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Optimisation of the Association of Electric Generator and Static Converter for a Medium Power Wind Turbine

Daniel Matt[1], Philippe Enrici[1], Florian Dumas[1] and Julien Jac[2]
[1]*Institut d'Electronique du Sud, Université Montpellier 2*
[2]*Société ERNEO SAS*
France

1. Introduction

This chapter shows the ways of optimising a medium power wind power electromechanical system, generating anything up to several tens of kilowatt electric power. The optimisation criteria are based on the cost of the electromechanical generator associated with a power electronic converter; on the power efficiency; and also on a fundamental parameter, often neglected in smaller installations, which is torque ripple. This can cause severe noise pollution.
For a wind turbine generating several kW of electric power, the best solution, without a shadow of a doubt, is to use a permanent magnet electromagnetic generator. This type of generator has obvious advantages in terms of reliability, ease of operation and above all, efficiency. Despite problems concerning the cost of magnets, almost all manufacturers of small or medium power wind turbines use permanent magnet generators (Gergaud et al. 2001). This chapter deals with this type of system. The objective is to demonstrate that only a judicious choice of the configuration of the permanent magnet synchronous generator, amongst the different options, will allow us to satisfy the criteria required for optimal performance. We will study examples of a conventional permanent magnet generator with distributed windings, a permanent magnet generator with concentrated windings (Magnusson & Sandrangani, 2003) and a non-conventional Vernier machine (Matt & Enrici, 2005). How these different machines work will be detailed in the following paragraphs.

2. Description of the electromechanical conversion system

The chosen electromechanical conversion system is represented in Fig. 1. The principle of a turbine directly driving a generator has been chosen in preference to adding a speed multiplier gearbox between the turbine and the generator.
There are many advantages to using a mechanical drive without a gearbox, which requires regular maintenance and which has a pronounced rate of breakdown. These devices are also a significant source of noise pollution when sited near housing. Noise pollution is one of the principal factors in the chosen optimisation criteria. Finally, the gearbox can cause chemical pollution due to the lubricant which it contains. However, the omission of a gearbox means an increase in both size and cost of the generator, which then operates at a very low speed.

For this reason, a balance between size, cost and performance of the system must be considered. More and more wind turbine manufacturers are using the direct drive concept.

