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the first polyphase system

a look back at two-phase power for ac distribution

THIS ARTICLE DESCRIBES THE first "polyphase" (more than one phase) system developed for the distribution of alternating current (ac) power. This two-phase system was subsequently rendered obsolete, however, by the superior three-phase system that is now universally used throughout the world.

The Origins of Two-Phase Power

Today, the large-scale generation, transmission, and distribution of electric power is by means of the three-phase ac system; that is, three individual single-phase voltages and currents having a 120° phase relationship to each other and intermingled on three wires (excluding a neutral). The three-phase system has been adopted because it provides for a constant rather than pulsating power flow to motors, and because it is an efficient system as far as the amount of copper required per kilowatt transmitted. The theoretical complexity of the three-phase system, however, delayed its complete acceptance in the early days of electric power system development.

During the early 1890s, understanding the behavior of simple single-phase ac was enough of a challenge. It was not until Charles P. Steinmetz, the legendary General Electric scientist, developed the concept of the use of the "j" operator (unity magnitude at a 90° phase angle) and complex numbers for ac circuit calculations that the behavior of voltages and currents in ac circuits and machines was truly understandable. Likewise, it was not until the introduction of what eventually came to be known as "symmetrical components," during the early 20th century, that the calculation of three-phase voltages and currents became relatively straightforward. This technique utilized an "a" operator that was of unity magnitude at a 120° phase angle (–0.5 + j0.866). This operator was of significant value since, in a balanced three-phase system, the voltages and currents are at 120° phase relationships to each other.

Symmetrical components actually facilitated calculations in unbalanced three-phase circuits. They were originally known as "Fortescue components" since the method was introduced in 1918 by Charles L. Fortescue of the Westinghouse Electric Corporation. Significant additional work in this area was later contributed by Edith L. Clarke of the General Electric Company. During the late 19th century, however, this calculation tool did not exist, and the fact that changes in voltage or current magnitudes in one phase of a three-phase system affected the voltages and currents in the other two phases contributed to the difficulty in understanding three-phase circuits.

Thus, the first ventures into the realm of polyphase electric power used only two alternating current phases rather than three. The two phases were generated with a 90° phase difference between them, and the system that resulted was called two-phase power. In fact, the first two-phase generators employed during the early 1890s were merely two single-phase machines coupled together with their rotors carefully set relative to each other so as to achieve the required quadrature phase relationship. Each generator, then, really fed a separate two-wire, single-phase circuit. Since the two phases were completely electrically isolated from each other, there were no interactions between voltage and current magnitudes in one phase with those quantities in the other phase. Therefore, from a theoretical standpoint, the two-phase system was more easily understood than was the three-phase system.

The two phases were used together in a four-wire system to enable the operation of the new Tesla (or induction) motor that had been developed by Nikola Tesla. In order to be self-starting, the Tesla motor required some form of rotating magnetic field that had to be produced by a polyphase type of supply. The two-phase system was adequate for this purpose. The Westinghouse Electric Corporation supplied the power plant and lighting for the Colombian Exposition in Chicago in 1893. Two-phase power, produced by pairs of coupled single-phase generators, was used throughout this installation.

Two-Phase Power at Niagara Falls

The experience gained with the use of two-phase power at the Colombian Exposition may have had some

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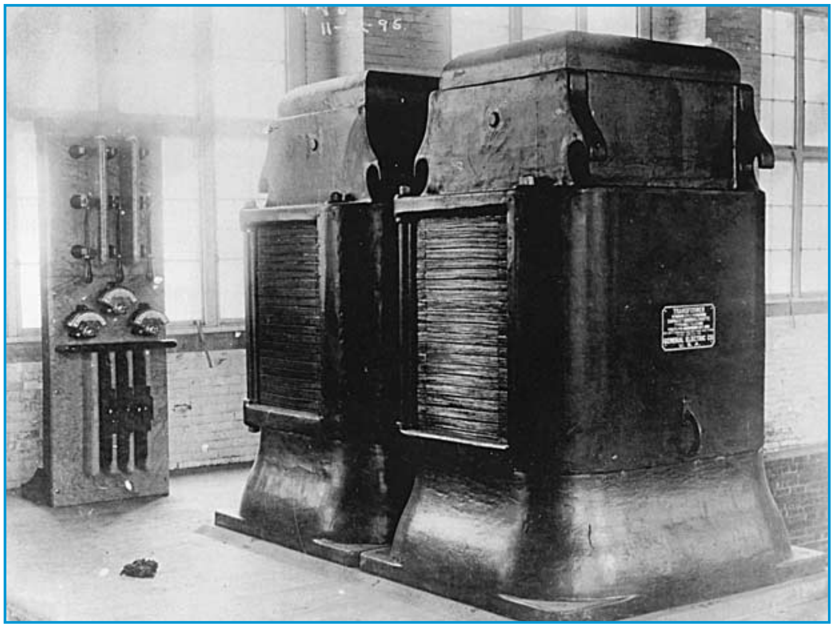


