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c0012 Development of permanent magnet generators to integrate wind turbines into electricity transmission and distribution networks

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s0010 12.1 Introduction

p0010 European guidelines for the production of a part of its energy with renewable sources impose on the governments of member countries a requirement to invest in new production systems (Directive 2009/28, 2009). After hydraulic energy production systems, wind turbines are the renewable solutions that are the most popular. These fixed objectives have led to solutions being sought for the installation of offshore wind turbines. The specific stresses linked to this type of system have led those involved in the market to develop new systems and generators adapted to this use: a direct drive permanent magnet generator limits the number of elements in the conversion chain and so increases the system reliability.

p0015 First, different solutions to convert wind into electricity will be presented. The conversion of the mechanical energy (rotation due to wind) into electricity is realized using different technologies. The most popular is the doubly fed induction generator (DFIG), where a small power converter is used to supply the rotor and the stator is directly connected to the grid, but synchronous machines (with permanent magnets or wound rotors) can also be used to make the conversion at a wider range of speeds. Second, we will give more details on the direct drive permanent magnet solution: advantages and drawbacks. We will see that this solution seems very interesting for offshore applications. Finally, we will focus on the design improvements that could lead to an increase in the attractiveness of permanent magnet generators for wind turbine applications.

s0015 12.2 Wind turbine power conversion: the induction generator

p0020 Different machine topologies can be found in the wind turbine power conversion chain. For a high power system (power delivery to the grid >1 MW), these solutions are presented. Induction and synchronous generators can be used; each solution will

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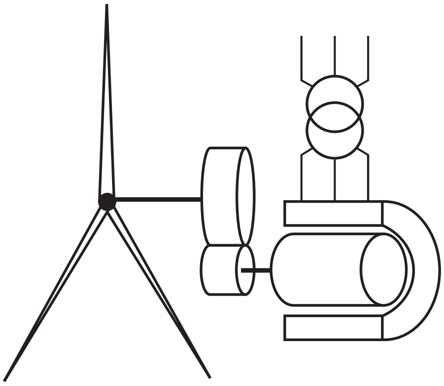
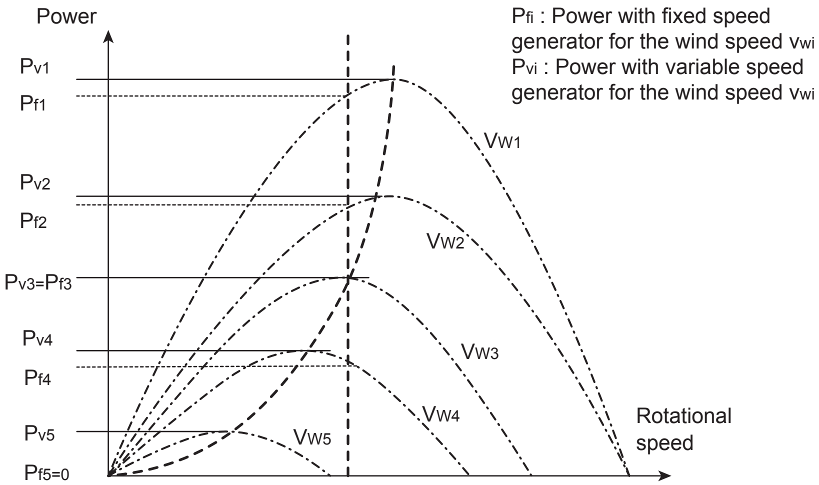


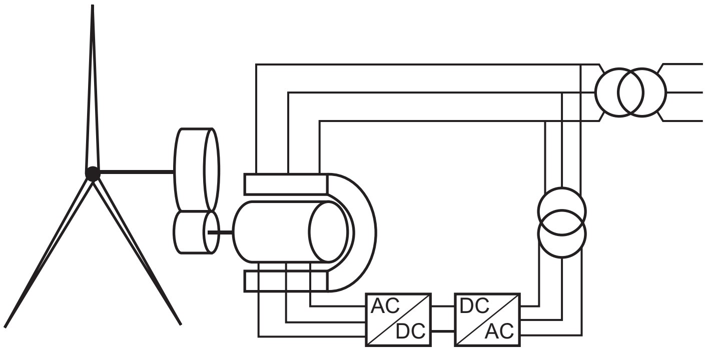
f0010 **Figure 12.1** Generator directly coupled with the grid.

have some advantages and some disadvantages. In this section, a detailed comparison is provided in terms of performance and cost, leading to the conclusion that permanent magnet generators can become of interest in terms of annual energy production. With the induction machine, what it is interesting is the simplicity of the realization of the rotor, but it will be necessary to use a converter in order to produce energy at variable speed. In the first wind turbine, a fixed speed was used; in this way, it was possible to directly connect the generator to the grid (Figure 12.1).

p0025 This solution was very interesting because of its simplicity: it is not necessary to supply the rotor. But the wind speed range is limited and the annual production is low. In fact, if we compare the power that can be achieved with a variable speed system compared to a fixed speed, we see (Figure 12.2) that for all wind speeds the power is bigger.



f0015 **Figure 12.2** Power for different wind speeds with fixed and variable speed solutions.



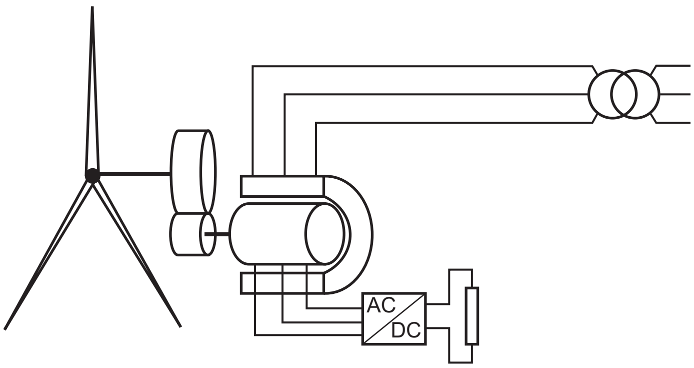
f0020 **Figure 12.3** Conversion chain for the doubly fed induction generator topology.

p0030 In order to limit the power rating of the converter and limit the cost of the global system, two solutions with variable speed can be considered for the wind energy conversion chains. The most popular solution currently is the DFIG (Fletcher & Yang, 2010). A description of the system that is used in order to convert wind into electricity is given in Figure 12.3.

