The invention of the synchronous motor by Nikola Tesla

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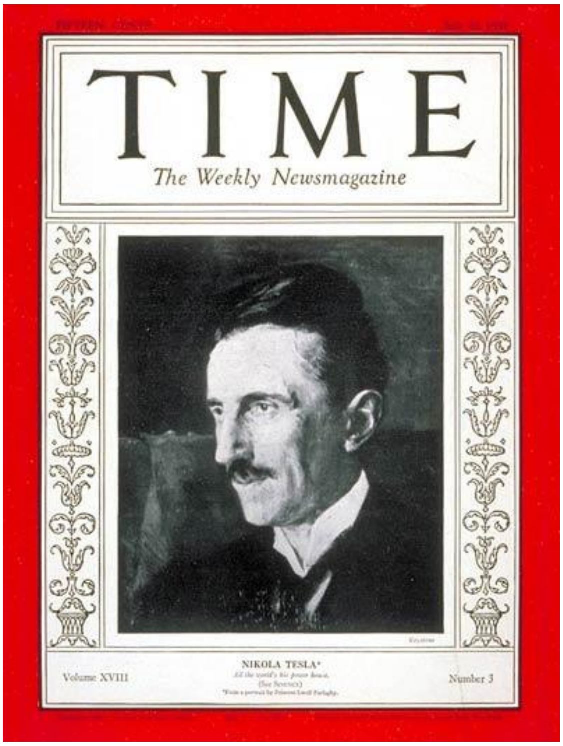


Figure 1:* The front cover of a special issue of** Time Magazine ***published on 20 July 1931, *marking Tesla's 75th birthday (©* Time Magazine*, New York).*

Nikola Tesla (1856–1943), born in the Croatian town of Smilijan, then part of the Austrian Empire, was the fourth of five children of a Serbian Orthodox priest. After studying at the Graz University of Technology and the University of Prague, he worked as an engineer in Budapest and Paris, where he tried, unsuccessfully, to develop his ideas on alternating current (AC) and the rotating-field electromagnetic motor. In 1884 he emigrated to the United States, where he would stay the rest of his life. He joined Thomas Edison's (1847–1931) electric company, but Edison, who had devoted his business affairs to direct current (DC), did not look favourably on the young Serbian's ideas. Disappointed, Tesla left Edison for George Westinghouse's (1846–1914) firm. At this time Edison and Westinghouse were engaged in a fierce battle to develop an electricity distribution system, a battle Westinghouse would win. The creative Tesla authored and contributed to many inventions: the induction motor, the AC distribution network, radio, wireless communications, and remote-controlled robots.

A BRIEF HISTORY OF ELECTRICITY AND MAGNETISM

One day in April 1820, in Copenhagen, the Danish physicist Hans Christian Œrsted (1777–1851), during a lecture to his students, connected a galvanic battery to a platinum wire placed just above a compass. In disbelief, the students saw that the electric current passing through the wire deflected the compass needle in a manner analogous to the Earth's magnetic field. A potential link between electrical and magnetic phenomena had been discovered.[1]

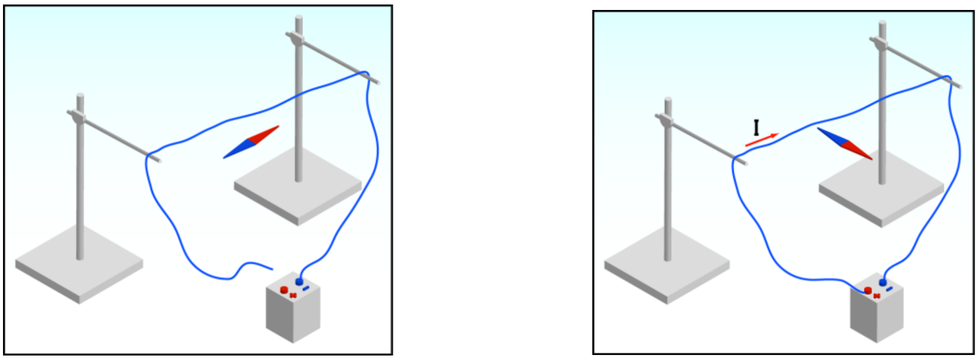


Figure 2:* Œrsted's experiment. When the circuit is closed (right-hand image), the electrical current passing through the conductor produces a magnetic field, which interacts with and deflects the compass needle. The needle aligns perpendicularly to the conductor (© Ilarion Pavel).*

This discovery was not a matter of luck, but the fruit of many years' research. A follower of *Naturphilosophie*, Œrsted was convinced that various observed mechanical, electrical, magnetic and chemical phenomena were simply different manifestations of a single, fundamental unitary force. Œrsted had the insight to use galvanic cells[2] in his experiments rather than the electrostatic machines or Leyden jars used by other physicists, which produce currents too weak to demonstrate magnetic phenomena. Electrostatic machines generate high-tension but weak and temporary currents. Since magnetic effects are

1. For an analysis of Œrsted's text (1820), see J.-J. Samueli and A. Moatti, "L'acte de naissance de l'électromagnétisme", *BibNum*, January 2010.
2. This article uses the terms galvanic cell and galvanic battery interchangeably.

proportional to the intensity of the current, it is practically impossible to demonstrate such effects using this type of equipment.

Œrsted's results received a muted reaction when Francois Arago presented them at a meeting of the Academy of Sciences of Paris in 1830. Most of the Academy's members, influenced by the work of Charles de Coulomb, believed that there was no link between electrical and magnetic phenomena. André-Marie Ampère did not share this scepticism and embarked on a tireless round of experimental and theoretical inquiries. After a few weeks, he was able to understand and quantitatively express the links between electric currents and magnetic fields,[3] leading to his invention of electromagnetic equipment such as the galvanometer[4] and the solenoid[5].

On the other side of the Channel, William Sturgeon (1783–1850) discovered that placing an iron bar inside a solenoid spectacularly increases its magnetic field, thereby inventing the electromagnet. As its name indicates, the electromagnet, which is powered by a galvanic cell, produces a magnetic field, one strong enough to lift iron pieces, for example. The electromagnet can thus **perform a mechanical action using electric energy**. It would play a crucial role in the development of the electric motor.

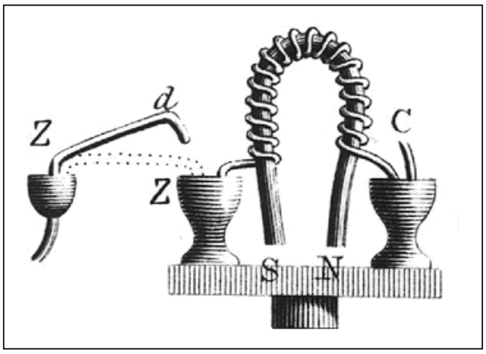


Figure 3:* Sturgeon's electromagnet, made out copper turns wound around an iron horseshoe-shaped core, could lift 4-kg weights. The electromagnet uses mercury cup connectors annotated Z and C (the third cup, on the left, which is connected to the magnet by rod d, acts as a switch. The copper wire is non-insulated and the iron is lacquered to prevent a short circuit between the turns (WikiCommons Illustration).*

3. See the Technical Annex at the end of the article.
4. The galvanometer is made from a compass needle placed inside the coil. When an electric current passes through the coil, this creates a magnetic field which deflects the needle. The intensity of the current is calculated by measuring this deflection.
5 The solenoid is made out of a conductor wire wound helically around a long cylinder. When powered by a galvanic cell, it produces a stronger and more homogenous magnetic field than a simple loop of conductor wire.

Across the Atlantic, Joseph Henry (1797–1878) was building ever more powerful electromagnets, reducing their size and increasing the magnetic force. Prefiguring the use of insulated electric cables, Henry wound compact and multiple layers of silk-insulated copper wire around a coil. This significantly increased the strength of the magnetic field even though the energy source was still the same modest galvanic cell. In no time at all the characteristics of Henry's electromagnet exceeded those of permanent magnets. They were principally used in research laboratories or in public demonstrations: one spectacular demonstration consisted in suspending an iron bar, weighing some several hundred kilograms, using electromagnetic attraction. When the power supply was removed, the bar crashed to the ground. In addition, some electromagnets were commercialised: one of Henry's was used by Penfield and Taft Ironworks (Crown Point, New York State) to magnetise steel cylinders used in the extraction of iron from its ore.

THE INVENTION OF THE ELECTRIC MOTOR

A rotating mechanical system[6] was first developed by Michael Faraday (1791–1867) in 1821, in his attempts to demonstrate that electric current passing through a wire generates a circular magnetic field. Faraday fixed a magnet bar upright in a cup filled with mercury and freely suspended a rod conductor above, so it was just touching the surface of the liquid. When he connected the rod to a galvanic cell, Faraday noticed that it revolved in circles around the magnet. This motion is due to the interaction between the current flowing through the rod and the bar's magnetic field.

This was the first example of a device that **converted electrical energy into continuous mechanical motion**. However, no practical applications were developed and the apparatus remained confined to the laboratory.

6. See Technical Annex, Figure A1.

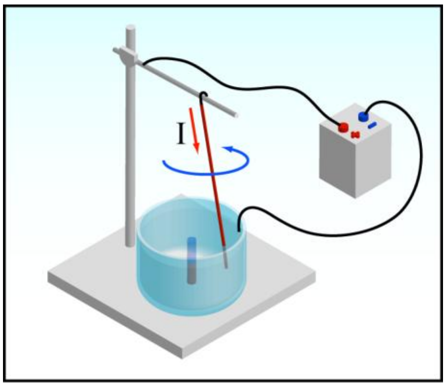


Figure 4:* Faraday's electric motor. *The current provided by the battery flows through the suspended conductor rod and interacts with the magnetic field produced by a magnet immersed in the mercury filled cup. As a result, the rod rotates on its vertical axis. The electric contacts are provided by the frame and the rod gently touching the mercury surface (© Ilarion Pavel).*

In 1831, Henry invented the first electric motor.[7] The mobile part of the electromagnet oscillates on its horizontal axis. The magnet's polarity automatically inverses as it moves due to the action of two pairs of conductor wires that are connected alternately to two galvanic cells. Two permanent vertical magnets with their poles oriented in the same direction alternately attract and repel the ends of the electromagnet, making it oscillate from side to side.

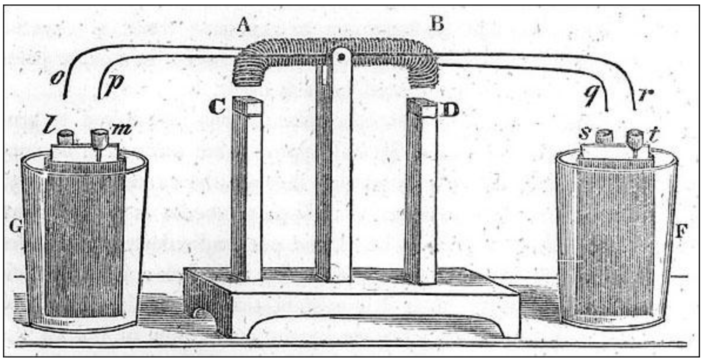


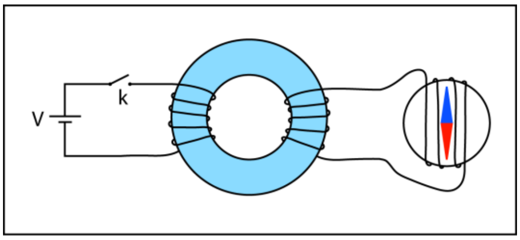
Figure 5:* Henry's oscillating motor. *Two permanent magnets (C and D) are fixed in place with their north pole pointing upwards. When the electromagnet is supplied by the battery on the right, its north pole B is pushed upwards by the D magnet, and its south pole A is attracted downwards towards the C magnet. This makes the electromagnet swing: the circuit is broken at the right battery and re-established in the left battery, and the batteries are connected in such a way that the electromagnet's north and south poles are reversed. The north pole A is thus repelled by the C magnet and the south pole B is attracted to the D magnet. The electromagnet swings the other away, cutting off the electricity supply from the left battery and re-establishing it in the right battery, and the process starts again. The electric contacts are provided by the metal rods q, r, o and p, joined to the oscillating electromagnet (© American Journal of Science).*

7. J. Henry, *American Journal of Science and Arts*, 20, 340 (1831).

THE ELECTRIC GENERATOR ARRIVES ON THE SCENE

Œrsted demonstrated that as long as an electric current flows through a conductor, it generates a magnetic field. In the true spirit of the unity of forces, adepts of *Naturphilosophie* immediately wondered if the opposite were true: can a magnet's magnetic field generate an electric current in a nearby inductor coil? The results of the first experiments were negative for they involved little more than placing a coil around a magnet, and the galvanometer registered no current.

It was only after several failures[8] that Faraday announced his success, in 1831. His method consisted in winding two separate coils around a common metal core. One of the coils was connected to a galvanometer, the other to a battery. When he connected or disconnected the battery, the galvanometer's needle would deflect momentarily and then returns to zero. Faraday found that the same phenomenon occurred if, instead of connecting the battery, he moved the coil closer to or further away from a permanent magnet. He had discovered electromagnetic induction: electric current is not produced by a constant magnetic field, but by a variable magnetic field.



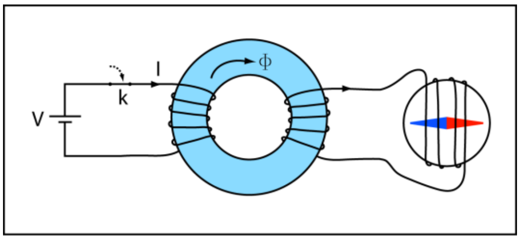


***Figure 6 :* Electromagnetic induction**. *When the switch k is closed, the electric current I flows through the first coil, generating a variable magnetic field in the toroidal core. The variation of the magnetic field produces an electric current in the second coil, as shown by the galvanometer (© Ilarion Pavel).*

Electromagnetic induction can thus transform **motion** (for example, that of a permanent magnet) into **electricity**, leading the way to the invention of the electric generator.[9]

It was Faraday again, no doubt drawing on electrostatic machines for inspiration, who would develop the first experimental device capable of producing

8. Unlike most scientists of the time and scientists nowadays, Faraday sometimes published experiments with negative results.
9. The electric motor is a device that produces motion, generally rotation, when supplied with electric current. The electric generator produces the opposite conversion: when it is driven manually, by a steam motor or a turbine, the electric generator produces electric current and can thus be used as an electricity source.

electricity. The device comprised a copper disc, attached to a frame, which rotated between the poles of a horse-shoe magnet. By connecting a galvanometer between the axis and rim of the disc, Faraday demonstrated that an current was flowing through it. However, Faraday's disc, like his electric motor, would remain confined to his laboratory, for its output as an electrical generator was very low.

