1 Appendix: Type Variety of Electrical Machines and Drives

The electrical energy converters presented in this lecture - regarding generators as well as drives - cover a wide spectrum of rated power ranging from about **0.1 W up to 10^9 W**, implementing a variety of designs and operating principles.

1.1 Electrical Motors and Drives

Electrical motors convert electrical energy to mechanical energy and are commonly classified in one of the two following categories:

- **stationary drives**
- **vehicle drives**

Electrical **vehicle drives** are required for small carts (like battery fed fork-lifts: typically several kW of power), electrical cars (typically 10 … 100 kW) and electrical locomotives (up to 1.6 MW power per wheel-set), but also for diesel electrical locomotives and ship drives (e.g. *Queen Mary*: twin drives with 2 x 22 MW; typically up to about 30 MW).

Stationary drives are employed in an even wider power range. Starting with micro motors (fractions of a watt) and mini motors (e.g. video camera: several drives with a few watts power) at the lower end of the spectrum, the range extends over the numerous small drives (typically 10 W to 1 kW, e.g. household appliances or fans for electronic devices) and the *lower* power range (1 … 100 kW) and the *medium* power range (100 kW to 1MW). Large drives including compressor drives in gas pipelines, pump drives in power plants and fan blower motors in wind tunnels represent the upper end of the power spectrum (1 … 100 MW; e.g. NASA research centre, *Langley/USA*: 100 MW wind tunnel motor).

1.1.1 Micro Motors

Micro motors form a "world of their own" due to their special production technology (e.g. etching technology) and special operating principles (piezo-electrical, dielectrical, capacitive and electro-magnetical effects). The variety of applications of these drives are steadily increasing (e.g. medical technology: miniature drills for invasive cleansing of clogged arteries in humans). This field is undergoing rapid technological and economical growth.

1.1.2 Miniature and Small Drives

Miniature and small drives are booming due to the increasing standard of living in the western world. The production quantities are steadily increasing. A single manufacturer can produce up to 1 million miniature drives a day (!) for use in video cameras. The demand for higher safety and comfort has lead to an increasing use of actuators in the automotive industry (Earlier: windscreen wipers, dynamo and starting motor. Today: window lift, mirror and seat adjustment, braking actuators, seatbelt fasteners, ...). The operating principle and the technology of small motors are solely electromagnetic, therefore the technology is based on copper, iron, permanent magnets and insulators, but the energy conversion occurs using different mechanisms. These include:

- **commutator motors** (AC powered universal drives, DC drives excited by permanent magnets)

- **induction machines** (as single phase motors e.g. split pole motor, single-phase hand-started motor, two phase motors on a single phase grid as a "capacitor motor", but also as small three phase motors)
- **synchronous machines** (reluctance motors, "electronic motors" (Fig. 1.1.2-1), hysteresis motors, permanent magnet synchronous motors)
- **stepping motors** (reluctance stepping motors, permanent magnet stepping motors, hybrid stepping motors, Fig. 1.1.2-2)

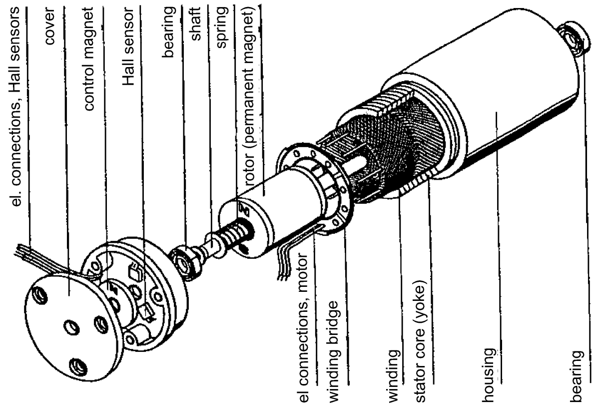


Fig. 1.1.2-1: Electronically commutated synchronous motor (2-pole) with a few watts of power. The rotor is excited with permanent magnets and the stator has an air gap winding. The winding is not placed in slots, but is glued directly onto the inner bore diameter of the stator. Hall sensors measure the position of the rotor and control a power converter in order to feed the stator winding correctly to maximize torque. Motors like these are used as wheel drives for the automated mars vehicles, e.g. the *SOJOURNER (Source: Maxon).*

Also, the **construction details** of the motors vary widely: Inner and outer rotors - bell, cylinder and disc shaped rotors with radial, axial or toroidal flux paths are used equally. Machines with relatively low power and high production quantities require a cost effective design. Being designed for a relatively short operating time and low power output, high power efficiency of these motors and thereby low operating costs are sacrificed in order to maintain low production costs. This is necessary due to enormous cost pressure on mass products like small motors. An example is the energy conversion method called split-pole principle, which suffers from low efficiency (15 … 30 %), but is cheap in production.

