Challenges in applying permanent magnet (PM) technology to wind power generators

Panu Kurronen[1], Minna Haavisto[2], Juha Pyrhönen[3]

[1]The Switch, Salpausselänkatu 291, 53850 Lappeenranta, Finland
[2]Magnet Technology Centre, Tiedepuisto 4, 28600 Pori, Finland
[3]Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

Abstract

More than half of the world's top 10 turbine manufacturers are investigating PM generator technology or are already offering PMGs to the market. Often, the easiest way to switch from traditional DFIGs to PMGs is just to replace the existing DFIG behind the high-speed gear with the same speed PMG and full-power converter. This requires only minimal design changes of the turbine and nacelle layout.

PM technology offers a large variety of different concepts, starting from 10 to 20 rpm, large torque and direct-driven generators. It also offers various constructional options, like outer rotor and axial-flux generators. PM excitation gives the machines both high efficiency and high torque, because the excitation does not require a continuous energy flow to the system. It also produces low synchronous inductance, and hence, large torque capacity for the machine.

Keywords*: permanent magnet generators, full-power converters, rare earth metals, remanence flux density and coercivity*

1. Technology trends in wind generators

As with all new technologies, PMGs have their drawbacks and risks, especially when it comes to uncertainty. Small PM machines have already been in the market in other applications for several decades, but it can be rightly stated that permanent magnet machines are still quite a new phenomenon both in industrial and wind energy applications. The biggest concerns are focused on the PM material itself. Questions include the following:

- What happens to the remanence flux density with the time?
- Can the magnets be demagnetized?
- Are the magnets mechanically and chemically stable?
- How long are rare earth raw materials available and where are they found?
- How will the price of the materials develop?

The purpose of this article is to answer these questions and illustrate the constructional options that can be used in wind generators as well as the challenges and changes when applying PM technology. Both the advantages and risks will be discussed.

As wind power is one of the fastest growing markets, if not even the fastest, there are a lot of global research activities in the field of wind power and permanent magnet machine development. Observing the status quo of patent applications with different key terms in their main title as of January 6, 2010, gave the following answers:

- “Wind power”: 10,429 applications or patents
- “Wind turbines”: 8,964 applications or patents
- “Permanent magnets”: 33,469 applications or patents mostly concerning PM materials and permanent magnet fixing in the rotor

In addition to these specific terms, there are many system-specific patents or applications such as “Aerodyn: multibrid” and “GE: variable speed wind turbine”, which raise a lot of discussion in the market.

2. Permanent magnets

The discovery of rare earth based permanent magnet materials in the 70s revolutionized not only the permanent magnet industry, but also the volume of applications. The superior magnetic properties of SmCo made it possible to build highly efficient, high-performance devices and motors, especially miniaturized ones. The high material costs, however, effectively hindered any large scale applications.

Although the basic magnetic properties of NdFeB magnets developed in the 80s are even better than those of SmCo, the limited temperature stability of the material initially restricted the possible applications for low-temperature devices, like voice coil motors, disc drives and MRI. However, the development of NdFeB grades with improved temperature and corrosion resistance in the past ten years has opened the road for efficient permanent magnet machines, even in medium and large applications such as wind turbines.

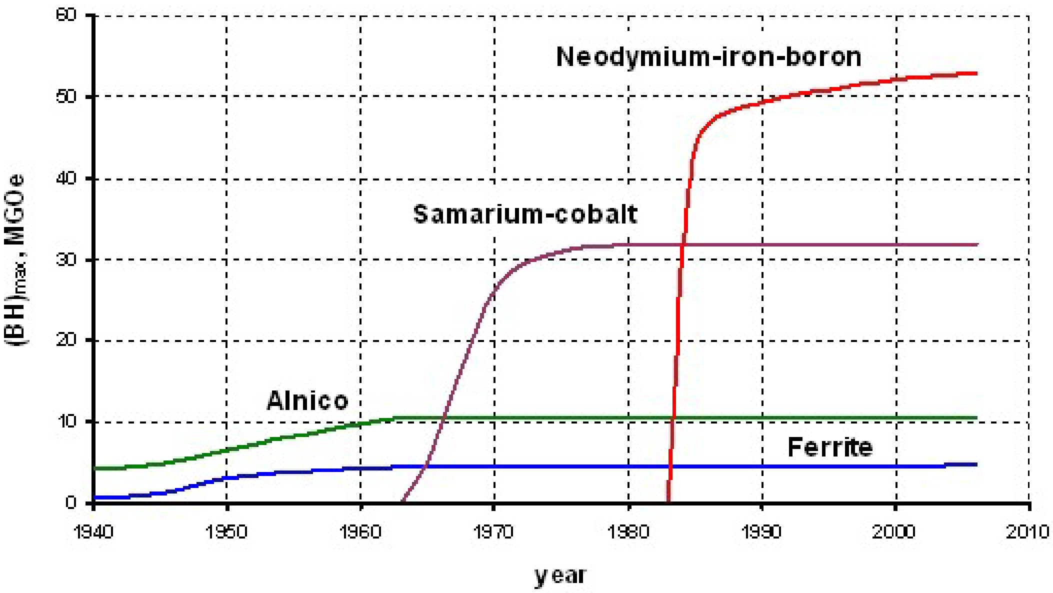


Figure 1. The development history of different types of permanent magnets. (BH)max describes the “strength” of the magnet. (www.magnetweb.com)

2.1. Stability of permanent magnets

As with all engineering materials, permanent magnet materials are stable within certain physical limits. The task of the machine design is to keep loads within those limits. NdFeB magnets have to be protected against demagnetization due to an uncontrolled temperature rise and against corrosion. The main improvements in the recent development of NdFeB magnets have thus been reached in corrosion resistivity and temperature tolerance. By using a proper application design, modern NdFeB magnets can be kept stable for decades.

2.1.1. Demagnetization

At temperatures below the Curie temperature (= 310°C – 400°C for NdFeB depending on the grade), the demagnetization is caused by an opposing magnetic field. This field can be due to an applied external field or the magnet’s own field. A magnet material’s behavior in an opposing external magnetic field is indicated by its demagnetization curves (Figure 2). Demagnetization curves at different temperatures are measured by hysteresis graphs.

