Specific Problems of High-Speed Electrical Drives

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1.0 INTRODUCTION

Electrical machines exist for different speed ranges. However, what a high speed is for one type, for instance a stepper motor, could be a low speed for another type, such as a permanent magnet synchronous machine. In brief: there is in fact no clear definition of a *high-speed machine*. In general, a machine is considered high-speed when its design needs to be adapted mechanically or electrically from that of the conventional machine in order to achieve the desired speed range.

High-speed machines may be required or become beneficial is certain applications such as gas compressors, pumps, centrifuges, distributed generation units (microturbines) and flywheel energy storage.

It is actually better to talk of *high-speed drives* since high-speed machines rarely can be operated 'open loop' from the electricity grid. At least a power electronic converter is required to supply the necessary high-frequency voltages. This is further completed by a controller with sensor-equipped feedback loops. In general the transmission to the mechanical load or power source is as simple as possible, a shaft, as high-speed machines are often introduced to omit more complicated transmissions, more in particular gears.

There can be different reasons to opt for a high-speed drive. Some typical advantages are:

- The presence of a gear can be avoided. Since every gear represents some transmission losses (efficiencies are around 95%) this may positively affect the total system efficiency if the high-speed motor does not exhibit relatively more losses. Noise and non-linearities (e.g. vibrations caused by hysteresis) of high-speed gears is an important issue.
- A high-speed motor is more compact than a geared low-speed equivalent. It can be proven that for most machines, the torque rating determines the size over the speed rating, so for an equal power rating, a smaller size is obtained. This is important when the electrical machine is to be integrated with the mechanical load or source.
- The cost of a high-speed motor may be lower than the cost of a low-speed motor of equal shaft power with a transmission.

2.0 LIMITS OF AN ELECTRICAL MACHINE DESIGN

The maximum operating range of an electrical machine is not easily described as it is characterized by several parameters. Nevertheless they can be grouped into three families: mechanical limits, thermal limits and electromagnetic limits. Additionally, one can enlist the limits of the power electronic converters, especially the switching frequency, as well.

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The maximum speed of a machine is limited by the centrifugal force and by elastic instabilities related to critical speeds. On the other hand the maximum power, peak as well as continuous, is limited by the allowed temperature rise of the rotor and stator. High speeds generally also mean high voltages and fluxes, which is to be accounted for in the electromagnetic and electrical design.

2.1 Mechanical Limits

First of all, the mechanical limitations of a high-speed electrical machine are not different from the mechanical problems encountered in any high-speed rotating device, for instance a turbine, compressor or pump:

- The bearing needs to be able to sustain, in a stable way, the envisaged speed. For higher speeds, non-touching air bearings or magnetic bearing may be a solution.
- Ventilations losses or any losses due to friction will rise in non-linear way. A different filling or vacuum operation may be a solution.
- Part of the structure comes to close to the elasticity/plasticity limit, which makes material choice difficult, since most strong materials are non-magnetic and reverse.
- The centrifugal force wants to radially push out any component in the rotor. This may cause difficulties for rotors with windings or permanent magnets, close to the air gap. It is then possible to use a thin non-magnetic bandage (e.g. fibre-glass). Any form of rotating end-winding or end-ring is also subject to this force. This last problem can be dealt with by introducing retaining caps over the end-winding region. It is very important that these are made of non-magnetic material.
- Any high-speed rotating device knows some critical speeds. In principle this shouldn't be a problem as long as the machine does not intend to stabilize in that region; a fast run-through prevents building up the energy in the resonance. However, the location of the critical speeds may be totally different from what a mechanical analysis might show as electromagnetic force can introduce additional 'elasticity'. Especially forces in radial direction are of large influence. An example is the force that arises due to eccentricity, static or dynamic, of the rotor in an induction machine: the magnetic flux just wants to close the air gap further, yielding an extra negative 'spring constant' (Fig. 2.1).

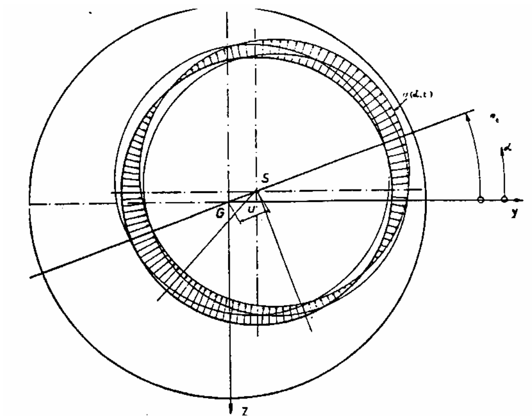

Figure 2.1: Force Distribution in Case of Eccentricity.

2.2 Thermal Limits

The thermal limit of a machine is defined by the maximum temperature that can be sustained by a constructional or functional part. The most come are:

- Insulation around the conductors sees its life-time diminished due to overtemperatures: a constant overtemperature of 10° halves the remaining life-time.
- Core material made of stacked iron may get 'brunt', which means the thin insulating coatings on the plate get damaged.
- Permanent magnets may get irreversibly demagnetised at higher temperature.
- Mechanical material failures, e.g. broken conductors, are more likely to occur.

An electrical machine represents a large thermal time constant as a whole, but locally a fast thermal transient may already be very damaging.

The *cooling* of an electrical machine is not obvious. Most standard machines are air-cooled, with external cooling fins, often by a ventilator mounted on the shaft. At higher speeds, this may be very noisy and take up a fair deal of torque, so an independent cooling is required. The cooling of the rotating parts is always very difficult and hard to quantify as it has to be accomplished by the air flow in the air gap and in the end-winding region. Often cooling fins are mounted on the ends of the rotor for this reason. For special machines, e.g. compact machines or machines in hot environments, water cooling may be required.

The internal heat sources are discussed in the next section, but one should not forget about the external heat sources. An often present heat source is conduction of heat through the shaft to the rotor. This may be the case in case of a connection to a combustion engine or turbine.

