Humanity's Largest Machine, the Global Electric Power Grid: Why and How Was It Created

Part One - "Two Systems Collide"

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INTRODUCTION

During the final two decades of the 19th century, the creation of what became the universal electric grid involved many twists and turns played out on the continents of Europe and North America. The two decades saw immense leaps in electrical engineering technology that brought about a radical alteration of the human landscape during the early 20th century. In 1900, 95 percent of Americans lit their homes with gas, kerosene, or oil, and less than 5 percent of US factory power was provided by electricity. During the next quarter century, these humble statistics would change swiftly in favor of the use of electric power provided by large and increasingly networked grids. What were the revolutionary changes in electric technology that gave birth to the world's largest machine?

REVERSE SALIENTS: THE CASE OF THE DC GRID

Despite its triumphant debut in September 1882, Edison's Pearl Street grid, the world's first commercial-scale grid, faced serious technical and economic challenges. An Edison confidant recalled that "in the fall of 1882 former ...boosters had become critics" and Edison's foremost investor, JP Morgan, had "*classed Mr. Edison as an imposter, a fakir and a charlatan*" because he had made so many false promises involving missed deadlines [1]. A year and a half later, in late April 1884, things had not changed much: "Edison found himself *in a very bad hole*" financially, as return on investment continued to suffer because of the slow rate of adoption of his central station business both in the US and Europe, where he had set up subsidiaries [2]. The slow rate was due to inefficiencies, technical and economic, that caused entrepreneurial developers to hesitate at the new technology's threshold.

Thomas P Hughes, an historian of science and technology, used the World War I military term "reverse salient" – a weakness in an army's line of advance – to describe how a new technological system's significant shortcomings must be solved before the system can progress and eventually become universally adopted or victorious. “A reverse salient appears in an expanding system when a component of the system does not march along harmoniously with other components” so that “the growth of the entire enterprise is hampered, or thwarted” [3].

Edison’s direct-current system had at least two major reverse salients to overcome. One was the system’s narrow range or reach, dictated by DC’s low-voltage transmission and the cost of copper, which together inhibited its profitability. According to Ohm’s Law, “the amount of electricity delivered, the current, is equal to [the] voltage” pushing it through a conductor “divided by the resistance,” resistance being a universal property of any wire or other electrical conductor. “In other words, direct-current electricity – with its low voltages – requires heavy and expensive copper wire” because the further electricity travels, the more it is subject to resistance, a force akin to friction, and the more energy it loses as heat [4]. To compensate for losses over distance heavier copper was used as it had less resistance than thinner wire (the thinner the wire, the more resistance and the greater the loss of power, especially over distance). But copper was expensive, the most expensive component of Edison’s grid system.

DC’s low voltage confined it to a limited service area, mainly high-density urban cores. But the demand for electricity was rising everywhere, not just in densely populated cities. “DC power could not be relied on to supply electricity to a nation expanding westward at an alarming rate” [5].

Another reverse salient was the lack of an efficient motor that could be widely adopted by industry and serve to balance the nighttime lighting load with enough daytime industrial demand, so that the extraordinarily expensive machine – the grid in its entirety – could be employed round-the-clock at close to full capacity.

Of these two, the more intransigent problem was the DC system’s meager potential for long-distance deployment. It was initially limited to a service area no more than a mile in diameter. In 1882, a young consulting engineer named Frank J Sprague helped Edison develop his three-wire system, which employed two connected 110-volt dynamos that doubled transmission voltage output to 220 volts and then utilized a middle or “neutral” third wire placed between the positive and negative sides of the system’s circuit to split the transmission voltage so it could be locally distributed at 110 volts for end users’ lighting needs on either side of the complete circuit. The 220-volt power effectively tripled the system's service range. At the same time, it reduced the cost of the copper by over 60 percent, since thinner wire could be used due to the increased voltage and lower current required.

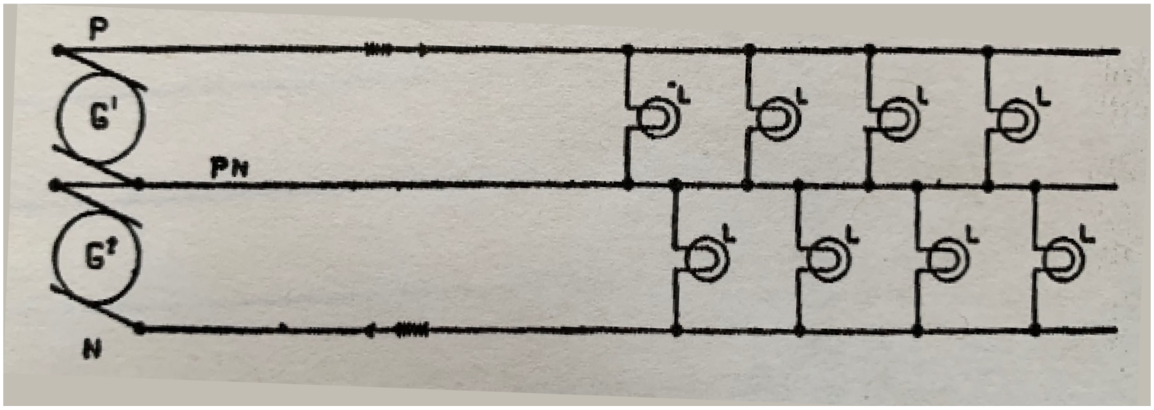


FIGURE 1. Schematic of Edison's 3-wire system, which is basically two circuits combined as one system. One side is positive, represented by the conductors P and PN, the other, negative, represented by the conductors PN and N. The central or neutral conductor "serves in two capacities – namely as negative to generator G^1 or as positive to generator G^2" but is "normally neutral" if the loads on both sides of the system are balanced. "Each side...has a potential of about 110 volts" which it feeds to the lamps connected in parallel. The potential of the outside, main circuit is 220 volts. SOURCE: https://www.gutenberg.org/files/820/820-h/820-h.htm

With the grant of Edison's three-wire patent in March 1883, licensing requests by start-up utilities started to flow in from all over the country. Edison chose Brockton, Massachusetts, and Sunbury, Pennsylvania, as his first tests for the three-wire system, one with less-expensive above-ground wires, the other with buried wires. In June 1883, Edison hired Sprague full-time to help him oversee the installation of the first overhead three-wire "village" utility in Sunbury, completed on July 4th to great local fanfare. Sunbury featured specially constructed poles that carried the three wires to customers and demonstrated that the installation costs of an overhead system were significantly lower. The Sunbury pilot increased small-town demand for electric utility service.

After Sunbury, Sprague oversaw Edison's much larger and more expensive buried three-wire system for the city of Brockton. It was completed in October 1883. Edison considered Brockton, not Pearl Street, "his first complete model and his first showcase system" [6], since his two-wire Pearl Street system was already anachronistic. The success of these two pioneering towns' overhead and buried three-wire systems spurred demand for electric lighting: “it was now ... possible to establish plants in towns where the large investment would otherwise have been quite prohibitive” [7]. Installations immediately followed in towns and cities in New England, New York, and Pennsylvania, spreading throughout the country as well as in some large European cities, starting with Milan in 1883.

Decades later Edison biographers could claim that the three-wire innovation “is in universal use today, alike for direct and alternating current” [8]. The Edison system’s first reverse salient had been *partially* resolved. Its reach was extended. But at two or so miles, it was still modest. It did not resolve the challenge of achieving long-distance universal service.

A Second Reverse Salient: Sprague’s DC Motors Balance the Load

While he worked in Brockton as the installation manager, Sprague, who over the course of 1883 had seen how primitive and inefficient the reversed dynamos employed as electric motors were, began devising new electric motors. Apart from reversed dynamo motors, most “industrial machinery was operated by stationary steam engines that were expensive, noisy, and dirty ... occupied substantial space, required water, boilers, coal delivery, and ash removal. Power was transmitted to tools by a dangerous, inefficient, and maintenance intensive system of shafts, pulleys, and belts. Casualties among the workers were common” [9]. The need for an industrial-capable electric motor beckoned inventors and investors.

Sprague quit work for Edison in the spring of 1884 to form the Sprague Electric Railway and Motor Company to make electric motors. To save investment costs, Sprague jobbed out the manufacturing of these motors to Edison’s Machine Works, and Edison and Sprague’s business enterprises remained linked on a very practical level. At the September 1884 Philadelphia Electric Exposition, Sprague displayed a range of new electric motors that were both powerful and efficient, and “operated at a constant speed with little or no sparking.” His new motors “took industry by storm” [10]. Edison himself immediately endorsed Sprague’s new motor “*as the only true motor; the others are but dynamos turned into motors. His machine keeps the same rate of speed all the time, and does not vary with the amount of work done*” [11]. In his first year of business, Sprague sold 3,000 motors to run fans, textile machinery, cranes, lifts, machine tools, as well as a variety of other industrial work. The sale of electric motors introduced a daytime load “that made small utility companies financially viable" [12] and within a decade "brought phenomenal growth and financial stability" to the new DC central-station-utility industry [13].

