TITLE: A History of Underground Secondary AC Networks

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Low voltage network systems have been in use since 1882. These early Edison systems distributed low voltage DC supplied by rotary converters with standby large storage batteries for contingency and generally utilized large conductors. Because of the economics of DC network systems, many outlying areas of cities were without electric service until the AC transformer was developed. Some of these DC networks systems continued to operate in downtown districts of many older cities until the late 1950's. The problem with networks became more complex when AC replaced DC — not so much with the secondary network, but with the primary supply to the network. A primary supply system, as reliable as the secondary network, was required.

The first low-voltage AC network system is reported to have been installed in Memphis, Tennessee, circa 1907. The network transformers were supplied by primary feeders through distribution cutouts and were connected to a solid grid of low-voltage cables that were protected with fuses. Early installations, as the Memphis system, were unsatisfactory due to the inability of the fuses between the transformers and the secondary mains to clear faults on primary cables and transformers. This shortcoming showed that a means of detecting power-flow direction was required to prevent a primary fault causing a complete loss of the network.

In Seattle, Washington, in 1921, improvements were made in the basic system by connecting the secondary terminals of the network transformers to the solid cable grid through network protectors that would trip automatically upon reverse power flow and were reset manually. In place of the secondary fuses for connecting each transformer to the secondary mains, a hand reclosed oil circuit breaker was installed which tripped only on reverse current from the network. Reverse power induction relays, under the circuit breaker, provided good instantaneous operation.

In 1922, the first AC network system, in which network protectors were automatically tripped and closed by relays, was placed in service in New York City by the United Electric Light and Power Company. This was the birth of the secondary network system, as it is known today.

On this radial primary supplied system, each transformer is connected to the secondary mains through an automatic network protector, which not only trips on current from the network but also has an automatic reclosing feature. A fault, on the radial primary feeder cable, causes the feeder breaker, at the substation, to open from excess current and all of the network protectors on that feeder to open because of reverse power-flow from the network.

The entire feeder, and its associated transformer banks, are thus removed from service, the load being carried by the remaining primary feeders and adjacent transformer banks. When the feeder cable has been repaired, all network protectors on that feeder will automatically reclose when the substation feeder circuit breaker is closed, provided that voltage and phase relationships are correct.

The NY cable grid was a three-phase, four-wire system and it operated at a nominal voltage of

208Y/120 V. By 1925, this type of system became an accepted method of supplying combined power and lighting load and six networks with a total load of 27.5MVA (over 100 transformers.)

This type of system gained rapid acceptance, and by 1952, 82 companies operated 414 networks. In 1974, 315 US companies used the low-voltage network system. Today's 208Y/120 V network grid systems are very similar in configuration and basic operation to the first systems.

Reliability of service is a paramount requirement of an electric distribution system, especially in the central business districts of large cities. The low-voltage network system is the method most commonly used to obtain this reliability. The underlying principle of all network systems is an interconnected grid of secondary mains operating at utilization voltage and energized from a number of primary feeders through step-down transformers. Today, there are over 350 cities, throughout the world, operating low voltage network systems.

All of these cities operate network systems utilizing fully automatic network protectors except the City of Philadelphia.

It should be noted that in the method of radial feeder supply to a network, the entire primary feeder, and all transformer banks associated with it, are removed from service in the event of a fault on any part of the feeder and also with a fault on any transformer tank supplied from the feeder.

It is from these early systems that the design, operating practices, and over-current protection practices evolved for the first 480Y/277 V spot networks installed in this country.

Grid networks served the needs of the commercial areas of many cities until the early 1950s, although it was necessary to develop network protectors of higher continuous current ratings to carry the increasing loads. By then, the loads in some commercial buildings were reaching the level where it was very difficult or not cost-effective for the utility to supply the load at 208Y/120 V from either a grid or spot network. These higher loads were due mainly to air-conditioning, higher lighting levels, and larger buildings. Furthermore, the wiring costs of the building systems became very high as the loads increased at this voltage level.

