War of Currents

In the War of Currents era (sometimes, War of the Currents or Battle of Currents) in the late 1880s, George Westinghouse and Thomas Edison became adversaries due to Edison's promotion of direct current (DC) for electric power distribution over alternating current (AC).

Edison's direct-current system generated and distributed electric power at the same voltage as used by the customer's lamps and motors. This meant that the current in transmission was relatively large, and so heavy conductors were required and transmission distances were limited, to about a mile (kilometre); otherwise transmission losses would make the system uneconomical. At the time, no method was practical for changing voltages of DC power. The invention of an efficient transformer allowed high voltage to be used for AC transmission. An AC generating plant could then serve customers at a great distance (tens to hundreds of miles), or could serve more customers within its economical transmission distance. The fewer much larger plants needed for AC would achieve an economy of scale that would lower costs further. The invention of a practical AC motor increased the usefulness of alternating current for powering machinery.

Edison's company had invested heavily in DC technology and was vigorously defending its DC based patents. George Westinghouse saw AC as a way to get into the business with his own patented competing system and set up the Westinghouse Electric Company to design and build it. The Westinghouse company also purchased the patents for alternating current devices from inventors in Europe and licensed patents from Nikola Tesla. In spite of a protracted anti-AC campaign waged by the Edison company, the economics of the alternating current system prevailed. Alternating current was selected in 1893 for transmission of power from Niagara Falls to Buffalo, New York - the technical and economic success of this project led the way for the adoption of alternating current as the preferred electrical system.

The "War of Currents" is often personified as Westinghouse vs. Edison.[citation needed] However, the "War of Currents" was much larger than that: It involved both American and European companies whose heavy investments in one current type or the other led them to hope that use of the other type would decline, such that their share of the market for "their" current type would represent greater absolute revenue once the decline of the other current type enabled them to expand their existing distribution networks.[citation needed]

Direct current remained in commercial power distribution use for about a century after the "war of the currents", confined to high density urban areas, where, for example, passenger and freight elevators ran on direct current motors. Direct current found a new application in high voltage direct current transmission used to connect power plants to distant customer load. Direct current remained useful in certain traction systems, within vehicles, and in battery-operated systems. Often direct current loads were powered from the alternating current public grid with a rectifier. Direct current is also seeing new application in computer data centers, where DC distribution within a building can provide useful energy savings.

Electric power transmission

DC

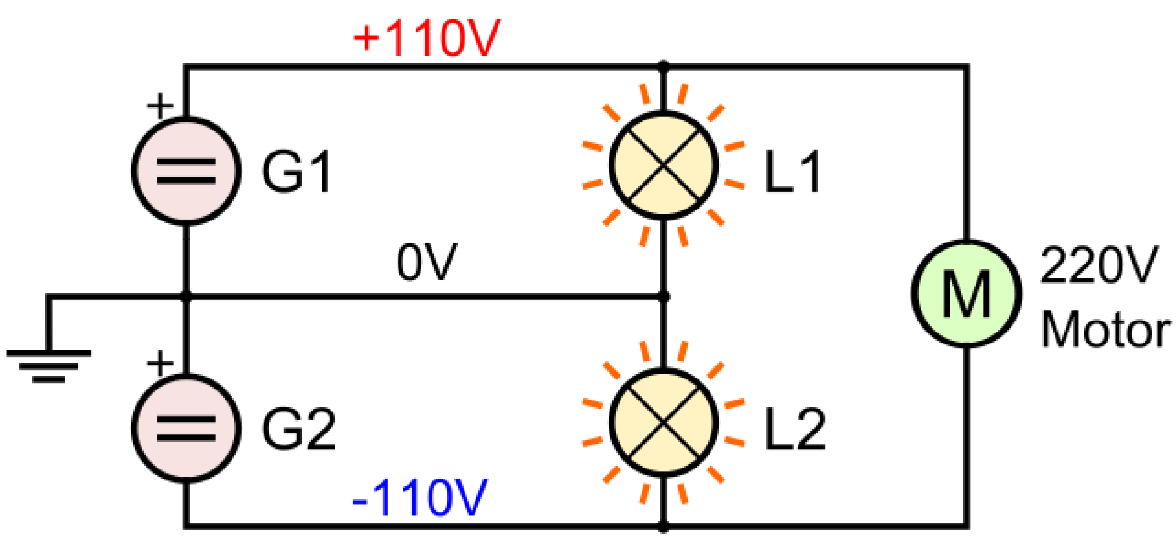

Figure 1 Schematic of Edison's three wire DC electrical power distribution system

