of common end-use equipment
- 1.5 kV at the level of sensitive equipment

AUTHOR'S CONCLUSIONS
(Translated excerpts)

SC28A and TC64 are at a dead end and the foundations of the [IEC 664] concept are shaking. Let us hope that enlightenment will come from the LV Arrester document from SC37A/WG3 ...

A cascade of arresters is always to be preferred over a single arrester!

REVIEWER'S ANNOTATIONS

This handout material was distributed in support of a presentation by J.P. Meyer at a workshop organized by Union Technique de l'Électricité. It makes reference to the objections raised by J. Huse on the proposed SC28A(Sec)47 explanation of interface devices. During the discussion period, Mr. Meyer projected on the screen a chart showing that the present situation in the EDF distribution system makes possible the occurrence of temporary overvoltages of 1.5 per-unit for 5 seconds.

Roulet, J.P. - La coordination de l'isolement et le concept de 'Catégorie de surtension' en basse tension. *Proceedings, UTE Workshop on Surge Arresters*, Paris, March 20, 1992 (In French).

AUTHOR'S ABSTRACT
(Adaptation from the French text)

This is a two-part presentation discussing the IEC 664 publication and its table of overvoltage categories, then the work of IEC TC64 to adopt and amend the concepts initially proposed in IEC 664

AUTHOR'S CONCLUSIONS
(Adaptation)

In the future, one may expect a less rigid organization of protection against overvoltages, made possible by regrouping equipment into categories that will make possible the application of various protective methods appropriate to the desired service continuity.

Application of surge arresters will be the work of SC37A/WG3. Let us wish them success, and a fruitful cooperation among Committees 28A, 37A, and 64.

REVIEWER'S ANNOTATIONS

In the discussion of the Overvoltage Categories concept, Roulet points out unresolved questions relating to cascade applications, potential rise of ground references, unwanted neutral-ground connection, and the need for end-of-life indication.

References are made to the forthcoming cooperation between SC28A and TC64/WG3.

Rousseau, A., Lafon, G., and Malpièce, F. - Les parafoudres face aux normes. *Proceedings, CEM 92, 6th International Workshop on EMC*, Lyon-Ecully, France, June 1992. (In French)

AUTHORS' ABSTRACT
(Translated)

Surge-protective devices for low-voltage systems are sophisticated devices which must be defined by several parameters: protection level, energy handling capability, end-of-life behavior, standby current, association with other devices of the same type, etc. This paper reviews currently applicable French standards and compares then to foreign standards. A review is presented of international activities, in particular studies on coordination of protective devices.

AUTHORS' CONCLUSIONS
(Adapted from final discussion)

The problem remains of the coordination between two SPDs. The cases studied so far generally involve ZnO varistors. However, many other components or module exist that raise even more problems of coordination. It seem therefore difficult today to coordinate products from different manufacturers, without prior testing or simulations. Thus, it is easier to rely upon coordination tests performed by a manufacturer on its own product line.

REVIEWER'S ANNOTATIONS

The paper presents a snapshot of the status of standards in France, Belgium, Germany, and the USA, underlining the differences in philosophy and postulated threat waveforms. Several unresolved questions are identified that merit consideration on the international level, such as protective level, energy handling capability, failure mode, standby current, coordination.

An example is given of successful coordination between a gapped varistor and simple varistor with an 8/20 μs wave and as little as 5 m separation, but no information is provided for coordination with the 10/350 μs wave which is cited elsewhere in the paper.

Scuka, V. - *Application of modern surge suppressors in low-voltage power installation networks*. Institute for High Voltage Research, Uppsala University, *UURIE:250-86*, 1986.

(Not available at press time)

AUTHOR'S ABSTRACT

AUTHOR'S CONCLUSIONS

REVIEWER'S ANNOTATIONS

Skuka, V. - EMI Control in Low-Voltage Power Installations. *Proceedings, 1987 EMC Zürich* Symposium, pp 429-434.

AUTHOR'S ABSTRACT
(Excerpts from 'Introduction')

According to Martzloff [3] the impedance of low voltage power installations in general is in the range of 50 to 100 Ω, therefore, the expected minimum current through the secondary suppressor must be in the range of 10 to 40 A until the gap of the primary surge arrester will be able to break down. It would therefore be of advantage, if the surge impedance of the installation circuit is not too low. Our measurements of impedances in low voltage power installations in different structures have shown, that the impedance may decrease by a factor of up to three by moving from a distant point in the installation to the main power distribution box of the structure.