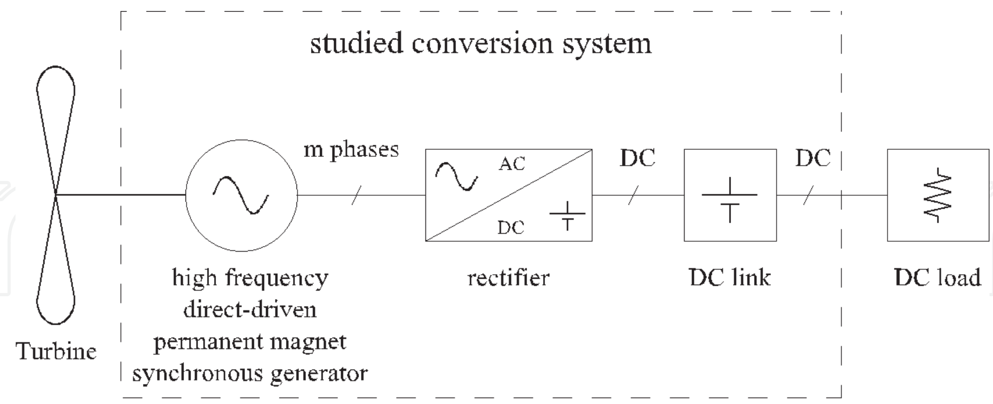

Fig. 1. Structure of the conversion system

As stated, one of the major design difficulties is sizing the generator, which whilst operating at low speed, must supply high torque. The size is proportional to the torque so the mass or volume power ratio of a generator tends to be low.
The main deciding parameter for the size of the generator is the electrical conversion frequency. These energy systems are therefore all sized on the same basis: the frequency of the completed conversion cycle (electric, thermal, mechanical). The optimal solution chosen for the generator will have the characteristics of a "high frequency" machine, typically between 100 and 200 Hz or even more in certain cases, for a rotation speed generally in the order of 100 to 200 rpm. In this context, optimised direct drive gives a mass-power ratio close to that obtained by an indirect drive, with increased efficiency and reliability. This quest for high conversion frequencies is beneficial to noise pollution, high frequency vibrations being more easily filtered by the mechanical structure of the wind turbine.
A second design difficulty concerns the choice of static converter associated with the machine, in order to fulfil the generating requirements of the end user. This is a difficult choice, because the behaviour of the converter can have serious repercussions on the behaviour of the generator with regard to the chosen performance criteria.
Whether the turbine is on an isolated site or is connected to the grid, most power electronic converters have a DC bus like that in Fig. 1. The study presented in this chapter will be limited mainly to DC bus systems i.e. combined with a permanent magnet synchronous generator and rectifier.
It should be noted that direct AC to AC conversion solutions, like that in Fig. 2, adapted for linking the generator to the grid, exist (Barakati, 2008), but while these solutions are appealing on paper, they haven't really been put into practice. They conflict with the design of the matrix converter which uses bidirectional switches for coupling (Thyristor solutions also exist).
We return to diagram on Fig. 1 which corresponds to the system under study. Different solutions exist for the rectifier. They are shown in Fig. 3.
Two of these are based on the concept of active rectifiers. The structure of these rectifiers is that of an inverted PWM inverter, the energy flowing from an AC connection to a DC connection (Mirecki, 2005; Kharitonov, 2010). A variation of this structure, called Vienna, also uses the notion of a bidirectional switch (Kolar et al, 1998).
The interest of an active rectifier lies in the fact that the driver gives complete control of the current waveform produced by the generator, the rectifier itself imposes no specific stress on

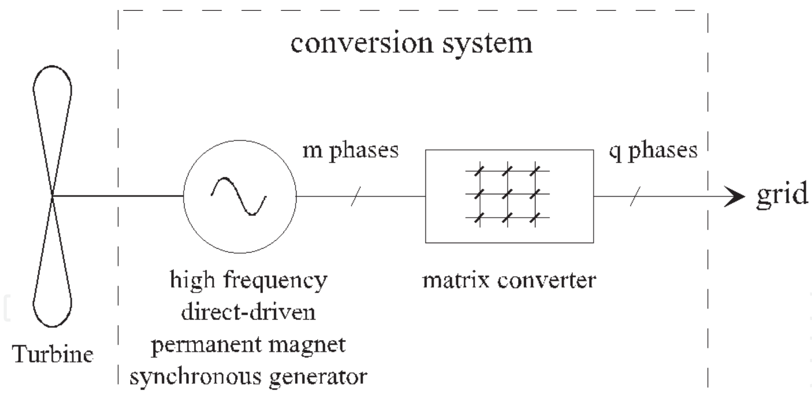

Fig. 2. Connection of generator to the grid using a matrix converter

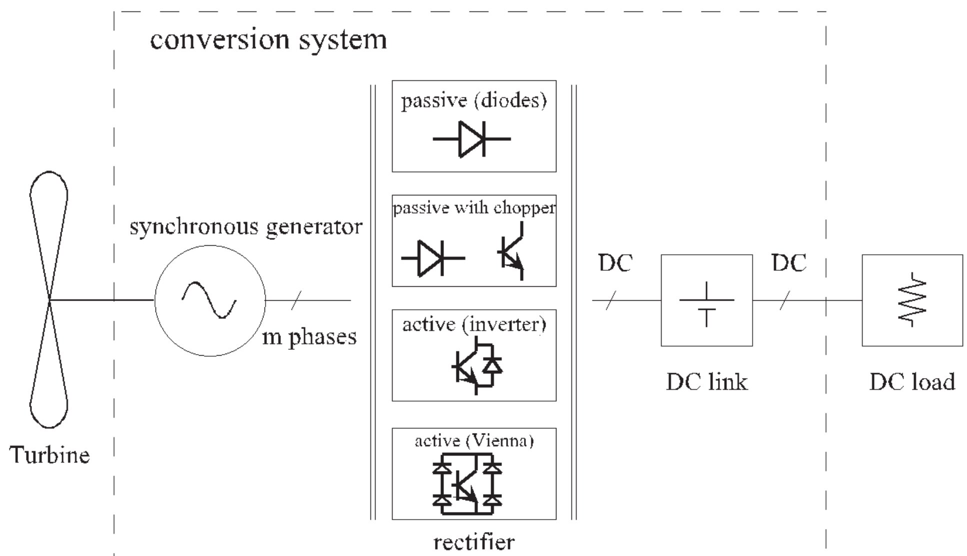

Fig. 3. Different configurations of rectifiers

the machine. If the EMF of the generator is sinusoidal, control of the rectifier will give a sinusoidal current in phase with the EMF, the ohmic loss will be minimised, the sizing optimal. This configuration and ideal operating mode will serve as a reference in the following paragraphs for comparing different generator configurations.

The disadvantage of using active rectifiers is essentially economic. The structure of the power electronic used, although classic, is complex, which makes for high costs and poor reliability, especially in comparison with the solutions which we are soon going to present. In the case of medium power, which is the focus of this chapter, the active rectifier, despite its drawbacks, is the most common solution.

