Surging the Upside-Down House: Measurements and Modeling Results

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Significance
Part 4 – Propagation and coupling of surges
Part 5 – Laboratory measurements

Electronic equipment with two input ports - power and communications - can be exposed to damaging differences of voltage between the two ports during surge events. To identify and quantify the significant variables and their effects during surge events in residential or commercial facilities, a representative configuration of the circuitry in a residence (metallic cold water pipe, power and grounding conductors, telephone and coaxial cable TV wiring) was set up in the laboratory, under the name of "Upside-Down House."

To evaluate the threat of surges impinging upon an actual installation, surges of various types, as defined in standards covering AC power circuits and communications circuits, can be injected at selected points of the Upside-Down House. Typical surge-protective devices (SPDs) can be placed at suitable locations of the Upside-Down House, corresponding to a variety of real-world exposure scenarios. Preliminary experimental results of two exposure scenarios were reported in a PQA'94 paper (see pdf file "Upsdown surging"). Additional measurements and parametric variations are reported here to characterize the impedance of the various components of the wiring system and the source impedance of the resulting overvoltages appearing between the ports.

SURGING THE UPSIDE-DOWN HOUSE: MEASUREMENTS AND MODELING RESULTS

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Abstract

Electronic equipment with two input ports - power and communications - can be exposed to damaging differences of voltage between the two ports during surge events. To demonstrate real-world scenarios, a replica of the wiring system in a typical residence was installed in the laboratory. This paper reports selected results from many measurements, and presents the corresponding numerical modeling, thereby leading to mutual validation of the two processes. Two exposure scenarios for producing differences of voltages between the power and data ports of appliances are illustrated. Additional measurements and parametric variations are reported here to characterize the impedance of the various components of the wiring system and the source impedance of the resulting overvoltages appearing between the ports.

Summary

To identify and quantify the significant variables and their effects during surge events in residential or commercial facilities, a representative configuration of the circuitry in a residence (metallic cold water pipe, power and grounding conductors, telephone and coaxial cable TV wiring) has been set up in the laboratory. The circuits have been suspended from the laboratory ceiling to de-couple them from nearby metallic masses and move them out of the way of laboratory personnel, hence the name "Upside-Down House".

To evaluate the threat of impinging surges in an actual installation, surges of various types, as defined in standards covering AC power circuits and communications circuits, can be injected at selected points of the Upside-Down House circuits. Typical surge-protective devices (SPDs) can be placed at suitable locations of the Upside-Down House, corresponding to a variety of real-world exposure scenarios. Preliminary experimental results of two exposure scenarios were reported in a PQA'94 paper [Key & Martzloff, 1994][3].

In this paper, the next step of the research is presented. Using the Electromagnetic Transient Program (EMTP)[4] [EPRI, 1989], computations were made for several combinations of applied surges, SPD characteristics, and wiring configurations. The results of these computations closely track the measurement results, thereby providing mutual validation.

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1. *Contributions from the National Institute of Standards and Technology are not protected by U.S. Copyright.*
2. *The initial part of Mansoor's modeling work was performed while at the University of Texas.*
3. *Limited references are given at the end of this paper, shown in the text as [Name, year].*
4. *Certain commercial instruments and software packages are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the instruments or software identified are necessarily the best available for the purpose.*

Physical Replica and Measurements

Figure 1 shows a simplified three-dimension diagram of the wiring of the Upside-Down House. The wiring includes a representative service entrance (revenue meter and service panel, not shown) and is made of typical components according to U.S. residential wiring practice, with the possibility of various combinations of branch circuit lengths and topology. As discussed later in the paper, the worst case scenario of shifting reference voltages for a combination of power and communications system occurs when the two services enter at opposite ends of the residence. In the Upside-Down House, this situation would require that the wiring replica be stretched out in a straight line. However, because the measurements of interest need to be performed at both ends of the straight line, they could not be performed simultaneously by the same instrument. Consequently, the ideal straight line was folded on itself, so that both ends of all lines (① and ④ in Figure 1) were accessible within a few centimeters

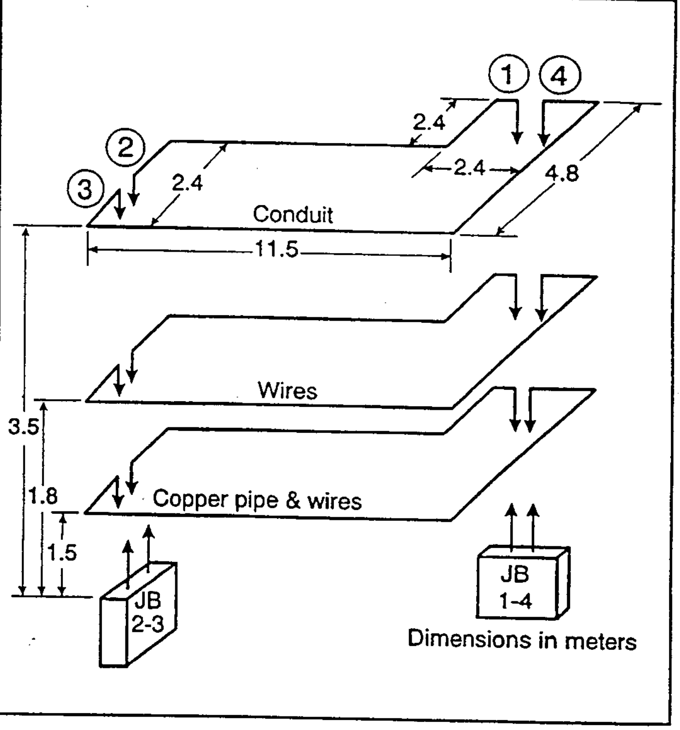

Figure 1
Three-dimension schematic of the wiring of the Upside-Down House

The conduit, wires, and copper pipe are suspended by insulators from the metal roof of the building (equivalent to "earth"). In the lower tier, wires are lashed to the copper pipe, maintaining an average distance of 16 mm from the copper surface. In the middle tier, designated as "loose", the wires are 300 mm away from the pipe. The upper tier (conduit) is not used here.

