ELECTRICAL MACHINES vol. 3

A. IVANOV-SMOLENSKY

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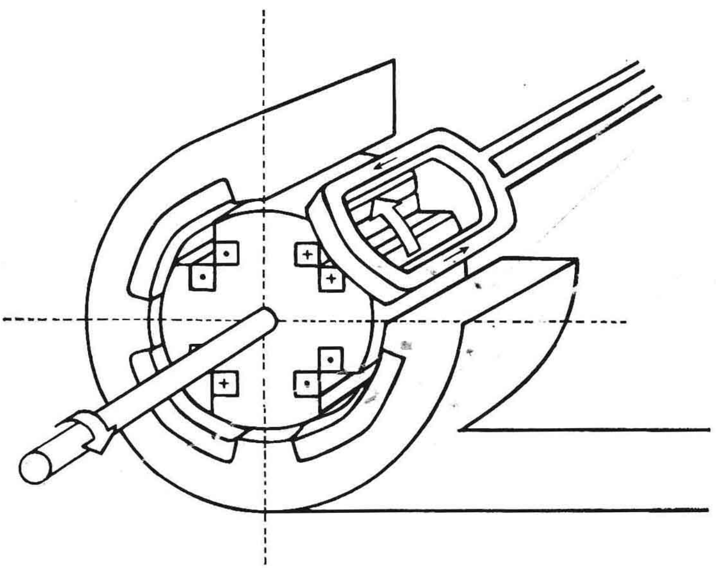
ЭЛЕКТРИЧЕСКИЕ МАШИНЫ



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A. IVANOV-SMOLENSKY

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64 Direct-Current Electrical Machines

64-1 Purpose and Applications

This part of the book will be concerned with electrical machines connected to the external circuit via what is known as the *commutator*.

The function of a commutator is to convert a.c. to d.c. in the generating mode and to invert d.c. to a.c. in the motoring mode. A commutator, in one form or another, is built into any d.c. machine because its armature winding must carry a.c.—it is only then that there will be a continuous and unidirectional energy conversion.

The most commonly used form of commutator is the *mechanical commutator*—a mechanical rectifier-inverter connected between the armature coils and the d.c. terminals. Quite aptly, such machines are called *commutator d.c. machines*. Recently, there has been a growing trend towards using electronic (or solid-state) commutators—switching arrangements based on thyristors, rectifying diodes, or transistors—to supplement or supplant the mechanical commutator function.

Unless otherwise qualified, the term "commutator d.c. machine" will refer to those fitted with a mechanical commutator. As already noted, they may be motors or generators.

D.C. motors. Direct-current motors have a broad range of speed control coupled with a high efficiency over the range, and can be built with torque-speed characteristics to suit any particular applications. This is why, although they are twice or three times more expensive to make than squirrel-cage induction motors, d.c. motors are preferable wherever their special qualities are desirable or decisive. For example, they are widely used in electric traction on railways where their drooping torque-speed characteristic and wide range of speed control are valuable. The same goes for the d.c. motors used in cranes and other hoisting equipment. Large d.c. motors (up to 12 MW) are used as drives in blooming and slabbing mills, as main propulsion units on Diesel-electric ships. In most cars, tractors and aircraft using d.c electric supply, all auxiliaries are driven by d.c. motors. Small d.c. motors (from a fraction of a watt to tens of watts) are employed in various automatic control applications.

Direct current for d.c. motors is supplied by d.c. generators, a.c.-to-d.c. converters or rectifiers.

D.C. generators. Direct-current generators supply d.c. for industrial purposes where low voltage is required (electrolysis, electroplating, and the like). In many cases, they serve as exciters for synchronous generators.

There are also various special-purpose d.c. generators (welding, train-lighting), d.c. rotary amplifiers (control generators), etc.

☆ 64-2 A Brief Historical Outline

In 1821, Faraday demonstrated a device in which a conductor carrying d.c. rotated around a magnet. In fact, his device was a primitive homopolar machine. In the years that followed, several more devices capable of converting electrical energy to mechanical were made. In 1824, Barlow described a device resembling a homopolar machine, in which a copper disc placed in the field of a permanent magnet would rotate when supplied with current.

In 1833, Ritchie described the first working model of a heteropolar commutator motor. In his device, the field was excited by a horse-shoe magnet between the poles of which there was an electromagnet fed with d.c. via the commutator. A unidirectional torque was produced by the interaction of the permanent magnet and the electromagnet in which the direction of current flow was reversed in a periodic fashion.

