The Effect of Neutral Earthing Practices on Lightning Current Dispersion in a Low-Voltage Installation

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Abstract - Computer modeling with the EMTP code has been applied to several configurations and earthing practices in use in various countries to show the effect of any differences in the dispersion (sharing) of a lightning stroke current among the available paths for the earth-seeking lightning current. Simplifying assumptions have been made to some details of the configurations to focus on the main difference -- earthing practices. Identifying such differences provides the necessary perspective on their significance and the strong need to take them into consideration when developing international standards on surge-protective device applications.

I. INTRODUCTION

When designing a lightning protection scheme for a low-voltage power system within a building, several scenarios must be considered for the point of termination of the lightning stroke. Common wisdom classifies these by decreasing order of severity: directly to the building, directly to overhead low-voltage distribution lines (or other utilities) outside of the building, to other objects near the building, distant cloud-to-earth strokes, and finally perhaps cloud-to-cloud discharges. Several standards-writing projects are underway, at the IEEE and at the IEC, based on present knowledge of the lightning flash characteristics and on assumptions about the way the lightning current divides among the many paths available for distributing (dispersing) this current to the ill-defined "earth" which is the termination of the cloud-to-earth strike.

The purpose of our paper is to show the effect that different practices for neutral earthing in the low-voltage distribution system can have on the relative dispersion of the lightning current which is seeking the path of least impedance to earth.

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To accomplish this purpose in an eight-page paper, and to concentrate on the essential difference, the models we present are simplified from the detailed reality, so that one of our first tasks will be to explain and justify the simplification. To avoid confusion in the meaning of the word "distribution" which can relate to the distribution of electric power by the utility or to the distribution of the lightning current among the available paths, we will use the term "dispersion" for the second meaning, lighting current dispersion. Another term used by some authors to convey the concept is "sharing" (among available paths). Note that the actual return stroke actually goes from earth to cloud in the majority of cases, but the scenario is generally described as if the stroke "terminated" on earthbound objects.

In the case of a low-voltage power distribution system, different countries have adopted different practices on earthing the neutral conductor, and writing a history of why that is so would give an interesting insight into the development of power systems. The fact is that today, two approaches are well entrenched in their respective territories, the so-called TN system and TT system where the difference lies in the mode of earthing the neutral. We will give a brief overview of the differences in a following section. Our purpose is to show how the difference in these practices affect the sharing, or dispersion, of the lightning current among the available paths to earth, and consequently affect the rating of surge-protective devices which may be included in these paths. We used the EMTP simulation code [1] to model several scenarios in each of the TN and TT systems, with small but possibly significant differences in the configuration. By postulating a direct stroke to one building, and requesting EMTP to compute currents in the (simplified) complete power system, we obtained results for the two most severe cases of lightning termination: the case of a direct stroke to one building, and the case of a nearby stroke which propagates and impinges at the service entrance of many buildings on that part of the low-voltage distribution system.

The literature and draft standards contain many examples of such scenarios, but it seems that each is confined to a specific approach or power system configuration with fairly detailed arrangements of load connections. The result is that from this plurality of examples, it is difficult to extract a clear perception of the significant parameters in the dispersion of the lightning current resulting from different earthing practices. In this paper, we will simplify the scenarios to concentrate on the fundamental difference between the neutral earthing practices.

II. THE TT AND THE TN SYSTEMS

The IEC has promulgated a letter code system describing the arrangement of the neutral earthing in single-phase and polyphase power systems [2]. For the purposes of our paper, we can summarize the TT system as being a distribution system where the neutral is earthed only at the distribution transformer secondary, and the protective earth in a building is obtained from a local earth electrode. This system is used in some countries. The TN system has its neutral earthed at any available opportunity outside of a building, including the distribution transformer secondary, some or all poles, and the service entrance. In the United States, an "Equipment Grounding Conductor" (EGC) is created at the service entrance, bonded to the incoming power system neutral and to the common local earthing point, after which the neutral conductor and the EGC are carefully (and by mandate from the National Electrical Code [3]) kept separate from one another.

III. NECESSARY SIMPLIFICATIONS

Another difficulty in making a detailed comparison of results from different authors is that different models are often used. When apparently different results are reported, a lingering question is that of differences attributable to the simplifying assumptions and possible modeling artifacts. We have used the well-known EMTP code [1] for which our previous experience in cross-validation between the computer model and full-scale experimental measurements [4], [5] gave us great confidence in the validity of the results.

The literature offers many contributions on the system simulation but our purpose is not literature review -- again, our purpose is only to focus on the neutral practices considerations. However, to support some of our postulates, we will cite some papers to show that in the maze of assumptions, simplifications, and simulations, we are not alone.

A. Down-conductor representation

Some authors have included in their modeling a down-conductor feeding the stroke current to the common bonding point of the building [6]. In our model, since we postulate that the current is delivered from a current source, the impedance of the down-conductor has no effect on the current being injected at the common bonding point which is the point at which dispersion (sharing) begins. Therefore, we did not include a down-conductor in our models.

B. Earthing impedance as a function of time and current

Some authors consider the fact that the exact value of the earthing impedance is variable as a function of time and current level. For instance, [6] initially proposes a model involving resistance, capacitance, and inductance, with some dependency on time or current, or both. But after studying the problem closer, the authors of [6] conclude that a reasonable approximation is merely a fixed 10-Ω resistance. We have used this value in our models of the building earthing, and postulated an improved, lower 5-Ω resistance at the earthing electrode of the distribution transformer.

