Fiberoptic SCADA System Safeguards Underground Distribution Network

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Pacific Gas & Electric Company (PG&E) uses a network distribution system to serve its large, dense loads in downtown San Francisco and Oakland. The network systems include over 1,100 transformers, most of which are in underground vaults. Each of these transformer vaults contains one or more transformers. A network system is designed for maximum service reliability, maintaining power to customers even if one of its primary feeders or transformers is down.

Fiberoptics does not require trenching, is nonconductive, and is immune to electromagnetic and radio interference

The network primary feeders are 34.5 or 12 kilovolts. The secondary services are 208Y/120V, 480Y/277V and 2,400Y/4,160V. Most of the spot networks are 480Y/277V due to the high loads and economics of large high rise buildings. The higher voltages result in significant reductions in building wiring costs and the cost of supplying power to the buildings.

Network Improvement Program

In 1983, PG&E began its network improvement program to improve the safety and operation of its network distribution system. Low current arcing faults on 480Y/277V secondaries could sustain themselves for extended periods of time and cause extensive damage, more so than at 208 volts. The greater potential allows the arc to restrike and sustain a fault, instead of just *burning in the clear.*

The program had three objectives:

- Prevent total network shutdown from secondary fault
- Prevent a catastrophic failure in a building vault
- Minimize damage to customer and PG&E facilities.

SCADA System Requirements

The supervisory control and data acquisition (SCADA) system would monitor 500 remote terminal units (RTUs) in San Francisco and 150 RTUs in Oakland. The information monitored includes:

- Protector status
- Protector heat sensor
- Transformer temperature
- Vault temperature
- Vault water level
- Three-phase secondary current
- Transformer sudden pressure relay.

Alarms would be triggered by any abnormal conditions so that corrective action could be promptly taken to avoid or minimize damage.

It was important that data be received in a predictable time and that positive, real-time, two-way communications be assured. The communication network had to be self-monitoring. If it failed, the operator needed to be notified immediately so that corrective action could be taken. All means of communication between RTUs and the SCADA master computers were considered.

Selecting a Communications System

The communications system chosen would utilize PG&E's ASCII byte SCADA protocol. Commercially available RTUs could communicate at a maximum data rate of 9,600 baud. It was decided that the maximum EIA-232 data rate

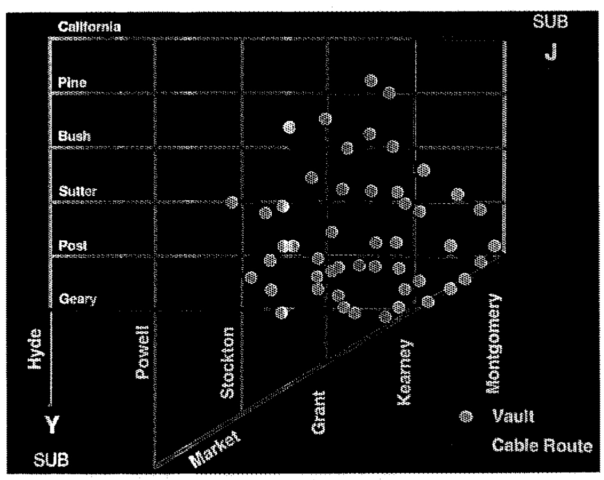

Figure 1. Multidrop ring configuration

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ISSN 0895-0156/92/$3.00©1992 IEEE

of 19.2 kilobits per second should be supported for expected enhancements and expansion of the system using the next generation of *smart* RTUs.

- Power line carrier was not selected because of the elaborate engineering necessary to tune to the various cable types, sizes, and lengths of the different feeders. Other reasons included broken communications in the event of a feeder fault or an open switch operation, difficulties in locating and repairing cable failures, and extremely slow and uneven data rates.
- 950 MHz radio was rejected because of concerns about coverage, the need for multiple repeaters, the difficulty in siting RTU antennas (mechanical installation and reliability issues), and concern that vault RTU antennas would be occasionally blocked by passing or parked motor vehicles.
- Copper wire (telephone or private lines) was rejected, as it would have required new electrically isolated ducting. Using conventional copper transmission technologies for the new system would have meant a significant amount of digging, since the company's underground ductwork was quite congested. Trenching is extremely expensive in downtown areas (about $300 per foot) and inconvenient, because there are only special times that streets can be shut off. Doing any excavating in downtown areas would have made the system cost prohibitive. In addition, ground potential rise during a fault could create an unsafe condition for communications service personnel as well as damage equipment.
- Fiberoptics was chosen as the most attractive alternative, since it would not require trenching. Being nonconductive, the fiber cables could be placed in existing ducts that contained 12 and 34 kilovolt feeder cables. In addition, fiberoptics is the ideal selection to carry signals because of its immunity to electromagnetic and radio interference.