Thus, changes to the 208Y/120 design standards were necessary for the construction and operation of a 480Y/277-volt secondary network. The result was the spot network, which many utilities decided to use, because of economics and equipment availability.

The spot is a network of two or more transformers and protectors, banked on the secondary side with a single “collector” bus. The customer’s loads are then fed from the collector bus, usually by cable connection to one or more service entrance busses stubbed into the vault by the customer. The transformers in a spot network could all be located in one vault, or may be placed in separate adjacent vaults depending on individual utility policies.

Higher utilization voltages, either 460Y/265 V or 480Y/277 V, were adopted for service to large commercial buildings. Use of these higher voltages resulted in significant reductions in wiring costs and in the cost of the utility system supplying the building load.

The change to the use of the higher voltage was gradual. Initially, these new loads were served by vaults operated at 480Y/277 volts without connections to adjacent 480Y/277-volt vaults. One utility made its first 480Y/277 V installation in 1937, and by 1954 had eighteen 480Y/277 V vaults in service.

The decision to not interconnect the secondary was driven by both technical and economic reasoning. Because the 480Y/277-volt vaults were widely dispersed within a network area, engineers felt the small increase in the reliability of the overall supply system to the customer did not justify long secondary cable runs between vaults.

More significantly was the difficulty of extinguishing any arcing faults on the secondary system - 480Y/277-volt faults do not self-extinguish. They will consume the material around the arc and generate significant heat. Heating inside a closed space, or in close proximity to other devices, can result in significant damage to nearby equipment. Also, this type of fault greatly increases the risk of injury to construction and operating personnel in the area.

The purpose and operating principles of secondary networks remain essentially the same since they were first installed in the early 1920's. The network load area is typically supplied from multiple dedicated primary feeders (usually 12kv to 35kv). Substations supplying these network feeders are usually designed with multiple transformer and bus configurations to prevent simultaneous feeder outages.

The primary feeders are directly connected to network transformers. Multiple network transformers are generally located in vault structures that may be constructed in public right-of-way or in a vault within an individual building. The network transformer secondaries are connected in parallel through secondary network protectors generally mounted on each network transformer. Network protectors trip to isolate transformer and primary cable faults from the energized secondary. Secondary voltage connections may be made between vaults using low-voltage cables. All customer loads are served from the secondary system.

The use of specialized design techniques and equipment result in the ability of secondary network systems to provide the highest level of service continuity possible from a distribution system. Generally, secondary networks are used in high density load areas where limited space is available to place electric distribution equipment, such as a "downtown" area of a major city. They are very expensive to install, maintain and operate, and for this reason, most utilities have not significantly expanded network service outside of traditional network areas.

Some of the major changes that have occurred in the design and operation of secondary network systems over the past 15-20 years:

- the evolution of 120/208 volt grid systems to 277/480 volt spot networks, and the inherent problem with secondary faults on 480 volt systems;

- expanded use of SCADA monitoring, alarm, and control schemes for real time monitoring of network conditions;

- use of sophisticated protection schemes to prevent catastrophic secondary failures;

- changes in network transformers, primary and secondary cables, and advances in network protector relays;

- increased customer use of emergency generators and uninterrupted power systems (UPS) on network services;

- increased demand by customers and regulators for access of non-utility generation systems to secondary network distribution systems;

- expanded use of computer-based load flow and ampacity programs to more accurately predict cable capacities and transformer loads.

Underground networks offer much greater reliability than other commonly used distribution systems. Unfortunately, because a network system is designed for maximum service reliability, maintaining power to customers, even if one of its primary feeders or transformers fails, there is no obvious indication that there is a malfunction. Low current arcing faults on 480Y/277V spot network secondaries can sustain themselves for extended periods of time and cause extensive damage, more so than at 208 volts. The greater potential allows the arc to re-strike and sustain a fault instead of just "burning in the clear".