Example 1.1.2-1:

Operating time of a small vacuum cleaner motor (750 W): 10 years life span, usage 1 time a week for 3 hours: total amount of operating hours: 10x52x3=1560 hours.

Example 1.1.2-2:

Cost pressure in large-scale production: If 10 eurocents of the production costs can be saved per motor, a company producing 10000 units a day can save 1000 Euros daily.

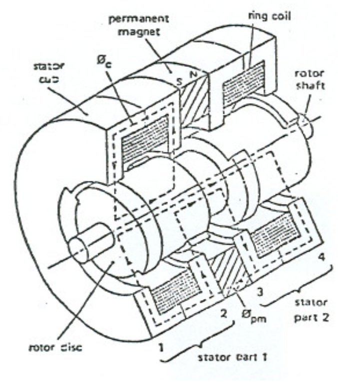


Fig. 1.1.2-2: **Hybrid stepping motor** (principle), implemented as homopolar machine. The term *hybrid* refers to the torque generation, which consists of a reluctance part (tooth and slot in rotor) and a permanent magnet part (ring magnet in stator, flux Φ_{PM}). For simplicity, the figure shows only one tooth in rotor and stator (at each disc 1 to 4). If phase 1 (ring coil in stator part 1) is excited (flux Φ_c), the permanent magnet flux is strengthened in disc 1 and weakened in disc 2. The motor locks with opposing teeth in disc 1. If the poles are reversed, the flux in disc 2 is strengthened and that in disc 1 weakened - the motor locks into a new position with opposing teeth in disc 2 (= one step is executed). Additional phases and increased number of rotor teeth and slots (= smaller slot pitch) reduce the step size. "*Homopolar"* implies that discs 1 through 4 only "experienece" oa magnetic field with one polarity, e.g. discs 1 and 2: north pole – 3 and 4: south pole (Source: *Philips*).

1.1.3 Industrial Drives – Medium Sized Machines

In the **lower and medium power range**, the variety of machine types becomes considerably smaller. Power and efficiency considerations, but also performance (like a smooth rotation), dynamics (torque to moment-of-inertia ratio for quick acceleration) and weight considerations (power to weight ratio) among others become decisive. For rated power **up to 50kW**, the following machines are in use:

- Grid and converter fed **induction machines** with 3 phase winding. Single phase operated machines (= two-phase capacitor motors) are only produced up to 5kW due to their lower efficiency of typically 75 %.
- **Synchronous machines** with permanent magnet excitation and rotor position control, also called *brushless-DC* drives (Fig.1.1.3-1), and synchronous reluctance machines. Brushless-DC drive principle is the same as with "electronic motors" of small power range (Fig. 1.1.2-1).
- Newer and still rare types are the switched-reluctance machines (Fig.1.1.3-2) - the big brother of the reluctance stepping motor with additional rotor position encoder - and the high-pole **transversal flux motor** (Fig. 1.1.3-1b).
- **DC motors,** the bigger excited electrically, the smaller by permanent magnets.

Nevertheless, the majority of drives is covered by **induction machines**, 90% of which are grid powered. The major part is designed as totally enclosed standard motors with surface cooling by shaft mounted fan (TEFC: totally enclosed fan cooled) and motor housing with cooling fins. Standardized are the main dimensions such as frame size, shaft end and key and the power to frame size relations. The dominance of these standard motors will only change slowly (e.g. in favour of synchronous machines with permanent magnet excitation or other types), as the cage machine is robust, cost effective and easily replaceable due to its standardized dimensions.

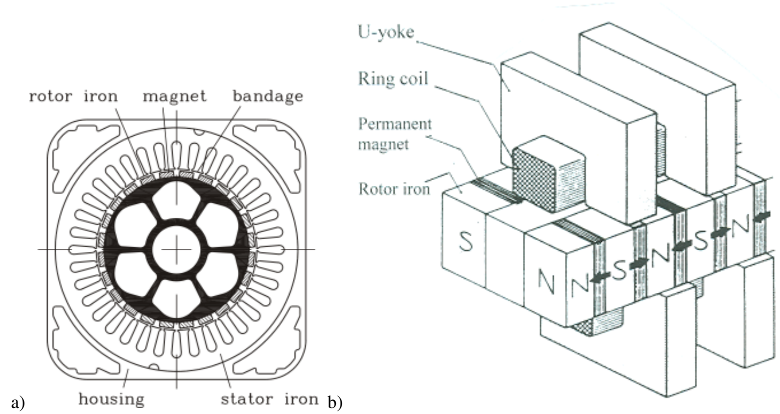


Fig. 1.3.3-1:

