The history of electric machines

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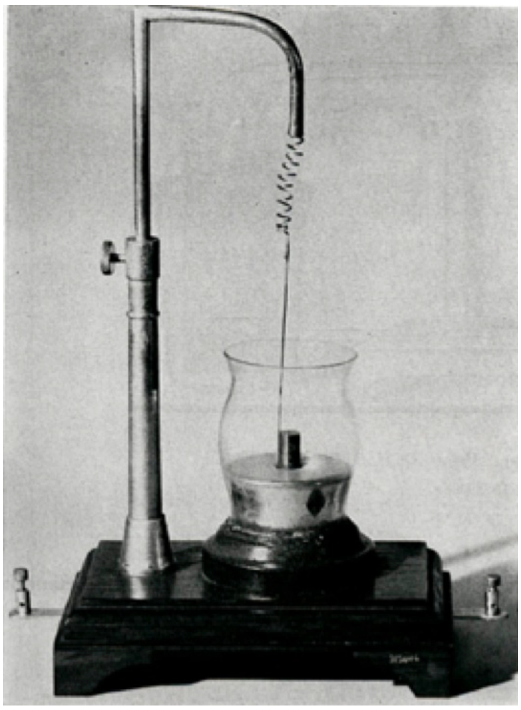
The foundation of electromagnetism

The foundation of electromagnetism had to be laid before electrical machines could be developed.
In **1800**, Allessandro **Volta** (Italian) produced a continuous electric current for the first time. In former times electricity was known only as sparks or static electricity. Volta built an early battery of a stack of silver and zinc plates, which became the basis for more systematic experiments with electricity.

20 years later, around **1820**, Hans Christian **Oersted** (Dane) found the generation of magnetic fields by electric currents. He observed the deflection of a compass needle near an electric wire. This was the very first time that a mechanical movement was caused by an electric current. The experiment may be regarded as the first electric motor, albeit a very basic one.

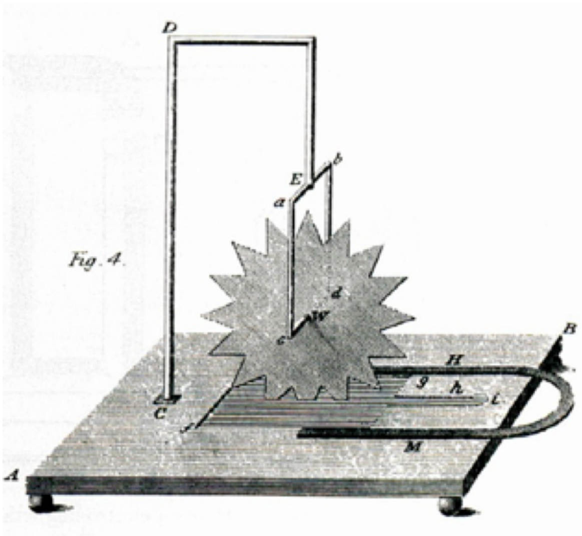
Only about half a year later André-Marie **Ampère** (French) invented the cylindrical coil (a solenoid), which would greatly enhance the magnetic field generated by electric currents.

In **1821**, Michael **Faraday** (British) started to experiment with the new-found phenomenon. He created two devices for the demonstration of electromagnetic rotation by placing a vertically suspended wire into a pot of liquid mercury. The wire would then move in a circular orbit around a magnet.



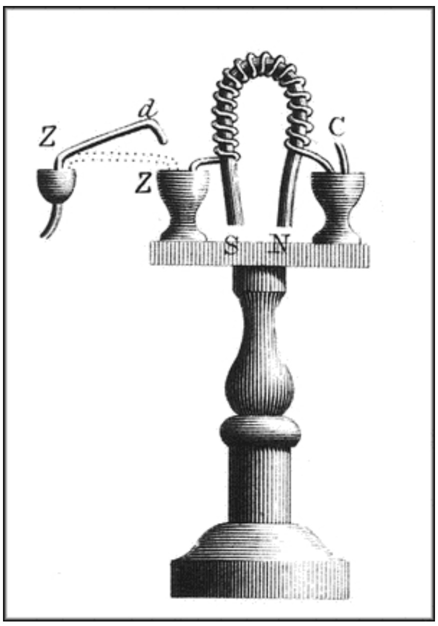
Faraday's rotating wire, 1821

In **1822**, Peter **Barlow** (British) built a device that can be considered the very first DC-motor: His unipolar machine (also called homopolar motor) used a vertically suspended, star shaped rotating metallic disk and a permanent magnet that provided a horizontal (axial) magnetic flux. The outside of the disk was electrically connected by a bath of liquid mercury.
When electric current was sent in radial direction from the center to the outside of the disc, the stream of electrons would be bended by the Lorentz force. In a simplified model, this "friction" creates a counterforce in the metallic disc, causing it to rotate. The power of Barlow's wheel, however, was much too small to perform any useful work.



Barlow's wheel, 1822; Philosophical Magazine, vol. 59

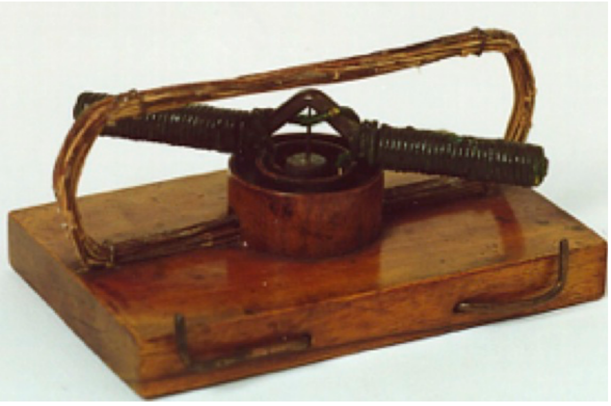
Only two years later much stronger magnets became possible by the invention of the electromagnet: A coil of wires wound around an iron core to enhance the magnetic flux. This was first found by William **Sturgeon** (British) in **1824**.

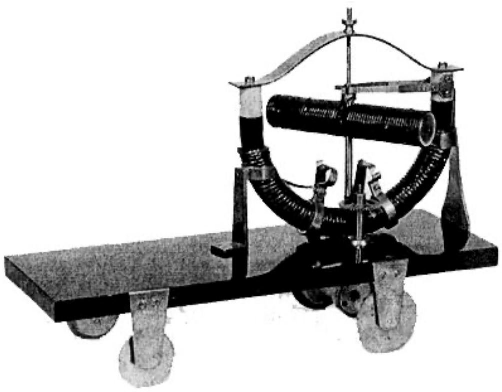


First electromagnet by Sturgeon, 1824; Transactions of the Society for the Encouragement of the Arts, Manufacturers and Commerce, vol. 43, pl. 3

Electromagnetism and Sturgeon's electric magnet became quite popular in Europe and in the United States. Many inventors started to experiment and competed in building stronger magnets. The idea of creating rotation from electric currents also became popular even before 1830.

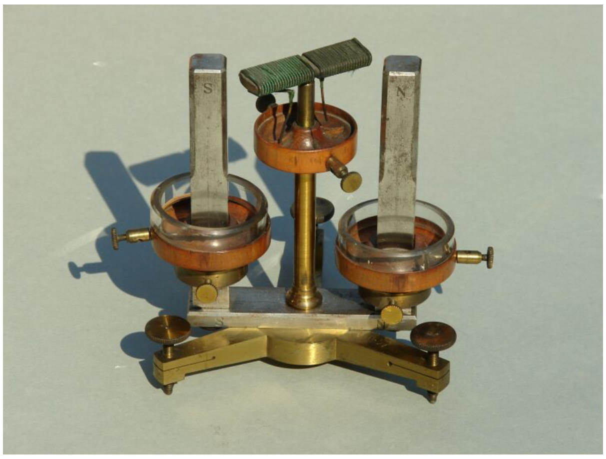
The first rotating electric machine based on electromagnets and a simple commutator was probably built around **1827/28** by Istvan (Ányos) **Jedlik** (Hungarian).
A functional model of his apparatus is displayed at the art museum in Budapest, Hungaria. Unfortunately, however, Jedlik did not publish his ideas, so the exact timing of his invention is unknown. His motor remained hidden for a long time and did not influence any of the following, more advanced developments in the rest of Europe and the United States.





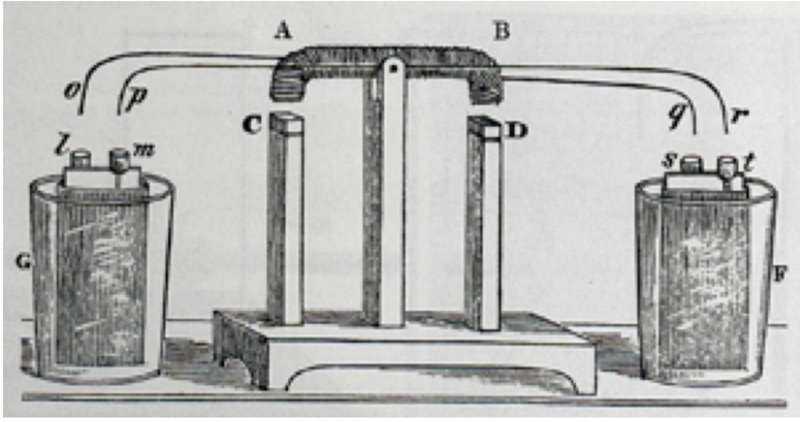
Rotary electromagnetic motor (left) and small model car (right) by Jedlik, probably around 1827/28; Photos: Wikipedia

Johann Michael **Ekling**, a mechanic from Vienna, Austria built a motor according to the plans and ideas of Prof. Andreas von Baumgartner (Austrian physicist; since 1823 Professor of Physics and Applied Mathematics in Vienna).
This apparatus was acquired in 1830 by the University of Innsbruck for the price of 50 fl c.m. (Gulden). The exact date of construction is unknown but must have been before 1830, which is the proven date of purchase.



Baumgartner's motor, built by Ekling before 1830; Photo courtesy of the University of Innsbruck, Museum of Experimental Physics, Ao. Univ. Prof. Mag. Dr. Armin Denoth.

In **1831**, Joseph **Henry** (US) described a small magnetic rocker in the *American Journal of Science*. His construction was quite different from a modern-day electric motor as it didn't even rotate. Henry named it a ‘philosophical toy’. Still, some authors call Henry the inventor of electric machines.



Henry's magnetic rocker, 1831; American Journal of Science, 1831, vol. 20, p. 342

Henry and Michael **Faraday** (British) discovered the law of electromagnetic induction independently in 1831. Induction is the generation of an electric current due to a varying magnetic field - basically the inversion of Oersted's discovery.

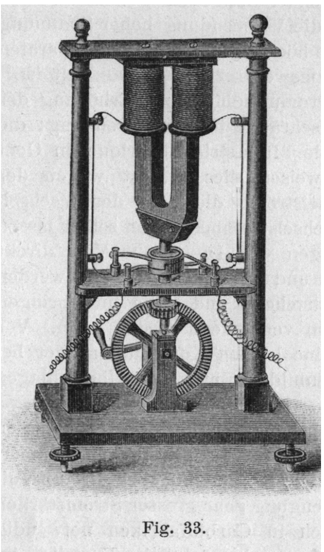
Faraday's work was stimulated by an experiment François **Arago** (French) already performed in **1824**. He discovered that a rotating magnetized needle was rotating a copper disk mounted directly underneath it.
Faraday was able to understand the physical principle of induced voltages and explained Arago's experiment. With these findings, Faraday laid the foundations for the development of electric DC (direct current) generators and of AC (alternating current) induction motors, which did not come until many years later.