Despite the undeniable advantages of active rectifiers, the conventional structure of passive diode rectifiers can be preferable in wind turbine systems because they are robust in most conditions. These are the two other solutions illustrated in Fig. 3. The rectifier can be used alone, or with a chopper when a degree of fine tuning is required in maintaining optimal performance of the system. The chopper is not always indispensable and only slightly improves the performance of the wind turbine. (Gergaud, 2001; Mirecki, 2005).

We will confine ourselves therefore to the study of a permanent magnet synchronous generator with a passive diode rectifier. We will show that by careful selection of the configuration of the generator, highly satisfactory operation of the conversion system is achieved, with minimal drop in performance (efficiency, torque ripple) compared to a system using an active rectifier.

3. Choosing the structure of the synchronous generator

To satisfy the conditions which we have imposed, we will study the behaviour of three distinct permanent magnet synchronous generators: a conventional structure widely used; a "Vernier" structure (Toba & Lipo, 2000; Matt & Enrici, 2005), less well known, but perfectly adapted to operating at very low speed; and a harmonic coupling structure (Magnussen & Sadarangani, 2003), nowadays a classic, but little used in the field of wind turbines. Their operating modes are reviewed in the following paragraphs. The conventional structure will serve as a reference by which to compare the other two structures, which are better adapted to running at high frequencies for low rotation speeds.
The electrical system under study will be modelled on the diagram in Fig. 4. The electrical generator is represented by a simplified Behn-Eschenburg model, which is sufficiently precise for this general comparison. This model is particularly pertinent, since the 3 machines studied generate sinusoidal EMF with almost no harmonics.
The addition of the "DC model" gives an accurate estimation of the reduction in average rectified voltage, E_s, due on the one hand to the overlap engendered by the synchronous inductance, Ls, of the generator (Δ_{Ee}), and on the other hand to resistive voltage drop, (Δ_{Er}), (Mirecki, 2005). This demonstrates the power limitation associated with synchronous inductance. Thus, conforming to the rules of impedance matching, the maximum power, P_{max}, transferred to the continuous load is obtained when $E_b = E_s/2$, which allows us to express the following:

$$P_{max} = \frac{E_s^2}{4(Y+R)} \tag{1}$$

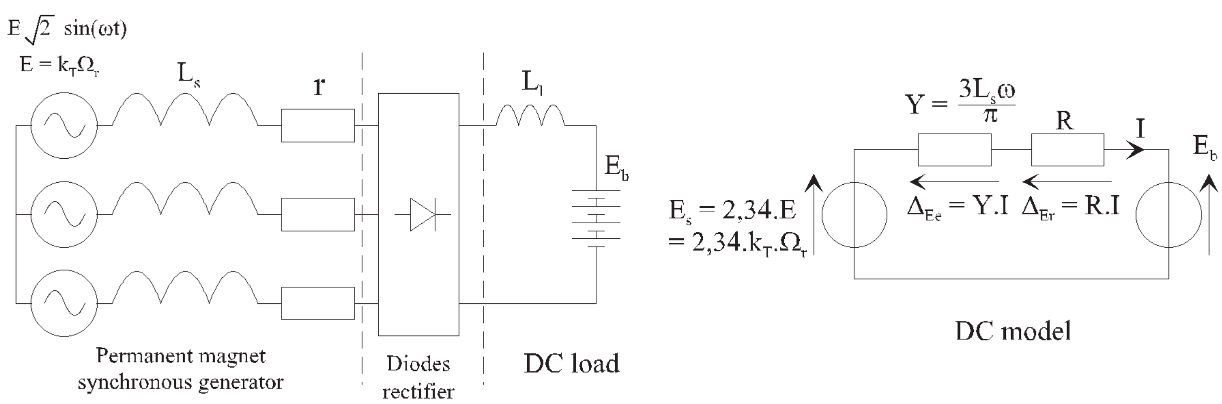

Fig. 4. Modelling of the Electrical System

This phenomenon of power limitation can be used to advantage in a wind turbine with a passive conversion system, without regulating power. It is then possible, with the appropriate value of parameter Y (see Table 1), to obtain close to maximum power (MPPT), at variable speed, without any control mechanism (Matt et al.; 2008). However, the optimisation of the inductance L_s on which Y depends, will be dictated by the compromises reached, which we will explain in the descriptions of the studied generators (Abdelli, 2007).
The following table shows the main notations used for the study of the electrical system.