Sprague's greatest impact on the nascent electric utility industry was, however, his traction motor, his main motivation for founding his company. Cities had been served by horse-drawn passenger cars since the 1830s, and in the intervening half century, the horse-drawn streetcar had become a huge industry. "In 1881...there were some 415 street railway companies in the United States, and they operated 18,000 cars over 3,000 miles of line and transported well over one billion Americans every year." Some "eight to ten animals that had to be fed" were required to keep each one of those 18,000 cars in service. They lasted on average two to four years performing the arduous work of hauling, and "thousands of new horses had to be acquired every year" to replace the dead, sick, and lame [14]. In New York City alone, the "horses were also dropping hundreds of tons of manure and tens of thousands of gallons of urine per day. Vacant lots were piled high with enormous mounds of stinking dung" [15]. By the mid-1880s "dissatisfaction with slow, smelly, crowded horse cars had been building up for a decade" across America in cities large and small [16].

Sprague tried to persuade the owners of Manhattan's elevated coal-and-steam-powered railroads, which by 1880 "were running close to 2,000 daily trains and transporting 61 million annual passengers," to shift to electric power. Manhattan's elevated system had been largely completed by 1880 and in 1885 Brooklyn was just beginning to build its own elevated system. Meantime Manhattan residents "and businesses along the elevated routes objected to the steady rain of smoke, cinders, and steam from the locomotives, while hot coals and sparks dropped into the streets below" [17].

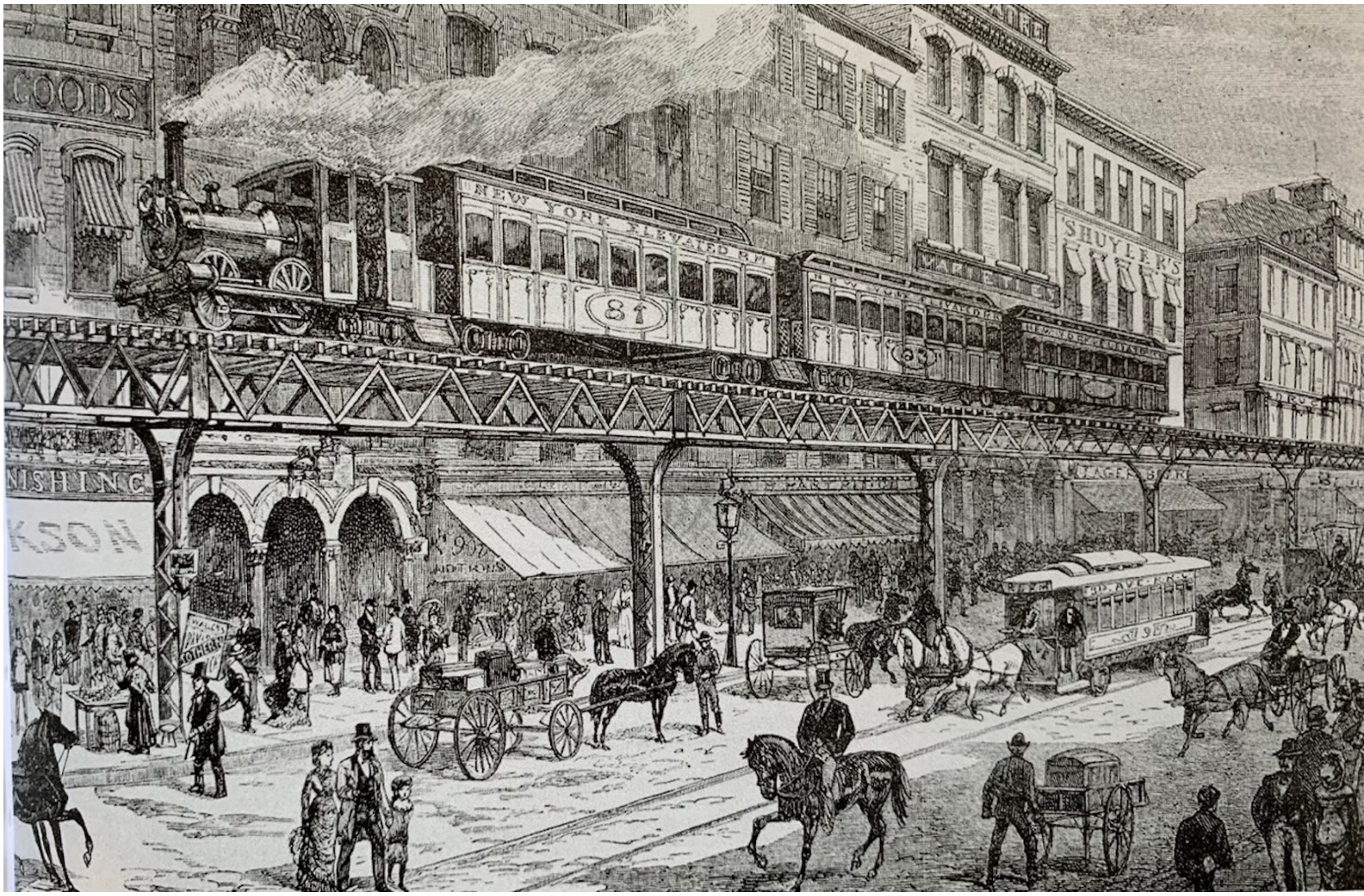
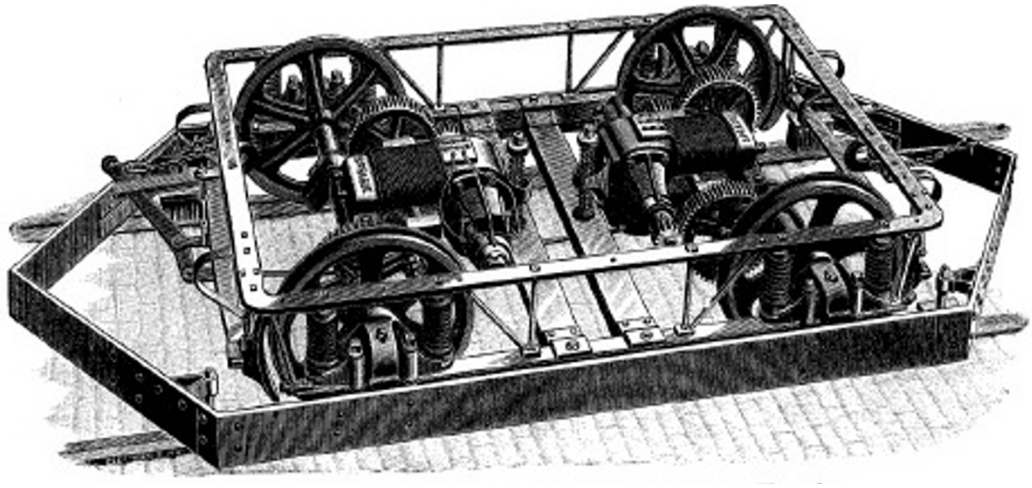


FIGURE 2. The New York Elevated Railroad in 1879. Note the horse-drawn, rail car or bus on the street below. The steam-powered "El" remained in operation for more than 20 years. SOURCE: https://www.mediastorehouse.com/granger-art-on-demand/new-york-el-train-1879-elevated-railway-7527444.html

Completely frustrated by his lack of success in Manhattan's elevated transport system, Sprague had begun to turn his attention to streetcar railways when the city of Richmond, Virginia, invited him to build what "would be by far the largest electric railway ever undertaken anywhere in the world" [18]. In mid-1887, Sprague confronted Richmond's "horse-killer" topography of steep grades, sharp turns, unpaved streets, and clay soil that had proved "ruinously expensive to operate" with horse-drawn cars [19]. He "had to build more electric cars than there were in the entire world," 40 in all, 30 of which had to be capable of simultaneous operation over 12.5 miles of track that had to be built afresh [20].

By mid-May 1888, Sprague and his engineers had revolutionized electric transport, creating a suite of interlocking technological innovations that would endure far into the future. “These included,” according to two Sprague biographers, “the use of a single overhead conductor with current collection by an under-running trolley” – a wheel adapted from an earlier Charles Van Depoele design that made overhead contact with the line – “motors on each car, mounted below the car [floor] and suspended by an arrangement that made it possible for motor and axle movement without misaligning the gearing,” as well as “a series-parallel controller ... mounted on each end of the car so that it could be operated in either direction” [21].

Sprague placed his 7.5 horsepower motors below the carriage floor, “wheelbarrow-style,” two per axle, enabling him “to gear the motors directly to the axles, removing the need for inefficient and unreliable chain drives” and freeing up “more room within the motor cars, increasing carrying capacity.” Sprague’s traction motors “maintained constant speed regardless of the load they were carrying” [22]. When the motor armatures overheated during the system’s steepest ascents, Sprague and his team modified “the car’s motors from a single reduction arrangement to a double reduction gearing” [23]. The positive 450-volt overhead circuit was completed by the car’s wheels running along the negative metal rails. When the train slowed down, its “shunt-wound motors...enabled the cars to return current to the line,” back to the central station’s steam-powered 375-horsepower generator, saving considerable energy [24].