2.2.1 Internal Heat Sources: Losses

The internal heat sources are mainly of electromagnetic nature, but friction or ventilation losses of any kind are important as well. The electromagnetic losses are discussed in detail, with special attention to the frequency (and thus speed) dependence:

Joule Losses

Joule losses are present in every current carrying conductor (non-superconductor). The Joule loss density q_{Joule} in a conductor is given by:

$$q_{\text{Joule}} = \frac{J_{\text{tot}}^2}{\sigma} \tag{2.1}$$

With σ the conductive (temperature dependent) and J_{tot} the current density. The current is the total current, containing the DC current value and additional eddy currents, arising due to induction effects. Although both terms 'Joule loss' and 'eddy current loss' are frequently used, it is theoretically not possible to separate the contributions of source and eddy currents in since both feature as part of the squared total current.

At higher frequencies, due the higher speeds[1], the current redistribution caused by internal eddy currents plays an important role. At low frequencies, the current can be assumed equally spread out over the conductor's cross-section, but when the 'skin depth', defined as the boundary of the region where the largest part of the current flows, becomes of the order of the conductor's size, the equivalent resistance (AC resistance), to be used in the total Joule loss expression $R.I^2$, is much higher. The skin depth decreases with the square root of the frequency:

[1] For instance, a four-pole machine running at 500.000 rpm, will have a fundamental frequency of 16.667 kHz.

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{2.2}$$

The resistance changes according to:

$$\frac{R_{AC}}{R_{DC}} = h/\sigma \, \frac{\sinh\left(2\,h/\sigma\right) + \sin\left(2\,h/\sigma\right)}{\cosh\left(2\,h/\sigma\right) - \cos\left(2\,h/\sigma\right)} \tag{2.3}$$

Iron Losses

Iron losses are a generic name for loss phenomena connected to non-constant magnetic fields present in ferromagnetic, often laminated, materials. They are split in pure hysteresis losses, associated with the magnetic hysteresis loop, and dynamic iron losses due to local eddy currents. The latter occur due to the fact that ferromagnetic materials are almost always electrically conducting as well. The dynamic losses themselves are distinguished in classical (macroscopic) Joule (eddy current) losses and excess or anomalous losses representing the loss contribution due to the motion of magnetic domain walls and interactions of the domain walls with the crystal lattice.

$$q_{\text{tot}} = q_{\text{hys}} + q_{\text{dyn}} = q_{\text{hys}} + \left(q_{\text{class}} + q_{\text{exc}}\right) \tag{2.4}$$

The local magnetic field vectors can be simply oscillating in magnitude (indicated as alternating) or rotating.

The *hysteresis loss* density is linked to the surface within the B/H characteristic followed in a period T (Figure 2.2) of the local magnetic field vectors:

$$q_{\text{hyst}} = \frac{1}{T} \int_T \boldsymbol{H} \, \mathrm{d}\boldsymbol{B} \tag{2.5}$$

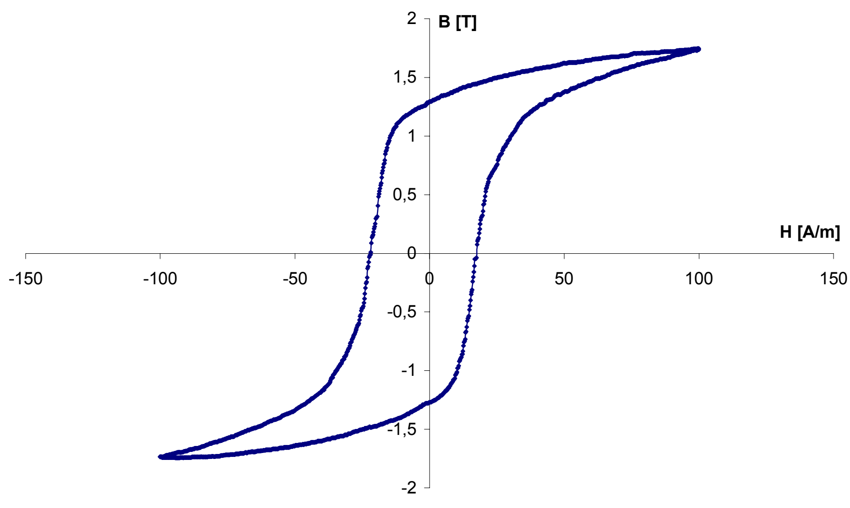

Figure 2.2: Typical Course of the Magnetisation Characteristic of Ferromagnetic Material used for Core Lamination.

Very often expressions based on the Steinmetz equation are used. They give the hysteresis loss density as a function of the peak value $\hat{B}$ of the flux density:

$$p_{\text{hyst}} = C_{\text{h}} f \hat{B}^{n_{\text{St}}} \tag{2.6}$$

with n_{St}≈1.6 for many steel types. When the flux is non-sinusoidal, the hysteresis loop is not followed as indicated in Fig. 2.2. Minor loops may arise locally. In this case, the losses increase and a correction factor is then added.

Classical Eddy Current Loss Term

The classical eddy current loss term is a local Joule loss in the electrically conductive ferromagnetic material. It is calculated assuming a constant flux density amplitude over the (thin) cross section *d* of the lamination. The metal sheet is assumed to be perfectly electrically insulated (e.g. by the coating) from the adjacent lamination sheets:

$$q_{\text{class}}^{\text{alt}} = \frac{\sigma d^2}{12} \frac{1}{T} \int_T \left(\frac{\partial B}{\partial t} \right)^2 \mathrm{d}t \tag{2.7}$$

When the coating is conductive, additional intersheet eddy currents may arise. In case of a sinusoidal flux, this reduces to the following formula, clearly showing the square frequency dependence:

$$q_{\text{class}}^{\text{alt}} = \frac{\pi^2 \sigma d^2 f^2}{6} B^2 \tag{2.8}$$

2.2.2 Influence of Temperature

The augmenting temperature may be dangerous when it gets too high, but before any damages take place, significant changes in the material parameters are encountered. So, the performance of the whole machine is affected: the torque-speed relationship changes and the electromagnetic time constants to which the controllers are tuned have altered. An overview:

Electrical Conductivity

An important temperature dependent characteristic, directly affecting the electrical current distribution, is the electrical conductivity σ.

$$\sigma = \frac{1}{\rho_{\text{E}}} = \frac{\sigma_{\text{ref}}}{1 + \alpha_{\sigma,\text{ref}} \Delta T} \tag{2.9}$$

Fig. 2.3 shows the change for copper: over a normal operating range, the value quickly changes 30%. Table 2.1 collects some values for common electrotechnical materials, including the electrical conductivity temperature coefficient α_σ.

