Underground Secondary AC Networks, A Brief History

By
Robert J. Landman
H&L Instruments, LLC
IEEE PES, Senior Member

Presented at
2007 IEEE Conference on the History of Electric Power

August 4, 2007

Newark, New Jersey

rlandman@hlinstruments.com
(603) 964-1818
PO Box 580
North Hampton, NH 03862

ABSTRACT

The first low-voltage AC network system is reported to have been installed in Memphis, Tennessee, c. 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. In 1921, improvements were made to the basic system in Seattle, Washington by Puget Sound Power & Light Co. This involved connecting the secondary terminals of the network transformers to the solid cable grid through network protectors. These protectors would trip automatically upon reverse power flow and were reset manually. 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. The cable grid was a three-phase/four-wire system which operated at a nominal voltage of 208Y/120V. By 1925, this type of system became an accepted method of supplying combined power and lighting load and there were six networks with a total load of 27.5MVA (over 100 transformers) in operation. By 1952, 82 companies operated 414 networks using this system. In 1974, 315 US companies had installed the low-voltage network system. Today's 208Y/120V network grid systems are very similar in configuration and basic operation to the first systems.

INTRODUCTION

Reliability of service is a paramount requirement of an electric distribution system, especially in the central business districts of large cities. The low voltage AC network system is the method most commonly used to obtain this reliability. The underlying principle of all AC 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.

EARLY NETWORK SYSTEMS

Contrary to the existing practice of the telephone and arc light companies, which installed their wires on poles above ground, Edison decided to put his conductors underground. The development of underground cables was expedited by the New York State Legislature, which, in 1884, enacted a law requiring the underground placement of "all telegraph, telephonic and electric light wires and cables used in any incorporated City of this State, having a population of five hundred thousand or over." The Consolidated Telegraph & Electric Subway Co. was formed in 1885 to install underground conduits in New York, and The Brush Electric Illuminating Co. went underground on August 1, 1888. But it wasn't until 1890, that the City Fathers forced the removal of ***all*** overhead wires in Manhattan. During the year of 1889, Mayor Grant reported that the Bureau of Incumbrances had removed 2495 poles and about 14,500,000 feet of electrical wires.

1-4244-1344-3/07/$25.00 ©2007 IEEE

Some of the smaller light companies were, thereby, forced out of business. Edison's D.C.Tube System was already underground, so his competitors had to develop a flexible cable suitable for installation in underground conduits and other types of insulation for the higher voltages at which they operated.

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 out-lying 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. The problems were not so much with the secondary network itself but with the primary supply to the network. A primary supply system was required to be as reliable as the secondary network.

In the early days, the network transformers were supplied by primary feeders through distribution cutouts. They were connected to a solid grid by low voltage cables that were protected with fuses. These early installations 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 short-coming showed that a means of detecting power-flow direction was required to prevent a primary fault from causing a complete loss of the network.

In 1921, improvements were made in the Seattle, Washington basic system by connecting the secondary terminals of the network transformers to the solid cable grid through network protectors. These protectors 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 April of 1922, New York City put in operation the first network system utilizing fully automatic network protectors. This was the birth of the secondary network system, as it is known today. An article, by Mr. A. H. Kehoe, an Electrical Engineer of the United Electric Company, was presented at the 1924 AIEE annual convention, which described the basic features of the AC network system and outlined his experimentation towards its development. This was the beginning of the AC network system which is now used extensively in New York City and in the downtown areas of most cities in the U.S. and many cities in other countries.

The main component, which made the network possible, was the development of the network protector which is essentially a circuit breaker with relaying features incorporated within it. These relays cause all network protectors, associated with a feeder, to open automatically when a fault develops on the high tension side. While large manufacturers, such as General Electric and Westinghouse, have been manufacturing these devices, the basic stimulation for the design and improvement of these devices has come mainly from the Consolidated Edison Engineers.

On this radial primary supplied system **(Figure 1)**, 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, is thus removed from service, with 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 (providing voltage and phase relationships are correct.)

