

## Small electric motors III

*In this last issue of our group of three on small electric motors [1] we give pride of place to an article on the early history of the electric motor, from Oersted's discovery of the movement of a magnetic needle in the neighbourhood of a current-carrying conductor until about the year 1900, by which time various types of electric motor were already in industrial production. This issue also includes a treatment of the optimum dimensioning of a small d.c. commutator motor; the results lead to dimensional ratios that are different from those usually*

*encountered. Next, there is a theoretical treatment of the brushless d.c. motor; the author shows how to construct diagrams from which some of the important characteristics of the motor can be read off directly. The issue concludes with a comparison of the various types of motor with particular reference to running costs; by using figures of merit and their dependence on the dimensions it can be shown that in general terms some types are more suitable as small motors, whereas others are more suitable as motors of larger dimensions.*

## The early history of the electric motor

Brian Bowers

The modern electric motor is the product of a century and a half of development. In this article the early stages of that development are followed from the first ideas for producing motion by electric action up to the point where the main kinds of motor had been conceived and put into production.

The first section deals with the very early period, and the second describes some of the many 'electromagnetic engines' made between 1832 and 1860. The third section considers some of the ideas which lay behind these machines. The fourth section shows how the practical d.c. motor evolved not from the electromagnetic engine but from the electric generator. The final section is concerned with alternating-current machines, which had to be invented when electricity-supply companies adopted alternating-current systems.

### Motion produced by electricity

A continuous electric current, as opposed to a spark or static charge, became available in 1800 as a result of the work of the Italian Alessandro Volta. Volta was following up the work of his fellow countryman,

Galvani, who had shown in 1786 that the muscle in the leg of a dead frog could be made to convulse by touching it with two dissimilar metals. Galvani thought that the source of the action was in the muscle; Volta thought it was at the junction of the two dissimilar metals. Volta wrote a letter from Italy to Sir Joseph Banks, the President of the Royal Society of London, in which he announced his 'Pile' and his 'Crown of Cups'. Volta's pile consisted of a stack of pairs of silver and zinc discs, each pair being separated by paper or cloth spacers soaked in salt water. The crown of cups consisted of a number of cups arranged in a circle and each filled with salt water into which strips of copper and zinc were dipped. Volta's discovery aroused great interest, and in November 1801 he demonstrated it before an assembly of scientists in Paris. Napoleon Bonaparte was present, and he decided to establish prizes to encourage new research on 'galvanism', as it was called, and remarked 'Galvanism, in my opinion, will lead to great discoveries' [1] [\*\*].

Among the scientists who studied galvanism, or current electricity, was the Dane H. C. Oersted. In July 1820 he published a four-page paper in Latin announ-

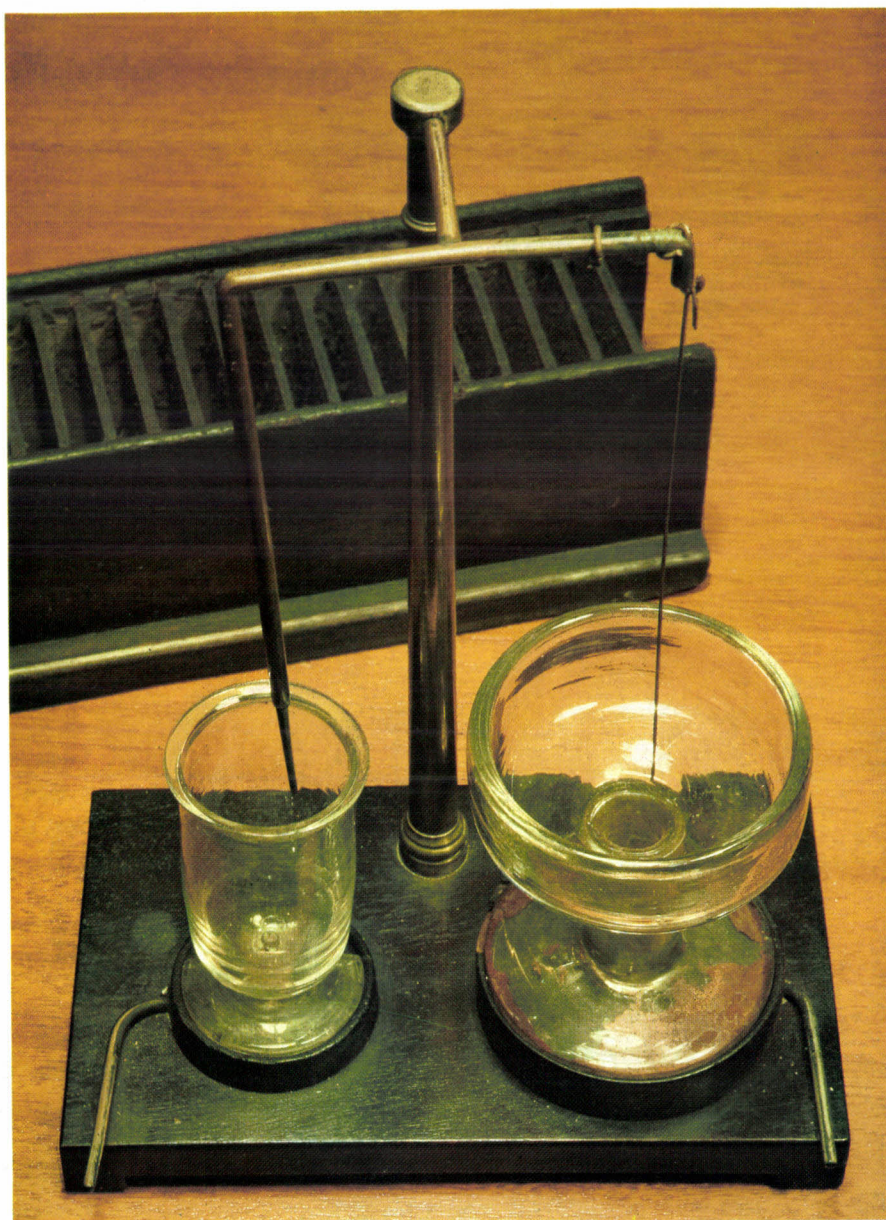
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[\*] The previous issues were Volume 33, No. 8/9, 1973, and 34, No. 7, 1974.

[\*\*] The references are listed at the end of the article.

cing his discovery that an electric current in a wire could cause a compass needle nearby to be deflected [2]. Oersted's discovery created great interest because it established for the first time a connection between

a magnetic needle were damped if a metal plate was nearby. Arago constructed a device in which a copper disc was mounted on a vertical spindle and rotated beneath a pivoted magnetic needle. He found that the



**Fig. 1.** The apparatus used by Faraday in 1821 to demonstrate 'electromagnetic rotation'. The two basins were filled with mercury; in the left-hand one a bar magnet floated vertically, with the lower end freely attached to the bottom of the basin. When a current flowed, the upper end of the magnet described circles around the fixed electrode dipping into the mercury. In the right-hand basin a bar magnet was fixed to the bottom. The loose wire dipped into the mercury and described circles around the upper end of the magnet when a current was passed. A wooden battery trough, divided into cells, can be seen behind the apparatus. (Photo Royal Institution, London.)

electricity and magnetism. Its significance in the history of the electric motor is that it was the first production of mechanical motion by an electric current.

Oersted's discovery was studied further by the French physicist Arago. He had noticed that the oscillations of

needle also rotated, albeit at a lower speed, in the same direction as the disc. The device has since been known as 'Arago's disc' [3].

The English scientist Michael Faraday, then only the little-known assistant to Sir Humphry Davy, took up the

subject of electromagnetism in the summer of 1821. He had been invited to write an historical account of electromagnetism for the *Annals of Philosophy* edited by his friend Phillips. With his usual thoroughness Faraday repeated all the important experiments of other scientists while writing his account. As he studied the subject he became convinced that it ought to be possible to produce continuous circular movement by making use of the circular magnetic force around a wire carrying a current. In September 1821 he found how to do it; he made two devices, which were really the first electric motors, to show 'electromagnetic rotation'. In the first he fixed a bar magnet vertically in a basin with a blob of wax. The basin was then nearly filled with mercury and a wire with a cork on its end was loosely fixed to a point above the basin. A battery was connected between the first wire and another wire connected to the mercury, and the first wire moved in a circular path round the magnet. 'Very satisfactory', wrote Faraday in his notebook. In the second arrangement the magnet was fixed at the bottom of the basin but the upper end was free to move. The wire from above was fixed, dipping into the middle of the mercury. With this arrangement the upper end of the magnet moved in circles around the fixed wire. Faraday then had a special demonstration apparatus made which combined the rotating wire arrangement and the rotating magnet (*fig. 1*), and he published an article on electromagnetic rotations in October 1821. The apparatus was copied and the experiments repeated all over Europe [4].

Peter Barlow, who lectured at the Woolwich Academy, repeated Faraday's rotation experiment and then replaced the rotating wire with a star-shaped wheel rotating between the poles of a horseshoe magnet. The wheel dipped into mercury maintaining continuous contact and when a current flowed between the axis of the wheel and the mercury then the wheel rotated (*fig. 2*) [5].

Faraday's electromagnetic-rotation device and Barlow's wheel both demonstrated that it was possible to produce continuous motion by electrical means, but they had the fundamental limitation that only a single current-carrying conductor was passing through the magnetic field. Barlow's wheel was basically the same machine as Faraday's disc generator, although that was not made until 1831.

The critical advance necessary before electrical machines — motors or generators — could progress further was first made in a generator. This was the concept of making a coil of wire pass through the magnetic field, rather than a single conductor. In 1832 the French instrument maker Hippolyte Pixii made a generator (though he did not call it that) in which there was relative rotation between a permanent magnet and

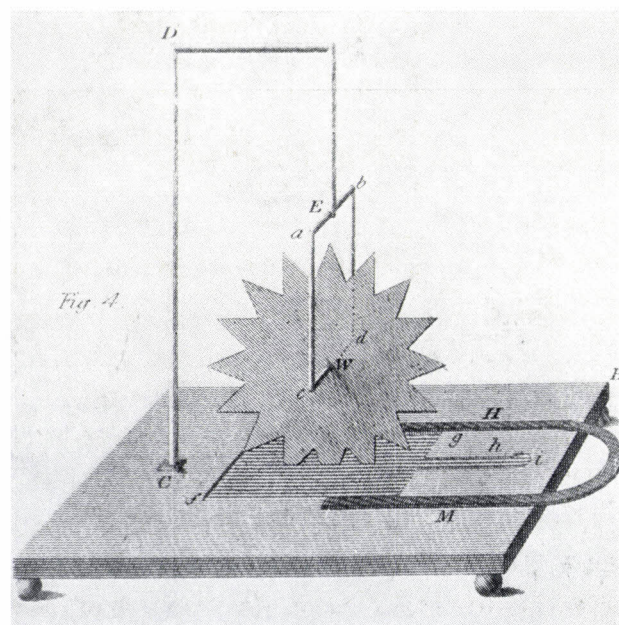
a coil of wire, and a crude, cam-operated reversing switch performed the function of a commutator and provided a direct-current output (*fig. 3*).