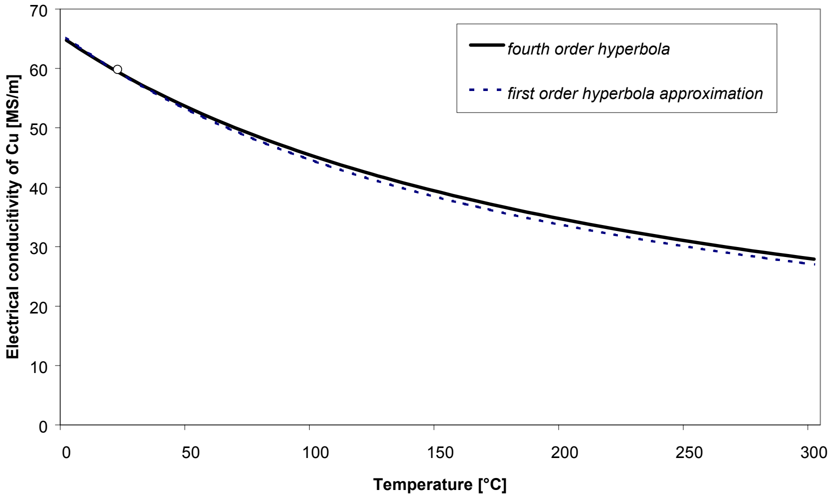

Figure 2.3: Electrical Conductivity of Copper.

Table 2.1: Electrical Conductivity and Related Temperature Coefficient for Common Electrotechnical Materials

Material	$\sigma\ [Sm^{-1}]$	$\alpha_{\sigma,20°C}\ [K^{-1}]$
copper	$5.8 \cdot 10^{7}$	$3.9 \cdot 10^{-3}$
aluminium	$3.5 \cdot 10^{7}$	$4.03 \cdot 10^{-3}$
(magnetic) steel	$3.5 \cdot 10^{6}$-$5 \cdot 10^{6}$	$4.5 \cdot 10^{-3}$

A special type of temperature related electrical conductivity phenomenon is superconductivity. For a special class of materials, electrical resistance vanishes at a certain low temperature. The transition to the ‘regular’ conductive state takes place in a very narrow temperature zone, i.e. almost discontinuously (quench). Experiments have been made with superconducting machines (rotors of turbo generators), but it never broke through.

Magnetic Permeability

The magnetic properties of metallic materials with a small hysteresis loop (so-called ‘soft magnetic’ materials), such as ferromagnetic laminations, have a temperature dependent permeability. All those materials have, apart from the saturation phenomenon, a transition temperature, the Curie temperature T_C, beyond which the magnetic properties vanish. For many metal alloys, square root or exponential expressions can be used to evaluate the permeabilities over a wide temperature range, e.g.

$$\mu(H,T) = \mu_0 \left(1 + \sqrt{\frac{T_C - T}{T_C}} \frac{\beta_\mu}{1 + \frac{H}{\gamma_\mu}} \right) \tag{2.10}$$

The magnetic properties evolution of magnetic steel ST44-3 is plotted in Figure 2.4.

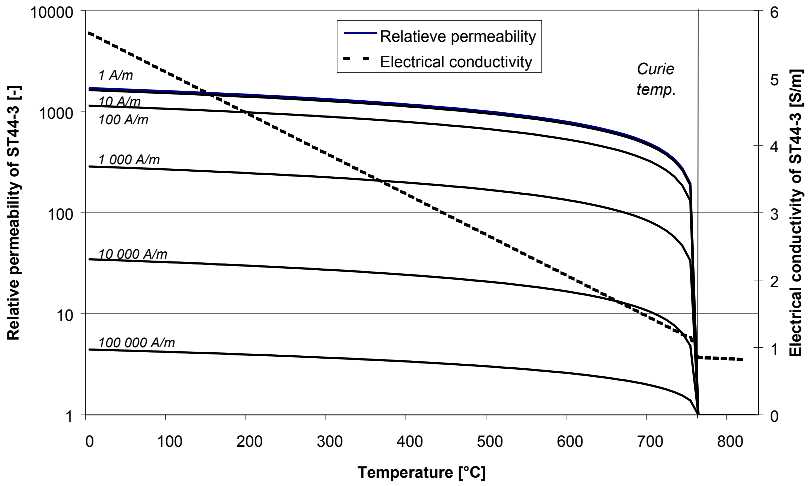

Figure 2.4: Temperature Dependence of the Magnetic Permeability and Electrical Conductivity of Stainless Steel ST44-3.

As can be noticed from Fig. 2.4, the permeability remains almost constant over a large range in the lower temperature region. Therefore, the magnetic properties in electric machines and energy converters are assumed to be constant in the rated operation ranges. The Curie temperature is usually too high for electrical machines.

Permanent Magnets

Permanent magnets are magnetic materials or composites with a wide hysteresis loop, resulting in an important remanent field. For these types of materials, the changing hysteresis loop in the second *B-H* quadrant needs to be considered. In Figure 2.5, the influence of the temperature on the magnetisation characteristic of NdFeB is shown. Both the magnetisation and the magnetic induction are plotted. It is, in fact, the magnetisation which is the temperature dependent quantity. Its characteristic shifts almost parallel downwards with rising temperature. Moreover, the point at which the irreversible demagnetisation continues, shifts to applied field values with a lower absolute magnitude for rare-earth magnets or to a higher absolute magnitude for ferrite magnets. The consequence of this is that the range of safe operation is limited at higher temperatures.