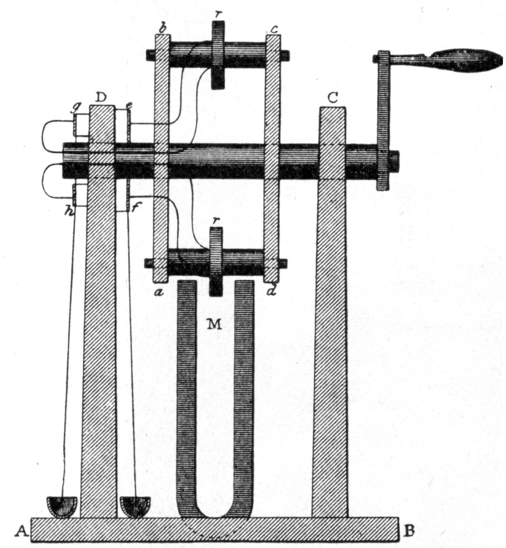
In the early years of electrical engineering there was a strict distinction between magnetic-electro machines, that is electric generators, and electro-magnetic machines, that is electric motors.
Already in **1833**, Heinrich Friedrich Emil **Lenz** (German) found the law of reciprocity of the magneto-electric and electro-magnetic phenomena, the reversibility of electric generator and motor. His scientific text was presented by the end of 1833 at the St. Petersburg Academy of Sciences and published in *Poggendorff's Annalen der Physik und Chemie* in the following year.
It took decades before Lenz's idea became commonly known and for a long time the developments of D.C. motors and generators ran in parallel and independent of each other.

Myths were created about the invention of the law of reciprocity and several people claimed its invention, for example the Italian Pacinotti in 1861.
Nevertheless, Emil Lenz reported already in 1838 in *Poggendorff's Annalen der Physik und Chemie* in detail how he operated a Pixii generator as a motor.

In **July 1832**, Hippolyte **Pixii** (French) built the first apparatus for generating an alternating current (AC) from mechanical rotation. The device was presented publicly in September 1832 at a meeting of the Académie des Sciences in Paris, France. His description was already published in the July 1832 issue of the *Annales de Chimie*.

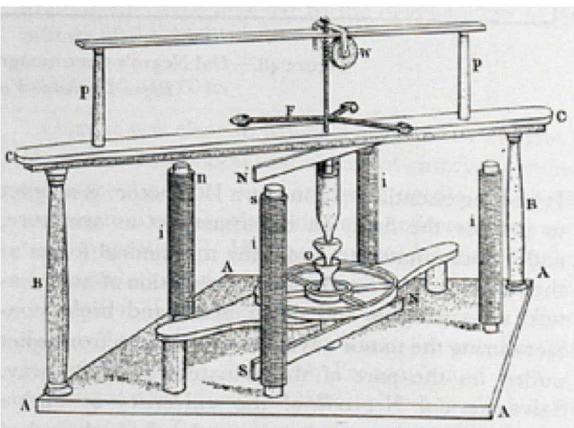
Pixii improved his generator and later added a switching device (commutator), which was first publicly described by William **Ritchie** (British) in **March of 1833** in the *Philosophical Transactions of the Royal Society of London, Vol. 132*. Pixii was now able to produce a pulsating direct current (DC).





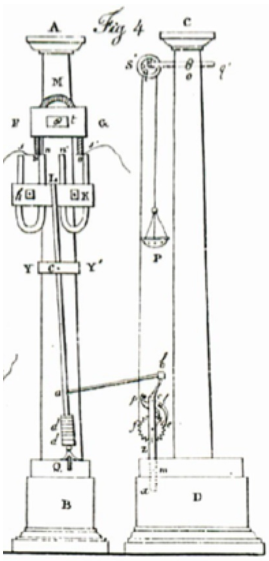
Left: Pixii's first DC generator, 1833; *F. Niethammer, Ein- und Mehrphasen-Wechselstrom-Erzeuger, Verlag S. Hirzel, Leipzig 190*;
Right: Ritchie's First DC generator with commutator, 1832/33

In **late 1836/early 1837** William Sturgeon established the first journal on electromagnetism, the *Annals of Electricity, Magnetism and Chemistry*. It was well received and ran for several years.
In an article of the first issue, Sturgeon claimed the invention of the commutator for himself. However, the exact timing of his invention, which he claimed was in autumn of 1832, remains unproven.



Sturgeon's rotation device, 1832 (?), first published in Sturgeon's Annals of Electricity, 1836/37, vol. 1

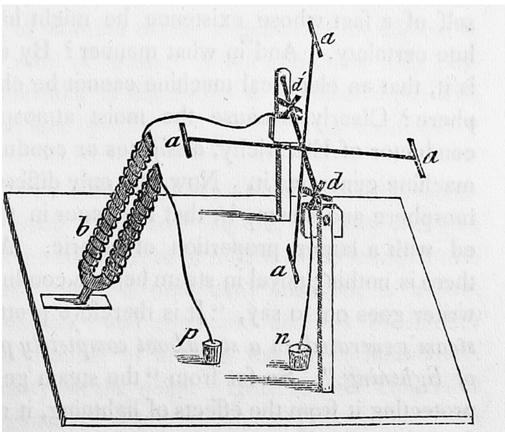
During **1832 and 1833**, many more machines were built by inventors in Europe, for example by Dr. Schulthess (Swiss) in Zurich, William Sturgeon (British) in London and by Savatore dal Negro (Italian) in Padua. Some of the machines were alternating like Henry's magnetic rocker. Others worked like a pendulum and created rotation by means of a ratchet.



Left: Dal Negro's electromagnetic pendulum, 1832; Annali delle Scienze de Regno Lombardo-Veneto, March of 1834, pl. 4; Right: Rotary machine of Botto, July 1834 (Reconstruction); Photo courtesy of Museo Galileo, Florence

During **1834 and 1835** more inventors became known who built slightly more sophisticated machines, for example Guiseppe Domenico Botto (Italian) in Torino, Francis Watkins (British), Sibrandus Stratingh and Christopher Becker (both Dutch) and Johann Philipp Wagner (German).

Prof. Siberius Stratingh (1785-1841) from the University of Groningen, Netherland and his assistant Christopher Becker designed a tiny electric model car already in 1835. Reportedly it weighted about 3 kg and could run for 15 to 20 minutes before the battery got depleted.



Left: Edmundson's electromagnetic wheel, October 1834; American Journal of Science, 1834, vol. 26, p. 205; Right: Replica of the electric model car by Stratingh and Becker, 1835; Boerhaave Museum, Leiden, Netherlands

However, all these early devices produced a very low mechanical output power. They could barely overcome their friction to maintain movement.

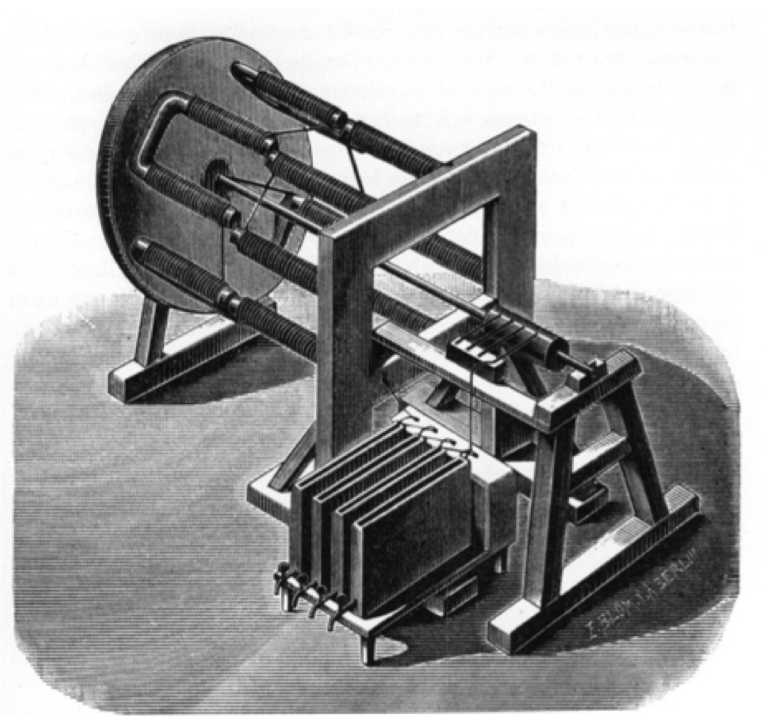
Early useful electric machines

Moritz Jacobi

Moritz Hermann Jacobi was born on September 21, 1801 in Potsdam, Prussia (now Berlin, Germany). He studied civil-engineering at the Universities of Berlin and Göttingen. Since 1833 he worked as master-builder in Königsberg (then Prussia, now Russia). In the beginning of that year, he started experiments with a horseshoe-shaped electromagnet.
In January 1834, he wrote a letter to Poggendorff, editor of the *Annalen der Physik und Chemie*, describing his success.
These experiments led him to the construction of the first useful electric motor, which he completed in **May 1834**. Jacobi reported that his motor lifted a weight of 10 to 12 pounds with a speed of one foot per second, which is equivalent to about 15 watts of mechanical output power.

In November 1834, Jacobi sent a first report to the *Academy of Sciences* in Paris, France and published a detailed scientific memoir in the spring of 1835. This paper earned him an honorary doctorate from the University of Königsberg in June of the same year. His text was divided into 23 sections and expanded in 1837 with 15 further sections.

While Jacobi's original machine has been lost, there are two fully functional replicas known to exist. One of them is displayed at the Institute of Electric Engineering (ETI) of the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany.

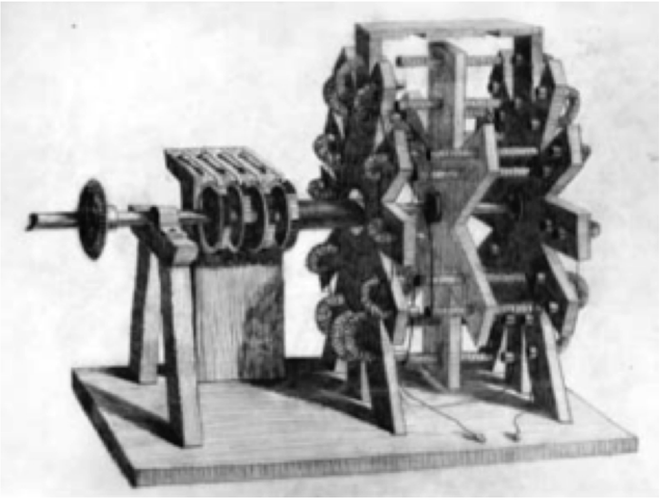


Jacobi's first electric DC motor, May 1834

In August of 1938 Jacobi moved to St. Petersburg at the request of the Russian Tsar. He was accepted at the St. Petersburg Academy of Sciences and generously supported by the Tsar in his further work on electric motors.

On **September 13, 1838**, Jacobi demonstrated the first actual application of an electric motor. His new machine delivered some 1/5 ... 1/4 hp mechanical power (about 300 W) and was used to drive an 8 m long boat with paddle wheels.