The fiberoptic equivalent of a multidrop copper wire system was the ideal solution

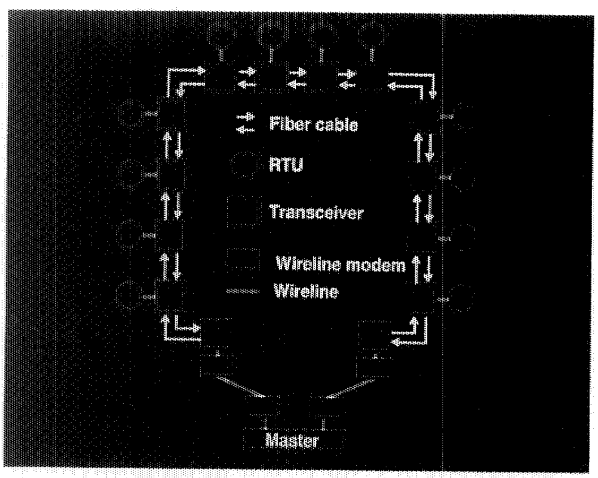

Figure 2. Dual redundant fiber loops

Selecting Fiberoptic Equipment

The *as built* documentation of the underground ductwork did not reflect collapsed or congested ductwork. As a result, it was decided that installation should proceed with a minimum of detailed route planning. Crews would try to place fiberoptic cable into primary feeder ducts between vaults. If a duct was blocked, a circuitous route would be found to get around the obstacle.

Various topologies were considered to interconnect the vaults and distribution substations using available fiberoptic communications equipment, including modems, drop-and-insert multiplexers, and optical splitters. After evaluating all possible choices, it was determined that the fiberoptic equivalent of a multidrop copper wire system would be the ideal solution as this was the least complicated topologically. Figure 1 illustrates a multidrop fiberoptic underground network.

Proposed New Product

The fiberoptic equivalent of a telephone cable repeater system with a repeater placed at each RTU location was proposed. Each repeater (called a fiberoptic transceiver) would modulate, demodulate, and reclock data so distortion would not accumulate. Furthermore, the configuration would be a loop with both ends connected to the master computer. The loops would be bidirectionally redundant for the obvious benefit that, if a transceiver or a section of fiber failed, communications to all other points in the system would still be possible.

A key feature, which added to the complexity of the design, was that the transceiver should receive and transmit a frequency shift keyed (FSK) modulated optical carrier signal. A carrier is a desirable feature because:

- Presence of a carrier confirms the integrity of the fiber cables, whether or not data is being passed.
- Receiver of an optical carrier system has a significantly higher signal-to-noise ratio (SNR) than a simple on/off modulated data link.
- Received optical power level (dBm) can be measured with a simple averaging optical power meter with or without data being present.

All transceivers are connected in a daisy-chain multidrop fashion as is illustrated in Figure 2.

As a cable failure or transceiver failure would result in isolating all RTUs beyond the point of failure, the linear bus is transformed into a loop by connecting transceivers at both ends of the bus to the master. For redundancy, two transceivers are connected to the loop ends and two master serial communications ports are connected.

Each fiberoptic transceiver modulates, demodulates, and reclocks data

As no such product existed, it was necessary to contract for the design and manufacturing of the fiberoptic transceivers.

Fiberoptic Transceiver Design

Discussion of the transceiver's functionality begins with a master-to-slave communication. Figure 3 shows a block diagram of the transceiver's communication flow. As there are two loops, the transceiver (shown in Figure 4) requires two sets of optical ports, left and right. Each port has a light emitting diode (LED) transmitter and a photodiode (PD) receiver. The transceivers have three EIA-232 serial ports to accommodate more than one RTU at a single location. (Some of the network vaults have five transformers which is too many points for a single RTU.)