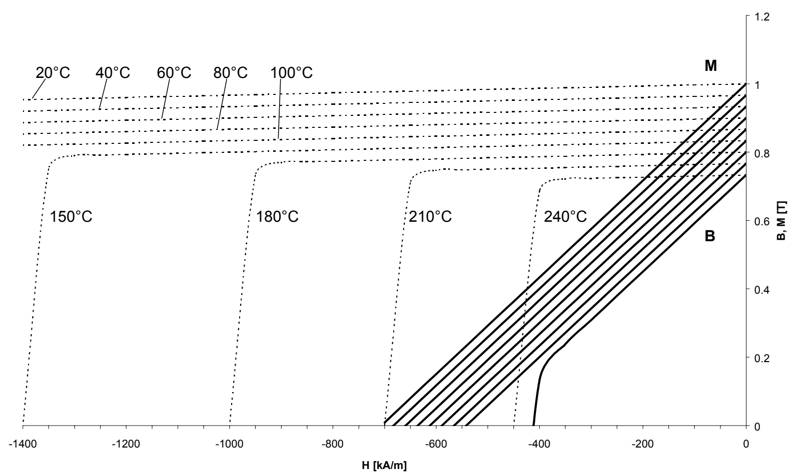

Figure 2.5: NdFeB Temperature Dependent Magnetisation Characteristic.

To quantify the temperature influence, a set of relative temperature coefficients is defined in Fig. 2.6. H_c^* is the linear extrapolation of the *B*-*H*-curve, beyond the irreversible demagnetisation point. The temperature coefficient associated with this extrapolated coercive field, α_{Hc}^*, is important for the modelling, since the magnetisation characteristic is assumed to be linear in design. In a later step, it is checked whether demagnetisation occurred for that temperature. Because of the almost parallel shift, α_{Hc}^* can be assumed equal to α_{Br}, the temperature coefficient associated with the remanent field.

$$\alpha_{B_r} = \frac{B_r - B_{r,T_{ref}}}{B_{r,T_{ref}}\left(T - T_{ref}\right)}, \ \alpha_{H_{cJ}} = \alpha_{H_{cB}} = \frac{H_{cB/J} - H_{cB/J,T_{ref}}}{H_{cB/J,T_{ref}}\left(T - T_{ref}\right)}, \ \alpha_{H_c^*} = \frac{H_c - H_{c,T_{ref}}^*}{H_{c,T_{ref}}^*\left(T - T_{ref}\right)} \approx \alpha_{B_r} \qquad (2.11)$$

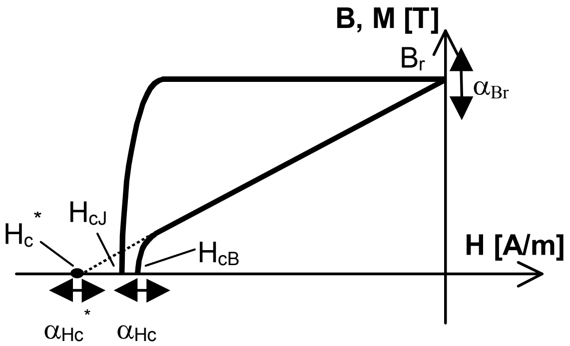

Figure 2.6: Temperature Coefficients Definitions for Permanent Magnet Materials.

The parameters α_{Br} and α_{Hc}^* are always negative. The parameter α_{Hc} may have a different sign, depending on the material family behaviour: it is negative for rare-earth magnets (higher demagnetisation risk for increasing temperatures) and positive for ferrite magnets.

For the major permanent magnet material families, typical values are given in Table 2.2. The electrical conductivity is mentioned since it is important for the magnets' internal loss mechanism, mostly Joule losses due to eddy currents, when they are subject to non-constant external magnetic fields. The other parameters are important for the thermal field modelling.

Table 2.2: Indicative Permanent Magnet Material Data

Material	*Ferrite*	*AlNiCo*	*SmCo*	*NdFeB*
B_r [T]	0.4	0.9	1.0	1.0
α_{Br} [K^{-1}]	$-2 \cdot 10^{-3}$	$-2 \cdot 10^{-4}$	$-3 \cdot 10^{-4}$	$-1 \cdot 10^{-3}$
H_c [kA/m]	300	50	760	760
α_{Hc} [K^{-1}]	$+3 \cdot 10^{-3}$	$-7 \cdot 10^{-4}$ – $+3 \cdot 10^{-4}$	$-2 \cdot 10^{-3}$ – $-3 \cdot 10^{-3}$	$-5 \cdot 10^{-3}$
μ_r [-]	1.1	1.5 – 3.0	1.1	1.1
λ [W/mK]	2 – 4	10 – 100	12	9
ρ [kg/m^3]	5000	7000	8400	7500
c [J/kgK]	800	350 – 500	390	440
T_C [°C]	450	800 – 900	800	300
T_{max} [°C]	200	500	300	200
σ [Ω^{-1}m^{-1}]	≈ 0 (10^{-6})	$2 \cdot 10^6$	$1.25 \cdot 10^6$	$0.7 \cdot 10^6$

Considering Table 2.2, one may conclude that in general SmCo and AlNiCo are the most temperature resistant magnet materials when it comes to extreme temperatures, but AlNiCo requires longer magnets due to the small H_c. NdFeB has a very good magnetic performance, is cheaper than for instance SmCo, but cannot sustain high temperatures, though new material evolutions will extend its limits.

All but the polymer bonded ferrite magnets have a significant electrical conductivity, therefore exhibiting loss generating eddy current when submitted to an external non-constant field.

2.3 Electromagnetic Limit

From an electromagnetic point of view, the following phenomena will play a role:

- Higher speeds means higher induced voltage with extra stress on the insulation.
- The skin effect due to high frequencies increases the AC resistance.
- The magnetic permeability and electrical conductivity decrease with temperature, affecting the characteristics and the operation within a drive.
- Permanent magnets are sensitive to temperature and the conductive types will develop internal eddy currents; a higher risk of demagnetisation arises.