Jacobi built zinc batteries with 320 pairs of plates and a weight of 200 kg. The batteries were placed along the two side walls of the vessel. The boat traveled with 2.5 km/h across the river Neva in St. Petersburg over a 7.5 km long route. It could carry more than a dozen passengers. Jacobi drove around many days on the river. Contemporary newspaper articles stated that after two to three months of operation the zinc consumption was 24 pounds, which costed a fortune at that time.



Jacobi's improved motor, September 1838

On August 8, **1839** Jacobi tested another, further improved machine that could deliver about 1 kW mechanical power. His boat was now reaching 4 km/h.

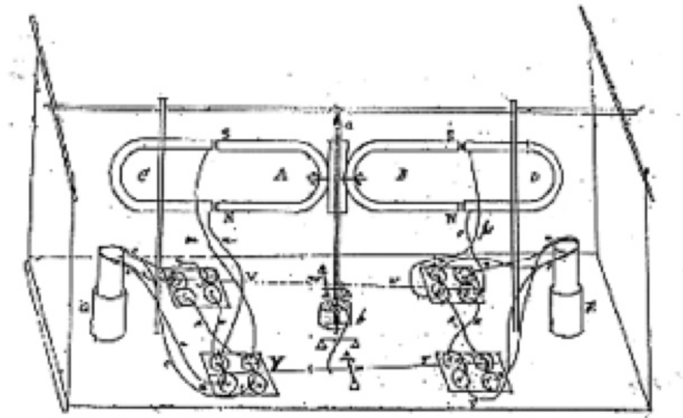
During the following years Jacobi's technical interest turned to other topics. He built the underground telegraph line from St. Petersburg to Zarskoje-Selo. With a length of 25 km, it was the longest of its time. He also worked on the standardization of the metric unit system. Jacobi became a highly respected scientist and was member of academies of science in several European countries. He died in 1874 from a heart attack.

Jacobi also started to develop a theory on the calculation of electric machines already in 1842. More sophisticated theories, however, could only be created after James Clerk **Maxwell** (Scot) summarized all the contemporary knowledge of electromagnetism and developed his four fundamental equations during 1861 to 1864. These equations were a remarkable achievement and are still valid until today. They fully describe the theory of electrical engineering.

Thomas Davenport

In December 1833, the blacksmith Thomas **Davenpor**t (*1802 in Williamstown, VT), who lived in a village near the town of Brandon, purchased an electric magnet and begun experiments in a workshop in Forestdale, Vermont.
In July 1834, he created his first rotary machine and improved the device in several steps before firstly demonstrating it publicly in **December 1834**.

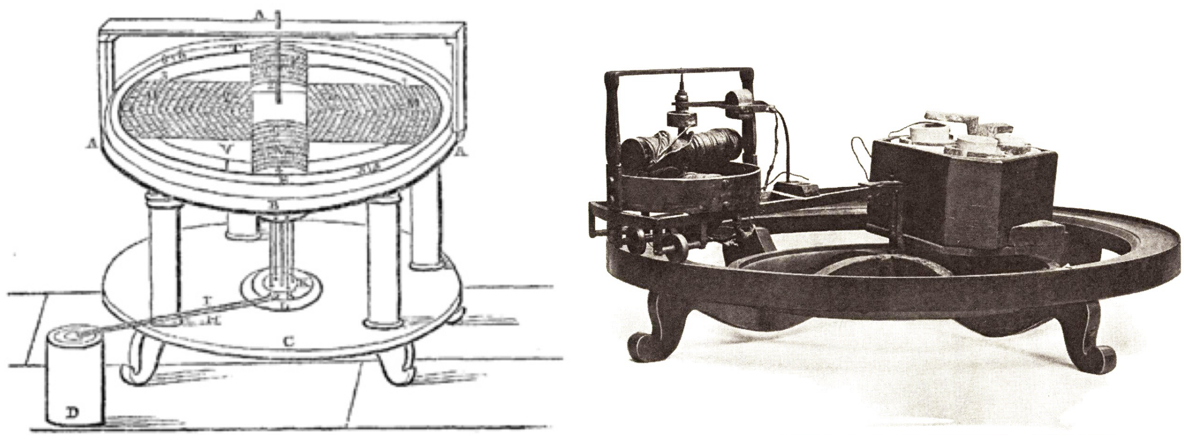
In the summer of 1835 Davenport traveled to Washington, D.C., to demonstrate his machine before the patent office and have it registered. Due to lack of money, however, he had to return home without success.



Davenport's first motor, Summer 1835, from his patent application.

The design of Davenport's first machine was not much different from other experimental devices known at the time, for example the one Edmundson had presented a year before. Its output power is unknown but was likely very low. For the most part of their rotation the two rotary coils were located far away from the magnetic field created by the stationary coils and hence would not produce torque.

Davenport continued to improve his motors in the following years. Early in 1837 he made a second trip to the patent office in Washington. The first U.S. patent on the design of an electric motor: *Improvement in propelling machinery by magnetism and electromagnetism* was granted to him on **February 5, 1837**.



Left: Davenports patented motor, February 1837, from his patent application;
Right: Model train built shortly before the patent application in the winter of 1836/37, from the Biography of Thomas Davenport by W.R. Davenport and J. Hartness, 1929

Davenport's patented motor and the small model train are now on display at the Smithsonian Institute in Washington, D.C. His design used four rotating electromagnets that were switched by a commutator and a ring-shaped fixed permanent magnet made of soft iron. The technical specifications of the patented motor are not known.

In August 1837, Davenport presented an improved device, which had 6 inches in diameter, rotated at about 1,000 revolutions per minute and could lift a 200-pound weight by one foot in one minute. This corresponds to a power of 4.5 Watts.

Davenport did not receive his patent on the invention of the electric motor as such but only on his specific electromechanical design. As Davenport redesigned his motor already during 1837 and improved it further in the following years, the patent became practically worthless. Over the years, Davenport manufactured quite a few machines. But unlike Werner Siemens, George Westinghouse or Thomas Edison, he was not the founder of an important company.

In January 1840, Davenport started to edit and publish his own weekly magazine on the subject of electricity in New York: *The Electro-Magnet, and Mechanics Intelligencer*. He used self-made electric motors to drive the printing press. However, already after three editions he stopped the project in February 1840 due to lack of subscribers and because the batteries needed to operate the motors were too expensive. Later in that year, he started a new approach, which also failed soon after.

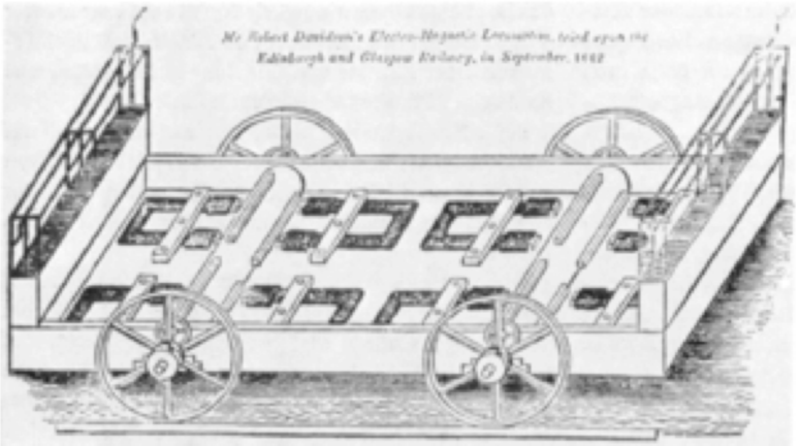
Davenport died early at the age of 48 in 1851 in Salisbury, Vermont.

Further achievements

In the years from 1837 to 1866, about 100 patents on electric motor designs were granted to many inventors in England alone. More patents were granted in the U.S. and the rest of Europe.

Robert **Davidson** (Scottish) developed electric motors since **1837**. He made several drives for a lathe and for model vehicles.
In 1839, Davidson managed the construction of the first electrically powered vehicle.
The rotor was equipped with steel bars that would be attracted by the field created from the stationary coils. To create a rotation, Davidson had to switch the coils on and off one after the other. This marks the principal invention of the switched reluctance motor that we still use today, albeit in a more refined form.

In September 1842, Davidson made trial runs with a 5-ton, 4.8 m long locomotive on the railway line from Edinburgh to Glasgow. His motor produced about 1 hp (0.74 kW) mechanical power and the wagon reached a speed of 4 mph (6.4 km/h).



First electric vehicle, Davidson, 1839, from *T. du Moncel, Electricity as a Motive Power, London, 1883, fig. 32*

In **1838**, Charles G. **Page** (US-American) started a lifelong occupation with electric motors. Over the next 20 years, Page tried to find better, more powerful machines. His motors were sold via catalog in the U.S. and reached a high level of public awareness.
In 1851, Page was able to build a 20 hp (15 kW) machine. With two such motors he drove a 10-ton locomotive from Washington, D.C. to Bladenburg, M.D. at a top-speed of 30 km/h in just 19 minutes. Three years later, he drove an electric train from Baltimore to Ohio.

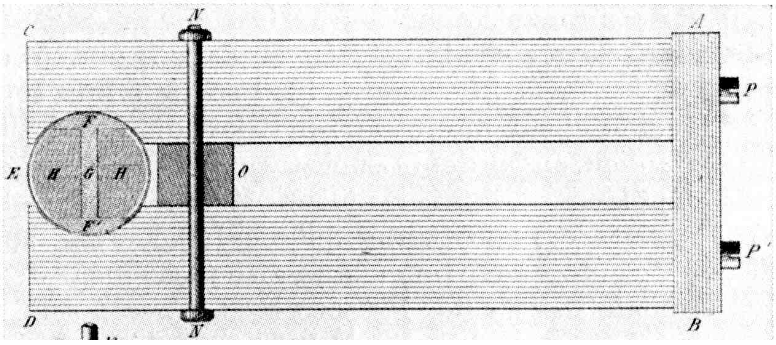
A fundamental problem of the early electric motors was the cost of electricity. Galvanic elements (zinc batteries) were far too expensive to compete with steam engines.
R. Hunt reported in 1850 in the British Philosophical Magazine that even under the best conditions, electrical power was 25 times more expensive than a steam engine.
The situation changed just slowly with the ongoing development of electric generators.

Modern day DC machines

Modern day DC motors are not direct descendants from the devices of Jedlik, Jacobi, Davenport, Davidson, Page or of the many other early inventors, whose constructions have all disappeared. The machine design still used today is instead based on the works of the inventors of electric generators.

These developments already started in 1832 and were driven by Pixii, Ritchie and others.

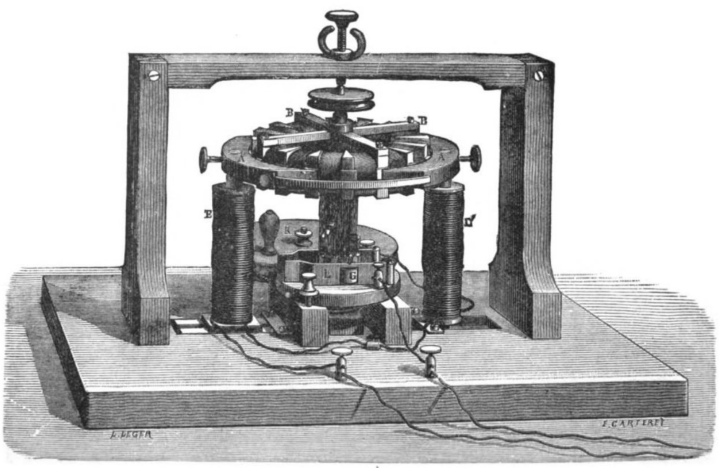
In **1856**, Werner **Siemens** (German) was the first to place windings into slots. His Double-T armature winding marks a turning point in the design of electrical machines. It took several decades but slowly all previous constructions disappeared from the market. Today, nearly all electric machines are built with windings (wires) placed inside of slots.