During the initial years of electricity distribution, Edison's direct current was the standard for the United States, and Edison did not want to lose all his patent royalties. Direct current worked well with incandescent lamps, which were the principal load of the day, and with motors. Direct-current systems could be directly used with storage batteries, providing valuable load-leveling and backup power during interruptions of generator operation. Direct-current generators could be easily paralleled, allowing economical operation by using smaller machines during periods of light load and improving reliability. At the introduction of Edison's system, no practical AC motor was available. Edison had invented a meter to allow customers to be billed for energy proportional to consumption, but this meter worked only with direct current. The DC distribution system consisted of generating plants feeding heavy distribution conductors, with customer loads (lighting and motors) tapped off them. The system operated at the same voltage level throughout; for example, 100 volt lamps at the customer's location would be connected to a generator supplying 110 volts, to allow for some voltage drop in the wires between the generator and load. The voltage level was chosen for convenience in lamp manufacture; high-resistance carbon filament lamps could be constructed to withstand 100 volts, and to provide lighting performance economically competitive with gas lighting. At the time it was felt that 100 volts was not likely to present a severe hazard of fatal electric shock.

To save on the cost of copper conductors, a three-wire distribution system was used. The three wires were at +110 volts, 0 volts and −110 volts relative potential. 100-volt lamps could be operated between either the +110 or −110 volt legs of the system and the 0-volt "neutral" conductor, which carried only the unbalanced current between the + and − sources. The resulting three-wire system used less copper wire for a given quantity of electric power transmitted, while still maintaining (relatively) low voltages. However, even with this innovation, the voltage drop due to the resistance of the system conductors was so high that generating plants had to be located within 1.6 km or so of the load. Higher voltages could not so easily be used with the DC system because there was no efficient low-cost technology that would allow reduction of a high transmission voltage to a low utilization voltage.

Since direct current could not easily be converted to higher or lower voltages, separate electrical lines had to be installed to supply power to appliances that used different voltages, for example, lighting and electric motors. This required more wires to lay and maintain, wasting money and introducing unnecessary hazards. These hazards, for example, proved fatal to a number of people in the Great Blizzard of 1888, with their deaths being attributed to collapsing overhead power lines in New York City.

Edison considered the need for many local power plants in the direct current system more democratic. Each locale could build electrical plants to suit its need and would not have to rely on a large monopoly to supply electricity. The proponents of AC counter-argued that building a local plant would be too costly for rural areas, leaving them with no electrical supply at all.

A bipolar open-core power transformer developed by Lucien Gaulard and John Dixon Gibbs was demonstrated in London in 1881, and attracted the interest of Westinghouse. They also exhibited the invention in Turin in 1884. However these early induction coils with open magnetic circuits are inefficient at transferring power to loads. Until about 1880, the paradigm for AC power transmission from a high voltage supply to a low voltage load was a series circuit. Open-core transformers with a ratio near 1:1 were connected with their primaries in series to allow use of a high voltage for transmission while presenting a low voltage to the lamps. The inherent flaw in this method was that turning off a single lamp (or other electric device) affected the voltage supplied to all others on the same circuit. Many adjustable transformer designs were introduced to compensate for this problematic characteristic of the series circuit, including those employing methods of adjusting the core or bypassing the magnetic flux around part of a coil.

The direct current systems did not have these drawbacks, giving it significant advantages over early AC systems.

