

Springer Theses

# Limits, Modeling and Design of High-Speed Permanent Magnet Machines

Bearbeitet von  
Aleksandar Borisavljevic

1. Auflage 2012. Buch. xxii, 218 S. Hardcover

ISBN 978 3 642 33456 6

Format (B x L): 15,5 x 23,5 cm

Gewicht: 526 g

Weitere Fachgebiete > Technik > Maschinenbau Allgemein > Triebwerkstechnik, Energieübertragung

Zu Inhaltsverzeichnis

schnell und portofrei erhältlich bei

  
DIE FACHBUCHHANDLUNG

Die Online-Fachbuchhandlung beack-shop.de ist spezialisiert auf Fachbücher, insbesondere Recht, Steuern und Wirtschaft. Im Sortiment finden Sie alle Medien (Bücher, Zeitschriften, CDs, eBooks, etc.) aller Verlage. Ergänzt wird das Programm durch Services wie Neuerscheinungsdienst oder Zusammenstellungen von Büchern zu Sonderpreisen. Der Shop führt mehr als 8 Millionen Produkte.

# Chapter 2

## High-Speed PM Machines: Applications, Trends and Limits

### 2.1 Introduction

High-speed permanent magnet machines are the focus of this thesis; this chapter offers an overview of their current and prospective applications and a theoretical study of their limits.

The following section explains the reasons behind the increased use of PM machines with particular attention to small-size, high-speed applications. Several prominent and promising applications of very high-speed machines are reported. In Sect. 2.3 the term high-speed is discussed and its meaning in this thesis is specified. Sect. 2.4 presents results of an empirical survey of the correlation between rated powers and speeds of existing high-speed machines; in particular, the section points out trends of speed increase of slotted and slotless PM machines.

The rest of the chapter is dedicated to speed limits of PM machines. Physical factors that lie behind speed limits of PM machines in general are defined in Sect. 2.5. Finally, Sect. 2.6 attempts to theoretically correlate maximum rated powers and speeds of PM machines with respect to their inherent limits defined in the preceding section.

### 2.2 PM Machines: Overview

Permanent magnet machines have become increasingly popular in the last two decades. They have replaced induction machines in a great number of converter-fed electrical drives and motion control systems<sup>1</sup> [1, 2]. Besides, many new applications, which require high-performance electrical machines, are invariably

---

<sup>1</sup> A simple indicator of the prevalence of PM machines can be achieved by examining the increase of the relative number of associated academic papers. For illustration, the ratio between number of papers that is associated with PM/PM synchronous/brushless DC and induction/asynchronous motors in the IEEE internet base grew from 0.13 for the period before 1990 to 0.54 after 1990 and to 0.65 after year 2000.

linked to PM machines. Two factors may be singled out as crucial for such development.

*Cost competitiveness and availability of rare-earth magnets.* After years of rather slow advance of SmCo magnets on the market, in the eighties, rapid commercialization of NdFeB magnets took place [3]. In the beginning of the nineties the production of rare-earth magnets started booming in China, relying on its large deposits of rare earths and cheap mining [3]. The price of rare-earth magnets went down which removed the main obstacle for using strong magnets in a wide range of applications; accordingly, PM machines became cost-competitive [4, 5]. However, not only has the price of the magnet been reduced in the past 20 years, a palette of different high-energy magnets has become readily available: sintered and plastic-bonded magnets with different energy products, Curie's temperatures, corrosion resistance, shape flexibility, etc [6, 7]. This has allowed the use of PM machines by even highly demanding customers such as the aircraft industry or military.

*Emergence of efficiency-driven applications.* Importance of economical exploitation of resources (fuel in particular) has brought about need for compact and efficient electromechanical systems. In practice it means that more-efficient electrical machines are to either replace traditionally pneumatic, hydraulic and combustion engines (e.g. in aircraft sub-systems, electric cars) or become physically integrated and directly coupled with mechanical systems (e.g. machining spindles, flywheels, turbines).

Qualities of PM machines make them a preferred choice for such systems. Owing to strong magnets, PM machines can have high power densities and also achieve high efficiencies due to no excitation losses, no magnetizing currents and very low rotor losses.

Virtue of high power density becomes particularly important for applications where low volume/weight and high-speeds are important. Undoubtedly, PM machines dominate the field of small high-speed machines [8]. This can be ascribed to their magnetic excitation—air-gap flux density of PM machines is determined mainly by the quality of utilized permanent magnets and does not depend on the size of the machine. Current-excited machines, on the other hand, lack space for conductors in small volumes and thus have comparatively smaller power densities.

For the same power requirement, a high-frequency design reduces size and weight of an electrical machine. High-frequency also often means elimination of power transmission elements. Thus, with downsizing and integration the resulting machinery becomes more efficient, lighter and even portable [9]. In the rest of this section a few typical applications for high-speed PM machines are discussed.

Miniature gas turbines are an exemplary application for high-speed generators. Small gas turbines are a promising means of converting fuel energy into electricity. Unlike large turbines whose output power is transmitted to generators via gears, these small gas turbines are conceived to be directly coupled with high-speed generators [9]. Resulting device would be a highly efficient power unit suitable as a portable power supply or a part of a distributed power network. Reliable gas turbines that utilize PM generators are available on the market [10]. Still, there is a great interest in academia for developing reliable high-speed generators that would keep pace with

newly developed turbines which are capable of rotating at speeds beyond 1 million rpm [11, 12]. A good example of such an effort in academia is work on high-speed generators in ETH Zurich [13].