Data coming into a serial port is encoded and modulates both left and right port LEDs.

The SCADA master is connected to one of the three EIA-232 serial ports on two transceivers placed at the ends of the loop. These transceivers cannot have RTUs attached, as data cannot loop from one serial port to another within one transceiver.

The modulated carrier signal is sent to the adjacent transceiver where it is demodulated, and the resulting serial signal is buffered in memory and sent out to all attached RTUs. At the same time, the serial signal is remodulated and sent out the opposite port to the next transceiver on the loop. The process is automatically repeated at every transceiver on the loop. There is no technical limit to the number of transceivers that can be cascaded; however, due to the internal delay caused by repeating (8 milliseconds at 1,200 baud), there is a practical limit to the number of transceivers on a loop. Fifty was chosen as the maximum number of transceivers on a loop.

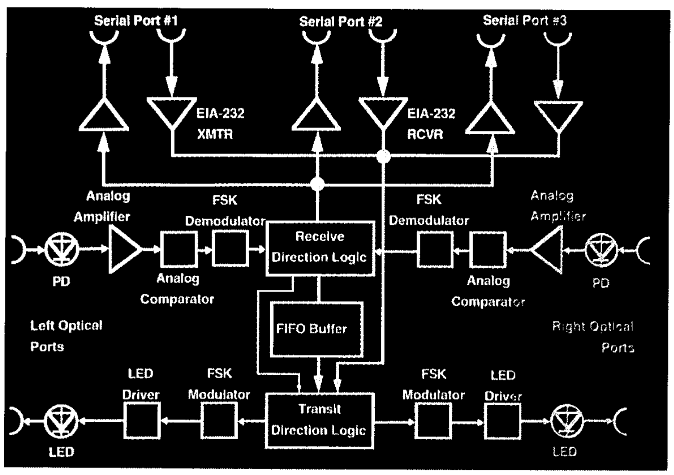

Figure 3 (above). Transceiver block diagram

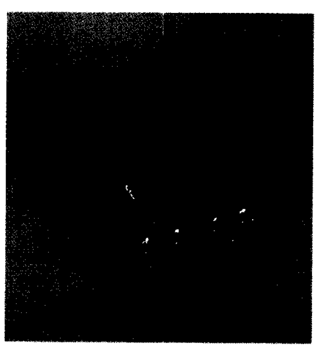

Figure 4 (left). Fiberoptic transceiver

When an RTU receives a polling request via a serial port and recognizes its address, it responds as requested. The transceiver modulates the serial signal from the RTU and transmits it through *both* left and right ports. The other transceivers repeat the signal all the way around the loop. The transceivers at the loop ends demodulate the RTU response signal and send it out the serial ports to the master.

The master station polls alternately (clockwise and counter-clockwise) and has diagnostic capability to identify if there is a break in the loop, based on which RTUs are responding and from which side of the loop.

Fiberoptic Cable Requirements

A transceiver with 850-nanometer LEDs is capable of driving a 6 kilometer (3.7 miles) multimode fiber cable. Optionally, with 1,300-nanometer LEDs, a 21 kilometer (13 miles) multimode cable can be driven. With single-mode 1,300-nanometer LEDs and single-mode cable, the distance between transceivers can be 40 kilometers (25 miles); 1,300-nanometer lasers further extend the distance to 80 kilometers (50 miles).

PG&E used about 26 miles of 6-fiber, loose-tube cable. The cable is approximately 13 millimeters (0.5 inch) in diameter, small enough to be pushed through feeder ducts and lay along side three 34.5-kilovolt plastic-jacketed cables or the older 12-kilovolt lead-sheathed cables. Each loose fiber tube has one 62.5 micrometer fiber. Two fibers are required for