AC

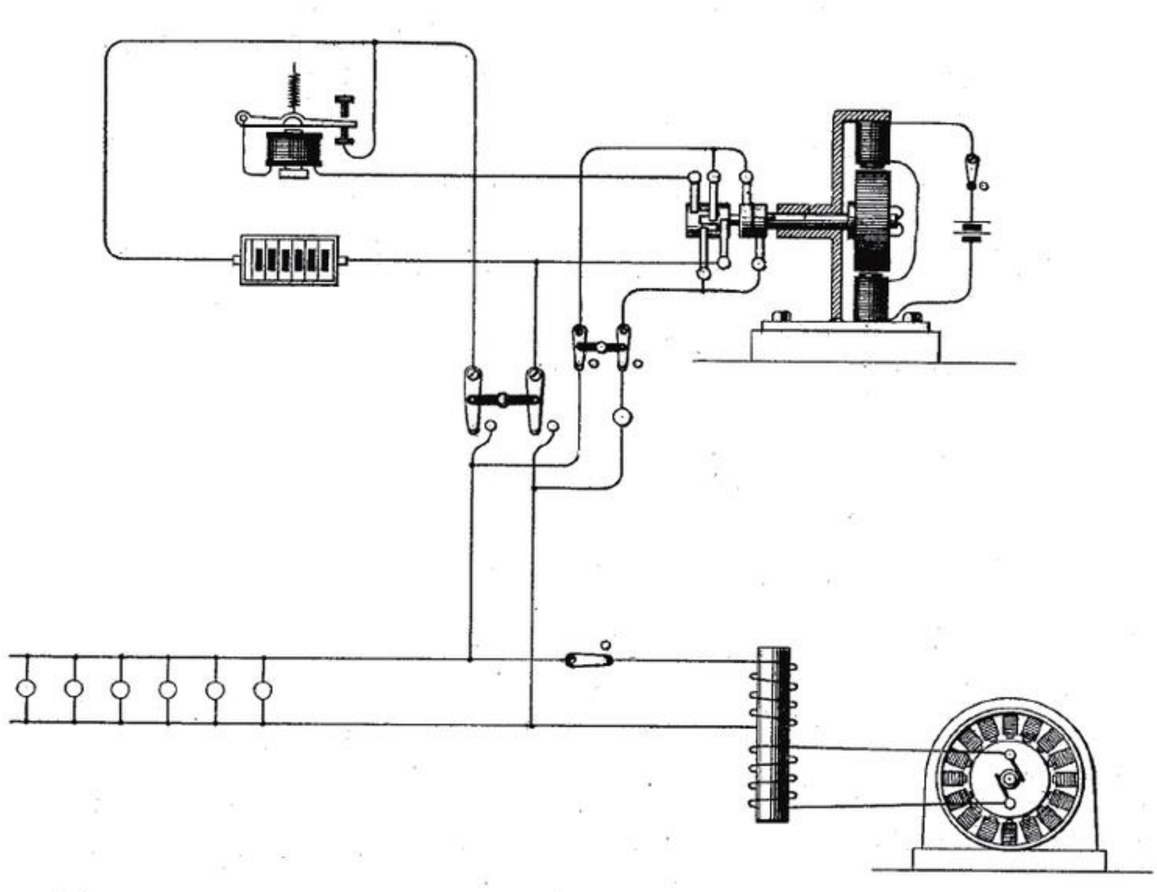

Figure 2 Westinghouse Early AC System 1887 (U.S. Patent 373,035)

In the alternating current distribution system power could be transmitted more efficiently over long distances at high voltages, around ten times that of the loads, using lower current. For a given quantity of power transmitted via DC or AC, the wire cross-sectional area is inversely proportional to the voltage used. Alternatively, the allowable length of a circuit, given a wire size and allowable voltage drop, increases approximately with the square of the distribution voltage. With AC current, a transformer is used to down step the (relatively) high voltage to low voltages for use in homes and factories. This had—and still has—the practical significance that fewer, larger generating plants can serve the load in a given area. Large loads, such as industrial motors or converters for electric railway power, can be served by the same distribution network that fed lighting, by using a transformer with a suitable secondary voltage.

Transmission loss

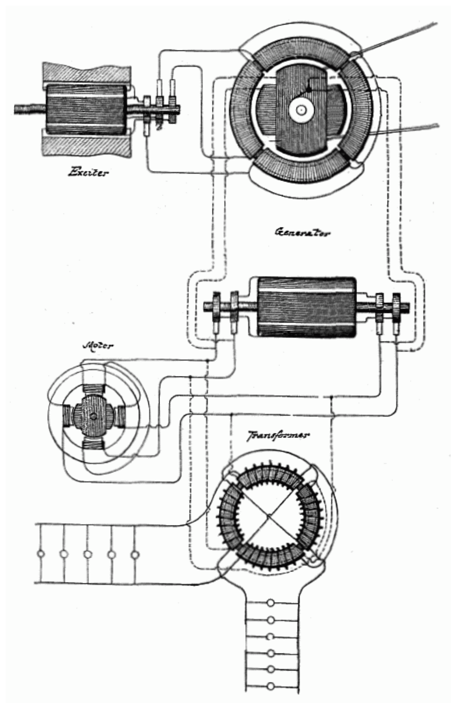

Figure 3 Tesla's US390721 Patent for a "Dynamo Electric Machine"

