Coordination of Overvoltage Protection in Low-Voltage Residential Systems

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Significance
Part 4 – Propagation and coupling of surges
Part 6 – Tutorials

This paper was presented as a summary tutorial aimed at the French-speaking Canadian community to solicit their comments on the development of the IEEE Std 587 Guide. The paper has been translated into English by the author to make the English-speaking community aware of that paper, which served at that time as one output for the release of the extensive test results that were reported in the 35-page GE Memo Report – still proprietary at that time – "Lightning protection in residential AC wiring" (see Part 4 of the anthology).

The tests were performed by injecting a simulated lightning flash current of unidirectional waveshape into the grounding system of a simplified residential wiring system, and observing the coupling and induction of oscillatory surges in the house wiring

Part 8 – Coordination of Cascaded SPDs
Excerpts from the complete test report found in this summary include a discussion of the performance of gapped arresters, as well as MOVs installed at the service entrance, with coordination with an MOV installed at the end of branch circuits.

COORDINATION OF OVERVOLTAGE PROTECTION IN LOW-VOLTAGE RESIDENTIAL SYSTEMS

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INTRODUCTION

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 [1].

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.

CIRCUIT MODEL

Given the complexity of distribution networks and the nonlinear response of the suppressors [2], it would be difficult to compute in detail the behavior of the system subjected to a current surge. Thus, it is more convenient, to the extent that reality can be modelled by a physical model, to make tests directly on the devices actually used in these buildings. Such tests have been performed at the High Voltage Laboratory of the General Electric Company in Pittsfield, MA. We injected, into a physical model, currents corresponding to lightning strikes amplitudes ranging from moderate to extremely high [3].

A model of a typical building was wired with the components used in a residential building: triplen overhead service drop from the distribution transformer, down-conductor to the revenue meter, connection to the service panel provided with circuit breakers, with four branch circuits ranging from 5 to 50 meters and provided with a receptacle at the far end.

Assuming a 100-kA strike on the primary distribution system, an extreme case in the probability of discharges [3], a current division is postulated as shown in Figure 1, resulting from the injection of 30 kA in the (grounded) neutral conductor supplying the building.

This 30-kA value is predicated by assuming that the lightning current transfers from the primary conductors to the grounding network as a result of the operation of the arrester, or by a flashover from the phase conductor to the ground conductor of the primary circuit, without involving the two conductors of the low-voltage distribution. Only the (grounded) neutral conductor of the service drop is involved, with 70 kA flowing through the grounding connection of the pole involved and toward the two adjacent poles.

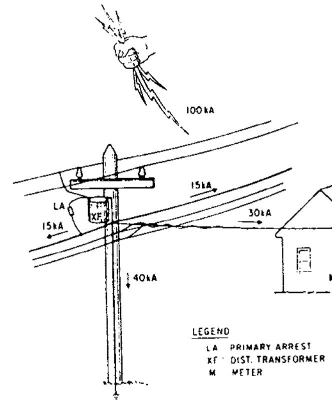


Figure 1. Distribution of the 100-kA current in the ground network near the building

Figure 2 shows schematically the path of the 30-kA current injected in the ground conductor to the building, as well as the mechanism for inducing currents and voltages in the circuit model, mostly by electromagnetic coupling into the loop formed by the service drop.

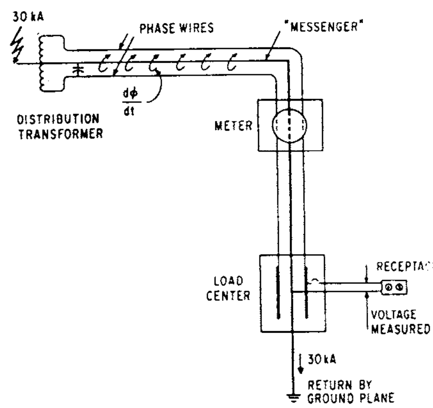


Figure 2. Injection of 30 kA in the ground conductor of the service drop, and resulting voltages

The complete circuit, including the surge generator and the instrumentation, is shown schematically in Figure 3. Of course, the usual precautions were taken in the setup (shielded room for the instrumentation, checks for interference, etc.).