The way was then clear for the development of early forms of motor, or 'electromagnetic engines', and many were made during the 1830s. One suggestion from the 1820s is worth mentioning, however: in 1824 the *Mechanics' Magazine* described a device to show the 'mechanical Effects of Electricity' [6]. A light wheel with vanes cut out of paper was mounted on an axle beneath two point electrodes in such a way that the vanes could move in the space between the electrodes from one electrode to the other. When an electric discharge from a frictional electric machine or a Leyden jar was passed between the electrodes then the wheel turned, with the vanes moving from the positive to the negative electrode (*fig. 4*).

### Electromagnetic engines

The first person to appreciate that electromagnetism might be used to provide mechanical power was probably the American Joseph Henry.

Electromagnets were studied by several people, one of the first being Sturgeon in England. Gerard Moll, Professor of Natural Philosophy in the University of Utrecht, was in England in 1828 and saw some of Sturgeon's experiments (*fig. 5*). Moll obtained an electromagnet and made experiments relating the weight supported by the electromagnet to the active area of zinc in the battery supplying the current. He



**Fig. 2.** Barlow's wheel. The teeth of the wheel *W* dip into mercury between the poles of a horseshoe magnet *HM*. When a current flows the wheel turns.

also tried to observe the speed with which the magnetism could be created and destroyed when the circuit was made and broken, and the rapidity with which the polarity could be reversed [7].

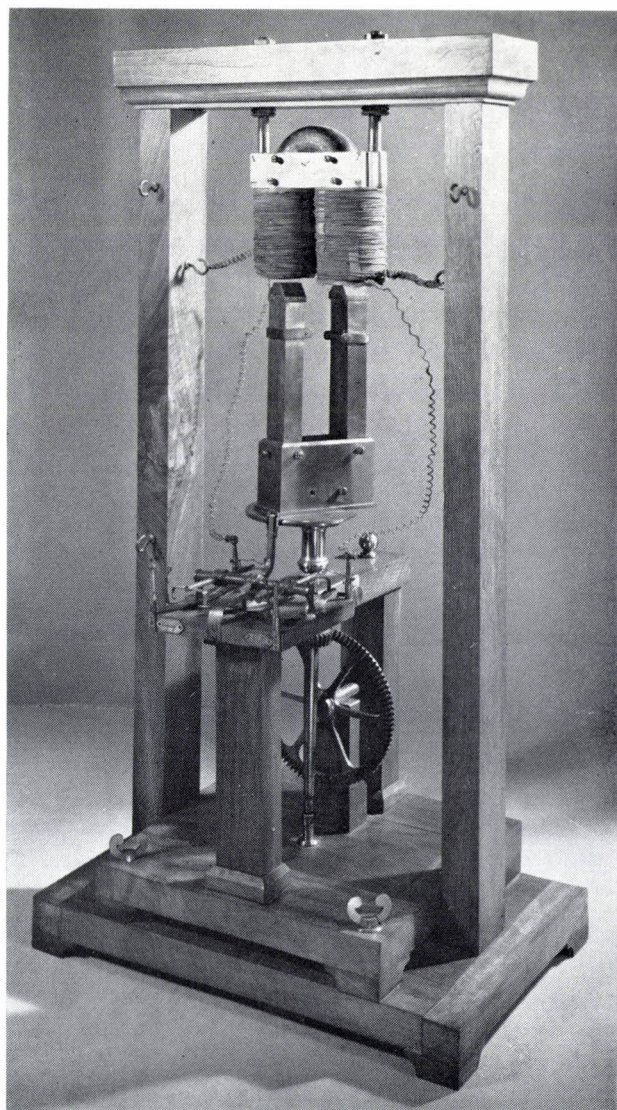
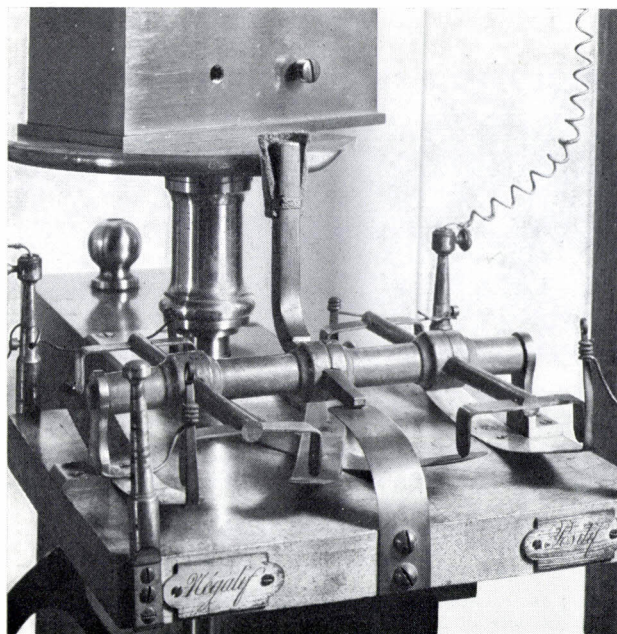
In 1830 Professor Salvatore del Negro, of Padua University in Italy, obtained rotary motion from an electric current by means of an electromagnet. A permanent magnet hanging from a pivot was attracted to the electromagnet and the electromagnet was energized through a contact which was broken when the permanent magnet moved from its rest position. In this way the permanent magnet was made to perform an oscillatory motion which was converted into rotary motion by a pawl and ratchet [8]. This has been called the first electric motor [9], but the title seems rather undeserved.

Henry made a reciprocating electric engine which he described in 1831 as follows [10]:

'I have lately succeeded in producing motion in a little machine by a power, which, I believe, has never before been applied in mechanics — by magnetic attraction and repulsion. Not much importance, however, is attached to the invention, since the article, in its present state, can only be considered a philosophical toy; although, in the progress of discovery and invention, it is not impossible that the same principle, or some modification of it on a more extended scale, may hereafter be applied to some useful purpose.'

This engine consisted of a straight electromagnet mounted horizontally and supported on knife-edges at its centre (*fig. 6*). A bar permanent magnet was placed vertically below each end of the electromagnet with the north poles facing in the same direction. The electromagnet coil was connected between two pairs of stiff wires, one pair at each end, and these wires dipped into

**Fig. 3.** Pixii's generator (1832). This was the first device in which a multi-turn coil was used to increase the electromagnetic effect. *Right:* The two bar magnets are rapidly rotated below the two coils on an iron core by the handwheel and gearing. *Below:* A cam operates a reversing switch, consisting of leaf springs, twice in each revolution, thus providing a simple commutator action. (Photos Deutsches Museum, Munich.)



## MECHANICAL EFFECT OF ELECTRICITY.

The mechanical Effects of Electricity are exhibited in its power of impelling and dispersing light bodies ; of perforating, expanding, compressing, tearing, and breaking to pieces, all conducting substances through which it is sufficiently powerful to force its passage.

If a light wheel, having its vanes made of card paper, be made to turn freely upon a centre, it will be put in motion when it is presented to an electrified point. The wheel will always move from the electrified point, whe-

ther its electricity is positive or negative. In this experiment the current seems to be produced by the recession of the similarly electrified air in contact with the point, and therefore the circumstance of the wheel turning in the same direction when the electricity is negative, cannot as Mr. Singer has remarked, be considered as any proof of the existence of a double current of the electric fluid. As an illustration take the following experiment :—

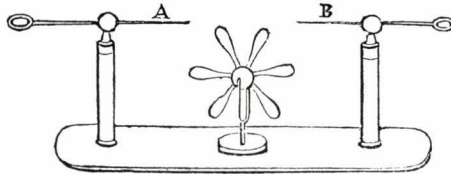


Fig. 4. Rotation of a paper wheel under the influence of an electric discharge. The vanes move from the positive to the negative electrode. (Mechanics' Magazine, 1824.)

Place upon an insulating stem a light wheel of card paper, properly suspended upon pivots, as represented in our Plate, and introduce it between the pointed wires (AB) of the universal discharger, placed exactly opposite to each other, and at the distance of little more than an inch from the upper vanes. Then having connected the wire A with the positive conductor, and the wire B with the negative conductor, of an electrical machine, the little wheel will revolve in the direction AB ; and if the wire B is connected with the positive end, and A with the negative end, the motion of the wheel will be from B to A. The transmission of a small charge through the wires, by an insulated jar, will produce the same effect.

The preceding experiment, imagined by Mr. Singer, is considered by him as a proof that there is only one electric fluid, and that it passes from the positive to the negative wire ; for, if there were two electric fluids, he concludes, "that the wheel being equally acted upon by each, will obey neither, and remain stationary."—*Chemist*.

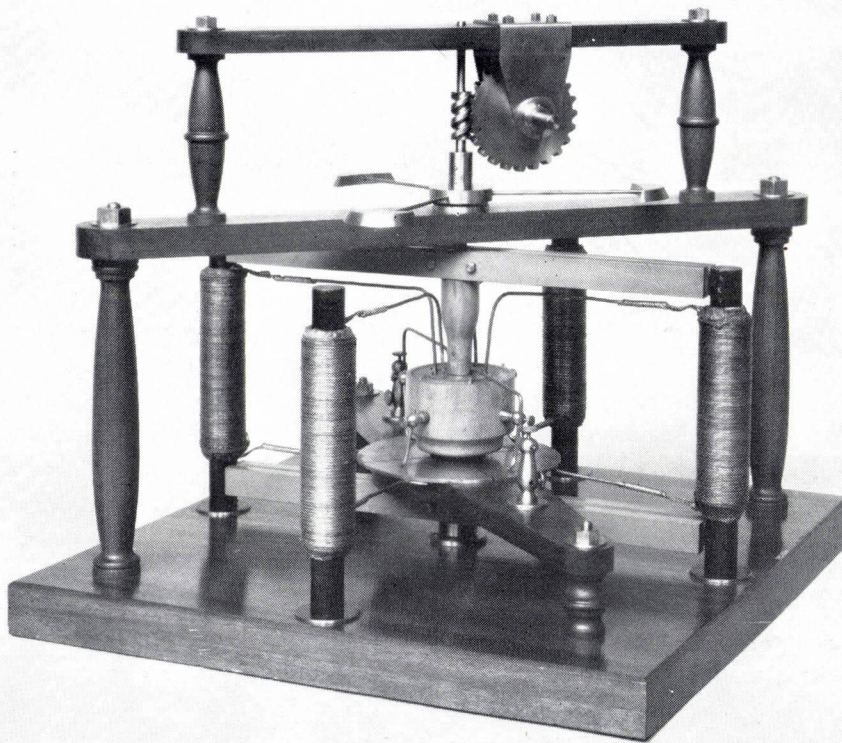


Fig. 5. Reconstruction of one of Sturgeon's motors. The rotor consists of two horizontal bar magnets, which rotate past the poles of four electromagnets. These are connected through a commutator, which consists of two concentric jars of mercury, four sliding contacts and a contact disc divided into four quadrants. (Crown Copyright. Science Museum, London.)

mercury cups when their end was down. A battery was connected to each pair of mercury cups. When one end of the bar was depressed the electromagnet was energized in such a way that the magnetic reactions between the poles of the electromagnet and those of the two

permanent magnets caused an attraction at one end of the bar and a repulsion at the other so that the bar rocked in the other direction. This movement shifted the connections of the coil from one battery to the other and the direction of current in the coil was reversed.