C. Other available current paths

Some standard proposals include telephone, water and gas connections as possible paths for the earth-seeking lightning current. Considering that the telephone service is a balanced system normally isolated from earth (until a network interface device becomes involved), that some water and gas services can include a cathodic-protection isolation or be implemented with plastic pipes, we chose a conservative approach of not including these as additional paths to earth.

D. Actual Circuit Configuration for Service Entrances

Figure 1 shows a schematic of a single-phase 3-wire TN 120/240-V service to a building. One surge-protective device (SPD) is connected between each of the two lines and the common earth at the service entrance, ignoring any SPDs within the building under the assumption that in a well-coordinated cascade [7] the majority of the current is carried by the service entrance SPD which has the lowest limiting voltage in the installation. The stroke current, postulated to have terminated on a point of the earthing system of the building, can seek a path to earth in two ways: directly through the earth electrode of the building, and by means of the three conductors back toward the power system.

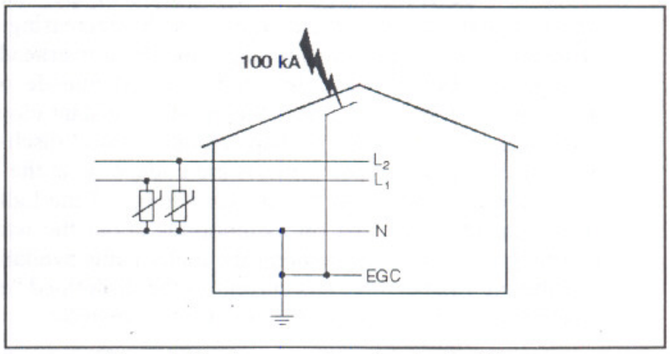


Figure 1. Service connections in a 3-wire TN system

Figure 2 shows a schematic of a three-phase 4-wire TT 230/400-V service to a building. A dedicated protective earth is created and connected to a local earth electrode, while the incoming neutral of the power distribution system is not bonded to this protective earth. At the service entrance, SPDs are connected between the local earth and each of the incoming lines and the neutral.

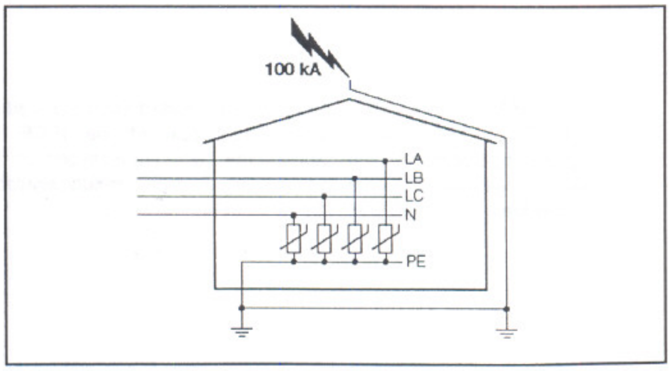


Figure 2 - Service entrance connections in a 3-phase, 4-wire TT system

E. Postulated lightning stroke current

While some authors propose a 200 kA, 10/350 μs surge [8], [9], others suggest that even a 100 kA peak might already be too high a value [6], [10], [11]. In agreement with the latter three references, we postulated a 100 kA peak, 10/350 μs surge current. This selection also offers the convenience that when we report current levels in kiloamperes in the various circuits, the numbers also represent the percentage of the sharing, making it easier to follow the process. Since many standards for surges impinging on SPDs (at the service entrance) are still based on an 8/20 μs current waveform, we will also show one example of the energy deposition in the SPDs when such an 8/20 μs surge is postulated.

The surge currents are modeled using the EMTP Type 60 Slave Source. Using the "Freeform FORTRAN" expression, any surge current waveform that can be expressed as a closed-form equation can be used as signal source in the main EMTP program. The equations for the 10/350 μs and 8/20 μs waveforms with a 100 kA peak are respectively (1) and (2) below:

10/350 μs: $$I(t) = [I_p/\eta]\,[\exp(-t/\tau_1) - \exp(-t/\tau_2)] \quad (1)$$

where $I_p = 100$ kA, $\eta = 0.9542$, $\tau_1 = 480$, $\tau_2 = 4$

8/20 μs: $$I(t) = A\, I_p\, t^3 \exp(-t/\tau) \quad (2)$$

where $I_p = 100$ kA, $A = 0.01243$, $\tau = 3.911$

(In both equations, t and τ's are in μs; $I(t)$ is in same units as I_p)

F. Influence of Distribution Transformer Simplification

The presence of distribution transformers has been included in many models in the literature, but their characteristics are not the same among authors. Some authors have used a coupled inductor with parasitic capacitor to represent the inter-winding capacitor in the transformer model [12].

While these models are more accurate in studying transformer failure modes due to low-side surges, for our main focus which is current dispersion among available paths, we have chosen the simple model postulated in [8] of a simple inductor to represent the winding. As results show, the presence of a transformer at the far end of a daisy-chain low-voltage distribution system does not have considerable effect on the results. Therefore, we felt justified in adopting the same transformer model as described in [8] for all of our circuit configurations.

G. Simplifying the Circuit for Modeling

The circuit impedances have been modeled in EMTP using discrete components. The wiring between buildings and from building to transformer is modeled as a series inductance with the following parameters: R = 1 mΩ/m and L = 1 μH/m, typical values for aluminum conductors of 34 mm² cross section (#2 AWG) [13]. The SPDs are modeled using the EMTP Type 92 Nonlinear Element model. Because of the simplified nature of the model, we performed parametric variations on factors such as line impedance and transformer inductance, and found that their influence on current dispersion is not large enough to warrant concern on the somewhat arbitrary values we have postulated in the baseline scenario.

