A Power Meter Application for the Control of Power Quality and Service

Domenico Lanera
IIT Research Institute
10 West 35th Street
Chicago, IL 60616

James E. Kietzer
Electro Specialties Inc.
P.O. Box 902
Park Ridge, IL 60068

ABSTRACT

Low line voltages and unsafe neutral voltages are infrequent events, but are better known to the public than service quality concerns such as surges and harmonics. A special need to monitor brownouts and neutral voltages spurred the development of a "Smart Switch," a kilowatt-hour power meter add-on device that also controls these problems. It uses a power switch to disconnect both 120-volt lines, then automatically reconnect them. The operation serves to isolate the problem, but also provides a rudimentary but adequate communication with the central office through the customer. The communication is nearly transparent, is of the lowest cost, and requires no cognitive awareness or active involvement on the part of the customer. Twenty prototype units of the Smart Switch were built and field tested, yielding an aggregate of nearly 13 years of field experience. The testing results demonstrate a successful design.

INTRODUCTION

The power quality problem is multifaceted. Bell Laboratories, concerned about commercial power supply to telephone facilities, conducted a noteworthy study [Ref. 1] in the early 1980s that statistically characterized commercial power service quality in terms of line voltage sags, swells, line outages, and impulses. The problem of surges, on the other hand, was recognized long ago and has been studied extensively [Ref. 2]. The problem of harmonics has become serious in recent years because of the increased utilization of non-linear devices in the home.

Low line-voltage conditions lasting for long periods, also known as brownouts, and unsafe neutral voltages are also part of the power delivery and quality issue. A brownout readily incapacitates computerized equipment, but has other effects as well. One of these problems is the stalling of induction motors, such as in refrigerators, leading to overheating and eventually to damage if the faulty power is not removed quickly.

The problem of permanent or intermittent unsafe neutral voltages results from faulted appliances and faulted wiring in the home, or from distribution line grounding and wiring problems. One notorious example is the stray voltage on the neutral in dairy farms, which has been an issue in the last decade [Ref. 3]. The Minnesota Public Utility Commission recently convened a group of Science Advisors to study the problem. Power-frequency ground currents have also come under focus recently as the cause of magnetic field in the home, in the study of human health and magnetic fields [Ref. 4 and 5].

While these problems normally are insignificant or of such low incidence as to warrant no special concern or regulation, there are some circumstances that can enhance their occurrence and severity. It then becomes necessary to seek solutions that will alleviate the problem and provide a warning to the customer, or at least a notification. Conventional approaches such as service power conditioning are not designed to address these concerns and are not economical for residential use. Also, these problems are beyond being controlled from the distribution line itself to the extent that customers are the cause of or contribute to the problems. There is a need for an application on the service drop to monitor and possibly control the problem of long sags and unsafe neutral voltages. Besides developing the means to perform these functions, there are obviously questions of communications, cost-effectiveness, and consumer expectation. The discussion starts with a detailed review of the problem, to establish the needs and basic facts of this application.

REVIEW OF PROBLEMS AND CONCERNS

The results of the Bell Laboratories study [Ref. 1], extrapolated to the general population, say that the probability distributions are such that no more than 50 power sags and no more than 12 power failures per year can be expected for 90% of the population. Furthermore, 90% of these sags will last less than 0.53 seconds, and 90% of the power failures will last less than 4.2 hours. Longer power sags are even more rare. Many anomalous conditions that would have led to power sags are being turned into power outages by reclosers and other protections on the power distribution system. For example, the Bell study noted that one of the effects of lightning is to cause a larger number of power sags than impulses, because the power line surge suppression system, when activated by lightning, temporarily grounds the whole line, a much farther-reaching effect than the lightning impulse itself.