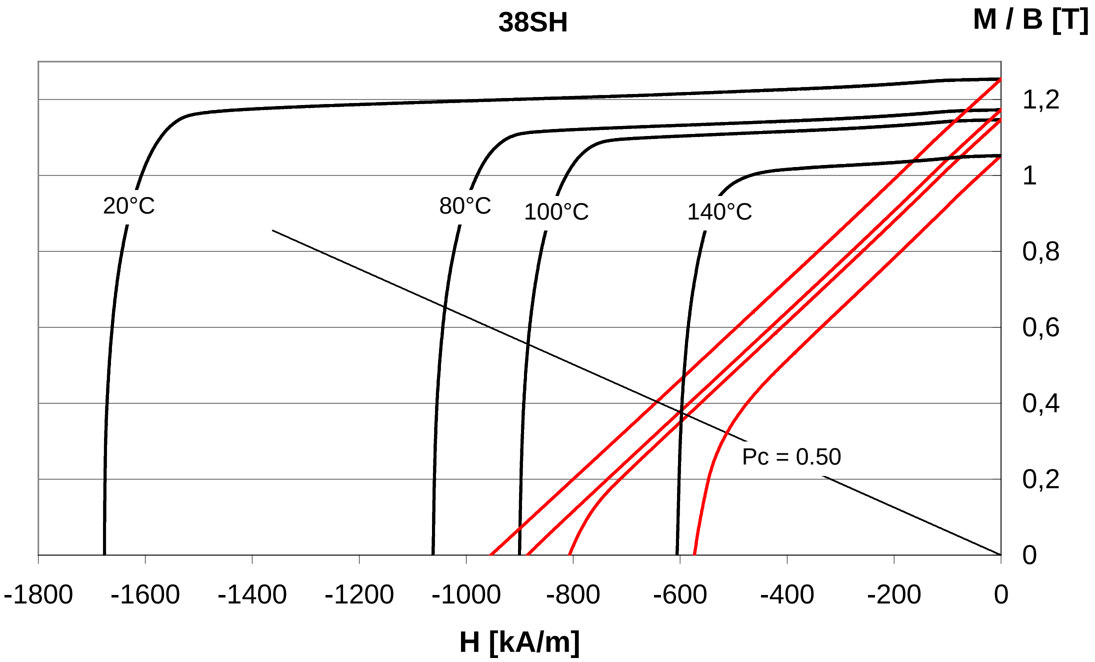


Figure 2. M(H) (black) and B(H) (red) curves measured at 20°C, 80°C, 100°C and 140°C for 38SH material.

The intersection of the demagnetization curve with the vertical (B) axis defines the remanence flux density, and the intersection with the horizontal (H) axis is the coercivity of the material. Coercivity can be understood as the capability of a material to resist opposing fields. It determines the opposing field strength at which magnets become demagnetized. In fields much lower than the coercive field, no permanent flux loss will occur.

The coercivity of NdFeB magnets decreases with increasing temperature. This means that considerable attention has to be paid to the design of the circuit, the cooling arrangements as well as the correct magnet material selection. NdFeB magnet coercivity can be increased by alloying it with other rare earth metals like dysprosium or terbium, or by refining the grain size. The basic NdFeB material with no alloying elements can only tolerate temperatures below 60°C. For example, with a sufficient addition of dysprosium, the maximum working temperature of NdFeB magnets can be increased even to 200°C and above. The addition of Dy, however, will decrease the remanent flux density and increase the price of the magnet. Thus, it is important to select an optimal magnet grade corresponding to the requirements.

Whether a permanent magnet will survive at a certain temperature without demagnetization depends on the coercivity of the material at a given temperature – for example, on the material properties and on the working point of the magnet, in other words, on the geometry of the magnet circuit. With the help of modern FEM calculations, the determination of the working point even in a complex geometry is a relatively easy task. The load line (Pc = 0.50) in Figure 2 represents the geometry of the magnet. As long as the temperature and magnetic field environment are under control, demagnetization of the magnets can be avoided.

2.1.2. Ageing

Demagnetization is a time-dependent process. At constant temperature, the magnetization of a magnet changes with time in a logarithmic fashion [1]:

$$M(t,H) = M(t_0,H) - S(H)\ln\frac{t}{t_0} \quad ,$$

where S is the magnetic viscosity constant and t_0 is a reference time. Magnetization is naturally also dependent on the field. In low fields, those much lower than the coercive field, the viscosity constant S will be extremely small and magnetization can be considered stable [2]. In cases where the external field approaches the coercive field, the magnetic viscosity effect starts to dominate, and S will start to increase, reaching its maximum in the coercive field.

As the time-dependent losses are linear on a logarithmic scale, it is possible to predict the long-term losses of permanent magnets in constant field conditions by measuring losses during a two-week elevated temperature exposure period. Figure 3 shows measured losses for 38SH magnets (Figure 2 shows the B(H) curves of the material) with a permeance coefficient of 0.5. Losses will be extremely small at temperatures of 110°C and below, also over the long run.

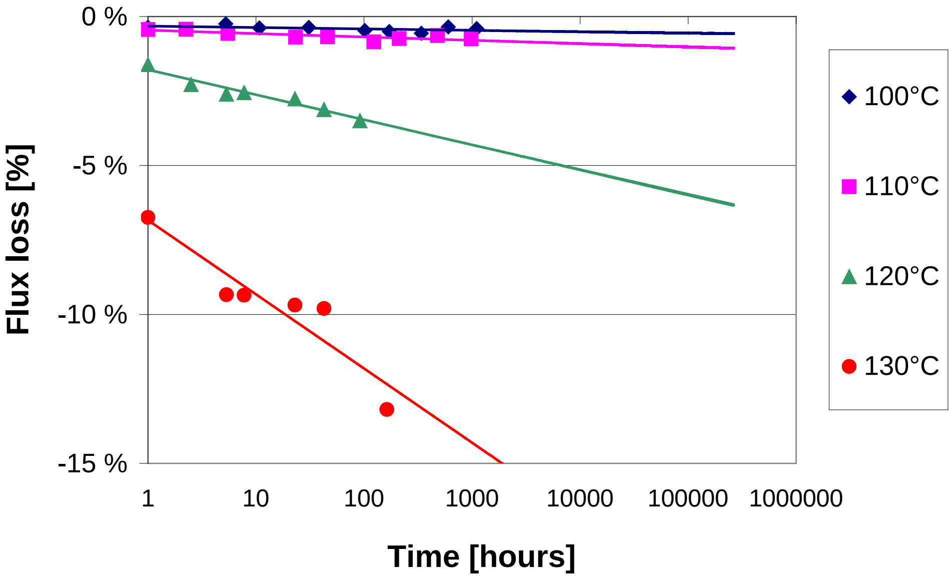


Figure 3. Irreversible flux loss as a function of time in a magnet (38SH grade, permeance coefficient = 0.50) at 100°C, 110°C, 120°C and 130°C. Trend curves are extended to 260,000 hours, which correspond to 30 years.