IV. MODELING RESULTS

In this section, we present selected results of EMTP runs for each of three TN or TT system configurations with points of lightning termination next to the distribution transformer ("first" case) or at the opposite end of the transformer ("last" case), for a total of seven scenarios. We postulated a separation of 100 m between buildings and 20 m from the transformer.

For each scenario, a pair of figures is given. The first figure of each pair is a schematic showing the configuration and point of stroke, together with indications of the peak current values in the circuit branches. The second figure of each pair shows selected current waveforms, generally currents leaving the house by way of the earthing electrode and the service conductors. Note that the peaks can occur at different times so that the sum of peak branch currents shown on the figures, Kirkhoff notwithstanding, is not always exactly zero.

A. TN-Radial, strike on one of the buildings

A distribution transformer supplies three buildings in a radial arrangement where all the service drops originate at the pole where the transformer is installed (Figure 3). This configuration is a typical U.S. residential configuration. The lightning stroke is postulated to terminate on the earthing system of one of the three buildings. Figure 4 shows the current waveforms.

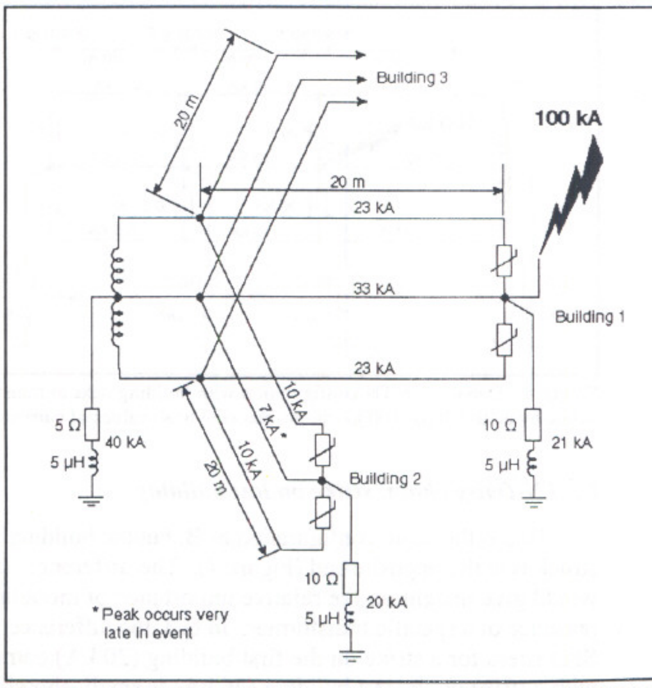
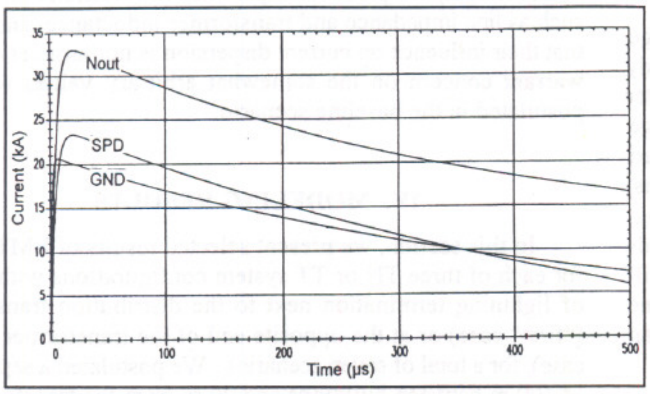


Figure 3 - Radial TN configuration with three buildings supplied by one distribution transformer, one building struck by a 10/350 μs, 100 kA surge, showing peak values of currents shared among available paths.



SPD - Current into each line of service drop, through SPDs
GND - Current into local building earth electrode
Nout - Current into neutral conductor of service drop

Figure 4 - Waveforms of currents leaving Building 1, as defined in Figure 3, for a 100 kA, 10/350 μs surge terminating on the building earthing system

B. *TN-Daisy chain, strike on first building*

Another typical arrangement uses a distribution transformer which supplies several buildings along a street, with short service drops from the poles to each building. The lightning stroke is postulated to occur upon the first building, next to the transformer. Figure 5 shows the circuit configuration and the peak currents in the branches; Figure 6 shows the waveforms of the currents leaving the building. Note the early peak of the current in the neutral -- directly connected to earth at the pole, thus a lower inductance compared with the inductance of the line conductors that include the transformer winding.

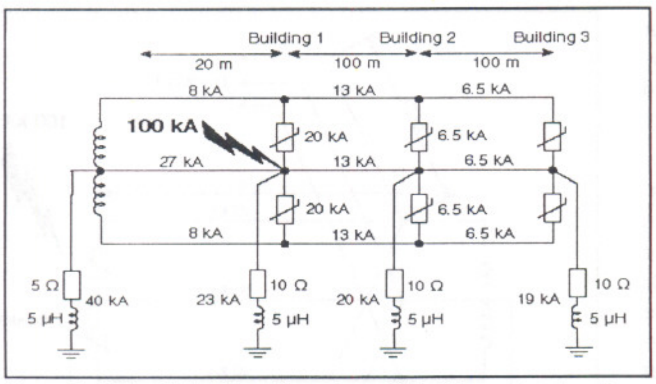
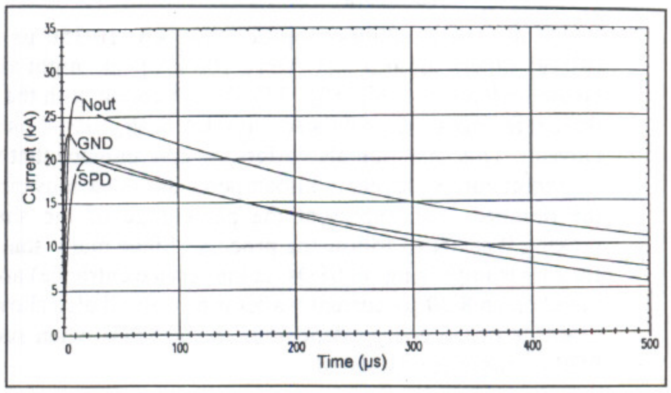