The forces acting on the bar were then reversed and the bar returned to its original position. In this way a reciprocating motion was established.

Henry's dipping contacts performed the function of the commutator in a conventional motor. According to Henry's own account the horizontal electromagnet was seven inches (18 cm) long and wound with three

section was connected to one pole of the battery. The ends of the electromagnet coil pointed downwards into the mercury. Initially Ritchie showed that this device would rotate in the Earth's magnetic field, but he found that it worked better when permanent field magnets were added, and he was able to raise a weight of several ounces (several tens of grams) [11].

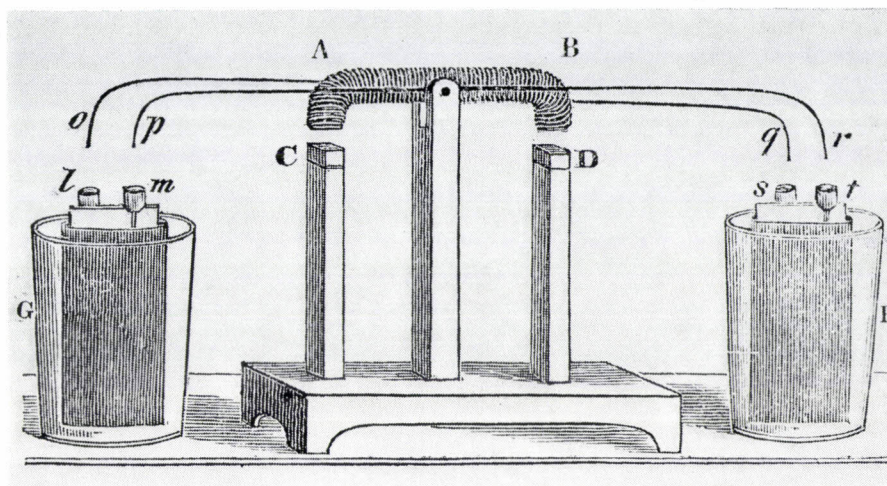


Fig. 6. Henry's reciprocating electric engine (1831). The reciprocating electromagnet *AB* is alternately connected to the batteries *F* and *G*. Attraction and repulsion between the electromagnet and the permanent magnets *C* and *D* maintain a continuous motion.

parallel strands of 'copper bell-wire' each twenty-five feet (7.5 m) long. (By 'bell-wire' Henry meant wire used for pulling mechanical bells, not of course the modern cotton-covered 'bell-wire' used for electric bells.) The machine ran uniformly at about seventy-five vibrations per minute.

In 1833 Ritchie described a rotary motor with a commutator. The Rev. William Ritchie was Professor of Natural Philosophy at the Royal Institution. His motor consisted of a straight horizontal electromagnet pivoted about a vertical axis (fig. 7). The commutator was a circular groove in the baseboard concentric with the axis and filled with mercury to above the level of the baseboard. The groove was divided into two semi-circular sections by partitions and the mercury in each

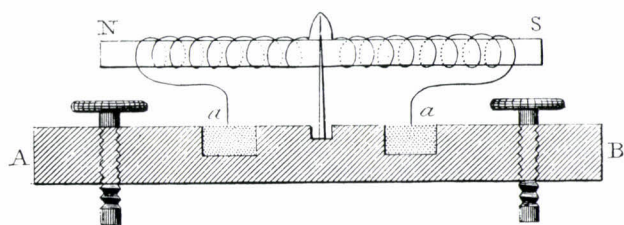


Fig. 7. Ritchie's rotary motor (1833). Current is supplied to the electromagnet *NS* through the mercury in two semi-circular grooves *a* in the baseboard. The motor would rotate in the Earth's magnetic field.

In 1835 the London instrument maker Francis Watkins designed a motor consisting of a group of stationary coils facing a bar magnet mounted on a shaft. The shaft also carried contacts which were arranged to send a succession of pulses of current from a battery to the coils at the appropriate intervals. Watkins stated that his machine was based on the generator recently made by Saxton, which suggests that he may have recognized the interchangeability of motors and generators. If he did, he did not make it very clear, and the fact that motors and generators are essentially interchangeable was not generally appreciated until much later.

Watkins wrote a paper for the Royal Society of London in which he described Henry's reciprocating engine, which he said was the first true electromagnetic motor, and some of his own machines including one which incorporated a speed-reducing gear. He illustrated some of the ways in which motors might be used as a source of power by using his machine to drive small models of hammers, pumps and dredging machines [12].

Also in 1835 Sibrandus Stratingh and his assistant Christopher Becker, an instrument maker, made an electric vehicle which ran on a table until the battery supplying it was run down. Stratingh was a doctor of medicine and a leading scientist in Groningen, Holland,

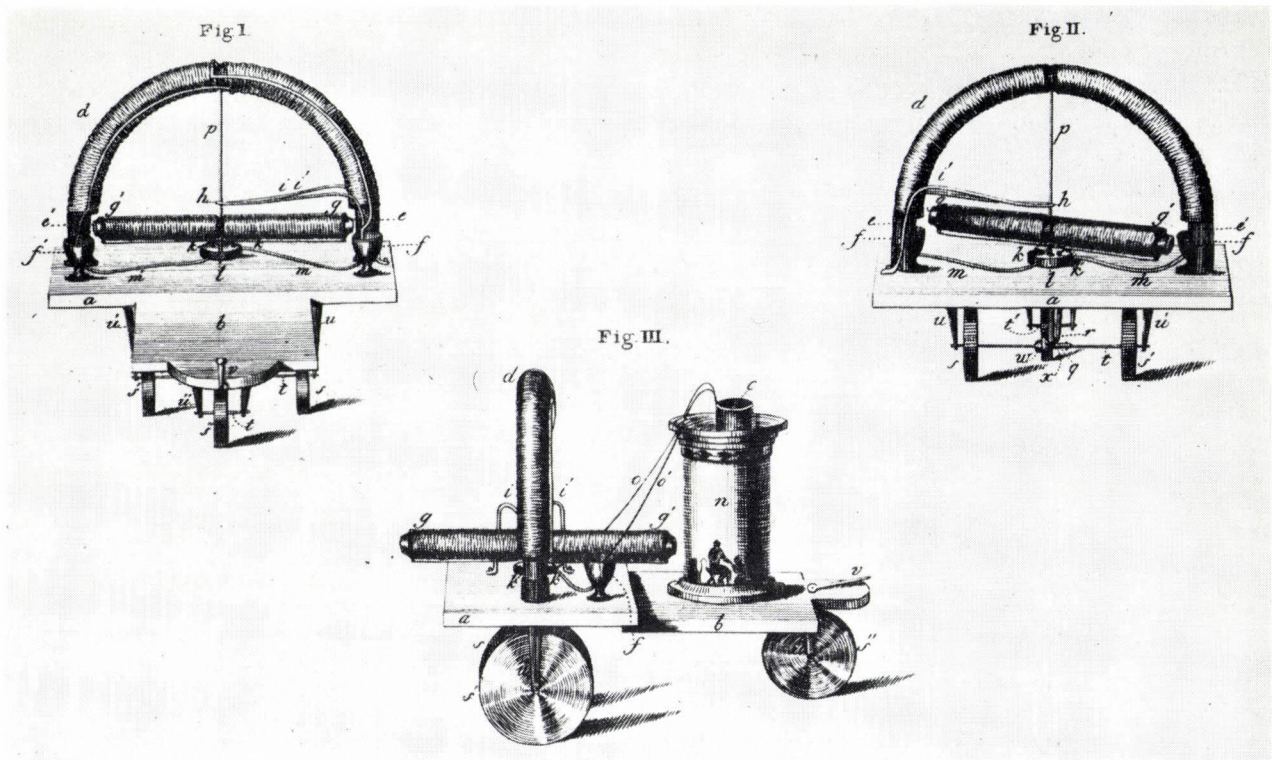


Fig. 8. Stratingh and Becker's electrically propelled model vehicle (1835). The horizontal bar magnet is the rotor; its motion is transferred to the wheels by gearing. The jar in Fig. III is a galvanic battery.

where in 1824 he became Professor of Chemistry at the University. In 1801 he is said to have driven in a steam car from Groningen to Zuidlaren, a few miles to the South. He read of the earlier work of Jacobi in Russia, and wanted to make an electric car. He never made a full-size car but is said to have had an electric boat in 1840 in which he could sail with his family.

An account of their work by Stratingh and Becker was published in Dutch in 1835, but is little known outside Holland. Their drawings (*fig. 8*) show a three-wheeled vehicle carrying a single voltaic cell and a rotating horizontal electromagnet with a commutator beneath it very like Ritchie's motor. The axis of the rotating magnet is geared to the running wheels, and the field excitation is provided by a semicircular electromagnet arranged in a vertical plane over the rotor [13].

The earliest patent for electromagnetic engines was obtained by Thomas Davenport. He had suggested using electromagnetism to produce motion in 1833, and he patented a machine in the United States of America in 1837 [14]. In the same year an English patent agent, Miles Berry, acting on behalf of Davenport, obtained a similar patent in England [15]. Davenport's patent specification gives a remarkably well developed description for the first patent in the field. The American Patent Office required a model, and that model is now in the Smithsonian Institution (*fig. 9*).

The rotor consists of four coils on a cruciform frame on a vertical shaft. Opposite coils are connected in series and there are four ends brought out below the coils as rudimentary brushes, which turn with the rotor. The fixed part of the commutator is made from two semicircular copper pieces, connected to the battery. The stator consists of two semicircular permanent magnets, with their like poles adjacent. The specification envisages the possibility of a four- (or more) pole stator, in which case the fixed part of the commutator requires correspondingly more segments. The stator magnets could be electromagnets rather than permanent ones.

