

**THIRD INTERNATIONAL CONFERENCE ON POWER QUALITY:
END-USE APPLICATIONS AND PERSPECTIVES**

PROCEEDINGS

PART 1

**OCTOBER 24-27, 1994
AMSTERDAM, THE NETHERLANDS**

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SURGING THE UPSIDE-DOWN HOUSE:
LOOKING INTO UPSETTING REFERENCE VOLTAGES

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Surging the Upside-Down House: Looking into Upsetting Reference Voltages

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Abstract - Electronic equipment with two input ports - power and communications - can be exposed to damaging differences of voltage across the two ports during surge events. Two exposure scenarios of producing such differences of voltages are explained and illustrated by measurements performed in a replica of a residential or light commercial installation of power, telephone, and cable TV wiring. Several mitigation methods are described, and one possible retrofit solution is shown. It is planned that in a further phase of this research, numerical simulation will be performed on a model of the system in order to expand the range of conditions and identify significant variables.

INTRODUCTION

As more and more electronic equipment enter the home and business environment, these often involve a communications port as well as their usual power cord port. In this paper, we will use the term "two-port appliance" or "appliance" for short, being understood that it covers two-port information technology equipment. Examples of such two-port appliances include fax machines, telephone answering machines, personal computers with modem communications or printer connections, and cable-connected TV receivers. Although each of the power and communications systems may include a scheme for protection against surges, the surge current flowing in the surged system causes a shift in the voltage of its reference point while the other, non-surged system reference point remains unchanged. The difference of voltage between the two reference points appears across the two ports of one appliance, or between the communications ports of two appliances linked by a data cable. Depending on the nature of the appliance and its immunity, which is not often defined, this difference of voltage may have some upsetting or damaging consequences. In this paper, we will present just two examples of measurements illustrating the broad variety of possible exposure scenarios.

To identify and quantify the significant variables and their effects, 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, according to U.S. practice. The circuits have been hung from the laboratory ceiling, to decouple them from nearby metallic masses and get them out of the way of laboratory personnel, hence the name "Upside-Down House" given to the project.

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, can be injected at various points of the Upside-Down House circuits. Combinations of surge-protective devices (SPDs) can also be placed at various locations of the Upside-Down House, corresponding to a variety of real-world exposure scenarios. A measurement can then be made of the resulting differences of voltage appearing between the power and communications ports of a single appliance, or between the communications ports of two appliances installed at some location within the Upside-Down House. No conclusions are drawn in this paper on the withstand capability of any particular appliance for this type of threat, because the manufacturers typically do not provide immunity data for any exposure scenario of this type of interaction. However, some of the voltages thus recorded in the Upside-Down House confirm the suspicion derived from field failures that damaging differences of voltages can occur.

APPROACHES

Various mitigation schemes have been proposed by researchers and industry, but not quantified, to remedy upsetting or damaging voltage differences. The most effective is likely to be a fiber optic decoupling inserted in the communications link, but the expense may be objectionable for residential

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and small commercial applications. Close attention to good wiring practices in new installations can offer some degree of remedy, but leaves out all existing installations. Increasing the appliance withstand capability may raise objections of market economics, and may not be practical for some of the voltages that can appear.

Many different exposure scenarios can be identified, even in a simple residential circuit replica. Reference voltage shifts are a multi-dimensional problem in the real world. In this paper, the problem has been simplified to looking at the effect of only two variables: spatial relationships of conductors and effectiveness (including some side-effects) of SPDs. Other important variables that were identified but not addressed at this stage of the research are cited in the discussion section of this paper.

In this paper, two simple exposure scenarios are illustrated: a voltage difference occurs between the ports of an appliance connected to two systems when a surge impinges on one of the systems, and a voltage difference occurs between the communications ports of two appliances powered by separate circuits of the same power system when a surge impinges on that system. In the final discussion, we will look into some ways of expanding these results and perhaps identifying a recurring set of variables that can be mitigated or avoided.