In some circumstances, the problem of brownouts is enhanced by the uniqueness of the line design. This is the case, for example, for power distribution systems in the vicinity of the U.S. Navy's extremely low frequency (ELF) radio transmitters, which are exposed to differential mode, magnetically coupled interference between the phase and neutral wires [Ref. 6 and 7]. One effective mitigation solution is to convert utilization transformer feed from phase-to-ground to phase-to-phase in the vicinity of the transmitter, leaving the distribution system as a multigrounded wye. If a phase wire faults to ground, however, in the presence of a poorly conductive earth, the line overcurrent devices often fail to detect the problem. The utilization transformer, designed in this special application for a *phase-to-phase* feed voltage, ends up being fed with a *phase-to-ground* voltage, 1.73-times smaller. This causes a drop on the residential supply voltage, down to 70 volts or less.

The other concern is with the neutral service conductor being at some voltage other than zero-ground potential. The source for this voltage could be anything and anywhere. Faulty customer appliances, such as corroded heating elements of a hot water heater, can put voltage on the neutral through the plumbing (part of the grounding system). Do-it-yourself customer miswiring, such as inverting the neutral and line connection at a mobile home, can render the whole mobile home electrically hot. Sources outside the residence include poor line grounding. This tends to be a problem more in rural areas because the overall grounding effectiveness is less than in urban areas, where the municipal water system provides an excellent ground [Ref. 8]. The breaking of the neutral conductor in a single-phase, lightly loaded rural line is often undetectable. The voltage drop on the isolated portion of the line neutral system can be significant and unsafe. Other external systems can create neutral voltages either conductively, such as with cathodic protection systems of pipelines, or inductively, such as the Navy ELF radio transmitter that causes ground currents to flow on the power line neutral wire [Ref. 7].

There are some conventional solutions that a power utility can implement in an attempt to control these problems. These include line grounding improvements and service neutral isolation for neutral voltage problems, and under-voltage line monitors for line voltage sags. Grounding improvement results depend on the earth conductivity, and in certain circumstances they quickly become ineffective or very expensive. Neutral isolation is very expensive, and serves only to keep out a problem that is coming in on the line; it does not eliminate a problem originating inside the residence. It is a practice that is restricted in some states. Line monitoring devices have been used together with reclosers or other disconnecting means to monitor line voltage and disconnect the rest of the line if the condition for voltage sag is detected. These devices are backward-looking and forward-acting; this leaves holes in the protection coverage. Closing the holes is very expensive, and could lead, in the extreme, to the installation of a protective device at every service transformer. Furthermore, the devices are subject to false operations; for example, when a single line fuse operates ahead of the controller.

With increased expectations on power service quality, the need has increased for an active and reliable approach to detect the problems at the time when they develop so that corrective actions can be taken. Technological changes and deregulation may bring about some helpful changes in this respect. Efforts in remote meter reading, real-time meter reading, and residential load demand control are likely to result in much smarter hardware and increased capabilities on power distribution systems. This will make possible many beyond-the-meter services such as the one being considered here. However, the costs and benefits are such that the future of these developments remains uncertain.

In contrast, the telephone industry developed a solution to a similar problem long ago. The problem is that of protecting telephone service wires from surges and power-wire contacts, and being able to prevent damage to the plant and prevent hazardous conditions on the customer premises while providing for an automated, self-annunciating method to detect protector failures. The incidence of lightning surges and power-wire contacts on telephone wires is sporadic; however, their presence becomes a problem because of the sheer number of telephone services. The cost to regularly inspect and verify the operation of telephone surge protection devices would have been prohibitive. The telephone protector concept was slowly perfected over the years to meet the need of having a device that safeguards the facilities, but also makes a malfunction manifest when it happens. This is done by shorting the customer telephone wires to ground. The customer becomes, involuntarily, part of the alarm loop, having to report a telephone outage. This approach has been very successful, and has many decades of experience across the whole United States to support it.

These types of concerns led, a few years ago, to the consideration of a special application device to provide an end-point, service entrance power quality check for line voltage sags and for unsafe neutral voltages. The major motivation for this development came from the interference problem and the mitigation measures for a number of utility systems that were being affected by the operation of the ELF radio transmitter in Michigan. The application was to use the customer in this monitoring and control system much as in the case of the telephone protector; this arrangement would provide for the least costly notification system commensurate with the rarity of the problem.