The simplified straight-line configuration of a residence wiring with utilities entrances at opposite ends has been folded in two halves: Section 1-2 and Section 3-4. See Figure 2 for justification of this folding. Each end is accessible in junctions boxes (JB) at working level in the room for easy connection of surge generators, SPDs, and instrumentation.

This configuration raises the question of possible flux interaction between the two halves of the line, which would introduce errors in the measurements. The question is how much of the flux radiated from one half of the loop, say the Section 1-2, would be coupled into the other half, Section 3-4, and induce spurious voltages.

To answer that question, a computation was made of the magnetic flux induced in a rectangular loop of which one side is the conductor carrying the surge current, and the perpendicular sides extend from the conductor. The classical equations for this computation and the resulting plot are given in Appendix A.

Figure 2 shows a plot of the voltage induced into the rectangular loop, normalized for a given waveform and a unit length of conductor, as a function of the radius (long side) of the rectangular collecting loop. While Appendix A shows this plot with semi-logarithmic scales for greater resolution near the conductor, Figure 2 uses linear scales to emphasize the very rapid rise of induced voltage near the conductor and the small additional gain after a few meters.

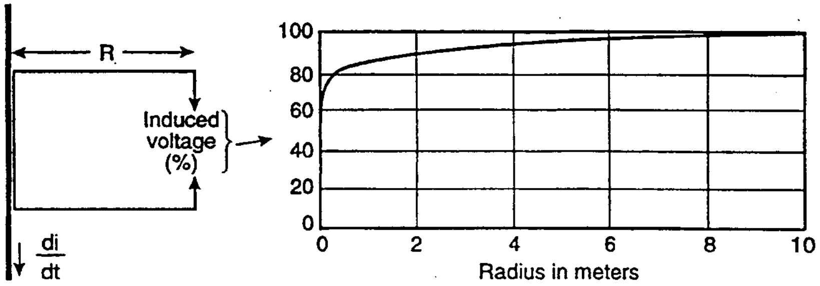

Figure 2
Voltage induced in rectangular loop of unit width and length R, adjacent to a conductor carrying a current with rate of rise di/dt, in percent of total voltage induced for R = 10 m

Most of the voltage is collected within the first few centimeters away from the surge-carrying conductor, and little additional voltage is collected by extending the rectangle past a 2-m radius.

The plot of Figure 2 yields two practical conclusions:

1. The distance between the two halves of the Upside-Down House replica (2.4 m) is sufficient to ensure very little coupling between the two halves. This small coupling justifies the folding of the straight line into a hairpin-shaped loop.
2. Common wisdom on electromagnetic compatibility (EMC) practices recommends routing cables as close as possible to any available ground plane or additional grounding conductors. However, if "close to" were interpreted by an installer as a few centimeters, all the expected benefits from the "close" installation would be lost – in other words, it is not very effective to attempt minimizing induced voltages by casual routing of unshielded cables "near" the ground planes. More effective means would be required -- beyond the scope of this paper.

This paper presents results from two scenarios. The first scenario is the situation created by a two-port appliance connection involving the power supply system and the telephone system, such as a Personal Computer (PC) with modem. Similar topologies would be produced by a Fax machine or an answering machine. Not treated here, but again a similar topology, would be the case of a TV receiver connected to the power system and to a cable TV system.

The second scenario is the situation created by two appliances powered by two separate branch circuits and linked by a communication cable. This situation is often encountered where attempts are made to supply the PC with "clean" power from a branch circuit separate from the "noisy" printer branch circuit.

The worst case of the first scenario occurs when the power service entrance and the telephone service entrance are located at opposite ends of the building. (Figure 3)[5]. Postulating a surge impinging on the telephone system, the telephone service entrance SPD and test point, called "Network Interface Device" (NID) in the telephone industry, will perform its intended function and divert the surge toward the "best" grounding point. This best grounding point -- with lowest impedance to earth -- is the multi-grounded neutral in the building rather than the dubious or nonexistent grounding rod at the telephone entrance. Thus, most if not all of the impinging current flows via the copper pipe or a dedicated grounding conductor, which are of necessity spanning the length of the building. This surge current then induces a voltage in the loop formed by the long copper pipe (or the dedicated, but equally long grounding conductor) and the long telephone line between the NID and the PC. This voltage then appears between the two ports of the PC with modem.