Figure 5 - Daisy chain TN configuration with building next to transformer struck by a 10/350 μs, 100 kA surge, showing peak values of currents

C. *TN-Daisy chain, strike on last building*

This is the same configuration as B, but the building being struck is at the opposite end (Figure 7). The difference, if any, would give insight on the relative importance of modeling the presence of a specific transformer. In fact, the difference in the SPD stress for a strike on the first building (20 kA) compared with a strike on the last building (26 kA) is small, showing the small effect of transformer position. In the building earthing, where there are no SPDs, a strike on the last building produces 42 kA compared with 23 kA for a strike on the first building.



SPD - Current into each line of service drop, through SPDs
GND - Current into local building earth electrode
Nout - Current into neutral conductor toward the transformer earth

Figure 6 - Waveforms of currents leaving Building 1, as defined in Figure 5, for a 100 kA, 10/350 μs surge terminating on the building earthing system

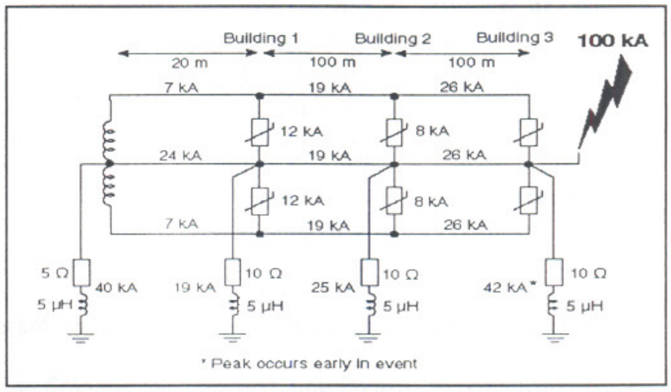
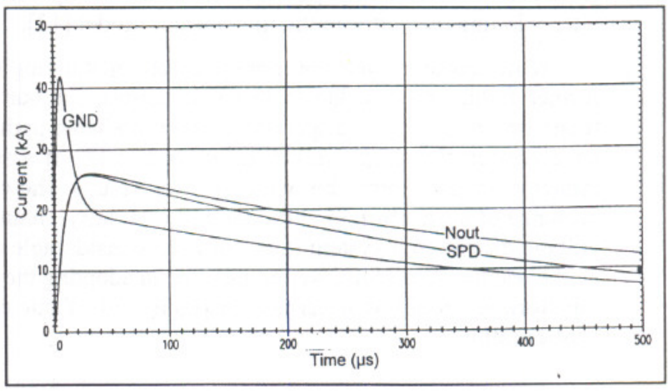


Figure 7 - Daisy chain TN configuration with building at opposite end of transformer struck by a 10/350 μs, 100 kA surge, showing peak currents



SPD - Current into each line of service drop, through SPDs
GND - Current into local building earth electrode
Nout - Current into neutral conductor toward the transformer earth

Figure 8 - Waveforms of currents leaving Building 3, as defined in Figure 7, for a 100 kA, 10/350 μs surge terminating on the building earthing system

For Figures 7-8, the greater distance (inductance) from the transformer earth electrode forces initially more current flow in the building earth than in Figures 5-6 for a closer transformer.

D. TT 2-wire, strike on first building

A transformer (single-phase or one phase of a three-phase transformer) supplies several buildings along a street, with short service drops from the street poles to each building. The lightning stroke is postulated to occur upon the building next to the transformer (Figure 9). The waveforms of the currents leaving the building are shown in Figure 10.

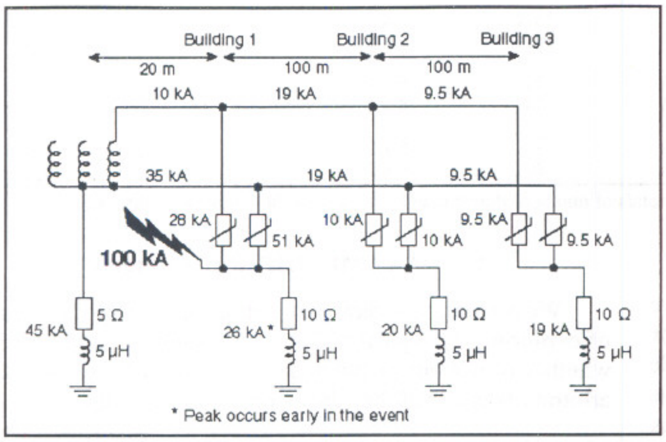
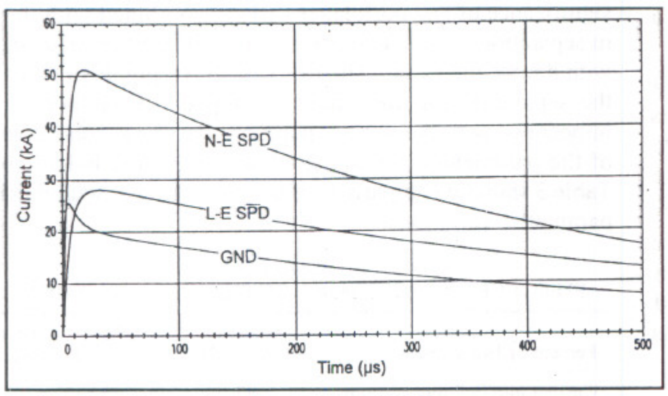