Smart Switch Application

The Smart Switch (SS) is the device that was conceived for this application. It is an apparatus installed at the customer service meter that monitors the line voltage for sags and the neutral for unsafe voltages. Because it is microprocessor based, it is programmed to provide a number of responses; additional measures can also be programmed, depending on the need. The SS is programmed to disconnect the customer service hot lines (interrupting power delivery) if the line voltage sags below a certain level. In response to a neutral voltage, the device is programmed to respond in one of two ways.

When the voltage on the neutral is serious (over 30 volts), the SS will disconnect the customer service. If the problem comes from the customer side, this disconnection will remove the problem and the SS will recognize the customer as the source. If the problem comes from the line, the service disconnection will not remove the neutral voltage; however, the customer will be induced to call the utility because of the service outage, thus implicitly providing the service anomaly announcement.

When the neutral voltage is below 30 volts, the SS is programmed to briefly interrupt the power service, at regular intervals, to attract the customer's attention. The SS recognizes when the problems have cleared and automatically restores power service or discontinues its power interruptions.

The key to the success of the SS is its reliability, so that it responds only to long-lasting, real events, and not to transients or other false situations. Even a small number of false alarms would be a serious nuisance, and would likely cause the rejection of this device. The SS was provided with filtering that causes it to respond only to events lasting more than 30 seconds.

The other major advantage of the SS is that it causes the problem to be self-annunciating, through a customer action. This is similar to the arrangement for telephone protectors. Contrary to telephone protectors, however, the SS is self-restoring. As in the telephone application, the customer participation is a subtle one. While an educational program would be beneficial, the expectation is that the customer would have no cognitive awareness of this device and would not be required to learn anything about it. He would be responding to a power outage, as in the case of a telephone problem.

The SS does not interrupt the neutral conductor continuity. Consideration was given to doing just that, to isolate the neutral voltage problem. However, the problem with neutral voltages is not that simple. Opening the neutral wire at the meter location will not remove the problem if the problem is caused on the customer side, and it is not likely to isolate the problem if the problem is coming from the line, because telephone and cable TV drops would provide electrical bypasses. The disconnection of power serves simply to attract the customer's attention so that he will call the power company for service. A direct alarm line to the company would provide a more transparent operation as far as the customer is concerned; however, the alarm line cost would be an unnecessary burden considering the rarity of these problems. Furthermore, it seems appropriate to make the customer a partner in this endeavor, since he can be part of the problem.

Smart Switch Description

Figure 1 shows the SS. The device employs a commercially available power switch that has an enclosure designed for placement between the power meter and its base. It is manufactured by the Automatic Switch Co. The supply side has straight-through connectors inside the housing, while the load side has the power switch in series so both 120 V lines can be interrupted simultaneously.

The power switch is a load breaker and comes in different ratings, compatible with typical residential services, including 100 and 150 A. This commercially available product was modified by IIT Research Institute and Electro Specialties Inc. The modification provided a customized, motor-driven mechanism for the power switch. The motor works from a 16-volt power supply under normal line conditions. During a power outage or low line-voltage

Figure 1. Smart Switch.

conditions, an internal rechargeable battery provides power for the motor. As illustrated in Figure 2, the motor moves a plunger, through a worm screw, attached to an actuator shaped like back-to-back saddles. Two roller-tipped pistons ride on the saddles under spring pressure, and serve to move the switch contacts.

Figure 3 shows a block diagram of the major components inside the SS. A Motorola 8-bit microprocessor is at the heart of the SS to provide control and analog/digital conversion. A power supply attaches to both 120 V connectors on the supply side going through the enclosure. This provides 5 V DC voltage for the microprocessor, and 16 V DC for operating the motor and for charging the battery. The power supply also provides the line voltage that, after proper scaling, is sampled by the microprocessor. A terminal is provided in back of the SS to connect to the neutral in the base of the kilowatt-hour meter. At installation, an external jumper is installed between this terminal and the neutral in the meter base. For monitoring the voltage neutral, a reference is needed to a point on earth. This is provided by a recessed terminal on the front of the SS and an entry for the wire through the side of the SS enclosure. At installation, a wire is run between this terminal and an earth reference location.