The advantage of AC for distributing power over a distance is due to the ease of changing voltages using a transformer. Available electric power is the product of current × voltage at the load. For a given amount of power, a low voltage requires a higher current and a higher voltage requires a lower current. Since metal conducting wires have an almost fixed electrical resistance, some power will be wasted as heat in the wires. This power loss is given by Joule's first law and is proportional to the square of the current. Thus, if the overall transmitted power is the same, and given the constraints of practical conductor sizes, high-current, low-voltage transmissions will suffer a much greater power loss than low-current, high-voltage ones. This holds whether DC or AC is used.

Converting DC power from one voltage to another required a large spinning rotary converter or motor-generator set, which was difficult, expensive, inefficient, and required maintenance, whereas with AC the voltage can be changed with simple and efficient transformers that have no moving parts and require very little maintenance. This was the key to the success of the AC system. Modern transmission grids regularly use AC voltages up to 765,000 volts.[6] Power electronic devices such as the mercury-arc valve and thyristor made high-voltage direct current transmission practical by improving the reliability and efficiency of conversion between alternating and direct current, but such technology only became possible on an industrial scale starting in the 1960s.

The Ganz AC system

Figure 4 The prototype transformer is on display at the Széchenyi István Memorial Exhibition, Nagycenk, Hungary

In the autumn of 1884, Károly Zipernowsky, Ottó Bláthy and Miksa Déri (ZBD), three engineers associated with the Ganz factory, had determined that open-core devices were impracticable, as they were incapable of reliably regulating voltage. In their joint 1885 patent applications for novel transformers (later called ZBD transformers), they described two designs with closed magnetic circuits where copper windings were either a) wound around iron wire ring core or b) surrounded by iron wire core. The two designs were the first application of the two basic transformer constructions in common use to this day, which can as a class all be termed as either core form or shell form (or alternatively, core type or shell type), as in a) or b), respectively (see images). The Ganz factory had also in the autumn of 1884 made delivery of the world's first five high-efficiency AC transformers, the first of these units having been shipped on September 16, 1884. This first unit had been manufactured to the following specifications: 1,400 W, 40 Hz, 120:72 V, 11.6:19.4 A , ratio 1.67:1, one-phase, shell form. In both designs, the magnetic flux linking the primary and secondary windings traveled almost entirely within the confines of the iron core, with no intentional path through air (see Toroidal cores below). The new transformers were 3.4 times more efficient than the open-core bipolar devices of Gaulard and Gibbs.

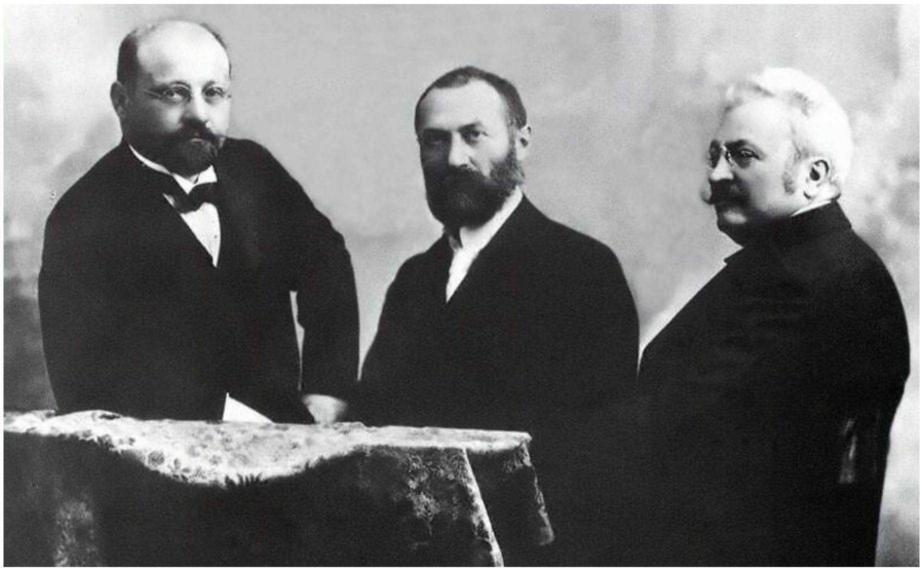

Figure 5 the Hungarian "ZBD" team invented the first high efficiency, closed core shunt connection transformer and practical parallel-connected distribution circuits.