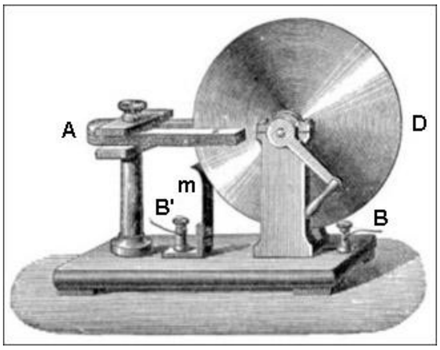


***Figure 7:* Faraday's disc** *turning between the poles of the magnet A. A galvanometer wire is connected to the contact B touching the disc D; another wire is connected to the contact B' connected to the disc rim by an elastic contact blade m (Wikipedia illustration).*

The first electrical generator put to practical use was designed in 1832 by Hyppolyte Pixii (1808–1835), an instrument maker who worked closely with Ampère. Crank-operated, it comprised a horseshoe-shaped magnet that rotated next to a coil wound on an iron core. The magnet's north and south poles periodically reverse the magnetic field in the iron core, thereby inducing an alternating current in the coil.

In order to replace galvanic cells with electrical generators, particularly in electrometallurgical applications, which necessitate a current with the same polarity, Ampère developed a commutator. A commutator is a split metal cylinder fixed around a rotating axis that reverses the current in the external circuit, producing a pulsating rather than alternating current.[10]

This generator contained a permanent magnet, hence its name: the *magneto*.[11]

10. DC current was discovered before AC current, initially after research into electrostatic discharges and then through the use of galvanic batteries. The first applications of electricity and magnetism, for example in electromagnets and electrometallurgy, used DC current.
11. The magneto is still used in the small combustion engines found in some motorcycles, motorboats, lawnmowers and chainsaws. The magneto uses part of the motor's rotation energy and transforms it into electricity. The electricity is then used by the spark plugs to light the mix of petrol and air in the combustion chamber. Thus, a magneto-powered engine does not require an electric battery, which makes it compact. However, this requires a manual start-up: to start, the engine has to be turned using a crank or "starter".

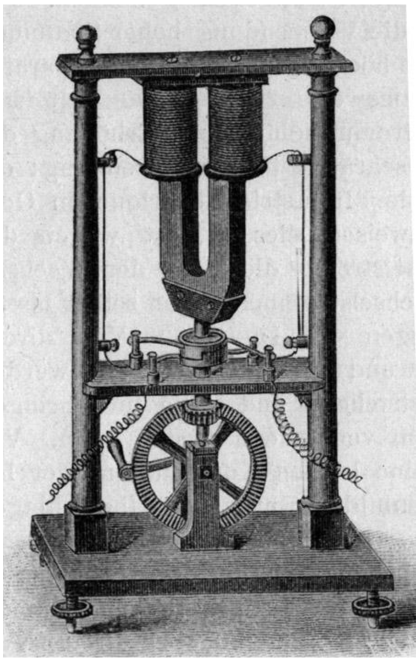


***Figure 8:* Pixii's magneto**. *Crank-operated, the horseshoe-shaped magnet rotates on its vertical shaft around a coil wound on an iron core. As the magnet's north and south poles approach and move away from the iron core, this produces variation in the magnetic field and induces an electric current in the coil. Ampère's commutator can be seen below the magnet, attached to the shaft (Wikipedia illustration).*

Almost at the same time, Joseph Saxton (1799–1873) developed a more powerful magneto, this time made out with a fixed magnet and a moving coil. Saxton used discs dipped into mercury cups to collect the current from the moving coil. Gradually, the **magneto would replace the galvanic cell in laboratories and demonstrations**.

THE COMMERCIAL FAILURE OF THE FIRST ELECTRIC MOTORS

At the beginning of the 1830s, the manufacture and sale of electrical technologies was still largely artisanal, and a few manufacturers could supply a market consisting solely of laboratories, scientists performing public demonstrations, and a few enthusiasts.

But, by the end of the decade, businessmen, financiers, and governments were becoming interested in the potential applications of this new technique. The number of manufacturers and consumers increased, patents were filed and newspaper articles published. The commercialisation of electrical products was consolidated by the concurrent development of the joint-stock company (incorporation), which allowed entrepreneurs to pursue capital-intensive, high-risk projects in the long term.

The electric motor was increasingly seen as a possible alternative to draft animals and human labour. The steam engine had already by and large replaced these energy sources; but it itself had several disadvantages. First, small steam engines, like those used in the workshops of the time, produced a low output, hence why the steam car did not succeed, unlike the steam locomotive and the steamship. The steam engine must run continuously: it cannot be switched off or on when it is needed. Maintaining the steam pressure requires a continuous supply of fuel, making the steam engine unsuitable for machine-tools that operate intermittently. In addition, the machine-tools are connected to the engine via a complicated mechanical system of shafts and transmission belts. Lastly, the steam engine is dangerous because it could explode, is also dirty, noisy, and requires a great deal of maintenance.

In the 1830s, attention turned to the multiple applications of the electric motor in the accomplishment of household tasks: water pumps, washing machines, fans, churns, roasters, and grinders. Its triumph seemed only a matter of time.

In 1833, while on a visit to an iron mine, the blacksmith Thomas Davenport (1802–1851) saw one of Henry's electromagnets in action. Intrigued, he decided to buy one and, back in his atelier, he took the electromagnet to pieces and examined it carefully. Convinced that electric power would soon replace steam power, a few months later Davenport would construct one of the first rotary electric motors,[12] which he patented in 1837. In order to mass produce and commercialise his invention, he set up a joint-stock company.

Alas, the results did not live up to expectations. The cost of the zinc used in the galvanic cells that powered the electric motor made it uncompetitive compared to the steam engine. The electric motor was a commercial flop and Davenport was forced to file for bankruptcy.

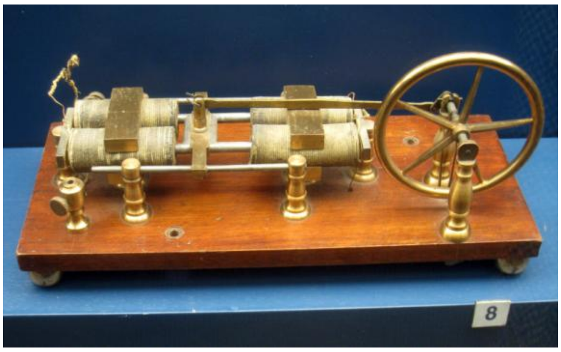
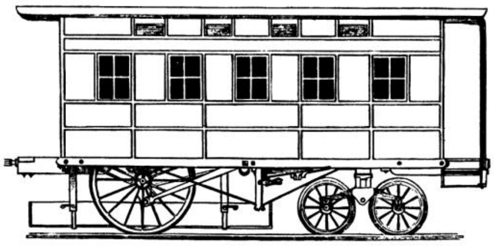
12. Davenport was not the first to try and build an electric motor. In 1839, in Saint Petersburg, Moritz Jacobi (1801–1874) tested an electric motor-powered passenger boat on the Neva.

***Figure 9:* Davenport's motor**, *made of two cross coils that rotate on a vertical shaft within a wooden ring equipped with two permanent semi-circular magnets. The coils are powered by a commutator, visible at the lower extremity of the shaft (© Smithsonian Museum).*

Initially very enthusiastic about the electric motor's future, James Prescot Joule (1818–1889) became increasingly sceptical over time. In a study published in 1841 he showed that a steam engine supplied with one kilogram of coal will produce five times more energy than an electric motor supplied by a galvanic cell containing one kilogram of zinc. The price of coal and zinc led Joule to conclude: "The battery-powered motor is a hopelessly impractical device."

Despite this pessimistic conclusion,[13] other inventors were not discouraged. In the United States, Charles Grafton Page (1812–1868), sponsored by the government, designed an electric locomotive powered by an oscillating electric motor. The motor consists of two coils aligned side by side, alternately supplied with electricity, which in turn attract an iron bar. The back-and-forth motion of the bar is then converted into rotary motion by a connecting-rod/crank mechanism.

13. This is the *electric battery-powered* electric motor, which runs on energy produced by a redox reaction (which consumes zinc), and which Joule rightly criticizes here.

THE FIRST LOCOMOTIVE THAT EVER MADE A SUCCESSFUL TRIP WITH GALVANIC POWER.

<u>Figure 10:</u> *On the left, a* ***replica of Page's oscillating motor****: two pairs of coils laid side by side, supplied alternately with electricity, attract an iron bar in turn. The alternating motion of the bar is transformed into rotary motion by a connecting-rod/crank mechanism. On the right, a* ***sketch of the electric motor****. (Left-hand image: Smithsonian's Museum/Public domain; right-hand image, Wikipedia illustration).*

The passenger-carrying locomotive was put to the test in 1851 on the Washington–Baltimore line. Sparks flew from the electrical insulation around the coils, and the vibrations of the engines damaged the galvanic cells' fragile diaphragms. After eight kilometres, Page was forced to turn back.

A similar experiment took place in Scotland in 1842, when Robert Davidson (1804–1894) built the first electric locomotive, known as the *Galvani*, and tried it out on the Edinburgh to Glasgow line. But Davidson's locomotive, like Moritz's motor boat and Page's locomotive, did not prove economically viable.

The electric motor seemed doomed.

THE DEVELOPMENT OF OTHER APPLICATIONS OF ELECTRICAL TECHNOLOGY

Despite the electric motor's many failures, **practical applications – other than the generation of motion** – were found for the following electricity-based techniques:

- *electroplating*, which emerged out of efforts to improve galvanic cells, and consists in using an electric current to coat materials with a thin metal layer, underwent rapid development and was used in many domains such printing plates, anti-corrosion protective layers, and the gilding of precious metals on mass-produced objects or works of art. This industrial success can be partly explained by the fact that building an electroplating workshop requires little material investment;

- the *electric detonator*, made out of a conductor wire heated by an electric current, gradually displaced the traditional and unreliable fuse, which caused many accidents due to the fact that its combustion time was difficult to control. First used by soldiers to remotely detonate underwater explosives and floating mines, the electric detonator can also be used in civilian contexts in mines and quarries, and in the construction of canals, tunnels and railways;
- the optical (semaphore) telegraph is superseded by the *electric telegraph*. The semaphore telegraph, which had been invented to convey messages over long distances, functioned only during the day, was dependent on weather conditions, could send no more than two words a minute, and required relay stations every 30 kilometres. The discovery that electrical signals could be transmitted over long distances by conductor wires paved the way for the electrical telegraph. Several scientists played their part in its development (Ampère, Arago, Gauss, Weber, Henry, Barlow, Wheatstone) but it was Samuel Morse (1791–1872) who produced the first successful operational system between Baltimore and Washington in 1844;
- in the years following the invention of the telegraph, several other electrical systems for *long-distance information transmission*, *alarms* and *controls* appeared, including communication systems between the bridge of a ship and the engine room; ship guidance systems; speed measurement instruments; boiler-pressure control instruments; burglar alarm systems; remote image transmission systems; temperature control systems; remotely synchronised electric watches; fire alarm systems and railway signal systems;
- theatres illuminated with hundreds of gas burners were equipped with *instant lighting systems*, in which an electromagnet opened the gas supply valve and a white-hot platinum wire lit the gas;
- the *electric arc*, which was used as a light source in photographers' studios and magic lantern shows, in spotlights during night-time military operations, or as lighting in halls, factories, and public places;
- with the growth of maritime trade and heightened security requirements, the electric arc was trialled in lighthouse signalling, since the bright light it produced was much more visible than the traditional

oil or gas lamps. These electric lighthouses consumed more electricity, so the existing electrical batteries had to be replaced by steam-driven electric magnetos.

The growing demand for electricity incited manufacturers to improve sources of electric energy, in particular magnetos.

THE RENAISSANCE OF THE ELECTRIC MOTOR

In 1845, Charles Wheatstone (1802–1875) had the idea of replacing permanent magnets in magnetos by battery-powered electromagnets, which were capable of producing far more powerful magnetic fields. In 1864, Henry Wilde (1833–1919) powered electromagnets with a small magneto coupled to the generator shaft, which removed the need for a battery.

When inventors discovered the principle of **autoexcitation**, they realised that they could also dispense with the small magneto. This is because even when electromagnets are not connected to a power supply, a remanent magnetization persists in their iron core. This remanence is sufficient to induce a weak electric current in the generator when the electromagnets are rotated. All we need is to couple the generator’s output to the electromagnets’ coils so that the current passing through the coils increases the magnetization. As a result, the generator produces a stronger current, which produces a stronger magnetization and so on, until the generator reaches the operating regime.

Several improvements were made in the following years.

Traditionally, each coil had its own iron core. At the end of the 1860s, Werner Siemens (1816–1892) and Antonio Pacinotti (1841–1912), working independently of one another, wrapped the coils around a single ring-shaped iron core, thereby inventing the dynamo.[14] At the beginning of the following decade, Zénobe Gramme (1826–1901) invented a new type of winding that reduced the distance between the rotor and the stator.[15] His dynamos were more efficient and achieved commercial success.

14. A dynamo is a magneto that uses electromagnets instead of permanent magnets. The electromagnet coils are placed on a single ferromagnetic frame, which optimizes the magnetic flux circuit. The dynamo is equipped with a commutator and therefore produces pulsating current. With the advent of alternating current, dynamos no longer required a commutator and would become known as *alternators*, a device that is still used in cars: to power the battery and electrical system, the AC produced by the alternator is transformed into DC by electronic circuits based on semi-conductor devices called *diodes*. A bicycle “dynamo”, it should be noted, is improperly named: it is in fact a magneto.
15. The immobile part of an electric generator or motor is called a *stator*; the mobile part, which rotates, is called a *rotor*.

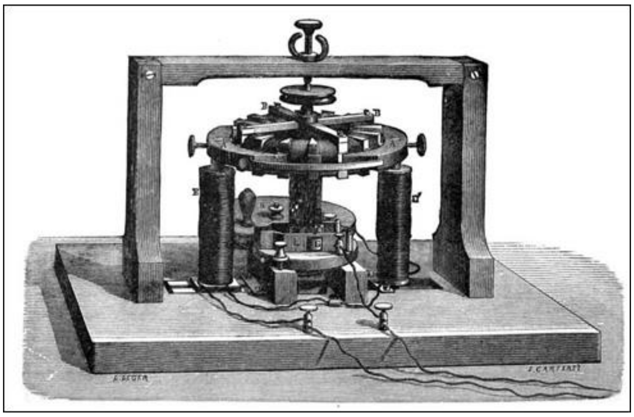
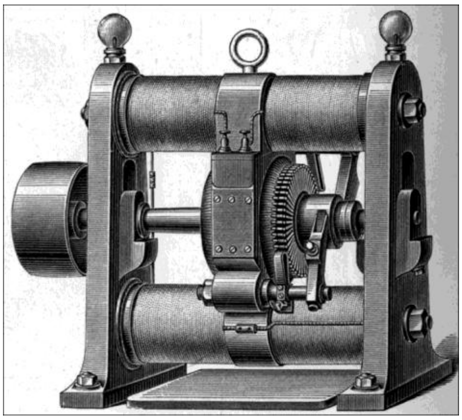
 

***Figure 11*: On the left, Pacinotti's dynamo. The magnetic field produced by the two vertical coils crosses the rotor coils. The crank-operated rotor turns on its vertical shaft. On the right, Gramme's dynamo. The stator is an iron frame equipped with four coils, designed to concentrate the magnetic field in the rotor (Wikipedia illustrations).**

The story goes that at the International Exhibition of Vienna in 1873, Gramme or one of his workers inadvertently connected the output wires of two dynamos and drove one of them by a steam engine, Then the other began to spin. Gramme had thus discovered that the dynamo was a reversible electric machine: it could also operate as a motor.[16] Subsequent trials showed that it was possible to connect a motor and dynamo by cables exceeding one kilometre. The electricity could thus be used for remote power transmission and would become the norm, displacing the mainly mechanical techniques that had previously been tested (compressed air tubes, water-filled pipes, belts coupled to a long rotating shaft, steel cables wound on pulleys).