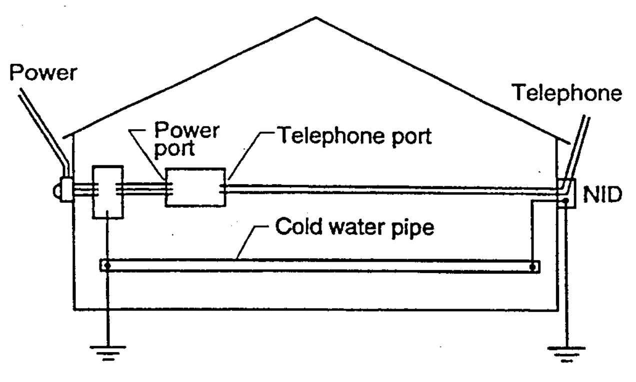

Figure 3
First scenario - One appliance connected to two different systems

As a worst-case scenario, the telephone and power service entrances are postulated to be at opposite ends of the building. This is not the preferred practice, but it is not uncommon.

The surge impinges on the telephone entrance and seeks the multi-grounded neutral via the Network Interface Device (NID) and water pipe.

The second scenario, Figure 4, is another example of intended behavior producing unexpected side effects. The commendable attempt to separate the power supply to the two appliances can involve provision of a line-to-ground SPD at the end of one branch circuit, while none is provided at the end of the other branch circuit. Because the two appliances have a signal-reference point which is generally the chassis, (connected to the equipment grounding conductor -- the "green wire"), the surge current returned to ground in the branch circuit outfitted with an SPD will create a shift in the reference voltage of the corresponding appliance. This shift creates a difference of voltage with respect to the signal reference of the other appliance -- a difference which appears at the data ports of the PC and printer.

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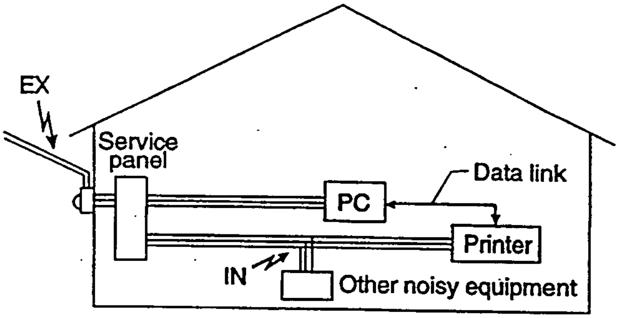
[5] *After completion of the test series and publication of this figure in the referenced Key & Martzloff paper, comments were received from G.J. Bagnall and E.H. Marrow that the NID grounding methods shown do not meet the current National Electrical Code requirements. The Code prohibits the use of an external ground rod as the only ground for communications or bonding more than 1.5 m (5 ft) away from where the pipe enters the premises. However, many such installations, which met the Code at the time of installation, still exist; for the purpose of illustrating the mechanism of voltage induction with widely separated service entrances, the geometry of the loop is applicable. The authors acknowledge and appreciate this clarification.*

Figure 4
Second scenario - Two appliances connected to two branch circuits

One appliance (the PC or the printer) is postulated as provided with a line-to-ground SPD at its power port (built-in or as plug-in by the user), while the other has none.

Surges can be expected as injected externally ("EX") or internally ("IN").



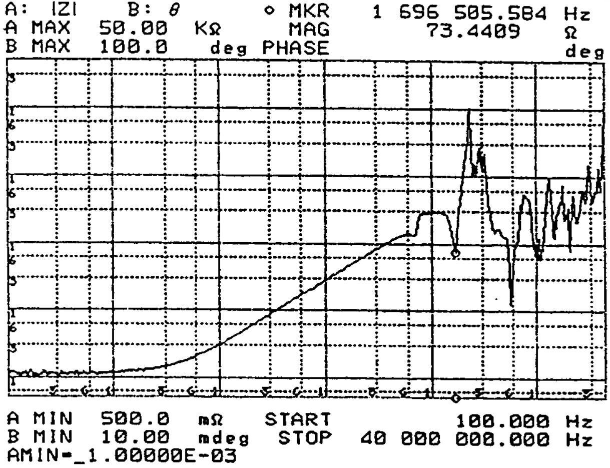
Impedance Measurements

To provide the necessary parameters for numerical modeling reported in the paper, or to be made by other researchers, impedance measurements were made with an impedance analyzer (Hewlett-Packard 4194A).[6] These measurements included the impedances of the various power and communication circuits in the Upside-Down House, as well as combinations of power and communication wiring loops. For the first scenario, the impedance was measured for a loop consisting of half the copper pipe and half the telephone line as shown in Figure 3. The Section 1-2 of the telephone line is routed 0.3 m above the corresponding Section 1-2 of the copper pipe. The end-points ② (Figure 1) are jumpered and the impedance is measured at end-points ① between telephone wire and copper pipe. Figures 5 and 6 show the impedance and the effective resistance of this loop as a function of frequency.

Figure 5
Impedance as a function of frequency for the loop formed by the copper pipe and telephone line in the first scenario.

The "loose" telephone line, Section 1-2 (see Figure 1) is routed 0.3 m above the corresponding Section 1-2 of the copper pipe.