In its present design, the SS has three LEDs visible on the side of the SS to provide status information through a waterproof window. The SS also has a reed switch that can be actuated by a magnet from outside the enclosure to reset the microprocessor. It also has thumb switches to change some operating parameters in the field. The design also includes fuses, lightning protection, and heating to moderate the environment inside the enclosure during winter months at northern latitudes. The modified enclosure is waterproof and absolutely safe.

The installation of the SS in the field is fairly straightforward, as is illustrated in Figure 4. The device can be installed in a few minutes, by first removing the kilowatt-hour meter from its base, plugging the SS in the socket, then plugging the kilowatt-hour meter into the SS. The kilowatt-hour meter then protrudes an additional 4½ inches out of the base, and requires an extra security lock ring, which is part of the enclosure. The installer has to connect a jumper wire between the back of the SS and the neutral wire inside the kilowatt-hour meter socket. A qualified power line electrician can accomplish this task with the socket energized, which removes the inconvenience of deenergizing the service main at the transformer. A wire is run between the SS and a short ground rod installed in the earth at a suitable distance from the house and away from the kilowatt-hour meter ground rod.

FIELD TESTING

Field testing was conducted with a number of prototype SS units at actual customer locations. The testing confirmed the application parameters and provided evidence that the SS design is on target. The SS logged nearly 13 years of aggregate field use without any false operations. It responded to an actual case of neutral voltage, and the

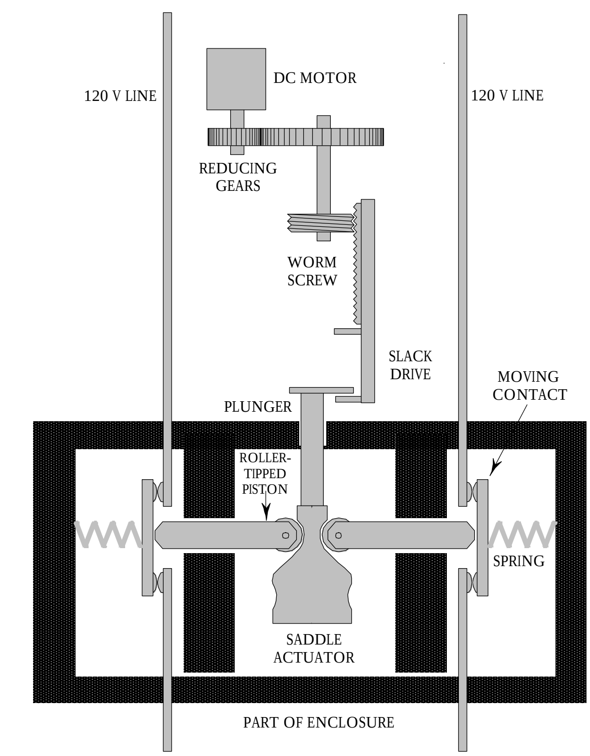

Figure 2. Mechanical details of SS operation.

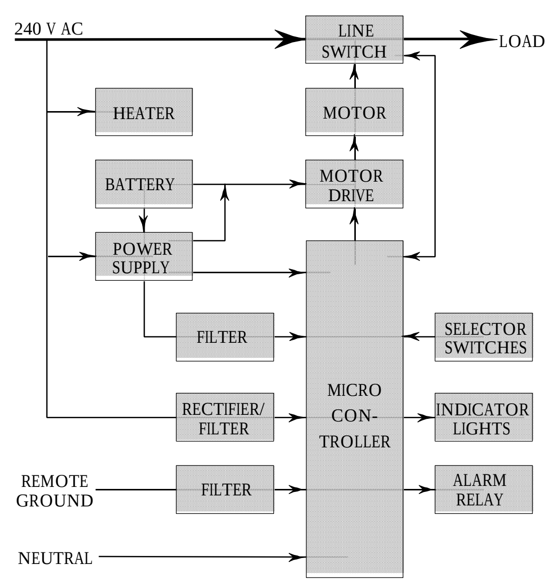

Figure 3. Smart Switch block diagram.

customer did respond to the power interruption. Remarkably, he never called the telephone company, even though he was also having problems with the telephone service, which was the source of the high neutral voltage.