Electrical parameters	Notations	Remarks
Electric frequency, pulsation	f_e, ω	-
Rotation speed, pulsation of rotation	N, Ω_r	-
Coefficient of torque or EMF	k_T	In steady state
Phase EMF	E	In steady state
Synchronous inductance	L_s	In steady state
Phase resistor	r	In steady state
Number of pole pair	p	-
Filtering inductance	L_1	Optional
DC bus voltage	E_b	-
Average rectified voltage	E_s	3 phases Graetz rectifier
Overlap "resistor"	Y	Non dissipative
DC model resistor	R	Dissipative

Table 1. Variables of the electrical system

The comparative study of the following three generators was done using a CAD power electronics tool (PSIM, Powersim Inc.), based on the diagrams in Figs. 1 and 4.
The three structures compared are of a similar cylindrical design and overall size. They are designed to supply an electrical output of 10 KW for a rotation speed of 150 rpm.

4. Operation using a conventional synchronous generator

The first permanent magnet generator studied is a classic design. Its general structure is represented in Fig. 5. The armature of this machine has a three-phase pole pitch winding with a large number of poles of which we will list the precise characteristics. The field system magnets are fixed along the rotor rim and form an almost continuous layer.

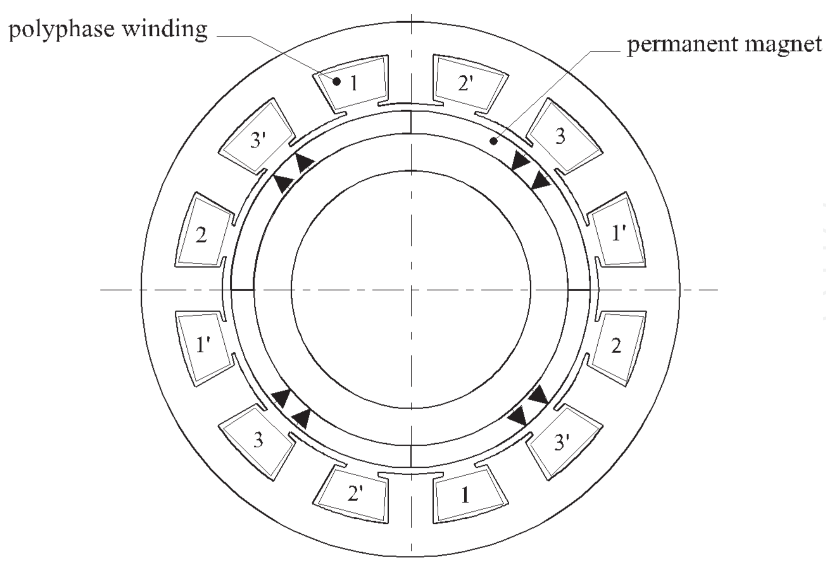

Fig. 5. Conventional Permanent magnet generator

Rather than designing a generator specifically for this comparison, we have chosen to adopt the characteristics of a commercial machine, currently used in medium power wind turbines. The useful characteristics for the model are summed up in Table 2 (refer to Table 1 for the notations).

Characteristics	Values
Nominal rotation speed (rpm)	150
f_e at nominal speed (Hz)	45
Nominal power with resistive load (W)	9740
E at nominal rotation speed (steady state) (V)	160
r (steady state) (Ω)	1
L_s (mH)	7,4
p	18
Joule losses at nominal current (W)	1600
Iron and mechanical losses (W)	200
Torque ripple without load (cogging torque) (Nm)	8
Nominal efficiency with resistive load (%)	84

Table 2. Characteristics of the reference generator

The principal characteristic of this generator lies in the angle of the slots which greatly reduce cogging torque ripple (8 Nm). Another consequence of this angle is the limitation of the harmonics of the electromotive forces which, as a result, are practically sinusoidal.
The optimisation of the mass-power ratio of this machine is achieved by using as many poles as possible in order to obtain a high electrical operating frequency. The winding, however, cannot have more than 36 poles because of the high number of slots (108). The working frequency is therefore equal to 45 Hz at the speed of 150 rpm. This phenomenon is a major structural drawback for conventional low speed designs.
This generator is sold as a kit, only the active parts are supplied. The stator comprises the armature, magnetic circuit and windings, inside an aluminium tube; the rotor is made up of a steel tube to which are attached the magnets. The dimensions are shown in Table 3.