The logarithmic plot sweep starts at 100 Hz until 40 MHz. For simplicity, only the scalar impedance was requested from the automatic instrument plot ("A: |Z|" on the plot legend, from a minimum of 500 mΩ to a maximum of 50 kΩ, auto-ranging on a logarithmic plot).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A: |Z|      B: θ          ○ MKR    1 696 505.584 Hz
A MAX   50.00   KΩ          MAG        73.4409    Ω
B MAX   100.0    deg  PHASE                       deg

A MIN   500.0   mΩ    START            100.000 Hz
B MIN   10.00   mdeg   STOP  40 000 000.000 Hz
AMIN=_1.00000E-03
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6. *The measurements reported in this paper have been made with instruments, transducers and attenuators for which the cumulative uncertainty should not exceed 5 to 6%. Given the process of applying the measurement results to the response of the Upside-Down House when exposed to environment characteristics that are at best known within an order of magnitude, this level of uncertainty does not affect the conclusions. Numerical modeling results and some automated print-out plots are reproduced here as delivered by the instruments, including a number of digits that are not really significant, but are only reproduced for the sake of authenticity.*

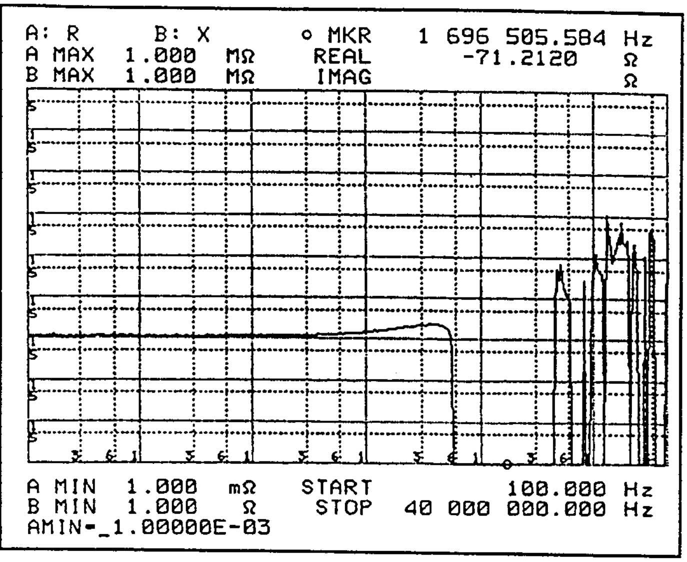


Figure 6
Effective resistance, including skin effect, as a function of frequency for the loop formed by the copper pipe and telephone line in the first scenario.

The logarithmic plot sweep starts at 100 Hz until 40 MHz. For simplicity, only the resistance has been requested from the instrument ("A: R " on the plot scales).

The apparent collapses of the resistance at higher frequencies are caused by the parallel capacitance of the circuit, resulting in phase angles greater than 90° which the instrument interprets as a negative resistance.

For the second scenario, the loop is formed by the two branch circuits and the communications link between the two appliances, as shown in Figure 4. In this case, only the impedance characteristics of the branch circuit conductors are involved. Figures 7 and 8 show respectively the impedance and effective resistance of one power branch circuit (Section 1-2). The measurements were initially conducted to serve as input for computer modeling of the Upside-Down House. As it turned out, the modeling was done by using built-in routines of the EMTP program to provide more flexibility for the parametric variations. Nevertheless, the availability of these impedance data will be useful if other models based on lumped R-L-C should be used by other researchers. In particular, the impedance characteristics of the branch circuit wiring will be useful when studying coordination of cascaded SPDs, another topic of research for the Upside-Down House [Annotated Bibliography, 1995].

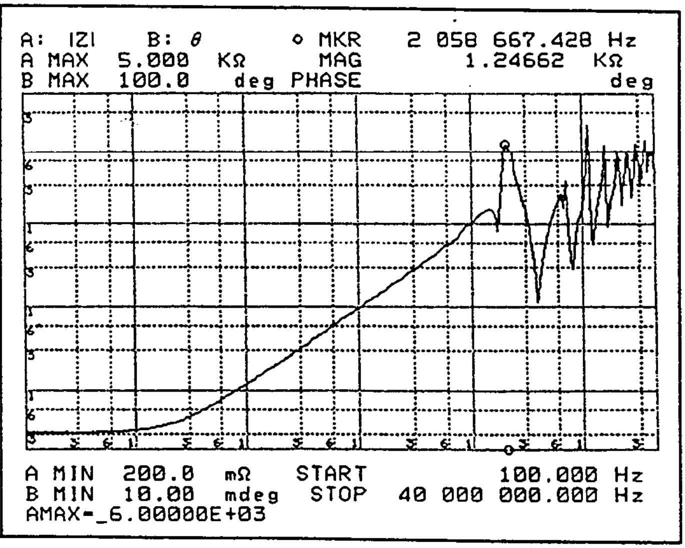


Figure 7
Impedance as a function of frequency for one power branch circuit supplying one of the two appliances of the second scenario.

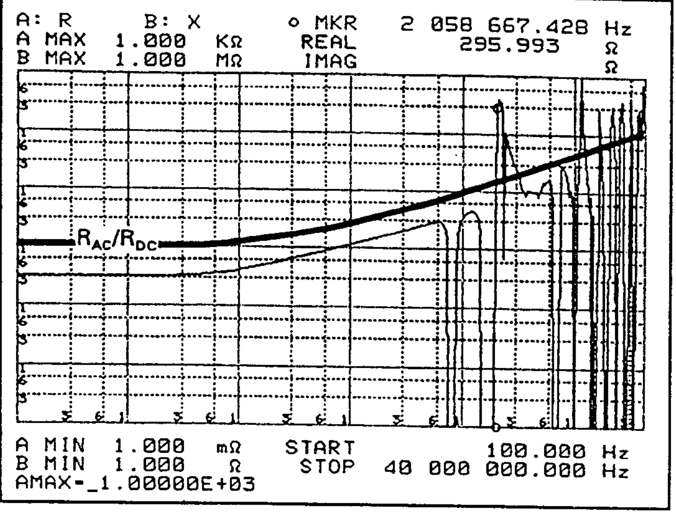
The nonmetallic jacket line, Section 1-2 is used for this measurement. The ends 2 (line and neutral) are joined and the impedance is measured between line and neutral at ends 1.