Irreversible flux losses can also be determined as a function of temperature (Fig. 4). Figure 4 illustrates different exposure times with different curves. For example, after 30 years at 120°C, the irreversible flux loss of this type of magnet will be over 6%, even though the loss after one hour is less than 2%. At temperatures under 110°C, there will be no detectable losses even after 30 years.

Note that the position of these curves (Fig. 4) on the temperature scale depends not only on the material, but also on the external field (permeance coefficient of the circuit). An increase in the opposing field will decrease the permeance coefficient, moving the curves to left, towards lower temperatures. Respectively, the increase in Pc will move the curves to the right.

This time-dependent loss behavior must be considered when selecting the magnet material for the application.

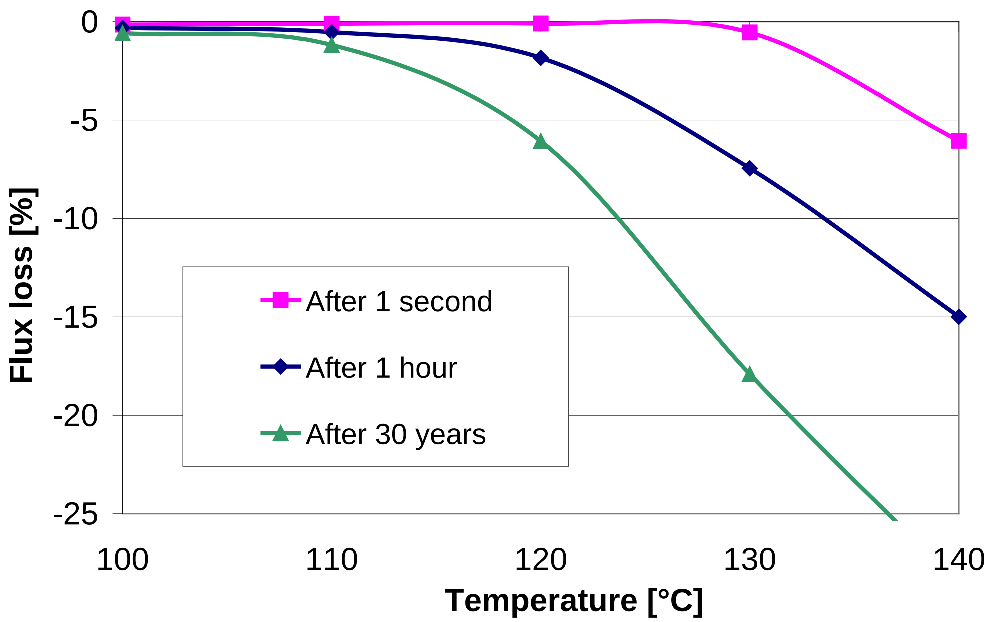


Figure 4. Irreversible flux loss as a function of temperature after different exposure times in 38SH magnets with a permeance coefficient of 0.50.

2.1.3. Structural stability

NdFeB magnets have to be protected against mechanical and chemical loads. Magnets are brittle and should never be used as tensile load carrying elements. This brittleness is a typical property for powder metallurgical products. Corresponding products are widely used in the industry.

When sintered NdFeB magnets came to market in the late 80s, they were known to be prone to intergranular corrosion. Insufficient corrosion protection often caused a pulverization of the magnets. In recent decades, solutions to these problems now exist. By manipulating the metallurgical microstructure of the magnets, intergranular corrosion can be minimized or prevented. Also, methods for corrosion testing have been developed. A widely used corrosion test nowadays is the so-called HAST test, where magnets are exposed to high temperature and high humidity at the same time.

In normal atmosphere, the modern NdFeB magnets can often be used without any corrosion protection, but proper surface coating is recommended in humid or marine environments. The magnet may also be well protected against the surroundings by means of the design. The resin used with impregnated buried magnets (Figure 5) have a very effective additional protection. Surface-mounted magnets may be protected with hermetically sealed modules (Figure 6) or a separate cap. All these methods protect the magnet both mechanically and chemically. Quite often, they also are part of the design to improve the magnet assembly methods.

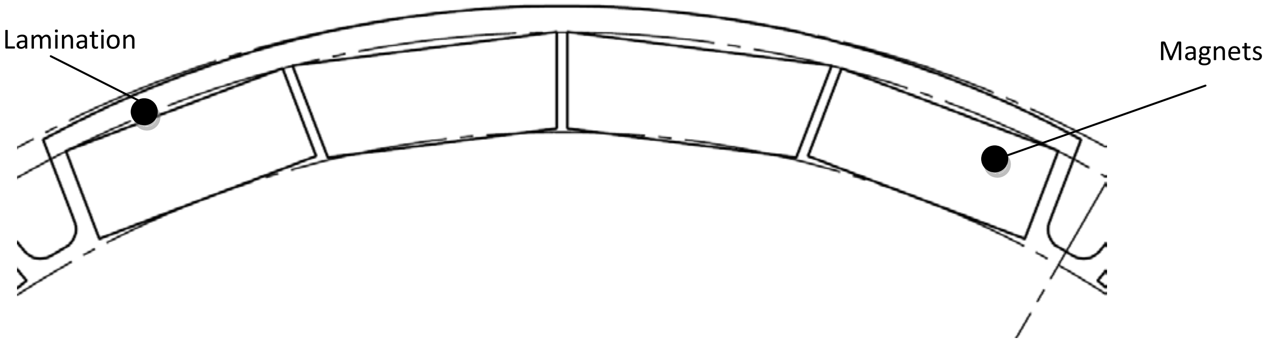


Figure 5. Buried magnets in side rotor. After assembly, the rotor is impregnated and all gaps are filled with resin. The magnet is protected from its surroundings.