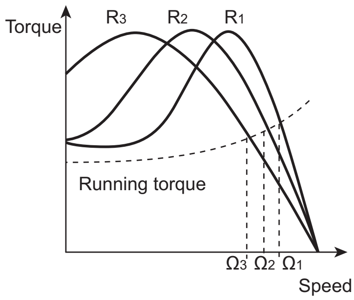
p0035 The rotor of this machine is a three-phase wound rotor, and brushes are used in order to supply the winding with adapted current. In fact, the management of the frequency of the rotor waveforms allows the network frequency to be used. To have the good voltage and transmit the power from the blades to the grid, it is necessary to control the amplitude and the phase of the rotor voltage. Two modes are used, depending on the speed compared to the grid frequency:

u0010 • hypersynchronous, when the rotating frequency is higher than the grid frequency;
u0015 • hyposynchronous, when the shaft speed is lower than the synchronous speed.

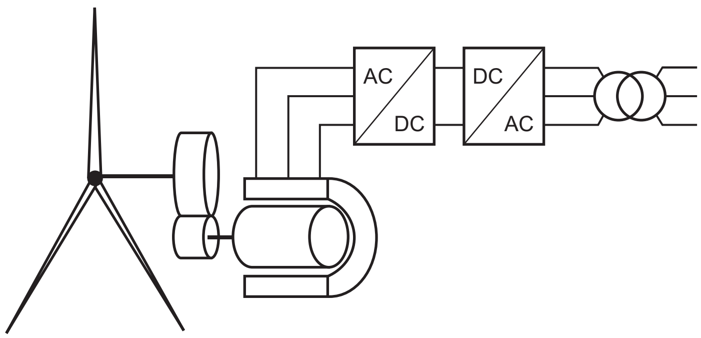
p0050 Another solution can authorize the machine to rotate at variable speed. For that, a load is added in series with the rotor winding (coils), as described in Figure 12.4.



f0025 **Figure 12.4** Conversion chain with load to modify the machine slip.



f0030 **Figure 12.5** Torque curves with variation of the rotor impedance.



f0035 **Figure 12.6** Induction generator supplied by full power converter.

p0055 In this case, the aim is to modify the rotor impedance; this leads to modification of the torque curve, as described in Figure 12.5, and to variation of the speed by increasing the slip.

p0060 The range of speeds is not the same for both cases; the solution presented in Figure 12.4 enables a small variation, and when the resistance increases, the losses are more important. For the solution of Figure 12.3, the speed range will depend on the converter sizing. For example, in the presence of a converter with a power rating around 30% of the nominal power that the blades can deliver, the system speed can vary from 70% of the rated speed up to 130%. The expression of the rotor losses is obtained by multiplying the slip with the mechanical power, so to have a slip of 30% it is necessary to have 30% of the mechanical power on the rotor. If a large speed range is suitable, it is more interesting to use a converter to supply the stator, as presented in Figure 12.6.

p0065 The generator in Figure 12.6 could be directly coupled to the blades, but this leads to a low speed machine, and for an induction machine it means having a low magnetizing inductance. In both cases, the consequences are:

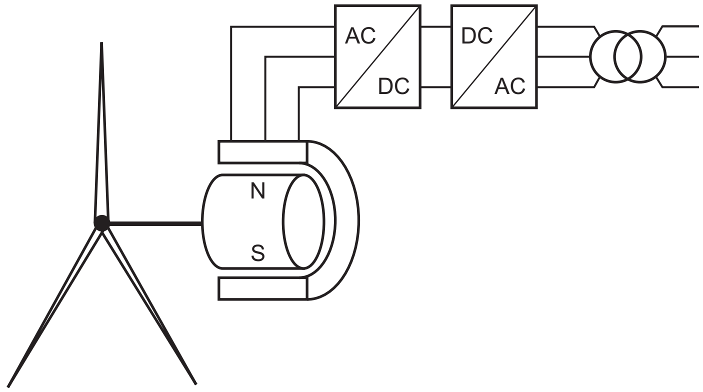
u0020 • a low power factor
u0025 • an important current to magnetize the rotor
u0030 • low efficiency

p0085 As a synchronous generator has good efficiency at low speed, we can connect it directly to the blade in order to avoid the use of a gearbox.

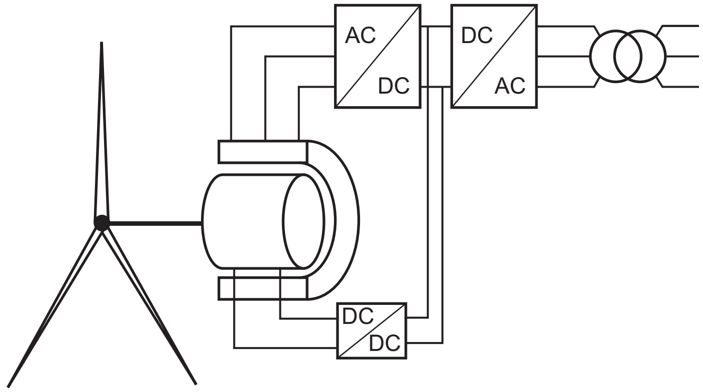
s0020 12.3 Wind turbine power conversion: the synchronous generator

p0090 Two technologies exist that can convert mechanical power into electricity, and they depend on how the rotor flux is obtained: with permanent magnets or with coils supplied with a DC current. These two solutions are described, respectively, in Figure 12.7 and in Figure 12.8.

p0095 In both cases, a full power converter is necessary to adapt the frequency of the currents coming from the machine (variable frequency) to the network frequency. When a wound rotor is used, a system is necessary in order to supply the rotor pole. Different



f0040 **Figure 12.7** Synchronous generator with permanent magnet rotor.