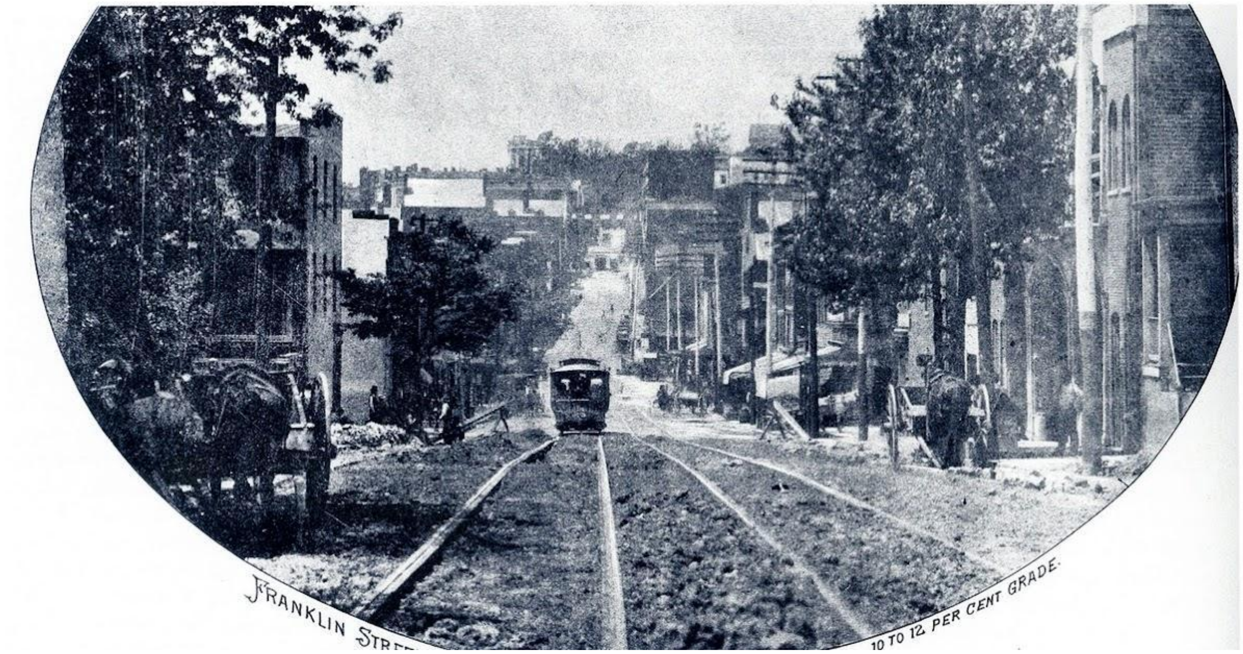


FIGURE 3. Top: an image of Sprague’s 7.5 horsepower axle-mounted motors with double-reduction gearing on a rail “truck,” or car. Bottom: an 1888 photograph of a Sprague electric car climbing Richmond’s steepest grade on Franklin Street. SOURCE: https://www.monroestreetbooks.com/item/ORIG-VINTAGE-MAGAZINE-COVER-CENTURY-MAGAZINE-AUGUST-1905_NA-414116

It soon became known that the new Richmond electric rail system ran “at a fraction of the operating cost of a horse-drawn railway” [25], and as the news of its success spread, it “set in motion an extraordinary shift in street railways to electric power” [26]. Within two years “one-sixth of all street railway track in the United States was electrified” [27]. Shortly after the turn of the century “some 30,000 miles of street railway lines were running, 98 percent of them electric,” in the US. The electric streetcar was “one of the most rapidly accepted innovations in the history of technology” [28]. The phenomenon was not confined to the US: the “Sprague-type of tramway spread into hundreds of cities and towns all over the world...the tramcar as the world knew it was Sprague’s” [29].

The Edison DC system’s second salient, creation of daytime industrial and mass transportation demand for power to offset the nighttime residential lighting load, was resolved, largely thanks to the rapid adoption of Sprague’s industrial and traction motors worldwide. In the 1890s Sprague’s new electric elevator motors added powerfully to the DC electrical system’s infrastructure, especially in large cities, and the early build-up of a worldwide DC-machine infrastructure would insure the future of the DC system well into the 20th century.

THE RISE OF THE ALTERNATING CURRENT (AC) SYSTEM

AC generators, or alternators, were first publicly used to light Yablochkov's "candles" or arc-light streetlamps, starting with the 1878 Paris Exposition, which created an overnight European demand for the new public lighting, followed within a year by American demand [30]. That same year, the Ganz Works in Budapest established an electrical engineering department under the direction of an engineer named Károly Zipernowski. The new department decided to develop a complete single-phase alternating current production and distribution system. By 1883, Ganz "had made over fifty installations" based on AC, and with the help of two young engineers who had joined Zipernowski, Miksa Déri and Otto Bláthy, Ganz launched an AC system in the Austro-Hungarian Empire more or less simultaneously with the early development of Edison's direct-current system in America. Offering "an entire system consisting of both arc and incandescent lamps, generators, and other accessories," the Ganz engineers "used parallel circuits and constant voltage generators" that they themselves had devised to create the world's first single-phase AC power system [31].

In the early 1880s "the prevailing thought was that electricity, whether DC or AC, could only be transmitted about a mile ... and only used for lighting" [32]. Both systems relied exclusively on generators to transmit power, and both were limited by how much voltage a generator could provide (far less than the future transformer). Thus, the "absence of a method for transmitting electric power over distance seriously handicapped plans for the more widespread use of alternate current electric power" [33]. In effect, the early single-phase AC systems mirrored the DC system's unresolved conundrum of long-distance transmission. The arc lamp and the incandescent light bulb otherwise responded equally well to either direct or alternating current.

The DC and AC power systems were not equals, however, when it came to long distance travel. In each, power or energy *moves differently*, and in the end this difference proved determinative.

Why AC and DC Systems Are Different

It is helpful to recall that direct current is what inventors and scientists were familiar with ever since Volta introduced his battery at the outset of the 19th century. Batteries make direct current. For almost 70 years batteries were the primary source of electric power, including the power that ran the worldwide telegraph system. In 1831, using a battery for power, Michael Faraday conducted a famous series of experiments that demonstrated what he called “Electro Magnetic Induction,” one of the most consequential discoveries in the history of science. By 1831, it was well known that if an iron bar was electrified it became what was called an electromagnet and its power to lift objects was considerably greater than an ordinary magnet’s.

In one of his 1831 experiments, Faraday wrapped two carefully insulated wires around opposite sides of an unmagnetized iron ring, one coil connected to a battery, the other, to a galvanometer. Neither coil made physical contact with the other. At the moment the battery was switched on, according to Faraday “*the galvanometer was immediately affected, and to a degree far beyond what has been described and it was again powerfully deflected when the battery was switched off*. Clearly, a temporary current was being generated in the second wire every time he connected and disconnected the battery” even though the second coil was not hooked up to the battery [34]. In initiating current in the first wire or coil – the primary – an electromagnetic force was created in the iron core, and that force *induced* an electric current in the second coil – the secondary – not otherwise connected to a power source.

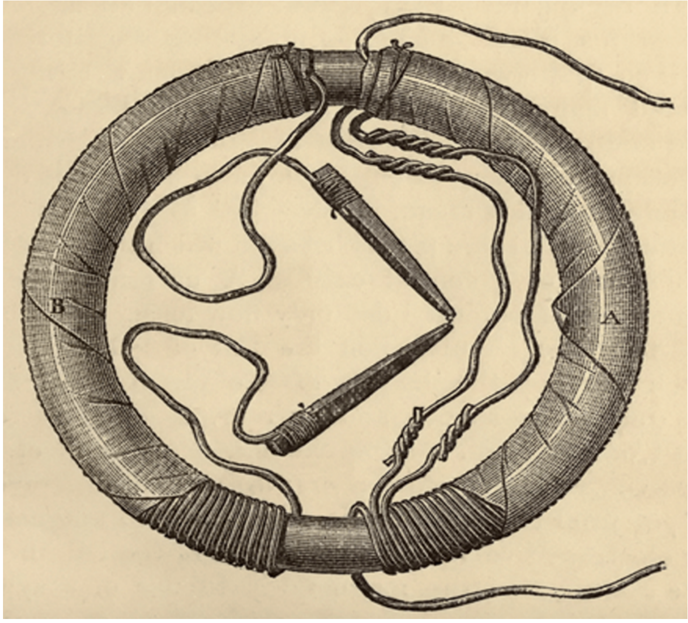


FIGURE 4. Faraday's iron-ring inductor. The right side "A" marks the primary winding whose wire ends were attached to a battery to make a complete circuit from its positive and negative terminals. The wire coils are deliberately exposed in the illustration to reveal both the windings and the insulation covering them. The left side marked "B" is shown with prongs used to touch the negative and positive terminals of a galvanometer. Faraday's invention was not a true transformer, as it had a 1:1 ratio between its primary and secondary coils, meaning their power output was equal. SOURCE: https://www.researchgate.net/figure/Left-Faradays-iron-ring-when-the-battery-current-passing-through-coil-A-starts-or_fig1_228743528

As scientists had known since Ørsted's 1820 experiment showing that an electrified wire placed near a compass needle caused it to deflect, electricity produced magnetism, or "electro-magnetism." Faraday proved that magnetism, in turn, could produce electricity. The two forces were mysteriously intertwined.