The ZBD patents included two other major interrelated innovations: one concerning the use of parallel connected, instead of series connected, utilization loads, the other concerning the ability to have high turns ratio transformers such that the supply network voltage could be much higher (initially 1,400 to 2,000 V) than the voltage of utilization loads (100 V initially preferred). When employed in parallel connected electric distribution systems, closed-core transformers finally made it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces. Bláthy had suggested the use of closed cores, Zipernowsky had suggested the use of parallel shunt connections, and Déri had performed the experiments; The other essential milestone was the introduction of 'voltage source, voltage intensive' (VSVI) systems' by the invention of constant voltage generators in 1885. Ottó Bláthy also invented the AC electricity meter to complete the competition of AC and DC technology. Transformers today are designed on the principles discovered by the three engineers. They also popularized the word 'transformer' to describe a device for altering the emf of an electric current, although the term had already been in use by 1882. In 1886, the ZBD engineers designed, and the Ganz factory supplied electrical equipment for, the world's first power station that used AC generators to power a parallel connected common electrical network, the steam-powered Rome-Cerchi power plant. The reliability of the AC technology received impetus after the Ganz Works electrified a large European metropolis: Rome in 1886.

In North America one of the believers in the new technology was George Westinghouse. Westinghouse was willing to invest in the technology and hired William Stanley, Jr. to work on an AC distribution system using step up and step down transformers of a new design in March 1886 at Great Barrington. Stanley's alternating current transformer, central-station system for public service was the "very first in America beyond all dispute." Westinghouse tested it more during summer 1886 in Pittsburgh, over a distance of 3 miles. This system used an alternator designed by Stanley to replace the Siemens model, which regulated voltage poorly. Satisfied with the pilot system, Westinghouse began commercial production and shipped his company's first commercial plant to Buffalo NY, where a local utility placed it in service. Orders for 25 alternating-current plants followed within months.With Stanley leaving Westinghouse, Oliver Shallenberger took control of the AC project. In July 1888, George Westinghouse licensed Nikola Tesla's US patents for a polyphase AC induction motor and transformer designs and hired Tesla for one year to be a consultant at the Westinghouse Electric & Manufacturing Company's Pittsburgh labs. Westinghouse purchased a US patent option on induction motors from Galileo Ferraris in an attempt to own a patent that would supersede Tesla's. But with Tesla's backers getting offers from another capitalist to license Tesla's US patents, Westinghouse concluded that he had to pay the rather substantial amount of money being asked to secure the Tesla license. Westinghouse also acquired other patents for AC transformers from Lucien Gaulard and John Dixon Gibbs.

Commercial rivalry

Edison's publicity campaign

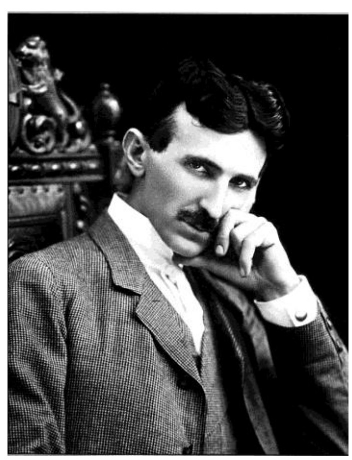

Figure 6 Nikola Tesla, inventor, physicist, and electro-mechanical engineer, who held several instrumental patents in the Westinghouse AC system.

Edison carried out a campaign to discourage the use of alternating current, including spreading disinformation on fatal AC accidents, publicly electrocuting animals, and lobbying against the use of AC in state legislatures. Edison directed his technicians, primarily Arthur Kennelly and Harold P. Brown, to preside over several AC-driven killings of animals, primarily stray cats and dogs but also unwanted cattle and horses. Acting on these directives, they were to demonstrate to the press that alternating current was more dangerous than Edison's system of direct current. He also tried to popularize the term for being electrocuted as being "Westinghoused". Years after DC had lost the "war of the currents," in 1903, his film crew made a movie of the electrocution with high voltage AC, supervised by Edison employees, of Topsy, a Coney Island circus elephant which had recently killed three men.