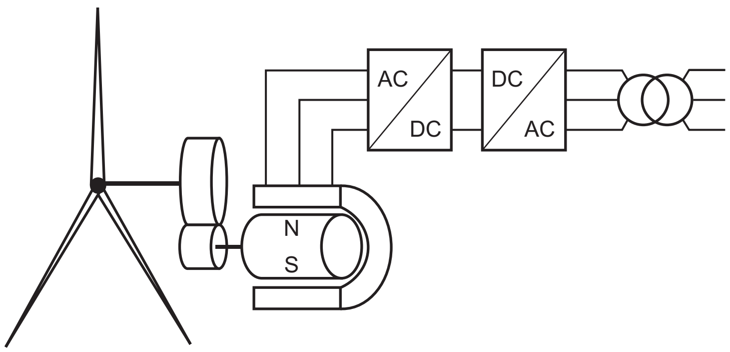


f0045 **Figure 12.8** Synchronous generator with wound rotor.

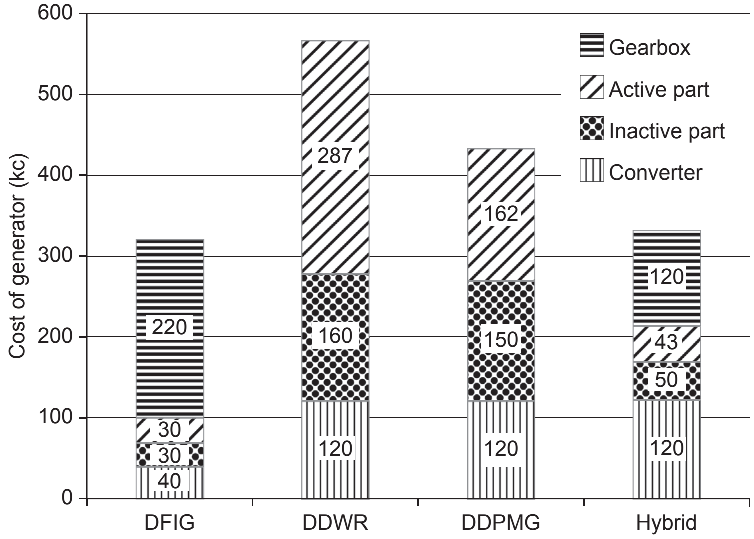
solutions can be considered. Brushes can be used, but this solution can lead to various problems—remember that a brush is one of the drawbacks that limited the expansion of DC machines, although these machines have a high torque density. To avoid brushes, it is possible to use a rotating transformer with a diode rectifier placed on the rotor, called an *exciter*. This system enables rectification of the induced waveform on the rotor coils in order to have a DC current. In both cases, a converter is necessary to manage the current seen by the machine poles. Depending on where the power is taken, the converter can convert DC to DC if it is connected to the DC bus (as in
[**AU2**] the case in Figure 12.8) or convert AC to DC if the machine is connected to the grid. With a synchronous machine the gearbox is not necessary even if it is possible to achieve the solution with higher shaft speed for the alternator in order to reduce the size of the machine; the conversion chain is given in Figure 12.9.

p0100 We have described different solutions but will only discuss four of them in order to make a comparison. We will keep the most popular—the DFIG and the wound rotor synchronous machine (DDWR)—and the two solutions using permanent magnets—direct drive (DDPMG) and the solution at a higher speed, often named hybrid. Some studies can be found in the literature concerning comparisons between different wind turbine topologies. For the four previous cases, we can recall the work of H. Polinder. A comparison of costs and losses is given in Bang, Polinder, Shrestha, and Ferreira (2008). The results are summarized in Figure 12.10.

p0105 In Figure 12.10, active parts of the generator are all the elements that are valuable for conversion of the mechanical energy into electricity: copper, permanent magnets, and laminated iron to drive the flux inside the machine. The inactive parts are elements that are just there to maintain the active parts: rotor and stator frame of the machine. Using a synchronous wound rotor generator is an expensive choice, but it enables removal of the gearbox. Because of the dimensions of the generator, the costs of active and inactive parts are important. It is the same for the DDPMG, even if the active part cost of this solution can be discussed, the price of the permanent magnet has been subjected to a large variation during recent years (the reference is dated 2008). The hybrid solution cost permits a competitive solution compared to the DFIG, cost of conversion being compensated by a cheaper gearbox. Nevertheless, the choice of topology must



f0050 **Figure 12.9** Synchronous generator using a gearbox.



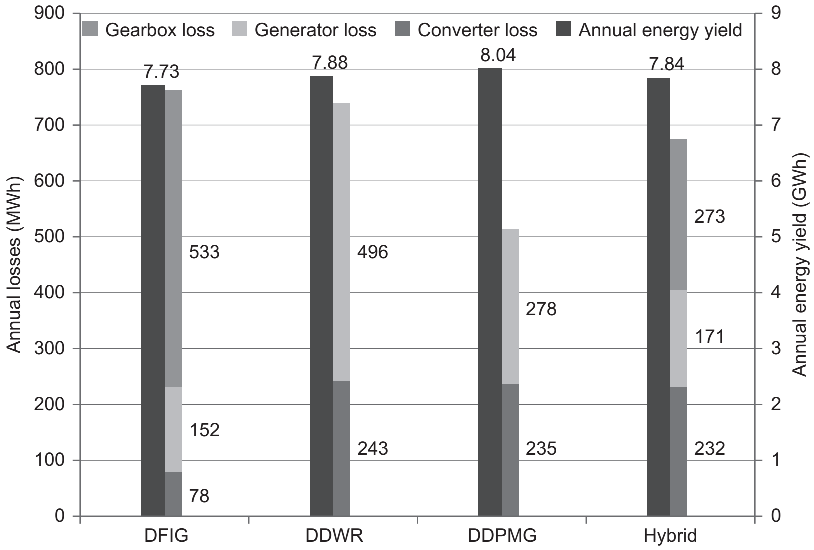
f0055 **Figure 12.10** Cost comparison of the different solutions (Bang et al., 2008).

not be made only by considering the cost. What is important is the time necessary in order to make a good return on investment. In order to have this information, it is necessary to know the performance of the global system and the annual energy production of the wind turbine. This information is given in Figure 12.11.

