Revolving and Evolving—Early dc Machines

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In an age largely characterized by information and communication technology, which uses more and more feeble currents, electrical power is experiencing a period of excellent health and heading toward a bright future. This success is largely due to electric motors, which are available in different types and powered by dc as well as ac sources operating at either utility or variable frequencies. The versatility and ubiquity of electric motors are so wide that they can be found almost everywhere: in many household appliances, technician power tools, building fans, factory machine tools, blowers and pumps of industrial fluid systems, cableways, railway and streetcar locomotives, computer disk drives, drivers and printers, and cell phone vibration alerts.

Tens of billions of electric motors are produced every year, with powers ranging from a few hundredths of a milliwatt to some tens of megawatts. Their future looks bright due to the rise of electric-powered transport, which will be enforced by government measures in many countries in the coming years. According to official statements, the sale of new 100% internal combustion engine (ICE) vehicles is expected to be banned in Norway and The Netherlands by 2025, Germany and India by 2030, and France and the United Kingdom by 2040 [1]. Austria, China, Denmark, Ireland, Japan, Portugal, Korea, and Spain are setting similar targets. Recently, Seigo Kuzumaki (Toyota's head of advanced research and development and engineering) predicted that the ICE will only power about 10% of new vehicles as part of a hybrid system by 2050. All remaining vehicles will be electrical [2].

The origin of this thriving technology dates back to the 1820s and the major developments that occurred over the following seven decades, in a period when steam engines (the main technological driver of the industrial revolution) demonstrated that unprecedented levels of power could be produced and harnessed. The steam railway showed that long distances could be covered at amazing speed. In the 19th century, the search for sources of power that could be transmitted far away had prompted the invention of cumbersome and fancy technologies, some of which achieved good success for several decades. Ceiling systems of shafts, pulleys, and belts were used in factories for distributing mechanical power to production machines. Compressed air was used for moving underground and surface trains. The Samuda Brothers' Pneumatic Railway could travel as fast as 30 mi/h in the United Kingdom in the 1840s. A remnant of those systems is the pneumatic mail system, which is still used in some banks and markets today.

Apart from some attempts to produce feeble mechanical actions by electrostatic forces in the 18th century, serious research in electric motors began with the discovery of the interaction between electricity and magnetism. It was made in 1820 by Danish physicist and chemist Hans Christian Ørsted (1777–1851) [4] when he observed the deflection of a compass needle placed in proximity to an electrical current produced by a voltaic cell [3]. Earlier observations of electromagnetic effects made by Gian Domenico Romagnosi (1761–1835) and reported in 1802 in local press had been overlooked. It was Ørsted's communication to the Académie des Sciences of Paris on 21 July 1820 that caused a sensation in the international scientific community and triggered immediate investigations and experimentations.

It only took a few weeks for André-Marie Ampère (1775–1836) to develop the first formulation of the electromagnetic interaction, which he communicated on 18 September. Ampère's study, where the "i" symbol for the electric current (intensité de courant) was introduced, founded the mathematical theory of electromagnetism. A large body of further scientific research culminated in the discovery of magnetic induction by Joseph Henry (1797–1878) and Michael Faraday (1791–1867) in 1831 [this had actually been preceded by Francesco Zantedeschi (1797–1873) in 1830], the definition of Maxwell's equation in 1864, Hertz's experiment on electromagnetic waves of 1887, and the definition of Lorentz's force of 1895. On the other hand, Ørsted's discovery showed that the interaction between an electrical current and a magnetic field produces a mechanical effect, which prompted the development of devices capable of exploiting such effects with better continuity and at a greater extent.

The first demonstration of Ørsted's effect with a rotary motion was given by Faraday in 1821. He hung a wire with the one end dipped into a mercury pool so as to pass a current through it. Placing a magnet nearby, he obtained the rotation of the wire. One year later, the English mathematician and physicist Peter Barlow (1776–1862) built the eponymous wheel, a purely demonstrative archetype of a homopolar electric motor. It consisted of a spoked wheel that was free to turn on its axis and spun due to the interaction between the axial magnetism of a permanent magnet and the radial electric current flowing from the hub to the tip of a spoke dipped in a mercury bath (Figure 1). In 1824, the French physicist François Arago (1786–1853) obtained the rotation of a magnetic needle placed close above a rotating cooper disk. Although no externally powered current was used and no electromechanical conversion occurred, this was the first observation of the effect of eddy currents, which were discovered later, namely, by the French physicist Léon Foucault in 1855. It took nine years to convert Barlow's wheel into a generator. In fact, Faraday observed the electromotive force that developed between the axis and the edge of a disk kept in rotation and subjected to the axial magnetism of a fixed permanent magnet (Faraday disk, Figure 2) in 1831.