Faraday's 1831 experiments revealed the principle of induction, which governs how a transformer – the central feature of an alternating current system – works. His next step was to move a permanent bar magnet in and out of a wire coil connected to a galvanometer. "By...constantly moving the bar magnet in and out" of a coil attached to a galvanometer, Faraday discovered he could make "the galvanometer needle vibrate from side to side in phase with the motion of the magnet" [35]. From a series of like experiments Faraday learned that *motion* was critical to induction.

Induction happened when a magnet was moved in relation to a coil, or a coil moved in relation to a magnet. In the earlier iron-ring experiment the magnet was not physically moved but instead the battery-powered DC current feeding the primary wound around one side of the iron ring was switched on or off, each time catalyzing a current that disturbed what Faraday termed the magnetic "lines of force" and caused a flux or magnetic "current" in the ring to induce an electric current in the secondary. In effect the movement was the abrupt on-and-off of the current.

Induction happened only at those exact instants the DC circuit was switched on or off, in effect creating a kind of motion or disturbance in relation to the magnetic lines of force, or flux. In between the on-and-off switching, when the direct current flowed without interruption, nothing was registered by the galvanometer. There were no changes, no disturbances, registered in the iron ring's magnetic field, and no current induced in the secondary wire.

To make the galvanometer needle move rapidly and register a current in the secondary, one had to turn the battery's DC circuit on and off rapidly, creating a bumpy current that cut the magnetic lines of force repeatedly, an awkward prospect for direct current machines. On the other hand, because of its many-times-per-second, up-and-down vibrational movement that jostled magnetic lines of force continuously, AC caused a primary wire's current to be *continuously induced* in a nearby, magnetically coupled secondary wire.

After Faraday's early experiments, several scientists invented the induction coil (a primary with many windings, sometimes involving thousands of feet or more of wire) that was connected to a battery (or series of batteries) and was capable of inducing very large voltages across a deliberate gap in the circuit, called a spark gap. These scientists used the induction coil to *step up voltages* for basic research into electrical phenomena, and over time they discovered how voltage could be exactly varied according to the number of windings in a coil. The more turns in a coil, the greater the voltage output; the fewer turns, the less output. "If the second coil has half as many turns as the first coil, the secondary voltage will be half the size of the primary...if the second coil has one tenth as many turns, it has one tenth the voltage" of the primary coil, and vice versa [36]. More numerically expressed, if the "voltage increases by a factor of 10, the power lost" on a transmission line "drops by a factor of 100," and "with the same factor of 10 increase in transmission voltage, customers could be 100 times as far away," all other factors being equal [37].

This proportionality made transformer power calculations relatively straightforward and provided the basis for creating a true transformer as opposed to an induction coil.

By the 1870s, electricians understood that electric power is comprised by voltage (the "pressure" or electromotive force that propels current) and current (the flow rate of electrons in a conductor), and how these two features of electric power behaved. A power line "will lose voltage at a rate that is constant and linear – the longer the line, the greater the loss." The loss is due to a kind of friction or "resistance," that according to Ohm's Law, manifests as heat. But, unlike the *linear rate* of voltage loss, "a transmission line will 'leak' power at a quadratic rate, a rate that increases with the square of the current" [38]. Power, in other words, loses current at a much greater rate than it loses voltage. This meant that by increasing the voltage and lowering the current, engineers could economically increase the range of electric power transmission. In effect, they had "the option of 'repackaging' the power as voltage (with *linear* losses due to resistance)," while simultaneously lowering the current's quadratic-rate losses [39].

In the early 1880s, it was possible to transmit power over relatively long distances by using generators that were then capable of delivering 500 to 2,000 or more volts. The problem was how to lower or "step down" these voltages to 100 or so volts so they could be safely used in businesses and residences. (No one was yet preoccupied with a transformer's other feature, its ability to significantly increase or "step up" a generator's power output to cover very long distances economically.)

The Transformer: Key to the Reverse Salient of Long-Distance Transmission

1. Europe & England

Almost immediately after Edison opened his Pearl Street grid on September 4, 1882, a London-based French engineer, Lucien Gaulard, and his English partner, businessman John Dixon Gibbs, filed for a patent for "A New System of Distributing Electricity for Production of Light and Power." They designed their system around an alternator and in the March 1883 issue of the British journal *Engineering* they described their system as a solution to the problem of "*further industrial development ... of a system of distribution limited neither by the distance of the central factory* [power station] *for the point of consumption*, *nor by the number of customers*" [40].

To reduce or "step down" those voltages to 100 or so volts for customers in the local distribution system was the challenge. In April 1883, Gaulard and Gibbs demonstrated their new device, which they called a "secondary generator" – a new kind of subsidiary "generator" able to change the main generator's voltage output in a circuit – in April 1883 at London's Westminster Aquarium exposition. Soon after, they signed a contract to illuminate London's Metropolitan Railway Company's track, using "a mix of arc and incandescent lamps at underground stations at Notting Hill Gate, Gower Street, King's Cross" and farther, covering a total of fifteen miles by the end of 1883. According to reports in the technical press the system worked, despite its novelty [41].

It was the beginning of a new system for the transmission and distribution of electric power, a system significantly less constrained by distance than its rival, the DC system.

An Italian physicist, Galileo Ferraris, was aware a high-voltage long-distance alternating-current transmission system, combined with a low-voltage local distribution component, was technically possible, and he wanted to promote the idea. “With great water-power sites in the Alps, the Italians were sensitive to the inadequacies of the Edison and other direct-current, low-voltage systems in transmitting energy from site to urban load centers” [42]. In 1884 Ferraris was in charge of the electricity section of the Italian General Art & Industrial Exhibition in Turin, Italy, and he arranged to showcase the best systems for long-distance electrical transmission.

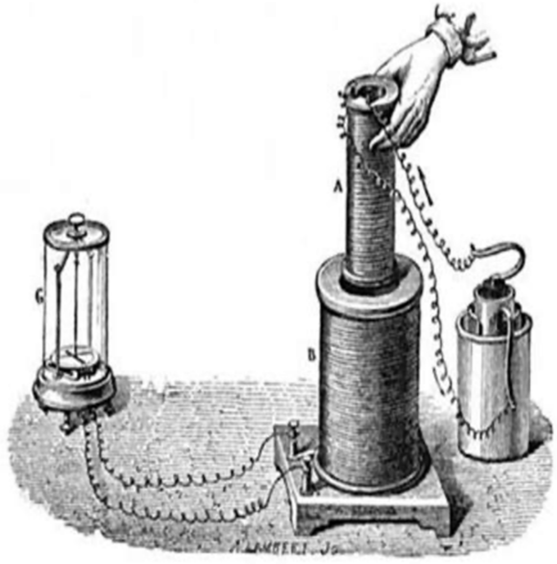
Gaulard and Gibbs entered the competition and “placed their transformers on a fifty-mile circuit that lighted the exhibition buildings, the Turin railway station, and stations at Veneria Reale and at Lanzo, a small village in the Savoy Alps” [43]. In Lanzo, they installed a 2,000-volt Siemens & Halske constant-current alternator that powered a series of step-down transformers along the 34 km route to the Turin exhibition buildings. The step-down transformers had their “primary windings connected in series while their secondaries had independent circuits of incandescent lamps connected in parallel.” The system “demonstrated that transformers allowed the transmission of ac electrical power at high voltage and low current through a great distance with a very high efficiency, while providing users with low secondary voltage...suitable for safe operations,” mainly for incandescent lighting [44]. The two inventors were awarded the exhibit’s grand prize of 10,000 francs for the best system of long-distance electrical transmission.

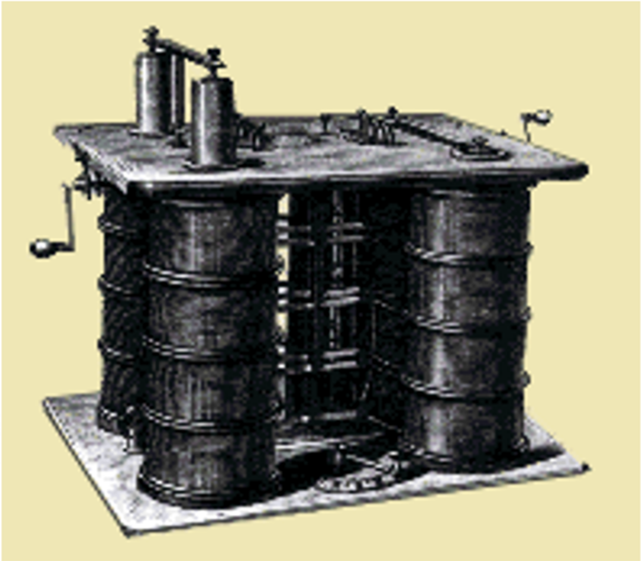
Later in the year, Professor Ferraris completed a technical report on the new system that underscored its high efficiency, lending academic credence to the claims of the new AC pioneers, especially in Europe.