The logarithmic plot sweep starts at 100 Hz until 40 MHz. For simplicity, only the scalar impedance was requested from the automatic instrument plot ("A: |Z|" on the plot scales).

Figure 8
Effective resistance, including skin effect, for one power branch circuit supplying one of the two appliances of the second scenario.

The logarithmic plot sweep starts at 100 Hz until 40 MHz. For simplicity, only the resistance has been requested from the instrument ("A: R " on the plot scales).

The line overwritten on the instrument plot shows a typical normalized rise in effective resistance (R_{AC}/R_{DC}) resulting from the skin effect, as computed with the EMTP.



These measurements clearly demonstrate that inductance is the dominant factor over the frequency range corresponding to the applied surges.[7] The skin effect in the conductors is only a second order factor (R on Figure 8 is 10 Ω at 1 MHz, while Z in Figure 7 is 100 Ω at 1 MHz). The skin effect is significant for damping subsequent oscillations, but not for significantly limiting the propagation of the surges. It is also worthwhile to compare the measured effective resistance, which includes skin effect, to the skin effect computations embedded in the EMTP model. In Figure 8, a curve has been manually overwritten on the resistance plot, showing the ratio of R_{AC}/R_{DC} computed with EMTP, where R_{AC} is the effective resistance including skin effect and R_{DC} the pure resistance.

Transfer (Source) Impedance

Because the voltages developed between appliance ports result from electromagnetic induction in the loop formed by the two systems, the transfer impedance of this coupling is of interest. Measuring only the open-circuit voltage between the two ports does not quantify the overvoltage threat. Any SPD that would be considered as a mitigation means for this scenario would "see" that transfer impedance as the impedance of the surge that the SPD would have to mitigate. To quantify that parameter, the classic technique of impedance matching was applied. Decreasing impedances were connected between the ports under measurements, until the recorded voltage reached half of its open-circuit value. The corresponding impedance is then equal to the "source impedance" – the interaction between the two systems. In this manner, information is provided for the design of any mitigation means that could or should be applied.

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[7] *The frequency spectra of common surge test waveforms is given in [Standler, 1989]. With the exception of the Electrical Fast Transient Burst (EFT), all spectra show at least 80 dB down at 1 MHz.*

Table 1 shows the values of this source impedance for the loose and lashed configurations of the first scenario. It is interesting to note that the loose configuration produces higher open-circuit voltages than the lashed configuration, but that the "source impedance" of the loose configuration is greater than that of the lashed configuration.

Table 1
Effective source impedance of surge occurring between power and telephone ports

Telephone wire and copper pipe configuration	Measurement across loaded circuit		Nominal effective source impedance (Ω)
	Load (Ω)	Voltage (V)	
Loose (300 mm apart)	none *	5040	300
	546	3200	
	303	2560	
Lashed (16 mm apart)	none *	1300	120
	303	800	
	120	620	

* This measurement was made for a 75 A/μs surge current rise time in the copper pipe, using a differential probe with 10 kΩ input impedance.
Adding a load of 10 kΩ between the two ports (total load impedance now 5 kΩ) did not change substantially the measured voltage.

Numerical Modeling with EMTP

Concurrently, a numerical model of the wiring was developed with the EMTP code for the equivalent parameters of the circuit, as measured in the real Upside-Down House. The selection of the EMTP code for this modeling is based on its widespread use among researchers and engineers in the power systems area. While it was initially developed for modeling transmission systems, it can be applied successfully, as demonstrated in this paper and various other papers, for end-use circuitry. Its ready availability for easy replication, corroboration or expansion of our results among our colleagues made the EMTP desirable. Other researchers might prefer other codes, and would be welcome in applying them to the Upside-Down House data base for even wider acceptance of shared conclusions.

The 'Line Constants' subroutine of EMTP was used to generate various line models which were subsequently used in the main data file to compute the response of the circuit to various surge waveforms. A time step of 0.01 μs was used for the EMTP simulation. Measurements taken with the impedance analyzer could have been directly used in the EMTP code. However, to provide greater flexibility for further parametric variations of circuit configurations, the Line Constants routine was used to generate the line models. This is only one example of the computational power available through the EMTP code.

The surge current waveforms postulated (from the measurement recordings) in the two scenarios were generated in EMTP using the Type-15 double-exponential current source with a damping resistance in parallel. Experimentally-recorded waveforms of surge current were digitized and, using the least-square fitting technique, parameters for the Type-15 source were determined. The source parameter values, along with other necessary input data for simulation of the Upside-Down House components are given in Appendix B.

With the "Freeform FORTRAN" expression of the EMTP code, any surge current waveform that can be expressed as a closed form equation can be modeled. This capability provides a means for analyzing circuit response to various other surge waveforms now under consideration by standards-writing organizations. In view of the prime importance of initial rate of rise -- over gross rise time and ultimate peak -- shown by the results, this capability will provide useful guidance in assessing the validity of postulated surge environment characteristics.