Meanwhile, a Slovak-Hungarian priest, Ányos Jedelik (1800–1895), had conceived a different design to build the first crude, but viable, electric motor in 1827. It had no permanent magnet but was provided with an early commutator and coils in both the stator and rotor (Figure 3), which was obtained by combining the electromagnetic multiplier proposed by the German physicist Johann Schweigger (1779–1857) in 1820 and the iron-cored electromagnet conceived by English physicist and inventor William Sturgeon (1783–1850) in 1825. Although it went largely unnoticed at the time, Jedelik's motor has been preserved until the present day and still works pretty well. Later, he used it for powering the first tiny electric car [5]. Several experimenters tried to develop more viable and more efficient motors in the following years. In 1835, the Russo-Prussian engineer and physicist Moritz Hermann Jacobi (1801–1874) built a more powerful electric motor capable of practical operation. In 1839, he used it to successfully propel a 28-ft boat, powered by an electrochemical battery, at 3 mi/h against the current on the Neva River in Saint Petersburg, Russia. In 1835, the American blacksmith Thomas Davenport (1802–1851) built a primitive electric motor, provided with stator winding, rotor winding, and a commutator, that was a rudimentary archetype of the stepper motor. It received the first American

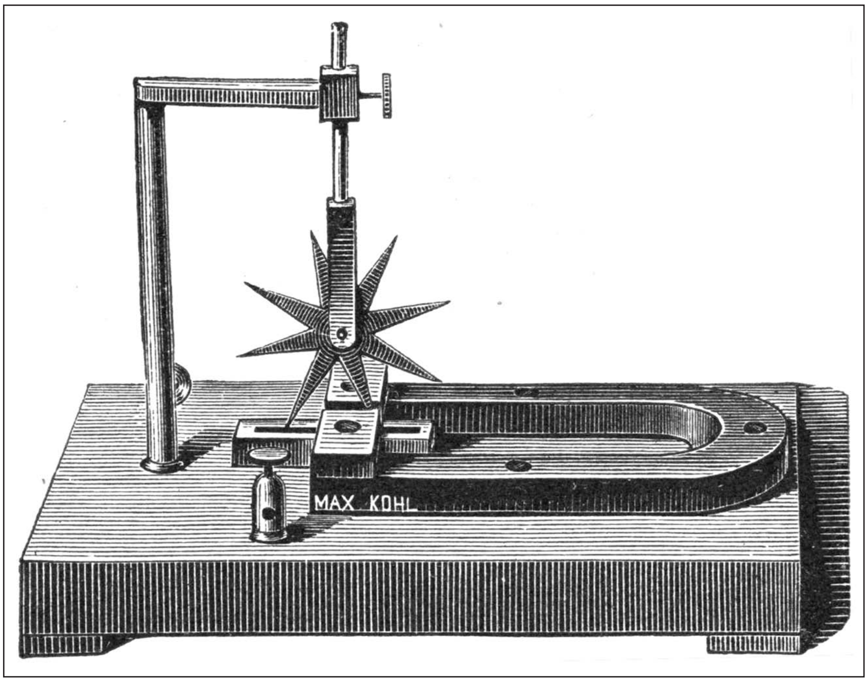


FIGURE 1 – Barlow's wheel of 1822 was a purely demonstrative archetype of a homopolar motor. (Image courtesy of Wikimedia Commons.)