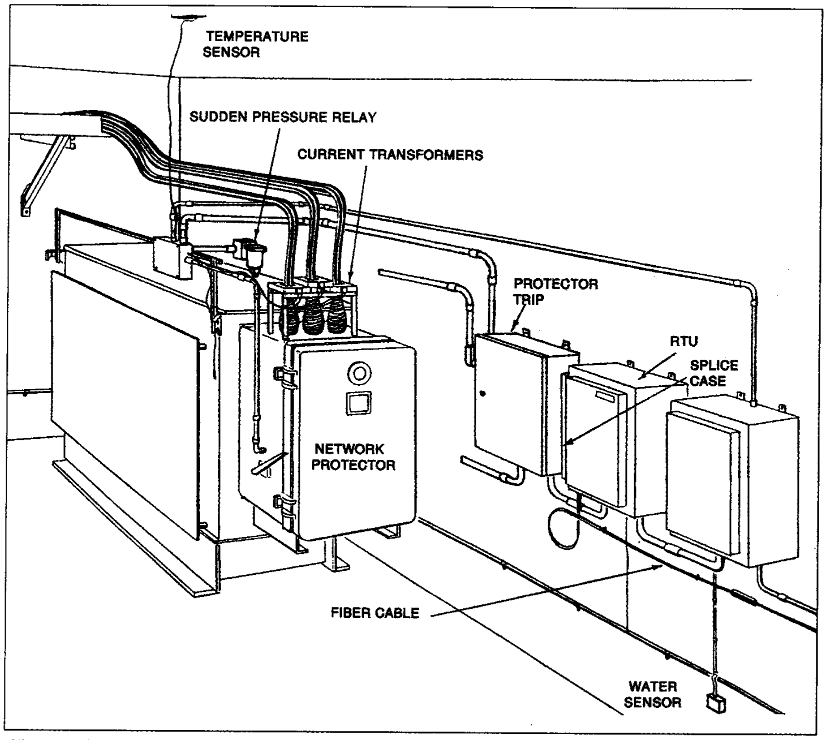

Figure 5. Network monitoring equipment

the SCADA system; this leaves four fibers for company telecommunications requirements. Preconnectorized 1-meter, tight-buffered pigtails were field fusion spliced to the loose tube fibers.

Vault Installation

A typical installation of network monitoring equipment is illustrated in Figure 5. Figure 6 shows a transceiver installed in an RTU enclosure. The fiber cable splice case is bolted to the left side of the RTU enclosure. The tight buffered pigtails pass through a pipe fitting into the enclosure to connect to the transceiver.

RTU Communications Scheme

There is no existing underground ductline between the downtown San Francisco network and the master SCADA computer, located in the Potrero District, 2.5 miles from the network. PG&E decided not to install overhead fiber cable but rather to utilize existing company wirelines to the substations, where 1,200-baud, 4-wire modems would be placed, connected to transceivers at the fiberoptic loop ends. This decision, unfortunately, meant that the fiberoptic loops and the RTUs were constrained to operate at 1,200 baud also. The desire to use a 386-based PC master with three remote terminals, one in the distribution operator's office located 5 miles from the master in Daly City, was also a factor in the 1,200 baud speed decision.

While path diversity of the wirelines, leading back to the master, was desired for reliability, this aspect was compromised due to economic considerations.

Oakland's system uses fiberoptic communications to the master, but, because the RTUs for both San Francisco and Oakland were purchased as one group, again for reasons of economy, the RTUs had a single speed serial port. Oakland's system speed is also 1,200 baud.

The PG&E ASCII byte SCADA protocol has a CRC error checking algorithm so that the RTUs report communications errors if they occur. The fiberoptics system has been error free; however, there have been errors due to the wirelines. The time to poll all 500 RTUs in San Francisco is 3 to 5 minutes at the 1,200 baud rate. As a work-around, the master software allows an operator to *lock on* to a single vault so that the terminal screens will update every 3 seconds.

The communications scheme used is deterministic (i.e., each RTU is polled individually). No spontaneous reporting is allowed, so collisions between RTUs do not occur.

Operating Experience

Initially, it was found that large phase imbalances (50 percent) were being reported by the RTUs. It was determined that some of the current transformers and transducers were incorrectly calibrated.

Based on 3.3 years of continuous operation, of the 699 units installed, the mean time to failure (MTTF) of a single transceiver is 96 years.

Master software improvements began immediately. Many new features were needed; existing features required enhancements due to ongoing operating experience. The following terminal screens were found to be most useful for the operators and engineers:

- Alarm log
- Quick scan of each loop (shows all RTUs)
- Vault screen (Figure 7)
- Feeder loads
- Two-unit spot clearances
- Diagnostic communications screen
- Protector operation count
- Protector blown fuse.