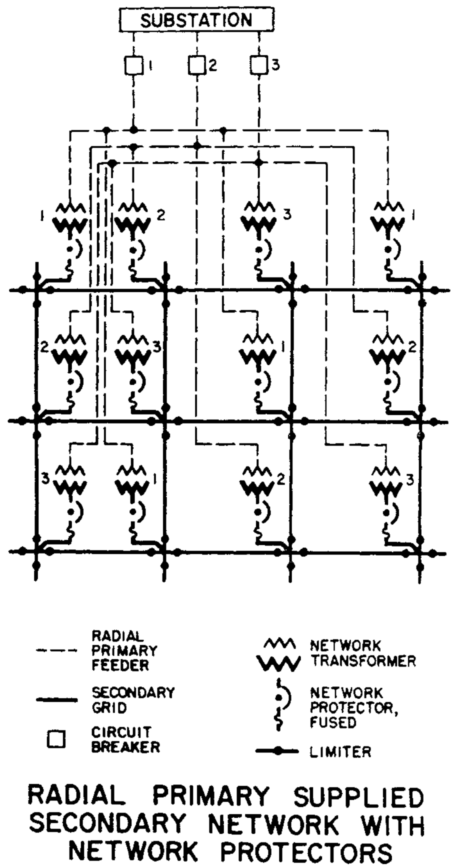


Figure 1

The first low-voltage AC network system was reported by many sources to have been installed in Memphis, Tennessee, c. 1907. That date is incorrect according to a document from the city's consolidated power company (now called Memphis Gas, Power & Light) written by W.J. Fransioli, Jr., dated December 1, 1959. It states that in the year 1922, the Memphis Power and Light Company, under the supervision of the Electric Bond and Share Company, was formed to operate the gas and electric utilities. This Company soon started planning to combine two underground systems into one. Network Protectors were now available and the Electric Bond and Share Company Engineers decided to try them in Memphis.

The first Network Protector was installed in Memphis, c. 1925, in the Columbia Mutual Tower vault. This was a "spot-network" only and open-type Network Protectors were used. It was gradually followed by other installations and the spot-networks were then interconnected to form a network grid. The grid operated initially at 115/199 volts, three-phase/four-wire and was composed of some of the old low voltage cables, which were used in conjunction with new 3 S.C. 300 MCM paper lead cables and 4/0 W.P. neutral. The new transformers, which were installed, were single-phase units, 10 per cent impedance, subway-type, rated 2300 – 115/230 volts, in 50, 75, and 100 kVA sizes.

These transformers were combined into three-phase banks and supplied by the regulated 4 kV underground circuits (consisting of 3-conductor, 300 MCM paper lead cables) from Beale Substation. Potheads and blade disconnect switches were used to terminate single conductor primary cable taps in the transformer vaults.

As previously noted, the original network voltage was 115/199 volts, three-phase/four-wire, and some large customers were supplied auto-transformers for their 220 volt motor loads. The voltage level on the network was later gradually raised to 120/208 volts and these customers were encouraged to remove the auto-transformers. Also, customers, which were still using 250 or 500 volt DC elevators, were requested to convert them for AC operation. Many customers were slow in modernizing their elevators, despite wiring concessions, high dc rates, and much "urging" from the M. P. & L. Co. The last DC customer was not finally eliminated until February of 1951.

The Georgia Electric Light Co. of Atlanta had its beginning in 1884 with the purchase of an electric plant for supplying 45 arc lamps of 2,000 candle power. The first large plant was constructed in 1891 with AC for lights and power at a voltage of 52 volts. The Edison 110/220 volt DC system was started in 1892 (apparently not the Edison Tube system), produced from the AC circuits through rotary converters. Due to the unreliability of the AC circuits, large banks of batteries were placed in parallel for downtown lights and power.

Thus, when the AC failed, downtown could operate for a while on the batteries. One additional DC plant was constructed in 1901, but without batteries, and one more in 1906, with batteries. In 1917, the DC system peaked with 8,400 kW and 2,415 customers covering an area approximately 1/2 square mile. DC to AC changeover was started in 1918 at 2.3 kV. with the last DC customer converted to AC in 1955. Existing transformer banks were converted from 2.3 kV. delta to 4 kV **wye** and the first network protector was installed in 1926.

By 1928, load growth in Atlanta indicated that the present 4 kv system would not be adequate to handle the projected load on the network and a study was made to convert the system to 19,800 volts (20 kV). The conversion to 20 kV began in 1929, and required the re-construction of the entire conduit system along with cables and transformers.

All this started out as one network and, as of today, Atlanta now has grown to 35 networks with 1,509 network transformers and 2,070,500 kVA connected capacity. The recent acquisition of the Savannah, Georgia electric system indicated that their electric system probably preceded that of Atlanta. Some of their **vaults** still had within them the abandoned three-wire solid rod Edison Tube system.