Davenport was apparently a blacksmith [16] in Rutland, Vermont, though his patent agent just described him as a 'gentleman' [15]. He seems to have been the first person to use an electric motor to do useful work. In 1837 he employed a motor weighing fifty pounds (23 kg) and running at 450 revolutions per minute to drill holes a quarter of an inch (about 6 mm) in diameter in steel [17]. Davenport had great hopes for future electrical developments which he expressed thus [18]:

'I hope not to be considered an enthusiast, when I venture to predict that soon engines capable of propelling the largest machinery will be produced by the simple action of two galvanic magnets, and working with much less expense than steam!'

The two pioneers of electric motors whose names are best known today are probably Jacobi and Davidson.

The Russian professor M. H. Jacobi of St Petersburg obtained a grant from the Czar to enable him to conduct research into electric power, probably the first example of a government grant for electrical-engineering research. Although some of Jacobi's earlier work was apparently known to Stratingh in 1835, the first detailed account published in Western Europe was con-

permanent magnet on each leg. A commutating arrangement with four contact discs and four wipers periodically reversed the connections between the battery and the coils so that the rotor would move always in the same direction. When supplied through a battery of 128 Grove cells the vessel travelled at just over four kilometres per hour. Jacobi reported that the motor could provide 'a force of one horse' from a battery with twenty square feet ( $1.9 \text{ m}^2$ ) of platina <sup>[19]</sup>.

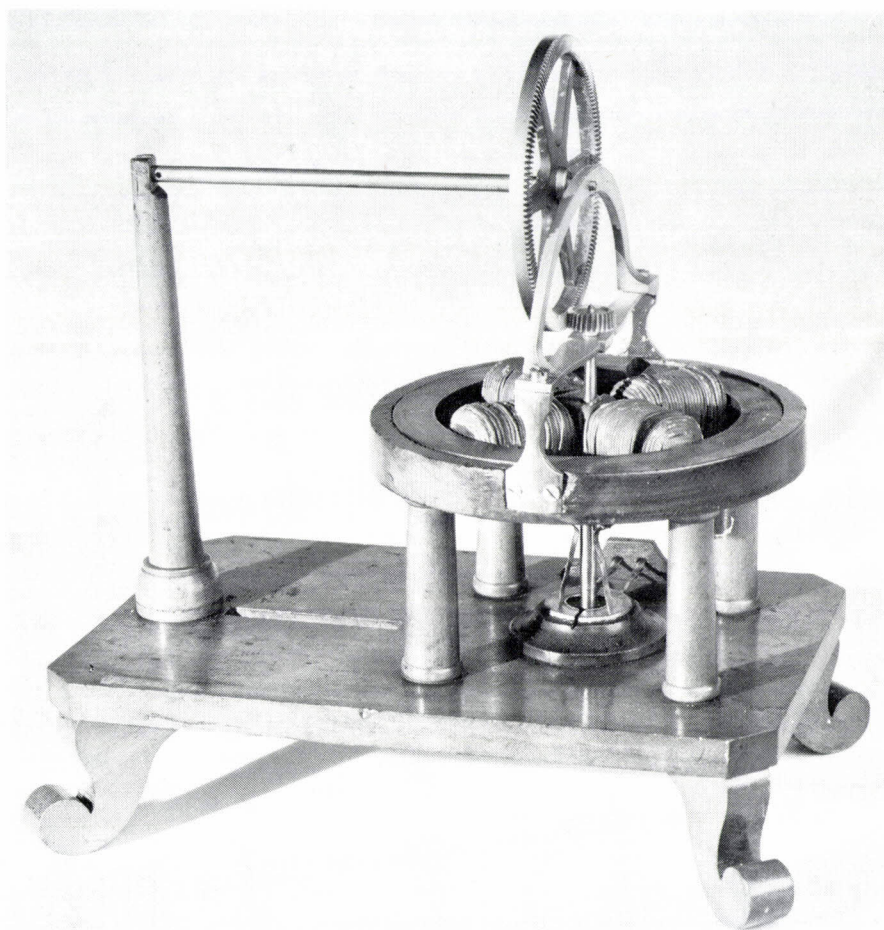


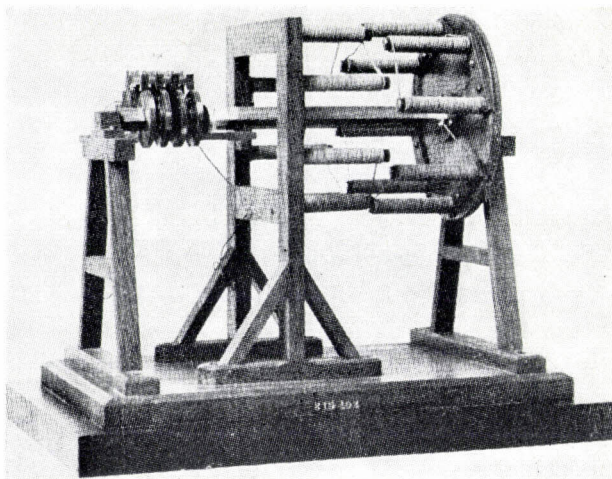
Fig. 9. Davenport's motor (1837). The rotor carries four coils on a cruciform frame, and the stator consists of two semicircular permanent magnets, with their like poles adjacent. The model was made for the American Patent Office. (Photo Smithsonian Institution, Washington.)

tained in a letter from Jacobi to Faraday which was published in 1839. In this letter Jacobi described his work with an electrically driven boat. The boat was a ten-oared shallop fitted with paddle wheels driven by an electromagnetic engine. He 'travelled for whole days', usually with ten or twelve people aboard, on the River Neva. Jacobi had a motor consisting of two wooden frames, each carrying a series of horseshoe electromagnets with pole pieces facing one another but spaced apart. The rotor moved in the space between the pole pieces. It had a six-legged spider with a straight

In a later motor Jacobi dispensed with permanent magnets and had two frames carrying straight electromagnets. One frame was fixed and the other rotated (fig. 10).

Robert Davidson was a Scotsman. The first account of his work was published in 1840 by Professor P. Forbes of King's College Aberdeen, who had seen an account of Jacobi's experiments in the *Philosophical Magazine* and wrote to say that 'A countryman of our own, Mr Robert Davidson of this place, has been eminently successful in his labors in the same field of

**Fig. 10.** Jacobi's motor. A motor rather similar to this one (but with permanent magnets) was used by Jacobi to propel a boat on the River Neva at St Petersburg. (Photo Science Museum, London.)



discovery'. With a machine which Forbes did not describe except to state that it had only two electromagnets, Davidson could drive a lathe and turn small articles using a battery with less than one square foot (9 square decimetres) of zinc surface. Another machine powered by the same battery would propel a small carriage with two people along the wooden floor of the room [20]. In the winter of 1841-42 the Royal Scottish Society of Arts gave Davidson financial help to continue his experiments. In September 1842 he tried an electrically driven carriage on the Edinburgh and Glasgow Railway; the four-wheeled carriage was sixteen feet (4.8 metres) long and weighed over 5 tons (*fig. 11*). The motors consisted of wooden cylinders on each axle with iron strips fixed in grooves in the cylindrical surface. Horse-shoe electromagnets on either side of the cylinder were energized alternately through a simple commutator on the axles. As shown in the drawing the batteries were arranged at each end of the carriage; they had a total of forty cells, each with a zinc plate between two iron plates just over one foot square (about  $10 \text{ dm}^2$ ). The plates could be raised out of the wooden troughs

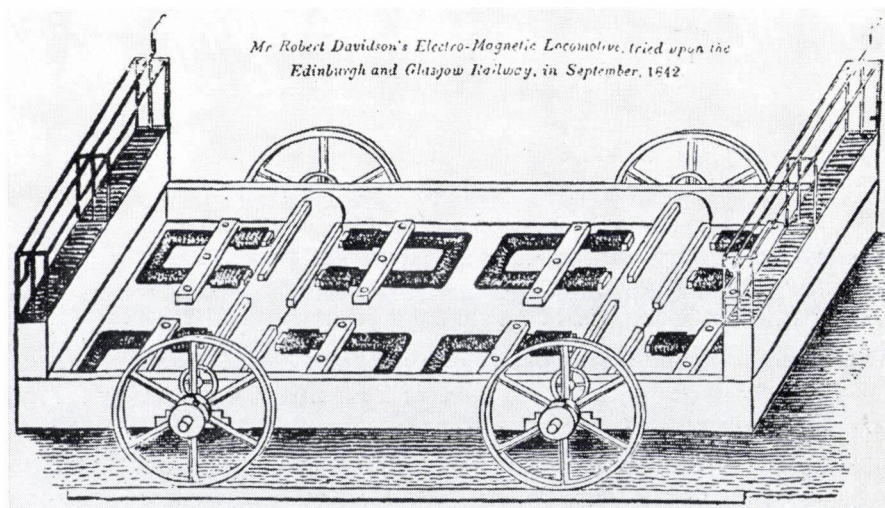
containing the electrolyte by a simple windlass arrangement. These batteries proved insufficient and more were added on each side of the carriage, roughly doubling the power. The carriage then ran at about 4 miles per hour (about  $6.5 \text{ km/h}$ ) on level track. Although the contemporary account says the experiments were carried out on the Edinburgh and Glasgow Railway, it does not say the carriage ran from Edinburgh to Glasgow. No indication is given of the actual distance travelled.

An odd feature of the construction was that the cores of the electromagnets were hollow. Each limb of the cores consisted of four iron plates arranged to form a box. According to a contemporary account this construction was adopted to save weight. Clearly Davidson did not appreciate that it was the total cross-section of iron which was important.

In the year of the great California gold rush, 1849, the United States Commissioner of Patents, Thomas Ewbank, included in his annual report some thoughts on the subject of electric motors [21]:

'... the belief is a growing one that electricity, in

**Fig. 11.** Davidson's electric locomotive, operated experimentally in 1842 on the Edinburgh and Glasgow Railway. The drive was provided by the attractive force between horseshoe magnets and iron strips fixed in grooves in wooden cylinders around the axles. The batteries were arranged at each end of the carriage.



one or more of its manifestations, is ordained to affect the mightiest of revolutions in human affairs . . . When, in addition to what it is now performing as a messenger . . . it can be drawn rapidly from its hiding place, and made to propel land and water chariots . . . then we may begin to think the genius of civilisation is vaulting rapidly toward the zenith.' He referred to the experiments with Jacobi's boat and Davidson's electric locomotive and various other applications of electricity all dependent upon the battery, and then continued in a somewhat pessimistic vein:

'but these experiments, interesting as they certainly were, have brought no marked results, nor afforded any high degree of encouragement to proceed. It might be imprudent to assert that electromagnetism can never supersede steam; still, in the present state of electrical science the desideratum is rather to be hoped for than expected. Great, however, will be his glory who in the face of these discouragements succeeds.'