Moreover, the electrical energy could be easily distributed by simply connecting the various motors to the same generator. It therefore became apparent that one network could supply both electric lighting systems and other appliances. All that remained to do was evaluate the conversion efficiencies and line losses to assess whether the scheme was viable from an economic point of view.

The variety of potential applications soon became apparent. In factories, mechanical energy transmission would no longer be confined to the use of line shafts, belts, compressed air or hydraulic pressure. Each machine could be equipped with its own easy-to-control electric motor, with an efficient power transmission and minimal losses. In agriculture, electric motors could replace

16. Given the many experiments with electricity taking place at the time, the reversibility of generators was probably already well known.

human labour and draft animals to mill wheat or pump irrigation water. Towns could be equipped with electric omnibuses. Families could benefit from a variety of new household appliances.

All these applications would become reality over time. But there was still one step to go. Electricity is easy to transport and distribute but difficult to store. The magneto, and then the dynamo, had increased the power supply in comparison with the galvanic cell, but had not resolved the problem of energy storage.[17] Scientists realised that the supply chain had to be understood holistically: electricity is produced in power plants by generators, carried away by distribution networks, and immediately used by consumers. This system requires enormous financial investments.

ALTERNATING CURRENT VS. DIRECT CURRENT

At the end of the 1870s, Edison, famous for inventing the phonograph, wanted to develop an electricity network to replace the existing gas lighting system. He rallied investors, established the firm Edison Electric Light, developed and marketed the electric light bulb, and filed a multitude of patents concerning generators, motors, conductors, fuses, and electricity meters.

In 1882, he constructed the first power plant to supply electric lighting in the Wall Street district of New York. The future inventor of the tramway and the electric elevator, Frank J. Sprague (1857–1934) joined his staff, and Edison took advantage of Sprague’s knowledge of mathematics to ensure that his projects were intelligently designed. Sprague’s improvements to the DC motor made it suitable for large-scale use: the new motor was powerful, turned at a constant speed despite variable load, did not spark and returned the surplus energy to the plant.

Edison was not the only person who wanted to construct an electricity grid. George Westinghouse, who had invented a braking system for trains, had turned his attention to electrical technologies. Unlike Edison, whose electricity grid was designed for direct current, Westinghouse placed his hopes in alternating current.

17. Even today, this problem has not been satisfactorily resolved. The best option is to use the excess of electricity in off-peak hours to pump water upstream of the hydraulic dams. Significant research efforts are now focused on improving electricity batteries in order to increase the autonomy of mobile consumer devices (electric cars, mobile phones, laptops).

Direct current cannot be efficiently transported over large distances due to ohmic losses in the conductors, whose value is the product of the resistance of the conductors and the current squared. To reduce these losses, either the current or the resistance should be lowered. Decreasing the current requires increasing the voltage in order to maintain the same electric power (that is voltage times current). However, this can damage appliances and be dangerous for users. Decreasing the resistance requires copper conductors with low electrical resistance. As the resistance of a cable is inversely proportional to its section and proportional to its length, this means either using very thick – and thus very expensive – cables, or transmitting the electricity only over short distances. **Edison chose the latter of the solutions and advocated the construction of small electricity plants in each neighbourhood.**

Another solution, advocated by Westinghouse, consisted in producing electricity in one large plant and then distributing it to consumers. This involved increasing the generator output voltage to reduce the ohmic line losses, transmitting the electricity through cables, and reducing it to the levels required by users once it had arrived at its destination. However, at the time, no electric device could raise or reduce the voltage of direct current, while this was already a very simple operation for alternating current, thanks to the transformer, which had been invented in 1881 by Lucien Gaulard (1850–1888) and John Dixon Gibbs (1834–1912).

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An electric light bulb works with both direct current and alternating current. For alternating current, a frequency of 60 Hz is high enough for the thermal inertia of the filament to provide constant light: the bulb does not flicker in response to current's oscillations. However, an electric motor designed for direct current cannot work in alternating current. Westinghouse needed an AC motor, which had not yet been invented. For this reason, he turned to Nikola Tesla's work on rotating magnetic fields.

Tesla, who had arrived in the United States in 1884, worked for Edison's firm, even though Edison himself was hostile to his employee's ideas about alternating current. As part of Edison's staff, Tesla was obliged, despite himself, to continue work on direct current. Over time, however, the differences between the two inventors intensified. Edison is said to have promised Tesla 50,000 dollars, at that time a considerable sum of money, to improve DC motors and generators. When Tesla demanded his payment, Edison apparently laughed in his face and told him: "Mr Tesla, you don't understand our American humour!"

In 1886, Tesla resigned and with the help of investors founded his own company, Tesla Electric Light, specialised in arc lighting. He wished to pursue his innovating ideas about alternating current but his investors, fearing failure, took control of the company and dismissed Tesla. To put food on the table, Tesla was forced to work on building sites digging ditches for electric cables. After a few months, he was contacted by other investors and the Tesla Electric Company was created. In his new laboratory, Tesla put his research on the AC motor and polyphase power systems into practice. In 1888, Westinghouse bought at high prices Tesla's patents and hired him as a consultant.

Chronological list of inventors and inventions mentioned

- Charles-August de Coulomb (1736–1806), France, laws of attraction and repulsion of electric charges
- Hans Christian Œrsted (1777–1851), Denmark, an electric current produces a magnetic field
- André-Marie Ampère (1775–1836), France, law of interaction between electric currents
- William Sturgeon (1783–1850), Great Britain, the first electromagnet (Fig. 2)
- Michael Faraday (1791–1867), Great Britain, electromagnetic induction (1831); the first electric generator
- Joseph Henry (1797–1878), United States, powerful electromagnets; auto-induction; the first electric motor (Fig. 4)
- Charles G. Page (1812–1868), electric locomotive
- Werner Siemens (1816–1892), Germany, the dynamo (end of the 1860s)
- 1820: Œrsted's article, followed by Ampère's and Arago's
- 1831: Henry's first electric motor
- 1831 Faraday discovers electromagnetic induction – a variable magnetic field produces an electric current (Fig. 5)
- 1832: first electric generator built by Pixii and Ampère (Fig. 7)
- 1844: Samuel Morse uses electricity in his telegraph
- George Westinghouse, (1846–1914), United States
- Thomas Edison (1847–1931), United States
- 1851: Charles Page's (unsuccessful) trial of the electric motor in railway traction
- Nikola Tesla (1856–1943), Serbia / United States

TESLA'S PATENT ON THE SYNCHRONOUS MOTOR

This publication[18] is one of a series of seven patents filed on 1 May 1888. The idea for a brushless rotating electromagnetic motor probably went as far back as the late 1870s, when Tesla was a student at the Graz University of Technology.[19] In the event, the patent presents several variants of synchronous motors and generators, the concept of two- and three-phase alternative current, and the associated distribution network.

From the very outset, at line 15, Tesla announces the principal characteristic of his invention, the synchronous motor, whose angular velocity is synchronised with the angular velocity of the rotating magnetic field and which, within certain value limits, is independent of the resistant torque opposed by the load:[20]

> *… demands a uniformity of speed in the motor irrespective of its load within its normal working limits*

At line 34, the inventor introduces the concept of the rotating magnetic field, generated by the stator coils traversed by sinusoidal alternating currents:

> *A motor is employed in which there are two or more independent circuits through which alternate currents are passed at proper intervals, in the manner hereinafter described, for the purpose of effecting a progressive shifting of the magnetism or of the "lines of force" in accordance with the well-known theory, and a consequent action of the motor.*

The rotor turns because its magnetic moment tends to align with the rotating magnetic field of the stator:[21]

> *It is obvious that a proper progressive shifting of the lines of force may be utilized to set up a movement or rotation of either element of the motor, the armature, or the field-magnet …*

The rotating field means that the motor supplied by alternating current does not need a commutator,[22] a mechanical device used in DC motors, as explained

18. U.S. Patent 0,381,968 - *Electro magnetic motor* - 12 October 1887, Nikola Tesla's patent on the contactless motor. This article is a commentary on the publication. Readers are advised to read the Technical Annex before turning to the patent publication.
19. In 1885, in Turin, Galileo Ferraris (1847–1897), who was searching for a mechanical analogy to circularly polarized light, used a rotating magnetic field to rotate a copper cylinder. He published his conclusions in 1888, a few weeks after Tesla had filed his parents. Ferraris had not considered any practical application for his finding.
20. "Load" refers to any energy consumer driven by a motor and which produces a resistant torque opposing this motion: for example, the wheels of an electric vehicle, a vacuum-cleaner turbine, a fan propeller, or a washing-machine drum.
21. In this type of motor, the stator is the field and the rotor is the armature. The field produces the magnetic field, which is received by the armature and transformed into mechanical energy (in a motor) or electricity (in a generator).
22. The commutator's function is described in the Technical Annex.

above, to periodically reverse the current direction in the rotor and thus ensure that it rotates continuously. The commutator tends to wear away over time, which increases the maintenance cost of the motor. On the other hand, the rotating magnetic field requires a source of alternating current, which forced Tesla to introduce the two-phase alternative current generator and the corresponding distribution network:

> *… if the currents directed through the several circuits of the motor are in the proper direction no commutator for the motor will be required; but to avoid all the usual commutating appliances in the system I prefer to connect the motor circuits directly with those of a suitable alternate current generator.*

The description of how this type of motor works is very detailed and follows the steps shown in the first eight figures in the patent, which describe the successive positions of the generator's rotor (on the left) and the motor's rotor (on the right), shifted by a $\pi/4$ phase, during one complete revolution.

The generator G's rotor is formed of two perpendicularly coils B and B', which turn together in the field of a magnet (the stator) and therefore produce two sinusoidal alternating currents shifted by 90°. This is a two-phase AC generator.

In Figure 1 in the patent, the coil B receives a maximum magnetic flux. The induced voltage, which is proportional to the flux derivative, is therefore zero. The coil B', on the other hand, receives zero magnetic flux. However the flux variation is maximum, the voltage induced is therefore also maximum.

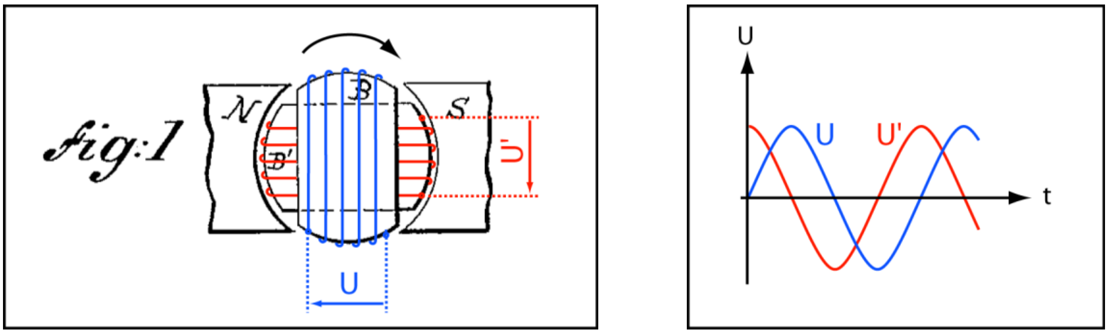


***Figure 12:* Two-phase AC generator** *described in the patent, made out of two perpendicular coils B and B', which rotate in the magnetic field of a magnet. The position of the coils at the point t=0 is shown on the left. For the sake of clarity, the windings on the coils are also shown. The voltages U and U', phase-shifted by 90 degrees, are shown on the right.*

Tesla used a classic system of four brush-slip rings to collect the current produced by the turning coils. Each of the four terminals of the two coils is connected to a ring fixed to the motor shaft. When the rotor turns, the four rings slip on the immobile brushes.

This system is prone to mechanical wear and tear, but less than a commutator. The latter, formed of separate ring segments, periodically interrupts the electrical contact, which produces sparks, heat and rapid wear. The brush-slip ring does not present these disadvantages: the electric circuit is never interrupted because it is the alternating current that carries out the switchovers.

The motor comprises two pairs of coils CC and C'C', wound around a torus or cylindrical shell and staggered at 90°. The magnetic field produced by one of the pairs is shown in the following figures:

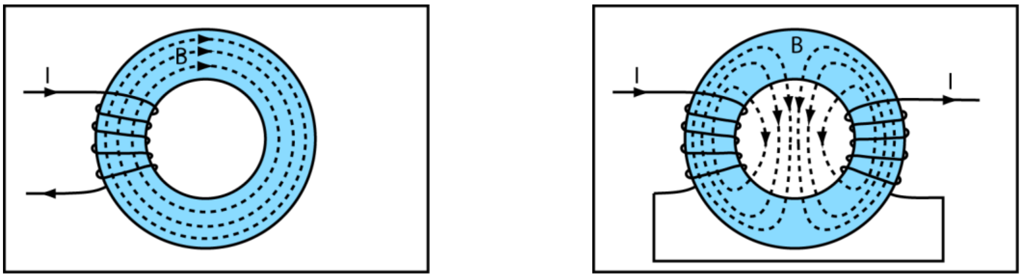


Figure 13: ***Magnetic field produced by a coil wound around a torus*** *(on the left). The field lines, guided inside materials of strong magnetic permeability, follows the contours of the torus. On the right, the two diametrically opposed coils, are serial connected in such a way that they generate opposite magnetic fields. As a result the resultant magnetic field leaves the torus and sets in the area at mid-point between the two coils. This phenomenon is even more pronounced if in the center of the torus, we replace the air, substance of low magnetic permeability, with a ferromagnetic material, able to better drive the field lines (© Ilarion Pavel).*

Supplied by two alternating currents phase-shifted of 90 degrees, the two pairs of coils produce a rotating magnetic field. The generator's B' coil supplies a voltage U' to the pair of coils CC in the motor, while the coil B supplies the pair C'C' with a voltage U.