Figure 9 - Daisy chain TT 2-wire configuration with building next to distribution transformer struck by a 10/350 µs, 100 kA surge



N-E SPD - Current through neutral-to-earth SPD
L-E SPD - Current through line-to-earth SPD
GND - Current into building earthing electrode

Figure 10 - Waveforms of currents leaving Building 1, as defined in Figure 9, for a 100 kA, 10/350 µs surge terminating on the building earthing system

E. TT 2-wire, strike on last building

The configuration is the same as in D, but the lightning stroke is postulated to strike the building at the opposite end of distribution line, away from the transformer (Figure 11). Figure 12 shows the waveforms of the currents leaving building 3.

F. TT 4-wire

Where end-users are provided with three-phase service, a three-phase transformer supplies several buildings along a street, with short service drops from the street poles to each building. In this configuration, the difference from a 2-wire, single-phase service is that four conductors instead of two are available as exit paths for the lightning current postulated to have struck the building of interest (first or last building).

To conserve space, we do not present two pairs of figures for that configuration, but the summary of Table 1 includes the current values computed by EMTP for the two scenarios in that configuration.

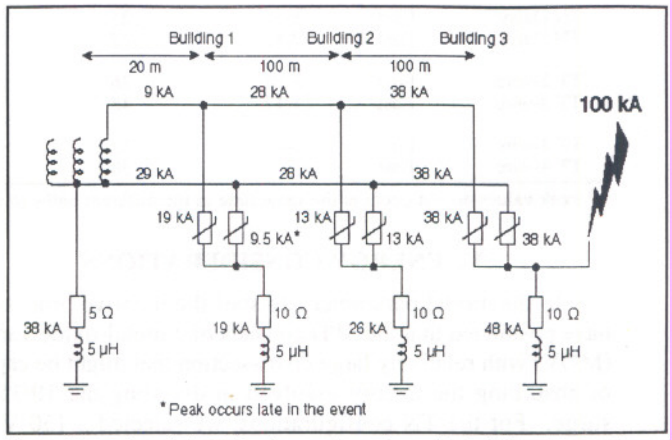
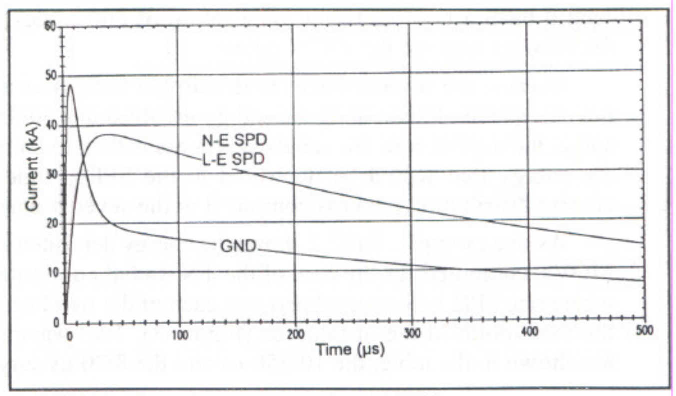


Figure 11 - Daisy chain TT 2-wire configuration with building at opposite end of distribution transformer struck by a 10/350 µs, 100 kA surge



N-E SPD - Current through neutral-to-earth SPD
L-E SPD - Current through line-to-earth SPD
GND - Current into building earthing electrode

Figure 12 - Waveforms of currents leaving Building 3, as defined in Figure 11, for a 100 kA, 10/350 µs surge terminating on the building earthing system

G. Comparison of the seven scenarios

Results of our model runs for the seven scenarios (Table 1) show that, contrary to some speculations or intuitive considerations on the sharing among service conductors, the earthing connection of the building does not carry anywhere near the 50% quoted in some proposed standards [9].

The most severe stress, for the parameters postulated, occcurs in the neutral SPD in Scenario D (TT 2-wire, first building struck) for which the configuration has the lowest impedance to earth and thus invites the largest share. Other scenarios generally reflect primarily the number of service-drop wires available for the current exit.

TABLE I
SUMMARY OF CURRENT SHARING AMONG CONDUCTORS FOR THREE CONFIGURATIONS IN SEVEN SCENARIOS FOR 100 kA STROKE

Configuration: Distribution system	Scenario: Building being struck	See figures	Most severe but rare - Building being directly struck Currents leaving building via building earthing and service conductors (peak kA or %) *				Less severe but more frequent Currents impinging onto adjacent buildings (peak kA or %)	
			Building earthing	Service neutral	SPD in the neutral	SPD in the lines	SPD in the neutral	SPD in the lines
TN Radial	Any	3-4	21	33	N/A	23 x 2	N/A	10 x 2
TN Daisy	First	5-6	23	27	N/A	20 x 2	N/A	7 x 2
TN Daisy	Last	7-8	42	26	N/A	26 x 2	N/A	8 x 2
TT 2-wire	First	9-10	26	N/A	51	28 x 1	10	10 x 1
TT 2-wire	Last	11-12	48	N/A	38	38 x 1	13	13 x 1
TT 4-wire	First	--	22	N/A	32	16 x 3	5	5 x 3
TT 4-wire	Last	--	38	N/A	20	20 x 3	6	5 x 3

* Peak values do not occur at the same time in the different paths so that totals of numbers shown may be more than the impinging 100 kA peak.