The Turin exhibit attracted over 14,000 exhibitors from 37 countries and 3 million visitors between May and November. After their success displaying the first long-distance AC electric power system, Gaulard and Gibbs were soon busy making “[p]ermanent installations at Tours, France; Rome, Italy; and Aschersleben, Germany,” and, in March 1885, at the high-profile Grosvenor Gallery, which serviced an exclusive neighborhood in London [45]. The seed for the revolutionary AC electrical system had been planted.

Gaulard and Gibbs had “invented, developed, and demonstrated” a new system of practical electrical energy that, once demonstrated, “stimulated a stream of improvements” [46]. Because their “secondary generator” was a complicated machine, it especially invited improvements. It had been devised to accommodate the stipulations of the British 1882 Electric Lighting Act, which proscribed suppliers dictating the voltages used by customers, customers who then had a wide variety of voltage needs, ranging from 45 to twice or more volts. (Not much later voltages would be standardized.) To accommodate the Act’s regulations, Gaulard and Gibbs had to design a machine that could be adjusted to the many different voltage needs of their customers.

Their resulting transformers “consisted of four sets of vertically stacked bobbins” which were “wound with wire, [and] constituted the secondary of the transformer. The primary consisted of an insulated copper conductor wound on a hollow paper tube. The open core...of the transformer was a soft iron bar fitted inside the tube on which the primary was wound,” and which served as the magnetic conductor that induced a voltage in the secondary windings. The stacks of bobbins (the secondary) could be variously combined and connected and “the iron core of the primary could be cranked in and out of the stack of bobbins” so that a variety of voltages could be induced by adjusting both the primary and the secondary. Thus, each consumer could use the Gaulard and Gibbs’ transformer to, in the inventors’ words, “*generate currents at a potential of 45, 60, 91, or other number of volts as he chose*” [47].





> FIGURE 5. Above left is one of Faraday's early "inductors," or prototype transformer. The hand-held primary coil is wrapped around an iron bar and connected to a battery. It is lowered into the opening of the secondary coil, which is connected to a galvanometer. Above right, Gaulard and Gibbs clearly followed Faraday's design in constructing their own prototype transformer, or "secondary generator." According to Gaulard and Gibbs' assistant Reginald Belfield, their device "consisted of a bundle of iron wire forming the magnetic circuit surrounded by a large number of copper discs, having a hole in their centers, one for each turn of both primary and secondary, and each soldered to its neighbor, this multitude of soldered joints, each a source of trouble" that invited simplification. SOURCE: https://en.wikipedia.org/wiki/Faraday%27s_law_of_induction,

The cumbersome complexity of the Gaulard and Gibbs transformers was soon improved by the Ganz engineers in 1884-1885, and later, in 1885 and 1886, by Sebastian de Ferranti at London's Grosvenor Gallery, and by William Stanley and other Westinghouse engineers in the US.

When he was still in Turin during the 1884 exhibition, Gaulard was visited by Ganz engineers Bláthy and Zipernowski, who purchased one of his transformers and returned with it to the Ganz Works in Budapest to improve on it. During the fall and winter of 1884/85, the two engineers and their colleague Max Déri made two major and enduring improvements: "Bláthy decided that a closed core," in effect a complete toroidal ring whose flux was confined and concentrated within itself (a ring such as that used by Faraday, but thicker), "could be used to provide a more effective magnetic field than the open core" [48] used by Gaulard and Gibbs, whose bipolar (north and south) magnetic lines of force lost flux to open air, resulting in a weaker than optimal magnetic circuit for the transport of electric power.

In addition, Déri and Zipernowski "recognized the ineffective voltage regulation in the secondary circuits," which were fed by a series-wound primary vulnerable to load fluctuations, so they "connected the primaries in parallel" thereby strengthening the reliability of the system [49]. Ganz Works had been producing single-phase, parallel-connected AC-circuits since 1878, and it was natural for their engineers to think of wiring their new transformers in parallel, fed by their own newly designed constant-voltage generators, which were able to vary their current according to load. "Since transformers with primaries wired in parallel and supplied by a constant-voltage generator were self-regulating, Ganz engineers could dispense with the complex regulator Gaulard and Gibbs had placed in the secondary circuit” to make it more reliable in fluctuating load conditions [50]

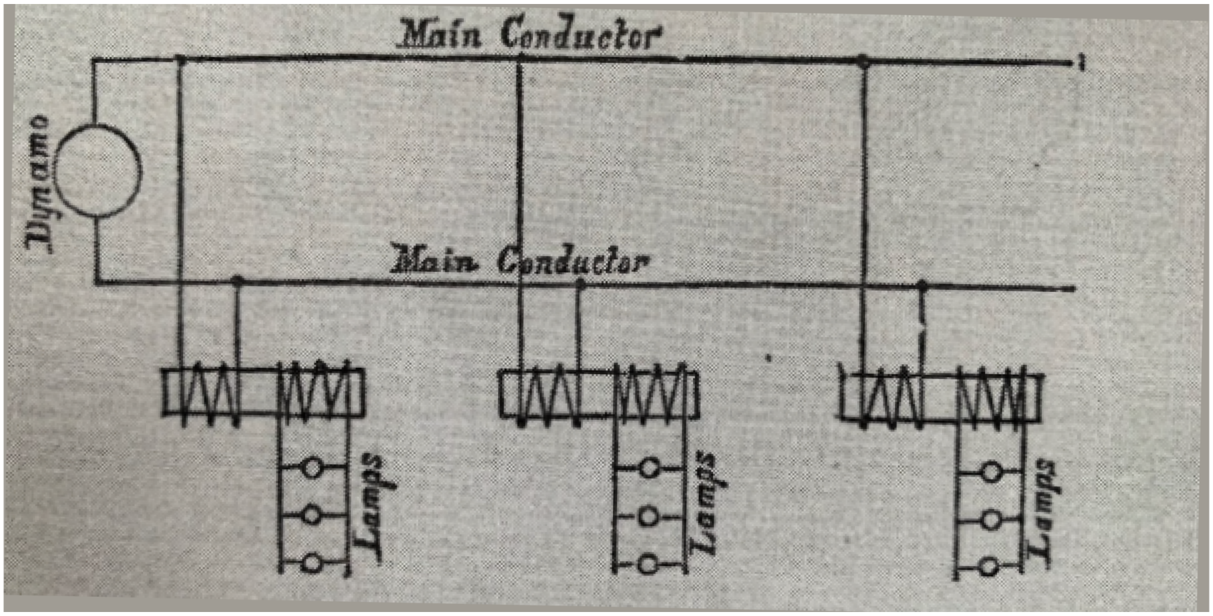


FIGURE 6. Transformers connected in parallel. The voltage/current is in effect “shunted” off the main conductor or circuit, without interrupting its flow to all the other subcircuits downstream, and creates a flux in each magnet that induces a current in each secondary subcircuit, each of which in turn feeds parallel-connected lamps. SOURCE: https://www.flickr.com/photos/internetarchivebookimages/14596449768/

By the end of 1884, Ganz Works shipped the world’s first closed-core transformers to five customers in Austria-Hungary and Russia, and in early 1885 the Ganz engineers applied for three patents covering two basic versions of their transformer: one, known as the “core type,” in which the toroidal iron core that provides the magnetic circuit is wound about by copper wires of the primary and secondary; the other, known as the “shell type,” was reversed, so that the copper primary and secondary windings were enclosed inside a ring of tightly wound iron wires or plates. Here the so-called iron “core” reversed its role and acted as a “shell” that surrounded the copper windings (see Fig. 7).

The new transformers were 3.4 times more efficient than Gaulard and Gibbs’ open-core, bipolar transformers. The two basic designs, the core and shell types, characterize transformers to the present day.

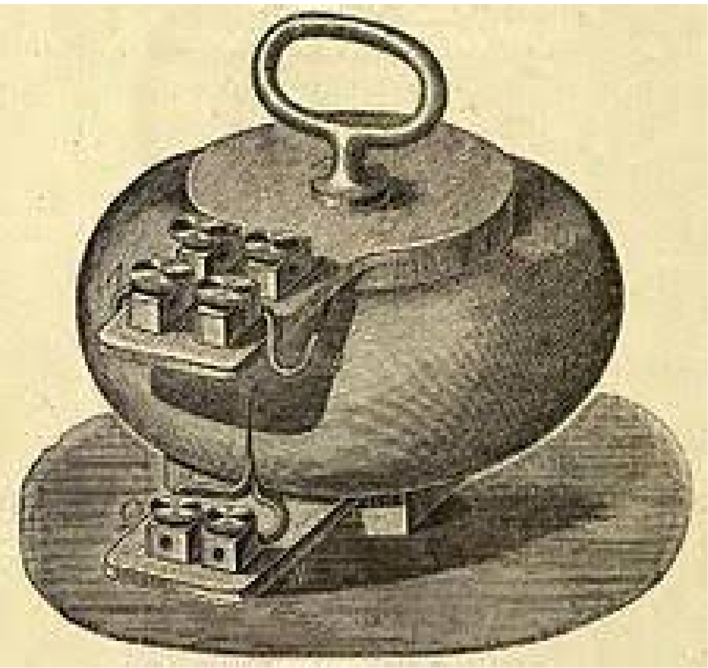


FIGURE 7. The shell-type ZBD transformer, with closed-core toroidal shape. The “doughnut hole” is concealed by the wooden lid with a handle. Inside are the primary and secondary copper windings “formed into a ring” and then “wound closely with thin iron wires.” The core and shell are wound parallel to one another so that “the circulation of Foucault [eddy] currents, and consequent heating of the apparatus is prevented.” Were the copper windings and the iron wound perpendicular to one another, as in the case of Faraday’s iron ring, eddy currents would be a serious hindrance to the device’s efficiency. The primary circuit is fed at the top platform and the secondary circuit emerges from below. The iron wire tightly wound around the inner copper windings makes an outer “shell” that gives this type of transformer its name. SOURCE: Nov. 2, 1886, patent for ZBD “Induction Coil.”