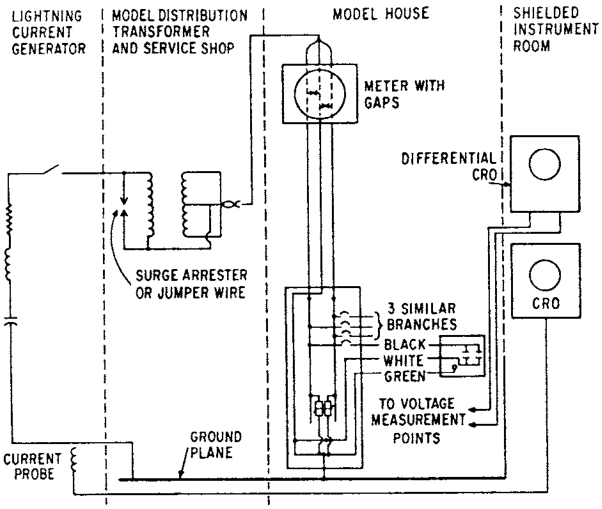


Figure 3. Schematic of the experimental circuit

Figure 4 shows an example of the waveform of the injected current, a 10/25 μs impulse, which is a conservative hypothesis for the current involved. Three different values of the peak current have been used in the tests, 1.5 kA, 10 kA, and 30 kA. The first value, 1.5 kA, is the standard duty test for a secondary arrester, the second, 10 kA, is the standard withstand test, and the last, 30 kA, is a pessimistic level.

Vertical: 500 A/div
Sweep: 5 μs/div

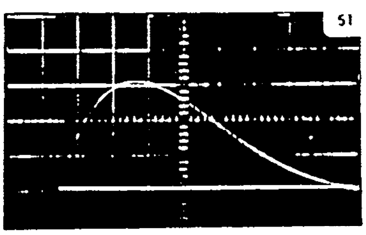


Figure 4. Injected current

TYPES OF SUPPRESSORS

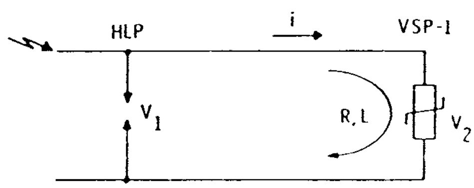
There are two types of commercially available suppressors: a surge arrester that can be installed on the service panel or at the point of anchoring the service drop, and a suppressor which is a plug-in device as previously mentioned.

The surge arrester type, which has been used for many years but only in limited numbers, meets the performance standard for a secondary arrester [4], in particular a rating of 10 kA, 8/20 μs surge. One of the reasons for the lack of market success of this suppressor is undoubtedly the fact that its installation must be contracted out to an electrician because it requires work on the live circuits inside the service panel. Furthermore, this type of arrester has a let-through of about 2000 V, which is excessive for sensitive electronic appliances. Varistor discs with a 32 mm diameter are now available, but only as an industrial component (at this time). These discs have the capability of diverting the 10 kA required by the standard, and thus are excellent candidates for a service-entrance arrester because they can clamp at voltages significantly lower than those of previously available arresters. In the tests that we performed, these discs turned out to be highly promising.

The plug-in type, represented in our test series by GE Model VSP-1, contains a 14-mm diameter varistor, with a rating of 6000 A and capable of absorbing a number of 3 kA surges during its service life.

COORDINATION OF SUPPRESSORS

In an installation where several surge suppressors are connected at different points of the system, the suppressor with the lowest clamping voltage will be called upon to "protect" the suppressor having a higher clamping voltage, by sparking over first or by preventing the second from sparking over. To reverse this situation, it is necessary that the voltage drop in the wiring, produced by the current flowing in the first suppressor and added to the clamping voltage of the latter, exceed the operating voltage of the second. In the case of varistors, which have been designed specially to produce a low clamping voltage, this situation may become critical. Figure 5 illustrates the arrangement where the VSP-1 might prevent the HLP from sparking over if the clamping voltage of the VSP-1 is much lower than the sparkover voltage of the HLP. This situation is another motivation for the tests, to verify that coordination can be maintained between the suppressors in practical applications.



Sparkover of HLP: $V1 \leq V2 + Ri + Ldi/dt$
All the current in VSP-1: $V1 > V2 + Ri = Ldi/dt$

Figure 5. Coordination between two suppressors separated by an impedance

TEST RESULTS

During a first test series conducted at 30 kA, we quickly noted that sparkover occurs at many points in the circuit, making it difficult to obtain reproducible results. It was necessary to reduce the current to 1.5 kA to reach a situation where no sparkover would occur. Even at "only" 10 kA, sparkover still occurred in the unprotected devices (receptacle, service panel). It should be noted that these sparkovers taking place between the conductors (black to white or black to green) result solely from injecting current in the ground conductor of the circuit, not from injecting the surge directly into the phase conductors.