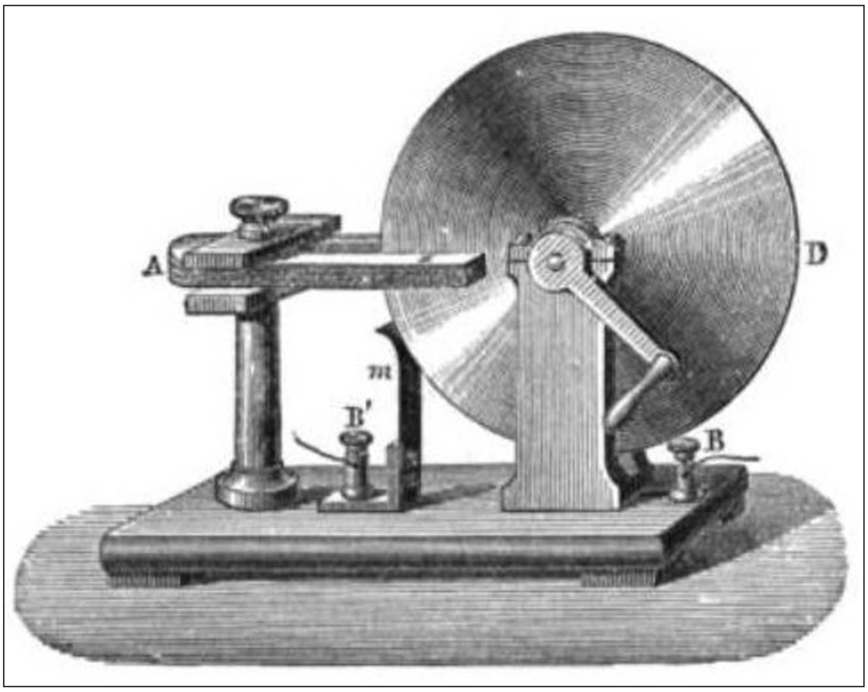


FIGURE 2 – The Faraday disk of 1831 was a purely demonstrative archetype of a homopolar generator. (Image courtesy of Wikimedia Commons.)

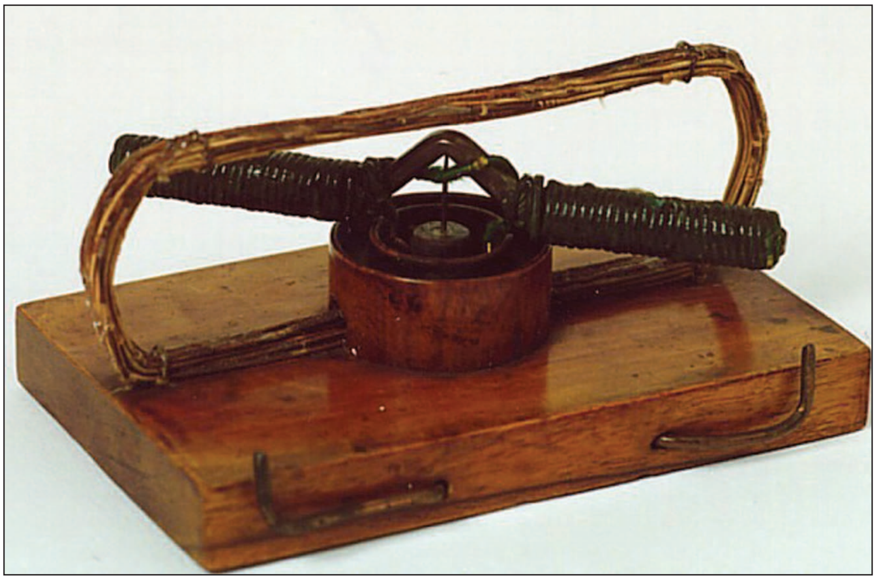


FIGURE 3 – The first Jedlik motor was provided with an early commutator and coils in both the stator and rotor. (Photo courtesy of Wikimedia Commons.)

patent for an electromechanical machine in 1837. Davenport used his motor to drive a small demonstration electric railway with a toy locomotive powered by batteries (1835) and power the first electric printing machine in 1840. Another electrical motor suitable for practical operation was developed by the Scottish inventor Robert Davidson (1804–1894) between 1837 and 1842. It was provided with a two-electromagnet stator and a three-salient-pole rotor, which made it a rudimentary archetype of the reluctance motor.