a) Six pole **synchronous servo motor** with permanent magnet excitation (cross section). The operation principle is the same as in Fig. 1.1.2-1. Depending on the rotor position (rotor position encoder!) the stator field is switched using a power converter and thereby pulls the permanent magnet rotor along. The stator winding is fixed in slots and the rotor has permanent magnets (each 4 of alternating polarity) glued onto it. A fibre glass bandage keeps the magnets in place, overcoming the centrifugal force.

b) The operation principle of *a)* built as a transversal flux machine, according to Prof. *WEH*/Braunschweig, shown linearly unrolled: one phase, consisting of two e.g. serially connected ring windings, which are aligned above and below of the permanent magnet rotor, is shown together with the corresponding rotor part. The rotor magnets are arranged in a *flux concentrating design* in order to increase the magnetic field in the air gap. A high pole count is possible even with a small pole pitch, as no slots exist. The flux is guided *transversal* to the motion direction. The machine has a high power density at low speed. (Source: *Prof. Weh*)

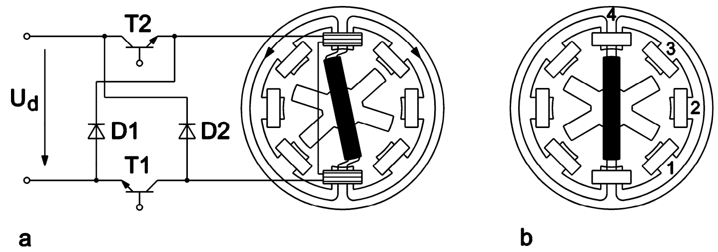


Fig. 1.1.3-4: 2-pole **switched reluctance machine** with four phases (phases 1 to 4): Using a power converter (consisting of two transistors T1, T2 and two free-wheeling diodes D1, D2 per phase), the voltage U_d from a DC circuit is fed into the phases (here: phase 4). As the number of teeth in the rotor is lower than in the stator, the rotor turns from position *a* to position *b*. In position *b* the current in phase 4 is switched off and the procedure is repeated with phases 1, then 2 and 3 and so on, so that the rotor keeps turning.

Beyond **100 kW up to 1 MW**, we usually find:

- 3-phase induction machines - mostly cage machines, but also slip ring rotors -
- electrically excited DC machines, fed from thyristor converter.

Synchronous machines in this power range are rare due to their high costs. All of these drives are commonly connected to a low voltage grid (rated voltage 1000V or below).

1.1.4 Large Drives

Large drives require medium voltage due to the increasing power rating. Thus the rated current values are limited and thereby the wire cross-sections. Rated voltages like 3.15 kV, 6.3 kV and 10.5 kV are in use. Up to 30 kV insulation technology is technically feasible nowadays. The main problem of these high voltages is the safe insulation of the slot conductors, which are situated in the slots, being only some millimetres or centimetres distanced from the grounded iron sheets. Resin impregnated mica and glass fibre composite insulation is used. The insulation problem differs strongly from that of oil insulated transformers or air-insulated overhead lines, and is more like the cable insulation problem. So, recently electrical machines are also constructed using cable windings **("Powerformer")** to raise the rated voltage up to 60 ... 100kV, avoiding dditional transformers (e.g. *Porjus* hydro power plant, *Sweden*). Future will show, if this technology will be used more widely.

The **induction machine** can also be constructed as a **large drive**, commonly built as a converter fed drive with an intermediate current- or voltage-source converter up to typically 10 … 20 MW, the limit being steadily pushed upwards. The maximum speed, voltage and thereby power of **DC machines** is limited by the commutator, which is sensitive to centrifugal forces and flashovers. That is why large DC machines are built with a maximum of about 10 MW rated power and are being replaced by **electrically excited synchronous machines**. Some of these converter-fed synchronous machines are used for high speed operation up to 10000/min, built as **"turbo rotors"** with massive rotors made out of hardened steel for unit power range from 10 … 50 MW (Fig. 1.1.4-1b). Applications are high speed compressor and pump drives without gear box, being operated at speed 3000 … 9000/min. Slowly rotating *direct synchronous drives* do not require a gear box, as they are able with salient pole rotor design to deliver high torque at low speed.