Many oscillograms were recorded, which cannot be reproduced in this paper. Some examples are given in the following figures, to enable comparisons among the various arrangements of the suppressors, showing that an effective protection scheme can be achieved, if only a few precautions are taken.

Effect of the inductance at the end of the line

Oscillograms 204, 247, and 248 (Figure 6) show the attenuation obtained from an impedance at the end of the line, for a 1.5 kA injection, at the end of a 25-m line. Oscillogram 204 shows an open-circuit voltage reaching 2200 V, with oscillations at about 500 kHz decaying in about 20 μs.

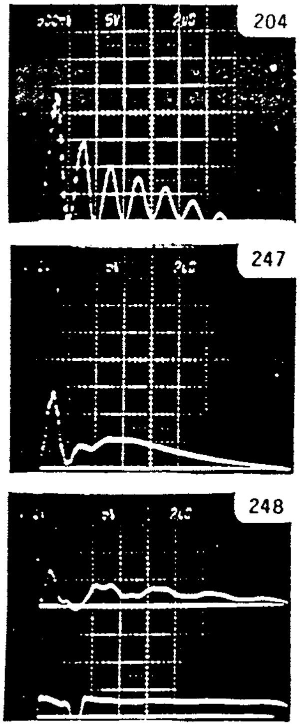


Figure 6. Effect of impedance at the end of the line

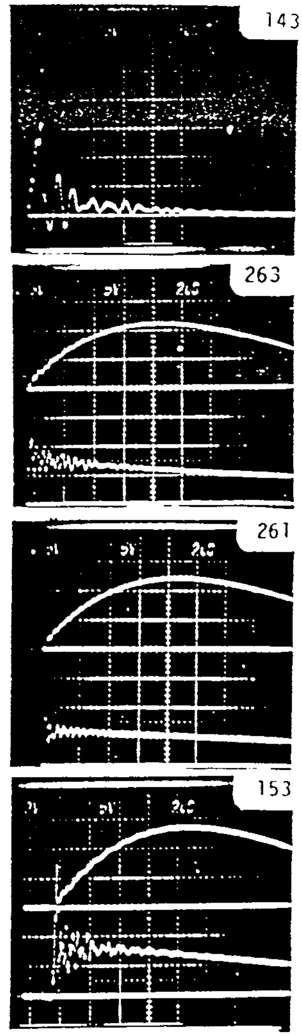


Figure 7. Compared performance of various suppressors at the service panel

By connecting a resistive load of 130 Ω at that point, the voltage is reduced down to 1400 V, and the oscillations are replaced by a damped waveform. Adding a varistor (VSP-1) to the 130-Ω resistor produces the clamping shown in oscillogram 248; this oscillogram also shows that only 15 A flow in the varistor. From these oscillograms, the following conclusions may be drawn: an oscillatory voltage at 500 kHz is induced in the line, superimposed to the unidirectional voltage produced by the injection of an unidirectional current. This oscillatory voltage appears to be the result of oscillations occurring in the line, oscillations that can be damped by adding a resistive load at the end of the line. Furthermore, connecting a 130-Ω resistor at the end of the line reduces the voltage at the end of the line from 2200 to 1400 V. One may view this situation as a voltage divider consisting of the source impedance and the impedance at the end of the line. A rough estimation of the "source" impedance, Zs, may be made by neglecting the complex nature of the impedances. The circuit equation may be written as $Vr = Vo\ 130/(130 + Zs)$, where Vr is the voltage (1400 V) recorded with a resistor in the circuit, and Vo is the open-circuit voltage (2200 V). Solving for Zs yields $Zs = 75\ \Omega$. This value, although inaccurate because the equation was not vectorial, is nevertheless a useful result to provide an order of magnitude for the source impedance, the perennial question.

Performance of suppressors at the service entrance

Oscillograms 143, 261, 263, and 153 (Figure 7) show the results obtained by installing various types of suppressors at the service panel, for a 10 kA surge. Without any protection (oscillogram 143), the voltage reaches 7 kV before collapsing to small oscillations. This collapse is actually the result of a breakdown occurring at some other point of the circuit, as demonstrated in other tests. This oscillogram shows that 7 kV peaks may be reached when no protection is provided.

By installing a 32-mm disk outside the service panel, an arrangement that requires a total of about 50 cm of wiring, the protective level shown in Oscillogram 263 is obtained, about 800 V, with high-frequency oscillations reaching 1500 V, while about 1100 A flow in the disc. If the disc is connected directly onto the bus bars of the panel, with a maximum connection length of about 15 cm, the protective level is substantially improved: oscillogram 261 shows oscillations of only 900 V and subsequent value of 600 V, with a current of about 1200 A in the disc. In contrast, the HLP arrester (oscillogram 153), which contains a spark gap and silicon carbide varistors, allows the voltage to reach 2400 V before sparking over, then holds a discharge voltage of about 900 V with a peak current of 1300 A. This set of measurements shows how important it is to hold the connections as short as possible. They also show how the new metal-oxide varistors can improve protection, if correctly installed.