However, Ewbank's pessimism was not shared by his government, and in the following year it gave money for research into electric motors.

Professor Charles G. Page of Salem, Massachusetts, began a series of motor designs in 1837. In 1838 he made a machine on Davenport's pattern and some of his machines were used for practical purposes in 1838. During the next decade Page produced a number of motors and in 1850 he received a congressional grant of 20 000 dollars to enable him to continue his investigations. With the aid of this he constructed a large double-acting reciprocating motor weighing several hundred pounds (100 lb = 45.4 kg); it had a flywheel and connecting rods. The power produced was one horse power and as a demonstration it was used to saw heavy timber. The machine was then reconstructed into a single-acting motor, which with a larger battery produced four horse power. Page stated in a report to the Secretary of the Navy in 1850 that he thought this type was especially suited to navigation and he recommended that a one-hundred-horse-power motor should be built. The next motor actually built by Page was for a locomotive which, with the battery and load, weighed about 12 tons (1 ton = 1.016 tonnes). This was tested in 1854 on the branch line of the Baltimore and Ohio railroad and gave a maximum speed of 19 miles (31 kilometres) per hour on a level track. By this time the government funds were exhausted and Page could obtain no more money for further experiments [17].

Such was the state of the electric-motor art in the middle of the nineteenth century. Most of what had been done had been experiments with little or no theoretical basis, but some electric-motor theory was evolving.

### Theoretical understanding

The first electromagnetic engines were designed on a purely empirical basis. Given the basic idea of producing motion by switching an electromagnet which attracts an armature, there are three basic choices for the designer to consider before proceeding to the detailed design:

1. The electromagnets may attract either a soft-iron armature or a permanent magnet. (The permanent magnet could of course be a continuously energized electromagnet.)
2. The electromagnets could either be reversed in polarity or merely switched on and off.
3. The motion of the armature could be either rotary or reciprocating.

Permanent magnets were not often used, probably because the materials available did not make very strong magnets and better results could be obtained by the use of electromagnets.

The question of reversing the polarity of the electromagnets or merely switching them on and off was an important issue in the technical press in 1840. In that year an American, W. H. Taylor, who had moved to London, obtained an English patent for a motor. His motor was a simple arrangement of four electromagnets on a frame surrounding a wooden wheel with seven soft-iron armatures on the periphery of the wheel (*fig. 12*). A simple commutator on the axis switched the four electromagnets sequentially. Taylor claimed that previous plans for electromagnetic engines had depended on changing the polarity of electromagnets and that his invention was the idea of switching them so that they were 'alternately and (almost) instantaneously magnetized and demagnetized without any change of polarity whatever taking place'. Taylor's wording is not very clear but he seems to have thought that earlier engines had failed because it took a significant time to reverse the polarity of an iron-cored electromagnet, whereas switching it was an almost instantaneous process [22].

Taylor's claim to novelty was quickly disputed. Professor P. Forbes of Aberdeen wrote a letter to Faraday which, when published, first brought Davidson's work into the public eye [20]. According to Forbes, Davidson had 'employed the electro-magnetic power in producing motion by simply suspending the magnetism without a change of the poles' in 1837.

A contemporary account of Davidson's work makes it clear that the maximum magnetic force available was not a limiting factor in the design of his locomotive [23].

'According to Mr Davidson's first arrangement, these magnets were placed so that their poles were nearly in contact with the revolving masses of iron in their transit; but so prodigious was the mutual attraction,

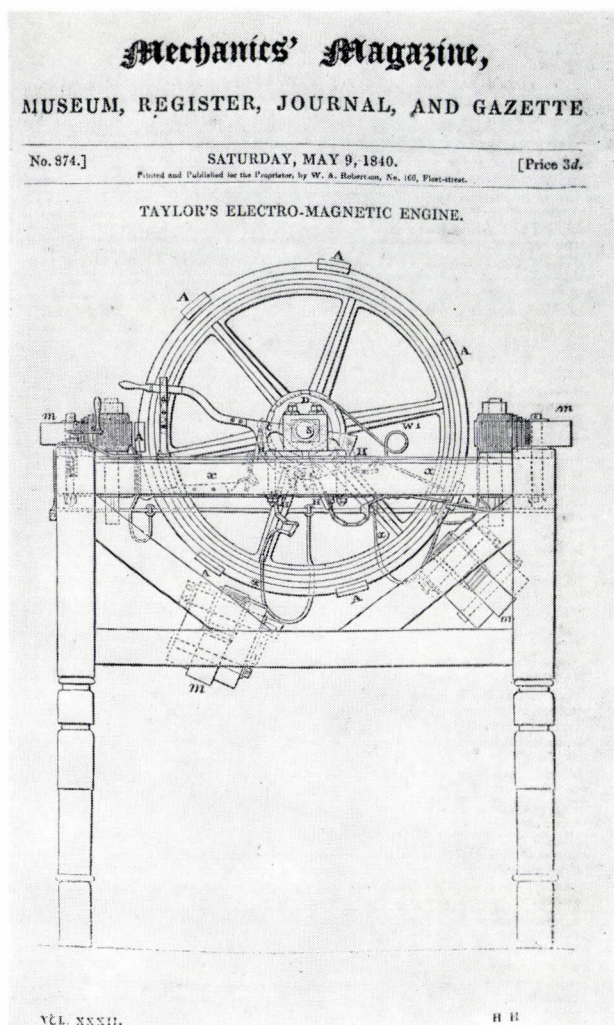


Fig. 12. Taylor's motor (1840). The rotor is a wooden wheel with seven soft-iron armatures *A*. Four electromagnets *m* are connected and disconnected in turn.

that the means taken to retain the magnets and iron in their assigned positions were insufficient. They required to be more firmly secured, and their distances had to be somewhat increased, by which considerable power was lost.'

So it was purely mechanical considerations which limited the power of Davidson's locomotive.

We have enough data to estimate the efficiency of this machine. The whole locomotive weighed over five tons and went at four miles (6.5 km) per hour on the level. A horse could pull such a vehicle<sup>[24]</sup>, and a likely power is about 500 watts. The batteries were of a kind capable of giving about 0.2 ampère per square inch (about 3 A per dm<sup>2</sup>) of surface of zinc plate<sup>[25]</sup>. Each cell had a zinc area of 360 square inches (23 dm<sup>2</sup>) and ought therefore to have given about 70 ampères at about one volt. In the original form with forty cells the theoretical power available was therefore about  $40 \times 70 \times 1 = 2800$  watts. However, that proved inadequate and

the battery capacity was almost doubled. The power available then would have been about 5 kilowatts. The overall efficiency of Davidson's locomotive is therefore in the range 500/5000 to 500/3000, or from 10% to 16%.

The efficiency of electromagnetic engines was a matter of some interest in the 1840s. In 1843 Charles Wheatstone described his rheostat, or variable resistance, in a paper to the Royal Society on Electrical Measurements<sup>[26]</sup>. The rheostat was developed initially as a measuring device, but Wheatstone stated that it could be used for controlling the speed of a motor or keeping it constant as the battery varies. He also stated:

'Since the consumption of materials in a voltaic battery . . . decreases in the same proportion as the increase of the resistance in the circuit, this method of altering the velocity has an advantage which no other possesses, the effective force is always strictly proportional to the quantity of materials consumed in producing the power, a point which, if further improvements should ever render the electro-magnetic engine an available source of mechanical power, will be of considerable importance.'

This, of course, is not correct, since it ignores the power wasted in the resistance. But it suggests that he had conducted some experiments designed to relate the power obtained from an engine and the consumption of materials in the battery.

In 1850 the Philosophical Magazine reported that one grain (about 0.07 g) of coal consumed in the furnace of a Cornish engine would lift 143 pounds (about 55 kg) one foot (about 30 cm), whereas one grain of zinc consumed in a battery would lift only 80 pounds through the same distance. The cost of zinc was much more than the cost of coal, and therefore under the most favourable conditions 'the magnetic power must be nearly 25 times more expensive than steam power'<sup>[27]</sup>.

The problem which designers of electromagnetic engines had to solve was that of obtaining a useful output stroke from a power source which gave great power but through only a short distance.

One approach was that adopted by Wheatstone who, in 1841, patented a number of rotary engines in which he sought to increase the output stroke in relation to the distance between the electromagnet and the armature. His idea was to make the armature move in a direction inclined to the direction of the magnetic force. He was not expecting to obtain more work from his machine (the relationship 'work = force  $\times$  distance moved in the direction of the force' was already well known) but he wanted it in a longer output stroke. He made at least three machines of different designs to exploit the idea. In the first design a number of horse-

shoe electromagnets are arranged in a circle around the stator with their poles pointing inward. The armature is a soft-iron ring whose outside diameter is a little less than the diameter of the circle which bounds the surfaces of the electromagnet poles. The armature is carried on a crank on the main shaft and the electromagnets are energized sequentially so that the armature rolls round inside the stator, pulling the crank with it. According to the patent drawings (*fig. 13a*) the armature ring acted as a commutator by pressing on contact strips as it rolled around the stator. The machine now in the Science Museum (*fig. 13b*) has a simple fixed commutator with a contact for each electromagnet and a single wiper carried on the main axis.

Wheatstone called these machines 'eccentric electromagnetic engines'. In another one the armature is an iron disc which performs a wobbling motion as a number of coils are energized sequentially. The patent drawing shows electromagnet coils in milled slots in an iron stator disc, though the actual machine in the Science Museum has four separate horseshoe electromagnets to act on the disc.

In both these machines the armature actually moves a distance equal to the spacing between two adjacent electromagnets, but, as can be seen in the illustrations, the magnetic pull has to be effective over only a much smaller distance.