Example 1.1.4-1: (Fig.1.1.4-1a)

Slowly rotating direct drive: Speed range 5 … 20/min, torque up until 5 000 000 Nm, used for driving ball mills to refine ore and revolving furnaces in cement production.

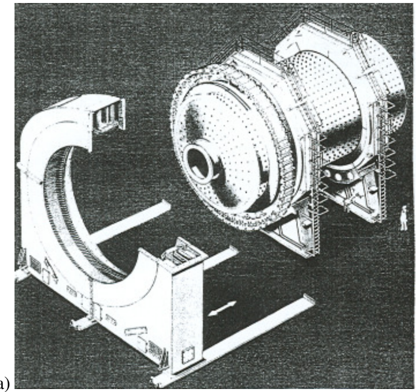
Example 1.1.4-2:

Comparison of the strain on small and large drives:

Application	*Vacuum cleaner fan motor*	*Refinery gas compressor*
Motor type	universal 2-pole motor	synchronous 2-pole motor
Rated power	1500 W	17 MW
Maximum speed	40 000/min	6060/min
Rotor surface speed	100 m/s	200 m/s
Life duty	10 years, 3 h per week	25 years, 24 h a day
Total operating hours	1500 h	220 000 h

While speed of 40 000/min at 1.5 kW may be considered high for a vacuum cleaner drive (universal motor), only 6000/min for a large drive at 20 MW are of much bigger technical challenge. Such a drive must be operate for 220 000 hours instead of only 1500 hours of an universal motor. Additionally, the larger rotor dimensions raise the mechanical stress of the rotor materials, expressed e.g. by rotor surface speed, to their limit.

Conclusion:
Large drives are usually far more mechanically stressed than small drives. Therefore, they require accurate design, precise manufacturing (single part production!) and special maintenance (on-line monitoring of e.g. bearing and winding temperature).

a) 

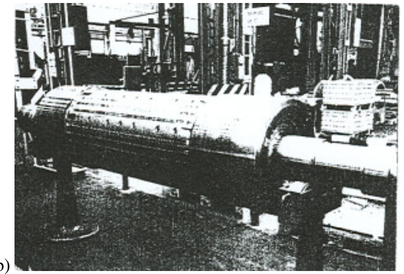
b) 

Fig. 1.1.4 -1: Synchronous direct drives (without gear box): a) ring motor as a revolving cement furnace drive, b) turbo rotor of a fast turning compressor drive (Source: *Siemens*)

1.2 Electrical Generators

Of course, all machines discussed in 1.1 are capable of acting as a generator, converting mechanical into electrical energy. This is what is needed during dynamic braking. However, customers buy these mainly in order to use them as motor drives. The main purpose of especially designed electric generators is to transform mechanical into electrical energy. They also cover a wide range of power and reach the highest unit power for single machines, currently 1800 MVA as four-pole nuclear power plant generators with direct water cooling.

1.2.1 Low Power Generators

The **low power** range (up to some kW) is dominated by the on board generator, or *dynamo*. In the automotive industry it is implemented as a claw field synchronous machine (LUNDELL machine, Fig. 1.2.1-1) with controlled electrical rotor excitation. This design is cost effective and therefore suitable for mass production, but has a low efficiency of below 70% due to eddy current losses in its solid rotor surface and high magnetic rotor leakage flux.

1.2.2 Medium Power Generators

In the **medium power range** (10 kW … 1 MW), electrically excited synchronous machines - salient pole rotors or cylindrical rotors - with mostly rotating exciter circuits are used. Also, induction generators, which draw their magnetising power from the grid or - in isolated applications - from a capacitor bank in parallel, are in use. Applications of such generators are *small hydro-power generators,* which have a gear box between the slowly rotating water turbine and the rapidly revolving low pole generator, *wind generators* (mostly with gear box) and *diesel emergency power generators.*

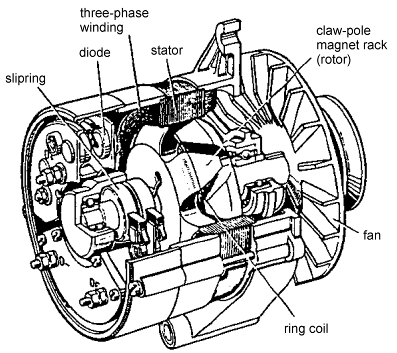


Fig. 1.2.1-5: **Claw field dynamo**: The rotor (magnet wheel) consists of two claw parts and an intermediate ring coil, which is excited by a DC current (field current) via slip rings. The magnetic circuit is closed by both claw parts, such that claws from one part form the north poles and those from the other part form the south poles. The revolving rotor induces a three phase voltage and current system into the stator winding, which is rectified by diodes in order to supply the vehicle's battery and loads. The field current is drawn from there, too (Source: *Bosch*).