Approaches have been made to artificially increase the impedance of low voltage power circuits by applying ferrite cores in coils of power network filters. It is unfortunately often forgotten that core saturation currents for the core dimensions normally used usually are very low, much lower than usual surge currents in the line. The most safe way in increasing the impedance of the particular installation line segment is to separate the surge suppressors by a properly designed physical line or a noise suppression transformer.

The need of international regulations and recommendations regarding the application of surge suppression in particular in industrial power lines and installations and the need of standardized equipment testing procedures and test-level specifications have been recognized. An overview of the situation of today has been given in a paper by Martzloff [8].

In the following we shall present and discuss our experimental and theoretical investigations made on an artificial low voltage power installation segment and on ordinary low voltage power installations in different structures. The investigations have been performed in order to determine the values of the basic electric circuit parameters and to deduce the electro-physical relationship for different components and circuit parameters of a modern low voltage power installation.

AUTHOR'S CONCLUSIONS
(Excerpts)

Spark gaps should only be used as overload protectors of varistors, or as insulation-coordination protectors where AC-short circuit follow currents are not to be expected. In a 380V AC power system the varistor V^1 - type should be installed in the main power distribution box in accordance with the established practice. In general, if there are no special reasons, additional varistors of type V^1 are not necessary to be installed in subdistribution boxes. Further more, varistors of type V^1 in the subdistribution boxes would draw high surge currents along the connection lines between the boxes. This could be a disadvantage from the point of interference suppression. The secondary varistors V^2 should be installed near the sensitive equipment. Preferably, such equipment should not be connected to the power line near the main distribution box. A long installation line may be of advantage.

A reasonable value of the nominal voltage for a secondary varistor of V^2 - type is between 620 and 750 V DC and the diameter between 14 and 24 mm. Referring to the Table 4, only a minor part of the total surge current will pass through the installation line and the varistor V^2. An optimized protection of the equipment, regarding the common mode and the transverse mode voltage surges, is obtained by using a set of three varistors [8].

The surge voltage across the varistor V^2 has an appreciable longer rise time than the original surge at varistor V^1. For an injected lightning current of 1/50 us, the dominant frequency of the voltage surge across V^2 will be in the range of 10 kHz. This makes it possible using an additional power transformer, e.g., an isolation transformer, which significantly reduce the surge entering into the protected equipment. We may also conclude that equipment with a power transformer is very suitable to be efficiently protected using a set of secondary varistors.

REVIEWER'S ANNOTATIONS

Paper reports computations with EMTP and makes reference to measurements, presumably reported in Scuka, 1986 for a cascade of two varistors.

The impinging surge is a current of 1/50 μs waveform - a steep front.

Paper seems to encourage varistor at end of branch circuit to have higher voltage rating than varistor at service entrance.

Smith, S.B. and Standler, R.B. - The Effects of Surges on Electronic Appliances. *IEEE Transactions PWRD-7*, No.3, July 1992, pp 1275-1282.

AUTHORS' ABSTRACT

With the dramatic increase of electronic equipment and appliances being used in homes, the topic of power quality and its relationship to appliance reliability has recently become very important to both the utility company and the consumer. We subjected a total of 16 different clocks, television receivers, microwave ovens, and dc power supplies to three different transient overvoltage (surge) waveforms with amplitude between 0.5 and 6 kV. All of these devices were operating from the ac supply mains when the overvoltage was applied. The switching power supplies and television receivers were damaged with surges between 4 and 6 kV. Three of five models of digital clocks were upset (temporary malfunction) with surges between 1.6 and 6 kV.

AUTHORS' CONCLUSIONS

Tests of 12 different models of consumer appliances and two switching power supplies showed that television receivers and switching power supplies are vulnerable to damage by surges with peak open-circuit voltages between 4 and 6 kV. Surge protection is desirable for these vulnerable appliances. However, some of the appliances in this project were not vulnerable to damage by a limited number of surges. Further research, leading to archival papers, is recommended on both (1) the effects of surges on appliances and (2) techniques to mitigate damage and upset by surges.

REVIEWER'S ANNOTATIONS

Two noteworthy paragraphs in the discussion presented by the authors read:

> The results of this research show that the conventional wisdom that electronic appliances are easily damaged by surges with a peak voltage of a few kilovolts *may* greatly exaggerate the effect of surges on modern consumer appliances.
>
> If manufacturers include metal oxide varistors inside appliances in order to prevent damage or upset, they should consider using varistors rated for twice the normal rms voltage. This relatively large conduction voltage will make it *possible* to install a secondary arresters upstream from the appliance that has good coordination with the varistors inside the appliance.