Edison opposed capital punishment, but his desire to disparage the use of alternating current led to the invention of the electric chair. Harold P. Brown, who was being secretly paid by Edison, built the first electric chair for the state of New York to promote the idea that alternating current was deadlier than DC.

When the chair was first used, on August 6, 1890, the technicians on hand misjudged the voltage needed to kill the condemned prisoner, William Kemmler. The first jolt of electricity was not enough to kill Kemmler, and only left him badly injured. The procedure had to be repeated and a reporter on hand described it as "an awful spectacle, far worse than hanging." George Westinghouse commented: "They would have done better using an axe."

Willamette Falls to Niagara Falls

In 1889, the first long distance transmission of DC electricity in the United States was switched on at Willamette Falls Station, in Oregon City, Oregon. In 1890 a flood destroyed the Willamette Falls DC power station. This unfortunate event paved the way for the first long distance transmission of AC electricity in the world when Willamette Falls Electric company installed experimental AC generators from Westinghouse in 1890. That same year, the Niagara Falls Power Company (NFPC) and its subsidiary Cataract Company formed the International Niagara Commission composed of experts, to analyze proposals to harness Niagara Falls to generate electricity. The commission was led by Sir William Thomson (later Lord Kelvin) and included Eleuthère Mascart from France, William Unwin from England, Coleman Sellers from the US, and Théodore Turrettini from Switzerland. It was backed by entrepreneurs such as J. P. Morgan, Lord Rothschild, and John Jacob Astor IV. Among 19 proposals, they even briefly considered compressed air as a power transmission medium, but preferred electricity. But they could not decide which method would be best overall.

International Electro-Technical Exhibition

The International Electro-Technical Exhibition of 1891 featured the long distance transmission of high-power, three-phase electric current. It was held between 16 May and 19 October on the disused site of the three former “Westbahnhöfe” (Western Railway Stations) in Frankfurt am Main. The exhibition featured the first long distance transmission of high-power, three-phase electric current, which was generated 175 km away at Lauffen am Neckar. It successfully operated motors and lights at the fair.

When the exhibition closed, the power station at Lauffen continued in operation, providing electricity for the administrative capital, Heilbronn, making it the first place to be equipped with three-phase AC power.

Many corporate technical representatives (including E.W. Rice of Thomson-Houston Electric Company, what became General Electric) attended. The technical advisors and representatives were impressed.

AC deployment at Niagara

In 1893, NFPC was finally convinced by George Forbes to award the contract to Westinghouse, and to reject General Electric and Edison's proposal. Work began in 1893 on the Niagara Falls generation project: power was to be generated and transmitted as alternating current, at a frequency of 25 Hz to minimize impedance losses in transmission (changed to 60 Hz in the 1950s).

Some doubted that the system would generate enough electricity to power industry in Buffalo. Tesla was sure it would work, saying that Niagara Falls could power the entire eastern United States. When finished, the first Niagara River hydraulic tunnel would have a capacity to develop 75 MW. None of the previous polyphase alternating current transmission demonstration projects were on that scale of power:

- The Lauffen-Neckar demonstration in 1891 had the capacity of 225 kW
- Westinghouse successfully used AC in the commercial Ames Hydroelectric Generating Plant in 1891 at 75 kW (Single phase)
- The Chicago World's Fair in 1893 exhibited a complete 11,000 kW polyphase generation and distribution system with multiple generators, installed by Westinghouse
- Almirian Decker designed a three-phase 250 kW AC system at Mill Creek California in 1893.

On November 16, 1896, electrical power was transmitted to industries in Buffalo from the hydroelectric generators at the Edward Dean Adams Station at Niagara Falls. The generators were built by Westinghouse Electric Corporation using Tesla's AC system patent. The nameplates on the generators bore Tesla's name. To appease the interests of General Electric, they were awarded the contract to construct the transmission lines to Buffalo using the Tesla patents

Competition outcome

As a result of the successful field trial in the International Electro-Technical Exhibition of 1891, three-phase current, as far as Germany was concerned, became the most economical means of transmitting electrical energy.

In 1892, General Electric formed and immediately invested heavily in AC power (at this time Thomas Edison's opinions on company direction were muted by President Coffin and the GE board of directors). Westinghouse was already ahead in AC, but it only took a few years for General Electric to catch up, mainly thanks to Charles Proteus Steinmetz, a Prussian mathematician who was the first person to fully understand AC power from a solid mathematical standpoint. General Electric hired many talented new engineers to improve its design of transformers, generators, motors and other apparatus.