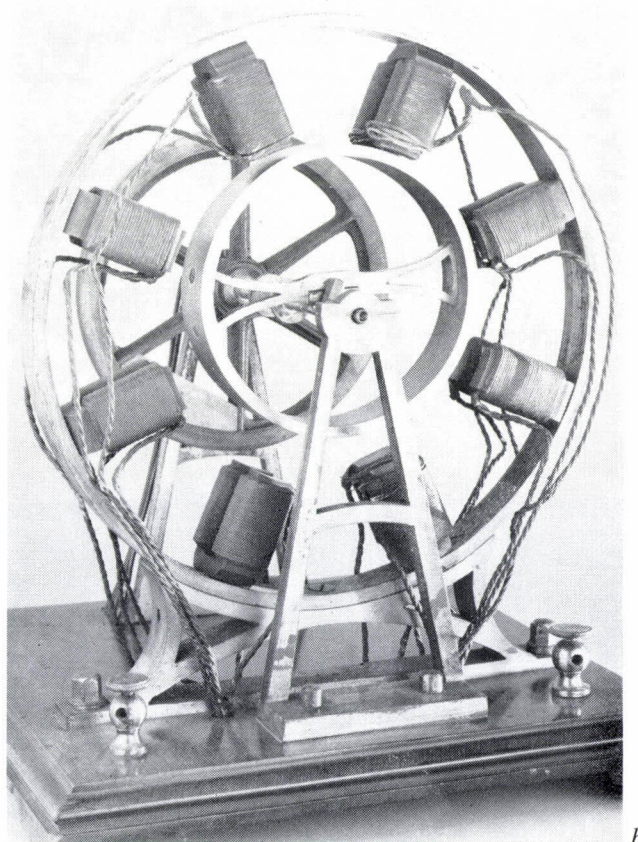
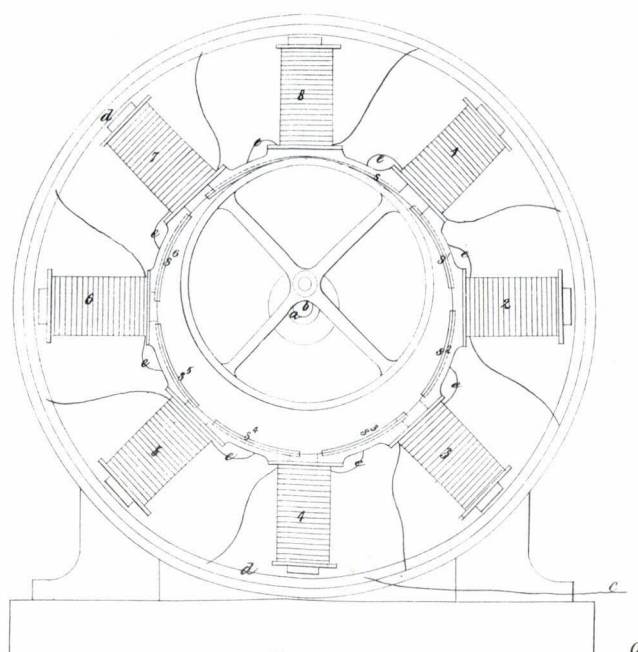
Froment was the only other person to make machines of this kind. He made a machine similar to Wheatstone's first in about 1847. It may be seen working at the Musée du Conservatoire des Arts et Métiers in Paris. Froment called it the 'électro-moteur épicycloïdal'.

Several methods of increasing the output stroke were tried in reciprocating electromagnetic engines. One of the first men to do this was Uriah Clarke of Leicester, who exhibited an 'electromagnetic carriage' at the Leicester Exhibition in 1840. Clarke's carriage weighed only 60 pounds (27 kg), so it must have been fairly small. The motor had a single electromagnet which acted on an armature on a pivoted lever (*fig. 14*). The lever was coupled by a chain to a crank, and Clarke's idea was that the electromagnet was energized to give the armature and hence the chain one brief, sharp pull during each revolution of the crank [28].

Later in the same year Thomas Wright published his idea for increasing the working stroke of a reciprocating electromagnetic engine. His proposal was that one edge of the armature should be fixed by a hinge to the electromagnet (*fig. 15*). In that way he thought he could increase the useful working stroke from  $\frac{1}{4}$  inch to  $1\frac{1}{4}$  inches (from 6 mm to 3 cm) [29].

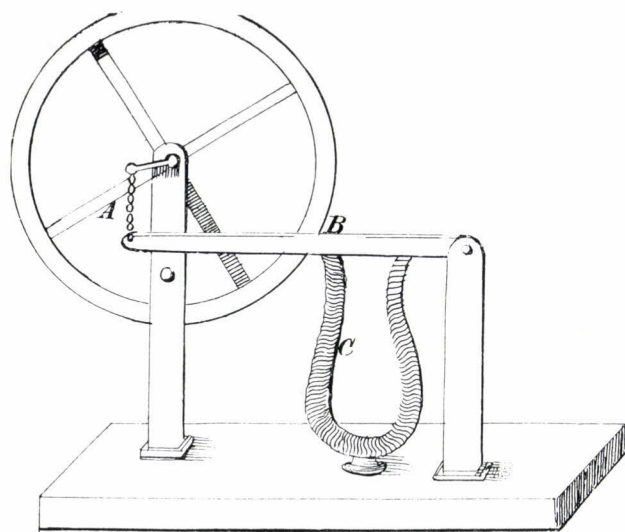
The most ingenious of all electromagnetic engines must surely be the machine constructed by Thomas

*Front Elevation.*



**Fig. 13.** Wheatstone's electromagnetic engines. The armature rolls round inside the stator; it is carried on a crank on the main shaft. The movement of the armature is therefore larger than the distance through which the attractive force operates. *a*) Drawing from an 1841 patent specification. The armature ring acts as a commutator by pressing on contact strips as it rolls around the stator. *b*) Model with a single wiper commutator carried on the main axis (at the rear). (Lent to the Science Museum, London, by Kings College, London.)

Allan in 1852. This is a reciprocating engine with four cranks and four 'piston rods' (*fig. 16*). Each piston rod carries four armatures which press on collars on the rod, but are not otherwise fixed to it. Sixteen sets



**Fig. 14.** Clarke's motor (1840). The output stroke of the electromagnet *C* was magnified by the lever *B*, which gives the chain *A* a brief, sharp pull during each revolution of the crank.

of coils, one set for each armature, are energized one at a time by a commutator. Each piston rod is active for one quarter of a revolution of the output shaft, and each armature is active for only one quarter of the working stroke of its piston rod. When an armature reaches its electromagnets it is stopped by them but the piston rod continues its travel, driven by the next armature in sequence [30].

None of these machines were successful, in the sense of being adopted commercially. They failed for two reasons. Firstly, the only electricity supply was from batteries and, as we have seen, they were much more expensive than steam power. But if that were the whole story then electromagnetic engines would have flourished in the 1880s when generators became available for electricity supply. However, the French writer on electrical engineering, Comte Th. du Moncel, wrote in 1878 that [31]

'Attempts have been made . . . to employ the attractive effect of electromagnets . . . as a motive force . . . But it can almost be predicted that those motors which are most successful when of small size are precisely those which give worst results when of large size, should they still give any, which does not always happen.'

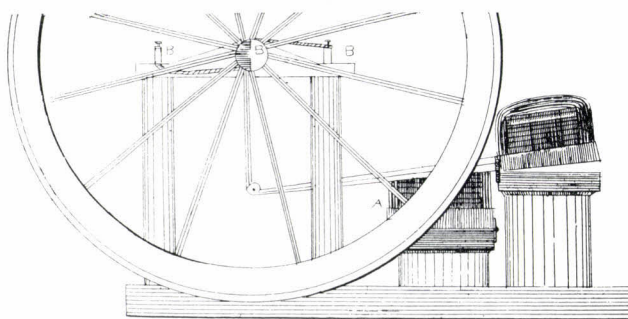
When practical generators were developed in the 1870s it was soon found that an identical machine would function as a motor and that larger ones were more efficient than smaller. The development of electro-

magnetic engines came to an abrupt halt, except in two applications. Until the widespread adoption of the telephone thousands of ABC telegraph receivers were in daily use, and each contained a tiny electromagnetic engine to turn the pointer. More recently battery-powered electric clocks, driven by an electromagnetic engine, have become popular.

### Practical electric motors

The electric generator was developed by several independent inventors in 1866. This invention made large-scale electricity supply a practical possibility. At first the new electrical industry supplied only electric lighting, but it was soon found that a machine identical to the generator could be used as a motor (*fig. 17*). It is not known whether such a machine was first tried as a motor because theoretical reasoning suggested the interchangeability of motors and generators, or whether the motor action was discovered accidentally by someone who tried to operate two generators in parallel.

The first public demonstration of the electrical transmission of power was given during the Vienna Exhibition of 1873. The motor and generator were identical Gramme machines with permanent-magnet excitation. The generating machine was driven by a steam engine and supplied current to the second machine, 550 yards (500 metres) away, which drove a pump [32].



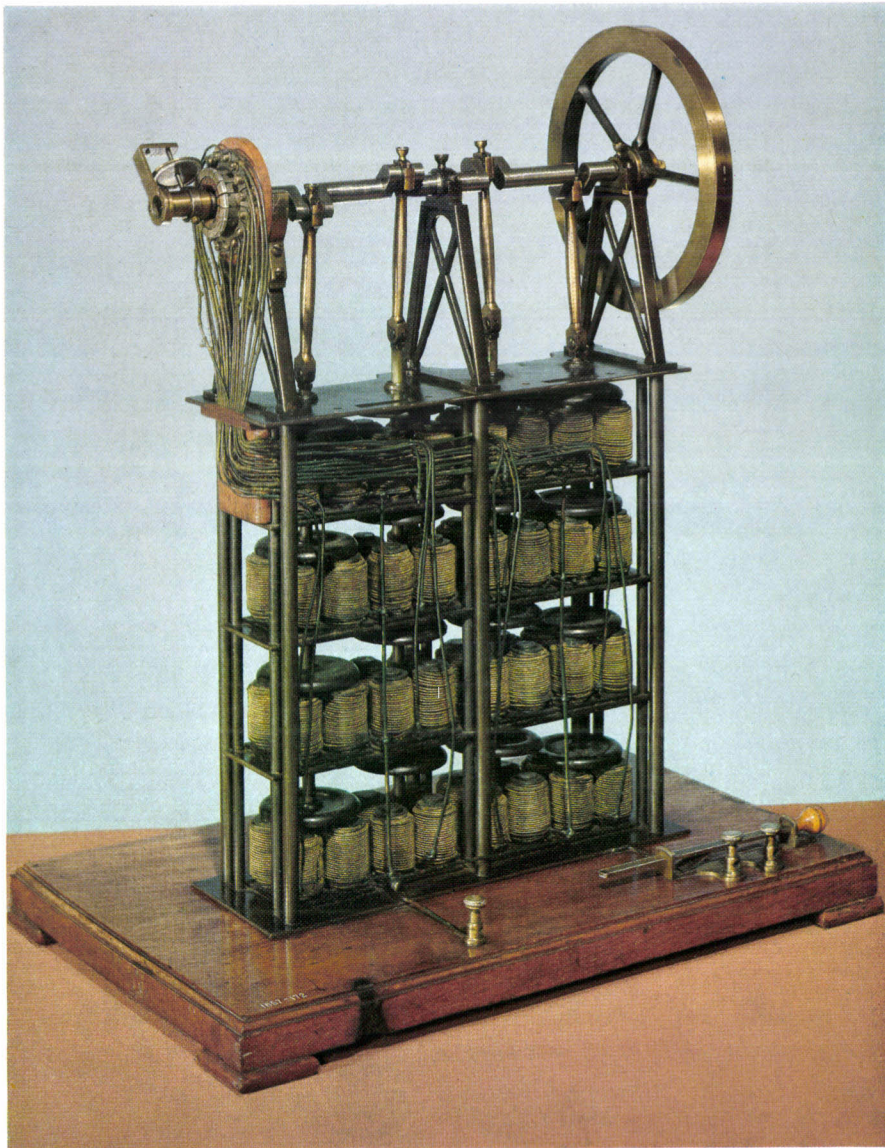
**Fig. 15.** Wright's motor (1840). The output stroke is again magnified by a lever; the armatures are hinged to the edge of the electromagnet.