2.4 Power Electronic Limit

The main stress in the discussion on high-speed electrical drives lies, for obvious reasons, on the machine. However, the problems for the power electronic circuit are not insignificant either. Such a circuit is present to adapt the frequency of the electrical supply or source (DC for a battery, 50 Hz for the grid) to the machine's frequency. The general lay-out of such a 'frequency converter circuit' is shown in Fig. 2.7. The three main parts are:

- The rectifier: shown with diodes, but can be made with switches if power has to be send back to the supply;
- The capacitive intermediate circuit: acting a smoothing filter for the DC voltage and an energy buffer for short transients;
- The inverter with six switches in bridge topology: the switches are mainly MOSFETs for small powers and IGBTs for larger powers.

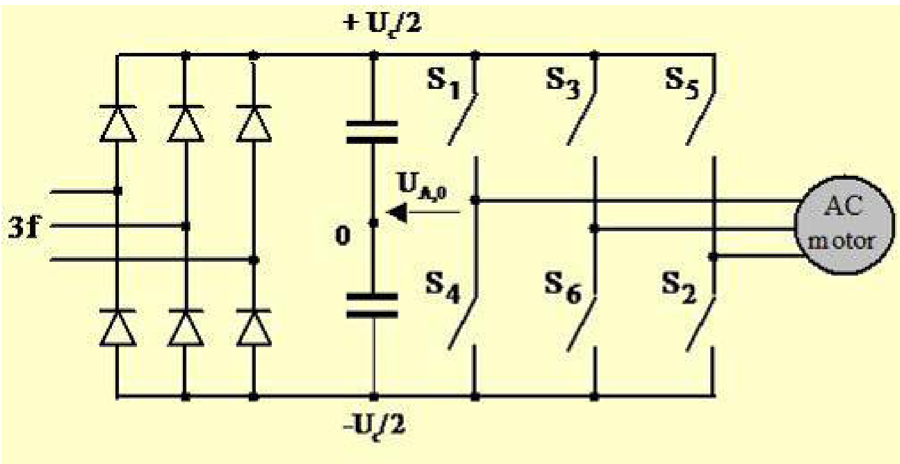

Figure 2.7: Frequency Converter in a Drive.

The inverter synthesizes the desired AC voltages by means of 'Pulse-Width-Modulation' (PWM): by altering positive and negative voltage chunks, a waveform with a fundamental being the AC voltage is constructed (Fig. 2.8). The harmonics are filters out by the inductances in the system.

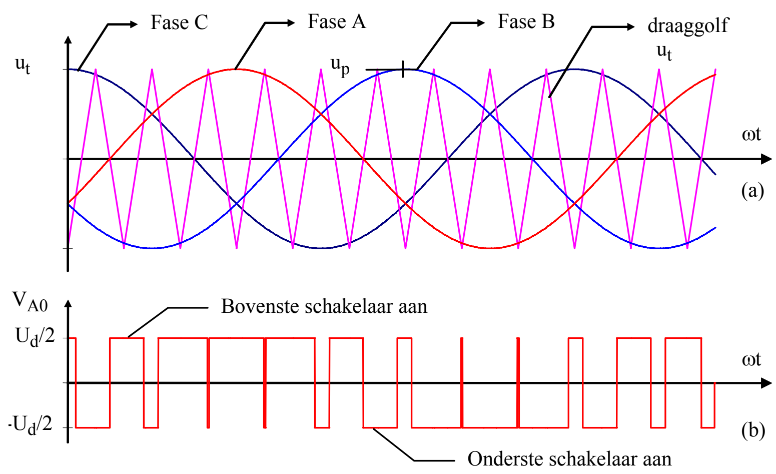

Figure 2.8: PWM Voltage.

To limit the harmonics, the switching frequency is an order larger than the fundamental frequency of the voltage, which may become problematic if the fundamental frequency is already large. In practice, power components switching at frequencies up to 20 – 50 kHz are possible. For higher frequencies, PWM may not be an option anymore. However, it is possible to use square wave voltages instead. These have a higher harmonic content and cause some more losses, but the switching frequency drops significantly. This mode of operation is also known as 'six-step' after the number of switchings for a three-phase voltage. The associated current is rather trapezoidal shaped (Fig. 2.9).

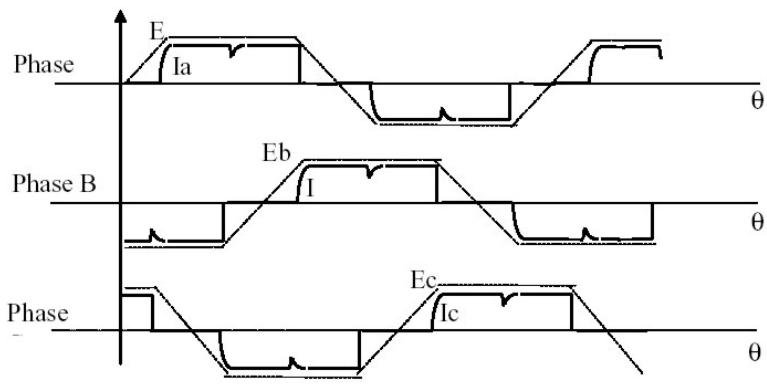

Figure 2.9: Six-Step Voltage.

The higher frequencies demand also a higher bandwidth in the control. As a consequence, the control algorithms and their (digital) implementations require more computing power.

3.0 HIGH-SPEED MACHINE TYPES

After a general discussion on the limitations of machines at high speeds, an overview of the main types with their high-speed variants is made.

Figure 3.1 shows in a log-log diagram the power rating vs. the rotational speed of a machine. Different families can be distinguished, associated to a certain range of surface speeds.