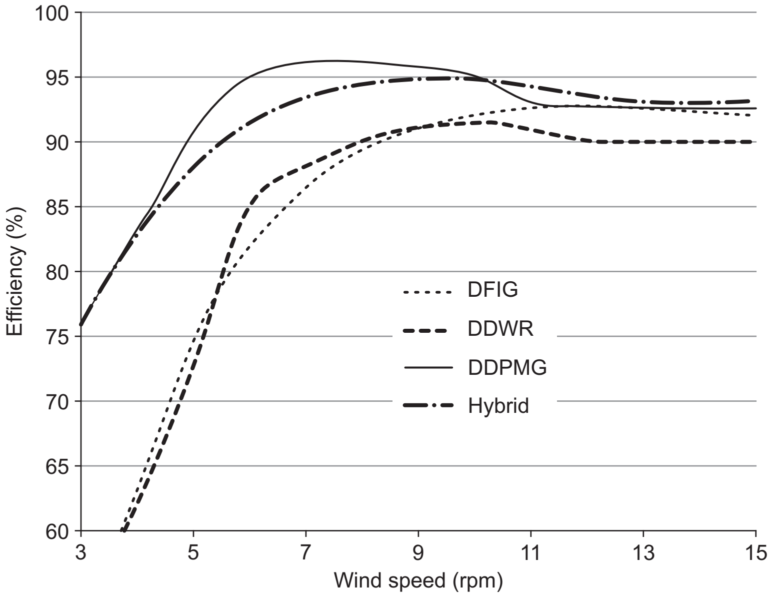
p0110 The important part of the losses due to the gearbox leads to the low energy production obtained with the DFIG. The highest energy is obtained with the DDPMG solution because this is the solution with the lower losses, especially if we compare the generator efficiency on the power range, as shown in Figure 12.12.

p0115 The solutions with permanent magnets have a better efficiency at low speed. Nevertheless, the losses due to the gearbox, used in the hybrid topology, lead to lower energy production than when choosing a DDWR, which has the lower efficiency for all operating points. Clearly, the solution leading to the best efficiency over the whole power range is the permanent magnet generator. Nevertheless, this solution is the most expensive. A compromise is necessary between the energy produced by year (and so money earned) and the initial cost of the solution. For an onshore installation, the wind turbine manufacturers made their decision some years ago—the permanent magnet generator was not a viable solution and it was too expensive compared to the induction solution at variable speed. This is why the most popular generator encountered in the nacelle in the case of variable speed systems is the DFIG.

p0120 However, for offshore applications the most powerful systems are required in order to limit the number of turbines and hence the number of foundations (cost of a turbine foundation in the sea is a nonnegligible part of the global cost) and for that the DFIG met some limitation. On the other hand, it will be necessary to have a more reliable system. Even if the reliability of the gearbox is improved, to have a system composed of many different components remains a drawback. Moreover, maintenance will be not



f0060 **Figure 12.11** Annual energy yield and losses for the different topologies (Bang et al., 2008).



f0065 **Figure 12.12** Generator efficiencies for different machine topologies (Matveev, 2011).

an easy task when the system is to be offshore. The money earned by the wind turbine owner will depend on the energy produced, but the number of years will also have an impact. To exploit the turbine for many years, it is necessary to have a highly reliable system. One way to increase the reliability is to reduce the number of elements in the conversion chains, which is the case for the DDPMG.

s0025 12.4 Improving reliability: the direct drive permanent magnet generator

p0125 The direct drive permanent magnet generator has a number of advantages:

- u0035 direct drive rather than gearbox
- u0040 magnets rather than wound rotor

p0140 Even if the gearbox is not the main cause of downtime, risk of failures is still important (Puigcorde & De-Baumont, 2010). The strongest constraint is the time necessary for the replacement of the gearbox when it is out of order. This time may be long, especially in offshore applications. For the farm owner it is an issue because there is no energy production before the gearbox replacement, and so this leads to a loss of income. Losses for a permanent magnet generator are less important than for an induction one, and the machine is able to work over a larger wind speed range. Moreover, choosing a synchronous generator, instead of a DFIG, enables the reduction of the entire nacelle weight (Fairley, 2010), limits the number of elements in the conversion chain, and so reduces the risk of failures.

p0145 The fact that no supply is necessary to create the rotation field is the main advantage of the permanent magnets. Most of the time, permanent magnet synchronous machines are called “brushless” to highlight this aspect.

p0150 With permanent magnets, the rotor weight and rotor losses are reduced, although there are losses in permanent magnets. Reduced rotor losses are interesting because rotor cooling is difficult. In industry, most permanent magnet machines have their magnets mounted at the surface of the rotor because there is an experience background, a mounting process that is under control and seems to be the easiest solution, especially for very large motors having an external diameter of several meters. But, when magnets are mounted on the surface of the rotor, flux-weakening workings are more difficult to obtain because poles are not salient. These modes can be interesting for limitation of the size of the electronic power converter, when overly large speeds or loads occur in wind turbine applications.

p0155 Although a brushless solution is a good thing, some issues can be encountered with permanent magnets. With a permanent magnet machine, there is a risk of having magnet demagnetization. This can be a big drawback because it leads to reduction of the energy production and it is difficult to remagnetize the magnets. Moreover, the manipulation of the magnets when they are magnetized is a complex task. Focusing on the technology, the solution with permanent magnets seems to be the best; it leads to lower losses, lower total weight, lower risk of failures, and more produced energy, even though the management of permanent magnets during manufacture is complex. Therefore, owing to its high performance and high reliability, the direct drive permanent magnet generator is the topology that seems of most interest for offshore applications.

p0160 The main drawback of permanent magnets is their cost, which is linked to the increase in the demand for rare-earth magnets. Some risks must also be taken into consideration: demagnetization, short circuit torque, bonding with other magnetic parts during manufacture, and the use of nonmagnetic tools. As described in de Vries (2011), the technology that is under development by wind turbine manufacturers for offshore applications is the permanent magnet generator. But, the direct drive solution is not the only solution. In the rest of this chapter, we will focus on the permanent magnet generator and present some improvements that could be achieved in order to increase the power density of such a machine.

s0030 12.5 Optimizing direct drive permanent magnet generators

p0165 A direct drive permanent magnet is an application with a high number of poles where the generator speed is low, so the frequency achieved is also low. This means for the machine that the ratio of iron losses generally will be low, but not negligible, compared to copper losses. It is possible to have more harmonics in the MMF and in the electromotive force (EMF) with a limited impact on the machine efficiency. In spite of its technological benefits, it can be seen that the cost of active components of a permanent magnet direct drive is high. Thus, even if the rules are not the same for active components as for a whole turbine (i.e., to minimize the active components cost does not necessarily lead to minimized wind turbine cost), we are going to propose some ways to optimize the active components weight of the generator. For the active components design of a wind turbine generator, the main points to consider are: power density optimization and loss reduction. These two aspects do not match because the weight increases when the losses decrease (see Figure 12.13); thus a compromise must be found.