Similar demonstrations were given at the Loan Collection of Scientific Apparatus in London and at the American Centennial Exposition, both in 1876. The people responsible for these demonstrations seem to have been very eager to transmit power over long distances, and they appreciated the advantages of high-voltage transmission. In 1880 at the Munich Exhibition Marcel Deprez transmitted electric power over a distance of 34 miles (55 km) from Miesbach to Munich through a double line of telegraph wire. The machines

used were ordinary Gramme generators, with wound fields (*fig. 18*), but the usual windings were replaced by coils with more turns of finer wire. The machines had a resistance of 470 ohms each and the line 950 ohms. The terminal voltage was 2400 V at the generator and

motors could be made to run at constant speed over a range of loads by adopting compound winding there also [21] [32].

Also in the 1880s electric power was used for ploughing in France. The arrangement was similar to that used



**Fig. 16.** An ingenious electromagnetic engine due to Allan, with four 'piston rods' (1852). Each piston rod is pulled downwards by four groups of electromagnets; these do not operate simultaneously but in sequence, thus magnifying the stroke. (Photo Science Museum, London.)

800 V at the motor, and the overall efficiency of the power transmission was 33 % [32].

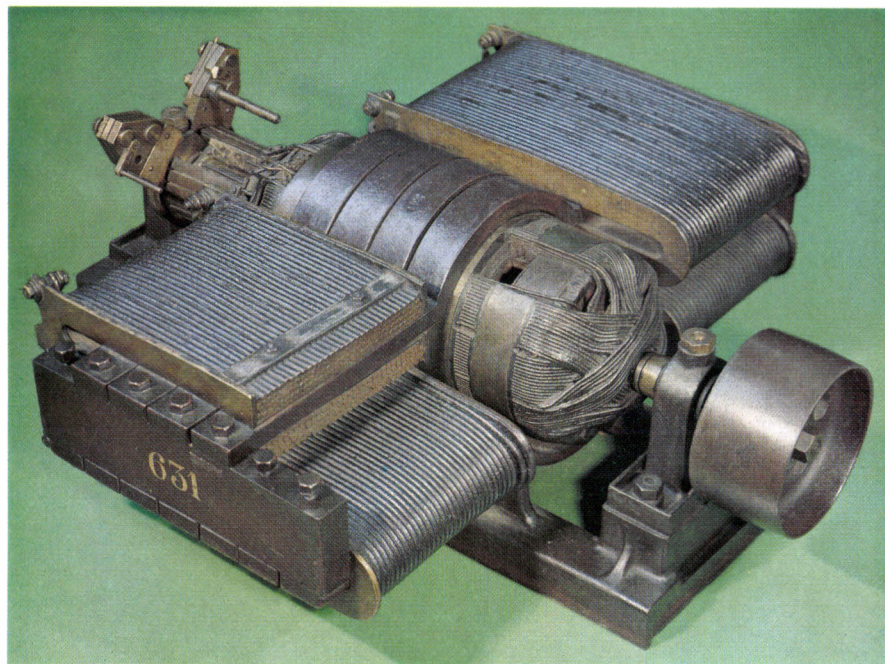
At the International Electrical Exhibition in Paris in 1881 Deprez demonstrated several motors, including some driving sewing machines and lathes.

Compound winding of generators to give a constant output voltage was developed in the early 1880s. Constant voltage was very important for the newly invented incandescent-filament lamps. It was soon shown that

for ploughing by steam power. Two Gramme machines were required, mounted on wheeled trolleys at opposite ends of the field, and the plough was then drawn along by a rope which was pulled first to one motor and then to the other. Current was supplied from a steam engine and generator installed under cover [32].

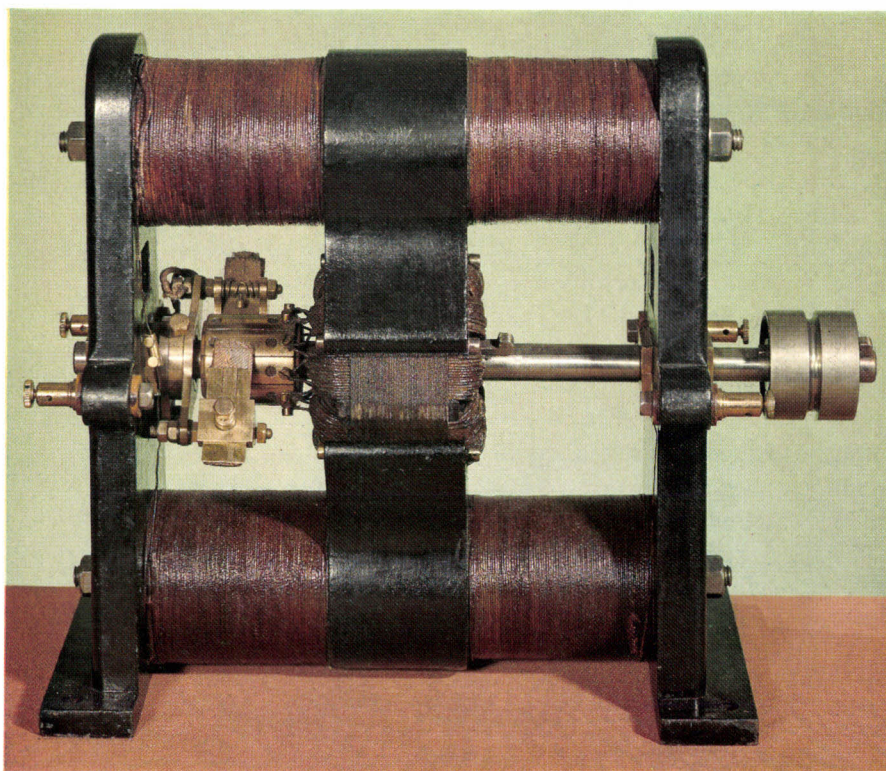
The first electric motor to be mass produced was probably the small motor used by Edison in his 'electric pen' (*fig. 19*). The electric pen was a stencil cutter in

**Fig. 17.** Cut-away view of an early Siemens generator that was used as a motor. (Photo Science Museum, London.)

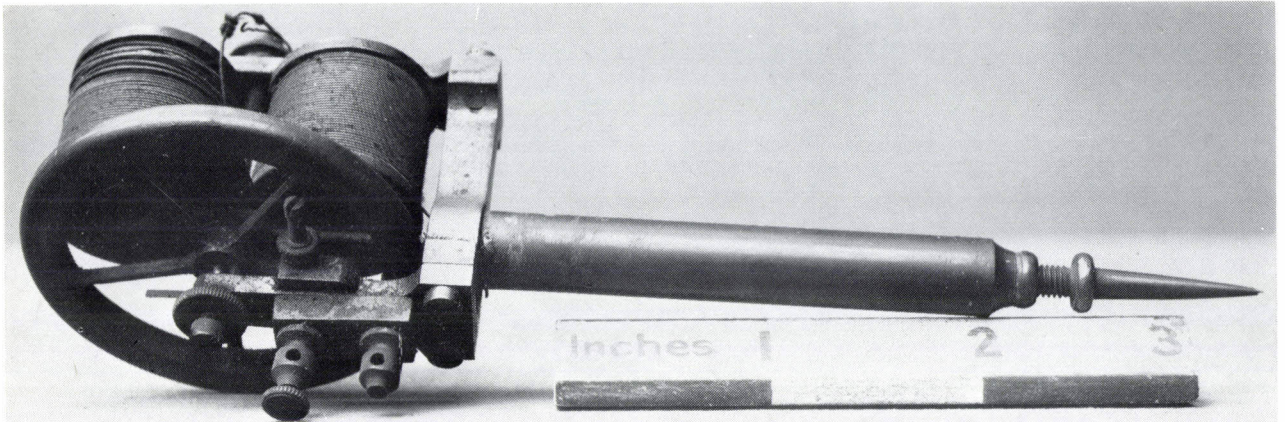


which a motor running at about 65 revolutions per second drove an oscillating needle to perforate the stencil. The motor was only 1.6 inches (4 cm) high and 0.8 inches (2 cm) wide. It had a fixed electromagnet, a rotor consisting of a straight permanent magnet, and a commutator which reversed the connections of the electromagnet twice per revolution [33]. Tens of thousands of electric pens were sold [9].

In 1879 Edison began marketing a small motor intended for running sewing machines and other light machinery from the electric-lighting mains. The construction was very similar to Edison's early generators, with their characteristic long field windings [33].



**Fig. 18.** Gramme generator with wound fields. (Photo Science Museum, London.)



**Fig. 19.** Edison's 'electric pen', the first electric motor to be mass-produced. The oscillating needle point was used as a stencil cutter; the motor ran at about 65 revolutions per second. (Photo Science Museum, London.)

The most important early application of electric power was for railways and tramways. Siemens and Halske gave the first successful demonstration at the Berlin Industrial Exhibition in 1879. They had a railway with 325 yards (300 m) of track formed into a closed oval. The locomotive was a four-wheeled truck carrying an ordinary Siemens dynamo/electric machine which was geared to the wheels (*fig. 20*), and it pulled an open carriage with passengers. The electricity supply was through a central live rail with the running rails providing the return path. In the following year Egger showed a railway at Vienna in which the two running rails were insulated from one another and formed the positive and negative conductors [32].