1.2.3 Large Generators

The most prominent role of the synchronous machine is the large generator. The **upper power range** starting at 1 MW is undisputedly dominated by the synchronous generator. Its unique ability to provide inductive as well as capacitive reactive power to the grid depending on the rotor excitation makes it indispensable, since the grid predominately demands inductive reactive power. This is why not the active power is stated in the machine data sheets, but the rated apparent power (e.g. 30 MVA). Due to the high power output, rated voltages up to 30 kV are needed.

Example 1.2.3-1:

Rated generator power: Active power of the turbine: $P = 24\text{MW}$, demanded $\cos\varphi = 0.8$ (for inductive load). Rated apparent power: $S = P/\cos\varphi = 30$ MVA

Typical large generator scenarios are:

- **hydro power generators**
- **steam and gas turbine turbo generators**

a) Hydro Power Generators

Hydro power plants at big rivers with a high water flow rate and low pressure head of a few metres require a special turbine in order to guarantee optimum efficiency independently of the water flow rate, which depends on the season. The ***KAPLAN* turbine** is a propeller turbine with adjustable rotor blades (typically four) and guiding blades. Thus optimum efficiency may be controlled at constant speed (Fig.1.2.3-1). Due to the low water velocity in rivers the rotational speed of the turbines is low (e.g. 50/min), making it necessary to build the directly coupled generator with many poles to make an induced AC current of 50Hz possible. These salient pole machines are built as *umbrella-type generators* with vertical shaft or *bulb-type turbines* with horizontal shaft with a power range of 20 MVA to 40 MVA.

Example 1.2.3-2:

Pole number of a slowly rotating umbrella type generator: $n = 50/\text{min}$, $f_{\text{grid}} = 50\text{Hz}$:
$2p = 2f_{\text{grid}}/n = 2{*}50/(50/60) = 120$ poles: 60 north and 60 south poles!

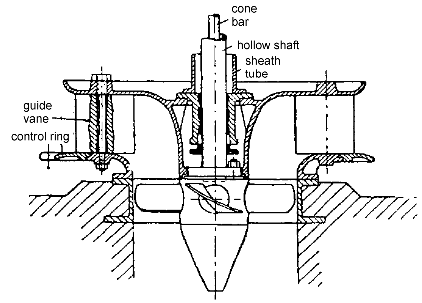


Fig. 1.2.3-1: Vertically supported ***KAPLAN* turbine** with four propeller blades: In order to operate the turbine with constant speed independently of the water flow rate, the rotor blades are adjusted via a rod and the guiding blades by a ring. A mechanical control device operates in dependence of turbine speed and water inflow the rod and ring. This allows the adjustment of an optimum angle of attack of the water flow onto the blades to get optimum efficiency.

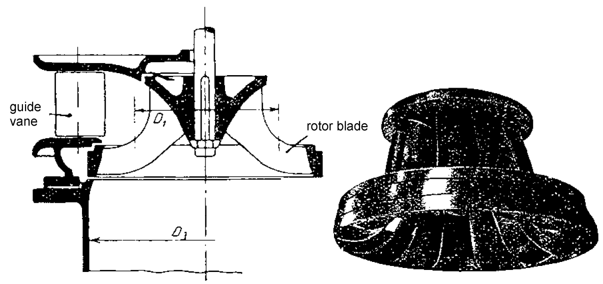


Fig. 1.2.3-2: Vertically supported ***FRANCIS* turbine**: The rotor blades are cast and therefore not adjustable. The water attack angle onto the rotor blades is controlled by the adjustable guiding blades (vanes), depending on the water flow rate.

Medium pressure power plants with pressure head of up to 30 m usually employ the ***FRANCIS* turbine**, which has non-adjustable rotor blades curved in three dimensions (Fig. 1.2.3-2). These turbines are commonly vertically supported and directly coupled to a synchronous salient pole generator. Large power plants like *ITAIPU* at the river *Parana* in South America at the border between *Brazil* and *Paraguay* reach power ratings of up to 800 MVA per generator.

Storage and pumped-storage power stations feature low water flow rate and high pressure head, resulting from big heights of up to 1500 m between the reservoir water surface and the turbine, thus calling for the use of ***PELTON* turbines** (Fig. 1.2.3-3). The rotor consists of twin cups instead of blades. 5 … 7 injectors, which are circularly installed around the turbine rotor, tangentially eject the water jet onto the rotor cups, thus driving the rotor. Reversing the turning direction is thus not possible. The turbine revolves rapidly due to the high water jet speed (e.g. 500/min, 750/min, 1000/min), requiring low pole, high speed **synchronous salient pole machines**. Due to their high power output of up to several 100 MVA per unit they are referred to as *"limit rating machines"*.