LIMITERS

One trouble occasionally experienced on the Con Edison NY network system, which was the cause of damage to many sections of distribution mains, was the solid short circuit which would draw fault currents for a considerable length of time. This would overheat long lengths of mains and cause their complete destruction. Explosive gases were distilled which, in combination with air, would initiate explosions in vaults and service boxes. Con Edison Company engineers developed the limiter which relieved this problem.

A limiter is a "fusible" connecting device which is designed to disconnect the faulted main just before the "roasting" condition described above. A series of patents were granted to Con Edison engineers covering the limiter design. The development work on this device was completed in 1938 and already in considerable use on the system by 1939.

In 1967, it was estimated that there were more than 1-1/2 million limiters on the Con Edison system. Most companies today use limiters.

CRAB JOINTS

Con Edison engineers developed what they called the "crab joint" method of interconnecting mains cables in 1935. This method utilized a novel pre-manufactured device called a crab joint which greatly reduced field splicing labor and increased the reliability of splices. The major application was in splicing non-leaded cables.

This device found major acceptance in many companies besides Con Edison. One variation of this device is the incorporation of network limiters in the device so that the protective function is made an integral part with the splicing function.

DEVELOPMENT OF THE PHILADELPHIA NETWORK SYSTEM

In the early 1920's, the Philadelphia Electric Company instituted studies for the development of an AC distribution system to replace the DC system in the central business district of the city. In these engineering studies, various systems and types of equipment were examined in their relation to four fundamental requirements**:** reliability, simplicity, flexibility and economy. It was realized that these requirements would be greatly influenced by the simplicity of the equipment which must be installed in **underground vaults** and operate reliably without constant supervision.

From these studies evolved a low voltage AC network system which is, in many respects, fundamentally different from the network protector systems found in other major cities. This network system was patented by Mr. P. H. Chase, former Chief Engineer of the Philadelphia Electric Company. This scheme was a simple 2400 volt primary loop—feed system sectionalized by means of automatic oil circuit breakers supplying a fused secondary network **(Figure 2)**. Automatic operation of the circuit breakers was controlled by a balanced current pilot wire system. Initially,

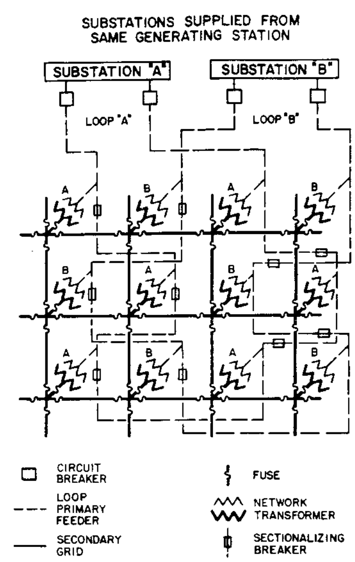


Figure 2
Loop Primary Supplied Secondary Network with Sectionalizing Breakers

it was decided to make provisions for a future change to 13,200 volt primary loop supply. Consequently, all of the equipment and cable was designed for 13,200 volt, 3 phase operation.

How did Philadelphia convert from DC to AC?

It's a very interesting tale and it's told in the book History of the Philadelphia Electric Company by Nicholas Wainwright, ©1961. It describes the development of the Network in the early part of the 20th Century under Joseph McCall's leadership. Joseph McCall was the first President of the newly unified electric system. This system was a collection of small utilities and electric cooperatives that came to be known as the "Philadelphia Electric Company."

The Edison District refers to the original DC Network that was present in the Center City District. Most large cities had an "Edison" District.

The mechanical difficulties, that disturbed McCall shortly after World War I, were particularly prevalent in down-town Philadelphia, the old Edison direct current district. It became shockingly apparent that the Company was short in capacity and failing in reliability in the most important area of its territory. The Edison Station was not only out-moded, but at times had to be operated in excess of its safe capacity. Moreover, the cables leading from the station were so crowded in some underground vaults that the slightest trouble on one was liable to pass to the others.