After some further development, in 1842, he used it to power the first full-scale electric locomotive, called *Galvani*, which was 16-ft long (5 m), and weighed 6 tons. It was tested on the Edinburgh-Glasgow railway line, reaching a speed of 4 mi/h, but without carrying passengers or goods. The high cost of energy supplies, in the form of on-board batteries, prevented further development at the time [6]. Another device that was a forerunner of the stepper motor was built by the French inventor Paul-Gustave Froment (1815–1865) in 1844. It was equipped with electromagnets that were intermittently powered to attract iron bars mounted on a flywheel (a scheme that reduced the moving parts), and this resulted in a more efficient model. Reciprocating electric motors appeared as an appealing option in the 1840s. Italian physicist Luigi Magrini (1802–1868) built one circa 1840, with movements resembling a steam engine. Another reciprocating machine was built by American experimenter Charles Grafton Page (1812–1868) in 1851, and he used it to drive a locomotive powered by an on-board cell battery. Again, the high cost of electricity produced by batteries prevented practical exploitation. Electrochemical cells were the only power source available at that time, and, despite progress in chemistry and technology, they remained an expensive power source, which limited the possible applications of electricity.

The invention of the Faraday Disk of 1831 triggered research in a different direction, namely, the construction of magnetomechanical generators capable of replacing batteries. Inspired by Ampère, the French technician Antoine Hyppolite Pixii (1808–1835) presented an electromechanical generator that was capable of higher electromotive forces, at the Académie des Sciences in 1832. It was a rudimentary alternator consisting of a fixed winding that was wound on a horseshoe-shaped iron core and subjected to the bipolar induction produced by a permanent magnet kept in rotation by means of a crank. It generated alternating electromotive force and electric current. In the same year, at the suggestion of Ampère, Pixii provided the device with a rudimentary commutator to rectify voltage and current. The first electromechanical generator for industrial use was the Woolrich Electrical Generator, which was designed by John Stephen Woolrich (1820–1850) at the Magneto Works, Birmingham, and provided to the Elkinson Electroplating Company in 1844. Another generator suitable for practical operation was patented by the Belgian Floris Nollet (1794–1853) in 1851. It was a permanent magnet alternator capable of relatively high levels of electrical power.

Nollet founded the Anglo-French company Alliance to produce the machine, but he died the same year. Developing this design and resorting to the advice of Faraday, the English engineer Frederick Hale Holmes (1830–1875) built a 36-magnet, 1.5-kW, 600-r/min, 2-ton generator that supplied the first electric lighthouse at South Foreland, Dover, United Kingdom, in 1858. Progress in electromechanical generator design then accelerated. In 1856, Danish inventor Sören Hjorth (1801–1870) built the first electromechanical generator with a magnetic field produced by a battery-fed electromagnet (that provided higher magnetic induction), and Werner Siemens (1816–1892) made the first electrical machine with a double T-armor rotor of solid iron, shaped for housing the windings. He also introduced the name "dynamo" for the dc electromechanical generator.

Several designs followed, including Pacinotti's ring armature of 1860, which allowed the generation of currents with higher values and lower ripples (Figure 4). The first self-excited generator (with self-powered electromagnetic field coils) was overlooked when it was first developed by Jedelik in 1861; but a few years later, the concept was reinvented, almost simultaneously and independently, by three people: Samuel Alfred Varley (December 1866), Werner von Siemens (with series connection, January 1867), and Charles Wheatstone (with parallel connection, February 1867). Electric dc generators reached maturity when Belgian-French technician Zénobe Théophile Gramme (1826–1901), a previous technician at Alliance works, built the first efficient dynamo, incorporating Pacinotti's ring armature and self-excitation (in 1869) and put it into commercial production two years later (Figure 5). It was capable of producing as much power as a steam engine. Electric motors benefited twice from dynamos. The latter made electricity cheaper than disposable batteries, making electricity competitive with other forms of power. The second benefit came from the discovery of the reversibility of the electric machine, which was announced by Siemens in 1867, observed by Pacinotti in 1869, and accidentally experimented by Gramme on the occasion of the 1873 Vienna World's Fair. It promoted the adoption of dynamo technology in designing electric motors. Gramme was the first to substitute the steam engine of his works for an electric machine in 1874. Gradually, dynamos and dc motors replaced steam engines and mechanical power distribution in factories.