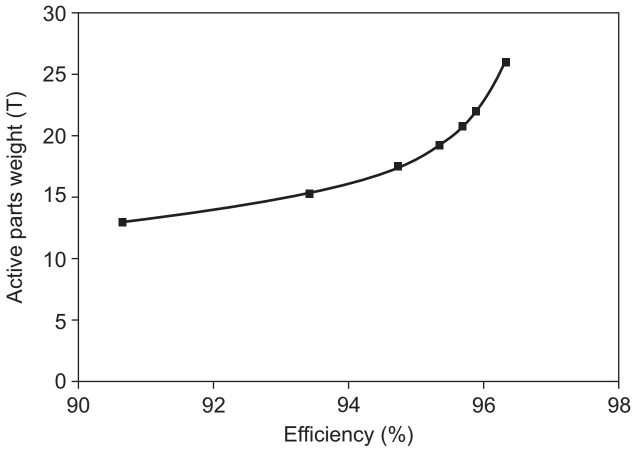
p0170 Some solutions can increase the power density of a surface-mounted permanent magnet machine and/or limit the losses:

u0045 • To reduce the copper with a concentrated winding and a fractional number of slots per pole and per phase (EL-Refaie);
u0050 • To modify the magnet's form to have back-EMF with harmonics and adapt the current waveforms (Jahns & Soong, 1996);
u0055 • To use an outer rotor topology instead of an inner rotor one, if the diameter is constrained;
u0060 • To increase the number of phases.

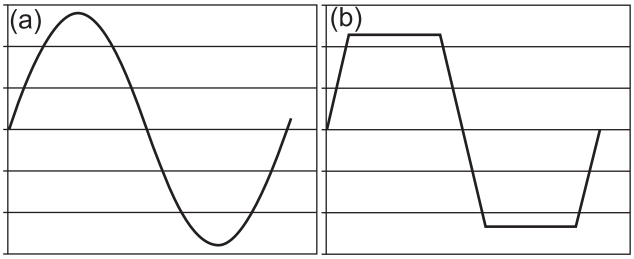
p0195 Nevertheless, in order to clarify the physical behavior, it is necessary to describe the choice of the air gap flux density and current waveforms.

s0035 *12.5.1 Air gap flux density*

p0200 In permanent magnet machines, two shapes can be considered for the air gap flux density waveform (Figure 12.14) and the back-EMF, knowing that these two signals have similar shapes. For each of these cases, in order to obtain a constant torque, the current



f0070 **Figure 12.13** Evolution of the weight as function of the efficiency.

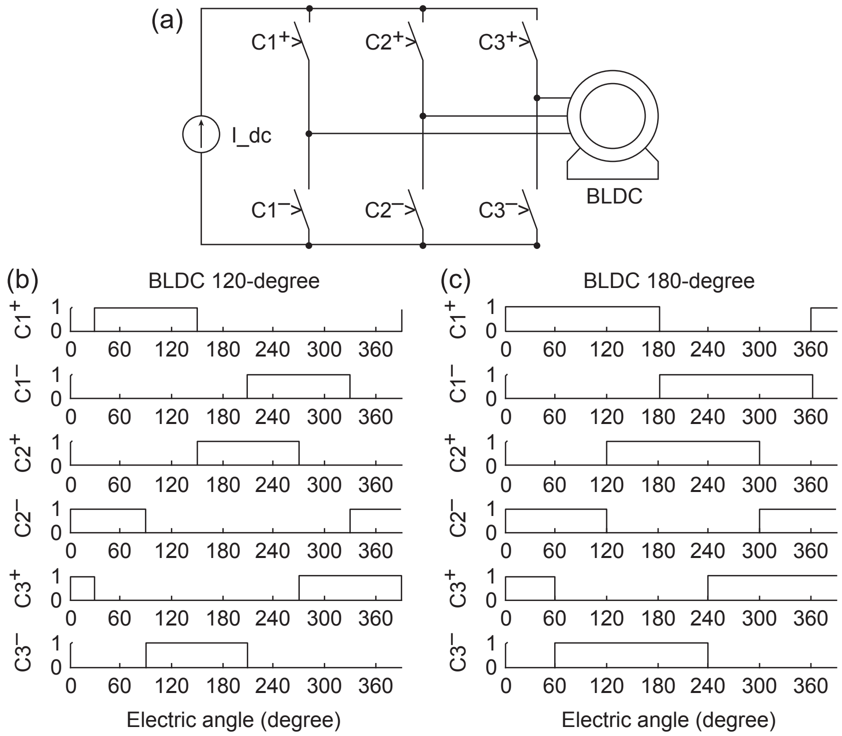


f0075 **Figure 12.14** Different air gap flux density: (a) sinusoidal and (b) trapezoidal.