Siemens Double-T armature with windings placed inside of slots; *Poggendorffs Annalen der Physik 101 (1857) Taf. II*

The first 50 devices were produced by Siemens to deliver electric pulses for telegraphs and purchased by the Bavarian railways. Between 1866 and 67, Siemens further developed his machine to produce a continuous (albeit pulsating) DC-current.

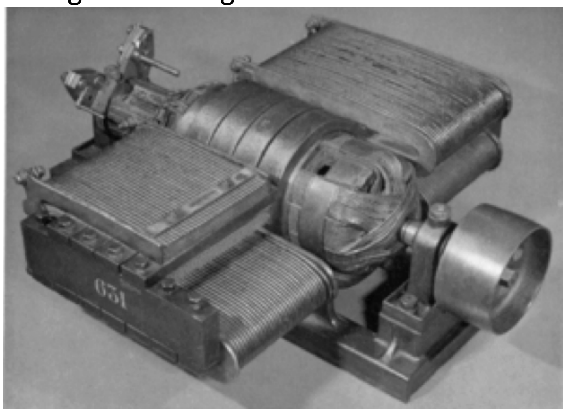
Around **1860**, Antonio **Pacinotti** (Italian) designed the ring anchor and created the first dynamo machine. The new design solved the problem of pulsating currents and produced a smooth DC voltage. He published his findings in the German magazine *Zeitschrift für Physik* in 1865, which was founded by Albert Einstein and other physicists.



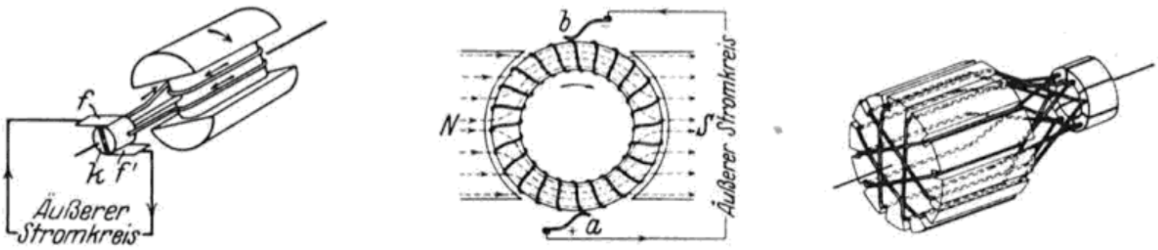
Pacinotti's dynamo machine with a ring anchor, 1863

Zénobe Théophil **Gramme** (Belgian) was inspired by Pacinotti's design and developed it further. He demonstrated his improved apparatus to the Academy of Sciences in Paris in **1871**. The ring winding design became quite popular for many years. Gramme's generator was effectively the first commercially successful DC dynamo machine. It was in strong competition to Siemens' Double-T armature machines.

Friedrich von **Hefner-Alteneck** (German), head of engineering at the Siemens company, finally solved Siemens' problem in **1875** with the invention of the anchor drum motor. He wrapped wires around a cylinder-shaped anchor and was now able to create a smooth DC voltage from his generator.



Siemens' drum armature, app. 1872 (sliced model); *Photo: Science Museum, London*



From left to right: Siemens' Double-T anchor (1857), Gramme-Pacinotti Ring (1860), Hefner-Alteneck's drum anchor (1872); *Lehrbuch der Physik: In elementarer Darstellung*, Arnold Berliner, 1928

Hefner-Alteneck reduced the eddy currents by using iron wires instead of a solid iron block for the magnetic core. The final solution to this problem, however, was firstly proposed by Auguste **Pellerin** (French) in **1873.** He subdivided the iron core into many thin, mutually insulated sheets of steel.

These developments slowly put an end to Pacinotti's and Gramme's ring winding, which is no longer used today. The ring makes inefficient use of the conductors and produces a high degree of stray flux as the parts of the wires at the interior side of the ring do not contribute to energy conversion. Many years later, Haselwander, Tesla and Dolivo-Dobrowolsky used a modified variant of the ring winding for the stators of their first rotating field AC machines.

With Ritchie's commutator, Siemens' slotted rotor, the drum armature of Hefner-Alteneck and finally the lamination of the magnetic core, all important design features of modern-day electric DC motors finally became available.

The war of currents - AC and DC power distribution systems

Just as in the history of DC machines, three-phase AC (rotary current) systems and the corresponding AC machines have many fathers who contributed to the development. Several inventors in different parts of the world worked in parallel without knowledge of each other. Some achieved remarkably similar results.

The first experiments with single-phase alternating voltages and currents already took place in **1832**, when **Pixii** introduced his first generator. At that time, however, the particular benefit of AC, which is the simple transformation of voltage to high levels resulting in low currents for near lossless transmission over long power lines, was not yet discovered.

Probably the first long distance DC line was built between the German towns Miesbach and Munich over a 57 km distance in September 1882 on the occasion of the Munich Electricity Exhibition. The line was operated at a voltage of 2 kV and powered by a 1.5 hp (1.1 kW) generator. It was built by the German Oskar **von Miller** and the French Marcel **Depréz**. However, the line's efficiency was only 25%. It failed soon and was disbanded already after a few days of operation.

Thomas Alva **Edison** (1847-1931, founder of the General Electric Company in 1890) promoted DC voltage for the electrification of towns and villages. He put the world's first commercial DC power distribution system into operation in lower Manhattan on September 4, 1882. Six 100 kW generators were installed in the powerhouse at Pearl Street and distributed DC power through 80,000 feet (24.3 km) of underground cable to 82 (some sources say 59) customers at a voltage of 110 V.

The principle of AC transformers was already found in **1875** by Pawel **Nikolajewitsch Jablotschkow** (Russian). The first actual transformer, using two coils wound around an iron core, was demonstrated in London in **1881** by Lucien **Gaulard** (Frenchman) and John Dixon **Gibbs** (Englishman). It was patented the following year.

Early experiments with single-phase AC transmission lines begun in **1884** in Torino, Italy by Gallileo **Ferraris**, a professor at the local University.

At first, George **Westinghouse** (1846-1914, founder of Westinghouse Electric in 1886) developed his own DC system in 1884. When he became aware of the European experiments with AC in the following year, he saw a chance to build a competitive system to Edison instead of just following his lead.
Westinghouse acquired the patent rights on transformers from Gaulard and Gibbs and imported several transformers in 1885.
During 1886, Westinghouse Electric installed the first AC power system in Great Barrington, Massachusetts. It used 3 kV voltage for transmission and 100 V for the customers. By the end of 1887, Westinghouse had installed 68 AC power stations against Edison's 121 DC based stations.
Although AC was better suited for power distribution than DC, there was no motor technology available. Westinghouse desperately needed an AC motor to compete against Edison's DC system.

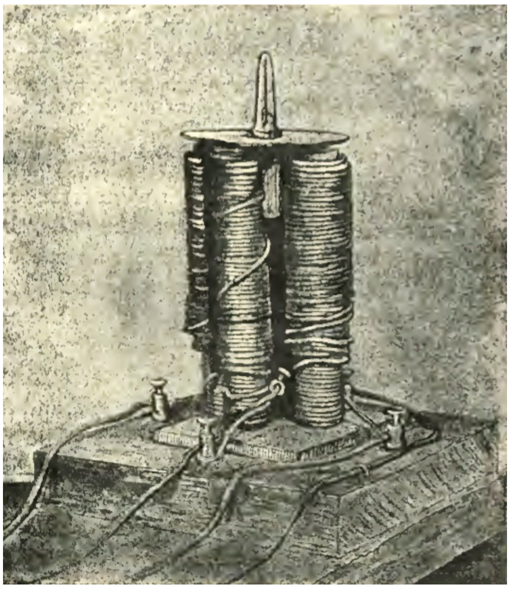
Polyphase AC motors and generators

By the time of the invention of AC transformers, around 1880, AC generators with multiple phases were already known and used in practical installations. However, none of them combined the individual phases into a single polyphase AC system. Instead, each was used as a single-phase AC line.

Polyphase machines were already embodied in some of Pacinotti's designs of 1861 to 1865. Gramme was building 8-pole generators with four coils per pole. He knew of the phase shift between the coils and that he could not connect them directly.
Hefner-Alteneck and Siemens were building two-phase AC generators since 1878. But they also used the two voltage systems independent of each other to power light bulbs.

None of the early machine designs suggested that the required rotor current could be generated from the stator field by electromagnetic induction. All the machines used brushes to transmit electric energy to the rotor.

The very first demonstrator of a two-phase AC induction motor was presented in **June 1879** to the Physical Society of London by Walter **Baily** (British). The idea was published on June 28, 1879.
Baily used four vertically mounted magnetic coils supplied by two-phase AC currents to create a rotating magnetic field. The rotating field would induce an electric voltage in a copper disk mounted horizontally above the coils and that voltage would create a current in the disk. Based on the Lorentz law, the current and the magnetic field interact with each other, thereby creating a force that spins the disk. Baily's experiment was stimulated by Arago's disk of 1824, but he replaced the compass needle by coils.

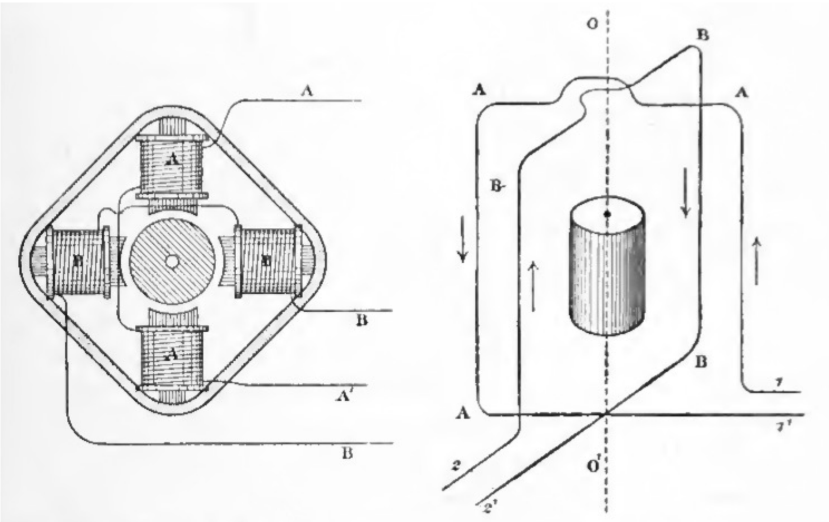


Walter Baily's polyphase induction motor, 1879; *Philosophical Magazine: A journal of theoretical, experimental and applied physics*

One year later, in 1880, M. Marcel Depréz published a paper on the electric synchronization of rotation. He effectively described the transmission of two-phase AC current. His apparatus, however, was very experimental.

Galileo Ferraris (1847-1897)

In **1885**, the Italian physicist Professor Galileo **Ferraris** of Torino found the basic principles of rotating magnetic fields and of induction motors.
He discovered that a steadily rotating magnetic field of constant amplitude could be created by using two coil pairs mounted at a right angle that are fed by two alternating currents with 90-degree phase shift. Such a magnetic field would then spin a solid copper cylinder mounted in the center of the coils.