The conclusions and discussion remarks point out that the quest for very low protective voltage, such as 330 V or 400 V may indeed be an exaggeration of the need for protection. The immunity to surges as high as 1.5 kV cited in the paper may be the result of inherent immunity of the power port circuitry, or the result of some built-in protection at the input. In either case, the authors have provided significant evidence that relatively high protection levels at the point of load connection, a requirement for a successful cascade, should not be viewed as a threat to the appliances.

Another anecdotal consideration is that the highest percentage of reported failures (50%) cited in the paper involves TV receivers and VCRs. The authors suggest that this finding may be related to the high cost of these appliances, more likely to be reported than the failure of a clock. This reviewer suggests that a possible contribution to the high percentage may be that TV equipment is a two-port system (power port and communications port), compared to a single-port clock, raising the issue of the need for special protection of two-port devices. (In the tests reported by the authors, only differential-mode surges were applied to the two-conductor line cord, no mention is made of the status and reference voltage of the signal port.)

Standler, R.B. - *Protection of Electronic Circuits from Overvoltages*. Wiley-Interscience, New York, 434 pp, 1992.

Excerpts from cover flap abstract:

Protection of Electronic Circuits from Overvoltages collects and logically presents the information in this field ion one convenient text. At the same time, it provides practical rules and strategies for the design of circuits to protect electronic systems from damage by transient overvoltages. These rules are, as often as possible, related to physical laws rather than traditional rules of thumb. ... Because many of these circuits operate from ac supply mains, protection of equipment operating from the mains is also discussed. ...

Reviewer's annotations:

The book contains 24 chapters organized in four parts:

Symptoms and threats
Protective devices
Application of protective devices
Validating protective measures

The following are excerpts from Chapter 19, under the heading of "Coordination of Protection" page 294:

... In most hybrid protection circuits, shunt devices with smaller clamping voltages are installed downstream, nearer the equipment to be protected. Some series impedance is installed between each pair of shunt protective devices to provide proper coordination. ...

... But for overvoltages with durations of a few milliseconds, it will be difficult to insert an adequate series impedance between shunt protective devices and still maintain normal operation of the load. ...

... One solution to the problem of coordinating multiple varistors on the mains is to reverse the normal order of devices. Place the varistor with the *smallest* value of V_N at the secondary arrester. Varistors downstream would have slightly *larger* values of V_N. .... (numerical example follows)

... It is sometimes difficult to coordinate multiple surge protective devices when you are aware of them. However, you can't even try to coordinate varistors that are hidden in a chassis unless you know about them! ...

Standler, R.B. - Coordination of Surge Arresters and Suppressors for Use on Low-Voltage Mains. *Proceedings, 1991 Zürich EMC Symposium*, pp 517-524.

AUTHOR'S ABSTRACT

A secondary arrester is used at the point of entry of the mains into a building to provide protection from severe surges, such as direct lightning strikes to overhead mains. A surge suppressor is used at the wall receptacle to protect vulnerable electronic equipment from damage by transient overvoltages. This paper discusses the sharing of current between the arrester and suppressor during surges. Results of both a theoretical analysis and laboratory experiments are reported. Conventional practice is to make the conduction voltage of suppressor. It is shown 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.

AUTHOR'S CONCLUSIONS

Good coordination of two metal oxide varistors can be obtained by specifying that the arrester have a lower conducting voltage than the suppressor. An example for use on mains with a nominal voltage of 10 V rms is to us (1) an arrester with V^N - 240 V and a diameter of 40 mm and (2) a suppressor with V^N - 390 V and a diameter of 14 mm. It is possible that future research will show that suppressor varistors with a diameter of 10 mm are suitable for use in this well coordinated method.

REVIEWER'S ANNOTATIONS

Computations are made with only resistance of wire between cascaded devices, no inductance.

Measurements as well as computations are reported for several combinations of service entrance arresters (650, 175, 150 V) and branch circuit end suppressors (130, 150, 250 V).

The conclusion that good coordination can be achieved with lower voltage clamping at the service entrance is well-founded but does not take into consideration the reality of uncontrolled low levels of clamping from billions of installed TVSSs and built-in suppressors.

Standler, R.B. - Calculations of Lightning Surge Currents Inside Buildings. *Proceedings, IEEE International EMC Symposium*, August 1992, pp 195-199.

AUTHORS'S ABSTRACT

This paper describes the distribution of surge currents inside a building during a direct lightning strike, on the basis of numerical simulations of building wiring, various loads, and five different combinations of metal oxide varistors connected inside the building as surge arresters and surge suppressors. The 10/350 μs wave with a peak of 20 kA, which is widely accepted as a simulation of current in a direct lightning strokes, is used as the source. The network inside the building is modeled as eight branch circuits, each with a different resistive, capacitive, or inductive load and each with a different length. The results of this modeling is compared with the 8/20 and 10/1000 standard surge test waveforms. It is shown that the surge test waveforms of ANSI/IEEE C62.41 have a peak current and duration that are both too small to represent the effects of a direct lightning strike to the mains. Instead of revising C62.41 to include larger stresses for the environment inside a building, it is urged that standards specify maximum allowable values of peak surge current and rates-of-change inside a building. Coordinated surge arresters and suppressors should be used to keep surge currents inside a building within the specified limits.