Waste heat from a gas turbine may be further used to heat water or space. As stated in [14]: “Because electricity is more readily transported than heat, generation of heat close to the location of the heat load will usually make more sense than generation of heat close to the electrical load.” Such an idea lies behind concept of combined heat and power (CHP) [9, 15] systems which, according to current predictions, will be employed as highly efficient heating, cooling and power systems of buildings in coming years [16].

Machining spindles were already thoroughly discussed in Introduction: integration of a PM motor with a spindle gives way to efficiency, compactness and high speeds for production of complex 3D parts. Spindles for medical tools represent also an attractive application for small high-speed machines. Today, dental drilling spindles are mostly driven by air turbines, however, replacing the turbines with electrical drives would facilitate adjustable speed and torque of the spindles and reduce number of hand-pieces needed by a dentist [17].

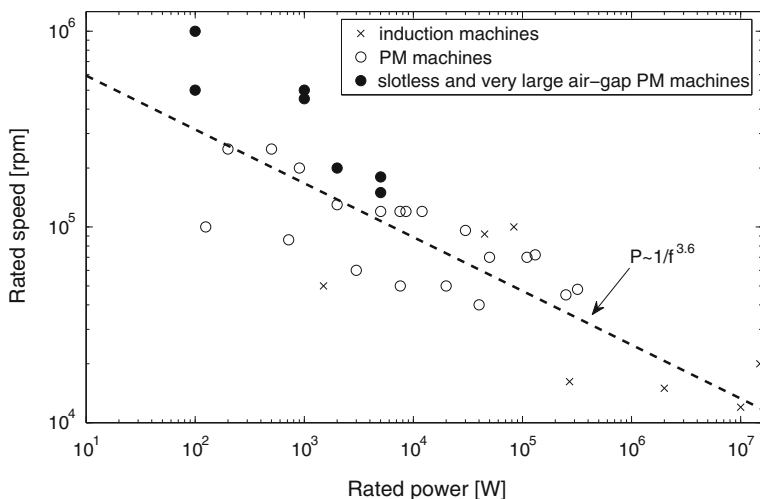
The new trend of replacing mixed secondary power systems in aircraft with electrical ones has brought forth requirements for light-weight, fault-tolerant machines [18]. To achieve powerful engines in small volumes high-speed machines are necessary.

Integrated with flywheel a high-speed PM machine forms an electro-mechanical (EM) battery which is efficient and long-lasting device for energy storage [19, 20]. These EM batteries have been used in many applications, such as hybrid cars, locomotives [8] and spacecraft [21].

### 2.3 Defining *High-Speed*

At this point, it would be wise to define the speed which will be taken as the decisive factor in this thesis when naming a machine a high-speed machine. As long as technology permits, arbitrary high rotational speeds could be simply achieved by scaling down the machine. Therefore, it would not be sensible to take rotational speed as a sole criterion for the high speed.

The tangential speed at the outer rotor radius is often taken as a criterion when defining high-speed because it also takes into account the size of a machine. Such reasoning could make sense since one of major limiting factors for the rotational speed, mechanical stress in the rotor, is dependent on the tangential rotor speed. However, this criterion practically represents the degree of machine’s mechanical utilization and it would favor very large generators that operate at 50/60Hz which are hardly perceived as high-speed machines [8]. For that reason, as Binder and Schneider [8] point out, only inverter-fed or variable-speed machines can, in common understanding, be called high-speed.



**Fig. 2.1** Diagram of rated speeds and powers of existing high-speed machines, [10, 13, 17, 20, 21, 25–48] © 2010 IEEE

In [22] super high-speed machines are classified according to operating power and rotational speed. A numerical limit proposed in [23] correlating power limit with the rotational speed of an electrical machine was used as a criterion for super high-speed in [22]. This type of relationship has commonly been used to evaluate operating speed range of machines [13, 24]. Binder and Schneider [8] also empirically found a correlation between rated powers and speeds of super-high-speed machines.

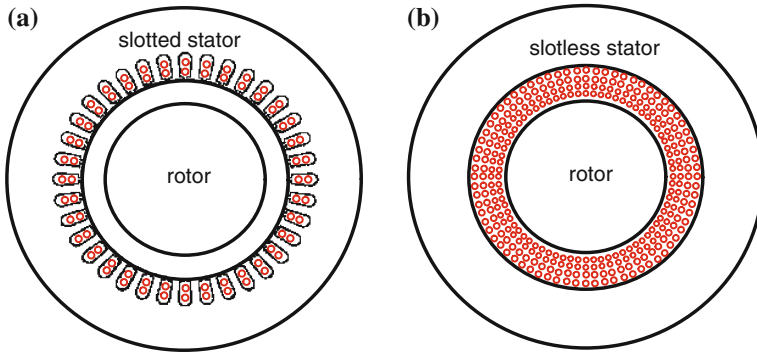
Consequently, this thesis will focus on variable-speed PM machines of small and medium size that have high speed with respect to their power. This correlation will be discussed more in the rest of this chapter. Rated power of the machines of interest is typically below 500 kW—the power range where PM machines appear to be prevalent. Nevertheless, a good part of the analyses found in the thesis is applicable to a broad range of high-speed electrical machines.