Series-connected self-excitation emerged as the arrangement of choice for traction motors because of its superior mechanical characteristics. Siemens and Halske presented the first demonstrative tramway, consisting of small carriages hauled by a 2.2-kW, 150-V motor, at the 1879 Berlin Industrial Exposition. It could carry six passengers per carriage and was powered by a dynamo-fed railway, extending for 300 m and shaped in a circle. The company used a similar motor in the first electric elevator, presented at the 1880 Mannheim Exhibition. Subsequently, Siemens and Halske put into service the first public electric tramway in Lichterfelde (a Berlin suburb) in 1881. It could accommodate 20 passengers and was hauled by a 7.5-kW, 180-Vdc motor (with power supplied through the rails) capable of carrying the carriage at 25 mi/h along the 2.5-km line (Figure 6). Siemens also demonstrated the first tramway fed from an overhead line by means of a trolley pole in a Berlin suburb in 1882. In a few years, other dc electric trams appeared: in Brighton (United Kingdom) and Vienna (Austria) in 1883 and then in Frankfurt (Germany), Paris (France), and Switzerland. The first large public electric tramway in the United States was designed and put into service in Richmond, Virginia, by Frank Julian Sprague (1857–1934) in 1888. It used an original and efficient dc motor that was conceived by Sprague in 1886 (Figure 7). It was fed from an overhead line by means of a trolley pole. The Richmond tramway surpassed all other systems built by that time in terms of extension and traffic, and its success promoted many similar electric tramways in other large cities, both American and European, replacing the unsanitary horses and streetcars. Tuberculosis cases immediately dropped in the cities that introduced electric trams. Electric traction was free of emissions and had obvious advantages compared to steam in underground transport. In 1890, the City and South London Line of the London Underground was completely buried and electrified at 500–600 V as part of a project by Thomas Parker (1843–1916). Electricity quickly became the power supply of choice

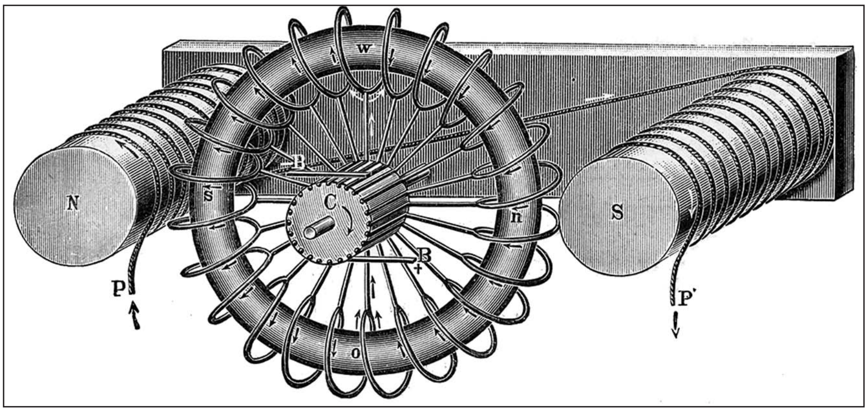


FIGURE 4 – The Pacinotti–Gramme Ring, conceived by the former in 1860 and industrialized by the latter in 1869–1871. (Image courtesy of Wikimedia Commons.)