V. ENERGY CONSIDERATIONS

In the model parameters, to start the iterative process, we have postulated that the SPD consists of a metal-oxide varistor (MOV) with relatively large cross-section that might be capable of absorbing the energy involved in diverting the 10/350 μs surge. For the TN configurations, we selected a 150 V rms rating, and a 300 V rms rating for the TT configurations. For the cross section, we postulated an area equal to ten 20-mm discs in parallel because available manufacturer's data [14] readily gives the 20-mm disc characteristic. Such a combination would have a total one-shot joule rating of 800 joules for a 10/1000 μs surge in the 150 V rating.

Because we suspect that even this array of ten discs might not be capable of dissipating the energy involved in a 10/350 μs surge, the next step in this iterative process is then to compute the energy that would be deposited in the SPDs, under the current distribution patterns computed in the seven scenarios.

As one example, Table 2 shows the energy deposited in the MOVs, computed for the case of the TN Radial configuration where one SPD is connected between each of the two lines and the earth point of the installation (Figure 3). Two waveforms are shown in the table, the 10/350 μs and the 8/20 μs surges.

TABLE 2
ENERGY DEPOSITION IN SERVICE ENTRANCE MOVS
FOR THE TN RADIAL CONFIGURATION AND TWO WAVEFORMS

Waveform	Rating for ten 20-mm discs	Energy deposition	
		Direct strike	Nearby strike
10/350 μs	800 J	3500 J	840 J
8/20 μs	800 J	200 J	80 J

For the 10/350 μs waveform, the rare scenario of a direct strike (energy deposited is 3500 J) would require a very large varistor at the service entrance -- four times the ten discs we postulated, while this ten-disc array would be sufficient in the less rare scenario of a nearby strike (840 J).

On the other hand, if we were to stay with the 8/20 μs as a postulated waveform, even the large 100 kA peak would be handled with comfortable margin by the ten-disc array. These results provide quantitative data which we will discuss further under the Cost/Risk heading.

VI. PARAMETRIC VARIATIONS

We performed several parametric variations for the purpose of exploring the typical "what if" questions, and also to show whether or not our postulated values might be viewed as too arbitrary because of their influence on the results.

A. Line impedance and building separation

The value of 1 μH/m for conductors has long been used by many researchers as a typical value. To investigate the significance of that postulated 1 μH/m combined with the 100-m separation, we ran two cases, one with half the value and one with double the value. The first case corresponds to either half the separation for the same unit impedance or half the unit impedance with the same separation. For the second case, one of the parameters is doubled while the other is held constant. Table 3 shows a comparison of the baseline case with these two parametric variations.

TABLE 3
EFFECT OF LINE IMPEDANCE ON SHARING - TN DAISY LAST

Percent of 100 kA peak	Baseline 100 m, 1 μH/m	Half baseline	Double baseline
Current into building earthing	42	32	53
Current in service neutral	26	27	25
Current in SPDs	26	26	25

This comparison shows no significant differences in the current sharing for each of the three available conductors (there are two line conductors, each with an SPD) when the postulated unit impedance or building separation is varied over a 1:4 range, so that our selection for these two parameters should not be a matter of concern.

B. Transformer pole earthing resistance and building earthing system resistance

By their relationship, these parameters can be expected to have an influence on the outcome. In the baseline case, we postulated a 5-Ω pole earthing resistance and a 10-Ω building earthing resistance. Table 4 shows the comparison of the baseline case with the reversed relationship between the pole earthing resistance and the building earthing resistance.

TABLE 4
EFFECT OF POLE EARTHING/BUILDING EARTHING - TN RADIAL

Percent of 100 kA peak	Baseline 5-Ω pole, 10-Ω bldg.	Reverse baseline 10-Ω pole, 5-Ω bldg.
Current in building earth	21	31
Current in service earth	33	14
Current in SPD	23	22

Indeed, the relationship of pole versus building earthing resistance has a significant effect on the current carried by the neutral, but not on the current carried by the SPDs. This is particularly true, although not obvious in the table (where only the peak values are shown, reflecting the inductive effect on initial current dispersion), for the tail of the 10/350 μs waveform where the subsequent sharing is determined by the resistance ratios [6], [12].

C. Length of circuit (more buildings along a street)

Postulating a greater number of buildings along the daisy chain, while keeping the resistance of the building earthing constant, can be expected to offer a path of lesser impedance to the currents exiting the building, because of the greater number of available earth electrodes. Table 5 shows the effect of going from 3 buildings (baseline) to 9 buildings, still with the last building being struck.

TABLE 5
EFFECT OF NUMBER OF BUILDINGS IN TN CIRCUIT ON SHARING, DISTANT HOUSE STRUCK

Percent of 100 kA peak	Baseline 3 buildings	9 buildings
Current in building earth	42	42
Current in service earth	39	14
Current in SPD	26	27

Again in this case, a difference is noticeable in the neutral conductor current, but not in the SPD current. Thus, this parametric variation shows that the number of buildings between the building being struck and the distribution transformer, while affecting the neutral current, does not affect the stress imposed on the SPDs in this TN configuration.

VII. DISCUSSION

A. Effect of postulated waveform

While we have adopted for our baseline the 10/350 μs waveform, many SPD standards cite an 8/20 μs or a 4/10 μs surge waveform as an SPD capability requirement [15], [16] or as a surge environment description [17]. To explore the effect on sharing of the stroke current with different waveforms, in particular during the initial part of the 10/350 μs surge where inductive effects dominate for the circuit parameters selected, we made one run with a 8/20 μs surge instead of the 10/350 μs used in the baseline case of the TN Radial. Predictably, given the small difference between a 10 μs and an 8 μs rise time, little effect was noted in the sharing during the first 20 μs. Of course, the energy involved for the total surge duration is another matter, already discussed in Section V.