## 2.4 Survey of High-Speed Machines

Based on collected data on commercially available high-speed machines and machines developed in academia [10, 13, 17, 20, 21, 25–48], a diagram of rated powers and speeds of high-speed permanent magnet and induction machines was made.<sup>2</sup>

Relation between rated powers and speeds in the diagram is in a good agreement with the correlation empirically found by Binder and Schneider [8]. Namely, from

<sup>2</sup> Most of the content of this section has been taken from Borisavljevic et al. [49], © 2010 IEEE.



**Fig. 2.2** Cross-section of a **a** slotted machine with a large air gap and **b** slotless machine © 2009 IEEE

a study on published data on high-speed AC machines, the authors obtained the relationship:  $\log f = 4.27 - 0.275 \log P$  (consequently,  $P \sim 1/f^{3.6}$ ), which is presented with a dashed line in the diagram.

The diagram (Fig. 2.1) shows prevalence of PM machines among small high-speed machines. To the author's knowledge, no machine other than permanent magnet has been reported to operate beyond speed of 100.000 rpm.

Slotless PM machines show a trend of the highest increases in speeds and extremely fast examples have been reported both on the market and in academia [17, 25]. Bianchi et al. [50] illustrated advantages of using a slotless, rather than a slotted, stator in high-speed PM machines. The authors optimized, constructed and, finally, assessed performance of machines of both types. Optimum flux density in very high-speed PM machines is usually low [50], affecting designs to result in machines with large effective air-gaps. Instead of increasing mechanical air-gap, it is sensible to replace stator teeth with conductors. In this manner, the increase of conductors' area enables rise of the rated current, and that, in turn, partly compensates loss of power density due to reduced air-gap flux density.

## 2.5 Speed Limits of PM Machines

Boost in speeds of PM machines is linked with overcoming or avoiding a number of machine limitations. Various physical parameters (stress, temperature, resonant frequencies) can limit the speed of an electrical machine. Aside from speed, these variables are also affected by power, size and machine electrical and magnetic loading.<sup>3</sup>

Only a small number of academic papers discuss the limits of high-speed machines. In the paper by Slemon [51] parameters of surface-mounted PM machines

<sup>3</sup> A good part of this section has been taken from Borisavljevic et al. [17], © 2010 IEEE.

were correlated with respect to physical and technological constraints. The paper derived general approximate expressions for acceleration and torque limits.

Bianchi et al. [50] evaluated thermal and PM-demagnetization limits of different types of high-speed PM machines. Those limits were taken into account in the proposed optimization procedure through constraints imposed on the design variables. In a later paper by the same authors [52] the demagnetization limit was disregarded in slotless PM machine design as it is too high to be reached.

In extremely high-speed machines, however, mechanical factors such as stress and vibrations, rather than electromagnetically induced heating, are likely to cause failure of the machine. A good modeling of elastic behavior and constraints of a rotor of an electrical machine can be found in the thesis of Larsson [53]. Other authors also took mechanical constraints into account when designing a PM rotor, e.g. [54, 55]. Finally, stability of rotation has been analyzed comprehensively in the field of rotordynamics [56–59], however some important conclusions on rotordynamical stability have not been included in literature on electrical machines.

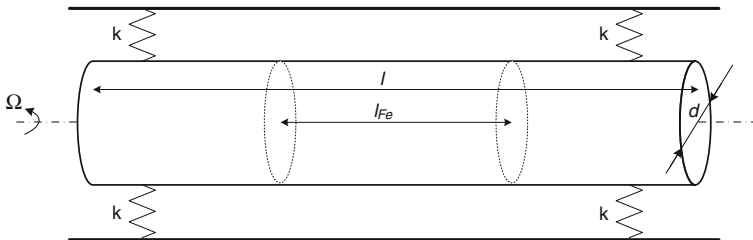
Speed limitations of PM machines in general are the topic of this section. Only physical limits that are inherent to PM machines will be discussed; speed limitations associated with bearing types, power electronics, control or technological difficulties will not be considered. Defining and quantification of the machine speed limits in the rest of the thesis will have an essential impact on the design of the test machine.

The limit that is common to all machines is the thermal limit. The thermal behavior of a machine depends on power losses that are further dependent on current and magnetic loading, as well as rotational speed. These parameters will be correlated with machine size and rated power in the next section in order to see how the speed is limited.

The strength or stress limit is inherently connected with the elastic properties of the materials used in the rotor. Mechanically, a PM rotor can be modeled as a compound of two or three cylinders: a rotor magnet that either leans on a rotor iron shaft or is a full cylinder, and an enclosure of the magnet. Given the interference fits between the adjacent cylinders, maximum tangential speed  $v_{t,max}$  of the rotor can be determined (see Chap. 4) at which either maximum permissible stress is reached in one of the cylinders or contact at boundary surface(s) is lost (Fig. 2.2).

The third limit that will be considered is related to rotordynamical properties of the mechanical system. For every rotor-bearing system two types of vibrations can occur that can (or will) limit the rotational speed of the rotor: resonant and self-excited. Resonant vibrations occur when the speed of the rotor coincides with one of the resonant frequencies. In literature are those rotor speeds referred to as *critical speeds*, among which those connected with flexural modes in the rotor are particularly dangerous. Self-excited vibrations make rotation impossible, that is, unstable, and they commence after a certain threshold speed [60].