Original two-phase to three-phase transformers installed at Niagara Falls in 1895 (photo courtesy Hall of Electrical History at the Schenectady Museum, Schenectady, New York).

influence on the decision by Westinghouse to employ a two-phase generator design for the first ac powerhouse at Niagara Falls, which went into operation in 1895. The generators used at Niagara Falls were of a more conventional design, being single machines having two interleaved windings rather than two distinct machines coupled together. These generators operated at a frequency of 25 cycles (25 Hz) since it was expected that a significant portion of the power produced would be used to operate rotary converters so as to obtain direct current (dc) for industrial uses such as aluminum production. These early rotary converters required a low frequency for satisfactory operation.

There was obviously still a mistrust of the practicality of three-phase power throughout the electric power industry at that time. For example, according to an 1896 article titled "Present Status of the Transmission and Distribution of Electrical Energy" in the *AIEE Transactions*:

> Where a two-phase transmission with separate circuits is used, then if the separate circuits are wound on different armatures, each can be regulated to give a constant voltage at the receiving end. This is the case, for instance, in the large dynamos built by the Westinghouse Company for use at the World's Fair in Chicago. The difficulty due to the uneven loading of the circuits is specially marked in the case of the three-phase system, and it is one of the principal objections that have been urged against the employment of this system for purposes of distribution.

It had already been realized, however, that the three-phase configuration was superior for transmission from the point of view of efficiency. Thus, special phase-changing transformers were designed by Charles F. Scott of Westinghouse in order to step up the two-phase generated voltage at Niagara Falls to 11,000-V, three-phase for transmission to Buffalo, New York. The General Electric Company was awarded the contract to build the phase-changing transformers and so was licensed by Westinghouse to utilize the connection developed by Scott for this purpose.

At Buffalo, some of this three-phase power was used for rotary converters that supplied 110/220-V dc power for the Edison distribution system downtown. However, some of the received power was converted back into two-phase power for general lighting purposes in outlying areas. Motor-generator sets were used for this latter conversion because the frequency of the ac power was increased as well in order to avoid undesirable flickering of incandescent lamps. The frequency used was actually 62.5 cycles, rather than 60 cycles, so as to simplify the design of these frequency changers. The conversion back to two-phase power was motivated by the conviction, at that time, that satisfactory voltage regulation was more easily achieved in the two separate phases of a two-phase system than in a three-phase system.

This belief in the superiority of two-phase systems with respect to voltage regulation led to the extended use of two-phase distribution in many locales. For example, in Cohoes, New York, (north of Albany) a 1915 hydroelectric station was designed to generate three-phase power. However, some of that power was converted to two-phase using "Scott" type transformers in order to supply an extensive network of existing two-phase feeders for lighting, rather than change those feeders to three-phase operation.

William Stanley Adopts Two-Phase

William Stanley, the man credited with the first practical application of the ac system using transformers (in Great Barrington, Massachusetts, in 1886), subsequently formed the Stanley Electric Manufacturing Company in Pittsfield, Massachusetts, in 1891. Stanley adhered to the design and construction of two-phase generators and motors throughout the 1890s. This was only partly a result of his belief in the superiority of the two-phase system for voltage regulation purposes. Another factor had to do with the increasing development of three-phase equipment by his major competitors, General Electric and Westinghouse, during the 1890s. Stanley's decision to manufacture two-phase equipment allowed him to avoid excessive patent infringement problems with his competitors. Regardless of the reasons, however, Stanley contributed to the perpetuation of the use of two-phase power in many locations.

The Stanley Works itself generated and utilized two-phase power. In 1907, this plant became the Pittsfield Works of the General Electric Company, and the two-phase power system that it had inherited from Stanley remained in use until the closing of the facility in 1987. In fact, to this day, there is still one elevator in an old office building there operating with a two-phase motor.