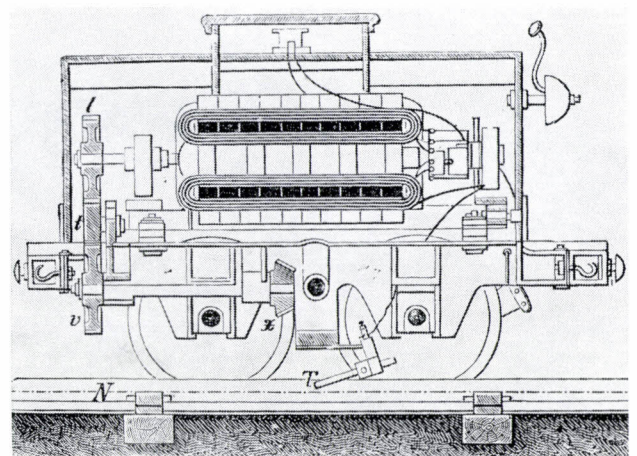
The first permanent railway open to the public was constructed by Siemens and Halske at Lichterfelde and opened in 1881. It ran for  $1\frac{1}{2}$  miles ( $2\frac{1}{2}$  km) between Lichterfelde station and an Army Training School. Each carriage was rather like a tramcar in appearance, and had a single motor fixed centrally under the floor [32].

The first electric railway in the United Kingdom was the line from Portrush to Bushmills, opened in 1883. The total length was six miles ( $9\frac{1}{2}$  km), and the railway had several features of interest. Electrical operation was not envisaged when the line was first proposed, but it was adopted because abundant water power was available at Portrush, where a hydroelectric generating station was built. The motors were placed centrally under the floor of the carriages, and the driver had a lever which enabled him to reverse the motor by moving the brushes. There was a driving position at each end of the carriages [32].

Direct-current motors for both traction and other applications were developed by many manufacturers during the later 1880s and 1890s. An important differ-

ence between early industrial motors and generators of the same period was that provision had to be made in the motors for reducing sparking at the commutator by keeping the brushes on the magnetic neutral axis as the load varied. Initially the engine-driver or other person in charge of the machine was given some means of adjusting the brush position as the load varied, but that was only practical when dealing with a single motor in an accessible location. The American engineer Frank J. Sprague, who established the Sprague Electric Railway and Motor Company in 1884, found that by making a compound-wound motor with the series field coil arranged at an angle to the main, shunt coil, he could maintain spark-free commutation under varying load with a fixed brush position [21].

The overall height of a traction motor is a critical dimension, especially when the motor is mounted on



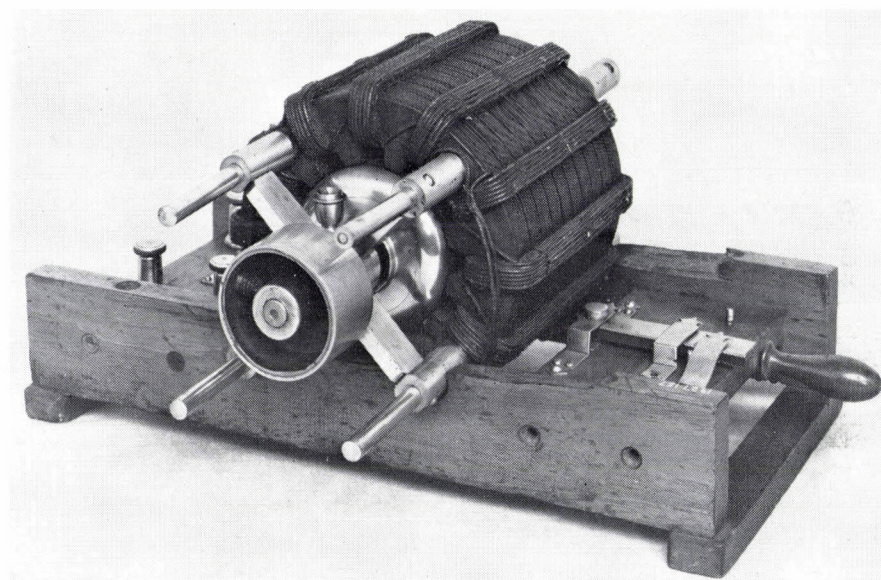
**Fig. 20.** Cross-sectional drawing of Siemens and Halske's electric locomotive (1879). A Siemens generator was used as the motor, and was coupled to the wheels by the gears *l*, *t*, *v*, *x*. The current was taken from a central live rail *N*.

the bogie of an eight-wheeled coach rather than on the floor of a simple four-wheeled vehicle. This requirement led to a design of motor which appears at first sight to have only two poles but does in fact have four, although only two poles are wound.

### Alternating-current motors

In the last years of the nineteenth century there was much controversy between the supporters of direct-current electricity supply and those who favoured alternating current. The advantage of a.c. was that transformers could be used; electric power could then be converted to high voltage at the power station, transmitted more efficiently than at low voltage, and

Since the synchronous motor is essentially a constant-speed machine, it can only be used in a few special applications. With the introduction of alternating-current electricity-supply systems there was a need for a general-purpose a.c. motor. It was found that the ordinary direct-current motor could be modified to run on alternating current. The problem was that the inductance of the field winding led to excessive sparking, and eddy currents in various parts of the machine caused power loss and overheating. The use of laminated construction for the stator as well as the rotor alleviated the situation, but a.c. versions of the ordinary d.c. motor have never proved satisfactory except in small sizes. The Siemens firm were developing a.c. commutator motors as early as 1884 and Alexander Siemens spoke



**Fig. 21.** Tesla's two-phase induction motor (1888). Neighbouring groups of three of the twelve stator coils are successively connected in series. The stator iron is laminated. (Crown Copyright. Science Museum, London.)

reduced to low voltage at the load. The supporters of d.c. pointed out that it was difficult to operate alternating-current generators in parallel, and d.c. motors were generally far better than a.c. motors.

In a lecture to the Institution of Civil Engineers in 1883, entitled 'Some Points on Electric Lighting', Dr John Hopkinson discussed the operation of alternating-current generators in parallel<sup>[34]</sup>. Even the possibility of parallel running was doubted by some engineers, but Hopkinson showed that it could be done if the machines had similar output waveforms. He then said that if two such generators were being run in parallel and the power driving one was cut off, then that machine would continue running as a motor. Furthermore, the motorising machine would maintain synchronism with the other machine which continued to generate.

on the subject at the Institution of Electrical Engineers in November 1884<sup>[35]</sup>.

The most important type of motor today, in terms of total power installed, is the induction motor. The origin of this is to be found in Arago's disc, for both Arago's disc and the induction motor utilize the force between a moving magnetic field and a conductor carrying a current induced by the magnetic field. Arago produced a rotating field by spinning a bar permanent magnet about an axis perpendicular to the bar. In induction motors a similar magnetic field is produced by currents in the field coils, without the need for any moving parts.

In 1884 two men, Galileo Ferrari in Italy and Nicola Tesla in America, showed, independently of one another, how fixed coils carrying suitable phase-displaced

currents could produce a rotating magnetic field and cause an armature to rotate. In Turin, Ferrari used two coils arranged at right angles and fed from the same a.c. supply, one directly and the other through an inductance. Although he produced rotation he did not develop his device into a practical motor [9]. At about the same time Tesla read a paper to the American Institute of Electrical Engineers in which he described

By 1897 Langdon Davies was producing single-phase induction motors commercially [9].

By the end of the nineteenth century, less than one hundred years after Oersted's demonstration that an electric current could produce motion, the main types of electric motor had been invented and were in production.

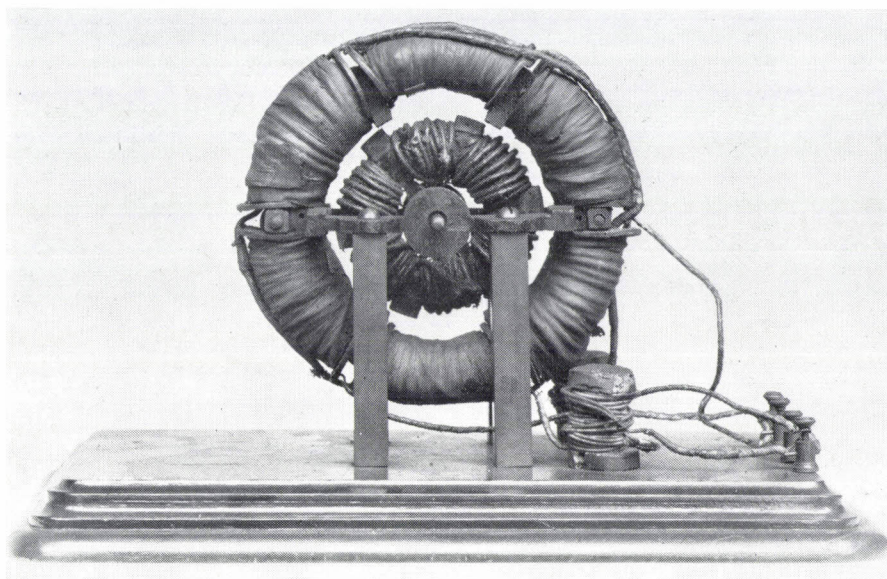


Fig. 22. Langdon Davies's induction machine for a single-phase supply (1891). Four of the six stator coils are connected directly to the supply, two via a resistance. (Lent to the Science Museum, London, by the Langdon Davies Motor Co.)

a two-phase generator and motor [36]. The generator was made by fitting two pairs of slip-rings to a d.c. generator; the motor consisted of an iron ring with four coils wound around it and each pair of opposite coils connected together and to one pair of slip-rings. He showed that the arrangement gave a rotating field and that pivoted metal discs placed within the iron ring would spin. The success of this experiment led Tesla to build the first practical two-phase induction motor (fig. 21). Within a few months he had made three-phase machines also, and the Westinghouse Company began to manufacture them.

In 1891 W. Langdon Davies showed that it was possible to run an induction motor from a single-phase supply. He made an experimental machine whose stator was an iron ring carrying six coils with six pole pieces between them (fig. 22). Opposite coils were connected together, so there were three groups of two coils. Two groups were connected directly to the supply, the third was connected through a resistance so as to introduce a phase shift. The rotor was a ring similar to the stator, but smaller, and wound with six short-circuited coils.

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**Summary.** The electric motor has a history of a century and a half. The article covers the period until about 1900. After Oersted's discovery in 1820 machines were made in many places to demonstrate that mechanical movement could be produced by electricity. From this time 'electromagnetic engines' began to appear; these were machines in which a continuous movement was produced by the attractive and repulsive forces from periodically switched electromagnets. Such machines were used as practical sources of mechanical power, and also in experiments to demonstrate the electric propulsion of boats (Jacobi) and railway carriages (Davidson). The electricity supply was provided by batteries, so that these machines were very expensive to operate. With the development of the d.c. dynamo (Gramme, Siemens), cheaper electricity became available; at the same time it was found that these dynamos could also be put to good use as motors. Many practical applications now began to appear: as a drive for tools (Edison) and the very important one of motive power on railways and in trams (Siemens and Halske, Sprague). Alternating current had advantages for the transmission of current over long distances; and the induction motor was developed (Tesla).