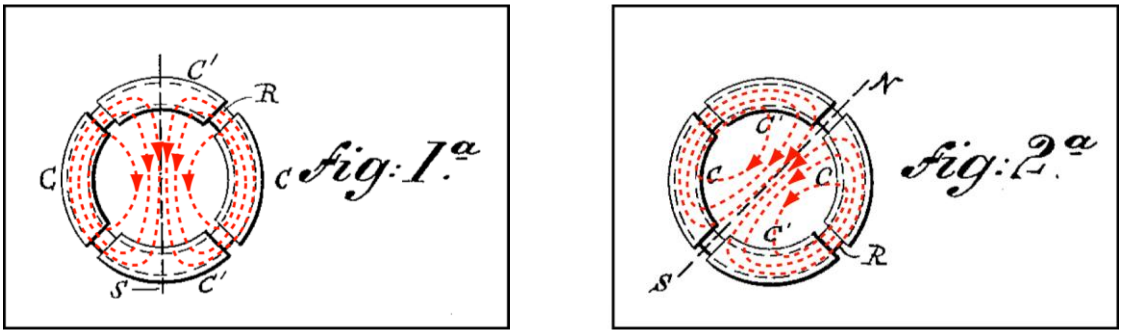


Figure 14: ***The motor's rotating magnetic field*** *described in the patent. For the sake of clarity, the magnetic field lines are shown in red. The pair of coils CC and C'C' are respectively supplied by the voltages U' and U, provided by the generator described above. The left-hand image shows the point t=0, when CC is powered while C'C' has no*

voltage. The right-hand image shows the situation after a π/4 phase delay, when the two pairs are supplied with an equal voltage: the two contributions to the magnetic field combine to produce a resultant field rotated by a π/4 angle compared to the initial position.

The disc D magnetization (its magnetic moment) is continuously aligning the rotating magnetic field and, as a result, it turns. The disc is, in fact, the motor's rotor. The successive rotor positions shifted by π/4, during one complete rotation, are shown in Figures 1^a-$8^{a.}$

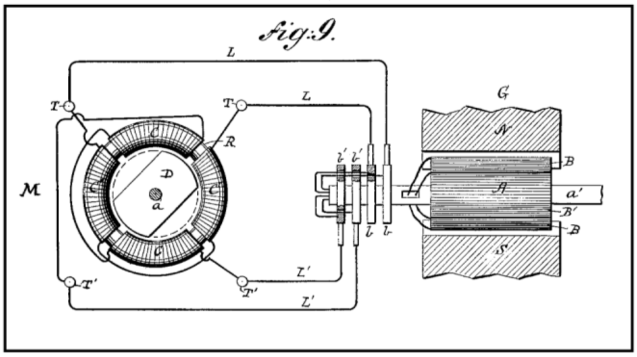
At line 101, on page 2, Tesla observes that rotor D rotates even if it has a perfectly circular geometric form and correctly ascribes this behaviour to the ferromagnetism of the material:

> *The disk D in Fig. 9 is shown as cut away on opposite sides; but this, I have found, is not essential to effecting its rotation, as circular disk, as indicated by dotted lines, is also set in rotation. This phenomenon I attribute to a certain inertia or resistance inherent in the metal to the rapid shifting of the lines of force through the same, which results in a continuous tangential pull upon the disk, causing its rotation. This seems to be confirmed by the fact that a circular disk of steel is more effectively rotated that one of soft iron, for the reason that the former is assumed to possess a greater resistance to the shifting of the magnetic lines.*

It was not until 1906 that the French physicist Pierre Weiss (1865–1940) would explain this *resistance to the shifting of the field lines*, which is characteristic of ferromagnetic materials, by the modification of the materials' magnetic microdomain walls, known as *Weiss domains*. And it was only in 1928 that Werner Heisenberg (1901–1976) explained ferromagnetism in terms of quantum mechanics, which had just been developed.[23] Steel behaves better than iron because it has a remanent magnetization (a nonzero magnetic moment even in the absence of the external field), which is not the case with iron.

As it rotates, the disc D's magnetic moment is not exactly align with the rotating field, but makes an angle with the latter, depending on the load coupled to the motor shaft.

23. The fact that a steel disc has remanent magnetization that points in a given direction, despite its perfectly circular symmetrical form, was not understood until the 1950s, with the discovery of what is known as spontaneous symmetry breaking.



To connect the motor to the generator, Tesla used four conductors, LL and L'L', to create a two-phase current distribution system, as we can see in the figure above.[24]

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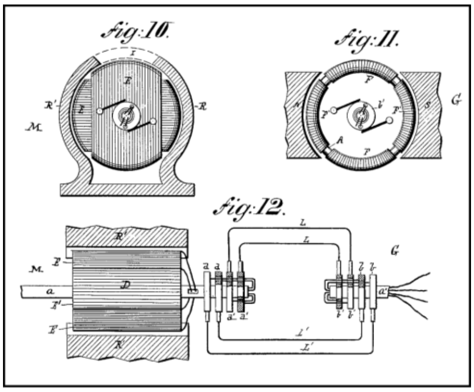
For the remainder of the article, Tesla presents other versions of and improvements to synchronous generators and motors.

In general, the coils of an electric motor or generator are arranged in two architectural structures: wound around a torus (or ring) or a drum.[25] Thus in the initial system, shown in Figure 9, the generator coils are wrapped around a drum and the motor stator coils around a ring.

As synchronous machines are reversible, the roles of the motor and generator can be easily switched around. It is also possible to vary the ring or drum structure, or the type of permanent magnet or electromagnet used to construct different versions of the generator-motor system.

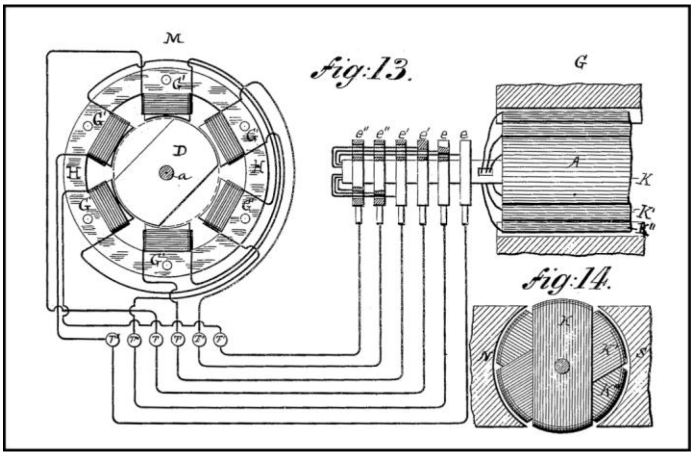
In the system shown in Figures 10, 11 and 12, generator G has a permanent magnet stator (whose north and south poles are shown in Figure 11) and a ring-type rotor, formed out of two pairs of coils FF and F'F'. The motor M's stator is made out of a ferromagnetic material, preferably steel because of its remanent magnetic properties.[26] Instead of a permanent magnet, the rotor is made out of two coils E and E' staggered at right angles (a coiled drum rotor) and requires a slip ring (rotating electrical connector) for the power supply.

24. For the sake of clarity, Figures 9 to 17 from Tesla's patent are included in this article.
25. The ring structure of rotors, introduced by Pacinotti and Gramme, was gradually superseded by the much more efficient drum structure. In a ring structure, the magnetic field penetrates from the exterior and then follows the ring's contours. When the rotor turns, the insides of the turns barely cross the field lines. The induced voltage is therefore almost zero, as the interior of the turns acts as an electric conductor and not as an inductor.
26. A permanent magnet could have been used, like in the generator. Once magnetized, the steel behaves like a permanent magnet due to its remanent magnetic properties.



In Figures 13 and 14, Tesla presents a three-phase generator-motor-distribution system. The generator rotor, made of three identical coils staggered at 120°, revolves in the field of a magnet and produces three sinusoidal alternating voltages, phase-shifted by 120°. The three-phase distribution system uses six conductor wires[27] to power the motor stator, which is made of three pairs of coils. These are staggered at 60° and produce a rotating magnetic field:

> *The variations in the strength and direction of the currents transmitted through these circuits and traversing the coils of the motor produce a steadily progressive shifting of the resultant attractive force exerted by the poles G' upon the armature D, and consequently keep the armature rapidly rotating. The peculiar advantage of this disposition is in obtaining a more concentrated and powerful field.*

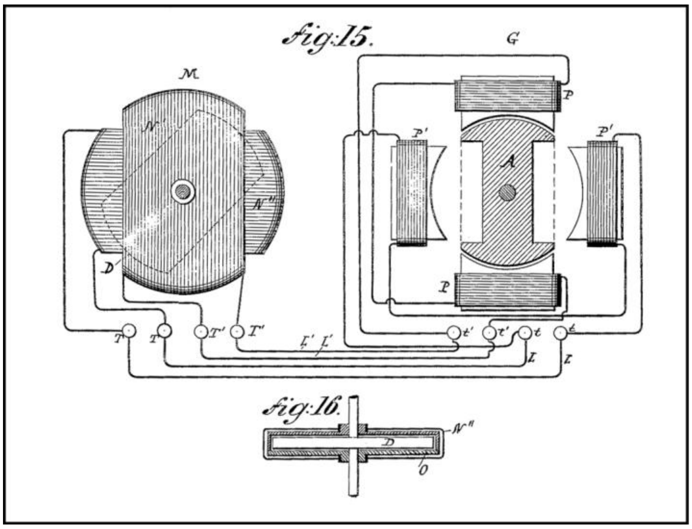


The rotor is made out of a ferromagnetic disc D and, just as in the system presented in Figure 9, this removes the need for a slip ring-rotor power supply.

27. Nowadays, preferred practice is to connect the six stator coils and group them in a star or triangle configuration, which reduces the number of conductors to four or even three, and saves material in the three-phase distribution network (Technical Annex, Fig. A12).

The arrangement of the coils, their number (three pairs) and the small air-gap (the space between the core of the coils and the rotor) produce a much stronger rotating magnetic field, and therefore a more powerful motor than the one shown in Figure 9.

Figures 15 and 16 show a motor M with a stator made out of two coils, N' and N'', wrapped around a drum and staggered at 90°. As in the previous example, the rotor D is made out of a ferromagnetic disc. The magnetic field produced by the drum coils is much more powerful than that produced by the coils wound around the ring, thereby making this a much more powerful motor than the one shown in Figure 9.



The stator of generator G, made out of the pairs of coils PP and P'P', is unusual in that it is also the armature: the voltage is induced in the stator and not in the rotor, as was the case in the generators presented above. Using the permanent magnet A as the generator's rotor produces a motor and generator system that can totally bypass slip-ring contact systems:

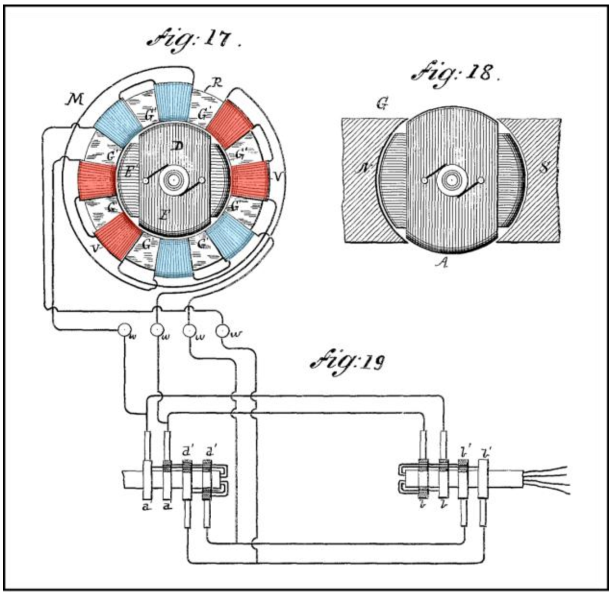
> *This mode of carrying out the intervention has the advantage of dispensing with the sliding contacts in the system.*

The generator stator is bipolar (made out of two pairs of coils) while the motor stator is unipolar. When the generator rotor makes a half-revolution, the induced current and the motor make a complete cycle. The motor thus turns twice as fast as the generator, as Tesla remarks at line 46 on page 4:

> *… the number of alternating impulses resulting from one revolution of the generator armature is double compared with the preceding cases and the*

polarities in the motor are shifted around twice by one revolution of the generator-armature. The speed of the motor will, therefore, be twice that of the generator.

Figure 17 shows motor M, whose stator and rotor are made only using electromagnets powered by a two-phase alternating current. In fact, both the stator and rotor produce their own rotating magnetic field. The electrical connections are arranged in such a way that the two fields rotate in opposite directions, which means that their relative speed is doubled compared to a motor with a single rotating field, which means that the motor's revolution speed is twice as high, as Tesla points out at the end of the patent, at line 55 on page 4.



The stator is bipolar. Each of its poles (shown in red or blue in Figure 17) is made out of four coils arranged in series and positioned in pairs diametrically opposite one another.

The rotor is made out of two coils E and E', staggered at right angles and powered by a slip ring, as in the rotor shown in Figure 10. The electric circuits of the rotor and stator are arranged in parallel (shunt) and connected to generator G (Figure 18) via a two-phase four-conductor distribution system (Figure 19). Generator G is identical to the one shown in Figure 9.

At the end of the patent, on line 34, page 4, Tesla provides arguments to explain the synchronism between the rotor and the rotating magnetic field:

… it will be observed that since the disk D has a tendency to follow continuously the points of greatest attraction, and since these points are shifted around the ring once for each revolution of the armature of the

> *generator, it follows that the movement of the disk D will be synchronous with that of armature A.*

Indeed, the rotating magnetic field magnetises disc D, which in turn produces its own magnetic field. Combined, these two contributions (rotating field and the disc's own field) produce the resulting field. The disc's tendency to orient itself in the direction of the rotating field lines causes the disc to turn at the same angular velocity as the rotating field, making it synchronous.

A few lines further down, Tesla repeats his arguments, adding that of the independence of the synchronous motion in relation to the motor's load:

> *… since the attractive effect upon the disk D is greatest when the disk is in its proper relative position to the poles developed in the ring R – that is to say, when its ends or poles immediately follow those of the ring – the speed of the motor for all the loads with the normal working limits of the motor will be practically constant … the speed can never exceed the arbitrary limit as determined by the generator, and also that within certain limit at least the speed of the motor will be independent of the strength of the current.*

It is true that when the motor is running, the resulting field is not perfectly aligned with the rotating field; the two directions form an angle. The magnetic field exerts a torque on the disc proportional to the sine of this angle, which counterbalances the resistant torque of the load: the greater the load, the larger the angle. Nevertheless, the disc will continue to rotate in synchronisation with the rotating field as long as the mechanical load is reasonable, with an angle inferior to 90° (see "Synchronous motor" in the technical annex).

The end of the patent lists the main characteristics of Tesla's induction motor:

> *… a uniform speed under all loads within the normal working limit of the motor without the use of any auxiliary regulator; synchronism between the motor and generator; greater efficiency by the more direct application of the current, no commutating devices being required on either the motor or generator; cheapness and simplicity of mechanical construction and economy in maintenance; the capability of being very easily managed or controlled; diminution of danger from injury to persons and apparatus.*

Tesla declares that he is aware of the DC motor, which requires a commutator, a mechanical device needed to reverse the direction of the current in the rotor coils in order to maintain the rotation. But he declares this solution impractical, without going into details:

I am aware that the rotation of the armature of a motor wound with two energizing-coils at right angles to each other has been effected by an intermittent shifting of the energizing effect of both coils through which a direct current by means of mechanical devices has been transmitted in alternately opposite directions; but this method or plan I regard as absolutely impracticable for the purposes for which my invention is designed – at least on any extended scale – for the reasons, mainly, that a great waste of energy is necessarily involved unless the number of energizing-circuits is very great, and that the interruption and reversal of a current of any considerable strength by means of any known mechanical devices is a matter of the greatest difficulty and expense.