Tackling the problem of rotor vibrations is a very complicated task that includes the mechanical design of the rotor and design of the bearings. However, the speed range in which the rotor will operate is usually decided on in the initial design stage: the working speed range must be sufficiently removed from the resonant speeds and below the threshold of instability. For a given rotor geometrical profile and bearings'



**Fig. 2.3** Rotor-bearings configuration © 2010 IEEE

stiffness the maximum ratio between the rotor length and diameter can be defined, Fig. 2.3:

$$\lambda_{\max} = \frac{l}{d} = \frac{l_{Fe}}{\alpha 2r_r}. \quad (2.1)$$

so as to insure stable rotation at the target maximum rotor speed.

From (2.1) maximum ratio between active rotor length (active machine length) and the rotor radius is determined:

$$\lambda_{Fe, \max} = \frac{l_{Fe}}{2r_r} = \alpha \lambda_{\max}, \quad (2.2)$$

where  $\alpha = l_{Fe}/l$  is ratio between active and total rotor length.

Parameter  $\lambda_{\max}$  can be viewed as a figure of the rotor slenderness or, conversely, robustness, with lower values for a more robust rotor.

## 2.6 Limits and Rated Machine Parameters

The goal of this section is to theoretically correlate rated power, speed and size of PM machines and, as a result, account for speed-power relationship in the diagram in Sect. 2.4. The correlation will be drawn considering the limiting factors mentioned in the previous section. The maximum slenderness  $\lambda_{\max}$  and tangential speed  $v_{r, \max}$  will be assumed known, as defined by mechanical properties of the system. Temperature in a machine depends on losses and on the cooling capability thus the surface loss power density will be maintained constant. The derivation is similar to the one in [8], with focus on loss influence in different types of PM machines (See footnote 3).

To analyze interdependence of power, size and speed the following approximate equation for output power will be used:

$$P_{nom} = \Omega T = \underbrace{2\pi f_{nom}}_{\Omega} \cdot \underbrace{F_d \cdot 2\pi r_s l_{Fe} \cdot r_s}_T \approx 2\pi^2 B_g A_c r_s^2 l_{Fe} f_{nom}. \quad (2.3)$$



In the equation  $P_{nom}$ ,  $T$  and  $f_{nom}$  are, respectively, rated power, torque and frequency and  $F_d \approx B_g A_c / 2$  [61] denotes machine's maximum force density, where  $B_g$  is maximum air-gap flux density and:

$$A_c \approx \begin{cases} k_w k_{fill} J h_s \frac{b_s}{b_s + b_t}, & \text{for a slotted machine} \\ k_w k_{fill} J l_w, & \text{for a slotless machine} \end{cases} \quad (2.4)$$

is current loading. In (2.4)  $J$  is amplitude of sinusoidal stator current density,  $h_s$ ,  $b_s$  and  $b_t$  are slot height, slot width and tooth width of a slotted machine,  $l_w$  is conductors' area thickness of a slotless machine and  $k_w$  and  $k_{fill}$  are winding and fill factors, respectively. If the ratio of slot to tooth width is kept constant and having  $h_s, l_w \sim r_r$ , the expressions (2.4) yield:

$$A_c \sim J r_r. \quad (2.5)$$

Using (2.1) in Eq.(2.3) and neglecting the air-gap length ( $r_s \approx r_r$ ) we obtain:

$$P_{nom} = 4\pi^2 B_g A_c \alpha \lambda_{\max} r_r^3 f_{nom}. \quad (2.6)$$

Due to increased losses, to maintain a given cooling capability, magnetic and current loading must be lowered if frequency is increased. Consequently, the ratio between maximum permissible power dissipation and cooling surface area is maintained constant:

$$\frac{P_{diss}}{S} = const, \quad (2.7)$$

while keeping in mind that  $S \sim r_r^2$ .

An analysis of the influence of the machine size and frequency on dominant, frequency-dependent losses will follow.

At very high frequencies iron losses in the stator are estimated as:

$$P_{Fe} = C \cdot m_{Fe} f_e^2 B_g^2 \sim r_r^3 f_{nom}^2 B_g^2, \quad (2.8)$$

where  $f_e$ :

$$f_e = \frac{N_{poles}}{2} f_{nom} \quad (2.9)$$

is electrical frequency and  $m_{Fe}$  is mass of the iron core.

Copper losses can be divided into two parts: (i) the conduction loss part  $P_{Cu,skin}$ , that also includes a rise in loss caused by the reduction of effective conductors cross-section due to skin-effect; and (ii) the proximity loss part  $P_{Cu,prox}$ , that accounts for eddy-current loss in the conductors due to the pulsating magnetic fields from the rotor magnet and neighboring conductors:

$$P_{Cu} = P_{Cu,skin} + P_{Cu,prox}. \quad (2.10)$$

According to [62] we can estimate the skin-effect conduction loss as:

$$P_{Cu,skin} = F(\phi) \cdot P_{Cu,DC} = \underbrace{(F(\phi) - 1) I^2 R_{DC}}_{\text{skin-effect}} + \underbrace{I^2 R_{DC}}_{DC}, \quad (2.11)$$

where  $\phi$  is the ratio between conductor diameter and the skin-depth:

$$\phi = \frac{d_{Cu}}{\delta_{skin}\sqrt{2}} = d_{Cu}\sqrt{\frac{\pi\sigma_{Cu}\mu_0 f_e}{2}}, \quad (2.12)$$

and function  $F(\phi)$  is defined as:

$$F(\phi) = \frac{\phi}{2} \cdot \frac{(ber(\phi)bei'(\phi) - bei(\phi)ber'(\phi))}{ber'^2(\phi) + bei'^2(\phi)}. \quad (2.13)$$