B. Selection of SPDs

If the design objective is to provide protection for a direct stroke to the building (a topic which will be the subject of the cost/risk analysis mentioned below), the SPDs must be selected with sufficient current-handling capability to survive the surges resulting from the postulated surge.

Alternate proposals have been made to use a spark gap as service entrance SPD. Such a gap must then be capable of clearing the resulting follow current, which may be an issue for systems having a large available fault current, such as the 10 kA rms specified for U.S. installations [3], [18].

We have made one run with a spark gap model instead of a varistor model. From the sharing point of view, the difference is small, which can be readily explained by the fact that inserting in the lightning current paths a varistor with a limiting voltage of 1 kV or so, or a gap with an arc voltage of 100 V or so, should have a very small effect on the sharing because of the many kilovolts developed by the lightning current flowing in the inductances and resistances of the line conductors and earthing connections.

C. Cost/Risk Analysis

An essential aspect of designing an effective surge protection system is to perform a cost/risk analysis involving the probability of a building being struck by a large surge, such as 100 kA, versus the cost of ensuring survival of the service entrance SPDs to be installed. This analysis introduces factors such as the flash density in the locale, the randomness of the distribution of the flashes over the area of attraction of the building which depends in part on the height of the building, and the distribution of peak amplitudes of lightning strokes. For instance, [11] reports statistics [19] whereby an 80 kA amplitude is exceeded for less than 5% of the strokes. Such an analysis is beyond the scope of our paper, but it must be mentioned here to keep the situation in perspective and remind developers of SPD application guides or standards to include it in their recommendations.

D. Applying field experience to standards

The ultimate test of the usefulness of a standard is that equipment manufactured according to that standard has satisfactory field experience, while being produced at a cost that users are willing to accept. Very low field failure rates can be seen as overdesign, high failure rates obviously as underdesign. It is the dream of one of the authors to establish a clearinghouse where field experience of manufacturers could be collected and applied to optimize the definition of the environmental stress [20]. Given the competitive nature of the industry, this is likely to remain only a dream. However, many U.S. utilities are now offering to their customers the installation of a meter-base adapter SPD. The field experience for these SPDs might be collected from utilities -- with safeguards on proprietary information -- and become an input to the process of moderating some proposals for high-stress requirements, on the basis of the successful field experience of SPDs with capabilities below those implied in proposed standards.

VIII. CONCLUSIONS

Modeling several typical TN and TT configurations of neutral earthing practices and scenarios of lightning strike point provides insights on significant effects, which should lead to more effective application of surge-protective devices (SPDs).

1. A direct lightning stroke to a building can produce high stresses on the service entrance SPDs as the earth-seeking current will exit in part by way of the utility service drop. SPDs in that building will be strongly affected, while nearby buildings will be impacted by much lower surge currents.

2. The major difference among the scenarios we have modeled appears in the current carried away from the building by the neutral conductor.

   - In a TN system where the neutral is bonded to earth at the service entrance, there is no SPD in that path, and thus no concern about neutral SPD integrity. In typical residential single-phase U.S. systems, the line SPDs can carry about 25% of the stroke current.

   - In a TT system where there is an SPD in the neutral path, a single-phase two-wire configuration can have 50% of the stroke current being carried by the neutral SPD. In a three-phase TT system where there are four conductors to carry away the stroke current, the neutral SPD can carry up to 30% of the stroke current.

3. For line conductors, the difference reflects primarily the total number of conductors in the system, which can be two, three or four. The earth-seeking lightning current will divide (but not always equally) among these conductors. While the initial dispersion (during the first 20 µs) is controlled by the inductances, the later dispersion is controlled by the relative values of the earthing resistances.

4. If the postulated stroke is as high as some of the proposed standards suggest, modeling the behavior of service entrance SPDs of the type installed in increasing numbers by U.S. utilities shows that some failures could be expected. As field experience seems to indicate an acceptable failure (if any) rate, one can question the need for imposing such severe requirements, unless the mission of the facility is such that even a rare failure would be unacceptable.

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Discussion

P. Hasse and **J. Birkl** (Dehn + Söhne, 92318 Neumarkt, Germany): The problem of lightning current distribution depending on the different kinds of current distribution systems and under the influence of possible variables has been very clearly represented with this contribution.

The curve development gained by the EMTP program matches very well with the simulation calculations conducted in Germany with the PSPICE program.

In respect to the described results, however, a few additions are necessary from our point of view:

1. Section III. G. and VI. A.:

The induction of a conductor system always results out of the geometric system of the slip-knot consisting of coming and going conductor. A separation in coming conductor impedance and going conductor impedance is not realistic.

In particular, in case of multiple conductor cables it is to be observed that in case of the same flow direction of the lightning current, the inductivity of the total system differentiates to a single conductor system.

2. Section VI. Schedules 3 - 5:

In particular, in case of longer connecting cables between buildings and between building and transformer a change in waveform of the surge flowing through these cables. Only the observance of the amplitude factor of the flowing lightning currents is not sufficient. In this situation, it would be more meaningful to consider also the energy distribution.

3. Section VII. B.:

For decades now, in Europe, spark gap arresters, with a mains follow current quenching capability, are being installed successfully as lightning current arresters at the building entrance. In particular, the high down-lead ability and impulse-time shortening of the rest impulse make a favourable co-ordination with connecting MOV's possible.