As mentioned earlier, the disadvantage of the commutator, as a moving part, is that it wears out quickly and has to be replaced at regular intervals. It cannot withstand either very powerful currents, because the ohmic contacts risk overheating, or high voltages, because the periodic opening and closing of the circuit produces sparks. This is probably what Tesla is referring to in the above citation, when he asserts that the induction motor is less dangerous for users.

Tesla ends the patent, as is customary, by summing up the list of inventions.

THE *WAR OF THE CURRENTS*: EDISON AGAINST TESLA AND WESTINGHOUSE

Despite the benefits of alternating current, Edison did not admit defeat. From 1887 to 1893, he led a concerted campaign to misinform investors, legislators and potential clients and convince them of the superiority of direct current. Westinghouse and Tesla retaliated and a battle ensued. It would later be rightly dubbed the *War of the Currents*.

Edison claimed that alternating current would be too dangerous for users and to prove this electrocuted dogs, cats, calves and horses in public demonstrations. He went as far as suggesting that alternating current should be used to executive convicts on death row and that executions by electrocution should be called *Westhousings*.[28]

Edison's opposition to alternating current was motivated by a desire to protect his investments, patents, and eventual royalties, all of which were based on DC technology. And his economic model was centred on the construction of a

28. The first execution by electrocution took place in New York State in 1890. As the voltage was too low, it was tortuous for the prisoner.

large number of small power plants, which would have generated a substantial sales revenues.

However, despite Edison's prestige and financial resources, Westinghouse gained an increasingly large share of the market. Exasperated by Edison's intractability regarding alternating current, his shareholders organised a merger of Edison Electric with Thomson-Houston, a company that had developed expertise in the field of alternating current. The new company, General Electric, made massive investments in AC technology, but it took the firm several years to catch up with Westinghouse.

The *War of the Currents* came to an end in 1893, when Westinghouse won a construction contract to build a hydroelectric power plant at the Niagara Falls. General Electric would have to make do with building a high-tension line between the Niagara hydroelectric plant and the city of Buffalo. Years later, Edison admitted that his opposition to alternating current had been "the biggest blunder" he ever made.[29]

But this bitter competition proved costly for on Tesla. The Westinghouse company was almost bankrupt. Under pressure from investors, in particular J. P. Morgan[30] (1837–1913), Westinghouse asked Tesla to forfeit his royalties in order to prevent him losing control of the company. Tesla accepted and tore up the contract granting him one dollar in royalties for every electrical horsepower sold, which would have guaranteed him a huge fortune.

OTHER INVENTIONS BY NIKOLA TESLA

In 1890, Tesla used one of his new inventions – the eponymous Tesla induction coil – to produce high-tension, high-frequency currents. He noticed that these currents circulated at the edge of the conductor, a phenomenon now known as the skin effect. A high-frequency current can thus pass through a human body quite safely, because it flows through the skin rather than tissue,

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29. It is an irony of fate that recent developments in power electronics have now made it possible to construct convertors that can easily increase and decrease DC voltage, to such an extent that, nowadays, a high-tension DC power line has lower losses than an AC line, in which losses are caused by the skin effect, and the capacity and inductance of the cable. The construction of solar and wind farms, and the storage of energy in electric batteries have led to a revival of DC distribution networks.
30. The same J. P. Morgan had forced Edison to cede control of his company. In fact, Morgan had invested in both Edison and Westinghouse's projects. It mattered little to Morgan which of two men came out on top; his only preoccupation was acquiring a monopoly over the US electricity sector and eliminating any competition. Morgan had already successfully applied this strategy in railways and the steel, iron and oil industries.

procuring a warm sensation in the subject. After studying the physiological effects of these currents, Tesla suggested that they should be used in medicine.

At this time, he also performed a series of sensational demonstrations. One of these involved using a high-frequency generator to produce powerful magnetic fields in a room, and in turn using these to light up gas-filled tubes, without connecting them by wire to a power supply. Sometimes, he held the tubes in his hand and allowed the high-frequency current to pass through his body, thereby creating lightning-like electrical discharges between his body and the laboratory facilities.[31]

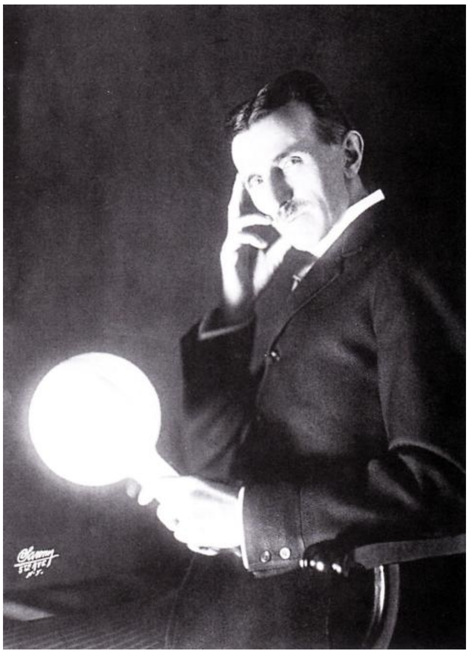

***Figure 15:* Tesla holding one of his so-called wireless lamps** *(photograph published on the cover of the magazine* Electrical Experimenter*, 1919). The lamp is powered by a high-frequency electric current passing through his body (Wikipédia illustration).*

In 1893 he uses a tuned resonant circuit made of a coil and capacitor to transmit electrical signals remotely, thereby laying the foundations of wireless telegraphy. A perfectionist, Tesla worked tirelessly to improve his appliances. Unfortunately, in 1895, a fire completing destroyed his laboratory, and years of his work were irretrievably lost. As usual, the inventor was working on several subjects at the same time, including the liquefaction of air. It is therefore possible that the blaze had been caused when liquefied oxygen came into contact with the oil from the transformer.

31. These demonstrations were partly motivated by a desire to show that high-frequency AC current was not dangerous. They were part of Tesla's arsenal in the *War of the Currents*.

During this unhappy year, 1895, Tesla also performed many experiments using Lenard tubes and began investigating what would later be called X-rays, producing several photographs of parts of the human skeletons.[32] One of his subjects was his close friend, the novelist Mark Twain (1835–1910). Tesla noted that prolonged exposure of his hands to X-rays irritated the skin, but he mistakenly attributed this effect to the ozone formed by the electric discharges. His laboratory equipment included forerunners of the electronic microscope and the particle accelerator. He advanced several hypotheses and displayed extraordinary intuition in predicting the existence of solar wind and radioactive disintegration.

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Aided by the financier J. P. Morgan, Tesla rebuilt his laboratory and in 1897 carried out the first wireless transmission,[33] in which signals were picked up 40 km away by a receptor on board a boat sailing on the Hudson River. Tesla had invented the radio.[34]

In 1898, Tesla applied the concepts he had developed for wireless telegraphy to construct a remote-controlled boat.[35] He tried, unsuccessfully, to sell the concept to the United States Navy, and it would not be until the First World War that the importance of guided missiles was understood. In his many public lectures, he promoted the idea of using remote-controlled robots. To command them separately, without risk of interference, he invented the logic gates AND and OR, which would be rediscovered 50 years later in the construction of computers and which, even today, remain the basis of computer architecture.[36]

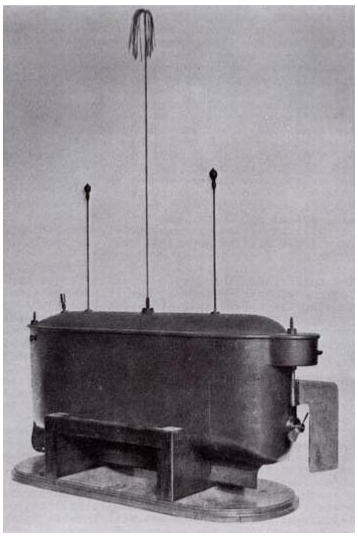
32. Well before Röntgen, experimenters like W. Crookes, E. Goldstein, H. Hertz, H. von Helmhotz, P. Lenard and J. J. Thomson had demonstrated the existence of X-rays. But it was Röntgen who undertook systematic study of the nature of this mysterious ray.

33. U.S. Patent 0,645,576 - *System of Transmission of Electrical Energy* - 2 September 1897 et U.S. Patent 0,649,621 - *Apparatus for Transmission of Electrical Energy* - 2 September 1897.

34. The first transatlantic wireless telegraphic transmission was performed in 1901 by Guglielmo Marconi (1874-1937), who built his equipment using Tesla's patents and took inspiration from Oliver Lodge's work. A legal battle ensued: Tesla won, but in 1904 the court ruled in Marconi's favour. A new trial in 1943 vindicated Tesla: the United States Supreme Court of Justice withdrew the title of inventor of the radio from Marconi. However, Marconi had received the Nobel Prize for Physics in 1901, with the German Karl Ferdinand Braun.

35. U.S. Patent 0,613,809 - *Method of and Apparatus for Controlling Mechanism of Moving Vehicle or Vehicles* – 1 July 1898.

36. U.S. Patent 0,723,188 - *Method of Signalling* et U.S. Patent 0,725,605 - *System of Signalling* - 16 July 1900.



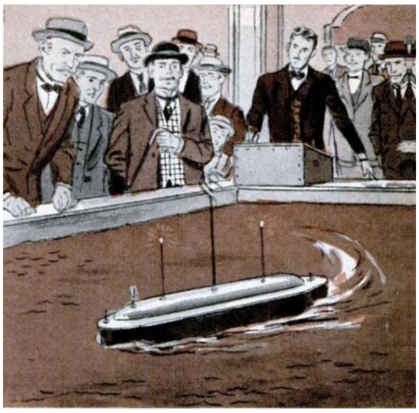
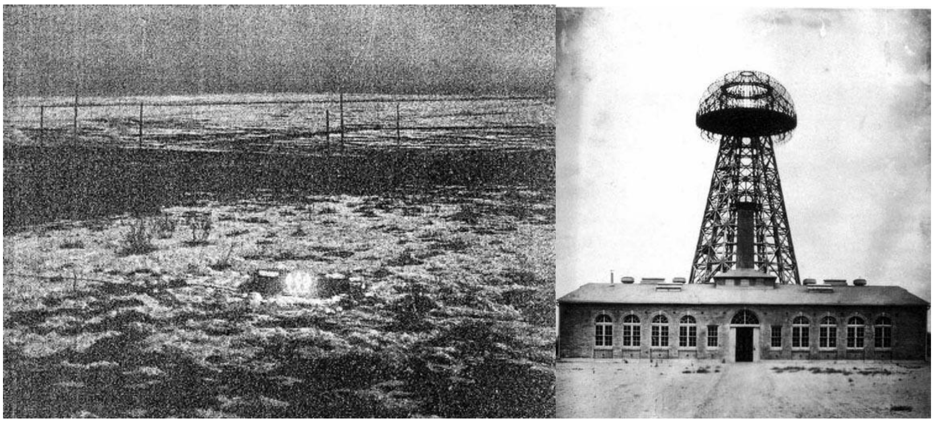


***Figure 16:* Tesla's remote-controlled boat**, *called the "teleautomaton", and one of its first public demonstrations, in 1989, in Madison Garden Square (Wikipedia illustrations).*

In 1899, to investigate remote power transmission, Tesla built a 200 kW-transmitter in Colorado Springs that produced voltages of 12 million volts and frequencies of a few kilohertz. Tesla conceived of the Earth and its ionosphere as an enormous capacitor that could be excited by electric signals. By injecting power into a certain point in the Earth's surface, he hoped to provoke oscillations in the atmosphere, then transmit these oscillations and recuperate them at another point on the Earth's surface. Tesla identified the resonance frequency of the ionosphere (around 8 Hz), which was rediscovered in the 1950s and is today called Schumann resonance.

In 1900, he undertook the construction of a tall tower equipped with an antenna at Wardenclyffe (Long Island), with the aim of continuing his research on remote power transmission. Indeed, Tesla dreamt of providing free electricity access at any point on Earth. He envisaged using a very powerful directive ultraviolet lamp to ionise air molecules and create a conduction channel between the Earth and the atmosphere. It was through this channel that he hoped to inject energy into the ionosphere, by sending electric discharges of millions of volts, analogous to lightning. The idea was that another lamp, positioned at another point on Earth, would produce a similar conduction channel, through which the injected energy would be recuperated and used for lighting in cities or to propel ships and aeroplanes. This project never materialised.



<u>Figure 17:</u> *On the left, one of Tesla's experiments of* ***remote power transmission*** *carried out at Colorado Springs. The power supply is situated 30 m from the lamp bulbs it lights up. On the right,* ***Wardenclyffe tower****, which Tesla intended to use to transmit energy through the ionosphere (Wikipedia illustrations).*

In 1901, after Marconi's first transatlantic wireless telegraphic transmission, J. P. Morgan withdrew financial support from Tesla's projects. With his monopoly on the supply of copper used in the manufacturer of electric cables, J. P. Morgan no longer saw the point in financing remote power transmission. Furthermore, calculating individual user consumption was not possible, and thus posed a problem of billing and, consequently, of return on investment. The prospect of free electricity distribution across the globe did not fill Morgan with enthusiasm, to the point that he discouraged other financiers from investing in Tesla's project.

Despite the lack of funding and a laboratory, Tesla continued his research work, inventing a bladeless turbine[37] and a vertical take-off propeller aircraft,[38] and setting out the fundamental principles of radar.[39]

In an attempt to end warfare, Tesla dedicated the last years of his life to design of a new weapon, the *death ray*, capable of producing and directing beams of ions, but he would never fully develop this concept.

Nikola Tesla was an exceptional inventor whose imagination and intelligence were beyond compare. He worked with feverish enthusiasm, often abandoning one research subject for another with a new idea occurred to him. Lack of time meant that he was never able to put many of his ideas into practice. Several of his techniques and laboratory innovations were never patented.

37. U.S. Patent 1,061,206 - *Turbine* – patent filed on the 21 October 1909.
38. U.S. Patent 1,655,113 - *Method of Aerial Transportation* – 9 September 1921.
39. *The Electrical Experimenter*, 1917.

An idealist who was totally uninterested in money, Tesla always hoped that his inventions would be used to make life more comfortable for his fellow human beings. He never protected his parents and always reinvested his profits to better equip his laboratory and finance his research. He made other people's fortunes but died in 1943 in New York, destitute and forgotten.

In 1960, at the General Conference on Weights and Measures, the tesla (T) was adopted as the unit for magnetic induction in the International System of Units.

■

(7 January 2013 | on the occasion of the 70th anniversary of Tesla's death)

(translated in English by Helen Tomlinson, published May 2014)

MAGNETIC FIELD

A long, straight conductor, traversed by electric current I, generate a magnetic field ***B***. The field lines are circular and surround the conductor and can be detected with a small compass or iron filings. The direction of the field lines is given by the right-hand rule: if the thumb is pointing in the direction of the current, the fingers will point in the direction of the field lines. The magnetic field is tangent to the field lines; its value is proportional to current I and inversely proportional to the conductor's distance r:

$$B = \frac{\mu}{2\pi}\frac{I}{r}$$

where $\mu = 4\pi \cdot 10^{-7}$ is a proportionality constant known as magnetic permeability, with the factor 2π chosen for convenience's sake in SI units.