SETUP AND MEASUREMENTS

Measurements reported in this paper describe exposure scenarios leading to voltage differences being developed during surge events across the power and telephone systems of the Upside-Down House, as well as between the signal reference points of two interconnected appliances linked by their communications ports, such as a personal computer (PC) and associated printer. For each case, the Upside-Down House circuits may include some form of upstream surge protection on the telephone service entrance or appliance port, as well as on the power service entrance or appliance port. It is planned to continue the project with similar measurements involving the cable TV port.

Figure 1 shows an isometric of the Upside-Down House configuration, with the arrangement of the three tiers of conductors shown in Figure 2. The power wiring includes two tiers of 3-conductor cable (2.05 mm dia. - #12 AWG, non-metallic jacket),

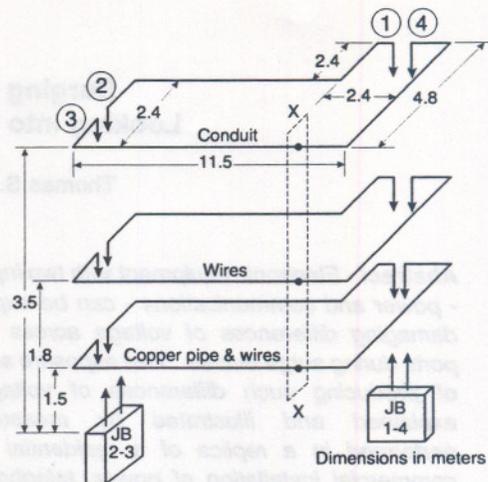


Figure 1 - Schematic representation of the Upside-Down House conductors

typical of residential wiring, and one tier of three 2.05-mm dia. conductors in a steel conduit, typical of commercial or office installation. A 4-conductor, two-pair telephone cable and a 70-Ω TV coaxial cable also run along the 3-conductor power cables.

To illustrate the expected benefit from good wiring practice (cables routed close to the earth reference -- the copper water pipe in the Upside-Down House), one tier has been lashed to the copper pipe. Of course, such idealized practice is not practical, but will serve here as baseline and illustration of EMC principles [Van Deursen, 1993]. In an actual installation, the system would exist in all three dimensions. For the sake of simplification, the Upside-Down House has been reduced to only two dimensions, one horizontal run spanning the house, and the vertical separation indicated in Figure 1. For the purpose of accessing both ends when injecting surges and measuring voltages and currents, the horizontal span has been folded into a hairpin with both ends accessible in junction box JB 1-4.

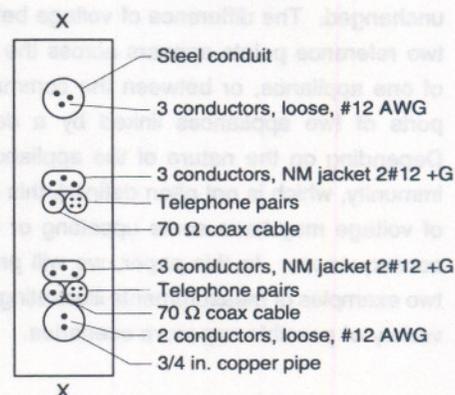


Figure 2 - Vertical arrangement of conductors in the Upside-Down House (X-X of Figure 1)

Junction box JB 2-3 provides access to an intermediate point of the span. Short cable runs (3 m), not shown on the diagram, provide for appliances located close to the service entrance.

Neglecting the vertical separation of the three tiers, the length of the span from end to end is 36 m. (This number is cited to give an idea of the size of the house. Any numerical computations will, of course, use the exact values.) A typical service entrance breaker panel and revenue meter have been provided at one end, upstream of junction box JB 1-4. A Network Interface Device (NID), typical of the U.S. practice for entry of the telephone service, has been installed next to junction box JB 1-4.

By connecting the NID grounding conductor (U.S. code terminology) to one or the other end of the copper pipe, it is possible to represent the scenario where telephone and power service enter at the same end of the house (the preferred practice) or at opposite ends (not preferred, but often encountered). All of the conductors are insulated from the existing earthing arrangement of the laboratory building, making it possible to represent various configurations of the earthing arrangement of the Upside-Down House.