4. Section VII. 4:

The lightning protection necessity for a system, as well as the deduced lightning protection class resulting from this, is described in IEC 1662. At the same time the lightning protection class is determined, the layout of the lightning protection system necessary lightning parameters are defined (IEC 1312-1). A deviating layout of protection measures on the basis of test currents 8/20 μs is therefore not permissible.

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François D. Martzloff (National Institute of Standards and Technology, Gaithersburg MD) :

We thank the two authors of the discussion for taking the time to review our paper and provide comments aimed at broadening the consensus on the subject. In particular, we are delighted to hear that our computations based on EMTP matches very well with the simulation calculations conducted in Germany with the PSPICE program. With respect to their specific four comments, we offer the following responses, preceded by the general remark that the purpose of our computations was to reveal the differences among various ***postulates*** for the circuit configurations, as influenced by the grounding practices for the neutral in effect in different countries, rather than the precise values for a particular set of parameters. We emphasize the concept of postulate, lest we fall into the trap of taking electromagnetic environment standards as an exact duplication of reality, while they are in fact only the documentation of an industry consensus on how reality might be represented [1].

1. Section II G and IV A

Indeed, the concept of inductance is based on a conductive loop that carries the current in a closed circuit. However, in the circuits we postulated for our computations, the conductors in question — phase and neutral — may be considered as one part of the closed circuit and might be called "coming," according to the terminology used by our colleagues, while the path consisting of the earth, the distant return to the cloud, the lightning channel, and even the down-conductor (see Section III A) may be considered as the other part of the loop and might be called "going" conductors.

For this reason, we represented in our figures the phase and neutral as if they were separate, while in reality they can be at some finite distance from each other (the so-called "open wiring" used in overhead lines) or in close vicinity, as in the case of an underground cable or an overhead "triplex." Aware of the differences, we started our computations for a given, postulated configuration — always the same for the variations in the neutral grounding — but performed a parametric variation in the line inductance (taking twice or half the value used in the baseline), as stated in the subject paragraph, to convince ourselves that the influence on dispersion is not large enough to cause concern. Space limitations for the paper prevented us from providing detailed numerical results — as they also do here — and we were hoping that our simple statement that we did consider the issue and found little effect on the differences ***among neutral grounding scenarios*** might be acceptable.

2. Section VI 3 to 5

One of the results of our computations based on a postulated 10/350 μs waveform was to show that, for the distances we selected, the impedance of the cable between buildings — and therefore their length — has only a small influence on the long-term current waveform and dispersion among conductors, which is primarily influenced by the postulated values for respective earthing resistances. With the values selected for inductances, the current dispersion is substantially affected by the respective inductances only for the first 20 or 30 μs.

We agree that additional information might be conveyed by reporting the energy distribution along the complex path of the lightning current, but here again space limitations intervene. We can offer the response, however, that in view of the large values of the earthing resistance compared to the other resistances in the circuit — cable resistances and dynamic "resistances" of the varistor or gap SPDs — the latter are not a priority in reporting results. The EMTP model of course has the capability of reporting any set of parameters if "asked" to do so.

For specific applications of one type or another of SPD technology, the EMTP model can provide detailed information on the energy that will be deposited in these SPDs for the various scenarios to be considered.

Section VII B

We are aware that in some countries, the installation of a service-entrance arrester is a common practice, and that gapped arresters may be used for that purpose. The issue is one of cost vs. benefits for an arrester designed for the large lightning currents associated with a rare direct strike to the building. We have observed, during our interactions with several international or IEEE technical committees, that consensus has not been reached on what current waveform and peak amplitudes should be considered when making the cost vs. benefits analysis. Depending on the nature of the installation, the cost vs. benefits equations are different. Several proposals for "risk analysis" are currently under consideration in several standards-developing bodies, and consensus is clearly not achieved at this point. This lingering question is addressed in our response to the fourth and last comment after the present one.

Our intention in making the remark on available fault current in the second paragraph of this section was not to contest the successful European experience cited by our colleagues, but to alert our readers at large to the importance of considering that requirement. The point that mains follow-current quenching capability is not trivial was confirmed in a comment by one of the reviewers of our forthcoming paper, "Gapped Arresters Revisited" (scheduled for presentation at the IEEE-PES Winter 1998 Meeting and later publication in *IEEE Transactions*).

Section VII 4

We are aware of the work conducted in the IEC Technical Committee 81, the responsible body for development of the IEC 61662 and IEC 61312 publications. We are also aware of some discomfort among other parties concerning the stipulations from that body which might result in less than fully cost-effective solutions to the question of real necessity for protection against worst-case scenarios. The footnote offered in support of our introductory remark applies here also. There is a long and successful history of application of surge-protective devices based on a postulated 8/20 μs surge current waveform, using the appropriate values of amplitudes. For that reason, we included in our paper as alternate postulate the 8/20 μs waveform. From the point of view of IEC TC 81, their recommendations might be considered normative and thus non-negotiable, but protection measures in the various countries are typically determined — if at all — by bodies that promulgate codes based on a consensus drawn from experience based not exclusively on TC 81 recommendations. Therefore, the use of the term "not permissible" appears somewhat strong in the context of voluntary or even regulatory practices.

In conclusion, we appreciate the opportunity to present more detailed background information on our computations and underlying postulates, thanks to the discussion contributed by our colleagues.

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1. Long ago, my mentor, Frank Fisher, taught me this concept which I recite in the following terms, well worth repeating in the present context: "The criterion of validity of an environment standard is not so much how closely it duplicates reality but rather how well equipment designed in accordance with this standard perform in the field. If equipment designed in accordance with the standard perform well in the field, while equipment ignoring the standard do not perform well, the chances that the standard be a good standard are pretty good."

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