The protector operation count was found to be most useful. The program was set to flag any protector that failed to close after a 3-day period. It was found that quite a few protectors only cycled a few times a month.

Burned out motors have been detected as protectors failed to close. Occasionally, the program would find protectors that maintenance crews had left on manual-open instead of auto-close when they had finished work in a vault. In an emergency, the customer load would have been dropped or a transformer would overload when the remaining feeder opened. Scheduling preventative maintenance on these units was wasting a considerable amount of money and human resources. It is estimated that the new system saves over $500,000 per year in maintenance and operating costs of two and three unit spots in the downtown San Francisco networks.

The master station polls alternately (clockwise and counter-clockwise) and has diagnostic capability to identify if there is a break in the loop

An operator noticed that one unit remained open when the other two units were overloaded after a feeder had been cleared the previous night for work. The protector never closed back in because a contact inside the protector was defective.

An extended, planned outage of a 34-kilovolt feeder resulted in high load alarms. The operator, using data provided by the SCADA system, was able to notify the customer immediately and avoid serious problems.

During a routine feeder clearance, it was found that the feeder remained energized. Protectors remained closed due to a reverse current relay not actuating properly. Instead of having to send a crew to check every protector on the feeder, which would have taken many hours and resulted in several crews being idle, the operator sent crews directly to the vaults with the hung-up protectors.

A newly rebuilt and thoroughly tested transformer was installed. Several days later, the B-phase secondary failed and was detected immediately.

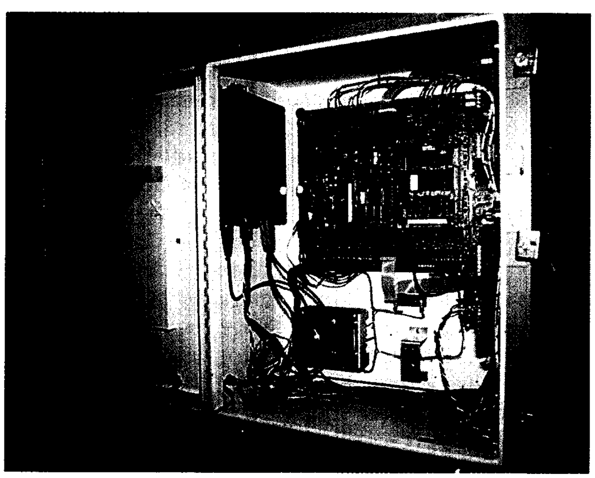

Figure 6. RTU Enclosure with transceiver

Vault over-temperature alarms have occurred when automatic vault ventilation fans broke down or when crews turned the fans off and neglected to turn them back on again.

There have been quite a few high water alarms in the network. During heavy rains, sump pump failures have been detected and, as was the case with the fans, have broken down or have been accidentally turned off.

The network is a fully automated system, so it will continue to give full service even when some components are not fully operational. For example, when a fusible link opens on one of the protectors, a customer still receives three-phase power because all customers are on two or three spot transformers. One of the transformers is now feeding only two phases because of the failure; this is immediately apparent with the new SCADA system. This could cause overheating of the transformer and reduces the manual and emergency loading capability of the vault. Corrective action can be scheduled to replace the link. Without the fiberoptic SCADA system, it would not be known that the link was open until a crew was in the vault for periodic, preventative maintenance.

As regards avoided costs, one failure is most significant because, had it not been detected, a protector fire and transformer explosion would have occurred. A protector heat sensor alarmed. The crew found water in the protector; the steam being created had caused the alarm. It is estimated that the expense of such an explosion, cleanup, and restoration would have equalled the cost of the entire SCADA system.

Operational and Engineering Benefits

As demonstrated, an operational benefit of the new SCADA system is identifying network distribution problems and correcting them in minutes instead of hours or days.

Once the basic SCADA system was in place, PG&E focused on developing a secondary fault protection system, which would rapidly isolate arcing and bolted faults on 480 volt spot networks. The protection system responds independently of the SCADA system. It notifies the distribution operator, via several status alarms in the SCADA system RTU, so that additional corrective action can be taken, if necessary.

