Lecture 7: Supply Systems- War of currents

7.1 War of currents. AC vs DC

The war of the currents (sometimes called **battle of the currents**) was a series of events surrounding the introduction of competing electric power transmission systems in the late 1880s and early 1890s. It included commercial competition, a debate over electrical safety, and a media/propaganda campaign that grew out of it, with the main players being the direct current (DC)–based Edison Electric Light Company and the alternating current (AC)–based Westinghouse Electric Company. It took place during the introduction and rapid expansion of the alternating current standard (already in use and advocated by several US and European companies and its eventual adoption over the direct current distribution system. Three aspects have been conflated into the "war": open competition involving large electric companies and a format war involving their developing systems, a general fear in the public's mind of death by accidental electrocution from high voltage AC leading to a debate over its safety and regulation, and the debate and behind-the-scene maneuvers associated with the introduction of the electric chair.

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 against alternating current (AC) advocated by several European companies and Westinghouse Electric based in Pittsburgh, Pennsylvania, which had acquired many of the patents by Nikola Tesla.

The direct-current system generated and distributed electrical power at the same voltage as used by the customer's lamps and motors. This required the use of large, costly distribution wires and forced generating plants to be near the loads. With the development of a practical transformer, alternating-current power could be sent long distances over relatively small wires at a convenient high voltage, then reduced in voltage to be used by a customer. Alternating current generating stations could be larger, cheaper to operate, and the distribution wires were less expensive. As the competing systems were protected by patents, there was commercial rivalry between the Westinghouse and Edison companies. A publicity campaign by Edison highlighted the safety issues of high voltage transmission.

The lower cost of AC power distribution prevailed, though DC systems persisted in some urban areas throughout the 20th century. The last DC power transmission system in the United States was decommissioned in 2007. While DC power is not used generally for the transmission of energy from power plants into homes as Edison and others intended, DC power is still common when distances are small and is used in essentially all modern electronic devices, such as computers, telephones, and automotive systems.

7.2 Background

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 the associated 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 operated in parallel, 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. As of 1882 these were all significant technical advantages of direct current. Several companies founded by Edison's investors were consolidated with the incorporation of the General Electric Company in 1889.

Alternating current had first developed in Europe due to the work of Guillaume Duchenne (1850s), Ganz Works (1870s), Sebastian Ziani de Ferranti (1880s), Lucien Gaulard.

Figure 7.1.The prototype transformer is on display at the Széchenyi István Memorial Exhibition, Nagycenk, Hungary

A prototype of the high efficiency, closed core shunt connection transformer was made by the Hungarian "Z.B.D." team (composed of Károly Zipernowsky, Ottó Bláthy and Miksa Déri) at Ganz Works in 1884. The new Z.B.D. transformers were 3.4 times more efficient than the open core bipolar devices of Gaulard and Gibbs. Transformers in use today are designed based on principles discovered by the three engineers. Their patents included another major related innovation: the use of parallel connected (as opposed to series connected) power distribution. Ottó Bláthy also invented the first AC electricity meter. The reliability of the AC technology received impetus after the Ganz Works electrified the large European metropolis of Rome in 1886.

7.3 The competing systems

Edison's DC distribution system consisted of generating plants feeding heavy distribution conductors, to customer loads primarily lighting and motors. 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, the margin allowed 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. 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 a mile (1–2 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.

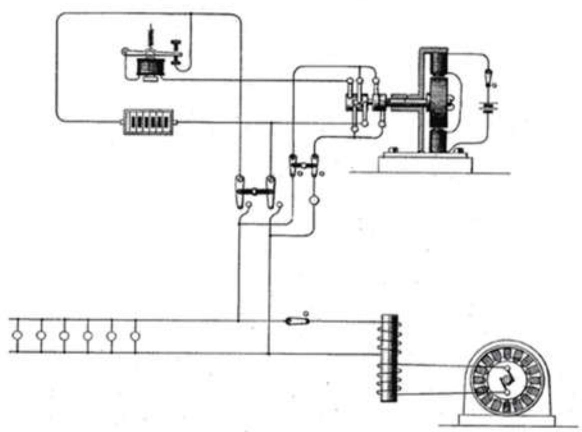

Figure 7.2 Westinghouse early AC system 1887 - U.S. Patent 373,035

In the alternating current system, a transformer was used to reduce the voltage from the (relatively) high voltage distribution system to a lower and safer voltage for the customer loads. Lamps and small motors could still be operated at some convenient low voltage, but the transformer would allow power to be transmitted at much higher voltages, of say, ten times that of the loads. For a given quantity of power transmitted, the wire cross-sectional area would be inversely proportional to the voltage used. Alternatively, the allowable length of a circuit, for a given wire size and allowable voltage drop, would increase approximately as the square of the distribution voltage. This meant that fewer, larger generating plants could serve the load in a given area. Large loads, such as industrial motors or converters for electric railway power, could be served by the same distribution network that fed lighting, by using a transformer that reduced the voltage to a suitable secondary voltage.

Edison's response to the limitations of direct current was to generate power close to where it was consumed (today called distributed generation) and to install large conductors to handle the growing demand for electricity, but this solution proved to be costly (especially for rural areas which could not afford to build a local station or to pay for the expensive, very thick copper wire), impractical (including inefficient voltage conversion) and unmanageable.