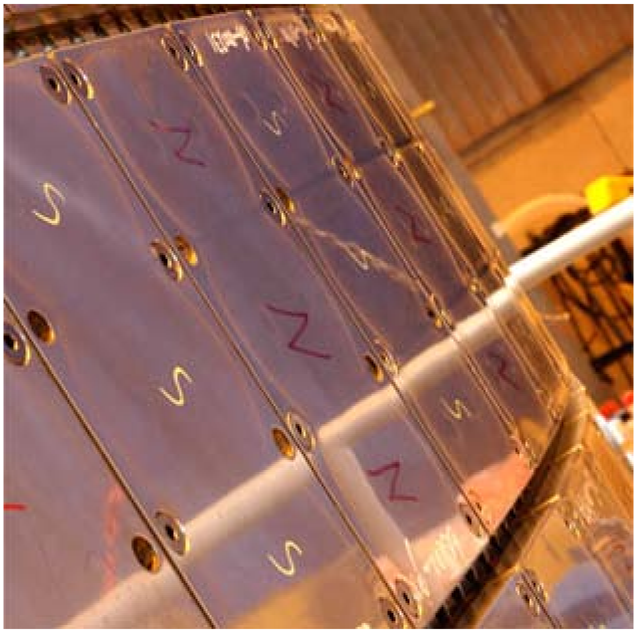


Figure 6. Magnet module in a large direct-drive generator.

3. Rare earth metals

The known reserves of rare earth metals should last more than 1,000 years at current consumption rates. The problem today is that due to the very low price level of the rare earth metals in the past, Western rare earth mines, like Mountain Pass operated by Molycorp, were shut down. Over the past ten years, this development has resulted in the fact that mining and refining is now almost solely concentrated in one single-source country – China. In 2007, it was feared that 2009/2010 consumption would exceed the annual production – especially due to all the emerging green applications, such as PM wind generators, electric cars, electric bicycles and others. This was also reflected in the price development of Nd, Dy, Pr and other rare earth metals used in permanent magnet production. But the shortage of the rare earth metals did not materialize, and the price levels are back to the same level as in 2007. In this respect, the worldwide decline in industrial production has been helpful.

Just recently, Western companies and investors have understood the importance of rare earth based minerals and metals, and several new ores have been identified, for example in Canada, Australia and the US. Development of alternative sources will, of course, take several years since the entire supply chain from mining operations to refining capacity needs to be built up from scratch. However, the forecast is that in a few years, increasing amounts of rare earth metals will come from non-Chinese sources. According to the latest estimations, these new sources will help to stabilize the situation so that no shortage of rare earth metals will occur (Fig. 7). There are also plans to restart NdFeB magnet production in the US, solely based on US raw materials.

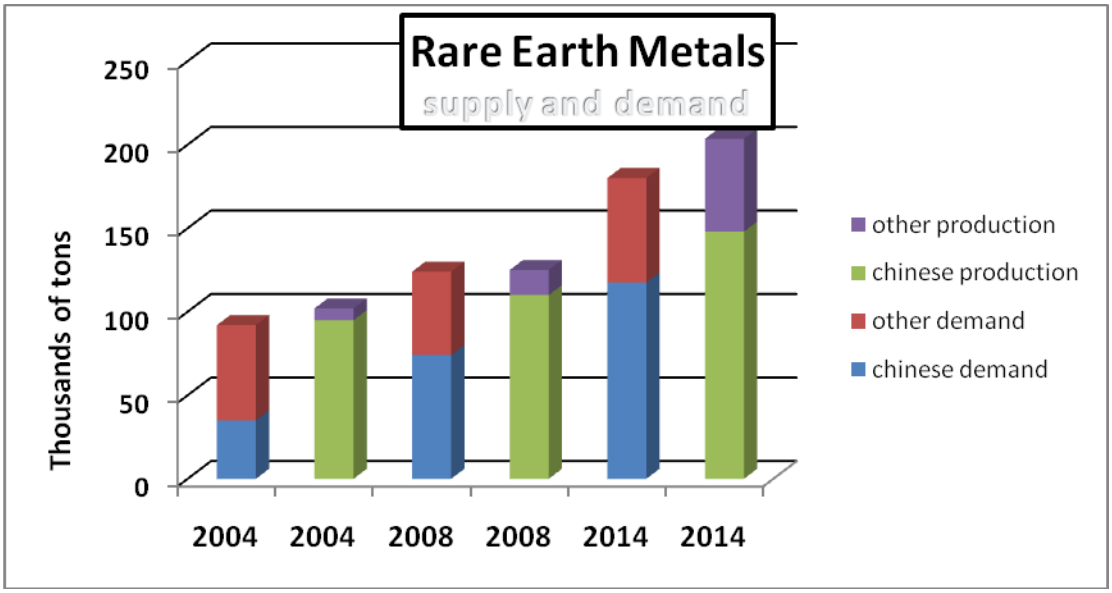
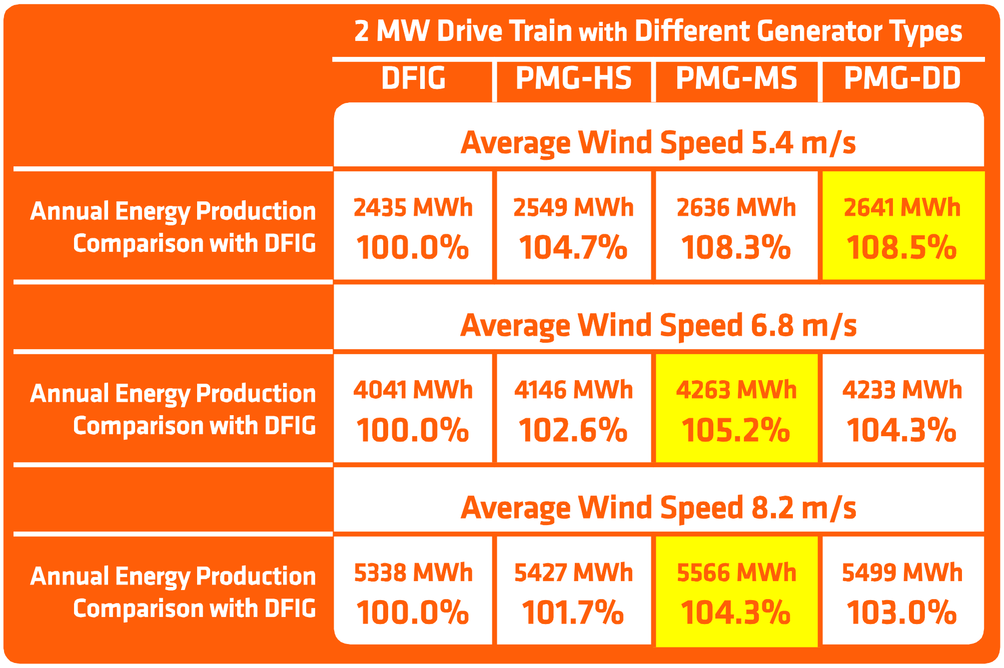


Figure 7. Predicted development in supply and demand of rare earth metals (source: Willie D. Jones, IEEE Spectrum, January 2010, pp. 68).