The SCADA system has proven to be a significant cost saver. For example, the time it takes to close network feeders and transformers has been significantly reduced. The company is more aware of the condition of the network when a planned outage is started. This allows use

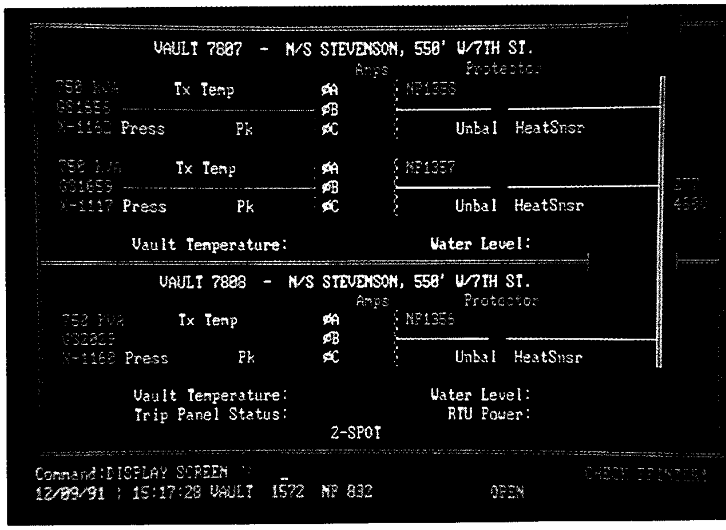

Figure 7. Typical vault screen

of two-unit spots as opposed to three-unit spots. If a scheduled clearance would cause an outage on the two-unit spots, the clearance is modified. Shifting of load can defer the need to upgrade feeders. The need to check protector status physically, which required three visits to each protector affected by a clearance, has been eliminated. The cost of a five person crew to inspect all vaults in San Francisco monthly has been eliminated and the crew redeployed.

Besides the numerous operational advantages, there are engineering advantages as well. PG&E can now load equipment and cables much more efficiently because the customer's true load factor is known, as is the load factor of individual pieces of equipment. Future benefits may include load management and meter reading. Since these are large customers, the dollar advantage in a faster turnaround of billing would be significant. A transfer trip scheme for network circuit breakers is under study.

There are several enhancements being considered. The first priority will be to upgrade the telecom wirelines, RTUs, and the master computer to 9,600 baud. Some RTUs may be replaced with units that have more points and more computational capabilities for fault detection. As an intermediate step, clamp-on fault indicators are being evaluated at a few RTU locations. Both triplex lead sheathed and simplex XLPE cables are being monitored. If this technique is proven to be an effective means of identifying cable faults, fault indicators will be installed in the network. If, in the future, the 9600 baud speed of the communications system becomes a limiting factor, it can be increased 50 times by replacing the transceivers with a high speed microprocessor based unit that has been recently developed.

Due to the flexibility of this fiberoptic SCADA system, its capabilities are considerably more than was originally expected. Because it exists, it causes people to think of more and more applications. There is no doubt that the system has paid for itself.

Acknowledgment

The authors thank Vladimir Manlapaz, Senior Distribution Engineer, Pacific Gas & Electric, San Francisco, for his contributions regarding operating experience with the fiberoptic system and a technical review of this article.

For Further Reading

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Biographies

Robert J. Landman has been President and Director of Research and Development for H&L Instruments (Burlingame, California) since 1979. H&L manufactures electro-optic equipment for fiberoptic data communications, semiconductor materials processing, aviation maintenance, and medical research. Formerly, he worked for Tektronix, Hewlett Packard, and Pacific Gas & Electric's Engineering Research Department. He majored in physics at the University of California (Santa Barbara), California State University (San Francisco), and American University (Washington, D.C.). He is an associate of the IEEE, member of the IEEE Power Engineering Society, the IEEE Communications Society, the Society of Photo-Optical Instrumentation Engineers, the American Society for Testing and Materials and the Semiconductor Equipment and Materials International.

Belvin Louie joined Pacific Gas & Electric in 1974, working in the Electric Underground Department. Subsequently he worked in Substation Operations and Electric Metering. His focus has been solid-state metering and distribution automation technologies. Currently, he is project coordinator of the Network Improvement Program and is the project manager for the Fresno Distribution Automation Technology Test. He is a consulting engineer with PG&E's Project Engineering/Distribution Automation Group. He majored in biology at the University of California (Berkeley) and received his BA in management from Saint Mary's College (Moraga, California) in 1988. He is a member of the Automatic Meter Reading Association.