Direct current could not easily be converted to higher or lower voltages. This meant that 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. Some deaths in the Great Blizzard of 1888 were attributed to collapsing overhead power lines in New York City. Any practical distribution system, capable of delivering commercially significant power, will use voltage levels sufficient for a dangerous amount of current to flow, whether it uses alternating or direct current. As precautions against electrocution are similar for both AC and DC, the technical and economic advantages of AC power transmission outweighed this theoretical risk, and it was eventually adopted as the standard worldwide.

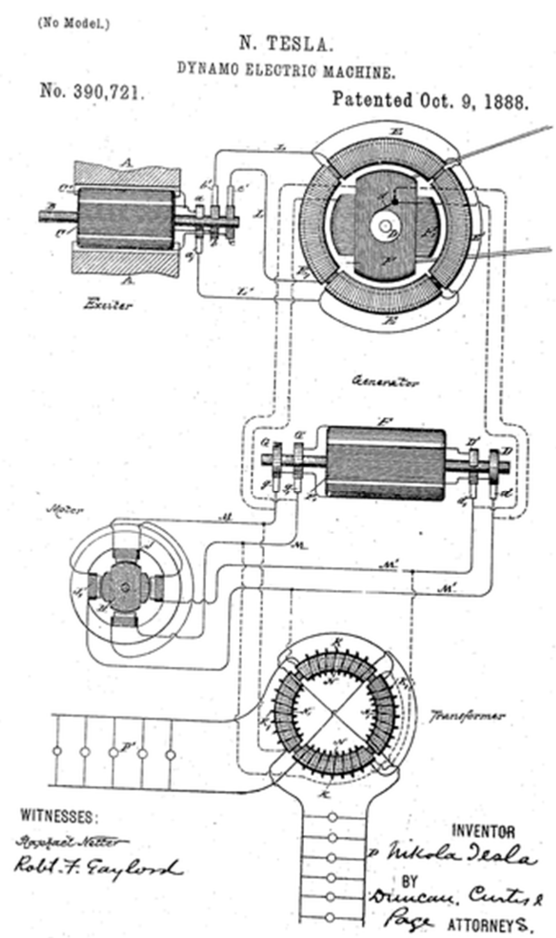

Figure 7.3

The advantage of AC for distributing power over a distance is due to the ease of changing voltages using a transformer. Available 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 laws 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 requires 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. 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.

Alternating-current transmission lines have losses that do not occur with direct current. Due to the skin effect, a conductor will have a higher resistance to alternating current than to direct current; the effect is measurable and of practical significance for large conductors carrying thousands of amperes. The increased resistance due to the skin effect can be offset by changing the shape of conductors from a solid core to a braid of many small (isolated) wires. Total losses in systems using high-voltage transmission and transformers to reduce (or increase) the voltage are very much lower than DC transmission at working voltage.

7.4 Edison's publicity campaign

Edison carried out a campaign to discourage the use of alternating current, including spreading disinformation on fatal AC accidents, publicly killing 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.[28] 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 system 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."

7.5 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.

7.6 International Electro-Technical Exhibition

The International Electro-Technical Exhibition of 1891, in Frankfurt, Germany, 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 attended, including E.W. Rice of the Thomson-Houston Electric Company (later merged into General Electric). The technical advisors and representatives were impressed.

7.7 AC deployment at Niagara

In 1893, Niagara Falls Power Company (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 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. None of the previous polyphase alternating current transmission demonstration projects were on the scale of power available from Niagara:

- 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.

7.8 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 merged with Thompson-Houston 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 and Halske became the dominant force. 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. High voltage power transmission allows generators (such as hydroelectric sites) to be located far from the loads.

7.9 Remnant and existent DC systems

Some cities continued to use DC well into the 20th century. For example, central Helsinki had a DC network until the late 1940s, and Stockholm lost its dwindling DC network as late as the 1970s. A mercury arc valve rectifier station could convert AC to DC where networks were still used.

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 still converted to and from alternating current at each side of the modern HVDC link. The advantages of HVDC over AC systems for bulk transmission include higher power ratings for a given line (important since installing new lines and even upgrading old ones is extremely expensive) and better control of power flows, especially in transient and emergency conditions that can often lead to blackouts. Many modern plants now use HVDC as an alternative to AC systems for long distance, high load transmission, especially in countries such as Russia, China, India and Brazil. One of the principal advantages is the ability to transfer power between two AC systems that are not in synchronized in phase.

DC power distribution is still common when distances are small, and especially when energy storage or conversion uses batteries or fuel cells. These applications include:

- Electronics, including integrated circuits, high-power transmitters and computers, Vehicle starting, lighting, and ignition systems
- Hybrid and all-electric vehicle propulsion with internal power supply, Telecommunication plant power (wired and cellular mobile)
- Uninterruptible power for computer systems
- Utility-scale battery systems
- "Off-grid" isolated power installations using wind or solar power

In these applications, direct current may be used directly or converted to alternating current using power electronic devices. In the future, this may provide a way to supply energy to a grid from distributed sources. For example, hybrid vehicle owners may rent the capacity of their vehicle's batteries for load-levelling purposes by the local electrical utility company.

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