Ferraris' two-phase induction motor, 1885 (first publicly shown in 1888)

Ferraris built a small demonstrator model already in 1885. Years later his model was displayed at the 1893 Chicago World's Fair. Ferraris also developed a theory of rotating magnetic fields and presented his findings to the royal academy of science in Tornio, Italy, on **March 18, 1888**.
Shortly after the presentation, his text on *Electrodynamic rotations produced by means of alternate currents* was published.
Also, included in this text was Ferraris' invention of the single-phase AC motor: The required 90° phase shift for the second winding was created by using an external inductance together with a resistor.

Mistakenly, Ferraris believed that the mechanical power of induction machines would peak at a slip of 50% and that the highest efficiency could therefore not exceed 50%.

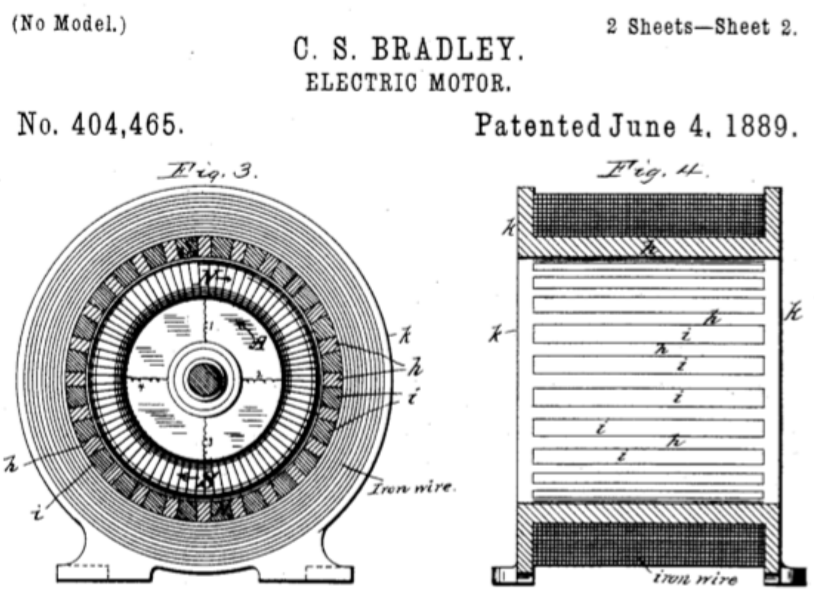
Nevertheless, his publication was well received, and a telegram was sent to Westinghouse in the United States to inform him of the good news. Westinghouse urged Ferraris to file a patent and offered 1000 US$ for the rights. Ferraris firstly declined but when he later accepted, Westinghouse was no longer interested as he had already found another inventor who was working on the same motor principle.

Charles Bradley (1853-1929)

The US-American Charles Schenk **Bradley** worked for Edison from 1880 until 1883 before establishing his own Electrotechnical laboratory in New York. Independent of Ferraris' ideas, he started experiments with polyphase generators and motors.

Bradley filed his first patent on two-phase synchronous AC generators and motors (US 390,439) on May 8, **1887**. The German company *Schuckert & Co.* had similar ideas, but their patent application of February 1890 was rejected due to Bradley's priority.

Bradley continued his work on polyphase distribution systems and finally described a three-phase AC system including a corresponding synchronous generator, a synchronous motor and a squirrel-cage induction motor with bars made of copper or brass in his next two patents (US 404,465 and US 409,450) both filed in **October 1888**.
Around the same time, Bradley also filed a patent in which he showed a method to split a single-phase alternate current into two of different phase.



Bradley's induction motor from his patent 404,465. The asynchronous rotor made of massive iron is on the outside.

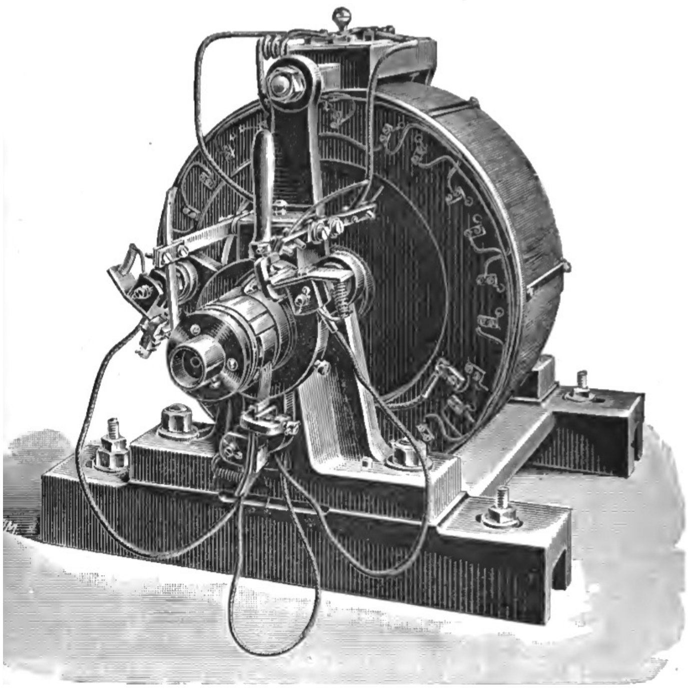
Unfortunately, Bradley only published his ideas in patent applications. As far as we know he never actually built prototypes, nor did he commercialize any of his ideas.

Friedrich Haselwander (1859-1932)

Friedrich August **Haselwander** was the owner of a small shop in Offenburg in the southwest part of Germany.
In early 1887, Haselwander was repairing a Thomson-Houston dynamo (a DC machine), designed by Professors Elihu Thomson and Edwin J. Houston of Philadelphia. This rather special machine had a ring winding, not unlike the Gramme ring. However, the ring was used as a stator (the original Gramme ring was used as a rotor) and subdivided into three parts. The three windings were internally connected on one end while the other ends were connected to a three-part commutator to produce DC voltage.

This machine inspired Haselwander to the idea of producing three-phase AC by removing the commutator altogether. The three phases could then be used directly to feed a second, similar machine that would operate as a motor.
Haselwander elaborated his idea further during the summer of 1887. He invented the three-phase AC synchronous machine and the modern-day electric energy transmission systems by means of transformed high voltage. Haselwander also found that an unsymmetrical three-phase AC power transmission was possible by using an additional wire for the star-point.

Already in **August 1887**, Haselwander began working on a second, 10 hp (7.5 kW) machine in the mechanical workshop of the company Bilfinger in Offenburg to prove his ideas in practice. It was put into operation on October 12, 1887, at the hat manufacturing company Adrion in Offenburg but only to provide electricity for the light system.

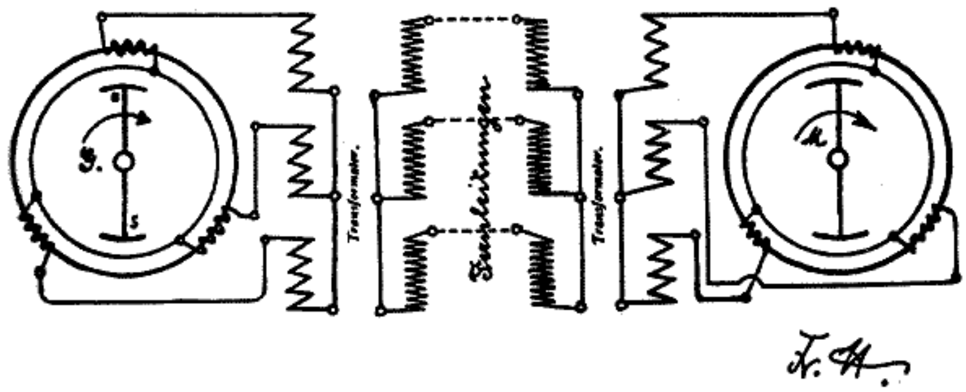


Haselwander's three-phase synchronous machine, 1887

Unfortunately, Haselwander got problems with the local postal authority, which banned three-phase AC operation because of alleged disturbance of a telegraph line. His generator was subsequently run as a DC machine.

In **March of 1888**, Haselwander was finally able to demonstrate his three-phase AC power transmission in an experiment using the two available machines. The planned stationary installation, however, was not allowed.

Haselwander also had problems with his first patent application, which was not submitted until July 21, 1888, although he publicly described his ideas already one year earlier in the summer of 1887.
Initially, his patent application was not understood by the German patent office and therefore rejected after a long dispute. A modified application of 1891 was trimmed down by the patent office due to priorities of Tesla's patents from May 1888, which presented similar ideas.



Haselwander's symmetrical three-phase AC transmission system using just three power lines, early 1888; Both machines are synchronous machines with internal star point connection.

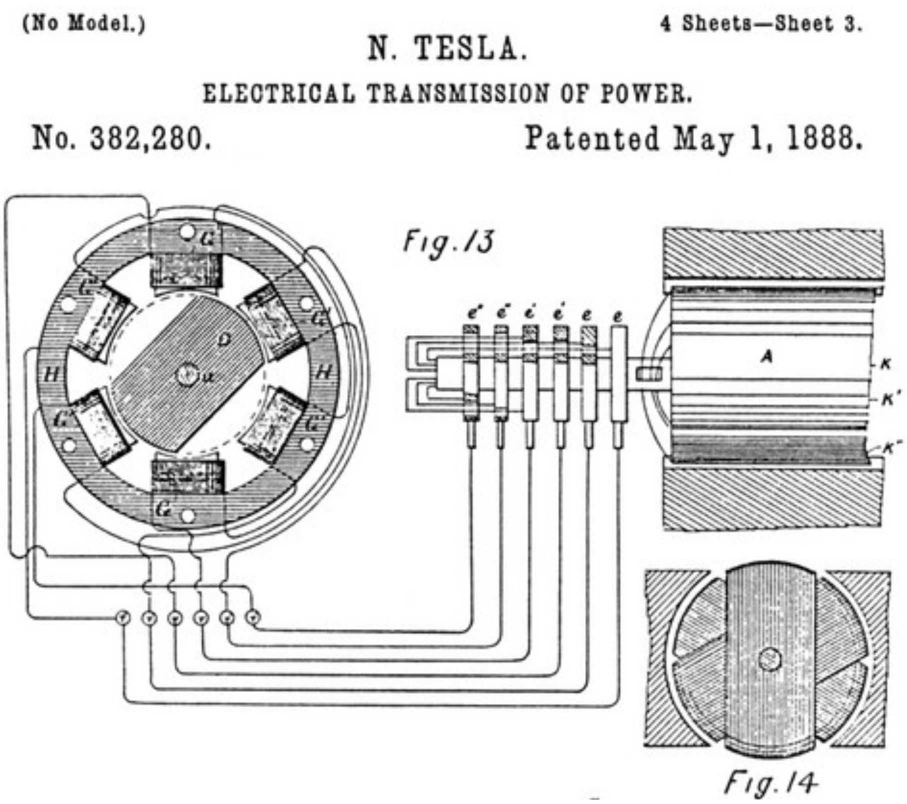
Nevertheless, Haselwander was able to sell his patents to the electrotechnical company Wilhelm Lahmeyer & Co. KG in Frankfurt am Main and from then on worked as chief engineer. The company still exists today under the name Lahmeyer International in Bad Vilbel, Hessen, Germany.
In 1920, Haselwander received the Honorary Doctorate of the University of Karlsruhe for his life achievements.