For reasonable conductor diameters and electrical frequencies of high-speed machines the skin-effect part of Eq. (2.11) comprises less than one percent of the total value of  $P_{Cu,skin}$ —see Fig. 3.17 in Sect. 3.6.2—and can thus be neglected. Therefore:

$$P_{Cu,skin} \approx P_{DC} = I^2 R_{DC} = J^2 S_w \rho_{Cu} l_{Cu} \sim J^2 r_r^2 l_{Fe} \sim J^2 r_r^3. \quad (2.14)$$

In Eq. (2.14)  $S_w$  is the copper cross-section area of the windings and  $\rho_{Cu}$  is the copper resistivity.

Regarding the proximity-effect part of the copper losses, in the example of slotless PM machines, it will primarily be influenced by the rotor permanent magnet field rather than by the field of the neighboring conductors. This part of losses can be estimated as [63] (for detail see Sect. 3.6.2):

$$P_{Cu,prox,slotless} = \frac{B_g^2 (2\pi f_{nom})^2 d_{Cu}^2}{32\rho_{Cu}} V_{Cu} \sim r_r^3 B_g^2 f_{nom}^2. \quad (2.15)$$

where  $V_{Cu}$  is volume of the conductors (copper).

In a slotted machine the influence of neighboring conductors on proximity loss is dominant, but dependence of this loss on frequency takes on a more complicated form. The loss in a single conductor can be expressed in a following form (see [62]):

$$P_{Cu,prox}^1 = \frac{G(\phi)}{\sigma_{Cu}} \cdot H_{e,rms}^2 \cdot l_{Fe} \quad (2.16)$$

where  $H_{e,rms}$  is the rms value of magnetic field strength of the neighboring conductors and:

$$G(\phi) = 2\pi\phi \cdot \frac{(ber_2(\phi)ber'(\phi) - bei_2(\phi)bei'(\phi))}{ber^2(\phi) + bei^2(\phi)}. \quad (2.17)$$

For a constant conductor diameter dependence of the expression  $G(\phi)$  on frequency is very closely quadratic—see Fig. 3.18 and Eq. (3.105) in Sect. 3.6.2—and the total loss caused by proximity effect for the slotted machine case can be approximated as:

$$P_{Cu,prox,slotted} \sim J^2 f_{nom}^2 V_{Cu} \sim J^2 f_{nom}^2 r_r^3 \quad (2.18)$$

To maintain the permissible surface loss density (2.7) in a slotless machine, from (2.8), (2.15) and (2.14) restrictions for magnetic flux density and current density are obtained as:

$$B_g \sim 1/(\sqrt{r_r} f_{nom}) \quad (2.19)$$

and

$$J \sim 1/\sqrt{r_r}. \quad (2.20)$$

Finally from (2.5), (2.6), (2.19) and (2.20) the correlation between the rated power and size for slotless PM machines is obtained:

$$P_{nom} \sim r_r^3. \quad (2.21)$$

In the slotted machine case, expressions for DC- (2.14) and frequency-dependent copper loss (2.18) yield different restrictions for current density:  $J \sim 1/\sqrt{r_r}$  and  $J \sim 1/(\sqrt{r_r} f_{nom})$ . Correlation between rated parameters of slotted PM machines can be expressed in a more general form as:

$$P_{nom} \sim \frac{r_r^3}{f_{nom}^k}, \quad 0 < k < 1, \quad (2.22)$$

where  $k$  depends on portion of frequency-dependent losses in total copper loss.

The last two equations explain trend of higher increase in rated speeds of slotless PM machines with respect to their slotted counterparts, as presented in Sect. 2.4.

Further, from (2.21) and (2.22) it is evident that it is not possible to gain power density by merely scaling down the machine and increasing its rated speed. Unfortunately, with increasing operating speed (to obtain the same machine power), losses in the machine will increase rapidly. To maintain a given cooling capability, magnetic and current loading must be lowered if frequency is increased.

However, the rationale behind using high-speed machines is compactness and efficiency of a particular electro-mechanical system and not of the machine itself.

Air-friction loss has not been analyzed yet in this section and it represents a great portion of overall losses in high-speed machines. Magnetic and current loading, however, do not influence air-friction and it is dependent solely on mechanical quantities: size, speed and roughness of the rotor and length of the air-gap. Power of the air-friction drag is given by:

$$P_{af} = k_1 C_f (v_t, l_g) \rho_{air} \pi \Omega^3 r_r^4 l. \quad (2.23)$$

Empirical estimations of the friction coefficient  $C_f$  for typical rotor geometries can be found in the thesis of Saari [64]. If the air-friction power is divided with the rotor surface area  $2\pi r_r l$  a surface density of air-friction loss power is obtained:

$$q_{af} = \frac{1}{2} k_1 C_f (v_t, l_g) \rho_{air} v_t^3. \quad (2.24)$$

Temperature in the air-gap is proportional to this power density. Whether this temperature will jeopardize operation of a machine depends on the coefficient of thermal convection on the rotor surface and that coefficient is rather difficult to assess. In any case, tangential rotor speed is a potential limiting figure for machine with respect to air-friction loss.