The mechanical and electro-thermal stress put on the material are at the limit of what is technically possible. Sometimes even direct conductor cooling with deionised water, flowing in hollow copper conductors, is necessary. Often, the machine is designed also for motor operation in times of low power consumption (e.g. during night), in order to pump water into the reservoir, storing the excess power from the thermal power plants, which operate in base load mode. The second shaft end of the machine is coupled with a multi-stage radial pump, or the turbine is designed in such a way, that it can directly act as a pump. This is only possible with *FRANCIS* turbines, but not with *PELTON* turbines.

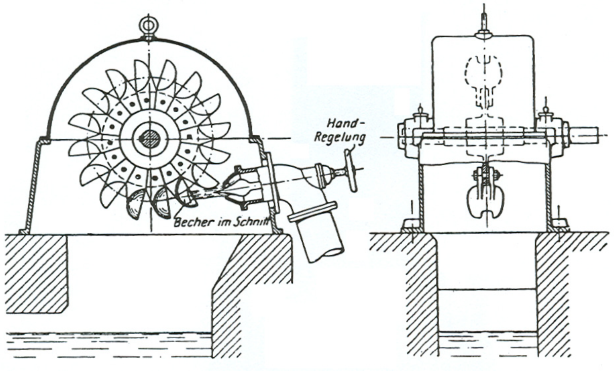


Fig. 1.2.3-3: Horizontally supported ***PELTON* turbine**: The rotor twin cups are attacked by water jets from injectors. The jets are adjusted in strength by needle valves. The pressure head of these jets is high, while the water flow rate is relatively low. (Here: Manually operated needle valve for injector, only one injector displayed)

Example 1.2.3-3:

Pole count of a fast turning generator: $n = 1000/\text{min}$, $f_{grid} = 50$ Hz:
$2p = 2 f_{grid}/n = 2*50(1000/60) = 6$ poles: 3 north and 3 south poles!

b) Generators in Thermal Power Plants

Steam and gas turbines are used in thermal power plants to convert thermal into mechanical energy. Turning at high speed of 3000/min or 3600/min, they need 2-pole generators in order to produce 50 Hz and 60 Hz respectively. Technology of **gas turbines** (Fig. 1.2.3-4) allow maximum power per unit up to 250 MW, while steam turbines have an output of up to 1000 MW when built as a full speed variant (3000/min or 3600/min) and 1600 MW and more as half speed machines (1500/min or 1800/min). As these generators are driven by thermal turbo machines, they are called **turbo or turbine generators** and are the electrical machines with the highest power output ever built. Due to their high rotational speed, they are highly mechanically stressed and therefore have massive rotors milled out of hardened stainless steel that is open-die forged and cutter processed. The high stress caused by the large centrifugal forces only allows for rotors with a diameter smaller than 1.2 to 1.3m for 3000 … 3600/min.

Example 1.2.3-4:

Rotor surface speed: Rotor diameter $d_r = 1.2$ m, speed $n = 3600/\text{min}$:
$v = d_r \pi n = 1.2\pi \cdot 3600/60 = 226$m/s (= 814km/h!) = 70% of speed of sound.