Surges were injected into the power system in the line-to-ground (L-G) mode. Note that the U.S. practice of bonding the neutral and grounding conductors at the service entrance makes any impinging L-G surge become also a line-to-neutral surge. Surges injected into the balanced-pair telephone system were in [tip & ring]-to-ground mode, with the NID acting to divert them to the common earthing point of the laboratory building and Upside-Down House via the copper pipe.

The waveform and amplitude of the injected surges were selected to harmonize with the values cited in industry standards. Because of the different values of the impedance of the various circuits into which the surges were injected, the resulting waveforms reflect the interaction of the surge generator and load impedances and do not exactly duplicate the familiar standard waveforms. Nevertheless, the resulting waveforms are representative and provide examples of the threat and needs of mitigation. These results will provide experimental data for later validation of computer modeling, so that the modeling can then expand the results to other waveforms and circuit impedances.

FIRST EXPOSURE SCENARIO: TWO SYSTEMS SERVING ONE APPLIANCE

In this exposure 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).

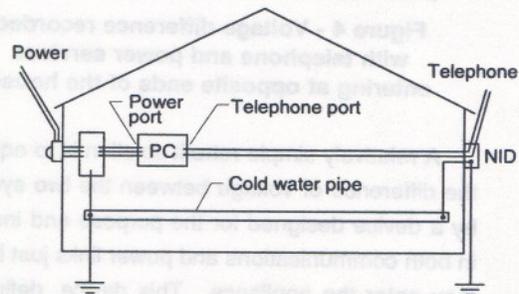


Figure 3 - Power and telephone services entering the house at opposite ends, with PC connected across the two systems

An open loop is formed by the copper pipe, the protective conductor (international symbol "PE") of the branch circuit feeding the PC, and the telephone wires from the NID to the PC. If a surge impinges on the external telephone plant, it is diverted by the NID via the copper pipe to the common earthing point of the house, at the power service entrance. The surge current in the copper pipe creates a changing magnetic flux around the pipe, which induces a voltage in the loop. This voltage will appear between the two PC ports if they are separated by a high impedance (of unknown surge voltage withstand capability).

With the telephone wires routed away from the copper pipe -- which can be expected in residential wiring -- a large loop is formed, embracing the flux produced by the surge current flowing in the copper pipe. With the telephone wires lashed to the copper pipe -- a theoretical more than practical routing -- the loop embraces less flux and one can expect a lower induced voltage across the two ports.

Figure 4 shows the recording obtained with the telephone wire routed away from the pipe. For a rate of change in the surge current of $75 \text{ A}/\mu\text{s}$, a peak of 4.3 kV is induced in the loop and appears between the two ports. For the same injection of current, a peak of only 1.3 kV was noted with the telephone wires lashed to the copper pipe.

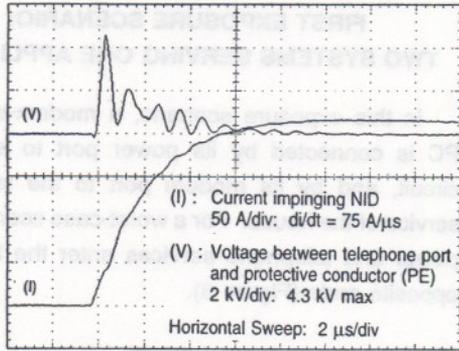


Figure 4 - Voltage difference recorded with telephone and power services entering at opposite ends of the house

A relatively simple retrofit solution is to equalize the difference of voltage between the two systems by a device designed for the purpose and inserted in both communications and power links just before they enter the appliance. This device, defined in IEEE standards [IEEE Std 1100-1992] as a "Surge Reference Equalizer" is commercially available in the U.S. as a unit featuring a plug and receptacle for the power link, as well as a pair of telephone jacks or TV coaxial fittings for the communications link. However, its necessary effectiveness has not yet been quantified in any performance standard.