In Europe, Siemens & Halske became the dominant force. Three phase 60 Hz at 120 volts became the dominant system in North America while 220-240 volts at 50 Hz became the standard in Europe.

Alternating current power transmission networks today provide redundant paths and lines for power routing from any power plant to any load center, based on the economics of the transmission path, the cost of power, and the importance of keeping a particular load center powered at all times. Generators (such as hydroelectric sites) can be located far from the loads.

Remnant DC distribution systems

1947 advertisement for the Dremel Moto-Tool. Note the "AC-DC" designation.

Figure 7 1947 advertisement for the Dremel Moto-Tool. Note the "AC-DC" designation.

Some cities continued to use DC well into the 20th century. In central Helsinki, there was a DC network in existence up until the late 1940s, and in the 1960s, Stockholm's dwindling DC network was eliminated. A mercury-arc valve rectifier station could convert AC to DC where networks were still used. In 1942, the Greenwich Village neighborhood in New York City used DC. Parts of Boston, Massachusetts along Beacon Street and Commonwealth

Avenue still used 110 volts DC in the 1960s, causing the destruction of many small appliances (typically hair dryers and phonographs) used by Boston University students, who ignored warnings about the electricity supply. New York City's electric utility company, Consolidated Edison, continued to supply direct current to customers who had adopted it early in the twentieth century, mainly for elevators. The New Yorker Hotel, constructed in 1929, had a large direct-current power plant and did not convert fully to alternating-current service until well into the 1960s. This was the building in which AC pioneer Nikola Tesla spent his last years, and where he died in 1943. In January 1998, Consolidated Edison started to eliminate DC service. At that time there were 4,600 DC customers. By 2006, there were only 60 customers using DC service, and on November 14, 2007, the last direct-current distribution by Con Edison was shut down.[49][53] Customers still using DC were provided with on-site AC-to-DC rectifiers. The city of San Francisco, California featured a DC power grid to supply power for pre-1940s winding-drum elevators. Around the end of 2010, the DC grid was divided into 171 separate islands with each island supplying 7 to 10 customers.

The Central Electricity Generating Board in the UK continued to maintain a 200 volt DC generating station at Bankside Power Station on the River Thames in London as late as 1981. It exclusively powered DC printing machinery in Fleet Street, then the heart of the UK's newspaper industry. It was decommissioned later in 1981 when the newspaper industry moved into the developing docklands area farther down the river (using modern AC-powered equipment). The building was converted into an art gallery, the Tate Modern.

Electric railways that use a third-rail system generally employ DC power between 500 and 750 volts; railways with overhead catenary lines use a number of power schemes including both high-voltage AC and high-current DC.

Long distance DC power transmission

High-voltage direct current (HVDC) systems are used for bulk transmission of energy from distant generating stations, or for interconnection of separate alternating current systems. These HVDC systems use electronic devices like mercury-arc valves, thyristors, or IGBTs that were unavailable during the War of Currents era. Power is converted to and from alternating current at each side of the HVDC link. An HVDC system can transmit more power over a given right-of-way than an AC system, which is an advantage in overall cost. HVDC systems allow better control of power flows in transient and emergency conditions, which help prevent blackouts. HVDC is an alternative to AC systems for long-distance, high-load transmission.

DC uses

DC power is still common when distances are small, and especially when energy storage or conversion uses batteries or fuel cells. Some of these applications include electronic devices, Vehicle starting, lighting, and ignition systems. "Off-grid" isolated power installations using wind or solar power may use DC between sources and loads, over limited distances. One concept for use in a computer data center would power individual processing units from a DC system distributed around a computer room or building. This would eliminate individual system rectifiers. The distributed DC system would eliminate some energy losses associated with individual computer power supply rectifiers. By feeding the system from batteries, the cost and unreliability of individual uninterruptible power supplies (UPS) would be reduced. The 380 volt level is compatible with the typical ratings of components now used in computer power supplies.[55] Similarly, copper telephone lines can be used to transmit network line power at 380 volts DC for long distances, which then can be converted to lower voltages to power outdoor electronic equipment. Power and safety standards for network line power (NLP) technology are defined in the National Electric Code (NEC) Article 830.