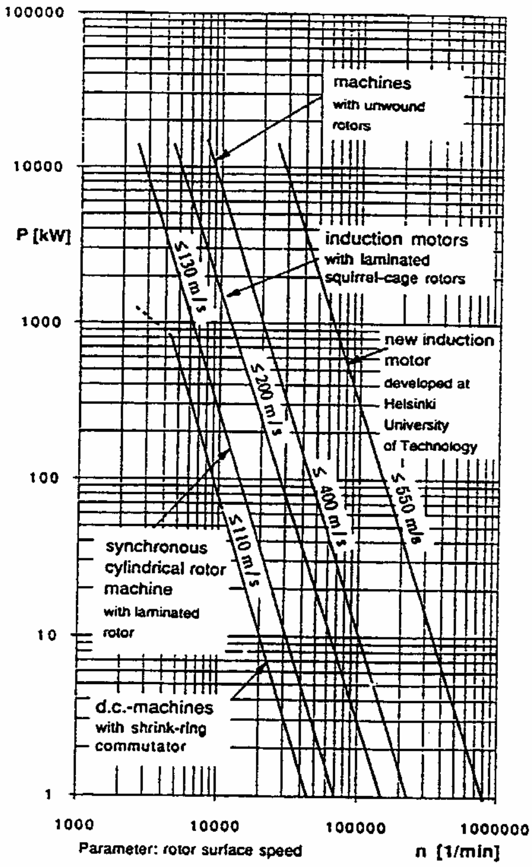

Figure 3.1: Power Rating for Different Speeds for Air-Cooled Machine, with Indicated Surface Speeds (source: T. Jokinen, H.U.T.-Finland).

3.1 DC-Machines

The DC machine has as huge drawback the collector (commutator) structure. First of all, brush wear at high speed becomes very high. Secondly, the structure is not favourable for large centrifugal forces. The commutation process itself is also a limitation as the current needs a finite time, due an electromagnetic time constant, to go to zero and go back to rated value.

3.2 Induction Machines

In induction machines no commutator is present, so the remaining problems are rather structural. Compared to the classical construction, some modifications have to be made:

- End-windings and end-rings are to be held in place by non-magnetic retaining caps.
- The package of laminations (also for synchronous machine types) is to be produced with tight tolerances, e.g. with respect to the fit onto the shaft, to keep it balanced throughout the speed range.

A first alternative is to uses solid rotor structures, with added conductors in cut-out slots (Fig. 3.2). This is a more rigid block with a higher centrifugal force resistance. Obviously a solid rotor is not ideal as eddy currents can develop due to the slipping of the machine, but with a well-designed cage 'in parallel', this proves to be limited.

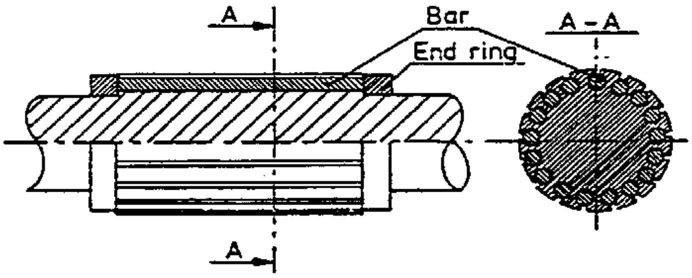

Figure 3.2: Solid Rotor Induction Machine with Cage.

As an alternative, the rotor bars can be replaced or supplemented by a thin conducting tube (coating), shielding the rotor iron even more. Another method to decrease the eddy current losses is to work on their source, more in particular, the field harmonics due to the stator slots, which can be diminished by enlarging the air gap and an adapted design of the stator. Decreasing the flux density also helps, but yields larger machines.

A monolithic solid rotor, without windings, could be considered as well, but the material choice is not obvious: on the one hand it should have a good magnetic permeability and on the other hand a good conductivity, two properties seldom present at the same time. A compromise is magnetic steel, but such a rotor exhibits a considerable skin effect and associated losses as the currents are developed in a surface region with high resistance. The efficiency and power factor are poor.

A first enhancement is the machining of grooves, mimicking a cage structure, with more controlled induced currents. At the end of the rotor, a copper ring (short-circuit end ring) is soldered (Fig. 3.3). As such the eddy current surface losses, more in particular the ones associated to harmonic components (due to the stator slotting or supplied voltage), are lower.

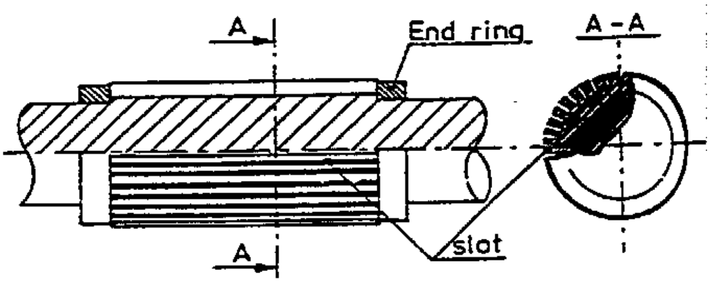

Figure 3.3: Grooved Solid Rotor Induction Machine.

The efficiency can be increased a bit by working with different layers of material types. However, the disadvantage of such machines is that the friction losses increase significantly due to the grooves: any high-speed machine must have smooth surface.

3.3 Synchronous Machines

In a synchronous machines of any type (e.g. PMSM, BLDC, SRM) solid rotors are no problem since the field frequency is zero as seen from the rotor, so only field harmonics could induce losses. Though, in general synchronous machines have larger air gaps, for real or ‘equivalent’ as permanent magnets behave as air for external fields.

Field-wound synchronous machines are not well-suited due to the delicate field winding and the slip-ring system. The claw-pole generator may be considered a limit-case. This machine is used as an immensely popular electricity generator in automobiles and has to work at a large range of speeds. It is a relatively short field-wound synchronous machine, with a radial flux in the air gap. The alternating magnetic North/ South poles in the rotor field are created by the ‘claws’ that guide the flux. The field winding is an axially wound coil inside the claws, so it generates a homopolar flux, which is split and guided to the claw ends by the magnetic material.