The closed core enhanced the new system’s power capacity, and the parallel-connected primaries increased the system’s reliability under varying loads. Bláthy coined the term “transformer” for their new device, a name that has endured. The Ganz engineers exhibited their complete AC system, including their new constant-current generator, at the National General Exhibit in Budapest in May 1885. A constant-current generator’s 1,350 voltage was stepped down “by 75 shell-type transformers to the voltage of 1,067 Edison lamps which illuminated the exhibition,” stretching across 2,600 meters in which hundreds of exhibitors showed their wares. The parallel connected transformers “made the regulation of a transformer independent from the load of the [other] transformers and made the distribution of electric energy through the transformers practical.” Within weeks “the three engineers showed their system at the Inventors Exhibition in London,” reaching international notoriety for their work [51].

Shortly to be known as the ZBD system, it “was widely adopted,” especially within Austria-Hungary, and was soon seen to be competitive with the established Edison DC system. “By 1890 nearly seventy central stations...had been placed in operation” and “supplied 100,000 incandescent lamps and 1,000 arc lamps” [52].

In London, the directors of the company incorporated to run the power for the Grosvenor Gallery and its neighborhood fired Gaulard and Gibbs, as their transformers had proven “unworkable” when the gallery’s load increased beyond a certain point, which point was reached by the end of 1885. In early 1886 they hired Sebastian de Ferranti as their new chief engineer. The young de Ferranti had invented his own alternator, and the gallery was already using his meter to measure its customers’ usage. De Ferranti replaced the Siemens alternators with his own, connected the primaries of the already installed Gaulard and Gibbs transformers in parallel instead of in series and otherwise “redesigned the station’s components systematically...The Grosvenor Gallery station then expanded impressively until 1888 there were five machines [generators], five circuits, and 34,000 lamps lighting a large district of London” [53]. By then the ambitious de Ferranti was allowed “to go ahead and put into service ... [England’s] first high voltage power station at Deptford on Thames. The 10-kV [10,000 volts] level, a record for the time, enabled electrical power to be transmitted 45 km away ... He also designed the power cables and their special joints (the very first for a high-voltage system)” [54].

Hobbled by squabbling local utility interests, it was not until 1891 that the big Deptford power station on the southeastern side of the Thames could send a then unprecedented 10,000-volt power to customers in various London neighborhoods, using step-down transformers to deliver safe levels of electricity to customers. As part of this new, much larger supply system, de Ferranti “converted the small Grosvenor Gallery station into a transformer substation,” where high transmission voltages could be stepped down and distributed to a specific neighborhood, where they would be further stepped down for domestic use, “showing the way to integrate older plants into a universal AC supply system” [55]. England otherwise ceded developments in the emerging world AC system to continental Europe and the US.

2. United States

In the US, two very different individuals led in pioneering the development of transformer technology: William Stanley, a brilliant and temperamental young engineer, and the person who was to become the founding titan of the US alternating-current industry, George Westinghouse.

Westinghouse was a founding titan in the same sense as his exact contemporary, Thomas Edison, was a founding titan of direct-current electricity. Both were, above all else, prodigal inventors and passionate about the process of inventing new machines for the benefit of humankind. Both were ferocious patent protectors who employed skilled patent attorneys to defend their patents and attack infringers. "Between 1869 and 1873, George Westinghouse was issued more than 20 patents on one of the great inventions of the 19th Century, the revolutionary air brake" [56]. His two prior and important railroad inventions, the so-called "car replacer" and the "frog," were patented when he was 20 and 21. They "were practical successes but commercial failures. The railroads adopted both but sidestepped his modest patent protection, yielding him little return" [57].When he filed for the first of his airbrake patents at age 22, he had already learned a bitter lesson, and hired capable attorneys who "artfully wove a web of patent protection around the flow of air brake improvements" that sprang from his restless, inventive mind from 1869 to 1873, so that they could not be breached. "This time the patents held, and the railroads paid; they paid big," and Westinghouse, a very young man, "was on his way to be a leading industrialist" [58].

Westinghouse was introduced to the importance of electricity when he merged various railroad electrical switch and signaling companies to establish the Union Switch and Signal Company in 1881. A year after Edison had launched his direct-current central plant system, Westinghouse had begun to think about the direct-current lighting business and had hired a few young engineers to look into such technical challenges as a constant-voltage dynamo. In early 1884 he met a brilliant, independent-minded, self-taught engineer named William Stanley, who had invented a self-regulating dynamo. "Unlike Edison, who preferred to use only his own patented work, Westinghouse already had long and reasonably happy experience with other inventors' better ideas and improving them in his own shops," which he staffed with exceptionally capable engineers [59]. He signed a contract with Stanley to head up his new electrical department, making him responsible for the development of a complete direct-current lighting system. Stanley agreed to assign all his inventions to Westinghouse, provided he manufactured and sold them.

Concerned about the limited potential of DC for long-distance transmission, Westinghouse was not yet committed to investing heavily in it. Neither he nor Stanley were inspired by DC's long-term prospects. Stanley was actively thinking about the technical challenges of alternating current well before he started working for Westinghouse on a complete DC system, that included lamps Stanley had co-invented. A September 18, 1883, entry in Stanley's notebooks showed he was aware that the counter-electromotive force – the voltage that opposes the [voltage] change in an induced current – could be used "as a means of maintaining constant potential. He now visualized the possibilities of applying such a means for the purpose of regulating alternating current" through transformers [60]. Well aware of the Gaulard and Gibbs "secondary generator," in the summer of 1885, he had begun to design prototype transformers, even as he worked on developing Westinghouse's direct-current system.

Though a contemporary German expert's appraisal that the Americans "quietly waited until the invention [of the transformer] gave useful results in Europe, and then simply imported it" [61] seems excessively cynical, it had some truth to it.

Just as the new ZBD alternating-current system was lighting up the National Exhibition in Budapest in May 1885, one of Westinghouse's young engineers, Guido Pantaleoni, went to Turin to attend his father's funeral. There he visited his former physics professor, Galileo Ferraris, who introduced him to Lucien Gaulard. Gaulard was installing a new system that connected a small town to the central station in Lanzi, which had powered his and Gibbs' new system at the 1884 Turin exhibit. He was also in the planning stages of another system that would provide Rome with its first electric lights in 1886, powered by a station in Tivoli, twenty miles distant. "Pantaleoni was so much impressed by what he saw and learned in Turin that he cabled an account to Westinghouse, who promptly requested Pantaleoni to secure an option upon the American rights" to the Gaulard and Gibbs transformer [62]. Pantaleoni also visited the Ganz engineers in Budapest, who advised him to do in the US what they were already doing in Europe and study the Gaulard and Gibbs transformer carefully. Pantaleoni next went to visit Gibbs in London, where he secured an option for American rights.

It is likely that Stanley and Westinghouse both knew about the ZBD alternating-current transformer system, as it was on display along with the Gaulard and Gibbs system at the International Inventions Exhibition in South Kensington, London, during the summer of 1885. The exhibition attracted great notice in the technical press, avidly read by scientists, engineers, inventors, and entrepreneurs, who also had access to the detailed texts of all awarded patents. Westinghouse is believed to have read about the new transformers in the British journal *Engineering*, and that might explain his swift response to Pantaleoni's cable. Stanley had also urged him to buy US rights. Obsessed with patents, Westinghouse asked his chief patent lawyer, Franklin Pope, himself an inventor, to thoroughly explore the Gaulard and Gibbs patents for any weaknesses, should he decide to exercise his American option. (By the time Westinghouse started looking into the ZBD patent in 1886, the option had already been sold to Edison, who did nothing with it.)

During the summer and fall of 1885 two of Westinghouse's young engineers, Stanley's assistants, Albert Schmid and Oliver Shallenberger, tested the Gaulard and Gibbs transformer and "found it to be unmanufacturable." And yet its basic function "was at the heart of any system of transmitting AC power" [63] – as both Stanley and Westinghouse understood.

Stanley recalled that "in the period prior to industry successes in 1885 it took '*definite self-conviction*' to keep working on AC power which was experiencing many setbacks in experiments. There were no useful books on the technology" and AC power was "*a despised and rejected line of work*," in the US, where the reputation of Edison and his new system loomed large [64]. He also recalled that "*in 1885, there were no alternating current machines built in America*," save those that were imported [65]. And so, in late November 1885 Westinghouse imported a Gaulard and Gibbs transformer, as well as a Siemens alternator, this time accompanied by the two inventors' principal engineering assistant, Reginald Belfield. Belfield possessed "substantial knowledge of transformer design and operation" [66] and was crossing the Atlantic to work for Westinghouse.