REVIEWER'S ANNOTATIONS

AUTHOR'S CONCLUSIONS

Computer simulations of simple arrangements of branch circuits, loads, and one or two varistors show that surge currents inside buildings during a direct lightning stroke to the mains have a larger peak current and longer duration than maximum surge test levels recommended in ANSI/IEEE C62.41-1991.

The discussion of this paper recommends that we do *not* continue to specify surge currents that *might* be found inside buildings. Instead, it is recommended that limits be set on the maximum permissible surge current inside buildings by considering principles of electromagnetic compatibility. Coordinated surge arresters and suppressors should be used to keep surge currents inside a building within the specified limits. Such an approach is an extension of the Lightning Protection Zone Concept of Hasse and Wiesinger in Germany.

Stringfellow, M.F. and Stonely, B.T. - Coordination of Surge Suppressors in Low-Voltage AC Power Circuits. *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991, pp 133-138.

AUTHORS' ABSTRACT

This paper reports on a theoretical and experimental study on the coordination of metal oxide varistors on an indoor low-voltage power system. The system studied was a 120-volt three-wire power line, equipped with phase, neutral and ground conductors. 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. Total line length studied was 30 meters (100 feet), with the distribution panel being located at the central point.

When unidirectional surges typical of lightning were applied at the service entrance, both experimental and theoretical studies showed similar results. Namely, 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. Distribution of surge current between movs in three locations is shown to be good for both low and high surge currents. Coordination of protective levels was shown to be achieved, even with long surges typical of lightning.

AUTHORS' CONCLUSIONS

The following conclusions may be reached regarding the protection of loads connected to low-voltage ac power systems inside buildings when subjected to external transients:

1) A service-entrance arrester or suppressor diverts the majority of surge current away from the building wiring.

2) The best protection is always obtained when suppressors are located on internal wiring at both distribution panels and at the load.

3) The lowest-rated mov does not have to be located at the service entrance, but can be effective when applied at the load.

4 Testing with the new ANSI C62.41 Category C3 combination wave gives results in reasonable agreement with those expected from more realistic lightning waves. However, the energy deposited in movs by this wave is much lower than expected from lightning.

5) Surge current waveshapes inside buildings have longer risetimes and wavetails than standard test waves. The 10x1000 μs wave is the closest standard wave to those predicted or measured.

REVIEWER'S ANNOTATIONS

Stringfellow, M.F. - Fire Hazard of Surge Suppressors. *Proceedings, Power Quality Conference*, Anaheim Ca, September 1992.

AUTHOR'S ABSTRACT

Surge suppressors can and do catch fire. One or two recent nationally-publicized incidents show that serious property damage and injury can result from such suppressor fires. The popular and much repeated theory of how this occurs is that suppressors degrade in service when exposed to transients or power disturbances. This degradation eventually leads to suppressor failure by overheating. The author shows in this paper that this theory is completely wrong. Suppressors removed from service throughout the U.S. and Canada show no signs of degradation. Suppressor damage from overheating can almost always be directly traced to power-frequency voltage overstress, usually resulting from building wiring faults. A laboratory test which simulates these faults is proposed. Preliminary test results on some of the most popular commercially-available surge suppressors show that many can be set on fire in a reproducible way. It is concluded that internal protection against overheating is required to ensure suppressor safety and that safety agency approvals should include fire hazard tests.

REVIEWER'S ANNOTATIONS

AUTHOR'S CONCLUSIONS

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. These incidents appear to be increasing in frequency due to the more widespread adoption of modular furniture with integral wiring. The many connectors used in this form of electrical distribution appear to be very prone to wiring problems.

The overvoltages resulting from broken conductors are very large (1.5 to 2 times normal voltage), may be sustained for many minutes, and can cause suppressors to overheat internally.

Products equipped with overcurrent fuses or magnetic circuit breakers may 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.

Suppressors equipped with thermal circuit breakers or thermal fuses appear to be very fire resistant. Products equipped with two independent thermal protective devices were never seriously damaged in testing, and are therefore expected to be essentially hazard free.

A fire hazard test, similar to that described in this paper, is proposed to be added to safety agency tests for surge suppressors and similar products.