Electro Specialties Inc. built 20 prototype units of the SS in July 1993 for use in this testing program, to evaluate the performance and design of the SS. A special alarming system by telephone was arranged at each site to continuously monitor the operation of the SS. The year-long testing program was completed in February 1995.

Logistical problems, such as delays in getting dedicated telephone lines for the monitoring, resulted in less than the hoped-for 20 years of field experience. The accumulated experience with documented 24-hour monitoring for all 20 installations amounts to 12.3 years, even though the SS was in place for a longer period. Over 7,000 records were collected during the monitoring program that documented daily the status of the SS and any operations that occurred during the day. The error rate in this documentation is less than 0.1 percent.

A total of 74 open-and-close SS operations were detected for all 20 units during the testing. An analysis of the data revealed that 24 of these operations were related to an actual intermittent neutral voltage problem at a single location that was difficult to diagnose; another 42 were due to line voltage outages; and 8 were unknown events.

These 8 operations are all the more interesting because they were one-time events unexplained at the time they occurred. They are considered nuisance rather than protection operations, and it is suspected that they could be eliminated by resetting some of the SS parameters. They could have been voltage sags, since the sag threshold in the SS was set at 105 volts for this field trial. If this were the case, the problem could be solved by lowering the sag detection threshold to its lowest value, 90 volts.

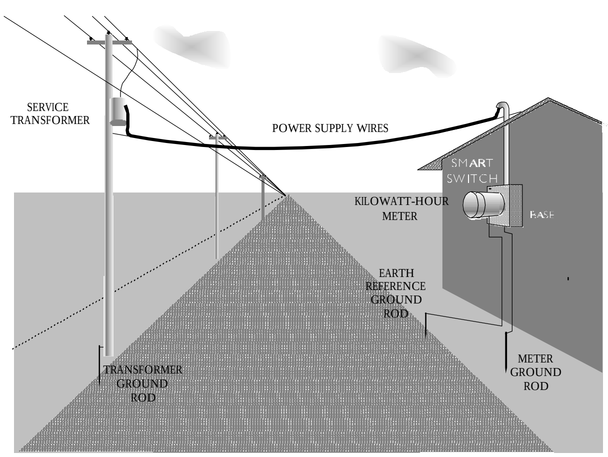

Figure 4. Smart Switch field installation.

These 8 operations could also have been caused by unsafe neutral voltage events. All 20 services were services mitigated for ELF neutral voltage by means of transformer neutral isolation, with high ELF voltages on the distribution neutral wire. Temporary bypasses, such as those caused by telephone or cable TV craftsmen while working on their respective systems, could have caused the SS to respond. The operations were nevertheless transparent to the customer, and did not cause service calls. One way to lower this response probability would be to lengthen the filtering time.

It can also be argued, in the worst-case scenario, that these 8 operations were faulty or erratic operations of the SS. If this were the case, the incidence of SS false operation would rise from zero to about one false operation per device for every 1½ years of customer service. This is still a good performance result, because the customer is unlikely to notice a brief service interruption occurring less than once a year. The authors believe, however, that this is not the case, and that the 8 operations were transients that marginally meet the minimum specifications set in the SS to recognize long-lasting line voltage sags or unsafe neutral voltages.

The other 42 line outage operations were unintended, spurious operations. The SS was programmed unintentionally to produce a response to a power line voltage loss as well as to a line voltage sag, when only the latter was of concern. It was thought initially that this extra response would not degrade the performance of the SS, would be transparent (because the customer already would be out of service), and might actually be beneficial, by creating delays that would ease load pick-up by reclosers. The high number of these operations in the field test was unnecessary, and the SS could be programmed to ignore power outages. This would at the very least minimize switch contact wear due to unnecessary operations.