4. PM technology in wind power

Quite often, one of the main criterions when comparing PM technology with traditional solutions is the rated point efficiency. In most cases, this is a totally incorrect approach. This is because typically more than half of the time the turbine is running on partial loads. Therefore, as the payback time is mainly dependent on the produced annual energy, the entire operational range should be carefully studied. As a synchronous machine, like the name defines, always rotates synchronously with the stator field, the only electromagnetic rotor losses are based on the air-gap harmonics, whereas in double-fed generators, the rotor losses are strongly dependent on the difference between rotor mechanical and electric frequencies. Also, the operational area of the double-fed generators is limited to about ±30% of the synchronous speed, which means operating between speeds of 0.54 – 1, while a

PM generator produces power at relative speeds of 0.2 - 1. Due to these facts, the overall efficiency of the PM drive train is higher, resulting in a higher annual production. Table 1 gives calculated annual energy production values of 2 MW turbines with different drive train concepts. It shows clearly, especially at low wind speeds, the advantage of the PM technology.



	2 MW Drive Train with Different Generator Types			
	DFIG	PMG-HS	PMG-MS	PMG-DD
	Average Wind Speed 5.4 m/s			
Annual Energy Production	2435 MWh	2549 MWh	2636 MWh	2641 MWh
Comparison with DFIG	100.0%	104.7%	108.3%	108.5%
	Average Wind Speed 6.8 m/s			
Annual Energy Production	4041 MWh	4146 MWh	4263 MWh	4233 MWh
Comparison with DFIG	100.0%	102.6%	105.2%	104.3%
	Average Wind Speed 8.2 m/s			
Annual Energy Production	5338 MWh	5427 MWh	5566 MWh	5499 MWh
Comparison with DFIG	100.0%	101.7%	104.3%	103.0%

Table 1. Annual energy production of different wind turbine concepts with different wind speeds (The Switch 2009).

The other fact that supports PM technology is the demand for service. As the technology requires no slip rings with brushes, there are practically no serviceable components in the PM generator.

4.1. Mechanical topologies of wind turbine drive trains

In practice, the wind generator drive trains can be divided into three basic systems: 1) high-speed (HS) drive train, 2) medium-speed (MS) drive train and 3) low-speed, direct-drive (DD) train.

Let us observe each of these topologies in more detail:

4.1.1. HS drive train

4.1.1.1. Double-fed HS system

The HS drive train is generally the most common in existing wind power systems. With this approach, a mechanical gear with a gear ratio of 1:100 is used to increase the speed of the system up to the traditional electric machine speed in the range between 1000 and 2000 rpm. Such a speed makes the design of the electric machine itself easy and offers a compact electric machine design. The machines are stand-alones, which also makes the responsibility questions between different suppliers easy.

Electric machine designers have considerable experience in designing induction generators especially in this speed range, as industrial machines often rotate in the same speed area. This fact actually has led to the use of the traditional slip-ring induction machines in wind power applications with minor changes in the machine construction. The HS drive train could be called the "business-as-usual" approach from the electric drive train supplier point of view. The ±30% variation around the synchronous speed results in a rotor converter having about 30% of the machine rated power as the converter rated power. In principle, from the energy efficiency point of view, this is a benefit, as only one third of the power is maximally driven via the power electronic system, which operates maximally at about 97% efficiency. However, fault situations are very challenging for the rotor converter and extra protection measures are needed. Still, traditional machine manufacturers have been successfully competitive with their HS drive trains.

4.1.1.2. Permanent magnet synchronous machine in the HS system

Introducing permanent magnets to the HS drive train concept, of course, changes the situation, as a full-power converter is needed. The full-power concept can offer effective tools, for example, to solve the problems of the DFIG system from the grid code point of view. Loss of mains (LOM) drive through is easier with the full-power converter approach.

The design of the HS permanent magnet generator has not yet matured in the same way as the design of synchronous machines or induction generators. This creates challenges for established manufacturers and offers possibilities for new innovative companies such as The Switch. A large power permanent magnet HS generator is quite a new approach in itself and presents significant challenges to the designer. Usually, embedded magnets are used in the HS designs to provide the magnets with a mechanical protection and to achieve a suitable safety margin against demagnetization.

One of the main design questions is if it is possible to lose the polarization of the permanent magnets. It can be stated that there is a possibility of losing the polarization in the case when magnets are hot and a two- or three-phase short circuit takes place in the generator terminals. This, of course, is a rare occasion in a converter-operated machine, but must still be kept as a design criterion. As the generator frequency should not increase too high, machines based on the HS concept have a relatively low number of poles. As the magnetizing inductance is inversely proportional to the square of the number of the pole pairs, a low pole pair machine has a relatively high magnetizing inductance typically in the range of

$$l_m \in (0.4 - 0.5) \text{ pu.} \quad (1)$$

and also a low stator leakage in the range of

$$l_{s\sigma} \in (0.1 – 0.15) \text{ pu} \quad (2)$$

resulting in

$$l_s \in (0.5 – 0.65) \text{ pu.} \quad (3)$$

During short circuits, such a machine with no damping creates a short-circuit current in the range of

$$I_k \in (1.55 - 2) \text{ pu.} \tag{4}$$

Because of the large ratio

$$l_m/l_s \in (0.72 - 0.83) \text{ pu} \tag{5}$$

the demagnetizing current linkage mostly affects permanent magnets, and the danger of demagnetization during a short circuit exists. For example, if $I_k = 2$ and $l_m = 0.4$, the demagnetizing per unit flux linkage will have a fundamental value of

$$\psi_{mDM} = I_k \cdot l_m = 2 \cdot 0.4 = 0.8. \tag{6}$$

If the original permanent magnet flux linkage is in the range of unity

$$\psi_{PM} = 1 \tag{7}$$

the flux linkage during the short circuit should be in the range of

$$\psi_{PMsc} = \psi_{PM} - \psi_{mDM} = 0.2. \tag{8}$$

Hence, the fundamental permanent magnet flux linkage is reduced to 20% of the original value. Often the magnet could tolerate this, but in practice the demagnetizing flux is not evenly distributed in the magnets, and there will be locations where the flux density is significantly lower and even negative in many short-circuit cases.