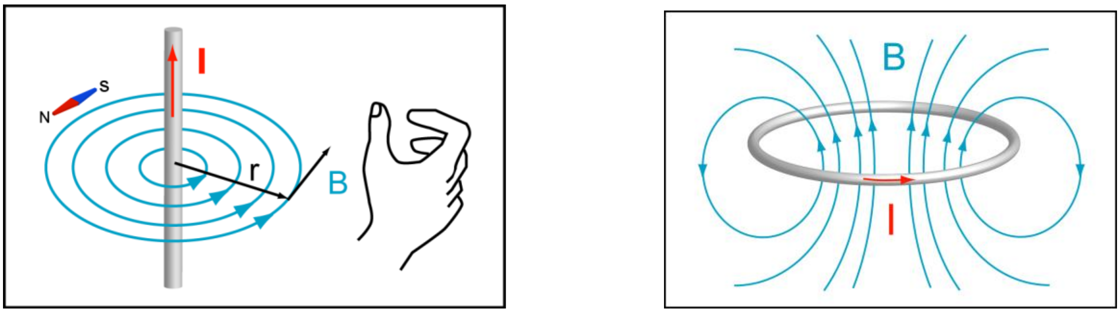


***Figure AI*: Magnetic field lines** *of a straight wire (left) and a current loop (right) (© Ilarion Pavel).*

In principle, we can compute the magnetic field of any distribution of current by using the superposition principle: we divide the distribution into small regions, compute the magnetic field for each of these, then sum up all the contributions.. If the geometry of the distribution is simple (infinite straight wire, circular loop, current sheet), the result can be expressed in analytical mathematical formulas; if the geometry is complex, numerical calculus should be used.

Thus, the magnetic field in the center of a loop traversed by an electric current is given by the expression:

$$B = \mu \frac{I}{2r}$$

@@@@@@@

The magnetic field of a solenoid is computed by adding together the magnetic field of each loop. Inside the solenoid, the magnetic field is given by the expression:

$$B = \mu \frac{N\,I}{\ell}$$

where *N* is the number of turns, I the current running through them and ℓ the length of the solenoid.

The magnetic field of a solenoid is virtually equivalent to that of a magnetic bar, which makes it very suitable for the construction of electromagnets. In order to increase the magnetic field, a ferromagnetic iron or steel core is placed inside the solenoid: the field produced by the solenoid orientates the atomic-level elementary magnets found in these materials. These elementary magnets generate their own magnetic field, thousand times greater than the initial solenoid magnetic field. Special alloys, which increase this factor to 100,000, are used in practice.

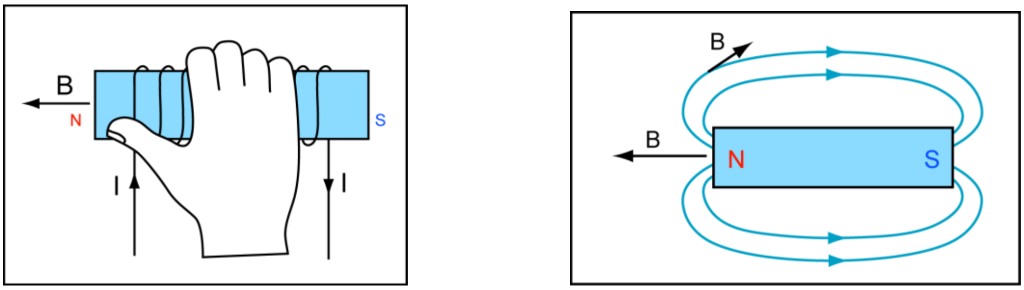


Figure A2*: A solenoid** *(on the left) behaves almost identically to* ***a magnetised bar *(on the right). The north pole is given by the right-hand rule: the fingers point in the direction of the electric current traversing the coil; the thumb points in the direction of the magnetic field (north pole) (© Ilarion Pavel).*

LAPLACE'S LAW

When a conductor carrying an electric current I is placed in a magnetic field **B**, the conductor is subject to Laplace's force, which is perpendicular to the plane formed by the conductor and the magnetic field. It is proportional to the magnetic field, the current, the length of the conductor and the sine of the angle formed by the conductor and the magnetic field:

$$F = I\,\ell\,B\sin\alpha$$

or in vectorial form:

$$\vec{F} = I\,\vec{\ell}\times\vec{B}$$

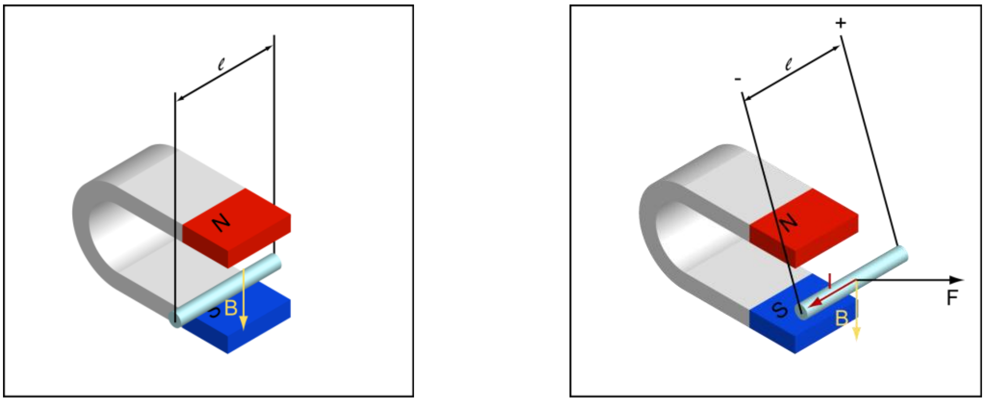


***Figure A3:* Laplace's force**. *When an electric current passes through a conductor suspended from two vertical wires situated in a magnetic field, the conductor undergoes a force F, which is proportional to current I, magnetic field B, and the length of the wire, and perpendicular to the plane formed by the conductor and the field. In this particular example, the angle between the conductor and the field is 90° (© Ilarion Pavel).*

If electric current I passes through a rectangular frame placed in the magnetic field of a magnet, Laplace's force acts on each edge and generates the torque *M*, which will cause the frame to rotate until its surface is perpendicular to the magnetic field (at which point the lever arm and therefore the couple of forces will be zero):

$$\vec{M} = \vec{r}\times\vec{F} = \vec{r}\times I\,(\vec{l}\times\vec{B})$$

which, after a few simple vectorial algebraic manipulations, gives

$$\vec{M} = I\,(\vec{B}\cdot\vec{r})\vec{l} = I\,\vec{S}\times\vec{B} = \vec{m}\times\vec{B}$$

where $\vec{S} = \vec{r}\times\vec{l}$ is the vector area of the rectangular frame. Le product $\vec{m} = I\,\vec{S}$ is known as the magnetic moment and, in a way, is a measure of the magnetic field generated by the current I passing through the frame.

This result can be expressed differently: a current passing through the frame produces a magnetic moment. The magnetic moment tends to align with the magnetic field of the magnet.

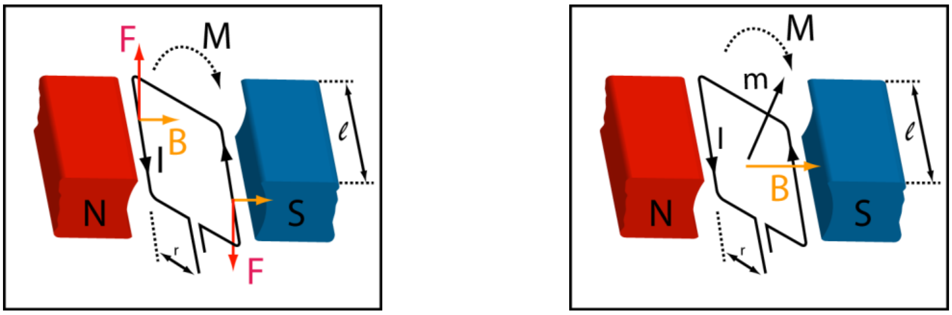


***Figure A4:* Effect of magnetic field B on a rectangular frame traversed by electric current I**. *On the left- and right-hand sides, the Laplace forces F produce a torque M, which rotates the frame until it is vertical, at which point the lever arm is zero (left-hand figure). The alternative explanation (right-hand figure) is that the magnetic moment m, produced by the current passing through the frame, tends to align with the magnetic field of magnet B (© Ilarion Pavel).*

The mechanical action exerted by the magnetic field on conductors traversed by an electric current, in particular rectangular or circular conductors, **is the operational basis of electric motors**.

THE ELECTRIC MOTOR

The rectangular frame mentioned in the previous section rotates until its magnetic moment is aligned with the magnet's field. If at this point, we reverse the direction of the current, the magnetic moment get also reversed and therefore opposed to the magnet's magnetic field. To realign itself with the magnetic field, the frame continues to rotate.

All that is needed to reverse the direction of the current is a mechanical device known as a commutator,[40] made out of two semi-circular rings welded to the ends of the frame and connected by brushes to a DC power supply.

40. This is almost the same commutator as the one invented by Ampère and used by Pixii to transform the magneto's alternating current into pulsating current.

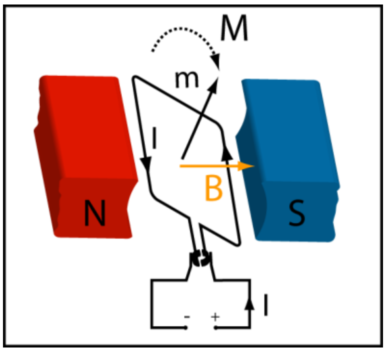


***Figure A5:* The operating principle of the electric motor**. *When the magnetic moment m aligns with the magnetic field B, the frame should stop rotating, However, at this point the direction of the current (and therefore of m), is reversed by the commutator. To realign the magnetic moment in the direction of the magnetic field, the frame continues to rotate and the process starts all over again (© Ilarion Pavel).*

FARADAY'S LAW OF INDUCTION

When a magnet is moved closer or further away from the permanent magnet of a coil connected to a galvanometer, the galvanometer needle deflects. The same result is obtained if the coil is moved instead of the magnet. But if both the coil and the magnet are immobile, the galvanometer reads zero: electromagnet induction is produced only if there is a variable magnetic field.

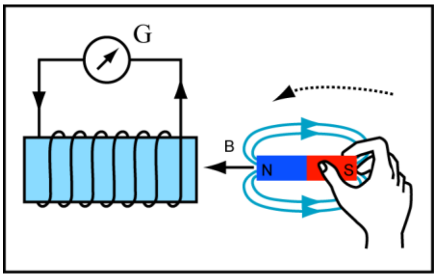


***Figure A6:* Electromagnetic induction**. *When a permanent magnet is moved closer to a coil connected to a galvanometer, the needle of the instrument deflects (© Ilarion Pavel).*

The flux of a magnetic field B passing through a surface S is given by the expression:

$$\Phi = \vec{B} \cdot \vec{S}$$

The scalar product indicates that it is the field projection perpendicular to the surface that matters.[41]

Faraday's law of induction holds that the variation of the magnetic flux in a circuit produces electromotive force (voltage):

$$e = -\frac{d\Phi}{dt}$$

If the circuit is closed, the electromotive force produces an electric current that can be measured using a galvanometer. The minus sign indicates that the induced current is opposed to the variation of the excitation flux and thus, so to speak, to the change in its initial state. This principle is known as *Lenz's law*.

When a mobile frame rotates in a magnet field, the magnetic flux passing through the frame surface varies and the induced electromotive force periodically changes sign. If we connect to the frame a consumer device by a slip ring (made of two brushes connected to the rings welded to the frame), we obtain **an electric current that periodically changes direction** in the circuit. **This is alternating current.**

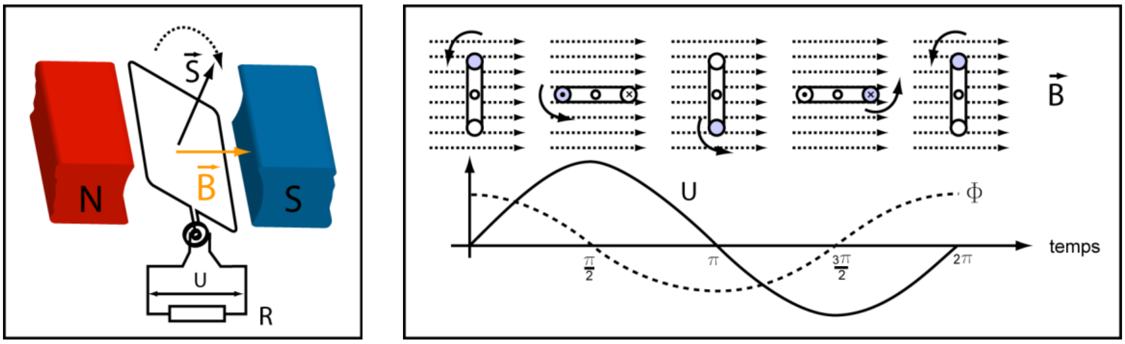


Figure A7:* Operating principle of the electric generator. The rotation of the mobile frame produces a variation of the surface the magnetic field passes trough, therefore a variation of the flux Φ, which induces an electromotive force U in the circuit. By connecting to the frame a consumer device R the circuit is closed and an alternating current arise in the circuit (© Ilarion Pavel).*

41. A parallel can be drawn with the flow of liquid. The speed flux across a surface is the flow rate, i.e. the volume of liquid that flows across the surface per time unit. Only the perpendicular component on the surface contributes to the flow.

The frame area crossed by the magnetic field B is proportional to the cosine of the angle formed B and the normal to the surface S.[42] If the frame rotates at a uniform angular velocity ω, the flux is expressed as:

$$\Phi = \Phi_0 \cos(\omega t)$$

where Φ_0 is the maximum flux crossing the surface (when the latter is perpendicular to the field). Applying the law of induction gives the expression of the induced electromotive force:

$$U = U_o \sin(\omega t)$$

where U_0 is the maximum voltage. If a consumer circuit is connected to the generator, an electric current passes through the circuit. In general, depending on the type of consumer, the current is not in phase with the voltage, but is shifted by a phase φ, which is called phase shift:

$$I = I_o \sin(\omega t - \varphi)$$

For a pure resistance, the phase shift is 0; for an ideal coil (without losses), it is π/2; and for an ideal capacitor, it is −π/2. In a regular circuit, the phrase shift is generally non-zero. The power dissipation in a consumer is given by the product of the voltage and the current:

$$P = U\,I = U_0 I_0 \sin(\omega t)\sin(\omega t - \varphi) = \frac{1}{2}U_0 I_0 \cos\varphi - \frac{1}{2}U_0 I_0 \cos(2\omega t - \varphi)$$

By developing the product of the sine functions, the expression can be written as the sum of the two terms: one is constant and represents the average power, the other is variable in time and oscillates with double angular frequency a.

It is convenient to use the root mean squares (RMS) as effective values:

$$U_{eff} = \frac{U_0}{\sqrt{2}}\ ; \quad I_{eff} = \frac{I_0}{\sqrt{2}}$$

Thus the average power dissipation in a consumer is written as:

$$P = \frac{1}{2}U_0 I_0 \cos\varphi = U_{eff} I_{eff} \cos\varphi$$

42. The use of rotating systems with constant angular velocity to generate alternating current implies that the signal form is a sine or cosine trigonometrical function.