Nicola Tesla (1856-1943)

Nicola **Tesla** was born on July 9, 1856 in Smiljan, a small village in Austria-Hungary (now Croatia). His parents were Serbian immigrants. Already in 1875, when he was a 19-year-old student at the polytechnic institute of Graz, Austria, he started thinking about getting rid of the commutator of DC machines during a demonstration of the strong commutator fire emitted from a newly distributed Gramme motor.

He developed his ideas further and presented them to leading engineers and managers of the French Edison company in Paris, France in 1883. In 1884, he showed prototypes of a two-phase synchronous AC generator and a corresponding synchronous motor to the major and financiers of the town of Strasbourg, France. Both presentations went without success and Tesla did not get any support.
Consequently, Tesla moved to the United States and demonstrated his ideas to Edison. Edison, however, was occupied with his work on DC and not interested in Tesla's polyphase AC motors and generators.

The following years in New York were quite difficult for Tesla as he hardly had any money to support his living and his experiments. Finally, he was able to find help and founded the *Tesla Electric Company* where he could develop his ideas on polyphase AC generators and motors further.

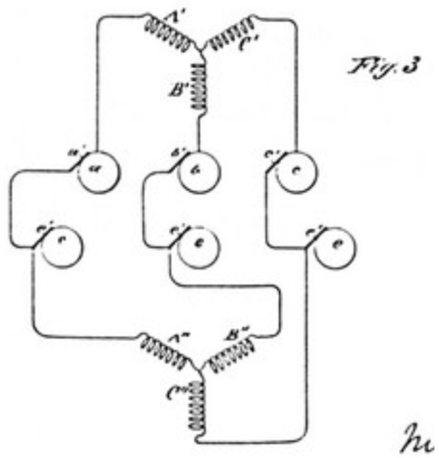


Tesla's electrical AC power distribution system from his patent 382,280, filed on October 12, 1887
Right: Three-phase AC synchronous generator; Middle: Three-phase AC transmission with six power lines; Left: Three-phase AC induction motor with concentrated stator windings.

On **October 12, 1887,** Tesla filed patent 328,280 (together with a number of other applications). It was granted on May 1, 1888. This was arguably his most important patent in the field of polyphase AC electric machines and power transmission. The patent included four pages of text and 19 figures to illustrate his inventions. It was followed by many more patents on the same matter, which, however, did not add fundamentally new ideas.

Tesla described a steadily rotating magnetic field created by the stator windings that was independent from the load. AC machines were fundamentally different from DC machines, which have a stationary magnetic field that does not rotate. Tesla initially used two and three AC phases but later also described single-phase AC machines in another patent.

Tesla explained further that his machines could either run in synchronism with the rotating field, in which case the rotor would be equipped with contact rings to feed the coils with DC current, or asynchronously to the field.
In the latter case, the rotating polar wheel would be replaced by a cylindrical drum-armature made of segmented iron sheets to prevent eddy currents. The core would carry two or more closed (short-circuited) coils.



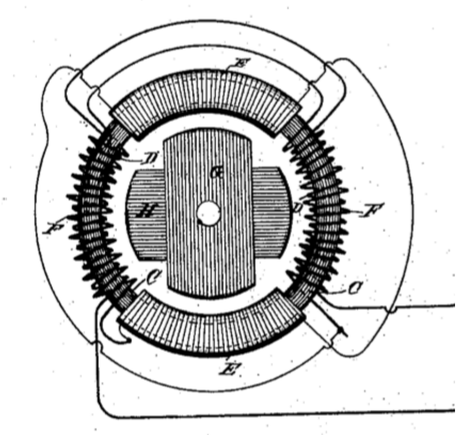
From Tesla's patent 390,414, filed on April 23, 1888, showing a three-phase AC system with just three power lines.

Remarkably, almost all of Tesla's illustrations showed either single- or two-phase AC with two or four power lines respectively. He also had patents on two-phase AC systems where both phases would share a common wire, effectively reducing the number of power lines to three. In this case, however, the common line would carry more current and needed to be larger. Tesla remained a strong advocate of the two-phase AC system for the rest of his life.

His few illustrations of three-phase systems mostly displayed six power lines. There is just one case (his US patent 390,414) where Tesla showed a star connected symmetrical three-phase AC system with three power lines. However, he never seemed to have utilized this concept or realized its true potential.

Segmented ring windings seemed to be Tesla’s favorite design as he showed them most often. Some of his prototypes also used modified ring windings where the inner parts of the coils were placed inside of slots to reduce the air gap.

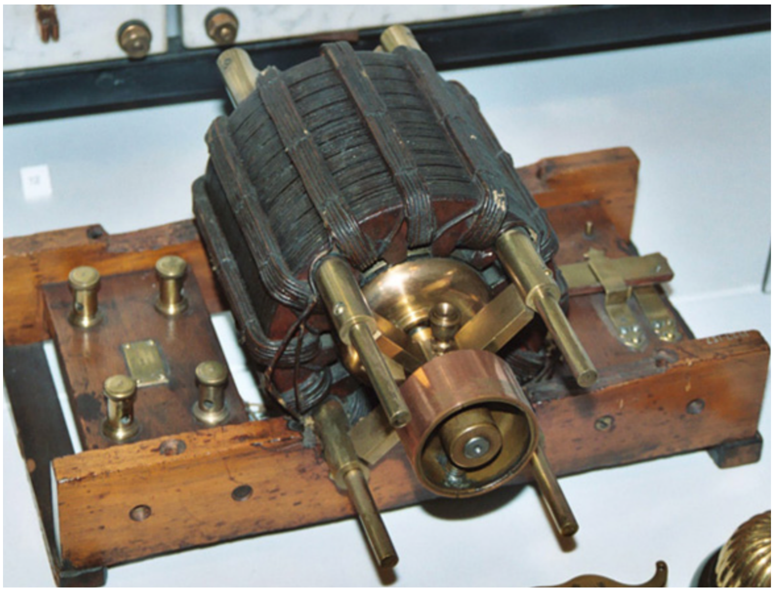
Tesla also described concentrated pole windings in the stator (see above). We know today that such windings do not work well for induction machines as they produce many spatial air gap harmonics, each of which leads to corresponding rotor fields. All these fields pull the rotor with different speeds in different directions thereby creating a lot of noise and vibration.



From Tesla's patent 555,190, filed on May 15, 1888: Single-phase induction motor with segmented main (D) and auxiliary phase (E) ring windings in a Gramme ring (C) style. The auxiliary phase (E) is supplied by a phase-shifted current derived from the induced voltages in coils (F), which are wound around the main coils (D).

Just like Ferraris and Bradley, Tesla understood single-phase AC motors with just one coil group are not able to run as the single coil group would not create a rotating magnetic field. Therefore, he used two-phase windings and supplied the second phase with a phase-shifted current, which he derived by induction from the first phase. This principle is shown in several of his patents in various forms. It is still used today, although the phase shifted current is normally created by means of a capacitor instead of an inductance for cost reasons.

On **May 16, 1888,** Tesla held a remarkable presentation before the American Institute of Electrical Engineers where he finally presented his ideas in public.
He also showed two prototype AC machines. The smaller motor was a 0.5 hp (0.37 kW) two-phase induction machine. Reportedly it started very well and reached about 50% efficiency. The larger motor was a two-phase synchronous machine with 1.5 hp (1.1 kW) power. It had an efficiency of about 60%.



One of the motors Tesla showed on May 16, 1888; British Science Museum, London; Photo by Jim Morford from Tesla Memorial Society of New York

Westinghouse was thrilled by Tesla's personality and his inventions. Just one month after the presentation he visited him in his laboratory in New York. The two men agreed on the acquisition of all of Tesla's patents (there were 40 at that time) by Westinghouse for the tremendous sum of 1 million US$ plus an additional Dollar per PS on all produced machines. Westinghouse hired Tesla as an advisor to his company in Pittsburg to help his engineers develop salable products from the patented ideas.

Westinghouse also hired Charles Felton Scott (1864-1944), a young electrical engineer who would later become professor at Yale University, to assist Tesla. They used single-phase AC at rather high frequencies (125 and 133 Hz) for their experiments, as such generators were available at Westinghouse's plant.
The engineers at Westinghouse created a few small prototypes. Some of them operated quite well when running but all suffered from low starting torque.
Another problem was Tesla's personality and his refusal to create technical drawings as he would memorize all technical details of the constructions in his head.

The collaboration between Tesla and Westinghouse ended unsatisfactory already after the first year. It did not lead to commercial products. Tesla turned down Westinghouse's offer to stay for a second year and left Pittsburgh in October of 1889. Westinghouse and his engineers stopped the development of induction motors the year after.

After the rather frustrating experience at the Westinghouse factory, Tesla returned to his laboratory in New York to do further research on electric power transmission.

By 1891, Benjamin Garver Lamme (1864-1924), chief engineer at Westinghouse, pushed for a new attempt to build a commercial induction motor – this time without Tesla. Due to the good experiences with DC railway motors they decided to use cylindrical, distributed windings placed in slots for both stator and rotor.
Already the first machine worked nicely. They further improved it by introducing a squirrel cage rotor, finally arriving at a design like the one Dolivo-Dobrowolsky had invented two years before (see below). The motor was finished and thoroughly tested in 1892.

In the following year, Westinghouse showed a 12-pole 220 kW (300 hp) two-phase AC induction motor at the Electrotechnical Exhibition at the Chicago World's Fair. The company started deliveries of commercial products during the following year. This marked a turning point in the war between DC (Edison) and AC (Westinghouse and Tesla) in the United States. During the next years, municipal DC power distribution systems slowly disappeared and were all replaced by AC.

Later, Tesla helped Westinghouse design the first two-phase AC power station and electric transmission line in Niagara Falls, NY between 1893 and 1896 (see below). After that, his interest turned to other topics, most famously wireless energy distribution on a large scale.

Tesla was a highly productive inventor and received 112 patents in the United States alone. Between 1885 and 1891 he received 37 patents on motors and generators and 13 patents on electric power transmission. But he could not commercialize any of his ideas and died in poverty in 1943.

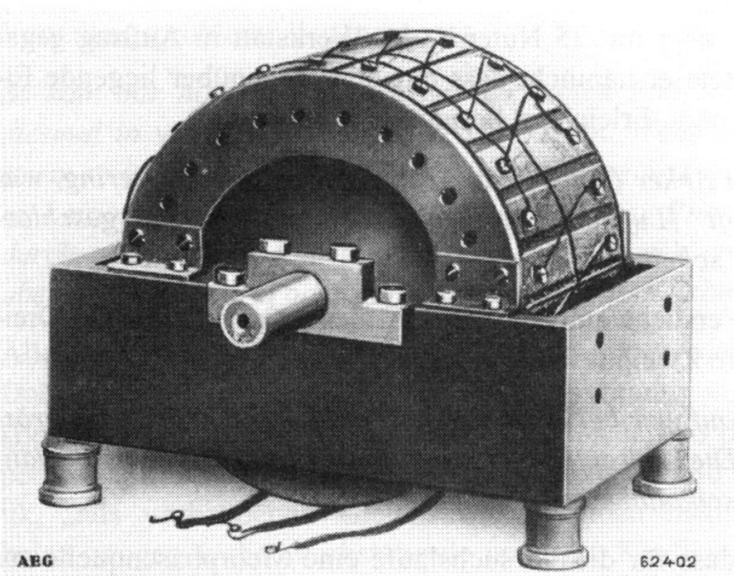
Michael von Dolivo-Dobrowolsky (1862-1919)

Dolivo-Dobrowolsky was born in Gatschina, a small village 60 km southwest of Sankt Petersburg in Russia. During 1878-1881 he studied chemistry at the Riga Polytechnical Institute in Russia and then moved to Darmstadt, Germany to study electrical engineering at the local University from 1883-1884. From 1885 until 1887 Dolivo-Dobrowolsky worked as research associate at the Institute of Prof. Erasmus Kittler, who was holding the world's first chair for electrical engineering in Darmstadt.