The possible demagnetization problem, however, can be solved by designing the machine so that the stator leakage is deliberately increased, by magnetizing inductance decreased, and by selecting magnets with a high coercive force together with a carefully detailed design. Optimizing the machine for both high efficiency and minimized demagnetization risk, however, easily results in an expensive construction, which weakens the competiveness of the permanent magnet machine approach.

4.1.2. Permanent magnet synchronous machine in the MS system

The MS approach is usually built as an integrated solution where the step-up gear ratio is in the range of 1:10, and hence the generator speed is in the range of 150 rpm. A compact and rugged solution can be found by using the permanent magnet technology. The machine design itself is somewhat different compared with the HS approach, as the number of poles in the machines is remarkably larger and hence the relative leakage inductance larger. Now the demagnetization risk is remarkably smaller compared with the HS approach, even if rotor surface magnets are used. As an example of an integrated system, Figure 8 shows a gear and generator construction in which the generator does not have its own bearings, but rather the rotor is supported by the secondary shaft of the gear. The saving in both required space and weight are remarkable.

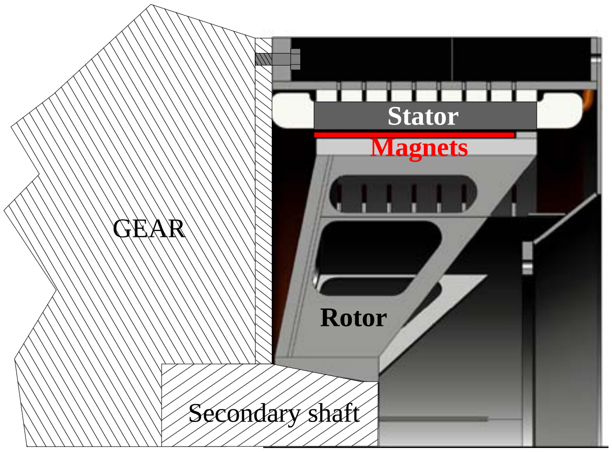


Figure 8. Integrated construction of a PM machine and gearbox.

Figure 8 shows an MS permanent magnet machine integrated into a 1:10 step-up gear. The machine has no bearings of its own. From an electrical machine design point of view, the MS approach is a good solution. Despite the relatively low speed, machine efficiency can be optimized and a good balance between iron and copper losses can be achieved as well as in the HS approach. The speed, however, is so low that the permanent magnet approach inevitably offers the best efficiency for the system, and it should be difficult to apply other machine types unless synchronous machines are used.

4.1.3. Permanent magnet synchronous machine in the DD system

In a direct-drive system, the permanent magnet machine rotates only at 12 – 15 rpm at the rated point. This is such a low speed that the electrical machine itself can no longer reach a good balance between the iron losses and copper losses. Copper losses dominate. Such a rated speed can sensibly only be reached with a synchronous machine or a permanent magnet synchronized machine (PMSM). The direct-drive concept also creates the largest permanent magnet machine, as the whole torque of the turbine must match the generator torque. The torque of the machine, in principle, defines the rotor size of the machine, as the tangential component of the Maxwell's stress remains in the same range for all the different approaches. In the DD concept, the maximization of the tangential stress is naturally one of the design principles. In such a case, surface rotor magnets are favored in order to get as small per unit magnetizing inductance as possible. In The Switch designs, tangential stresses have grown from the initial value of about 45 kPa to the present value of about 60 kPa, and hence the same rotor volume now produces about 4 MW instead of the original 3 MW at 14 rpm.

Increasing the tangential stress will necessitate an even more effective cooling system, and system efficiency will gradually decrease if the torque density of the machine is increased from the present values. Of course, the direct-drive machine size is very large. Therefore, increasing the torque density is a more attractive approach than increasing the machine size. If the 5 – 6 MW range with the DD concept should be reached, a direct cooling approach may be needed in the design.

The Switch approach for the 3 – 4 MW DD generators is based on a segmented structure. The machine stator consists of 12 independent stator segments that can be driven even by different converters. Such a segmented structure provides redundancy for the drive, and the turbine may even remain operable in cases of minor faults in a segment.

The direct-drive machine can also be realized with an outer rotor structure (Figure 9). This structure is inherently the best alternative from a permanent magnet temperature point of view. As the magnets are attached to the inner surface of the outer rotor whose outer surface rotates in free air, the cooling of the magnets takes place most effectively. The large number of poles and large per unit leakage inductance provide a substantial tolerance against demagnetizing forces, and the magnets are safe in all possible operating conditions.

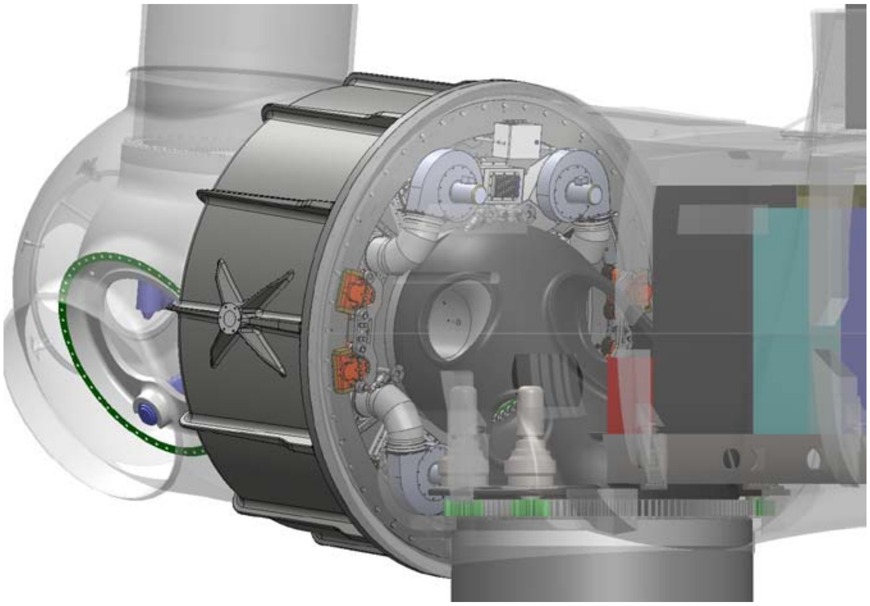


Figure 9. One approach to integrate the outer rotor PM machine with a wind turbine.