Lightning problems were encountered with the telephone lines and the monitoring systems. The SS is provided with internal surge protection where it connects to the power line. This was not affected by lightning, which proves its design effectiveness. The signaling part that was hastily arranged with the telephone line was, however, affected and caused some failures. Some telephone lines were not grounded properly. This signaling is not part of the normal SS operation.

The test program, because of its brevity, does not provide information on the life expectancy of the SS. The design, however, has been thoroughly tested in the laboratory; furthermore, all 20 prototype units survived a harsh winter, with temperatures averaging in the teens, and dropping frequently to -30ºF. The SS failure mode was also not addressed in this brief testing program. The SS, in response to an internal failure, leaves the power switch closed. An open-mode failure, however, would be more desirable for annunciating the problem.

COST-EFFECTIVENESS

The installed cost of the SS, in quantities of hundreds, is around $1,100 each, $950 for the device and $150 for the installation (one man with truck for two hours and installation material). Knowing the dollar value of the problems that the SS resolves and the consequences that it prevents could lead to a cost-benefit determination. A look at other systems and approaches that might be useful for monitoring and controlling these problems provides a cost-effectiveness comparison that answers many questions about the value of the SS.

The rates used in these cost and financial analyses are: labor at $20/hr, truck at $5/hr, overhead of 100%, fee of 10%, inflation of 4%, interest of 8%, and a life-time application of 20 years. Operating and maintenance costs are assumed to be fixed at about 2% of the capital investment, and tax effects are not considered. Costs are rounded off to the nearest dollar. The present value of the SS, considering the initial capital investment of $1,100 and an annual commitment to maintenance for 20 years, is $1,399 (see Table 1).

A simple annual inspection by a company employee represents an approach often used for special problems such as the ones addressed here. A single employee in a truck would take ⅓ hour to perform the visit. This would constitute an annual commitment of about $18/yr. The present value of this commitment over 20 years is $249.

A feasible alternative to the SS is to use a simple voltage monitoring system with a telephone alarm line to the power company. The commercial value of the SS without the power switch is around $500. Indeed, the price of a near-equivalent commercial product to the SS, without the power switch, is the Scientific Atlanta Universal Network Monitor, priced near $500. The installation cost would be about $186 (a crew of two working for 1½ hours, requiring a truck and installation material). The monitoring operation over a 20-year period includes a one-time telephone line installation fee of $50, an average telephone cost of $336 per year, and an average office labor of about 0.5 hours per year to monitor this alarm line. The present value of this approach is $5,792 with a dedicated telephone line.

Table 1. Comparison of alternative approaches.

	Present Value ($)	Continuous Monitoring	Real-Time Control
Annual Inspection	249	No	No
Telephone Monitoring	5,792 (3,508 †)	Yes	No
Radio Monitoring	2,408	Yes	No
Smart Switch	1,399	Yes	Yes

† Shared telephone line.

To reduce costs, one could use the existing customer telephone line on a shared basis for this application. This approach would likely be resisted by customers, because it might be construed as an invasion of privacy. However, an economic incentive such as sharing the telephone cost might induce customer cooperation. Assuming that the basic telephone cost would be evenly shared, the present value for this approach is $3,508.

Another feasible alternative is a radio-based alarm system. The voltage monitor (described earlier in conjunction with telephone monitoring) would be tied to a dedicated telemetry radio system. A one-way radio with a range of a few miles would be viable, at a cost of about $500. A rainproof enclosure (NEMA 4X) with power supply and antenna would cost about $200. Cellular designs with dedicated telephone lines would provide the means for complete area coverage. The cost of the support infrastructure would be divided among the cellular population. For this comparison, the apportioned cost is estimated to be $100 capital for each customer station. Long-term commitments include central office monitoring, 0.5 hours per year per site, and apportioned annual telephone costs of about $2 per site per year. The installation is estimated to require nearly three hours by a crew of two with truck. The present value of this approach is $2,408.