In 1887 Dolivo-Dobrowolsky moved to Berlin to work for the *Allgemeine Elektrizitätsgesell-schaft (AEG)*, which was founded in 1883 by Emil Rathenau. AEG had acquired the rights to use Edison's patents but was generally interested in all kinds of electrical equipment and not just lighting.

Quickly, Dolivo-Dobrowolsky became the head of the research department at AEG. He first worked on DC generators but closely followed the international publications on the developments of AC motors. He knew about Ferraris' invention and found the error in his assumption, the efficiency of an induction motor could not exceed 50%: The highest output power was reached at a much lower slip, which resulted in much better efficiency.

Early in 1889, Dolivo-Dobrowolsky had a small induction motor built according to his design.



First three-phase squirrel-cage induction motor built by the AEG in Berlin, Germany in early 1889 according to plans by Dolivo-Dobrowolsky

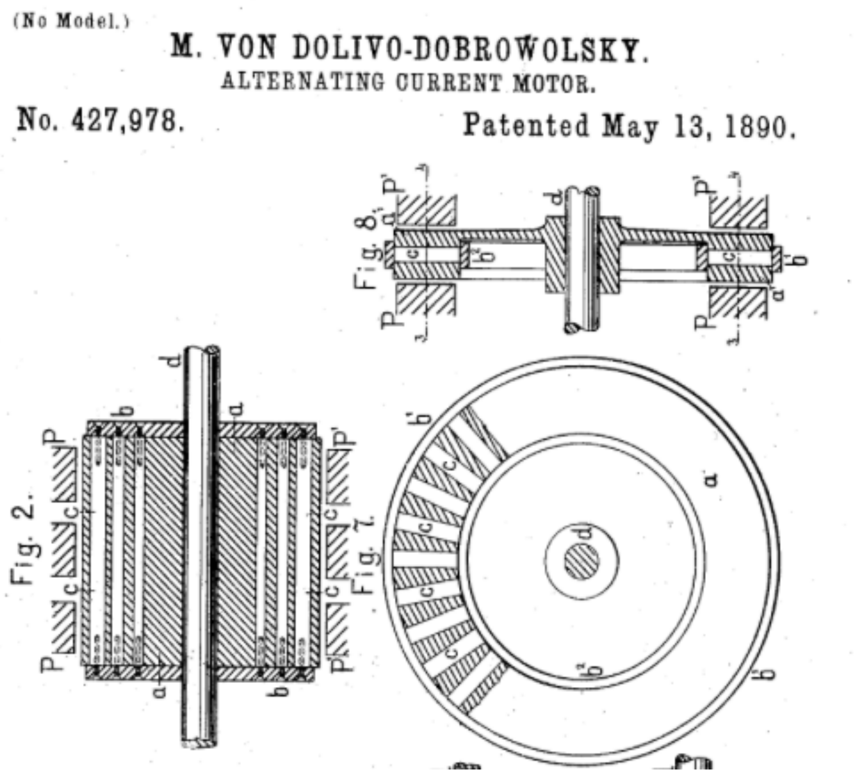
Dolivo-Dobrowolsky thought a lot about the stator winding design. He wanted a smooth sinusoidal spatial distribution of the magnetic field during rotation that was independent from the angular position. Finally, he used a modified ring-winding with 24 individual coils and slots on the inside, which was quite like the windings Tesla had used in his prototypes.

However, Dolivo-Dobrowolsky did not connect the 48 coil ends internally so he could experiment with different numbers of phases. He finally decided that a symmetrical three-

phase AC system with just three power lines, which Haselwander had invented earlier, would be the best option. He called it *Drehstrom* - rotary current.
The rotor was very different from Tesla's in that it was a squirrel cage of 24 copper bars (Dolivo-Dobrowolsky later experimented with different numbers of bars) embedded within a massive iron cylinder.

The small demonstration motor was an instant success. It had a high start-up torque and reached an efficiency of 80% at full power (0.1 hp).

On **March 8, 1889,** Dolivo-Dobrowolsky filed a patent on his squirrel cage rotor. The patent was granted on April 19, 1890, under the number 51 083. A patent on the star- and delta-connection of three-phase generators and motors followed on December 5, 1889, in England and was granted on October 18, 1890 under number 19 554.



Dolivo-Dobrowolsky’s US Patent 427,978 on squirrel-cage rotors, filed on November 13, 1889

Dolivo-Dobrowolsky continued to develop his design further. Already in 1890, he started to build motors with distributed cylindrical windings in the stator instead of the ring windings of the early prototypes. This would create an even smoother magnetic field, reduce the stray flux, and better utilize the electric conductors, thereby improving material utilization and power density considerably.

To the present day, nearly all industrial induction motors are built according to Dolivo-Dobrowolsky's principal designs.

The first prototype motor was later shown to Edison, who visited Berlin in September of 1889. However, Edison violently refused it, telling Dolivo-Dobrowolsky that he did not want to know anything about AC.

Dolivo-Dobrowolsky's second motor, built in late 1889, was delivering some 3 … 4 hp but had a low start-up torque even though the start-up currents were high. It made a howling sound until it reached full speed.
This disappointment led to more experiments and finally to an alternate rotor design: The new rotor built in 1890 would carry a distributed three-phase AC winding with internal star point connection just like the stator. The three winding ends were accessible through slip-rings.
Dolivo-Dobrowolsky started the machine with resistors between the slip-rings and short circuited them for normal operation. This solved all startup problems of the earlier prototypes but on the cost of a more complex rotor design. Such wound-rotors are also used today, mostly in asynchronous generators of windmills.

It is interesting to look at the various design stages and the similarities and differences of the induction motors built by Tesla and Dolivo-Dobrowolsky. In the following three tables, the lines are ordered according to the development stages from old to modern.

AC power supply	Used by	
Single-phase with internal phase-shifted auxiliary phase	T	First described by Ferraris. Patented by Bradley and Tesla. Used today in larger motors for household appliances and small businesses. However, the early inventors used inductances to create a phase shift while modern motors use capacitors.
Two-phase with four wires	T	Tesla was a strong advocate of the two-phase system, even though it is less performant (more spatial harmonic fields) and costlier (more coils, more connections) than the three-phase system. No longer used today.
Two-phase with three wires	T	Tesla also patented a two-phase system with one common wire shared between the phases. However, this wire would have to have a bigger diameter as it was loaded with more current. Later, he wanted to remove this line altogether by connecting the devices through ground. But due to the high earth resistance this concept was not very practical. Not used today.
Three-phase with six wires	(T)	Patented by Tesla but probably never tried by him. Not used today.
Three-phase with internal star or delta connection and three external wires	H (T) D	Invented by Haselwander. Shown by Tesla in just one illustration in one of his many patents but likely never tried by him. Fully developed by Dolivo-Dobrowolsky. Used today in all industrial synchronous and induction motors and in all large-scale AC power transmission installations.

(T = Tesla, H = Haselwander, D = Dolivo-Dobrowolsky)

Induction machine stator design	Used by	
Concentrated poles	T	Shown by Tesla in many patents. Not suitable for induction machines due to high amount of spatial harmonic fields. Not used today.
Segmented ring winding (preferably with inner slots)	H T D	First used by Haselwander based on a DC machine designed by Thomson/Houston. Tesla's favorite design. Limited performance due to high stray flux and low utilization of the wires. Not used today.
Distributed cylindrical winding	D	First applied to AC stators by Dolivo-Dobrowolsky. Optimal material utilization. Used today in nearly all induction and synchronous machines.

Induction machine rotor design	Used by	
Concentrated poles	T	Shown by Tesla in many patents although the design is not suitable for induction machines. Not used today.
Surface coils	T	Patented by Tesla. Was used in most of his drawings. Poor performance due to large air gap and low number of coils. Not used today.
Squirrel-cage	D	Patented by Dolivo-Dobrowolsky. Very good performance due to small air gap and large number of conductors with low resistance. Used today in nearly all induction machines.
Three-phase coils within slots with slip-rings (wound-rotor)	D	Invented by Dolivo-Dobrowolsky. Improved startup performance and noise behavior but costly. Still used today for special purposes (windmills).

As AEG was interested in electrical power transmission, Dolivo-Dobrowolsky worked in that field as well. Already in **August of 1889** he patented the three-leg transformer, which further simplified three-phase AC transmission.

Also in 1889, AEG displayed a three-phase synchronous generator at a local exhibition (*Berliner Ausstellung für Unfallverhütung*) that was coupled to a steam turbine built by the *Maschinenfabrik Oerlikon (MFO)* from Zurich, Switzerland.

In the following year, Oberst (colonel) Peter Emil Huber, chairman of the board of directors of MFO and his chief engineer **Charles E.L. (Eugene Lancelot) Brown** visited AEG in Berlin. The two companies concluded a license agreement and established a fruitful collaboration during the following years.

Already during 1890, MFO successfully built a 2 hp (1.5 KW) three-phase induction motor. During the next year, MFO and AEG built the world's first three-phase AC transmission line from Lauffen am Neckar to Frankfurt am Main in Germany.

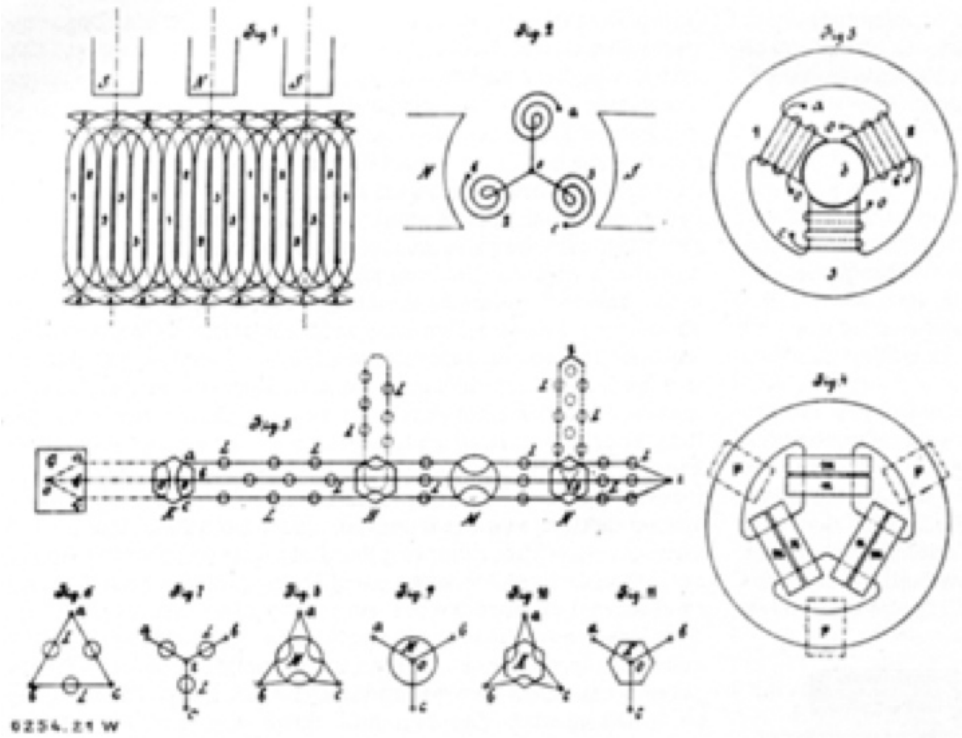
Charles E.L. Brown was never fully convinced of the three-phase AC system. He concentrated his efforts on single-phase AC motors and experimented with different slot numbers and geometries of the squirrel-cage rotors to overcome the problem of a howling start-up noise. Some years after the joint Lauffen project Brown turned against Dolivo-Dobrowolsky who strongly supported three-phase AC.