Underground network fires and explosions happen. We'll never totally eliminate them. There remain a need to prevent total network shutdown from secondary faults, prevent a catastrophic failure in a building vault, and minimize damage to customer and utility facilities.
Until SCADA systems became practical, periodic visual inspections were required, as well as preventative maintenance, to detect incipient failures. Practically speaking, inspections could not, and still cannot, be frequent enough to detect defective equipment. Scheduling preventative maintenance on network protectors wasted a considerable amount of money and human resources.

As the overall loading levels of the network systems increase, utilities may choose to use advanced SCADA systems to monitor device loading levels beyond simple currents and voltages. For example, more main frame computers and individual workstations located in each office building, each having switching power supplies and UPS back-up sources, coupled with the lighting ballast loads, have driven the third harmonic neutral currents much higher than in the past. The addition of these non-linear loads has created a need for specially rated power transformers to ensure that the system can successfully operate under these conditions. The network SCADA system can be used to pinpoint the harmonic "hot spots" and allow the network engineer to properly size equipment being installed.

The Consolidated Edison New York network system is the largest in the world, consisting of more than 22,000 transformers and network protectors. In 1971, ConEd developed a one way powerline carrier communications system to bring back to the control center the protector status, fuse status, transformer oil temperature (above or below 90°C), and load current, in percent of nameplate.

At the time the ConEd system was developed, only radio, telephone, and powerline carrier technologies were available. The system had to run submerged; radio was too expensive and it was doubtful that coverage would be uniform: the need for multiple repeaters, it would be difficult to site radio antennas. Telephone and electric vaults were separate systems and would have been too costly to be considered, so powerline carrier was ConEd's choice. It was (and still is) a one-way reporting system with no control capability.

In later years, other companies such as Georgia Power and PEPCO have successfully used two-way 900MHz radio to communicate to network vaults.

In 1985, Pacific Gas & Electric Company decided that neither radio nor powerline carrier was acceptable so they contracted with H&L Instruments to develop a two way fiberoptic communications system for their 700 network transformer/protector systems in San Francisco and Oakland California. The Model 542 Fiberoptic Transceiver repeater system was developed by the author's company (H&L Instruments, LLC). With RTUs and sensors in the vaults, the SCADA system monitors protector status, protector heat sensors, transformer temperatures, vault temperature, vault water level, 3-phase secondary current, and transformer sudden pressure relays.

PG&E has found the master station at the control center to be most useful for the operators and engineers. Their system provides alarm logs, quick scans of each loop, individual vault screens showing temperature in the vault, transformer temperature, voltages and amps on each phase, percent loading, protector status, feeder loads, 2-unit spot clearances, diagnostic communications screens, protector operation counts, and protector blown fuses. Control is possible because it is a high speed two way communications system.

In 2009, PG&E began to upgrade their system, upgrading now obsolete electro-mechanical relays in protectors that were connected to SCADA RTUs with modern solid-state microprocessor relays. They chose the Eaton MPCV relays and Eaton's VaultGard translator units with Qualitrol sensors to report on transformer oil to translate Eaton's relay protocol to PG&E's preferred IEEE standard protocol, DNP 3.0.

The fiberoptic transceivers are being upgraded to H&L's newest unit, the Model 570, a self-healing loop system which detects and heals itself in less than 4 milliseconds. It is able to carry up to 128 channels of serial communications and includes two Ethernet ports which will allow the VaultGard's web servers to be viewed at the control center as well as in the vaults.

Via an externally supplied wireless WiFi VoIP (Voice Over Internet) unit, workers will have hand held radios which will enable them to talk to the Control Center as well as other radiophones in the H&L system.. With the H&L PBX unit, they will be able to make calls into the utility's telephone system.

Since many network distribution problems can be identified and corrected in minutes, instead of hours or days, SCADA systems can result in significant cost savings as well as reliability and safety benefits for utilities. Utilities can 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. This becomes extremely important during system emergencies, when more than one feeder is out of service.

Future benefits may include load management and meter reading. Since these are large customers, the dollar advantage in a faster turn around of billing may be significant.