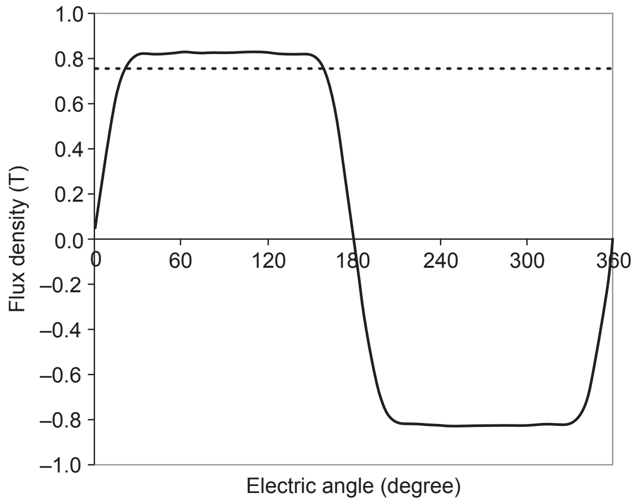
waveform in the slots will be different: the current will be sinusoidal when the flux density is sinusoidal, whereas the current will be trapezoidal (ideally rectangular) when the flux density is trapezoidal.

p0205 As the waveforms are similar to the classical alternative machines, when the waves are sinusoidal, the machine is called brushless AC (BLAC). In the other case, as the principle is closed to the brushed DC machine, these machines are called brushless DC (BLDC). Two control strategies can be used with rectangular currents to keep the torque constant (Qiang, Samoylenko, & Jatskevich, 2007). In the first case, each phase is open circuited during a part of the period. With three phases, a phase must be supplied with a constant current during 120 electrical degrees; the switch command signals are adapted, as shown in Figure 12.15(b). In the second case, the phases are always connected so that they are fed with a constant current during 180-degrees, as shown in Figure 12.15(c).

p0210 In order to have an air gap flux density close to a square wave, we need to have magnet width close to the pole pitch and the number of slots per pole and per phase equal to one. In this case, the air gap flux density shape is as given in Figure 12.16.



f0080 **Figure 12.15** Machine converter (a) scheme, (b) 120-degree control, and (c) 180-degree control. BLDC, brushless DC.



f0085 **Figure 12.16** Air gap flux density when the magnet width is equal to pole shoe and its RMS value (dotted lines).

p0215 To obtain a constant torque, the EMF waveforms should be constant during 180 electrical degrees, which is only a theoretical possibility. Indeed, due to flux leakages between two magnets, the flux density (and as a consequence the back-EMFs) cannot be constant under the pole transition. Because of this, performances in the case of 180-degree control are not so interesting and should be corrected.

s0040 12.5.2 Stator with a concentrated winding

p0220 In order to reduce the length of the end winding, a solution, which is often used for machines having power lower than 10 kW in the avionic and car industries, consists of having a fractional number of slots per pole and per phase, which obviates crossing between the different coils. This can be interesting for increasing the power density of permanent magnet machines. Particular design rules, different from conventional ones, must be followed to find a solution suitable for large machines. Some combinations between the number of slots and the number of poles can be used. Each will lead to a different winding factor, as presented in Figure 12.17.

p0225 Having a high winding factor is interesting for achieving a high torque density. But it will be necessary to check the forces on the active components. In some cases, it is possible to have some magnetic unbalance, as mentioned in Magnussen and Lendenmann (2007). Other advantages can be induced by the fact that there are no crossings between the coils. For example, when a winding with two coils by slots is chosen, an air gap will be present between the two coils, as described in Figure 12.18. This air gap can be used as an air duct, resulting in air flow in order to enable cooling close to the heat source (coils).

p0230 A second example is the simplicity of removing a coil during the exploitation of the machine, which can make the maintenance operations of the stator easier. As explained before, this is a significant advantage for offshore wind applications.

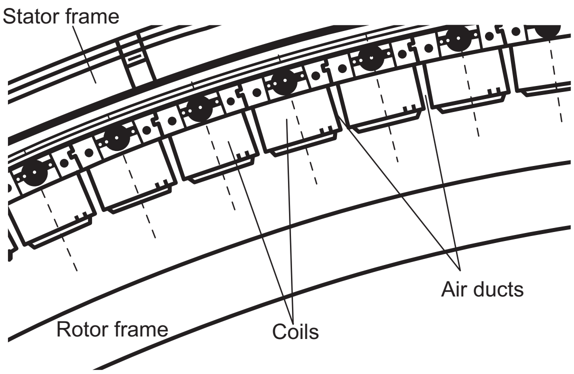
s0045 12.5.3 Rotor location

p0235 Once again, with the aim of increasing the torque density, two structures of surface-mounted permanent magnet machine can be studied. These structures are shown in

Number of poles

Number of slots	4	6	8	10	12	14	16	18	20	22	24	26	28	30
6	0.866		0.866				0.866		0.866				0.866	
9		0.866	0.945	0.945	0.866						0.866	0.945	0.945	0.866
12			0.866	0.933		0.933	0.866							
15				0.866		0.951	0.951		0.866					
18					0.866	0.902	0.945		0.945	0.902	0.866			
21						0.866	0.89		0.953	0.953		0.89	0.866	
24							0.866		0.933	0.949		0.949	0.933	
27								0.866	0.877	0.915	0.945	0.954	0.954	0.945
30									0.866	0.874		0.936	0.951	
33										0.866		0.903	0.928	
36											0.866	0.867	0.902	0.933
39												0.866	0.863	
42													0.866	
45														0.866

f0090 **Figure 12.17** Winding factors for different configurations.



f0095 **Figure 12.18** Localization of the air ducts.

f0100 **Figure 12.19** Scheme of a pole pair of outer rotor topology (left) and inner rotor topology (right).

Figure 12.19. The difference between these two structures concerns the rotating part (rotor), which is placed with regard to the fixed part (stator). In the first case, corresponding to the outer rotor topology, the stator is placed in the center of the rotor. For the inner rotor topology, the rotor is in the center. A comparison between these solutions is made in the next paragraph.

p0240 This modification can be used for all types of machines. A comparison between stators having a conventional design (with crossing between coils) and concentrated winding is given in Table 12.1 for a wind turbine generator of 2.2 MW rotating at 17 rpm.

p0245 It can be seen that the gap on the frame weight can be important, depending of the location of the rotor.

t0010 **Table 12.1 Design comparison for a 2.2 MW generator**

Case	BLAC	BLDC 120-degrees	BLDC 180-degrees
With q phases (q being odd)			
Current peak/RMS	$\sqrt{2}$	$\sqrt{\frac{q}{q-1}}$	1
EMF peak/RMS	$\sqrt{2}$	$\sqrt{\frac{3q}{3q-2}}$	1
Power	$\frac{q}{\sqrt{2}}E_P I_{RMS}$	$\sqrt{q(q-1)}E_P I_{RMS}$	$qE_P I_{RMS}$
With 3 phases			
Power	$\frac{3}{\sqrt{2}}E_P I_{RMS}$	$\sqrt{6}E_P I_{RMS}$	$3E_P I_{RMS}$
Theoretical gain	1	1.15	1.41
Real gain	1	1.15	1.32

BLAC, brushless AC; BLDC, brushless DC; EMF, electromotive force.