In 1834, Jacobi built an electromagnetically excited d.c. motor which could be used as a drive for various machines. It had two groups of U-shaped magnets, with four magnets per group. One group was mounted on a stationary frame, and the other on a rotating disc, so that the two groups faced each other. The coils of all the magnets were connected in series (today, we would call it "series-excited" or "series-wound"). Direct current was supplied by a battery of primary cells. The polarity of the rotating magnets was periodically changed by a commutator. In 1838, Jacobi built a better and larger motor which could propel a small boat. In fact, it was a combination of 40 small units each of which differed from the machine of 1834 only in that the axes of the rotating and stationary magnets were arranged radially and in the same plane. A major limitation of Jacobi's motor was the pulsating torque, because both the armature and the field structure used a salient-pole core.

In 1859, Pacinotti built an electric motor which had a nonsalient-pole, distributed-winding armature and produced a practically constant torque. The armature core was a toothed steel ring mounted on the shaft by means of brass spokes. The slots received coils brought out to commutator bars. The commutator had as many bars as there were armature coils. Current was conveyed to the commutator bars by contact rolls. Placed across from the armature teeth were two electromagnets of opposite polarity, fitted with pole-pieces. The electromagnets were connected in series with the armature winding and took a small current for excitation (owing to the teeth on the armature core). For all of its advantages, Pacinotti's motor failed to become a practical machine because, like Jacobi's motor, it required an economical d.c. source which was nonexistent at that time.

Direct-current generators lagged behind d.c motors at all times. For the first time, Faraday thought of building a homopolar d.c. generator in the form of a disc rotating in a magnetic field in 1831, that is, a decade after he had built his homopolar motor. In 1832, the Pixie brothers built a heteropolar d.c. generator employing a commutator for rectification of the alternating current induced in stationary coils mounted on a U-shaped iron core. The field in the core was periodically reversed in polarity by a rotating U-shaped magnet placed opposite to the core.

For practical purposes, a permanent-magnet d.c. generator was first used by Jacobi in 1842. In contrast to the Pixii machine, the magnets were stationary and the coils were rotating. In the 1840-50s, some prominence was gained by Störer's permanent-magnet generator with three rotating magnets. For larger output, several such machines would be combined into a single assembly. From 1856 to 1865, permanent-magnet generators of this design were produced by the Alliance Company (France). They were driven by a steam engine with a power output of 6 to 10 hp.

In 1851, Sinsteden proposed to replace the permanent magnets by electromagnets energized from another permanent-magnet generator. This idea was embodied, for example, in 1863 in Wilde's generator which was built in two modifications, as a single-phase a.c. generator (see Sec. 51-2) and as a d.c. generator. In the d.c. generator, a.c. was rectified by a simple commutator. The excitation field was produced by a U-shaped electromagnet whose pole-pieces encircled a concentrated-winding, salient-pole armature. The voltage at the brushes was a pulsating one.

In 1854, Hjort took out a patent for a self-excited machine. For "initial" excitation, he proposed to use permanent magnets, so his machine actually used a combination of excitation.

In 1856, Jedlik came out with the idea to use residual magnetization for self-excitation; in 1861, he built a self-excited d.c. generator based on his idea.

In 1866, Siemens applied self-excitation to series-wound generators—a feature which made them attractive as sources of direct current for lighting.

However, d.c. generators remained unattractive commercially until 1870 when Gramme took out a patent for a self-excited generator with a ring-shaped armature and a toroidal winding divided into a multiplicity of coils brought out to the bars of a commutator of a nearly present-day design.

Although the Gramme ring armature was basically similar to Pacinotti's invention made in 1860, it differed in two important aspects: the ring core was made of a bundle of iron wires (as a way of reducing eddy-current losses) and had no teeth (which was a step backward from Pacinotti's idea and could not but lead to an increased reluctance of the magnetic circuit). Its advantages were obvious (a practically constant terminal voltage, freedom from an additional excitation source, a relatively smaller weight, and high efficiency), and the Gramme generator quickly ousted all the other types. At that time, the principle of reversibility had been well established, and the Gramme machine came to be used as both generator and motor.

In 1873, von Hefner-Alteneck and Siemens replaced the ring armature by a drum design in which both sides of each coil contributed to the output emf. In 1878, it was proposed to cut slots in the drum armature core, and this substantially reduced the radial gap length.