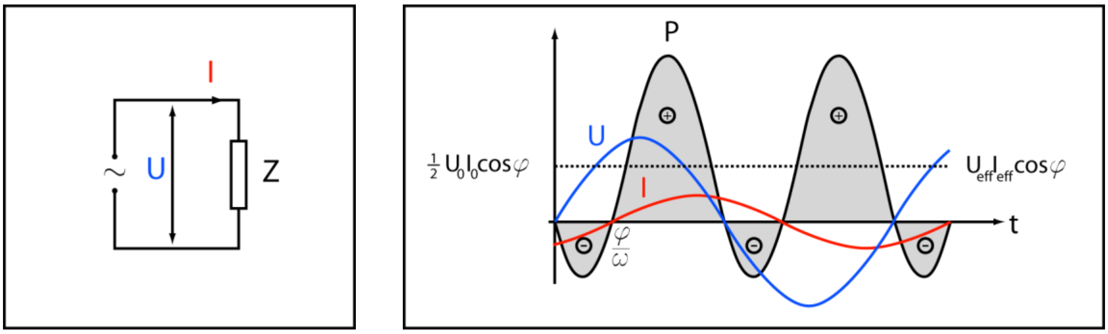


***Figure A8:* AC power**. *An AC voltage U applied to the impedance Z produces an alternating current I through the circuit, generally shifted by a phase φ. The power dissipation oscillates with a double angular frequency (2ω) around the average value of* $U_{eff} I_{eff} \cos \varphi$*. If the impedance Z is not purely resistive, during some time intervals the power dissipation is negative: the consumer returns the power to the source (© Ilarion Pavel).*

The RMS voltage U_{eff} is defined as the voltage of a DC that would produce the same heat dissipation in a resistor as an AC with a maximum voltage U_0.

This equipment is the reverse of the electric motor presented in the previous section and lays at the base of the electric generator, a device that converts the mechanical energy of rotation into electrical energy.

AC GENERATOR

To obtain higher voltage, the rectangular frame should be replaced by a coil. Passing a high voltage through a slip ring would produce sparks and disturbances, it is therefore preferable to keep the coil fixed and to rotate the magnetic field.

The electric generator is thus formed of a mobile part, the rotor, and an immobile part, the stator. The stator is made of a iron core attached to a pair of coils; the rotor is an electromagnet powered by a DC source[43] connected to a slip ring.[44]

[43] Some of the current produced by the generator can be transformed into direct current and then injected in the rotor coil. Otherwise an external DC electric generator can be used, mechanically coupled to the rotor axis.

[44] The electromagnet's supply voltage is much weaker than the voltage produced by the generator coil. As a consequence, wear and tear and disturbances provoked by the contact between the brushes and rings are far less pronounced than was the case in the demonstrative appliance presented in the previous section.

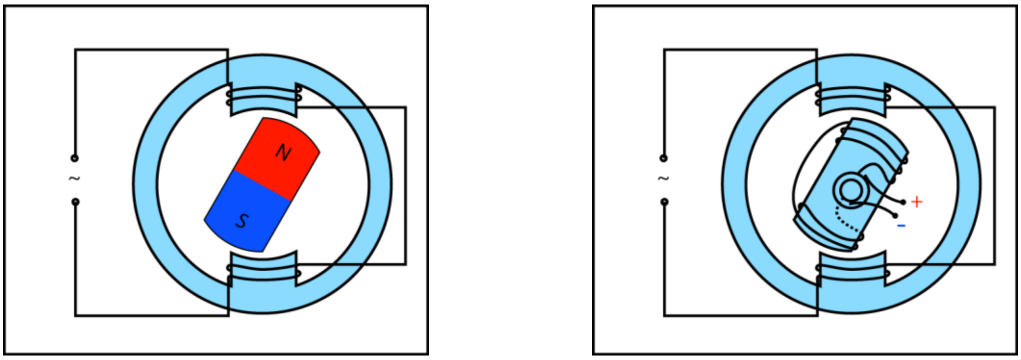


***Figure A9:* Electric generator**. *When a magnet rotates around a pair of coils connected in series, its variable magnetic flux induces an alternative electromotive force in the coils (left-hand figure). In practice, the permanent magnet is replaced by an electromagnet, since the electromagnet produces a much more powerful magnetic field (right-hand figure). It is supplied by a DC source by a slip ring made of brushes which slide on the rings (© Ilarion Pavel).*

To produce an alternating current of 50 Hz, used in electricity networks in Europe, the electromagnet must rotate at the same frequency, which is feasible if the electromagnet is driven by a steam turbine but not possible using a hydraulic turbine (steam achieves flow velocities far superior to water). One solution consists in building multipolar generators: by equipping the stator with N equidistant pairs of coils connected in series, instead of one coil, the rotor velocity could be decreased by a factor N while the induced current retains the same frequency. This type of generator is therefore used in hydroelectric power plants. Figure A10 shows a bipolar electric generator (N=2).

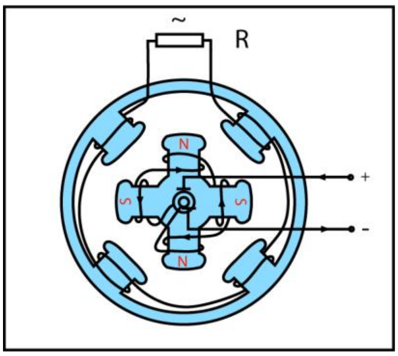
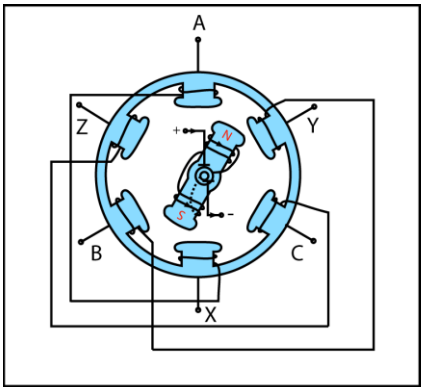


***Figure A10:* Bipolar electric generator**. *The rotor (in the centre), made of an electromagnet with two pairs of coils, induces a voltage in the stator's two pairs of series-connected coils. As a half-rotation of the rotor is enough for the alternating current to complete a full period, the frequency of the AC is thus double that of the rotor (© Ilarion Pavel).*

THE THREE-PHASE GENERATOR

In real life, a three-phase system is used to transmit electricity over distances because it is more economical than a monophase system. A three-phase electric-generator stator is made of three pairs of identical coils staggered at 120°; the rotor is consists of a single coil. The voltages induced in the three coils, known as phase voltages, are phase-shifted of 120° (2π/3 radians):

$$U_{AX} = U_0 \sin(\omega t), \quad U_{BY} = U_0 \sin(\omega t - \frac{2\pi}{3}), \quad U_{CZ} = U_0 \sin(\omega t - \frac{4\pi}{3})$$



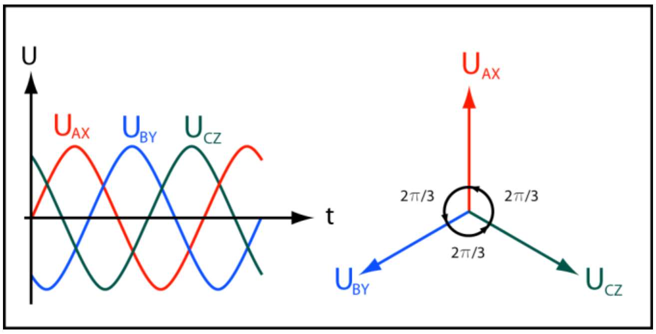


***Figure A11:* Three-phase generator**. *The stator is made out of three pairs of series-connected coils aligned in two by two (A-X, B-Y, C-Z). The rotor (in the centre) induces electromotive forces in the coils, known as phase voltages. These are phase-shifted of 120° (or 2π/3 radians). Their time variation and phase diagram are shown on the right (© Ilarion Pavel).*

In reality, it is not standard practice to use six conductors to transport the electricity produced by the three pairs of coils. Instead, they are either connected in a star or triangle configuration.

In a star connection, the coils' end windings (X, Y and Z) are connected to what we call a neutral point. The start windings (A, B, C) and the neutral conductor are connected to four power lines, which transmit the electricity to three consumer devices, which are also connected in a star (or triangle) configuration.

The currents in the power lines are equal to those in the coils, and are called phase currents. Generally speaking, the impedances of the consumer devices are identical (balanced network), and the three-phase currents are thus equal in module and phase-shifted by 2π/3. Their sum total, which is equal to the neutral conductor's intensity, is thus zero. It is therefore possible to dispense with the neutral conductor, which in practice is connected to the ground.

The voltage between the two lines, on the other hand, called line voltage, is given by the vector sum of two phase voltages, for example $U_{AB} = U_{AX} + U_{YB}$. Its modulus is thus equal to $\sqrt{3}$ times the phase voltage. To conclude, then, for the star connection, $U_{line} = \sqrt{3}U$; $I_{line} = I$.

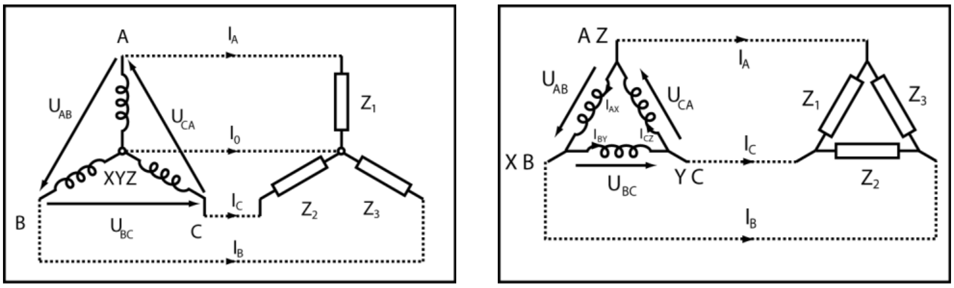


Figure A12:* Star** *(left)* **and triangle** *(right)* **connections. The consumer is represented by the impedances Z_1, Z_2 et Z_3 ; the dotted lines represent the transmission lines (© Ilarion Pavel)*

In a triangle connection, all the coils are connected in series by joining the end windings of one coil to the start windings of the next one (X and B, Y and C, Z and A). This gives three points that can be connected to three conductors to create a transmission system. This time, however, the line voltages are equal to the phase voltages. The line current, on the other hand, is given by the vector sum at two phase currents, for example $I_A = I_{XA} + I_{CZ}$. Its modulus is thus equal to $\sqrt{3}$ times the phase current. In conclusion, for the triangle connection, $U_{line} = U$; $I_{line} = \sqrt{3}I$.

In a balanced network, the phase currents passing through the generator coils are given by the following expressions:

$$I_{AX} = I_0 \sin(\omega t - \varphi), \quad I_{BY} = I_0 \sin(\omega t - \varphi - \frac{2\pi}{3}), \quad I_{CZ} = I_0 \sin(\omega t - \varphi - \frac{4\pi}{3})$$

The instantaneous power generated is therefore the sum of the products of the phase voltages and currents $P = U_{AX} I_{AX} + U_{BY} I_{BY} + U_{CZ} I_{CZ}$, i.e.:

$$P = U_0 I_0 [\sin(\omega t)\sin(\omega t - \varphi) + \sin(\omega t - \frac{2\pi}{3})\sin(\omega t - \varphi - \frac{2\pi}{3}) + \sin(\omega t - \frac{4\pi}{3})\sin(\omega t - \varphi - \frac{4\pi}{3})]$$

and, by developing each product of the sine functions:

$$P = \frac{3}{2} U_0 I_0 \cos\varphi - \frac{1}{2} U_0 I_0 [\cos(2\omega t - \varphi) + \cos(2\omega t - \varphi - \frac{4\pi}{3}) + \cos(2\omega t - \frac{8\pi}{3})]$$

In the second term, the sum of three cosine functions is zero (since each is phase-shifted by 2π/3 in relation to the others). By using the phase voltages and currents' effective expressions (RMS), the instantaneous power is thus written:

$$P = 3U_{eff} I_{eff} \cos\varphi$$

Unlike in monophase networks, instantaneous power in a balanced three-phase network is not dependent on time, which is very importance in real-life scenarios. Because three-phase generators and motors produce and consume electricity in a uniform manner, they do not vibrate, unlike monophase equivalents.

A three-phase network is also more economical than a monophase network in terms of the cable infrastructure deployed to transmit the electricity. By replacing the values of the phase voltages and currents by the line value, the expression of the transmitted electrical power, whether in a star or triangle network, is:

$$P = \sqrt{3}\, U_{line} I_{line} \cos\varphi$$

Thus the line losses in the three cables, due to their electrical resistance R, are expressed as:

$$3RI_{line}^2 = R\frac{P^2}{U_{line}^2}\frac{1}{\cos^2\varphi}$$

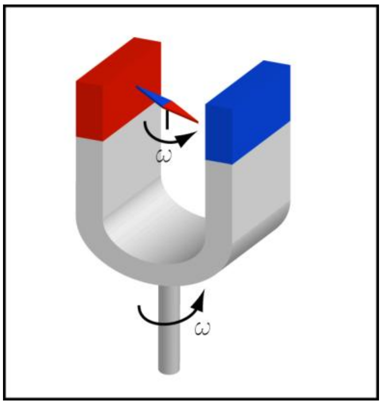
If the same power is transmitted by two cables in a monophase system, **with the same line voltage and phase shift**, the losses are expressed by the relationship:

$$2RI_{line}^2 = 2R\frac{P^2}{U_{line}^2}\frac{1}{\cos^2\varphi}$$

The losses are thus doubled in the monophase network. In other words, a three-phase network can be equipped with cables twice the electrical resistance of those used in a monophase system, while the line losses remain the same. They will be thinner since the electrical resistance is inversely proportional to the cable section. As a result, the weight of the three cables needed to build the lines in the three-phase network is three quarters that of the two cables used in the monophase network.

SYNCHRONOUS MOTOR

If a permanent horse-shoe shaped magnet is rotated upright on its axis of symmetry, it produces a rotating magnetic field on the horizontal plane of the two poles. A compass placed in this field will continuously orientate itself within the magnetic field, and will turn at the same speed as the permanent magnet.



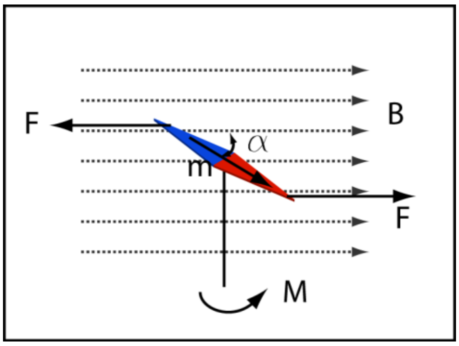


***Figure A13:* The rotating field**. *The compass needle is oriented by the magnet field. If the magnet rotates with an angular velocity ω the compass needle will turn at the same angular velocity (left-hand figure). The direction of the compass magnetic moment m makes an angle α with the magnetic field B and this creates a torque M. The torque tends to align the compass with the magnetic field (right-hand figure) (© Ilarion Pavel).*

This device is the basis of synchronous motors: **all that is needed is to couple the compass axis to make the mechanical system rotate**. In this case, the load (consumer of the mechanical energy supplied by the motor) produces a resistant torque opposing the rotation and the compass continues to turn but is no longer aligned with the rotating magnetic field.