The Switch has paid significant attention to the torque quality of the DD generators. It is important to have a low torque ripple, as the ripple frequencies easily encourage mechanical vibrations in the turbine system. Especially at the lowest operating speeds, the torque quality should be very good to avoid harmful vibrations. The Switch has reached a high torque quality by using patented sinusoidal magnets on the rotor surface. The maximum peak-to-peak torque ripple in the DD approach is 0.5%.

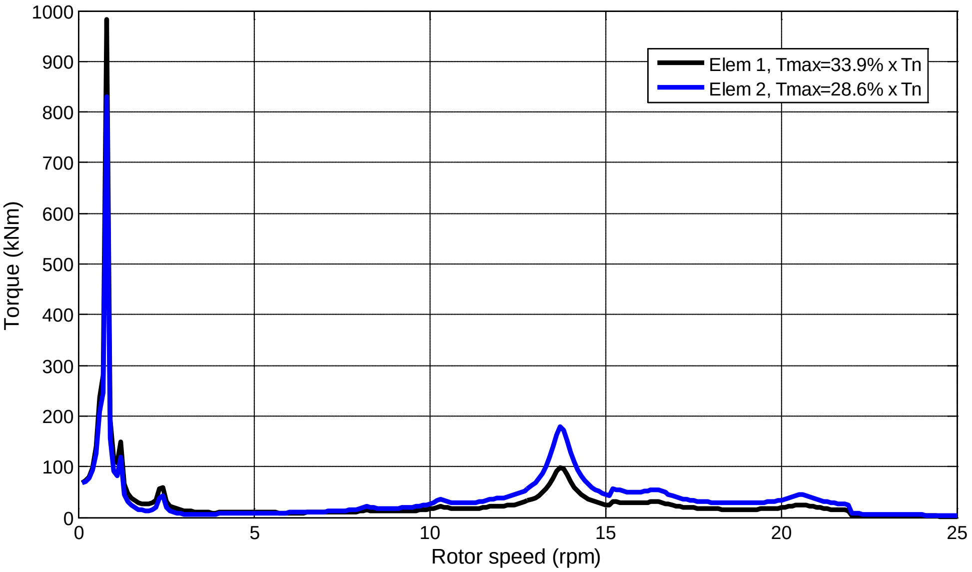


Figure 10. Turbine-generator torsional vibration in a DD system with torque ripple. The ripple is amplified at the start (2 rpm) and close to the rated speed (14 rpm).

Figure 10 clearly indicates the generator's need for high torque quality. Espcially at low speeds, operation becomes impossible if cogging is present.

4.2. Materials used in permanent magnet machines

The permanent magnet material itself has a big influence on the design. As mentioned above, tangential stress is one of the most important design features. The stress $\sigma_{F\tan}\left[\mathrm{Pa}\right]$ is directly proportional to the air gap linear current density *A* [A/m] and the air gap normal flux density B_δ [Vs/m^2].

$$\sigma_{F\tan} = \frac{\hat{A}\hat{B}_\delta \cos\varphi}{2} = \frac{A\hat{B}_\delta \cos\varphi}{\sqrt{2}} \qquad (9)$$

In low-speed, high-torque machines, attaching the magnets directly on the rotor surface most efficiently uses the magnet material. The flux density in the air gap can be increased by selecting the best available permanent magnet materials that have a high remanence and high temperature tolerance together with a high coercive force. A larger magnet thickness is also selected so that the operating point of the magnet becomes close to the remanent flux density of the material. This procedure also makes the design expensive, as relatively large amounts of magnet material must be used. The material is used in a flux density above the material's optimum BH point. Using thick permanent magnets with the highest remanence guarantees the lowest machine weight and increases the price. A suitable compromise is made between material costs and the machine weight.

The iron losses remain very small compared with the copper losses. Hence, the magnetic core material should have a high saturation flux density as the DD concept produces almost solely copper losses. A high saturation material allows a maximum slot surface for the winding.

In low-speed DD machines, the pole pitch is in the range of 0.1 m and the machine length is in the range of 1 – 1.5 m. Hence, the winding type is not very essential from the end winding minimization point of view. Integral slot windings with the number of slots per phase and pole $q = 1$ are quite well suited for low-speed machines. Fractional slot winding machines with concentrated pole windings having approximately $q = 0.4 – 0.5$ can be applied, too. In $q = 1$ machines, the fundamental winding factor is $k_{W1} = 1$, and in $q = 0.4$ machines, $k_{W1} = 0.933$ or $k_{W1} = 0.966$, depending on the winding type. A suitable compromise must be made between these alternatives.

The winding material in large, low-speed machines is usually form wound windings. The need to avoid a skin effect or circulating currents is not very large in low frequency machines. Yet at higher speeds, modern Litz wire windings are an attractive solution. In the HS concept, The Switch has tested new Litz wires with good success. The manufacturing of the winding is easier and cheaper with Litz wires than with traditional form wound windings.

Random wound round wire windings are somewhat difficult in large power machines, and The Switch does not recommend their use. Roebel bars guarantee a very low skin effect and circulating currents, but are expensive to manufacture.

4.3. Required tools, calculations and analysis required to design a reliable electric machine

When designing permanent magnet machines, modern tools must be used in evaluating the details of the design. Analytical methods are valid when making the basic design of the generators, but soon finite elements method (FEM) based tools must be used in refining the designs. Losses in different parts and evaluation of the torque quality can be done, in practice, only with FEM.