Horace P. Liversidge, the operating engineer, decided that a new substation would have to be built at the corner of Ninth and Sansom Streets to strengthen the Edison system. The old Edison Station simply could not hold the converter equipment necessary for transforming alternating current into direct current. As Liversidge began to develop his plans, he became dissatisfied. Why, he asked himself, should the Company bring in alternating current just to convert it at large expense and inconvenience to direct current, sustaining losses of about twenty-five per cent of the electric energy? Looking ahead, he could see that the expansion of the direct current system would involve staggering costs and greater complications in operation. More substations to house converter equipment would have to be built and be provided with costly heavy-duty electric storage batteries. It would be far better to do away with the direct current system altogether. His preliminary studies on this revolutionary idea indicated that the changeover would cost $9,000,000 and take ten years to accomplish.

Liversidge took his plan to McCall, but failed to interest the president in it. Continuing power failures in the Edison district, however, forced McCall to reconsider. Liversidge now played his trump card. He pointed out that it would cost nearly as much to strengthen the direct current system as to replace it with alternating current, which was much cheaper to operate. Without even consulting his board of directors, McCall said, "go ahead." But that was easier said than done. An enormously complicated task lay ahead and many special studies had to be made. To help in the planning, Philip H. Chase, an expert in transmission and distribution, was employed in 1921. Chase undertook to devise a system just as good as Edison's, but one which would use alternating current.

In New York one day to attend a meeting of utility executives, McCall casually told a few of them about the changeover on which Liversidge was working. Their reaction was almost violent. Samuel Insull of Chicago declared that Liversidge must be crazy. Backing McCall into a corner, Insull, the greatest utility leader of the day, addressed the Philadelphian in the following vein:

"Didn't Thomas Edison originate this electric lighting system? Didn't he design everything from his dynamos through the switchboard to the distribution system, including even junction boxes and manholes, right on through to the lamp? He's the man who designed all this and now along comes an upstart, a man who is prepared to tell you that Edison was all right in his day but here's a plan and here's a program that's much better than Edison's. Can't be. Why, Joe, you don't use any batteries with this alternating current system. How's he going to guarantee continuity of service? There isn't an Edison system in the country that doesn't have to rely on batteries because we are bound to have interruptions to our generating and converting apparatus—bound to have it. Downtown areas in big cities absolutely require one hundred percent continuity. All the theaters and hospitals, all the big stores are there. Would you depend on an alternating current system to supply this important load? It won't work, Joe."

The other executives supported Insull. Alex Dow, president of Detroit Edison, and John W. Lieb, vice-president of New York Edison, were among those who advised McCall that he was wrong to make the change. McCall returned from New York a discouraged man. He called Liversidge into his office and told him to abandon the project.

Continuing failures in the Edison district again forced McCall to reverse himself. By this time, Philadelphia Electric's direct current system was one of the poorest in the country because Liversidge had been systematically refusing to spend money on it. At his wit's end, McCall had the following conversation with Liversidge:

McCall: "I don't care what they say, and I don't care what difficulties you may have. You say you can do it?"

Liversidge: "I know I can, Mr. McCall."

McCall: "Well, go ahead and do it."

Fortunately for Liversidge, Philip H. Chase soon came up with a workable transmission system which, without depending on storage batteries, would provide the continuity that Insull had said was impossible. While the replacement part of the changeover did not begin until 1926, in 1923, a program was initiated for installing a network of 2,300-volt alternating current feeders and secondary mains in the Edison district to relieve the load on the direct current substation and the Edison distributing system. In certain sections, all new business were to be connected to the alternating current distribution system. This limited the extension of the old system and facilitated the eventual changeover.

The changeover from direct to alternating current was a far larger project than the elimination of arc lamps. It took a great deal longer to accomplish, not being finally completed until 1935, by which time the changing of customers' installations had cost the Company nearly $8,000,000. This was a lot of money, but it was insignificant when compared to the advantages of a single system for Philadelphia; better continuity of service, reduced capital investment and smaller operating expense. Although several cities had completed changeover programs before Philadelphia Electric, none of them was of the same magnitude.

Electric motors, rather than lights, created the most perplexing and multifarious problems for the changeover engineers. Most motors ran on DC and had to be replaced or converted. Philadelphia Electric did not believe that its customers should pay for this changeover and offered two plans for supplying AC machinery in place of DC equipment. By one agreement, the Company leased AC apparatus to a customer, who would have free use of it as long as he remained a customer at the address recorded in the lease. By a direct exchange agreement, AC motors were traded to the customer for his DC motors. There were at least two hundred and fifty kinds of apparatus in one hundred classes to be ex-changed, including seventeen carloads of electric fans. In the "shirtwaist district," there were thousands of sewing machines of every type and age to be reckoned with. It took considerable ingenuity on the part of the changeover branch to solve the countless problems involved.