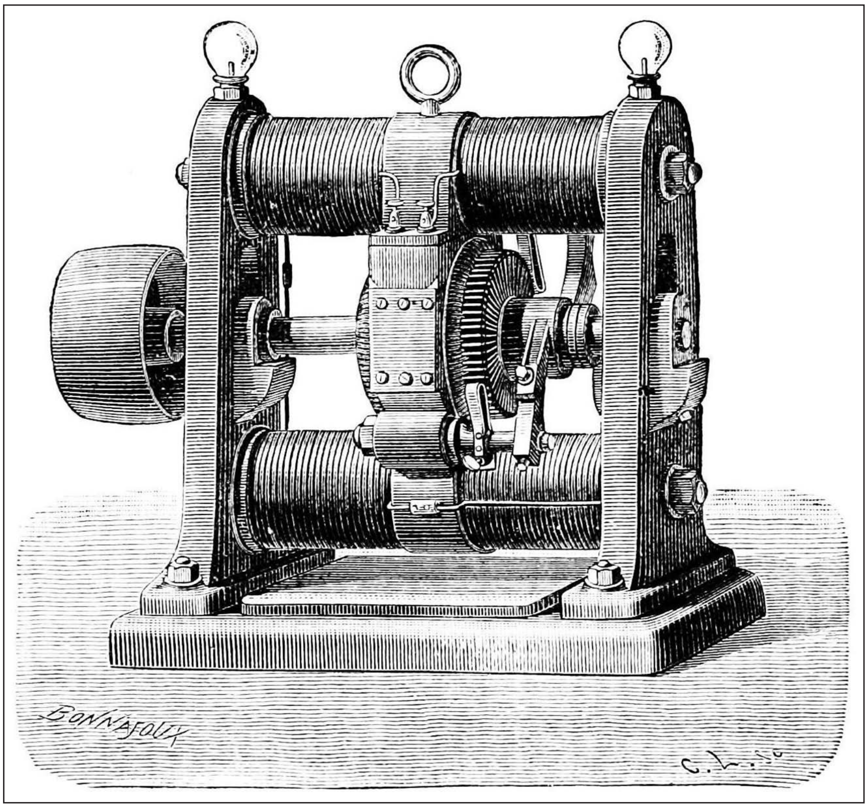


FIGURE 5 – A Gramme dynamo of 1880. Gramme machines were the first effective electric generators that achieved commercial success, since 1871. (Image courtesy of Wikimedia Commons.)

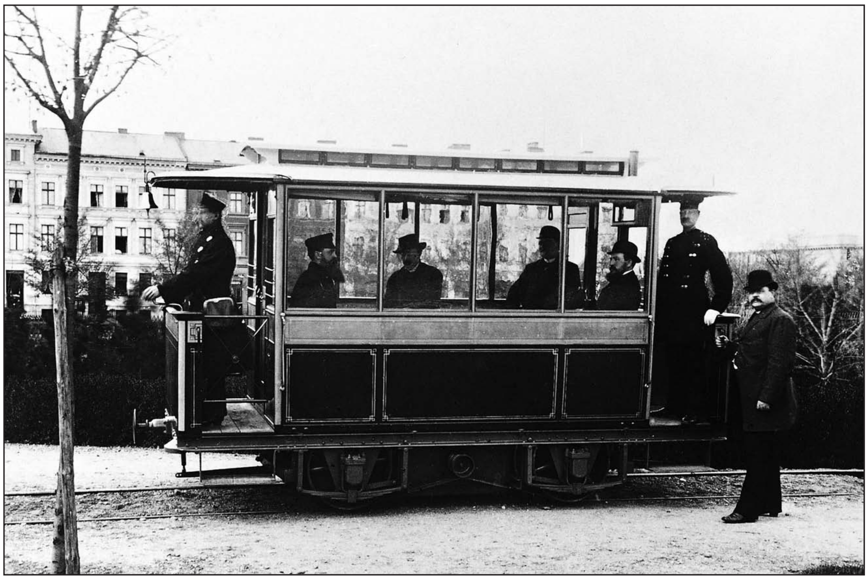
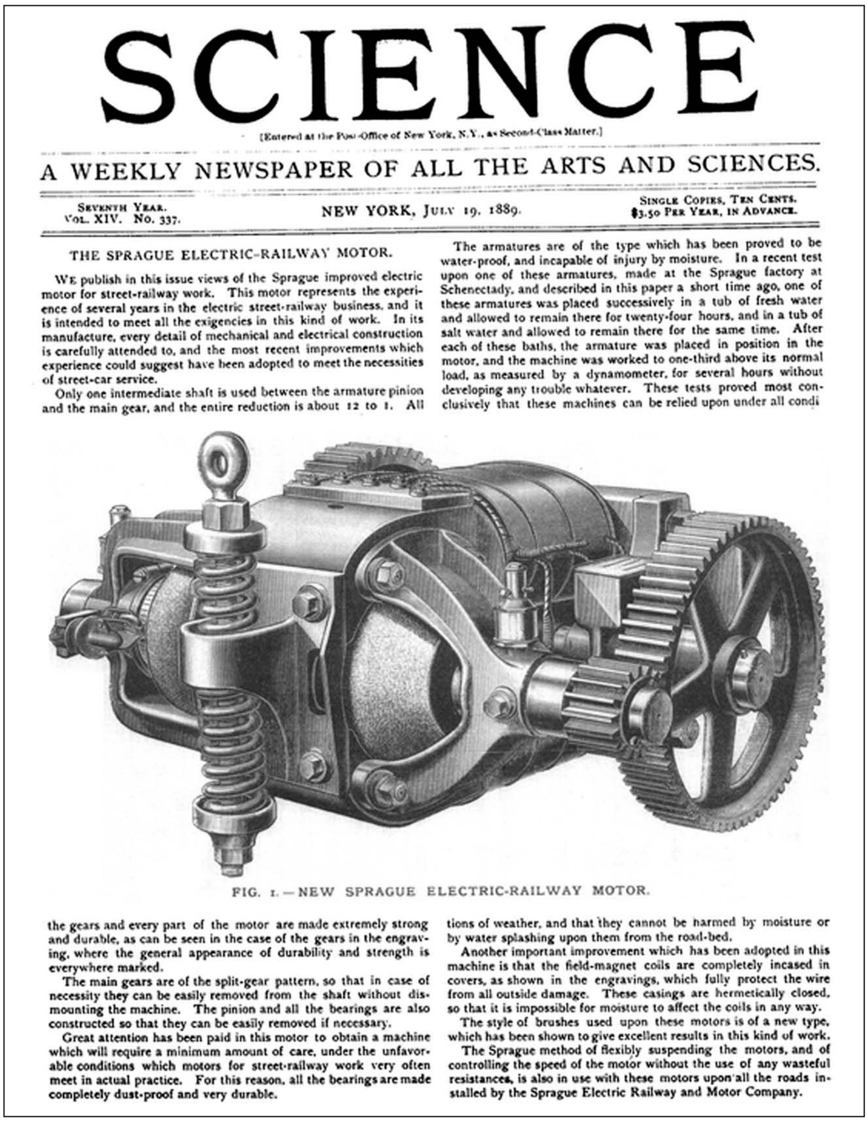