Dimensions	Values
External diameter (mm)	500
Airgap diameter (mm)	400
Stator length (mm)	175
Rotor length (mm)	110
Internal diameter of the rotor (mm)	350
Mass, rotor and stator (kg)	73

Table 3. Principal dimensions of a conventional generator

The electrical parameters in Table 2 are given for operation with the armature giving directly onto a resistive load. The power factor is then unitary but the current is slightly out of phase in relation to the electromotive force (dephasing of an angle $\Psi \approx 20°$).
Operating with an active rectifier as mentioned in paragraph 2 allows minimisation of the armature current for any given power due to the phasing of the current with the

electromotive force. This ideal mode of operation will give us a reference efficiency of 10 kW at 150 rpm. With sinusoidal current, the electromotive force being sinusoidal, torque ripple is negligible; only cogging torque remains, measured at 8 Nm by the manufacturer. Simulated study of this operating mode is pointless, given the simplicity of the waveforms produced through the use of this rectifier.
With the data in Table 2 we get the following characteristics:

Characteristics	Values
Output power (kW)	10
EMF, E (V)	160
Armature RMS current (A)	20,8
Joule losses (W)	1300
Iron and mechanical losses (W)	200
Efficiency (%)	87
Torque ripple (%)	1

Table 4. Operating in cosΨ = 1 (active rectifier)

The slight gain in efficiency obtained here, as we have already mentioned, is at the cost of an increase in complexity of the conversion system.
We are now going to study the consequences of operating with a strictly passive rectifier, which we recommend for this kind of application.
Digital simulation of the above gives the following waveforms for armature current (set against the electromotive force) and the electromagnetic power.

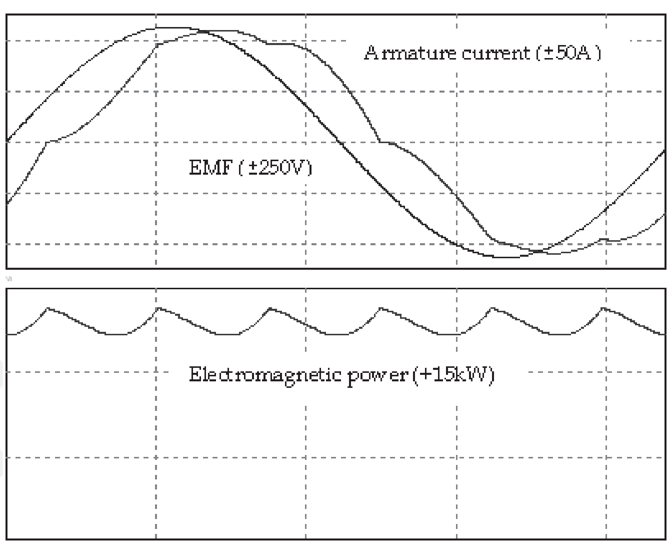

Fig. 6. Waveforms with passive rectifier

Table 5 shows the results obtained.
The deterioration of the current form engendered by the rectifier has two important consequences. In the first place, the appearance of harmonics and the dephasing of the current with the EMF leads to a significant increase in the RMS value of the current for any given power, the output passes from 87% with an active rectifier to 76% with a diode rectifier. There is significant derating of the generator. Secondly, the current harmonics increase significantly the rate of torque ripple which goes from a value of almost zero to

Characteristics	Values
Output power (kW)	10
EMF, E (V)	160
Armature RMS current (A)	31,5
Joule losses (W)	2976
Iron and mechanical losses (W)	200
Efficiency (%)	76
Torque ripple (%)	13

Table 5. Operating with a diode rectifier

close to 13%. This phenomenon is far from being insignificant: it causes operating noise, one of the main disadvantages of wind turbines.

Torque ripple produces a resonant frequency that is audible and unpleasant, often close to the natural frequency of the structure. In our example, this frequency is equal to six times the first harmonic frequency, i.e. 270 Hz.

Medium power wind turbines are often situated near to residential areas so this torque ripple problem can be very disturbing. An effective way of remedying the problem would be to augment the parameter L_s of the generator, but this would reduce efficiency even further. Therefore, the type of generator presented does not work well with a passive rectifier.

The result presented is obtained with a voltage source load, E_b. This is possible thanks to the synchronous inductance of the generator which smooths out the output current. Further filtering, through the inductance L_1, is often added, if only to limit ripple current load when E_b is an accumulator, or to smooth out the output voltage in the case of a load on a capacitive bus.

The waveforms obtained with an inductance L_1 of 20mH are shown in Fig. 7.