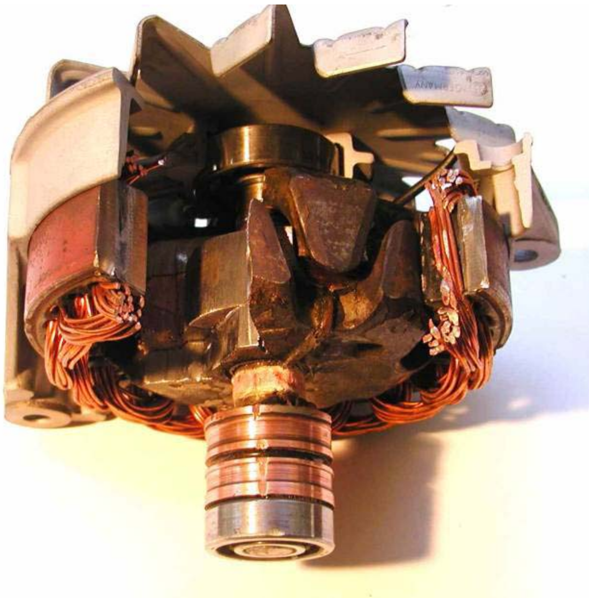

Figure 3.4: Automotive Claw-Pole Generator.

A *switched reluctance machine* may also be considered, but it still has a toothed rotor and a very rough surface, be it that by using altering magnetic/non-magnetic composite is used and thus magnetic asymmetry is created. However, this composite need to be kept together at high centrifugal forces.

3.4 Permanent Magnet Machines

A type of synchronous machine better-suited to be applied as high-speed machine is the permanent magnet machine, either as PMSM or BLDC. The latter has the advantage that it is designed to be used as six-step voltage machine, so the power electronic inverter has a relatively lower switching frequency.

The main problem to be solved is structural: keep the magnets in place. This can be done by a (non-magnetic) ring, which is to be added to the air gap (Fig. 3.5a).

A popular alternative is a bell-shaped rotor, in which an outer parts turns and the stator sits on the inside. In that case the air gap is not enlarged as the rotor itself is the retaining ring (Fig. 3.5b).

For small machines, it may be possible to make the whole rotor out of permanent magnet material, diametrically magnetised, but still with a retaining ring for strength (Fig. 3.5c).

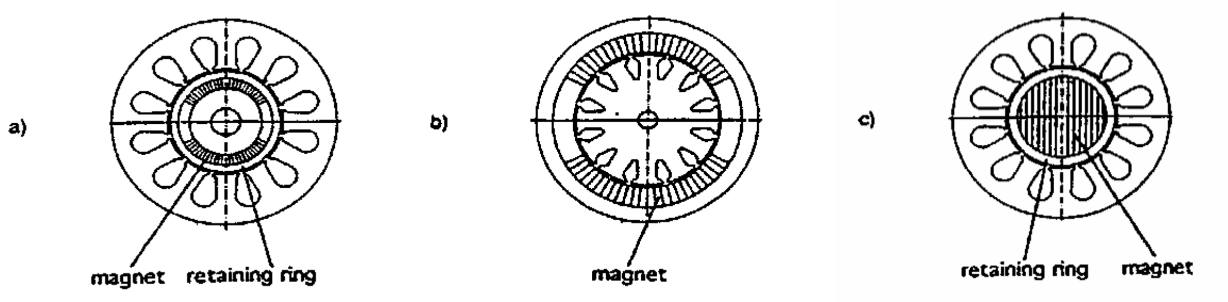

Figure 3.5: High-Speed Permanent Magnet Structures.

3.5 Homopolar Machines

As the goal is to obtain a more or less smooth, monolithic, solid rotor structure, one can consider removing any field source, either permanent magnets of windings from the rotor and use this only as a 'flux conductor'. This means moving the field winding or magnet off the rotor to the stator. Such an arrangement is accomplished in the 'homopolar machine' (Fig. 3.6).

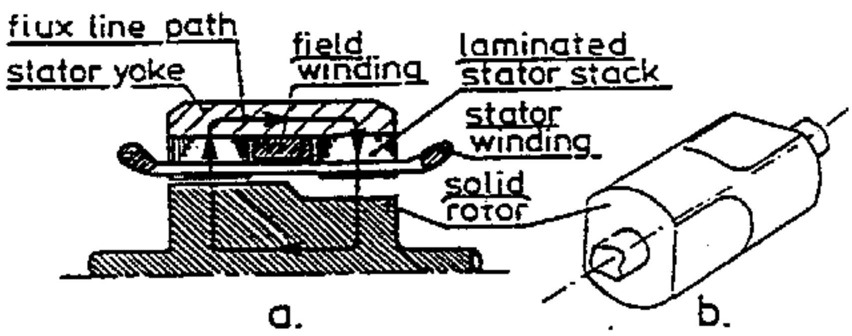

Figure 3.6: Principle of a Homopolar Machine.

The stator winding is a three-phase winding with radial flux. The field excitation, a coil of permanent magnet is mounted behind the stator winding and its yoke or in between when the yoke is in two halves. This field is in principle axially oriented, so identical for all windings to which the name 'homopolar' refers. This flux component is spatially bent 90° to cross the air gap radially. The poles in the field are created by the magnetic asymmetry of the rotor, which consist of two parts which are shifted 90° (electrically) to each other. Due to this offset, an alternating North-South pattern is created in the air gap, but only in half of it. Inside the rotor the fluxes follow a short homopolar path from one section to the other.

The advantage is the solid compact structure, but a form a magnetic point of view, the machine is not used optimally. Fig. 3.7 shows the design of a homopolar motor/generator, with a speed of up to 100.000 rpm, integrated in a solid-steel flywheel mass.