To illustrate the effectiveness, Figure 5 shows the reduction of the voltage obtained by inserting a typical surge reference equalizer in the power and telephone lines at the point of connection of the PC. The generic design of such a device includes insertion in the two telephone wires of two matched gas tubes, two series resistors, and two silicon avalanche diodes, with a shared earthing reference. Figure 5 shows the immediate clamping effect of the diodes down to 200 V, followed by a further reduction of voltage as the gas tube sparks over.

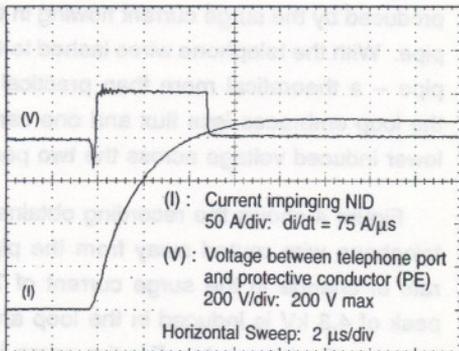


Figure 5 - Mitigation obtained by inserting a surge reference equalizer in the power and telephone lines

A smaller loop would exist if the telephone and power service entered at the same end of the house, the recommended practice. With such a configuration, a reduction in the voltage difference of about 75% of the large loop value was found in the test series. Available space limits the number of records that can be shown in this paper for various combinations, but a more comprehensive report will be prepared and published later.

SECOND EXPOSURE SCENARIO: ONE SYSTEM SERVING TWO APPLIANCES VIA TWO BRANCH CIRCUITS

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 6). Both branch circuits originate at the service panel, but might not have the same length.

In a first case of this scenario, a slight difference may occur in the time of arrival at the two ports of a surge originating outside of the building ("EX" in Figure 6). A greater difference in the time of arrival would occur if the surge were internally generated ("IN") along a branch circuit, propagating directly in that branch toward the printer and in a roundabout path via the service entrance and the other branch circuit toward the PC. With the internally generated surges having steeper fronts than the externally generated surges [Martzloff, 1990], the difference in arrival time would be significant since the voltage spike occurs upon the initial current rise, not at the peak of the current surge.

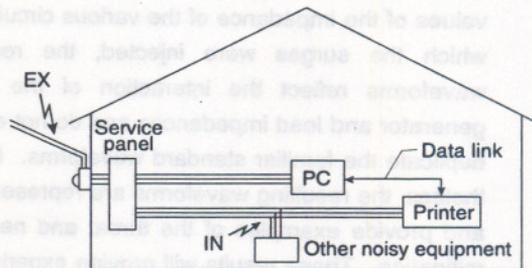


Figure 6 - Personal computer and printer linked by a data cable and powered from two separate branch circuits

As a second case of this scenario, a more severe situation is created by mismatched protective devices at the power ports of the two appliances. A shift in the reference voltage can occur if one SPD provided in either the printer or the PC invites a disproportionate surge current in its PE conductor. These can be built in the appliance or be a plug-in device installed by the user. Such a device, if it includes an SPD connected L-G, will return the surge to the service entrance through the protective conductor PE ("equipment grounding conductor" is the U.S. term) and produce a shift in the voltage of the corresponding chassis. The resulting difference of voltage between the two chassis will be applied across the communications link with possible upsetting or damaging consequences.

The effect of such difference in SPDs is illustrated in Figure 7, for the worst case scenario of one SPD connected L-G in one appliance, and none in the other. An oscillatory difference of voltage peaking at 3.2 kV, with a spike in the nanosecond range, occurs *at the time of the initial rise*, for the 400 A/μs rate of current change corresponding to an 8/20 μs 1400 A peak surge injected at the service entrance. Note the decay of the voltage to a low value *at the time of the current peak*.

DISCUSSION

The two exposure scenarios described in this paper represent the mechanisms most likely responsible for many of reported, but seldom well-documented, field failures of two-port appliances.