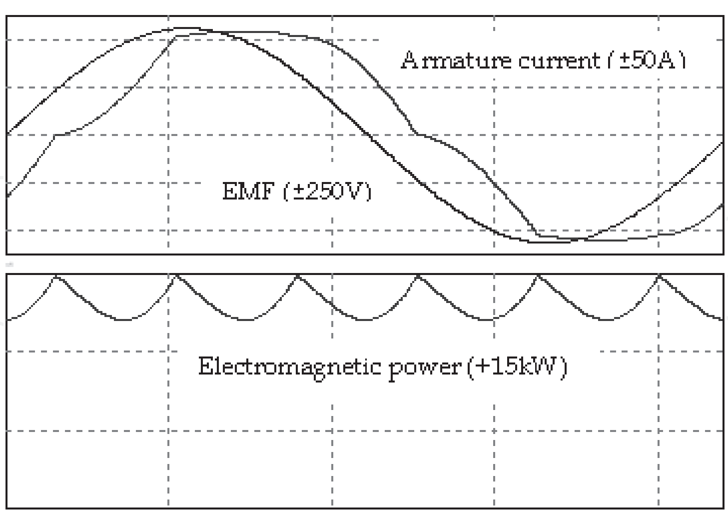

Fig. 7. Waveforms with a passive rectifier and filter choke

The introduction of a filter choke L_1, has the notorious consequence of increasing the rate of electromechanical power ripple, which is precisely what we wish to reduce, as shown in the results in Table 6.

From here on, we will no longer factor in the inductance L_1 which is detrimental to operation.

Characteristics	Values
Output power (kW)	10
EMF, E (V)	160
Armature current (RMS) (A)	32,7
Joule losses (W)	3207
Iron and mechanical losses (W)	200
Efficiency (%)	75
Torque ripple (%)	21

Table 6. Operating with diode rectifier and filter choke

To recap, two intrinsic characteristics of the conventional structure of a generator limit performance in a passive rectifier configuration: the operating frequency, which is difficult to increase because of the way the armature is designed, and ohmic loss which remains high for this application.

5. Operation of a Vernier permanent magnet synchronous generator

The Vernier synchronous generator, using magnets, is an interesting and viable alternative to the last configuration. Despite being the subject of numerous studies (Toba & Lipo, 2000; Matt & Enrici, 2005; Matt et al, 2007) it is less well known. It is represented in Fig. 8.

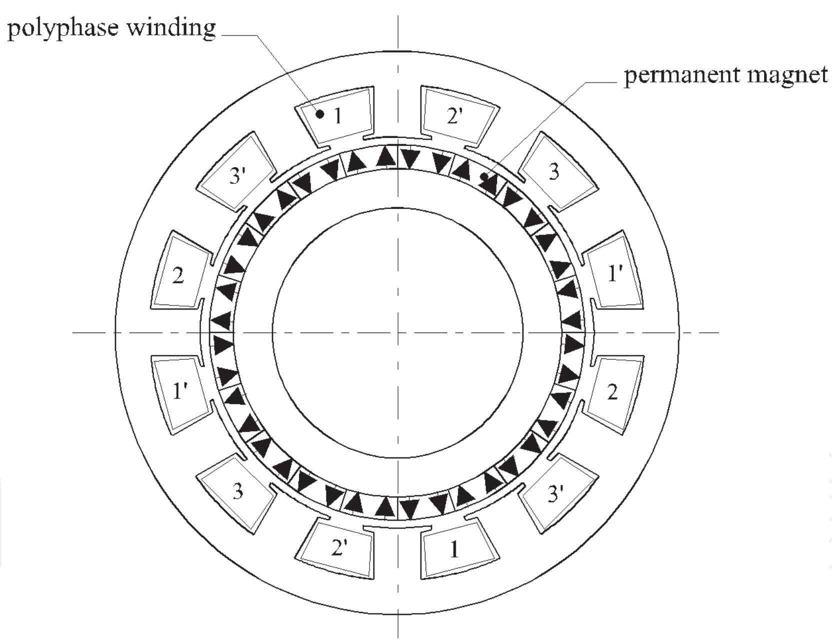

Fig. 8. Vernier permanent magnet synchronous generator

The design of the Vernier generator is similar to the example previously studied (Fig 5), but with the Vernier machine the component used in the magnetic field results from the coupling between the field system magnets and variation of reluctance due to the armature slots. Operation is modified as follows.

The armature of the Vernier machine has exactly the same structure as a conventional machine, the polyphase winding with p pole pairs spread out through the N_s slots which are wide open.

The structure of the field system is also similar to that of a conventional machine, but the number of pairs of magnets, N_r, along the rotor rim is not at all related to the number of pole-pairs: it can be much larger. This is what makes the Vernier generator unique. The working electrical frequency of the machine is now uniquely linked to N_r, as seen in the following formula:

$$\Omega_r.T_e = \frac{2\pi}{N_r} \Rightarrow f_e = \frac{1}{T_e} = \frac{N_r.\Omega_r}{2\pi} \quad (2)$$

This frequency can be high, even though the number of pole-pairs may be small. The limitations on frequency increase at low rotation speeds are generally lower than for the preceding configuration.