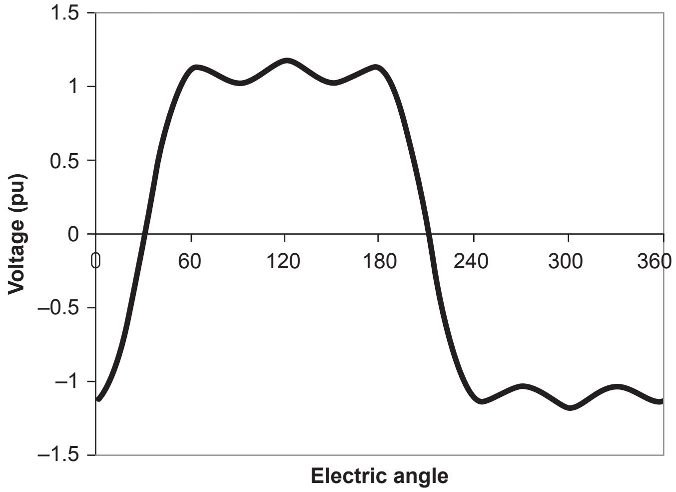
s0050 12.6 Comparing different configurations

p0250 To achieve a comparison between various machines for equivalent losses, the back-EMF peak values must be the same to have the same iron losses, and the current RMS values must be the same to have the same copper losses. Real gain is obtained when the difference between back-EMF peak and RMS value is taken into account; this corresponds to the correction mentioned in the previous section. A comparison at equivalent losses can be interpreted as a comparison at equivalent active component weights. Indeed, iron and copper volume are preserved and variations of magnet volume do not have a significant influence on the total weight. To keep the same EMF peak value, in all cases, some geometric parameters can be preserved, such as magnet thickness, air gap length, and rotor diameter, but the magnet width can vary. For the currents, with the same RMS value, to keep the current density leads to a constant copper volume. In conclusion, BLDC machines have a better power density than the BLAC.

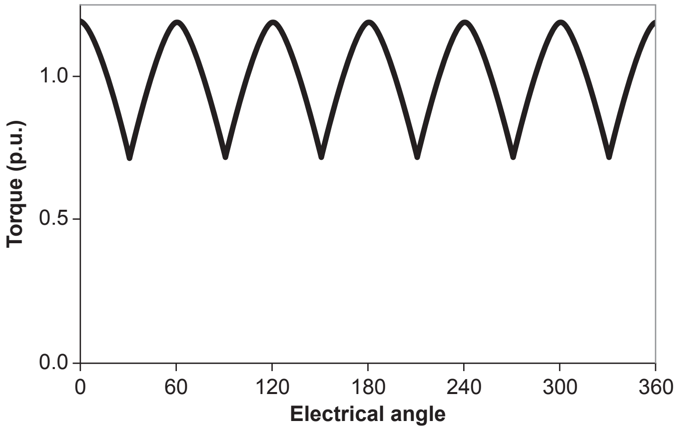
p0255 A drawback of the BLDC motor is the difficulty in obtaining a constant torque. With a 120-degree converter, it is necessary that the currents are perfectly rectangular and in phase with the back-EMFs. To have a constant torque, it is also necessary to have a constant back-EMF on 120 electric degrees. With 180-degree control, this becomes nearly unfeasible, as explained above. The back-EMFs are calculated by using finite element simulations (FLUX2D); the waveform obtained is plotted in Figure 12.20 for the example of a three-phased machine.

p0260 Torque is determined by considering the currents as perfectly rectangular on 180 electric degrees; the waveforms are given in Figure 12.21 for three phases.

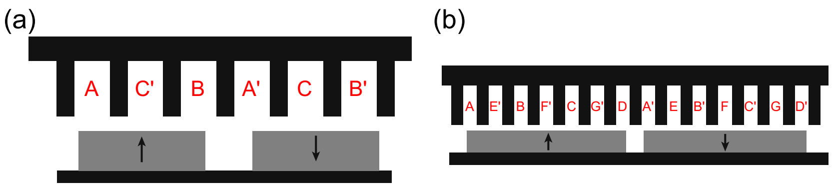
p0265 We now discuss what happens when the number of phases (i.e., the number of slots per pole in this case) increases. The winding scheme will have to be adapted according to the phase number (see Figure 12.22).



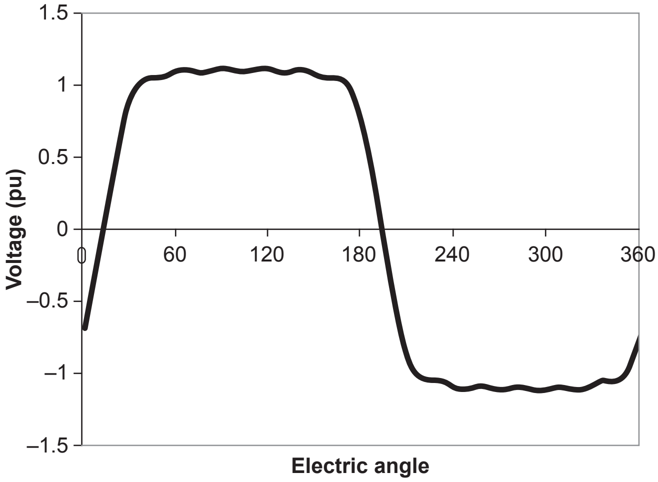
f0105 **Figure 12.20** Back-electromotive forces in the three-phased machine.