FIGURE 6 – The first public electric tramway was started by Siemens and Halske in Lichterfelde, Berlin, in 1881. (Photo courtesy of Wikimedia Commons.)



SCIENCE

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THE SPRAGUE ELECTRIC-RAILWAY MOTOR.

WE publish in this issue views of the Sprague improved electric motor for street-railway work. This motor represents the experience of several years in the electric street-railway business, and it is intended to meet all the exigencies in this kind of work. In its manufacture, every detail of mechanical and electrical construction is carefully attended to, and the most recent improvements which experience could suggest have been adopted to meet the necessities of street-car service.

Only one intermediate shaft is used between the armature pinion and the main gear, and the entire reduction is about 12 to 1. All

The armatures are of the type which has been proved to be water-proof, and incapable of injury by moisture. In a recent test upon one of these armatures, made at the Sprague factory at Schenectady, and described in this paper a short time ago, one of these armatures was placed successively in a tub of fresh water and allowed to remain there for twenty-four hours, and in a tub of salt water and allowed to remain there for the same time. After each of these baths, the armature was placed in position in the motor, and the machine was worked to one-third above its normal load, as measured by a dynamometer, for several hours without developing any trouble whatever. These tests proved most conclusively that these machines can be relied upon under all condi

FIG. 1.—NEW SPRAGUE ELECTRIC-RAILWAY MOTOR.

the gears and every part of the motor are made extremely strong and durable, as can be seen in the case of the gears in the engraving, where the general appearance of durability and strength is everywhere marked.

The main gears are of the split-gear pattern, so that in case of necessity they can be easily removed from the shaft without dismounting the machine. The pinion and all the bearings are also constructed so that they can be easily removed if necessary.

Great attention has been paid in this motor to obtain a machine which will require a minimum amount of care, under the unfavorable conditions which motors for street-railway work very often meet in actual practice. For this reason, all the bearings are made completely dust-proof and very durable.

tions of weather, and that they cannot be harmed by moisture or by water splashing upon them from the road-bed.

Another important improvement which has been adopted in this machine is that the field-magnet coils are completely incased in covers, as shown in the engravings, which fully protect the wire from all outside damage. These casings are hermetically closed, so that it is impossible for moisture to affect the coils in any way.

The style of brushes used upon these motors is of a new type, which has been shown to give excellent results in this kind of work.