In closing this descriptive summary, we can summarise the coupling relations between the magnetic fields, expressed in terms of the only spatial variable, θ, which is the azimuthal coordinate in the airgap.

The N_s slots airgap permeance has a periodicity equal to 2π/Ns. The airgap magnetomotive force created by the magnets, having a remanent flux density equal to M, has a periodicity equal to 2π/Nr. Consequently, the field component, b_{1an}, created by the magnets, and having the periodicity 2π/|Ns-Nr|, comes into play. This can be expressed thus:

$$b_{1an} = k_1.M.\cos((N_s\text{-}N_r).\theta) \quad (3)$$

The coefficient k_1, which defines the field amplitude $b_{1an}(\theta)$, is deduced using the finite elements method (of an elementary domain) (Matt, & Enrici, 2005), as in Fig. 9. It's value, which depends on the ratios of the dimensional proportion parameters, is generally between 0,1 et 0,2. This is not the most precise of methods since the slot pitch is slightly different from the magnet pitch, but in most cases it is sufficiently accurate.

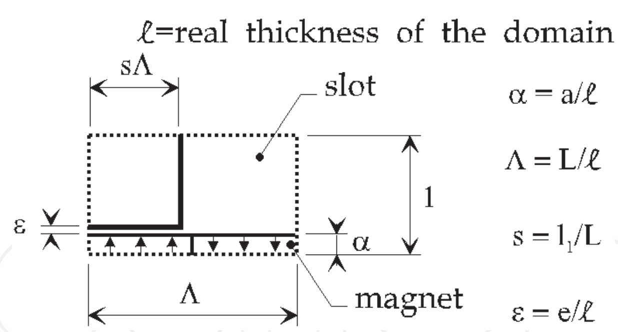

Fig. 9. Magnet-slot interaction in the elementary domain

The flux density field component, b_{1an}, is the main component used in the Vernier machine.

The armature currents can be likened to a thin coating (Matt et al, 2011) of current, conventionally called electric loading, λ_1, with a periodicity equal to 2π/p, which we will express thus:

$$\lambda_1 = A_1.\cos(p\theta) \quad (4)$$

The amplitude, A_1, of the electric loading, is obtained by looking at the ratio of the amount of current at the core of the slot and that at the slot pitch, taking into account the winding factor.

The magnetic field, b_{1an}, and the magnetomotive force created by the electric loading, λ_1, combine to generate electromagnetic torque, C_{em}, provided that the spatial periodicity of b_{1an} and λ_1 are identical. The following formula must therefore be verified:

$$|Ns\text{-}Nr| = p \tag{5}$$

Once this first condition is met, and the functions (3) and (4) are in phase, the electromagnetic torque will be maximised.
The formula (4) shows that the number of pole-pairs, p, is dissociated from the number of magnet pairs, N_r, since the choice of number of slots is relatively large.
For the electromechanical conversion to take place, it is necessary to verify a second condition: the rotation speeds of b_{1an} and the magnetomotive force produced by λ_1 must be identical, which, taking into account the spatial periodicity of the two functions, leads to the following expression:

$$\frac{N_r.\Omega_r}{|N_s - N_r|} = \frac{N_r.\Omega_r}{p} = \frac{\omega}{p} = \Omega_c \tag{6}$$

The expression (6) obtained being identical to the expression (2), the main criteria for optimal operation are met.
The formula (7) above demonstrates the ratio of the field speed, Ω_c, to the rotor speed, Ω_r:

$$\frac{\Omega_c}{\Omega_r} = K_v = \frac{N_r}{p} \tag{7}$$

The coefficient K_v, the speed ratio, is called the Vernier Ratio, and is characteristic of the eponymous machine.
We shall conclude this explanatory part by expressing the electromagnetic torque, C_{em}, of the Vernier machine, which refers to the principal elements that we have just cited:

$$C_{em} = K_v.R^2.L. \int_{2\pi} b_{1an}.\lambda_1.d\theta \tag{8}$$

The dimensions R and L of the expression (8) represent the airgap radius and the iron length respectively. This expression can be misleading: the coefficient K_v seems to be a torque-multiplying coefficient if we refer to traditional expressions, whereas here, this coefficient compensates the low flux density b_{1an} (see (3)).
In practice, direct comparison of the performance levels of the Vernier configuration and that of a conventional configuration is delicate (Matt & Enrici, 2005). We simply note here that increasing the operating frequency, which the design of the Vernier machine allows, gives a gain of 50 to 100% in the mass-power ratio at very low speed, at the price of a substantial increase in rotor manufacturing costs.
The Fig. 10 shows an example of industrial production for a small electric car with a Vernier engine.
Unfortunately, at present, there is no commercialised Vernier generator specific to the field of wind turbines. We will therefore base our comparison on a theoretically scaled model. The sizing calculations are not within the scope of the summary that we are presenting and will not be detailed, but the references given in the prior explanations cover the main elements.