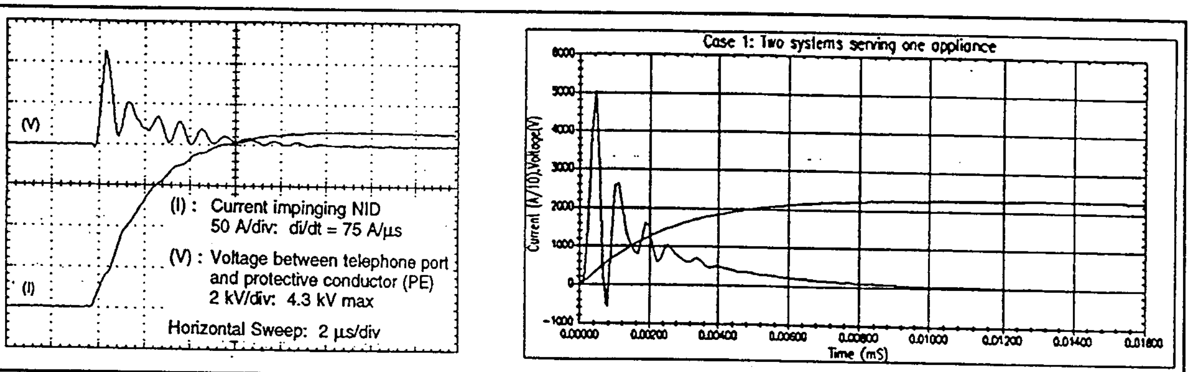
Comparing measurement results and EMTP results

First exposure scenario: Two systems serving one appliance

In this scenario, a modem-equipped PC is connected by its power port to a branch circuit, and by its modem port to the telephone service of the house. For a worst-case scenario, the power and telephone services enter the house at opposite ends (Figure 3). A surge is impinging on the telephone service entrance, and is diverted to the facility ground (typically the multi-grounded neutral system) by the telephone "Network Interface Device" (NID) installed at the point of entry. The surge current flows in the copper pipe, radiating a magnetic field that induces a voltage in the loop formed by the copper pipe and the telephone line between the entrance and the modem port of the PC. This voltage in effect appears between the modem port and the equipment-grounding conductor of the power port of the PC.

For this test, the applied surge was that obtained when applying the output of a KeyTek 801+ surge generator delivering a standard surge, CCITT 0.5/700 µs to the pair of telephone wires at the entrance, and returning from the grounding point of the Upside-Down House. The generator was set for a particular peak value of this well-defined waveform; however, the relatively large impedance of the loop presented to the surge generator resulted in the surge current waveform shown in the oscillograms of Figure 9, with a rate of rise of 75 A/µs. As we will see from the results, shown later in Tables 4 and 6, the crucial parameter is the ***initial rate of current rise,*** not the amplitude or duration of the current surge. This fact makes any conclusions on the level of the threat directly dependant on the rate of rise, a parameter not well known in the real environment, compared to arbitrary, well-defined test waveforms. For this reason, the complete study includes some parametric variations, a few of which are presented later in this paper.

Figure 9 shows the recording of the voltage measured between the power port and telephone port, as well as the EMTP-computed voltage for the same current waveform. The similarity of the two oscillograms is remarkable. The only (small) difference appears to be the damping; this damping is of course the result of the effective resistance of the circuit, including skin effect and current diffusion. During the EMTP modeling, several representations were used for the effective resistance, showing small differences in the damping. The oscillogram of Figure 9 was obtained for a frequency-dependent model of the resistance.



Measurement from the Upside-Down House

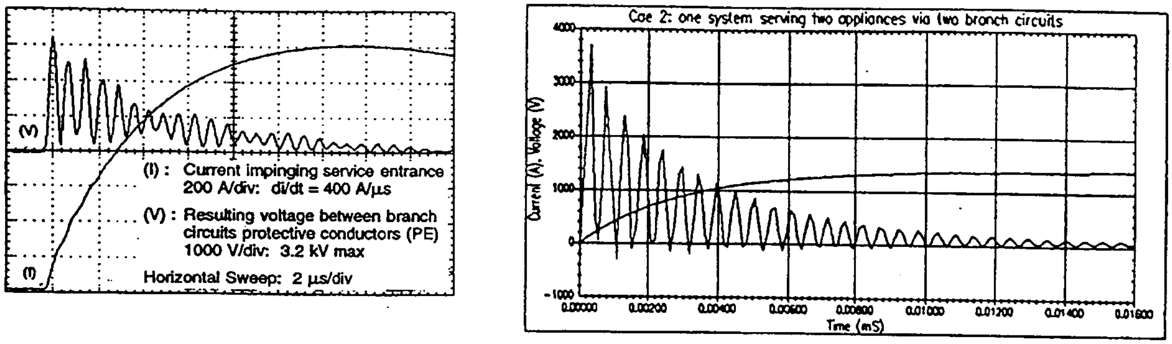
Plot from the EMTP model

Figure 9
Voltages measured and computed between power and telephone ports for the first scenario

Second exposure scenario: One system serving two appliances

In this scenario, a PC and the associated printer are connected by the usual communications cable, and each is powered by a separate branch circuit. This situation is often encountered when a printer is shared among several users, or when an installation has been deliberately configured to provide a separation of the "clean" branch circuit supplying the PC from the "noisy" branch circuit supplying the printers and other peripherals (Figure 4). As a worst-case scenario, it is postulated that the PC power supply includes an SPD with line-to-ground protection (either built-in or provided as a plug-in addition by a careful, surge-conscious user), while the printer is postulated to have no line-to-ground SPD protection.