Actually, if a compass of magnetic moment *m* makes an angle α with the magnetic field B, a torque arises:

$$M = mB\sin\alpha$$

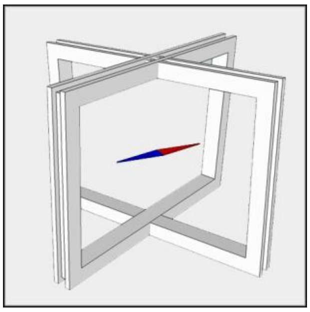
and is balancing out the resistant torque. If the resistant torque increases, the angle also increases but the rotation speed remains constant:[45] this is why it is called a *synchronous* motor.

45. However, the resistant torque must remain below a critical value (for which the angle reaches 90°), otherwise the rotating magnetic field will not drive the compass any more and the functioning becomes unstable.

To achieve rotating magnetic fields, static systems are preferred. Two frame coils, their surfaces perpendicular to their common vertical axis of symmetry, are supplied by two $\pi/2$ phase-shifted alternating currents. In the center, the two perpendicular components of the magnetic field are:

$$B_x = B_0 \cos(\omega t)\,; B_y = B_0 \cos(\omega t - \frac{\pi}{2}) = B_0 \sin(\omega t)$$

These are exactly the components of a rotating magnetic field of angular frequency *ω.*[46]



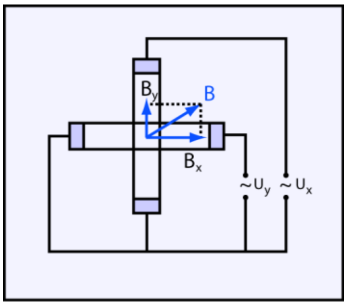
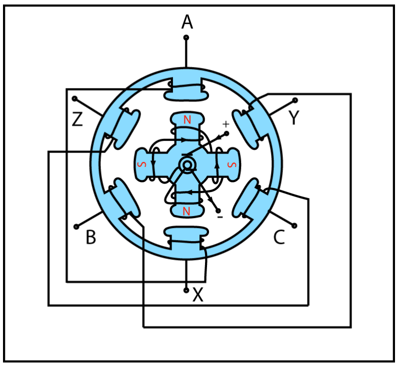


Figure A14:* Rotating field and alternating current. Two perpendicular frame coils, traversed by two alternating currents phase-shifted by π/2, produce a rotating magnetic field (© Ilarion Pavel).*

In industrial applications, the frames are replaced by coils wound around iron cores and capable of producing more powerful magnetic fields. For the same reason, the permanent magnet (the compass) is replaced by an electromagnet, powered by a DC voltage source connected to a slip ring.

Lastly, a three-phase system is preferable to a two-phase rotating field system: a three-phase system consists of three pairs of coils staggered at 120° and powered by a three-phase electricity network. This is the three-phase synchronous motor, and it is almost identical to the three-phase generator outlined above. Indeed, it is a reversible electrical machine that can operate either as a motor or as a generator. A three-phase motor can be connected to a three-phase generator by star or triangle connections. Their roles can be easily reversed depending on the load.

46. The projections on two perpendicular axes of a rotating vector of constant angular velocity naturally lead to sine and cosine functions. Reciprocally, adding the sine and cosine time varying components on the two axes gives a rotating vector of constant angular velocity.



***<u>Figure A15:</u> Three-phase bipolar synchronous electric motor**. The stator has the three pairs of coils staggered at 120° that are characteristic of three-phase systems, and which can be connected in a star or triangle configuration to the electric network. The bipolar rotor (in the centre), formed out of two pairs of coils positioned at right angles, is DC-powered via a slip ring. This motor therefore resembles the three-phase synchronous generator (Figure A11), the two machines being reversible (© Ilarion Pavel).*

The advantage of the synchronous motor is that it rotates at a constant speed regardless of its load, certain operational limits notwithstanding. Its disadvantages include a complicated start-up process (the motor has to be driven by an auxiliary motor to attain the synchronisation rotation speed), and a risk of instability if the resistant torque exceeds the critical value.

Low-power synchronous motors can be used when a constant rotation speed is necessary, such as in electric clocks, production line conveyor belts, and motors used in industrial robots. High-power motors are used for mechanical traction, particularly in high-speed trains. Lastly, the reversibility of the motors makes them particularly useful for mixed usages in hydraulic dams: in normal operating mode, the motor functions as an electric generator, but when there is a surplus of electric energy it commutes into motor mode and pumps the water upstream to fill up the dam, thus storing the energy.

Asynchronous motor

Some of the synchronous motor's disadvantages, mentioned above, are mitigated by the asynchronous motor, which was also patented by Tesla.[47] Both motors remain complementary in their uses.

To return to the experimental example presented in the section on the synchronous motor, if the compass is replaced by a closed loop free to turn on a vertical axis, this will create an asynchronous motor.

47. U.S. Patent 0,382,279 - *Electro magnetic motor* - 30 November 1887.

According to the principle of induction, the rotating magnetic field produces an electromotive force in the loop. Therefore an electric current arises in this loop, interacts with the field and generates a torque that aligns the loop perpendicularly to the field. As a result, the loop rotates on its vertical axis, but a lower angular velocity than the rotating field (hence the name *asynchronous*), whose value is determined by the resistant torque produced in the motor shaft by the load.

The difference between the field rotation speed and the loop rotation speed determines the variation of the excitation flux, therefore the induced current and lastly the value of the torque. When the load is very small, the resistant torque is almost zero, the field rotation speed is almost equal to the loop rotation speed – and the motor is almost synchronous. As the mechanical load is increased, the resistant torque increases, the loop slows down, and the difference between the two rotation speeds increases. Therefore the flux variation increases, hence the electromotive force and the induced current too. In consequence, the torque increases until it equals the load and the speed of the loop stabilises.

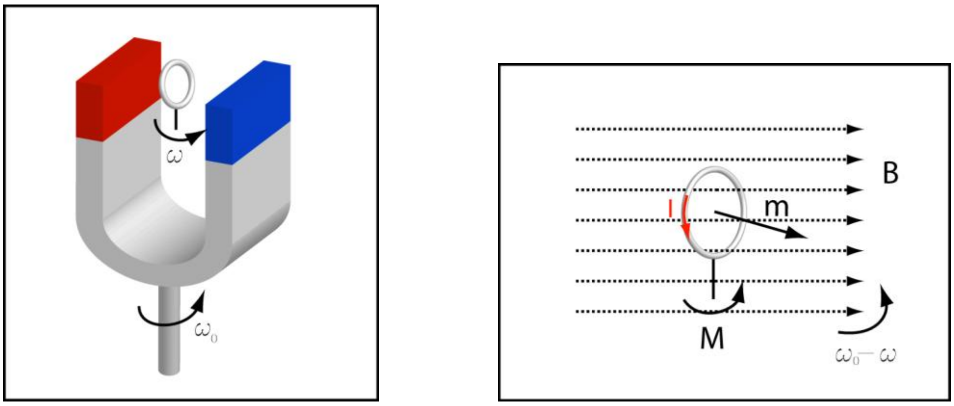
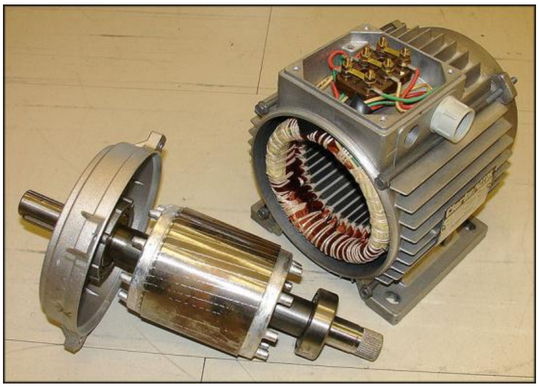


Figure A16:* Operating principle of the asynchronous motor. The magnetic field B rotates at an angular velocity ω_0, the loop turn at a lower speed, ω. In the reference system of the loop, the magnetic field thus turns at a speed of ω_0-ω, the magnetic flux variation induces an electric current I, and thus a magnetic moment m, which interacts with B to give the torque M, which counterbalances the resistant torque of the load (© Ilarion Pavel).*

In practice, the rotating magnetic field is created by a system of coils analogous to that of the synchronous motor. The rotor, on the other hand, is made our of several rectangular frames equally spaced around a common rotating axis and connected together in short circuit, in a geometric configuration known as a *squirrel's cage*.



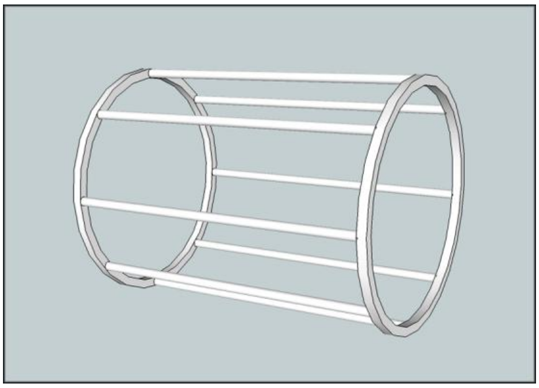


***Figure A17:* Asynchronous electric motor**. *This illustration shows the stator coils and their electric connections as well as the short-circuit end-rings in a squirrel-cage rotor, all of which are represented schematically in the right-hand figure (Wikipédia illustrations).*

Unlike the synchronous motor, the asynchronous motor can be started up easily and without using other equipment. It can be adapted to different loads and is therefore widely used to drive machine-tools, household appliances and electric vehicles. It does not require a slip-ring mechanical contact system, which makes it reliable and long-lasting.

The asynchronous motor is also used to start up high-power synchronous motors. The latter are mixed motors, containing both the coils specific to a synchronous operating mode but also the squirrel's cage, specific to the asynchronous operating mode. The motor starts up in asynchronous mode and continues thus until its rotation speed synchronises with the current frequency, after which it switches to synchronous mode by coupling the coils' power supply. At synchronous speed, the squirrel's cage turns at the same speed as the rotating magnetic field, so the induced current passing through the cage is zero and therefore does not disturb the functioning of the synchronous motor.

THE ELECTRIC TRANSFORMER

The electric transformer was designed to transmit electricity over long distances with minimal losses.

According to Ohm's law, when an electric cable of resistance R is traversed by a current I, the voltage loss in the cable is equal to the product RxI. The power loss, dissipated as heat (Joule-Lenz law), is given by the product of the voltage and the current; it is therefore equal to the product RI^2. Therefore the weaker the current, the higher the efficiency. For a given electrical power to transport (UxI), the weaker the current the higher the voltage.[48]

The electricity produced by hydroelectric, coal and nuclear power plants, whose voltage is around one kilovolt, is step up by a transformer into high-voltage electricity of several hundred kilovolts. The electricity is then transported by high-voltage power line and, when it reaches the consumer, it is step-down into low-voltage electricity (220 V), less dangerous for users.

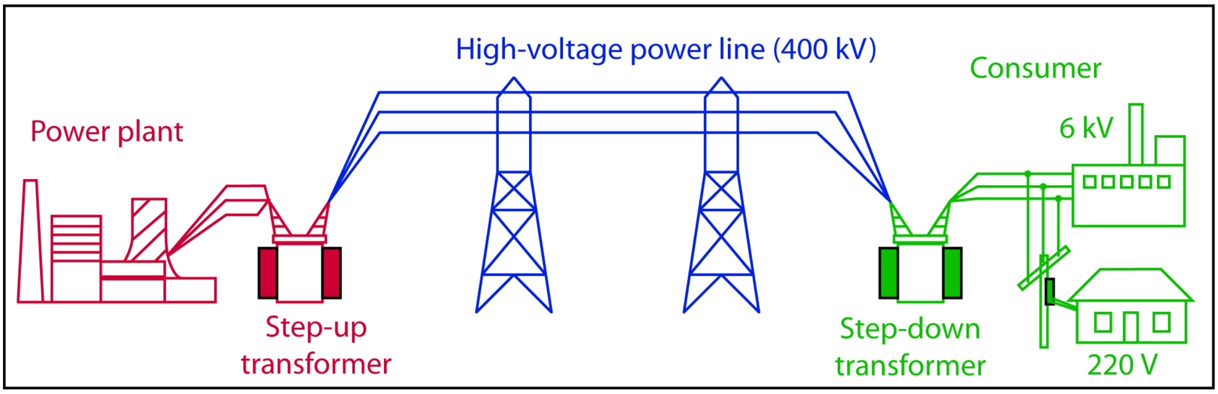


***Figure A18:* The transportation of electricity** *(© Ilarion Pavel).*

The transformer is made of two copper-wire coils, one primary and one secondary, wound around an iron core. The AC supplying the primary coil generates a variable magnetic field, which is transmitted trough the iron core's magnetic field and induces a voltage in the secondary coil. The magnetic flux produced by the primary coil is proportional to the number of turns in the primary coil; the voltage induced in the secondary coil is proportional to the number of turns in the secondary coil. Thus the ratio between the primary and secondary coils voltages is equal to that between the number of turns in the two coils:[49]

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Depending on the number of turns chosen to construct the coils, transformer can be built to either raise or lower voltage.

48. Due to the quadratic dependence, multiplying the voltage by 20 reduces the losses by 400.
49. In the first instance, the ohmic losses, which are due to the electric resistance of the coils and magnetic losses in the iron core, can be discounted.

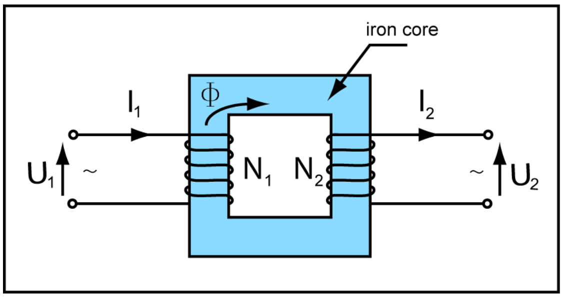


***Figure A19:* The transformer**. *The AC voltage U_1 supplies the primary coil (N_1 turns) and produces a variable magnetic flux Φ in the iron core, which induces a voltage U_2 in the secondary coil (N_2 turns) (© Ilarion Pavel).*

Since it contains no mobile parts, and therefore no losses due to mechanical friction, the transformer is much more efficient that electric motors or generators, sometimes reaching 99% efficiency. With a good approximation we consider that the power injected into the primary coil equals the power in the secondary:

$$U_1 \times I_1 = U_2 \times I_2$$

thereby completing the previously mentioned relationship:

$$\frac{U_1}{U_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

The transformer is also used to supply electronic appliances such as television sets, radios, computers, DVDs, in order to lower the mains voltage from 220 V to a dozen volts, i.e. the voltage at which electronic circuits operate.

■