If tangential speed  $v_t = 2\pi r_r f_{nom}$  is used in (2.21) and (2.22) instead of the radius, the following correlations are obtained:

$$P_{nom} \sim \begin{cases} v_t^3 / f_{nom}^{3+k}, & \text{for a slotted machine} \\ v_t^3 / f_{nom}^3, & \text{for a slotless machine} \end{cases} \quad (2.25)$$

Equation (2.25) practically establish connection between the nominal powers of PM machines, their rotor radii (sizes) and nominal rotational frequencies. Usually, tangential speed in PM machines is limited by stress in the rotor and today does not exceed 250 m/s (the highest reported rotor tangential speed is 245 m/s and it is associated with a very large turbine generator in Germany, operating at 50 Hz [8]). Hence, correlation between nominal powers of PM machines with their *highest permissible* nominal speeds can be expressed in a general form as:

$$P_{nom} \sim \frac{1}{f_{nom}^{3+k}}, \quad 0 < k < 1, \quad (2.26)$$

which Binder and Schneider [8] found with an approximate value of  $k = 0.6$  for the frequency exponent (Fig. 2.1), however, by including also induction and homo-polar machines in the study.

## 2.7 Conclusions

The chapter gives an introduction to high-speed permanent magnet machines: it analyzes prominent and prospective applications of these machines, defines the attribute “high-speed” for the purpose of this thesis and presents a general theoretical study of speed limits of PM machines. By doing so, the chapter explains the reasoning behind choosing the slotless PM machine as the type of the test-motor and, more importantly, it defines the scope and outlook for the modeling and design presented in the thesis.

Two reasons are singled out for the prevalence of PM machines in the last two decades: (i) rapid commercialization and availability of rare-earth magnets and (ii) the emergence of efficiency-driven applications. Qualities of PM machines—high efficiency and power density—have made them a preferred choice for high-performance applications, particularly at medium and low powers.

High power density of PM machines can be ascribed to their magnetic excitation—air-gap flux density of PM machines is determined mainly by the quality of utilized permanent magnets and does not depend on the size of the machine. At the same time, relatively simple, cylindrical rotor can be robust enough to sustain the stress caused by the centrifugal force at high speeds.

In the thesis, *high-speed* machines are defined as variable-speed machines of small and medium size (typically, below 500 kW) that have high speed with respect to their power. Empirical study on such machines developed in industry and academia also showed the predominance of PM machines. Obtained relation between rated powers and speeds is in good agreement with the correlation empirically found by Binder and Schneider [8].

Slotless PM machines show a trend of the highest increase in speeds and extremely fast examples have been reported both on the market and in academia. Since the optimal air-gap flux density in high-speed PM machines for highest efficiency is usually low it is sensible to replace stator teeth with conductors and, in that way, partly compensates loss of power density due to reduced air-gap flux density.

Finally, the chapter identifies inherent (physical) speed limits of PM machines—thermal, structural (elastic) and rotordynamical. Taking into account their physical limits, the chapter theoretically correlates speed, power and size of PM machines and accounts for the correlations appearing from the empirical survey. It is concluded that, if the cooling method is maintained, it is not possible to gain power density by merely scaling down the machine and increasing its rated speed. This study can be viewed as the main contribution of this chapter.

## References

1. Z. Zhu, K. Ng, D. Howe, Design and analysis of high-speed brushless permanent magnet motors, in *Electrical Machines and Drive, 1997 Eighth International Conference on (Conf. Publ. No. 444)*, pp. 381–385, 1–3 Sept 1997
2. K. Binns, D. Shimmin, Relationship between rated torque and size of permanent magnet machines. *IEE Proc. Electr. Power Appl.* **143**(6), 417–422 (1996)
3. S. Trout, Rare earth magnet industry in the USA: current status and future trends, in *17th International Workshop on Rare Earth Magnets and Their Applications*, University of Delaware, 2002
4. T. Shimoda, A prospective observation of bonded rare-earth magnets. *IEEE Trans. J. Magn. Jpn.* **8**(10), 701–710 (1993)
5. P. Campbell, Magnet price performance, in *Magnetic Business and Technology*, 2007
6. W. Rodewald, M. Katter, Properties and applications of high performance magnets, in *18th International Workshop on High Performance Magnets and Their Applications*, pp. 52–63, 2004