In an actual situation, the surge could occur internally on the "noisy" circuit, or occur from the outside. In the example of Figure 10, the surge was applied line-to-neutral at the service entrance, with an initial current rate of rise of 400 A/µs, the result of injecting a surge of 1400 A peak and 8 µs rise time. Figure 10 shows the recording of the voltage measured between the two data ports of the printer and the PC, as well as the voltage computed by EMTP. As in the first scenario, the measured and the simulated oscillograms exhibit essentially the same characteristics, with only minor differences in damping.



Measurement from the Upside-Down House *Plot from the EMTP model*

Figure 10

Voltages measured and computed between the two data ports for the second scenario

Expansion of the scenario matrix through numerical modeling

To illustrate the capability of simulation, several parametric variations were performed with the EMTP model. The following tables provide examples for the two scenarios.

Parametric Variations for First Scenario

Table 2
Effect of Distance from Telephone Wire to Copper Pipe on Voltage between PC-Modem Ports

Distance (m)	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0
Voltage (kV)	3.16	3.94	4.34	4.62	4.87	5.07	5.63	5.58

The voltage increases as the separation of the telephone wire from the copper pipe increases, but at a slower rate -- not surprisingly, the same observation was made in the discussion of Figure 2.

Table 3
Effect of Distance from Power to Telephone Entrances on Voltage between PC-Modem Ports

Distance (m)	10	20	30	40	50	60	80	100
Voltage (kV)	1.25	2.34	3.66	4.34	5.86	7.33	10.2	12.9
Highest frequency of overvoltage (MHz)	5.0	3.3	2.5	1.5	1.2	1.0	0.66	0.59

This table shows, predictably, the linearity between the separation between the two service entrances. The effect should be a strong incentive to providing entrances for the services at the same point of a building, a classic recommendation in EMC guidelines.

Table 4
Effect of Surge Current Rate of Rise on Voltage between PC-Modem Ports

Surge current rate of rise (A/μs)	25	50	75	100	150	200
Voltage (kV)	1.20	2.27	4.34	5.98	10.9	20.2

The increase in voltage is approximately proportional to the increase in the rate of rise. This should be expected because the circuit is essentially linear and, as discussed earlier, the inductive coupling of voltage in the loop is directly related to the rate of flux variation in the loop.

Parametric Variations for Second Scenario

Table 5
Effect of Branch Circuit Lengths on Voltage between Data Ports of PC and Printer

Length of PC branch circuit (m)	16			10	16	20
Length of printer branch circuit (m)	10	21	30	21		
Voltage between ports (kV)	4.41	3.69	3.55	2.27	3.69	4.25

This table presents the effect of combining different branch circuit length for the two appliances. The major effect is still the presence of only one SPD connected line-to-ground, but different length of the branch circuits introduces yet another variable.

Table 6
Effect of Surge Current Rate of Rise on Voltage Data Ports of PC and Printer

Surge current rate of rise (A/μs)	200	300	400	500	600	800
Voltage (kV)	1.82	2.78	3.69	4.72	5.77	8.34

In spite of the presence of a nonlinear element in the circuit (the SPD connected at the power port of one appliance), the proportionality of voltage to the surge current rate of rise is maintained.

Conclusions

1. The close similarity of results from measurement and modeling provides mutual validation and gives confidence in the broad parametric studies.
2. The observed values of the overvoltages could be a threat to appliance survival; however, in the absence of reliable information on appliance immunity (which could eventually be provided by the manufacturers or obtained by extensive testing), especially between different system ports, no firm conclusion can be drawn at this time concerning the risks.
3. The most crucial factor for overvoltages is the initial rate of current rise of the surge, not rise time and peak. This fact is a challenge to the development of standards describing the expected surge environment, where arbitrary and always picture-perfect waveforms are defined by the peak amplitude and rise time, not by actual initial rate of rise.
4. Parametric information has been developed to allow defining other scenarios. The authors invite their colleagues to participate in a data base development.

Acknowledgments

This project was made possible by the joint support of the National Institute of Standards and Technology (NIST) and the Power Electronics Applications Center (PEAC). NIST granted a sabbatical to Martzloff, allowing him to experiment with his concept of the "Upside-Down House." This Upside-Down House was installed at PEAC, with support of the Electric Power Research Institute, as a permanent facility of the Power Quality Testing Network. Numerical modeling was initially performed at the University of Texas (Austin) with support from PEAC, and pursued further at PEAC. Asif Jakwani performed the parametric variations at the University of Texas.

As noted in the reference section, many researchers have contributed to the general body of knowledge on surge occurrence, propagation, and mitigation. These cumulative contributions are acknowledged here, but not recited exhaustively.

The authors explicitly invite their peers to conduct similar experiments and computations to build a consensus on the threat represented by shifting reference voltages. Such a consensus would be an important step toward the development of standards for system compatibility in the not-quite-yet-defined surge environment.

References

Annotated Bibliography (Unpublished, on-going): Bibliographic information available to the authors includes over one hundred publications, and is still growing, on the subject of surge occurrence, propagation, and mitigation. For the sake of space conservation, these references are not recited here except those having direct bearing on the paper. The authors will gladly share upon request a working copy of this bibliography, and would welcome suggestions for additional listings.