Immediately on his arrival in Pittsburgh, Belfield took apart the transformer to repair it, as it had been damaged in transit. Westinghouse, "who had machines in his blood," stood by and "thoroughly enjoyed examining the whole Gaulard-Gibbs apparatus," watching Belfield disassemble and then reassemble it, and disassembling it himself, "as was his wont," when confronted by any new machine [67].

In matters electrical Westinghouse "was not an inventor of fundamentals. He invented many useful details, but his great work was in stimulating, combining, and directing the work of other men" [68]. And he motivated his engineers to work fast. The Westinghouse transformer team consisted of himself and Belfield, Schmid and Shallenberger, and Stanley, who had the longest-standing commitment, knowledge, and ambition to make an alternating current system work. "*In 1883 I attempted to devise a system of alternating current distribution*," Stanley recalled, "*that would be inherently self-regulating, but I found I knew too little of the subject to venture into it*" [69].

But two years later, working as part of a team of engineers, the fundamental invention of a new alternating current system, the transformer, was worked out in just three weeks, between December 1 and December 20, 1885, "*an astonishingly short time*," so that, in Belfield's words, "*the absolutely uncommercial secondary generator was converted into the modern transformer*" [70].

The group understood the ZBD transformer's parallel-wound design was a clear improvement over the Gaulard and Gibbs open-core, series-wound design, and they adopted it from the outset, with Stanley eventually filing for patents for his own designs for the parallel system. The ZBD closed toroidal core, on the other hand, was expensive to manufacture, as wires "could not be easily wrapped around it by a machine" [71]. Westinghouse suggested "using insulated copper wire that could be machine-wound on a laminated core assembly of thin steel sheets" [72]. The thin sheets were less dense than the heavy, solid toroidal core and lessened the negative impact of eddy currents, which acted to heat the iron and thus weaken the electro-magnetic circuit. It was "only a few days before he [Westinghouse] had evolved the H-shaped plate" whose crossbar could be machine wound with the primaries and the secondaries. I-shaped end plates could then close the H's top and bottom, making a closed magnetic circuit inside of which the copper wires of the primary and secondary windings would be nested – in effect, a shell-type transformer [73].

Stanley next made two significant suggestions, each tied pragmatically to the other. First, he "suggested that the primary and secondary coils...could be wound separately from the core...around a rigid, hollow paper form with a square cross-section...the steel core laminations could then be inserted through the hollow part of the paper form" that carried the windings [74]. (The paper mold around which the copper wire was wrapped could be any shape, circular, rectangular, oval, or square.) Next, since the H shape was not amenable to this innovation, "Stanley suggested making the iron stampings in the form of an E so that the center prongs could be slid into a pre-wound coil. The E-shaped stampings were inserted in alternating directions, and straight pieces of iron were laid across the ends of the arms to complete the magnetic circuit" [75]. These were lasting design innovations; they persist in today's transformers.

FIGURE 8. The Stanley transformer used in Great Barrington, 1886. The transformer's copper windings are wrapped around a paper mold whose curved ends protrude a bit beyond the wooden frame's four end pieces. The wooden frame is bolted together top-and-bottom, on both sides. The middle arms of the E-shaped iron plates extend through the windings, alternating from one side to the other, opposite side. The top and bottom arms of the E plates may be discerned as dense narrow shapes outlined at the top and the bottom of the figure. The ruler placed in right foreground indicates the unit is about one foot long. [SOURCE: https://edisontechcenter.org/GreatBarrington.html]

To further reduce the eddy currents that weakened the magnetic field, thin paper was pasted to one side of each plate. "Pasting paper on the plates was highly objectionable as a manufacturing process, and this led Albert Schmid" to discover "that the oxide formed on the surface of the iron sheets served as a sufficient insulation and, with the decreased separation of the sheets, resulted in increased efficiency" [76]. Paper insulation was discontinued.

At the end of December, Westinghouse and Stanley negotiated a new contract that relieved Stanley of his responsibilities in Pittsburgh for the development of Westinghouse's direct-current system, and supported Stanley's work in Great Barrington, where Stanley had moved for health reasons, developing a trial alternating-current system based on the new transformer they had just designed. Westinghouse agreed to cover lab costs and pay Stanley a salary. Early in January, Belfield went to Great Barrington to help Stanley build several new transformers (see Figure 8) in an old factory building Stanley leased to serve both as laboratory and powerhouse on the outskirts of the village. A 25-horsepower Westinghouse coal-fired steam engine arrived in late January along with a Siemens alternator on loan from Westinghouse. Stanley had to find a boiler for the steam engine.

As construction of the transformers was completed, Belfield "braved the February cold to string four thousand feet of heavy copper electrical wire onto ceramic insulators fastened to the huge bare elms" along Great Barrington's Main Street. Stanley placed each one of his six step-down transformers "in a wooden box installed out of sight in the basements of those buildings to be lighted," and each box was locked [77]. Wiring was next extended "to light thirteen stores, two hotels, two doctor's offices, one barber shop and the telephone and post offices. The lamps were 150, 50, and 16 candlepower...In the laboratory's new power plant, two 50-light and four 25-light transformers were installed. The generator...produced current at 500 volts" [78]. Stanley stepped up the central station generator's 500 volts to 3,000 volts to travel less than a mile to the center of town, where it would be stepped back down to 500 volts and run to the six basements, where it would be again stepped down by the six concealed transformers to 100 volts to light all 36 of his customers' Edison bulbs. The generator's 500 volts could have powered the town's lamps without the aid of a step-up transformer, but Stanley wanted to show it could be done. His demonstration would be the world's first.

The system was ready, and Stanley took a two-week holiday break with his wife. While he was away, Edison opened the town's first incandescent lighting operation at a mansion, newly built by the widow of railroad mogul Mark Hopkins, at the edge of the town's business center. The opening of the brightly lit mansion was heralded "A Brilliant Spectacle" (in capital letters) the following morning in the town newspaper. When Stanley opened the nation's first alternating-current lighting system a week later, on March 16, hundreds of townspeople celebrated because lighting finally arrived in the stores and businesses on Main Street. In Great Barrington, none, save Stanley and Belfield understood the difference between the two systems.

There is evidence Westinghouse, and certainly his cohort engineers, did not initially invest much faith or interest in Stanley's heroic venture. "No one...had any real expectation of anything commercial coming out of the alternating current system," save Westinghouse himself [79]. Stanley was something of a loner and regarded as quirky and unpredictable by his peers, and by Westinghouse himself. Meantime a man named Colonel H M Byllesby had assumed Stanley's former responsibilities for developing and selling and installing Westinghouse's new DC system. Byllesby admired Stanley's abilities and understood his need to do innovative work on his own. While he was overseeing one of the first installations of a stand-alone Westinghouse DC system at the Windsor Hotel in New York City, Byllesby was paid a visit by Stanley, "*who impressed me with the fact that he actually did have a small alternating current central station running at Great Barrington, and he quite pathetically implored me to go back to Great Barrington with him to look at it* [80]. Byllesby did return to Great Barrington with Stanley and witnessed the system for himself, returning directly to Pittsburgh where he persuaded Westinghouse to see for himself how admirably Stanley's proof-of-concept system was working.

On April 6, Westinghouse and several of his close associates visited Great Barrington. Impressed, the group returned in May, when Stanley had added several dozen more customers. Stanley, meantime, was learning "how to proportion the magnetic and electrical circuits so as to minimize the energy loss when there was no electrical load on the system and to give constant voltage when there was a load, no matter how many lamps happened to be turned on at any moment – an important consideration because small changes in voltage had dramatic effects on the life and efficiency of light bulbs" [81]. His customers were pleased.

"Westinghouse directed that a new version of Stanley's AC system be installed back in Pittsburgh at the Union Switch and Signal Company and an electrical line strung three miles out to East Liberty," and new transformers be made and placed at each end of the line [82]. The system was tested and improved throughout the summer. Stanley's new design for an alternator was built to replace the Siemens generator that had been designed to power arc lamps. In residences of the suburb of East liberty 400 incandescent lamps were illuminated continuously for two weeks, using the step-up and step-down transformers at either end. By fall Westinghouse was ready to launch the country's first commercial AC system. He moved one of the new Stanley alternators and some of the new transformers to the Buffalo Electric Company's central station to begin service at the city's huge emporium, Adam, Meldrum & Anderson, "a gigantic four-story Italianate palace of manifold consumer delights" on Main Street. When it opened on November 30, a local paper reported "'the store was so thronged with visitors that it was difficult to get about'" and everyone "'expressed great admiration at this Westinghouse light'" [83].

As happened in Great Barrington, no one understood the significance of the new lighting system, in part because neither Westinghouse nor Stanley made "any great public declarations." Nevertheless, "AC's virtues," invisible to most, "were swiftly appreciated by those who could not be served by DC" [84]. Orders began to trickle is, and then they poured in, and Westinghouse had to expand his factory, which soon employed 3,000 people. Within eighteen months the Westinghouse Electric Company had completed over 100 installations throughout the country.