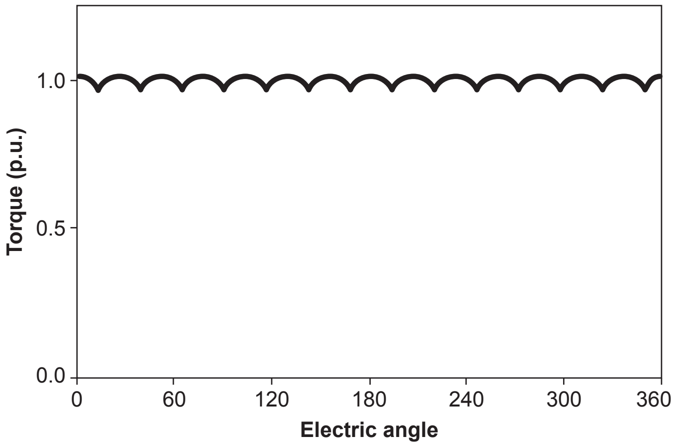
f0110 [**AU3**] **Figure 12.21** Torque with three phases.



f0115 **Figure 12.22** Winding connection under a pole pair when the number of slots by pole and by phase is one for three phases (a) and for seven phases (b).



f0120 **Figure 12.23** Back-electromotive forces in the seven-phase machine.



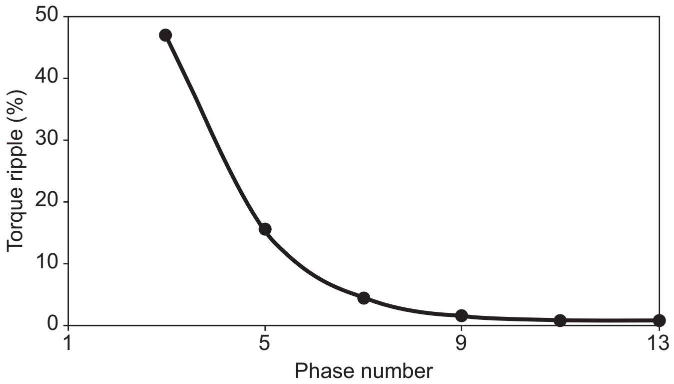
f0125 **Figure 12.24** Torque with seven phases.

p0270 For a phase number of seven, the back-EMF is given in Figure 12.23 and the torque in Figure 12.24.

p0275 It appears that the modification of the phase number has an influence on the torque ripple, which does not seem to be negligible. On the other hand, when the number of phases rises, its influence becomes small, as shown in Figure 12.25.

p0280 The torque ripple is characterized using:

$$\Delta\Gamma = \frac{\Gamma_{\mathrm{MAX}} - \Gamma_{\mathrm{MIN}}}{\Gamma_{\mathrm{MEAN}}} \tag{12.1}$$



f0130 **Figure 12.25** Evolution of the torque ripple with the phase number.

Number of poles

Number of slots	4	6	8	10	12	14	16	18	20	22	24	26	28	30
6	0.866		0.866											
9		0.866	0.9848	0.9848	0.866									
12			0.866	0.9659		0.9659	0.866							
15				0.866		0.9945	0.9945		0.866					
18					0.866	0.9397	0.9848		0.9848	0.9397	0.866			
21						0.866	0.9309		0.9972	0.9972		0.9309	0.866	
24							0.866		0.9659	0.9914		0.9914	0.9659	
27								0.866	0.9182	0.958	0.9848	0.9983	0.9983	0.9848
30									0.866	0.9135		0.9781	0.9945	
33										0.866		0.945	0.9718	
36											0.866	0.9063	0.9397	0.9659
39												0.866	0.9035	
42													0.866	
45														0.866

f0135 **Figure 12.26** Winding factors for different configurations when the phase number is equal to the number of slots.

p0285 Moreover, the phase number can be limited by the teeth size, which can become too small and unfeasible when the pole number is high. Increase of the number of phases is interesting for reliability because as the number of phases increases the capacity to run in fault-tolerant modes also becomes of interest. We can also combine this advantage with a concentrated winding stator. If we consider Figure 12.17, where the results are given for a machine having three phases, and we modify the number of phases, which become the same as the number of slots, we obtain the new winding factors, as presented in Figure 12.26.

p0290 Increasing the winding factor leads to an increase of the power density, so the use of a high number of phases is interesting for the permanent magnet machine. Nevertheless, it will be necessary to adapt the control strategy; some studies on this subject can be found in Crevits (2010).

s0055 12.7 Conclusion and future trends

p0295 The offshore installation of wind turbines has led to the discovery new solutions for power conversion. The solutions must be more reliable and achieve higher power than current wind turbines in order to limit their number. The use of permanent magnets has been developed for this purpose, and new generators have started to be installed. The interest in this solution is that the energy produced by year is higher than with the other solutions and the number of elements in the power chain is reduced, which is interesting in terms of reliability. The application of high torque and low speed bring different constraints for the realization of the machine than is usual. Some improvements to increase the attractiveness of permanent magnet generators can be considered, as described in this chapter. We have shown that having a higher phase number is an interesting choice in the presence of high torque density and a high reliability system. The gain that could be obtained with nonsinusoidal waveforms is interesting, but the work necessary to adapt the supply of this type of machine is still important. On the design of the machine, it seems more interesting to go for a stator having a concentrated winding.

p0300 The main drawbacks of the permanent magnet generator are the cost of the rare-earth components, which impacts directly on the cost of the generator. To avoid this impact, developments have been made in order to limit the dysprosium in the NdFeB magnets and thus reduce the magnet cost. Some work on the development of new technology is being carried out in order to increase the power density of the machine. For example, there has been work on high temperature superconducting materials and also a machine with a magnetic gearbox (Matveev, 2011). Even with permanent magnets, some machine topologies are under investigation where the magnets are not located at the rotor surface. For example, there are the flux switching and the doubly salient permanent magnet machine, which could increase the power density of the machine (Hua, Zhu, Cheng, Pang, & Howe, 2005).

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BESSEDE: 12

Non-Print Items

Abstract:
In order to install offshore wind turbines, the solution of a permanent magnet synchronous generator can lead to a high reliability and high performance system compared to other solutions on the market. To increase the attractiveness of this topology by reducing its cost and its weight, some design improvements can be made to the machine. A comparison of the power chains for wind turbine applications is presented. Then, the improvements that could be achieved for the permanent magnet machine in order to increase its torque density are given.

Keywords:
Direct drive, Machine design, Permanent magnet machine, Torque density, Wind turbine generator.