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Appendix A
Voltage Induced in a Loop Adjacent to the Surge-Carrying Conductor

The flux density B at a distance R from a thin linear conductor of infinite length (R small compared to the length of the wire) carrying a current I is given by:

$$B = \mu_0 I / 2\pi R$$

For the case of a loop involving the telephone wire and the copper pipe (Scenario 1, Figure 3), the surge current in the copper pipe is approximated by:

$$I = A(e^{C1t} - e^{C2t})$$

Using least-square curve-fitting on the measured current surge waveform, we find the constants of the equation $A = 235$, $C1 = -1600$, and $C2 = -400\,000$. We assume that for the Upside-Down House dimensions, small compared to the wavelength, the surge is propagated instantaneously around the circuit. The usual criterion for "small" in comparison with the wavelength is a ratio of 1/8, which holds true here for a wavelength of 300 m at 1 MHz, compared to the 18 m of each half of the loop. According to Faraday's Law, the total emf induced in a closed circuit is equal to the time rate of change of the total magnetic flux linking the circuit. In symbolic form:

$$v = - d\phi_m / dt$$

The total flux through a circuit is equal to the integral of the normal component of the flux density B over the surface bounded by the circuit. The total magnetic flux is:

$$\phi_m = \int B \cdot ds$$

Combining the two equations, and substituting the expression for the surge current waveform, we get the peak value of the voltage induced in the loop of unit length and radius 10 m:

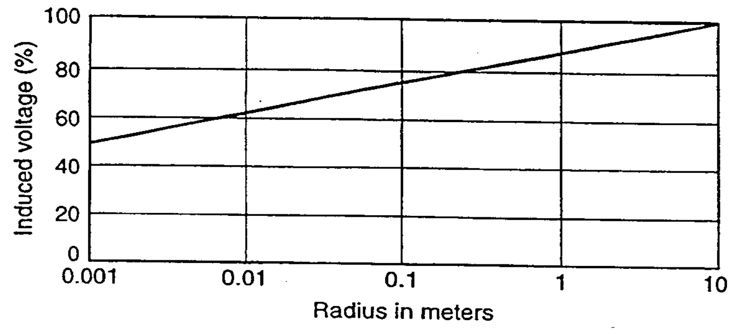
$$V = [\mu_0 A/2\pi]\ (C2 - C1)\ ln\ 10/R_0 \Big|_{R_0 \to \varepsilon}$$

Thus, the normalized voltage induced in a rectangular loop of unit length and radius R, in percent of the total voltage induced in a loop of 10-m radius (Figure A1), is:

$$\%\ of\ voltage\ induced = [ln\ R/R_0 + ln\ 10/R_0] \times 100\%$$

Figure A1
Normalized voltage induced in a rectangular loop of unit length and radius *R*, in percent of the total voltage induced in a loop of 10-m radius

This plot has been used to draw the linear plot of Figure 2, showing the small increment of the induced voltage beyond a 2-m radius.



Appendix B
EMTP Input Data for Simulation of the Upside-Down House

B1 - First exposure scenario: Two systems serving one appliance

Surge Current Model: EMTP Type 15 double-exponential source. The parameter values are: Amplitude 235, Coefficients: C1 = -1600, C2 = -400 000.

Line model: The EMTP 'Line Constants' auxiliary routine was used to determine the impedance parameters of the telephone wire - copper pipe configuration. The line models that were used for the simulation include frequency dependent, constant parameter traveling wave, and coupled R-L-C lumped model at 500 kHz [EPRI, 1989].

Instead of using impedance measurements results directly in the simulation (as was initially planned when making the experimental measurements), the 'Line Constants' routine was used to allow variation in line configuration for parametric studies. No noticeable difference was observed in the voltage computed between the two ports for the different line models. The input data used for the 'Line Constants' program are:

Telephone wire pair: diameter 0.5 mm each; 0.25 mm insulation; $R_{DC} = 87.8\ \Omega/\text{km}$
Copper pipe: 22.23 mm outside diameter; 19.05 mm inside diameter; $R_{DC} = 0.0161\ \Omega/\text{km}$

For the loose configuration, the distance between the center of the telephone wire pair and the copper pipe was 300 mm. In contrast, for the lashed configuration, it was only 16 mm -- but not zero, see the plot A1 of Appendix A

B2 - Second exposure scenario: Two appliances powered by two branch circuits

Surge Current Model: EMTP Type 15 double-exponential source. The parameter values are: Amplitude 1400, Coefficients: C1 = -50, C2 = -340 000.

Surge-Protective Device Model: The SPD connected at the end of one branch circuit is modeled as a piecewise linear resistance using the Type-92 nonlinear device model in EMTP. The I-V characteristic of the device is obtained from experimental measurements on the actual device and interpolation from typical characteristics for such devices, as shown in Table B1.

Table B1
I-V Characteristic of SPD connected Line-to-Ground at end of one branch circuit

Amperes	0.001	0.01	0.1	1.0	100	1000	10 000
Volts	199	218	239	263	316	360	380

Line model: The input data used for the 'Line Constants' program are:
Conductor diameter = 2.05 mm; insulation thickness = 1.0 mm; $R_{DC} = 5.21\ \Omega/\text{km}$