7. W. Pan, W. Li, L.Y. Cui, X.M. Li, Z.H. Guo, Rare earth magnets resisting eddy currents. *IEEE Trans. Magn.* **35**(5, Part 2), 3343–3345 (1999)
8. A. Binder, T. Schneider, High-speed inverter-fed ac drives, in *Electrical Machines and Power Electronics, 2007. ACEMP'07. International Aegean Conference on*, pp. 9–16, 10–12 Sept 2007
9. J.F. Gieras, High speed machines, in *Advancements in Electric Machines (Power Systems)*, ed. by J.F. Gieras (Springer, Berlin 2008)
10. E.A. Setiawan, Dynamics behavior of a 30 kW capstone microturbine, in *Institut fuer Solare Energieversorgungstechnik eV (ISET)*, Kassel, Germany, 2007
11. K. Isomura, M. Murayama, H. Yamaguchi, N. Ijichi, N. Saji, O. Shiga, K. Takahashi, S. Tanaka, T. Genda, M. Esashi, Development of micro-turbo charger and micro-combustor as feasibility studies of three-dimensional gas turbine at micro-scale. *ASME Conf. Proc.* **2003**, 685–690 (2003)
12. J. Peirs, D. Reynaerts, F. Verplaetsen, Development of an axial microturbine for a portable gas turbine generator. *J. Micromech. Microeng.* **13**, S190–S195 (2003)
13. C. Zwysigg, S.D. Round, J.W. Kolar, An ultra-high-speed, low power electrical drive system. *IEEE Trans. Ind. Electron.* **55**(2), 577–585 (2008)
14. R. Lasseter, P. Paigi, Microgrid: a conceptual solution, in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, vol. 6, pp. 4285–4290, 20–25 June 2004
15. P.A. Pilavachi, Mini-and micro-gas turbines for combined heat and power. *Appl. Therm. Eng.* **22**(18), 2003–2014 (2002)
16. MTT Recuperated Micro Gas Turbine for Micro CHP Systems, Micro Turbine Technology BV, <http://www.mtt-eu.com/>
17. C. Zwysigg, J.W. Kolar, S.D. Round, Megaspeed drive systems: pushing beyond 1 million r/min. *IEEE/ASME Trans. Mechatron.* **14**(5), 598–605 (2009)
18. G.J. Atkinson, *High Power Fault Tolerant Motors for Aerospace Applications*. Ph.D. Dissertation, University of Newcastle upon Tyne, 2007
19. S. Jang, S. Jeong, D. Ryu, S. Choi, Comparison of three types of pm brushless machines for an electro-mechanical battery. *IEEE Trans. Magn.* **36**(5), 3540–3543 (2000)
20. A. Nagorny, N. Dravid, R. Jansen, B. Kenny, Design aspects of a high speed permanent magnet synchronous motor/generator for flywheel applications, in *Electric Machines and Drives, 2005 IEEE International Conference on*, pp. 635–641, 15 May 2005
21. A.S. Nagorny, R.H. Jansen, D.M. Kankam, Experimental performance evaluation of a high-speed permanent magnet synchronous motor and drive for a flywheel application at different frequencies, in *Proceedings of 17th International Conference on Electrical Machines—ICEM*, 2006
22. M. Rahman, A. Chiba, T. Fukao, Super high speed electrical machines—summary, in *Power Engineering Society General Meeting, 2004. IEEE*, vol. 2, pp. 1272–1275, 10 June 2004
23. A. Maeda, H. Tomita, O. Miyashita, Power and speed limitations in high speed electrical machines, in *Proceedings of IPEC, Yokohama, Japan*, pp. 1321–1326, 1995
24. J. Oliver, M. Samotyj, R. Ferrier, Application of high-speed, high horsepower, ASD controlled induction motors to gas pipelines, in *5th European Conference on Power Electronics and Applications, EPE'93*, pp. 430–434, 1993
25. High Speed, Calnetix Inc., <http://www.calnetix.com/highspeed.cfm>
26. Danfoss Turbocor Compressors, Danfoss Turbocor, <http://www.turbocor.com/>
27. Ultra-High Speed Motors & Generators, SatCon Applied Technology, <http://www.satcon.com/apptech/mm/uhs.php>
28. Permanent Magnet Rotor with CFRP Rotor Sleeve, e+a Elektromaschinen und Antriebe AG, <http://www.eunda.ch/>
29. M. Caprio, V. Lelos, J. Herbst, J. Upshaw, Advanced induction motor endring design features for high speed applications, in *Electric Machines and Drives, 2005 IEEE International Conference on*, pp. 993–998, 15 May 2005
30. P. Beer, J.E. Tessaro, B. Eckels, P. Gaberson, High-speed motor design for gas compressor applications, in *Proceeding of 35th Turbomachinery Symposium*, pp. 103–112, 2006