The annual inspections (see Table 1) clearly represent the least costly option. This approach, however, is close to taking no action, and cannot control the problems or provide a timely warning. The visit might address other company functions, and represents a highly visible public relations response.

The continuous monitoring approach using telephone lines is the most expensive of all alternatives, over four times the cost of the SS for a dedicated telephone line, and 2½ times the cost of the SS for a shared telephone line. The major contributor to this cost is annual telephone line usage. It was recognition of this factor that led the developers of the SS to appreciate the cost-free benefit of disconnecting the customer service as the real-time problem-reporting link. Besides providing continuous monitoring at one-fourth the cost of a telephone-based monitoring system, the SS provides immediate control of the problem.

The radio monitoring system is less expensive than telephone monitoring, but nearly 2 times more expensive than the SS. Furthermore, it provides no problem control. Adding control to this option would result in an SS with a radio link. For an application such as the one considered here, where the incidence is sporadic and the benefits are uncertain, adding a radio link when the customer will report the outage anyway constitutes an ineffective resource allocation. If the cost of the monitoring box were reduced–for example, by simplifying the monitoring functions and circuitry–the radio link would provide a cost-competitive approach to the SS.

CONCLUSIONS

Line voltage drops and neutral voltages are unquestionably problems in power delivery, and they are familiar occurrences. Yet their incidence is so sporadic and the nature of their source so varied that there has not been a concerted effort to provide an end-point monitoring or even control of these problems. If the problem were lack of a technological solution, the SS represents a customized application for these problems. Increased awareness of the problems and increased expectations on the quality and reliability of power service may create a niche for this application.

The SS has nearly 13 years of aggregate field experience and seems to be a solid and reliable device. Some corrections and enhancements have been identified that would improve the design and the application. Additional features and measurement capabilities could be incorporated into the SS. The cost, however, remains a major problem that will limit its marketability for residential application. Mass production would definitely lower its cost.

The lack of a device in the market may not represent lack of need, but rather lack of an available solution. Now that a prototype solution has been generated with the SS, the question turns into marketability and application optimization based on cost, benefits, and effectiveness. The SS approach, using power disconnection, provides both real-time control of the problem and a means for the utility company to become aware of these problems as they develop.

For the type of problems addressed here, this notification may not be rich in detail, but it is basic and timely. Experience with the telephone station protector suggests that this is basically a sound approach. The key to the success of this approach is reliability of performance, because a number of unexplained or false operations would cause the customer to reject this protection measure. The field testing of a prototype SS indicates that the approach is successful.

REFERENCES

[1] Goldstein, M., and Speranza, P. D., “The Quality of U.S. Commercial AC Power,” IEEE, CH1818/ 82/0000-0-0028, 1982.

[2] “Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits,” IEEE C62.41-1991.

[3] “Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part IV–Distribution,” Appendix B, Techniques for Interconnecting Primary and Secondary Neutral, IEEE C62.92.4-1991.

[4] Mader, D. L., Peralta, S. B., and Sherar, M. D., “A Model for Characterizing Residential Ground Current and Magnetic Field Fluctuations,” Bioelectromagnetics 15:53-65, 1994.

[5] Mader, D. L., and Zaffanella, L. E., “Network Analysis of Ground Currents in a Residential Distribution System,” IEEE Transactions on Power Delivery, Vol. 8, No. 1, January 1993.

[6] Miller, D. A., and Valentino, A. R., “ELF Earth Return Coupling Into Power Systems,” IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-15, No. 4, pp. 160-165, November 1973.

[7] Lanera, D., and Colby, J. A., “Seasonal Variations of Grounding Impedance and Neutral Voltage in Cold Climates,” Proceedings of the American Power Conference, Vol. 56-II, pp. 1617-1624, 1994.

[8] Lanera, D., Colby, J. A., and Puskala, D. A., “The Effect of Urban Plumbing on Power Line Grounding, Ground Current, and Magnetic Field,” Proceedings of the American Power Conference, Vol. 57-I, pp. 194-201, 1995.