In 1879, Siemens used a series-wound generator to power the first electric railway demonstrated at the Berlin Exhibition.

In 1880, Edison proposed to build up the armature core of insulated iron laminations—a feature which led to a sizeable reduction in eddy-current losses and armature reaction. In 1884, it was proposed to add a compensating winding, and in 1885, commutating (or intermediate) poles as a way of reducing armature reaction still more and improving commutation. Thus, towards the end of the past century the d.c. machine had become almost what it is today.

64-3 Construction and Principle of Operation

As has been noted in Sec. 64-1, we shall deal with d.c. machines, that is, those connected to a d.c. system via a mechanical rectifier-inverter or, simply, a *commutator*.

To simplify the commutator design, the machine must be of inverted construction, that is, its d.c.-fed field winding must be on the stator, and the armature (output) winding on the rotor. With this arrangement, the commutator is mounted on the rotor and consists of a multiplicity of bars or segments to which the terminal leads of the armature coils are taken, and a set of stationary brushes held in contact with the commutator bars.

(a) Construction. In sketch form, the construction of a d.c. machine is shown in Fig. 64-1. Referring to Fig. 64-2, the stator consists of a yoke (or frame) *6*, the cores of main poles *1* and commutating (or intermediate) poles *3*, and the field coils encircling the poles. The number of main poles depends on the power rating and rpm. As a rule, four or six main poles are provided. Fractional-hp machines have two main poles, and very large machines up to several tens. Figure 64-2 shows the stator of a four-pole machine. The main-pole cores are built up of structural-steel sheet

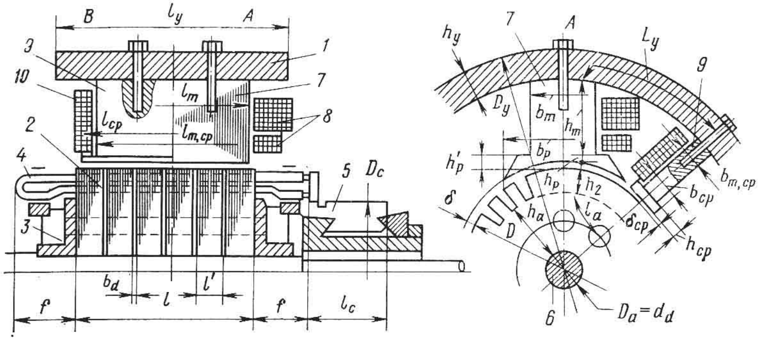

Fig. 64-1 Arrangement of a d.c. machine:
1—frame (yoke); *2*—armature core; *3*—coil-holder; *4*—armature coils; *5*—commutator; *6*—shaft; *7*—main pole core; *8*—field coils; *9*—compole core; *10*—compole coils

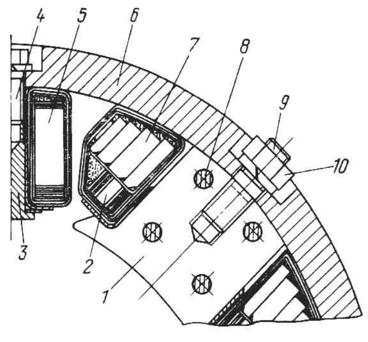

Fig. 64-2 Stator of a d.c. machine

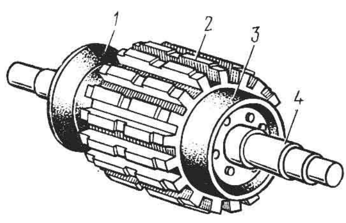

Fig. 64-3 Unwound armature

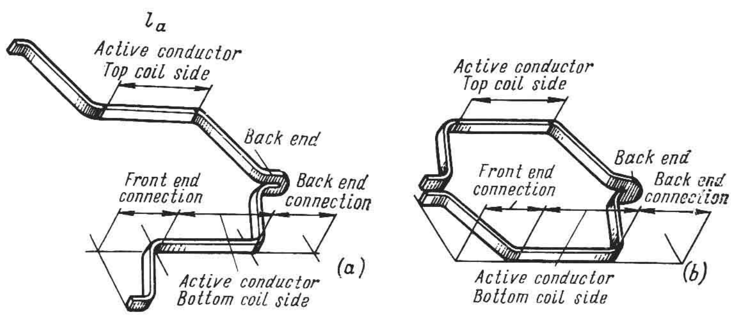

Fig. 64-4 Single-turn armature coils: *a*—wave winding; *b*—lap winding

laminations 1 or 2 mm thick, clamped together by studs *8*. Attachment of the poles to the yoke is by studs *9* screwed into the cores, and nuts *10*. The compole cores are solid pieces of iron attached to the yoke by bolts *4*.