The two-phase system in this plant was somewhat unusual in that it was a three-wire system. One wire from each phase was combined into what was called a "common" wire (not a "neutral"). The advantage in this was the ability to use more commonly available three-pole circuit breakers and switches. A disadvantage, however, was that even with the two phases balanced, the common wire carried 1.414 times the current in the other two phase wires. Thus, economy in pulling circuits through conduits required the use of two different sized cables. Eventually, the plant had two power distribution systems, the original two-phase system and a newer three-phase system. The two systems were interconnected by means of phase-changing transformers. These were of a design by Louis F. Blume of the General Electric Company and utilized a winding configuration differing from the "Scott" connection, presumably to avoid patent conflicts with the Westinghouse Electric Corporation.

Since Stanley supplied equipment to the local municipal power company, the Pittsfield Electric Company, downtown Pittsfield was also served by a two-phase system. This, however, was the more conventional four-wire type of two-phase distribution requiring four-pole service switches. This two-phase distribution system remained in use until the middle of the last century, and vestiges of it in the form of four-pole switches could still be found on the service switchboard of at least one old building in Pittsfield in the early 1980s. Also, two-phase motors were still being used to drive the elevator motor-generator sets in Pittsfield's only department store when it closed in 1988.

Other Two-Phase Installations

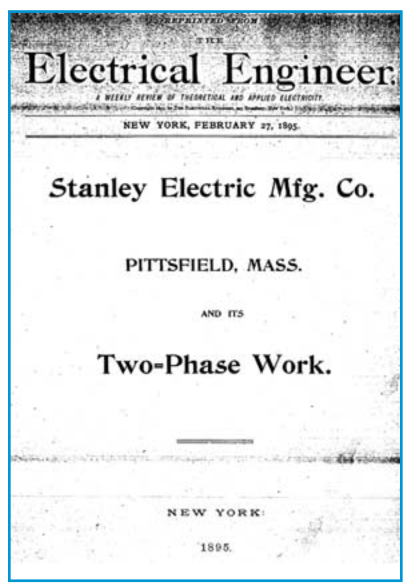
In the village of Middle Falls, New York, (northeast of Albany) the Niagara Mohawk Power Corporation operated a 1900 vintage, 350-kW Stanley two-phase generator in a small hydroelectric power station there until 1987. Another identical unit had been retired in 1976. The output of the station was coupled to Niagara Mohawk's three-phase grid by means of phase-changing transformers.

The generation of two-phase power was not exclusively an East Coast phenomenon, however. In 1898, the Pacific Light and Power Company installed four 300-kW Westinghouse two-phase generators in a hydroelectric station located in San Gabriel Canyon, near Los Angeles, California. This station served the nearby town of Azusa.

As the use of ac motors expanded during the early 20th century, the problem of providing both 115 V for lighting and 230 V for motor use from two-phase distribution systems became significant. One solution was the adoption of a two-phase, five-wire system in which center taps on both phases were connected together to create a neutral. This, then, resulted in a "star" configuration (analogous to the three-phase "wye" connection) and, technically, was a four-phase system. As such, 115 V (single-phase) for lighting was available from any of the four phase wires to the neutral, while 230 V (two-phase) was available for motors from the four phase wires themselves.

In New York City, the Bronx District of the New York Edison Company adopted this form of secondary distribution around 1925. At that time, the Company was interested in upgrading its existing 2,400-V, two-phase primary distribution system to 13,200 V, three-phase. The connected two-phase motor load, however, was too great to consider changing the secondary distribution system from two-phase to three-phase as well, so "T"-connected (Scott) phase-changing transformer banks were installed to supply a two-phase, five-wire secondary distribution system.

During this era, the use of the three-phase, four-wire wye-connected distribution system was often considered to be unacceptable because of the nonstandard voltage (199 V) between phases with 115 V available from phase to neutral. Early induction motors, designed for operation at 230 V, were less satisfactory when operated on lower voltages than are induction motors of today. The ability of the two-phase, five-wire distribution system to supply the standard voltages of 115/230 V was a main feature in a lengthy article published in the AIEE Transactions in 1925 by an engineer associated with the Philadelphia Electric Company in Pennsylvania. This article justified the continued use of that system.



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Stanley Electric Mfg. Co.

PITTSFIELD, MASS.

AND ITS

Two-Phase Work.

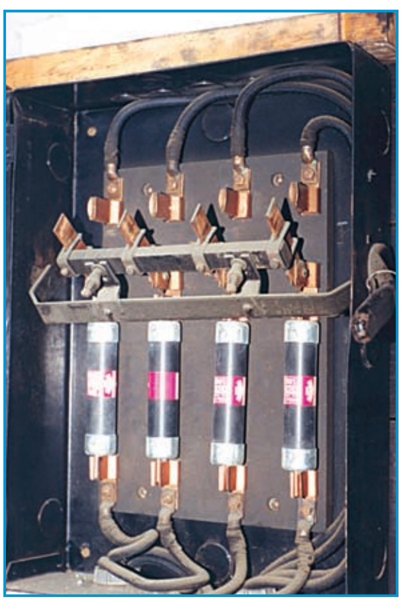
NEW YORK:
1895.