The variables considered in these two scenarios are marked in the cells of Table 1, (1) for the first scenario, (2) for the second. The columns in the

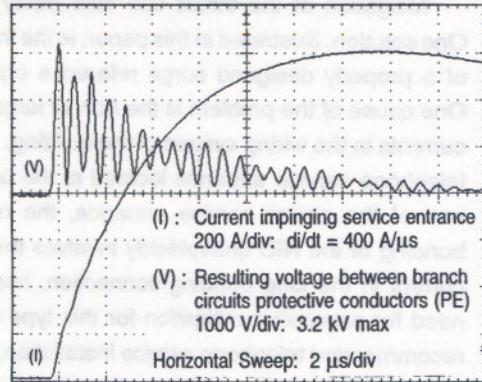


Figure 7 - Difference of reference voltages caused by different protections in the two separate branch circuits

table correspond to spatial variables; only a few of all the possible variables are shown. The rows in the table show a few of the possible variables corresponding to the nature and combinations of the SPDs. This table is a beginning toward defining the multi-dimensional matrix of all possible variables.

Many other variables need consideration, such as the presence of more than two ports in the appliances, different types of ports (serial RS232, Ethernet ...), different power system configurations (single-phase 120/240 V or three-phase 120/208 V in the U.S., three-phase systems in other countries), wiring errors and poor practices, lack of coordination between upstream and downstream SPDs, larger or higher buildings, separate buildings, immunity levels of equipment and consequences of insufficient immunity (upset vs. failure, failure modes), and, last but not least, economic trade-offs. By review of these many variables, it may be possible to identify a limited number of scenarios and thus define effective mitigation means.

Table 1
Two-dimension matrix of variables considered for reference voltage shifts in two scenarios

| Spatial variables SPD variables | Single entrance of services ("ground window") | Multiple points of entrance of power & telephone service | Wiring routing and practices | Other spatial variables of the installation ... |
|--|---|--|------------------------------|---|
| Power service entrance SPD | | (1) | (1) (2) | |
| Equipment power port SPD * | (2) | (1) (2) | | |
| Telephone service entrance SPD | | (1) | (1) | |
| Equipment telephone port SPD * | | (1) | (1) (2) | |
| Other SPD locations and types | | | | |

* Built in the appliance, or external, user-provided plug-in SPD

Mitigation of the threat can take many forms. One solution, illustrated in this paper, is the insertion of a properly designed surge reference equalizer. One cause of the problem is the flow of large surge currents in the wiring system of the building. With a telephone service entrance located at the opposite end of the power service entrance, the required bonding of the NID unavoidably involves the surge current in the long bonding connection, hence the need for preventive mitigation for this type of non-recommended telephone service installation, unless adequate between-ports immunity of the appliance is documented. While these examples of two such exposure scenarios have illustrated the mechanisms, only a computer-driven model might cover all possible combinations of the many variables that could be encountered in all existing or future installations. Hence, it is essential that a comprehensive and well-documented experimental data base be established for validation of the model.

For surges impinging on the power service entrance, the problem is associated with large surge currents flowing in the branch circuits. If the surge current were diverted at the service entrance by a suitable SPD, the problem would be reduced. However, the specification of a "suitable SPD" at the service entrance involves the issue of coordinating cascaded SPDs [Martzloff-Lai, 1992]. The ongoing program of measurements at the Upside-Down House will include measurements and numerical simulation of cascaded SPDs. A joint Working Group of the IEC is developing guidelines for cascade coordination, based on the work of many researchers [Goedde, 1990]; [Standler, 1991]; [Hostfet et al., 1992]; [Hasse et al., 1993].

CONCLUSIONS

1. Quantitative measurements in the Upside-Down House clearly show objectionable differences in reference voltages. These occur even when, or perhaps because, surge-protective devices are present at the point of connection of appliances.
2. Accounting for all the variables may be done in a multi-dimensional matrix, a task for computer analysis, the next step of this project.
3. The analysis should be directed toward obtaining a limited set of typical scenarios resulting from the many combinations of many variables.

ACKNOWLEDGMENTS

The laboratory measurements were made with the kind assistance of Doni Nastasi and Kermit Phipps. Glenn Grotz and Donald Worden provided peer-review comments on the test procedure and interpretation of the results.

This project was made possible by a sabbatical granted by NIST 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.

The authors also 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.

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