The main poles carry the coils of one or several field windings (the series field winding *2* is traversed by the rectified armature current, the shunt field winding *7* is connected to the armature brushes and energized from an external d.c. supply). The compole coils are connected in series with the armature winding.

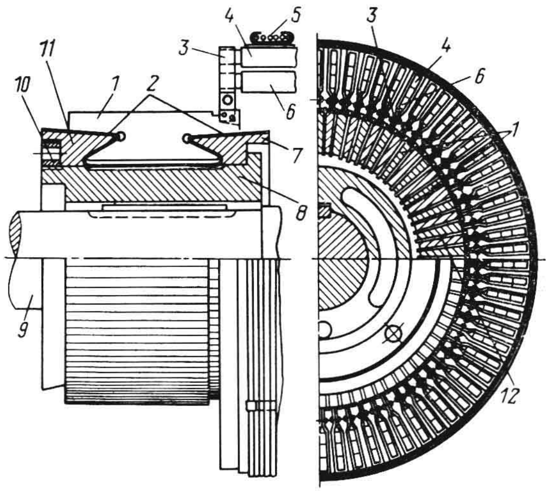

Fig. 64-5 Connection of armature coils to the commutator

As is seen from Fig. 64-3 the armature core consists of one or several blocks, *2*, of varnish-insulated electrical-sheet steel laminations 0.5 mm thick. The blocks are separated by radial ventilation ducts (not shown in the figure). The core laminations and blocks are clamped together by rings *1* and *3* which also double as coil-holders. The core armature may be mounted either directly on the shaft, *4*, or on a spider. If the outer diameter of the core exceeds 100 cm, it is assembled of segments.

The slots on the armature core receive the insulated coils of a two-layer armature winding, with the lower sides nearer to the bottom, and the upper sides nearer to the top of the slots (Fig. 64-4). As shown in Fig. 64-5, the terminal leads, *4* and *6*, of the coils are soldered to risers *3* on the commutator bars *1*. The centrifugal force of the leads is taken up by a wire binding *5*. The terminal lead *6* from the lower side of one coil is connected to the terminal lead *4* of the upper side in another coil, and all the coils are interconnected so as to form a closed winding (for the winding circuits, see Sec. 64-4).

The commutator (Fig. 64-5) is an assembly of copper bars or segments *1*. The bars are insulated from one another by mica (or micanite) spacers *12* and from the ground by tapered or cylindrical micanite washers *2*. The commutator-bar assembly is held together by a commutator shell *8* and Vee-rings *7* and *11*. In turn, the Vee-rings are held in place by a nut *10*. The commutator assembly is press-fitted on the shaft *9* and its outer surface is machined together with the bearing seats. In this way, the commutator is given a regular cylindrical shape.

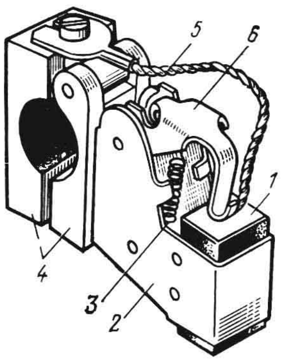

Fig. 64-6 Brush holder: *1*—brush; *2*—box; *3*—spring; *4*—brush-finger clamp; *5*—pig-tail; *6*—rocker

Electric connection between the armature winding and the external d.c. circuit is by means of brushes held in brush holders (Fig. 64-6). The brush holders are so built that the brush pressure can be adjusted at will and automatically maintained at a constant value as the brushes wear

Tangentially, a brush usually spans two or three commutator bars. Axially, the length of a brush does not exceed 3 or 4 cm. Therefore, in order to obtain a safe current density at the sliding contact, it is usual to mount several brush holders on one brush finger. The total number of brush fingers is equal to the number of poles (one half is in positive polarity, and the other, in negative polarity). The brush fingers are secured in and insulated from a rocker arm by insulating sleeves. In turn, the rocker arm is fastened to the end-shield or yoke (in the case of machines with pedestal bearings). The brush fingers of the same polarity are interconnected by brush shunts.