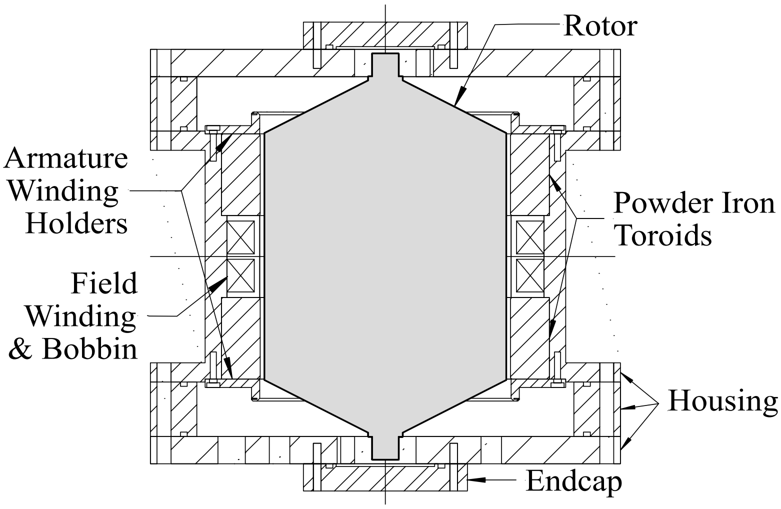

Figure 3.7: Flywheel with Integrated Homopolar Motor/Generator (U.C. Berkeley).

3.6 Axial-Flux Machines

AC machines treated up till now are radial-flux machines. However, at high speeds, a short shaft may be advantages, for instance to obtain different critical speeds. In that case, a machine with an axial flux may be interesting. In such a machine the rotor is much shorter and lighter as the flux only has to pass through. For robotics applications, induction machine and permanent magnet machine types are available. For higher powers, machines can be stacked, as is common with stepper motors. Such constructions are used in certain types of microturbines for distributed generation.

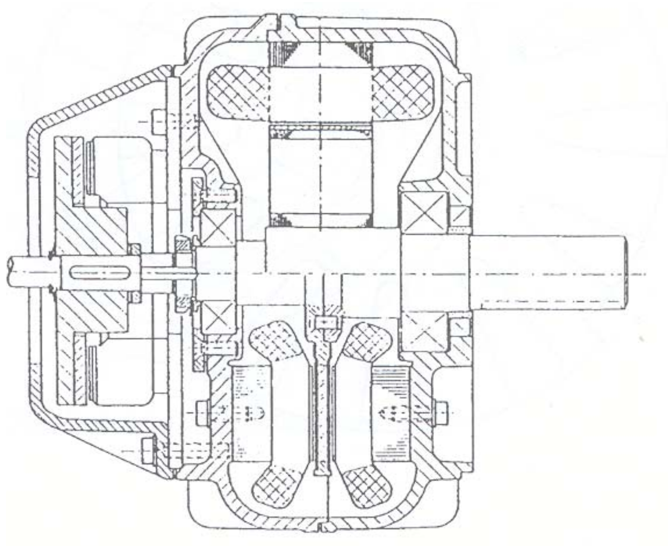

Figure 3.8: BLDC-Machine of 1.5 kW with Nd-Fe-B magnets; the upper part shows a design with radial flux, the bottom part is a two-sided axial flux machine.

The balancing of such machines is not simple and one has to take into account an axial force if the stator is only single-sided. Fig. 3.9 shows such as micromachine design.

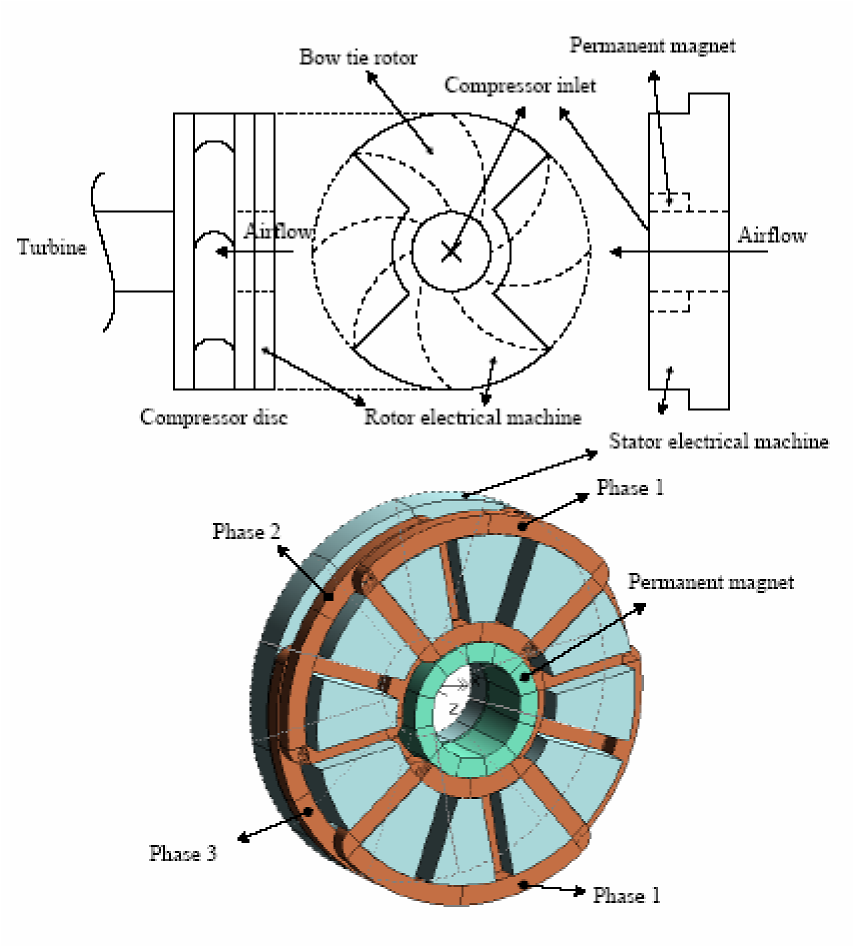

Figure 3.9: High-Speed Axial PM Machine (S. Stevens, K.U.Leuven).