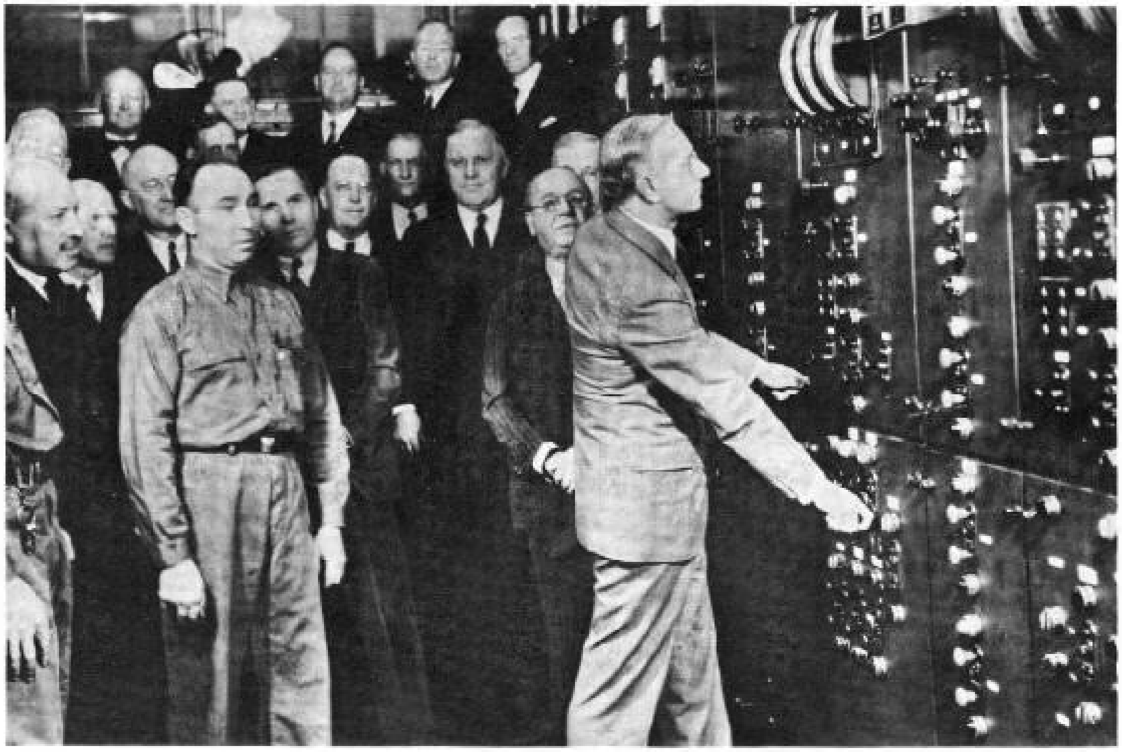
During the first four years of the program, the load on the DC system increased rather than decreased. No one had thought it possible that the load in the Edison district would grow so fast, and it was obvious that the Company had started to make the changeover none too soon. By refusing to become discouraged, and by keeping relentlessly at the task, the changeover crews slowly began to win out, until, at last, DC was eliminated from the system.

In 1935, Liversidge sat in his office, relaxed in the thought that one of the most fantastic efforts ever made by an electric company had been brought to a successful conclusion. Suddenly he was aware that the lights were dimming—they went out! Dashing down to the load dispatcher's office, he found nothing but pandemonium and darkness. A total shutdown at Schuylkill Station had interrupted the electric supply to a portion of the central city district, including a section of the new AC network. "We can't get it back," cried the load dispatcher. "Every time we close in a feeder switch, it opens; it is impossible to hold it in."

The horrible thought crossed Liversidge's mind that perhaps Philip H. Chase's system would not work after all. Perhaps Insull was right. Maybe the changeover was nothing but a multi-million-dollar blunder. But Liversidge knew Chase's original calculation, and he knew that if he closed in on everything and blocked relays, from a theoretical standpoint the system would hold. He issued a series of orders: clear one bus at Schuylkill; after blocking the relays, throw all feeders in the area affected onto the cleared bus; place a generator on this bus at low voltage and then slowly raise the voltage. Liversidge waited, his eyes glued to a lamp. In a matter of seconds the lights were back, the telephone rang and the word came through - "everything's holding!"