The Battle of the Systems: Phase One (1887 – 1890)

Edison was alarmed that a man of Westinghouse's stature had decided to enter the electricity market, using a novel technology that solved the one reverse salient his direct current system could not seem to solve, long-distance transmission. In early November 1886, Edison wrote one of his closest lieutenants, Edward Johnson: "*Just as certain as death Westinghouse will kill a customer within six months after he puts in a system of any size. He has got a new thing and it will require a great deal of experimenting to get it working practically. It will never be free from danger*" [85]. Three weeks later Westinghouse had "a system of size" installed in Buffalo.

According to two historians, Edison "'feared that that poorly designed and installed a.c. systems would impede the broad adoption of electric power'" [86]. From the outset Edison's strategy was to provide not just a price-competitive product but a safe one. In a market dominated by the gas lighting industry safety was one of the values Edison emphasized to compete against a technology many believed unsafe – gas. Edison had gone to great trouble and expense to bury his conduits in urban cores. By developing a high-resistance lamp filament, he was able to also supply his buried urban circuits with low-voltage power that added further to the safety of his system

[87]. Westinghouse's reckless adoption of a more economic but less safe system could destroy the entire electric lighting business Edison had so painstakingly built.

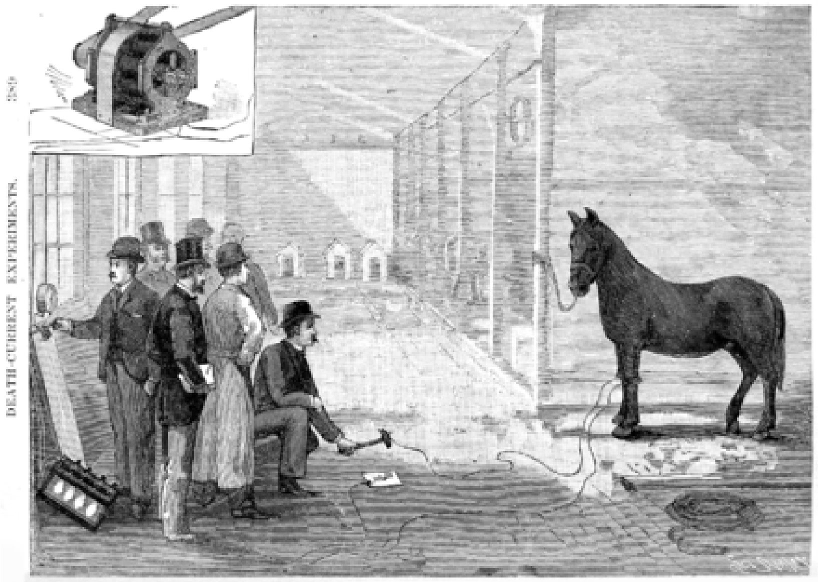
Events in 1887 changed what had been Edison's laissez-faire outlook toward his competitors. The supply of copper was being controlled by a Paris syndicate backed by international financiers. During 1887 the price rose by over half, from 10 cents a pound to 16 or 17 cents by year's end. In February 1888 the *Electrical Engineer* noted that if the price stayed high it would handicap Edison's low-voltage distribution system and unduly favor Westinghouse's high-voltage system. The "new Westinghouse AC central plants required a third as much copper" as Edison's DC plants to deliver electric power to their customers [88].

"Out in the far-flung marketplace of the new central stations, the Edison camp was encountering continuous and embittering setbacks." Edward Johnson, in whom Edison had confided his certainty about the Westinghouse system's fatal weakness, was now "rebuking Edison that without AC 'we will do no small town business, or even [make] much headway in cities of minor size'" [89]. To build a central station DC grid it was, in the words of an Edison executive, "'necessary to establish the entire system of distribution at the outstart'," while "an alternating system could be started on a small scale and then extended as necessary to add new customers" [90]. AC's much greater flexibility was a thorn in the side of Edison's managers.

At the end of 1887, after more than five years in business, Edison "had built or had under contract 121 DC central stations in places as far-flung as Birmingham, Alabama, and Grand Rapids, Michigan." But the "hard-charging Westinghouse, after but one year in business, had constructed or had under contract 68 AC central stations." A third competitor, Thomson-Huston, an important electrical company with a high-profile arc-light business, "had already up or under contract 22 AC central stations" [91]. Westinghouse and Thomson-Huston had agreed to allow each other to use some of their technologies, notably the transformer and the Sawyer-Man lamp patents, to avoid litigation in their competition with the larger, more entrenched DC system. After one year the new AC system had three-quarters as many central stations built and under way as the older DC system.

During 1887 "Edison's rancor toward Westinghouse continued to fester and grow with each passing month" [92]. In early November Edison was approached by the recently formed New York State Death Commission to help them assess the viability of using electricity to cause a more humane death than hanging. After rebuffing the commission on moral grounds in November, Edison reconsidered when they approached him again in December, replying that "*the most suitable apparatus for the purpose* [of electrocution] *is that class of dynamo-electric machinery which employs intermittent currents. The most effective of these are known as 'alternating machines', manufactured principally in this country by Geo. Westinghouse*," adding that the current of the AC machines "*produces instantaneous death*" [93].

Edison's advice reinforced the commission's decision to recommend electrocution as the new form of execution to the legislature in January 1888. By June 1888, death by electrocution became law and went into effect on January 1, 1889. By spring an ax murderer, William Kemmler, was arrested and slated to undergo the country's first electrocution. His execution was delayed until August 1890. In the intervening months, Edison colluded with an anti-AC activist, Harold Brown, in the latter's performance of multiple trial electrocutions of stray dogs, cats, calves, and horses that were intended to prove alternating current was a more efficient killer than direct current. Although Westinghouse refused to sell New York state his generator to execute criminals, the Brown-Edison alliance arranged for a Westinghouse alternator to be provided to electrocute William Kemmler on August 6, 1890.



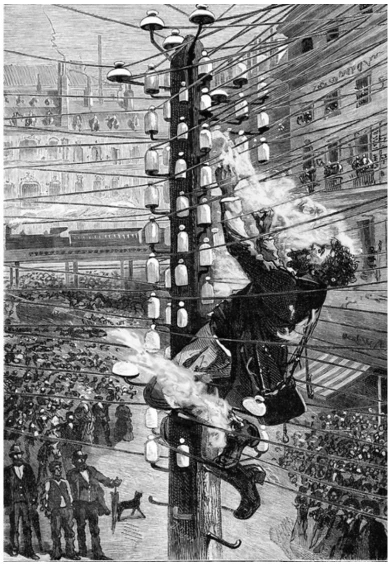


FIGURE 9. Above left, Harold Brown about to electrocute a horse in response to complaints that dogs were smaller than humans and thus not reliable test subjects for the proposed electrocution of criminals. Above right, the accidental execution of lineman John Freeks, who grabbed a telegraph wire that had been shorted by a high-voltage arc-lamp wire. After the Great Blizzard of 1888 took down many electric lines in major eastern seaboard cities, the issue of "death by wire" exploded in the press and was part of the background that made Edison's anti-AC campaign so virulent. SOURCES: https://en.m.wikipedia.org/wiki/File:Harold_Pitney_Brown_edison_electrocute_horse_1888_New_York_Medico-Legal_Journal_vol_6_issue_4.png#:~:text=The%20image%20depicts%20Brown%20in,of%20alternating%20current%20for%20executions and https://en.m.wikipedia.org/wiki/File:John_Feeks_Western_Union_lineman_killed_by_AC_October_11_1889.png

"The Edison interests ... resorted to unorthodox political tactics" because, in the words of the historian Thomas Hughes, they "realized that their failure to solve the transmission problem called for a nontechnical compensatory response" in the form of what today we would call lobbying and public relations [94]. In February 1888, the Edison Electric Company published an 84-page booklet entitled "A Warning of the Edison Electric Company," effectively a "diatribe" warning consumers "that if a transformer failed to step down the current, the whole building served would be a possible death chamber reverberating with a high-voltage electricity [95]. Edison argued in the pages of *The New York Times* that the most appropriate word to substitute for "electrocuted," a term the paper disproved of, was "Westinghoused." Edison promotional brochures warned "homeowners: 'Don't let your house be Westinghoused'" [96].

In the end, the Edison campaign did not alter the course of technological history. Despite the stinging, ad hominem three-year publicity campaign, there was "a steady and rapid increase in the number of central stations using the Westinghouse system of alternating current" during 1888-1890 [97]. The AC system's undeniable progress did not mean the DC system lagged: at the end of 1890 Edison had in service 1,500 central stations, and Westinghouse 300, though that dominance would diminish and reverse itself over the course of the century's last decade.

The first phase of the “war of the currents” was waged by two systems, the direct current and the single-phase alternating current, neither of which was destined to become the “universal system” in the early 20th century. Those laurels, as we shall see in Part 2 of this essay, belonged to the polyphase AC system that emerged in Europe in 1891 and in the US a year or two year later.

In the meantime, Edison continued to hold a trump card – the DC motor. A practical AC motor remained that system’s most important reverse salient. In Part 2, we will learn how overcoming that handicap changed the outcome of the war between the currents and provided the technological basis for constructing the world’s largest machine.

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