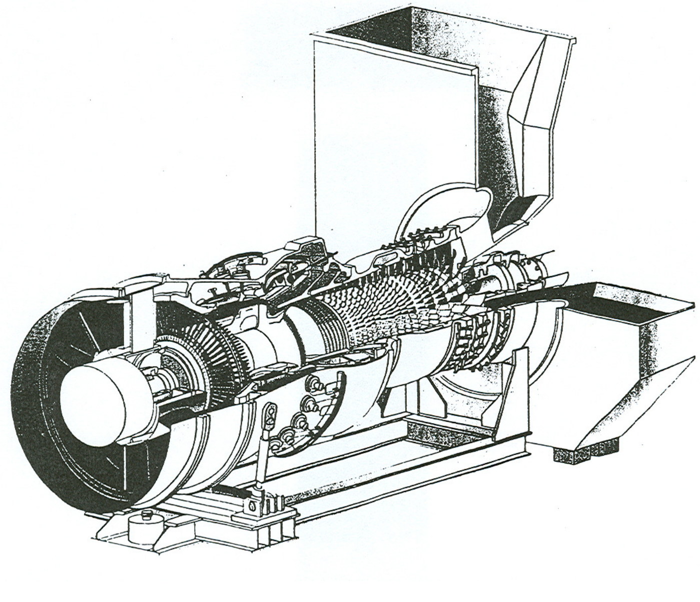


Fig 1.2.3-4: **Gas turbine**: The air inlet and the air compressor (compression ratio about 1:30) can be seen at the right side, followed by the fuel supply (e.g. crude oil, natural gas) and the combustion in two circular combustion chambers. The hot gas (up to 1300°C) expands in the adjacent turbine at the right side, which comprises several stages. As the gas volume increases, the rotor blades increase in length from stage to stage. The gas outlet at the left front end with about 600°C gas temperature can be used to vaporise water, which can power a steam turbine (combined gas and steam power plant = combined cycle). The efficiency of the gas turbine is around 38% and can be increased to 58% when combining with a steam turbine. When using excess heat for long distance heating, the thermal efficiency of the entire plant can reach 90% (Source: *ABB/Alstom*)

Whereas the turbo generator converts the total unit power in **one** machine, the power generation in the coupled steam turbine has to be done in **three** machines: The **high, medium and low pressure** turbine. As the steam in the low pressure part has a much larger volume compared to the high pressure part due to expansion, it large cross-sections for the steam flow. The turbine blades in the low pressure part are therefore long (e.g. 1m) and have a large outer diameter D (e.g. 4 m). Due to the high centrifugal forces, they must be produced with high mechanical quality, for example out of forged martensitic-ferritic steel with a 12% chrome concentration.

Example 1.2.3-5:

Lignite coal power plant *Lippendorf*: 930MW per generator 3000/min, 50 Hz
High pressure turbine: 250 bar at 550°C
Low pressure turbine: Steam expands from 0.5 bar to condenser pressure 0.038 bar, which is

near vacuum pressure.
Total efficiency of the plant at full load: 42.4% (generator efficiency at 99%)

<u>Example 1.2.3-6:</u>

Mechanical strain on the turbine at over-speed speed $n_{max} = 1.2 n_N$ in case of load drop (n_N = 3000/min):

(i) Top circumference speed at the blade tips:
$v_{max} = 1.2\ n_N D\pi = 1.2*50*4\pi = 753$ m/s = 2710 km/h (!)
The steam speed is partially **supersonic.**

(ii) Centrifugal force on one blade: Blade length is 1m, mass m = 10 kg, centre of gravity at r = 1.2 m from the centre of rotation axis.
$F_{blade} = m \cdot r (1.2*2\pi\ n_N)^2 = 1700$ kN = 170 tons

This corresponds to the weight of two high performance electrical locomotives (e.g. *Austrian Railways* locomotive *Taurus* 1016: 6.4 MW, 84 tons).

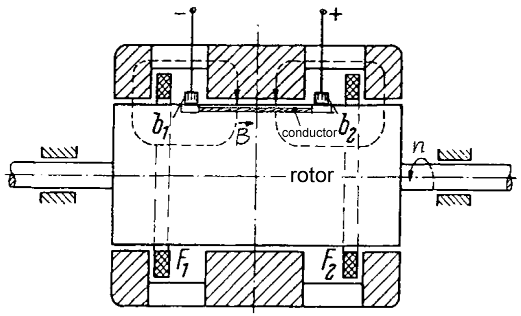
The power output for a single generator ("unit rating") has been steadily increased in the past decades, such that the power generated in the steam turbine can be electrically converted in **one** generator. An **increase in power** by means of enlarging the diameter is not possible above 1.2 m at 3000/min. Also, increasing the active rotor length above 7 m is not feasible, as the rotor becomes too thin and therefore elastic bending is too big ($l_{Fe}/d_r = 7/1.2 = 5.8$!). The remaining option is to increase machine utilisation (i.e. more power from the same volume) - thus the conductor current and/or the magnetic field have to be raised. The iron saturation prohibits an increase of magnetic flux in the air gap above 1.2 T. The power can only be increased by increasing the current and the current density, which leads to elevated resistive losses. This calls for more effective cooling. Up until 300 MVA, this can be done with air. But above that, direct conductor cooling using hydrogen gas or de-ionised (electrically non-conductive) water in the hollow copper conductors is necessary.