31. M. Harris, A. Jones, E. Alexander, Miniature turbojet development at hamilton sundstrand the TJ-50, TJ-120 and TJ-30 turbojets, in *2nd AIAA "Unmanned Unlimited" Systems, Technologies, and Operations Aerospace, Land, and Sea Conference and Workshop & Exhibit*, pp. 15–18, 2003
32. The Smallest Drive System in the World, Faulhaber Group (2004), <http://www.faulhaber.com/n223666/n.html>
33. ATE Micro Drives, ATE Systems, <http://www.ate-system.de/en/products/ate-micro-drives.html>
34. U. Schroder, Development and application of high speed synchronous machines on active magnetic bearings, in *Proceedings of MAG'97, Industrial Conference and Exhibition on Magnetic Bearings, Alexandria, Virginia*, p. 79, August 1997
35. M. Ahrens, U. Bikle, R. Gottkehaskamp, H. Prenner, Electrical design of high-speed induction motors of up to 15 mW and 20000 rpm, in *Power Electronics, Machines and Drives, 2002. International Conference on (Conf. Publ. No. 487)*, pp. 381–386, 4–7 May 2002
36. M. Larsson, M. Johansson, L. Naslund, J. Hylander, Design and evaluation of high-speed induction machine, in *Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE, International*, vol. 1, pp. 77–82, 1–4 Sept 2003
37. B.-H. Bae, S.-K. Sul, J.-H. Kwon, J.-S. Shin, Implementation of sensorless vector control for super-high speed pmsm of turbo-compressor, in *Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE*, vol. 2, pp. 1203–1209, 30 Sept 2001
38. M. Aoulkadi, A. Binder, G. Joksimovic, Additional losses in high-speed induction machine—removed rotor test, in *Power Electronics and Applications, 2005 European Conference on*, pp. 10 pp.–P.10, 0–0 2005
39. H.-W. Cho, S.-M. Jang, S.-K. Choi, A design approach to reduce rotor losses in high-speed permanent magnet machine for turbo-compressor. *IEEE Trans. Magn.* **42**(10), 3521–3523 (2006)
40. I. Takahashi, T. Koganezawa, G. Su, K. Ohyama, A super high speed pm motor drive system by a quasi-current source inverter. *IEEE Trans. Ind. Appl.* **30**(3), 683–690 (1994)
41. PCB Spindles, Westwind Air Bearings, <http://www.westwind-airbearings.com/pcb/index.html>
42. J. Oyama, T. Higuchi, T. Abe, K. Shigematsu, R. Moriguchi, The development of small size ultra-high speed drive system, in *Power Conversion Conference—Nagoya, 2007. PCC'07*, pp. 1571–1576, 2–5 Dec 2007
43. OilFree, Motorized Compressor Systems, Mohawk Innovative Technology, <http://www.miti.cc/>
44. J. Bumby, E. Spooner, J. Carter, H. Tennant, G. Mego, G. Dellora, W. Gstrein, H. Sutter, J. Wagner, Electrical machines for use in electrically assisted turbochargers, in *Power Electronics, Machines and Drives, 2004. (PEMD 2004). Second International Conference on (Conf. Publ. No. 498)*, vol. 1, pp. 344–349, 31 March 2004
45. BorgWarner Turbo & Emission Systems, <http://www.turbos.bwauto.com>
46. C. Zwysig, M. Duerr, D. Hassler, J.W. Kolar, An ultra-high-speed, 500000 rpm, 1 kW electrical drive system, in *Proceedings of Power Conversion Conference—PCC'07*, pp. 1577–1583, 2007
47. A. Binder, T. Schneider, M. Klohr, Fixation of buried and surface-mounted magnets in high-speed permanent-magnet synchronous machines. *IEEE Trans. Ind. Appl.* **42**(4), 1031–1037 (2006)
48. O. Aglen, A. Andersson, Thermal analysis of a high-speed generator, *Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the*, vol. 1, pp. 547–554, 12–16 Oct 2003
49. A. Borisavljevic, H. Polinder, J. Ferreira, On the speed limits of permanent-magnet machines. *IEEE Trans. Ind. Electron.* **57**(1), 220–227 (2010)
50. N. Bianchi, S. Bolognani, F. Luise, Potentials and limits of high-speed pm motors. *IEEE Trans. Ind. Appl.* **40**(6), 1570–1578 (2004)

51. G. Slemon, On the design of high-performance surface-mounted pm motors. *IEEE Trans. Ind. Appl.* **30**(1), 134–140 (1994)
52. N. Bianchi, S. Bolognani, F. Luise, High speed drive using a slotless pm motor. *IEEE Trans. Power Electron.* **21**(4), 1083–1090 (2006)
53. R. Larsonneur, <Emphasis Type="Italic">Design and Control of Active Magnetic Bearing Systems for High Speed Rotation</Emphasis>. Ph.D. Dissertation, Swiss Federal Institute of Technology Zurich, 1990
54. C. Zwyszig, J.W. Kolar, Design considerations and experimental results of a 100 W, 500,000 rpm electrical generator. *J. Micromech. Microeng.* **16**(9), 297–307 (2006)
55. T. Wang, F. Wang, H. Bai, J. Xing, Optimization design of rotor structure for high speed permanent magnet machines, in *Electrical Machines and Systems, ICEMS. International Conference on*, pp. 1438–1442, 8–11 Oct 2007
56. T. Iwatsubo, Stability problems of rotor systems. *Shock Vib. Inform. Digest (Shock and Vibration Information Center)* **12**(7), 22–24 (1980)
57. J. Melanson, J.W. Zu, Free vibration and stability analysis of internally damped rotating shafts with general boundary conditions. *J. Vib. Acoust.* **120**, 776 (1998)
58. W. Kim, A. Argento, R. Scott, Forced vibration and dynamic stability of a rotating tapered composite timoshenko shaft: Bending motions in end-milling operations. *J. Sound Vib.* **246**(4), 583–600 (2001)
59. G. Genta, *Dynamics of Rotating Systems* (Springer, Berlin, 2005)
60. V. Kluyskens, B. Dehez, H. Ahmed, Dynamical electromechanical model for magnetic bearings. *IEEE Trans. Magn.* **43**(7), 3287–3292 (2007)
61. A. Grauers, P. Kasinathan, Force density limits in low-speed pm machines due to temperature and reactance. *IEEE Trans. Energy Convers.* **19**(3), 518–525 (2004)
62. J. Ferreira, Improved analytical modeling of conductive losses in magnetic components. *IEEE Trans. Power Electron.* **9**(1), 127–131 (1994)
63. E. Spooner, B. Chalmers, ‘TORUS’: a slotless, toroidal-stator, permanent-magnet generator. *IEE Proc. B. Electr. Power Appl.* **139**(6), 497–506 (1992)
64. J. Saari, *Thermal Analysis of High-Speed Induction Machines*. Ph.D. Dissertation, Acta Polytechnica Scandinavica, 1998