Stress on the suppressors

Considering the limited capability of the VSP-1 device, which is only a 14-mm disc and does not purport to be a lightning arrester, it is interesting to determine the stress that might be imposed by injecting a surge with extreme value.

32-mm disc inside
Voltage and current
for VSP-1 at 12 m
500 A/div
500 V/div
2 μs/div

32-mm disc outside
Voltage and current
for VSP-1 at 12 m
200 A/div
500 V/div
2 μs/div

No protection on the panel
Voltage and current
for VSP-1 at 12 m
1000 A/div
500 V/div
2 μs/div

No protection on the panel
Voltage and current
for VSP-1 at 25 m
1000 A/div
500 V/div
2 μs/div

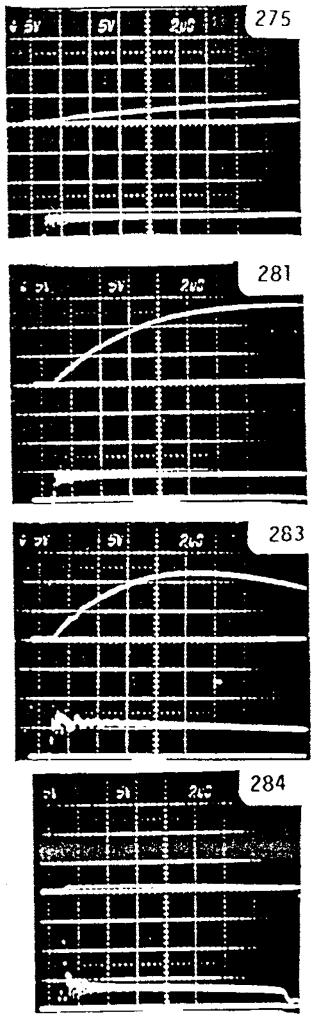


Figure 8. Stresses on the suppressors

Figure 8 shows the results of tests made with an appropriate protection at the service panel (oscillogram 275), with a poor protection at the service panel (281), and without any protection at the service panel (283 and 284).

With a disc connected directly across the bus bars (275), the ideal situation, the current in a VSP-1 located 12 m away from the service panel, resulting from injecting 30 kA, is less than 400 A; the voltage across its terminals, to be applied to the protected load, is less than 500 V. If now the disc is installed outside of the panel (281), a reduction of the effectiveness of the protection, the current in the VSP-1 is slightly increased, with a corresponding increase in the clamping voltage. If no protection is installed at the service panel (283), the VSP-1 would tend to absorb all the current, in this case a 3.3-kA peak with a clamping voltage of 650 V for a VSP-1 installed 12 m away. In contrast, for a VSP-1 installed 25 m away, the voltage drop between the panel and the VSP-1, associated with the line impedance, is such that a breakdown occurs upstream from the receptacle (in this case in a parallel branch circuit), hence the limiting effect shown in oscillogram 284.

Thus, this set of measurements shows that even in the extreme case of injected currents, the current imposed to the VSP-1 remains within acceptable limits for a limited number of surges. Its rating of 6000 A at 8/20 μs allows considering a limit of 4000 A for the product line, with high reliability. Furthermore, this example illustrates the fact that breakdown can occur in a poorly coordinated installation. From the point of view of the safety of the VSP-1, the breakdown shown in oscillogram 284 might be viewed as a safety valve, but from the overall safety point of view, it is not recommended to rely upon a breakdown occurring in the wiring or at the terminals of the wiring devices, because such breakdown may initiate a power fault with significant fire hazard.

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.

b) 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.

REFERENCES

[1] Surge Voltages in Residential and Industrial Power Circuits, F.D. Martzloff and G.J. Hahn, *IEEE Transactions PAS* Vol 89, pp 1049-1056, July/August 1970.

[2] Qu'est-ce .... les varistances ? Paper by "D.M." *EEE Journal.* No. 410, pp 50-55, 28 September 1977.

[3] *A Ground Lightning Environment for Engineering Usage,* N. Cianos & E.T. Pierce, Stanford Research Institute, Menlo Park CA, August 1972.

[4] *Surge Arresters for Alternating-Current Power Circuits,* ANSI C62.1-1975.

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