1.3 Outdated Machine Designs

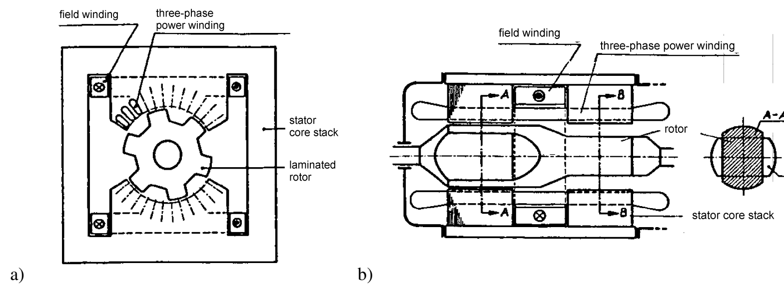
There are of course many more machine designs in existence, than can be described in this overview. Many special designs are only applied in niches or are no longer produced, as their technical and economical advantages are outweighed by their disadvantages. This led to the disappearance of several machine concepts such as the **repulsion motor**, a special variant of the AC fed commutator motor, the "cross-field" welding generator after *ROSENBERG*, the **three conductor machine**, the **Amplidyne**, the **Rototrol drive**, the *PESTARINI* drive and the exciter machine with isthmus poles.

Furthermore, **rotor- and stator-fed AC polyphase commutator machines** are being used in rare cases as variable speed drives and are manufactured by some specialised companies. The stator-fed variant has a typical maximum power rating of 500 kW, the rotor-fed type of only about 50 kW. These commutator machines with an adjustable brush position and a three phase winding in the stator allow for variable speed operation at the 50 Hz grid without the need for a power converter. However, the lack of inter-poles makes the commutation of rotor armature currents in the brushes critical, limits the power rating and makes the maintenance (brush exchange) extensive. Therefore their use is limited.

Sometimes, the **unipolar machine** (Fig. 1.3-1), a DC machine without commutator featuring direct armature current, is still in use today. Regarding electrical rocket drives and military applications (**electric gun**), it is undergoing a revival.



<u>Fig. 1.3-1:</u> Schematic cross section of an **unipolar machine**: The field coils F_1, F_2 (ring coils) produce a stationary magnetic field, that shows only one polarity (**unipolar**, here north pole) in the area of the armature conductors (rotor conductors). A low voltage is induced into the rotor conductors, which are connected in parallel. By means of slip rings and the brushes b_1, b_2 this low voltage and - due to the parallel connection – the large armature current are guided to the terminal box. The magnetic flux lines close outside the armature area.



<u>Fig. 1.3-2:</u> Medium frequency machines:

a) Axial cross-section of a 12-pole **heteropolar machine** after *SCHMIDT-LORENZ*: The exciting coils produce a static field in the air gap, which enters the upper part of the rotor as a north pole and exits its lower part as a south pole (**heteropolar field**). A pulsating alternating field with a frequency proportional to the rotor teeth is generated by rotating of rotor cog wheel, modulating the stator field. The air gap field per half e.g. in the upper half of the rotor is higher in the rotor tooth than in the adjacent slots thereby producing the field modulation. This alternating field induces a three phase voltage into the three phase stator winding with rotor teeth frequency (e.g. 6 rotor teeth, n = 9000/min, $f = Q_r n$ = 6*(9000/60s) = 900 Hz). As the rotor turns in the static field, its magnetisation is changing with rotational frequency. In order to suppress eddy currents, therefore the rotor has to be laminated by insulated iron sheets.

b) Section of a 4-pole **homopolar machine** after *ARCO*: The exciting ring coil produces a unipolar flux (**homopolar field**) in both axial machine parts. This flux is modulated by the rotor teeth (here: Q_e = 2), which induces a three phase voltage in the three phase winding with rotor tooth frequency. Rotor slots and tooth sections are swapped in both machine parts, as to reverse the phase change of the induced voltage (first machine half: north homopolar field, second half: south homopolar field). The rotor "experiences" no change of polarity of the magnetic field and can therefore be massive, enabling the machine to act as a robust drive for very high speed.

Medium frequency generators, such as synchronous cog wheel rotor machines in hetero- and homopolar design have mostly disappeared (*SCHMIDT-LORENZ* machine in Fig. 1.3-2a), *ARCO* machine in Fig. 1.3-2b), *GUY*- or oscillating field machine). Medium frequencies in the range of several kHz are nowadays more easily produced using solid state power converters. However, the homopolar machine after *ARCO* has - due to its solid rotor without any winding - still got a special application as a robust rotor for high speed (e.g. drive for **flywheel storage**). *Homopolar* means that only north *or* south poles occur at the machine's circumference. This is why the homopolar machine consists of two halves, when seen from an axial point of view. *Heteropolar* on the other hand refers to the common design with magnet poles of alternating polarity (N-S-N-S...) at the machines circumference.