The Sprague method of flexibly suspending the motors, and of controlling the speed of the motor without the use of any wasteful resistances, is also in use with these motors upon all the roads installed by the Sprague Electric Railway and Motor Company.

FIGURE 7 – The original and efficient dc motor designed by Sprague in 1886 was presented in the 19 July 1889, edition of *Science*. (Image courtesy of *Science*.)

for subways [7]. Electric subways were built in Budapest, Hungary, in 1896 and Paris, France, in 1900, on the occasion of the Universal Exhibition. Sprague built the first electric elevator in the United States in 1892, with advanced floor control. The same year, he installed the Chicago and South Side Rapid Transit Railroad, the first of many elevated tramways, provided with multiple-unit control of self-powered passenger cars.

The drum rotor was introduced by Friedrich von Hefner-Alteneck (1845–1904) of Siemens and Halske to replace Pacinotti's ring armature in 1872, thus improving the machine efficiency. The laminated rotor was introduced by the same company the following year, achieving reduced iron losses and increased induced voltages. In 1880, Swedish inventor Jonas Wenström (1855–1893) provided the rotor with slots for housing the winding, further increasing the efficiency. He later cofunded the ASEA Company. Important contributions to the design of rotating machines came from British mathematician and engineer John Hopkinson (1849–1898), who introduced the dynamo's voltage-current characteristic in 1879 and developed the magnetic circuit theory in 1886 [8], building on early analyses carried out by American physicist Henry Augustus Rowland (1848–1901) in 1873. The Austrian-British engineer Gisbert Kapp (1852–1922) extended the studies on dynamos and their magnetic circuits in 1887, providing more elements for their rational design.

These improvements helped dc machines to mature. In the following years, dc motors became more and more efficient while being used in electric streetcars, trains, and motor cars in Europe and America. The latter benefitted from the invention of viable rechargeable batteries, which became commercially available in 1881 [9]. Electric cars were first marketed in France in 1894, and the reversibility of the dc machine allowed Louis Antoine Krieger (1868–1951) of Paris to produce cars with regenerative braking, i.e., electromagnetic braking with energy recovery. A young Ferdinand

Porsche (1875–1951) built his first car for Lohner-Werke in Vienna, Austria, in 1898. It was an electric car with hub-motors at the front wheels. Three years later he developed the first hybrid car. It was provided with an ICE, rotating at constant speed and powering a dynamo that charged a reduced-size (and reduced-weight) battery, which in turn fed the electric hub-motors at all four wheels. The first electric starter for an ICE was installed in 1896 on a Benz Velo car, built under license in Great Britain, but the idea was brought to success years later in America. In 1911, Charles F. Kettering (1876–1958) patented an electric starter suitable for intermittent operation (it could provide an overload starting power for a few seconds) powered by a rechargeable battery. A year later, the device went into production for luxury Cadillacs. An electric starter was fitted to the Ford T in 1919, and by 1920, it was installed in most gasoline-powered vehicles.

At the turn of the century, an important application of dc generators and motors was their use in the long-distance, high-voltage dc system developed by René Thury (1860–1938). Starting with the 30-kW, 500-V system in Bözingen, Switzerland, of 1885 and culminating in the 230-km, 20-MW, 125-kV Lyon-Moûtiers project of 1906, Thury's systems resorted to a series connection of both generators at one end of the line and motors driving low-voltage dynamos at the other end [10].

Another major achievement utilizing dc motors is the electric railway. The Harlowton-Avery railway (that extended across the Rocky Mountains for 706 km) was electrified with an overhead line at 3 kV dc in 1916. Expanded by 333 km between 1917 and 1920, it was the largest electrified railway in the world at the time [11]. The on-board dc motors were used to support the steam engines on the steep and challenging route, particularly in winter where temperatures reached −40 °C. In 1920, the Turin-Ceres railway in Italy was electrified at 4 kV dc. It was the first dc electric railway at that voltage level. After the advent of high-voltage mercury rectifiers in the late 1920s [12], the system spread in Italy in the 1930s. In other European countries, and elsewhere, the French 1.5-kV dc system was adopted. With these dynamos and motors, dc current had reached full maturity but a redoubtable competitor had already emerged: ac power.

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