Exhausted by strain, his nerves on edge, Liversidge did something he always regretted. Turning to the chief dispatcher, he barked, “Why in the hell did I have to come down here to tell you what to do? Why didn’t you do it yourself?”

Then, on legs that could hardly support him, he made his way back to his office.



HORACE P. LIVERSIDGE TERMINATING DIRECT CURRENT SERVICE, OCTOBER 4, 1935

The changeover simplified the marketing of electric motors in Philadelphia. Only alternating current motors were sold, and they could operate anywhere in the city. Philadelphia Electric promoted the sale of electric appliances of all sorts. In a five-year period ending in 1927, the Company sold $9,000,000 worth, which represented about forty per cent of the sales in the Philadelphia area. Next to Commonwealth Edison of Chicago, Philadelphia Electric was the largest retail distributor of electric household devices in the country. Among the major types of equipment it sold in these years were the following:

95,761 irons
2,057 ironers
23,409 lamps
566 refrigerators
21,289 washing machines
340 oil burners

Despite hard campaigning, refrigerators were not yet popular. "Domestic refrigeration is here to stay," stoutly advertised Philadelphia Electric in offering easy payment terms on refrigerators or refrigeration units for iceboxes. Oil burners were also slow in winning public acceptance. In 1924, the Company vigorously advertised the advantages of automatic oil heating for the home. It took its first step in radio broadcasting that autumn by sponsoring a series of non-technical talks about electric service. More than 1,000 electrically driven, oil-heated furnaces were on its lines, it proudly announced. Three years later, there were twelve times that number, but this was merely the beginning.

As new apparatus went on the lines, old equipment was removed. On October 4, 1935, Liversidge shut down a rotary converter at Cherry Substation, taking the last central city DC equipment off the system. The Evening Bulletin Building, the largest conversion job of the entire changeover, had been completed in June, and City Hall on October 4, the day Liversidge opened the switch. The territory between Vine and Pine Streets, river to river—an area of 240 city squares where half a million people lived or worked—was thus successfully changed from DC to AC at a cost of $7,637,345.

During the entire complicated change, not a single serious controversy had arisen. Indeed, customer relations were strengthened by the move. What customer could complain about receiving a brand new desk fan for his 1892 model?

Some of the relics gathered by the Company are now to be seen in the Philadelphia Electric Company's historical collection at 2301 Market Street, others at the Henry Ford Museum in Dearborn, Michigan.

The completion of the Company's changeover, coming at a time when many other companies were just initiating similar changes in their systems, was an outstanding tribute to the foresight and pioneering spirit exemplified by Philadelphia Electric.

REFERENCES

"First AC network system with automatic network protectors installed in New York City in 1923", AIEE Transactions, June 1924

"City of New Orleans layout for AC network systems", AIEE Transactions, Nov. 1924

"Low Voltage AC Networks of the Standard Gas & Electric Co. in Minneapolis, St. Paul, Oklahoma City, Louisville, and Pittsburgh", AIEE Transactions, Jan. 1930

"Philadelphia AC Network System", AIEE Transactions, Sept. 1931

History of the Philadelphia Electric Company, Nicholas Wainwright, 1961. excerpts by Joseph S. Hay, P.E. Senior Engineer, PECO Energy Company, Warminster, PA

Personal communications re Georgia Power Co., Pete Risse, Principal Engineer, Georgia Power Co., Atlanta, GA

Personal communications re NSTAR (Boston Edison), Tom Zazulak, EE

"The Diamond Jubilee of Consolidated Edison Underground Cable", Dave Williams, Wire and Cable Section of the National Electrical Manufacturers Association, Atlantic City, N. J. November 14, 1956

"Original Design of AC Underground Network Systems and Development and Use of Low Voltage Protectors", Nov 1967, provided by Frank Dougherty, EE, ConEd

"Development of Underground Electric System in Downtown Memphis" by W.J. Fransioli, Jr. December 1, 1959

Electric Power Distribution System Engineering, Turan Gonen, McGraw-Hill, 1986

Standard Handbook for Electrical Engineers, 14th Ed., Fink & Beaty, McGraw-Hill, 2000

Standard Handbook for Electrical Engineers, 5th Ed., Fowle, McGraw-Hill, 1922