FEM is not only required for the basic design of the machine, but one of the most critical calculations while designing a permanent magnet machine is extreme conditions to ensure the survival of the magnet against demagnetization. As the magnet coercivity and thus the capability to resist external fields is strongly dependent on temperature, a short-circuit calculation at the utmost high rotor temperature has to be performed. This calculation defines the parameters required of the magnet. Figure 11 illustrates the fields at the worst moment of a short circuit in a permanent magnet machine. The risk of demagnetization may be analyzed for the flux densities in different parts of the magnet(s) (Figure 12).

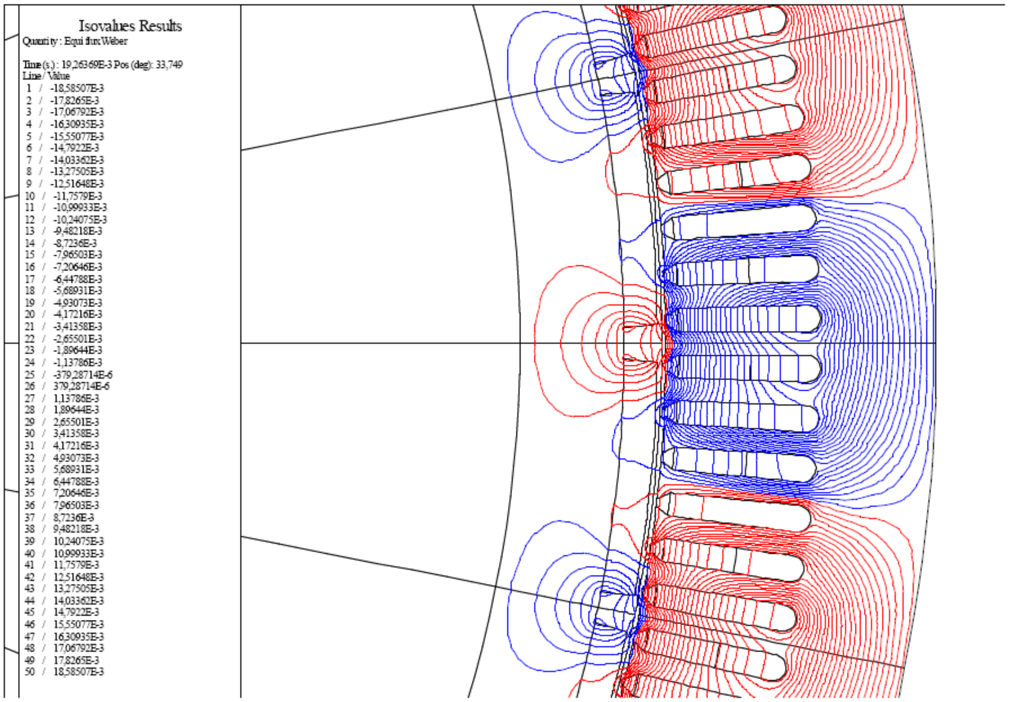


Figure 11. Flux plot of a surface-mounted PM machine in a 3-phase short circuit.

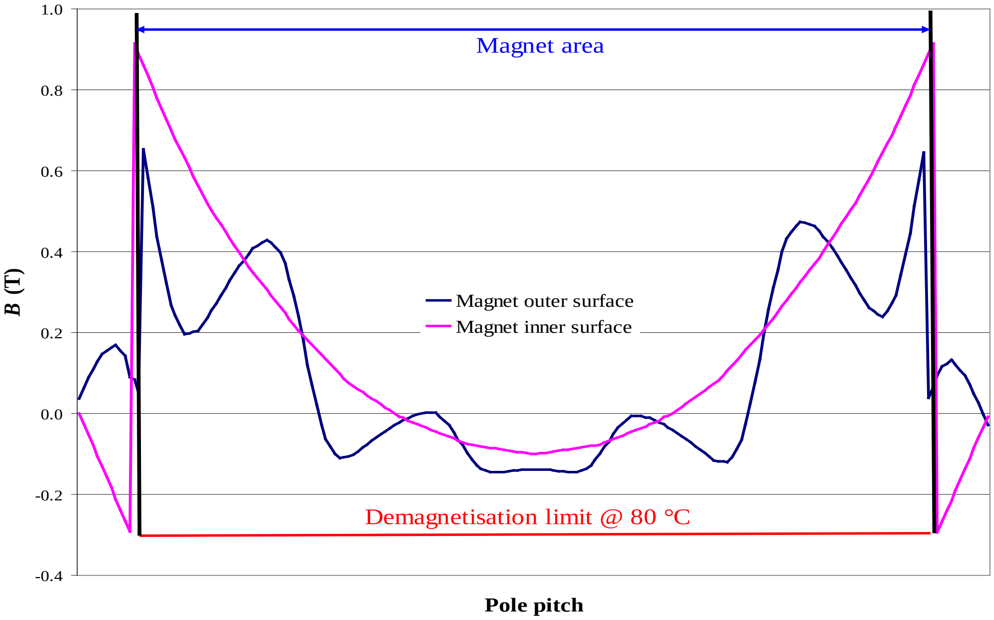


Figure 12. Flux density of the magnets under the demagnetizing effect of a short circuit. The distribution of the flux density is not uniform. Thus, in practice, only FEM results can be used in analyzing the demagnetization risk in detail.

To summarize, the rotor temperature – or to be more precise – the magnet temperature is a critical parameter when considering the risk of demagnetization. Additionally, it has an effect on the performance and losses of the machine, as the remanent flux density is also dependent on the magnet temperature. The higher the magnet temperature, the lower the generated voltage. Plus, higher current requirements from the stator lead to higher copper losses. Therefore, the temperature distribution and required cooling have to be carefully analyzed. There are commercial tools available for this task such as finite element analyzing (FEA) or computational fluid dynamics programs (FCD).

References

1. Skomski, R. and J.M.D. Coey, *Permanent Magnetism*. Studies in Condensed Matter Physics, ed. J.M.D. Coey and D.R. Tilley. 1999, London: Institute of Physics Publishing.
2. Haavisto, M. and M. Paju, *Temperature Stability and Flux Losses Over Time in Sintered Nd-Fe-B Permanent Magnets.* Magnetics, IEEE Transactions on, 2009. 45 (12): p. 5277-5280.