Dolivo-Dobrowolsky continued to work for AEG on the field of electric energy transmission. Between 1903 and 1907, he commenced further research in Lausanne, Switzerland where he also obtained Swiss citizenship for himself and his family. When he got back to Germany, he became Technical Director of the AEG Apparatus Factory in Berlin. In 1919, Dolivo-Dobrowolsky died in Heidelberg, Germany on a severe heart disease. His grave is in the forest cemetery in Darmstadt, Germany.

Jonas Wenström (1855-1893)

Jonas Wenström was a Swedish engineer who worked first on DC generators. He received a patent on his design in 1883.
Jonas' younger brother Göran (1857-1927) founded the company *Allmänna Svenska Elektriska Aktiebolaget* (ASEA) together with Ludwig Fredholms in Västerås, Sweden to build such generators.

Some years later, Jonas Wenström developed all components of a symmetrical three-phase AC transmission system: Generators (including star and delta winding connections), synchronous and induction motors and transformers.
Wenström finished the construction of his first AC generator in 1889 and had a prototype built in 1890. In the same year, he received a British and a Swedish patent for his power distribution system.



Sketch from Wenström's patent on three-phase AC power distribution systems, 1890

Very likely, Wenström was unaware of the works of the other inventors in this field although they were ahead of him by one or two years.

In 1893, ASEA successfully built a commercial 13 km three-phase AC transmission line in Sweden based on Jonas Wenström's patent.

In late 1891 Charles E.L. Brown and Walter Boveri, head of the mechanical assembly department at *Maschinenfabrik Oerlikon (MFO)*, founded *Brown, Boveri & Cie (BBC)*.
BBC took over MFO in 1967 and later merged with ASEA to become *Asea Brown Boveri (ABB)* in 1988. ABB's corporate head office is still in Oerlikon, Switzerland.

Early long-distance AC power transmission

The first experimental single-phase AC transmission line was already built in **1884** by Galileo Ferraris for the International Electrical Exhibition in Torino, Italy. It connected the town of Lanzo Torinese over a 40 km distance to Torino delivering 20 kW power at 2 kV voltage.

Probably the first commercial single-phase AC transmission line was installed in the mining district of Telluride, Colorado by Westinghouse in **1891**. The company connected a 100 hp synchronous generator that was placed near two waterfalls to a synchronous motor over a distance of about 4 km and used a voltage of 3 kV. The mill motor had to be brought up to synchronous speed by a single-phase induction motor (built according to Tesla's designs), which itself had to be started by hand as it was lacking startup-torque.

Soon after the introduction of symmetrical three-phase AC systems, experimental and commercial installations were built world-wide.

Lauffen to Frankfurt, Germany (1891)

The world's first long distance three-phase AC power transmission line was built for the Electrotechnical Exhibition in Frankfurt am Main, Germany to demonstrate the capabilities of the new power system.

The line connected a hydro generator plant in the small town of Lauffen am Neckar to Frankfurt over 175 km. It was designed and built by the two companies AEG in Berlin and MFO in Zürich under the supervision of their chief engineers Dolivo-Dobrowolsky and Charles E. L. Brown.
The line was commissioned on August 28, 1891, and operated at various voltages up to 25 kV over a couple of months.
It could transmit up to 220 kW (300 hp) power. The line had 3,000 poles, 9,000 oil-insulators and was built of 60 tons of copper wire of 4 mm diameter. Oil-filled three-leg transformers according to Dolivo-Dobrowolsky's patent were installed on both ends. At its highest voltage, the line had an end-to-end efficiency of about 75% (including transformer losses).
Nominal operation of the 220 kW, 40 Hz, 32 pole three-phase synchronous hydro generator in Lauffen was at 150 /min, 50 V and 1400 A. It was designed by Charles Brown, built by MFO and had a remarkably high efficiency of 95.4%.
Several induction and synchronous motors made by AEG, MFO, Schuckert, Lahmeyer and a Haselwander Generator were also installed at the exhibition in Frankfurt. The largest motor was a 100 hp (75 kW) three-phase wound-rotor induction machine built by AEG. MFO delivered a 20 hp (15 kW) squirrel-cage induction motor.

After the exhibition, most of the line was dismantled or used as a telegraph line. But the power station in Lauffen continued to operate and produced three-phase AC for the city of Heilbronn, located 15 km from Lauffen, over the next 50 years. Thus, Heilbronn became the first town to use the new power system.

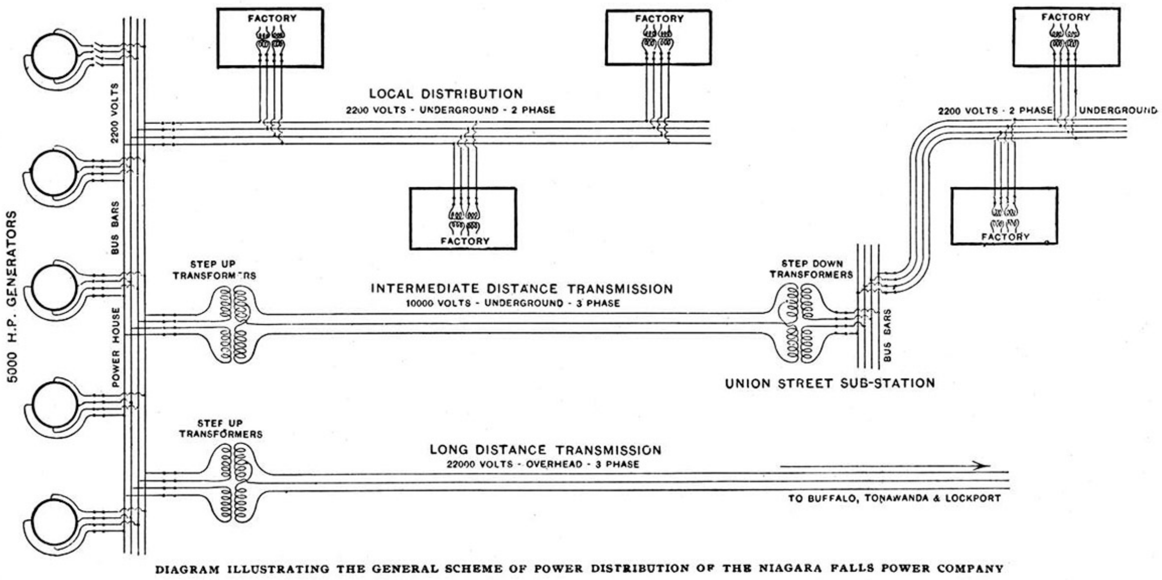
Hellsjön to Grängesberg, Sweden (1893)

The Swedish power line between the Hellsjön (or Hällsjön) hydroelectric power plant and the Grängesberg iron-ore mine was built by ASEA based on Wenström's patent. It was put into operation in late 1893.
Four turbines of 100 hp (75 kW) and one of 20 hp (15 kW) were installed in the powerhouse. Two of the large generators were used to feed the three-phase line with three wires of 4 mm diameter. Another generator fed a parallel single-phase AC line with two wires of 3 mm diameter for lighting purposes. The lines supplied electric power to various places in the iron-ore mine at distances between 8.5 and 13.7 km. A frequency of 70 Hz at voltages of 5.5 kV and 5 kV were used.
Six induction motors with powers between 6 hp and 45 hp were installed in the ore-mine. Eight transformers fed a total of 300 light bulbs and 23 arc lamps.
The line was decommissioned in 1912 when it could no longer serve the growing power needs.
Today, a new line between the historic places serves as a test range for ABB's latest high-voltage DC (HVDC) components. It operates at up to 10 kV and transmits about 3 MW.

Niagara Falls to Buffalo, USA (1896)

Around 1890, the Niagara Falls Power Company decided to build a large power generation station with three hydro generators of 3,700 kW (5,000 hp) each. In 1893, the order was given to Westinghouse to supply the electric equipment of the station. On the recommendation of Tesla, the whole station was designed for two-phase AC. The equipment for the power station was put into operation late in August 1895. The station mainly supplied nearby consumers, but it was also planned to transmit electricity to the City of Buffalo, NY.

On November 15, 1896, the power line was commissioned. Interestingly, the power line was three-phase using just three wires while the rest of the station was two-phase with four wires. The line transmitted up to 750 kW (1,000 hp) over 35 km (22 miles). It was operated at 11 kV.



Power distribution scheme of the Niagara Falls Power Station, 1896

This installation marked the zenith of the two-phase AC system, which later became obsolete. Already when the first extension of the Niagara Plant took place seven years later in 1903, the new generators were all three-phase AC as were all subsequent plant additions.

The benefits of symmetrical three-phase AC were simply too convincing: Fewer number of lines (three instead of four) and better electromagnetic utilization of the material in all electric equipment (generators, motors, transformers and powerlines). Remarkably, three-phase transmission allows a 15.5% increase in power over two-phase transmission with the same copper usage.

Single-phase AC remained popular due its simpler design and is still widely used today mainly in the UK and the US for supply of households.

As DC transmission was also still around shortly before the turn of the century, city councils now had four electrical systems to choose from for the electrification of their city. However, it was not too long before three-phase AC finally prevailed.

Summary

In 1820, Hans Christian Oersted built the first apparatus that could transfer electrical energy into a rotary motion. The first useable DC generator was built in 1833 by Hippolyte Pixii and the first useable DC motor in May 1834 by Moritz Hermann Jacobi. However, the laminated drum anchor rotor, which is used in nearly all of today's DC machines, was not developed until 1875 by Siemens.

The principle of AC transformers was found in 1875 by Pawel Nikolajewitsch Jablotschkow. The first actual transformer, using two coils wound around an iron core, was demonstrated in London in 1881 by Lucien Gaulard and John Dixon Gibbs.

Early experiments with single-phase AC transmission over a 40 km distance were already conducted in 1884 in Torino, Italy by Galileo Ferraris.

Today's electrical power distribution system, that is three-phase AC rotary current produced by synchronous generators and sent over long distance high-voltage power lines with three wires, was first envisioned and publicly demonstrated by Friedrich August Haselwander in mid 1887. Michael Dolivo-Dobrowolsky invented the three-phase transformer in 1889.

The principles of AC induction machines were first presented to a large audience by Galileo Ferraris in March 1888 in Torino, Italy and in May of the same year by Nicola Tesla in New York, who also showed two prototype motors. The modern-day induction motor with all its essential design features (three-phase rotary current, internal star-point or delta connection, distributed cylindrical stator winding, squirrel-cage rotor) was invented in 1889 by Michael Dolivo-Dobrowolsky at the company AEG in Berlin, Germany.

The first large-scale three-phase AC distribution system was built by the companies AEG and MFO under the lead of Michael Dolivo-Dobrowolsky in 1891. It connected the small town Lauffen am Neckar to the Electrotechnical exhibition in Frankfurt am Main in Germany over a distance of 175 km. Heilbronn, which is located 15 km from Lauffen, became the first city to use the new power system.

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