William Stanley's company specialized in two-phase equipment.

The Demise of Two-Phase Systems

Eventually, a hybrid type of three-phase distribution system, which was known as a three-phase, four-wire, "delta" system, came into use in certain regions of the United States. This system included a center tap on one phase of a bank of delta-connected transformers supplying 230 V. The center tap formed a neutral and, in conjunction with the two phase wires of that particular phase, was used to supply 115/230 V services on a single-phase, three-wire basis. Motors operating at 230 V were supplied from the three phase wires of this type of service connection.

Buildings requiring both motor and lighting service were sometimes provided with two separate services, a single-phase, three-wire service for lighting and a three-phase, three-wire service for motors. Otherwise, a single four-wire service was brought into a building, but care had to be exercised by electricians so as not to use the odd phase wire along with the neutral to supply lighting loads. This odd phase was referred to as the "high phase" or "wild phase" because considerably more than 115 V existed between it and the neutral. This complication associated with the four-wire delta type of service led to its gradual abandonment during the latter 20th century because fewer and fewer practicing electricians were able to truly understand it. Also, by that time, induction motors had been developed that operated satisfactorily on voltages lower than 230 V. As a result, the three-phase, wye-connected service, giving 208 V between phases and 120 V from phase to neutral, has become the standard commercial type of service. Also, over the years, old two-phase primary distribution systems were gradually replaced with three-phase systems. A common practice became the conversion of a 2,300-V, two-phase, four-wire distribution system into a 4,000/2,300-V three-phase, four-wire system (with neutral).



A two-phase, four-pole service switch in a building in Pittsfield, Massachusetts (Tom Blalock photo).

Several clever and complex plans were devised for the temporary supply of remaining two-phase loads from a new three-phase system, without the expense of purchasing special phase-changing transformers. One such technique took advantage of the fact that there is a 90° phase relationship between one phase-to-phase voltage and the voltage from the third phase to neutral in a three-phase, four-wire system. Customers were encouraged to purchase three-phase motors, rather than add to their existing inventory of two-phase motors. Many of the old motors, however, lasted for quite some time. Occasionally, a customer actually had to be supplied with two services, one two-phase and one three-phase.

With rare exception today, the two-phase distribution system has become a thing of the past. Its extensive use throughout the 20th century, however, created interesting situations for electrical engineers accustomed to three-phase systems. Occasional oversights, resulting from the unrecognized need for four-pole motor control contactors due to the existence of an old two-phase system, have been known to cause havoc for electrical equipment designers and suppliers.

For Further Reading

J.O. Kraehenbuehl and M.A. Faucett, *Circuits and Machines in Electrical Engineering*. New York: Wiley, p. 268, 1939.

Electrical Transmission and Distribution Reference Book (4th ed.). East Pittsburgh, PA: Westinghouse Electric Corporation, p. 12, 1950.

E.L. Clarke, "Determination of voltages and currents during unbalanced faults," *General Electric Rev.*, pp. 511–513, Nov. 1937.

C. Passer, *The Electrical Manufacturers* (1875–1900). Cambridge, MA: Harvard, 1953.

L.B. Stillwell, "The electric transmission of power from Niagara Falls," *AIEE Trans.*, pp. 444-486, 23 Aug. 1901.

"Present status of the transmission and distribution of electrical energy," *AIEE Trans.*, vol. XIII, Sept. 1896.

H.G. Stott, "The distribution and conversion of received currents," *AIEE Trans.*, pp. 125-163, 22 Mar. 1901.

B.R. Connell, "The Hydro-Electric Development of the Cohoes Company at Cohoes, N.Y.," *General Electric Rev.*, pp. 340–352, May 1915.

L.F. Blume, "Transformer connections for three-phase to two-phase transformation," *General Electric Rev*. pp. 552–559, Sept. 1912.

W.A. Myers, *Iron Men and Copper Wires: A Centennial History of the Southern California Edison Company*. Glendale, CA: Trans-Anglo Books, 1983.

"Distribution for congested areas," *Electr. World*, pp. 1031-1032, 16 May 1925.

P.H. Chase, "Two-phase, five-wire distribution," *AIEE Trans.*, pp. 737–749, June 1925.

"Changing from two-phase four-wire to three-phase four-wire distribution," *Electric J.*, pp. 214–216, June 1923.