For this theoretical sizing, we will use a maximum number of the characteristics of the preceding generator in order to ensure the most precise comparison, notably when discussing the thermic aspects, which are always difficult to comprehend in a scaled model. The size is similar (even the external dimensions), and the configuration of the armature winding will be identical (same number of slots, same number of poles).

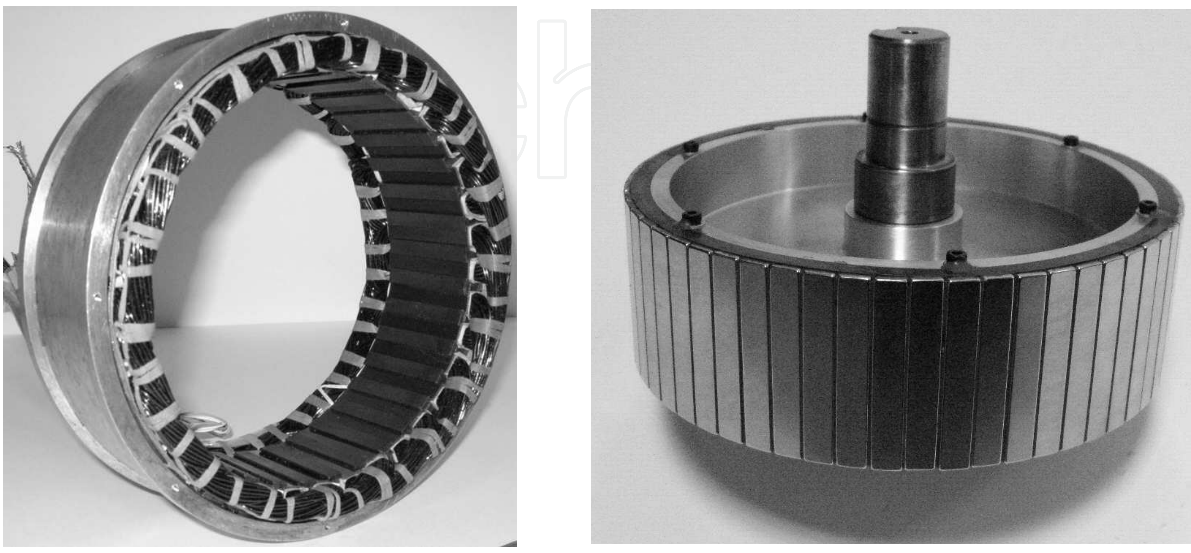

Fig. 10. Vernier engine for an electric vehicle (photography ERNEO)

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For this theoretical sizing, we will use a maximum number of the characteristics of the preceding generator in order to ensure the most precise comparison, notably when discussing the thermic aspects, which are always difficult to comprehend in a scaled model. The size is similar (even the external dimensions), and the configuration of the armature winding will be identical (same number of slots, same number of poles).

The following table presents the principal characteristics obtained with a Vernier generator operating in association with an active rectifier.

The main dimensions of this generator are shown in Table 8.

The advantages of this configuration in the context of wind turbines, which impose an operating point with high torque for a very low speed of rotation, are shown in the folowing two tables.

Given that the mode of interaction between the magnets and slots results in a continuous and gradual shift of the magnets relative to the slots, which increases as the numbers N_s and N_r increase, the Vernier structure is a machine of naturally sinusoidal electromotive force with almost zero cogging torque and no slot tilt.

We observe that the high operating frequency at low speed, 225 Hz instead of 45 Hz, leads to a mass-power ratio of more than two times that obtained previously. We go from 140 W/kg to around 380 W/kg (without the housing) taking into account only the weight of the active parts.

Finally, the efficiency of the sized Vernier machine is comparable to a conventional machine, in the same operating conditions, with three times more iron loss, but with half the Joule

Characteristics	Values
N_s / N_r	108 / 90
Number of pole-pairs, armature winding	18
Nominal rotation speed (rpm)	150
f_e at nominal rotation speed (Hz)	225
Output power (kW)	10
E at nominal rotation speed (steady state) (V)	166
r (steady state) (Ω)	0,44
L_s (mH)	2,2
Joule losses (W)	650
Iron losses (W)	720
Torque ripple without load (cogging torque) (%)	0
Efficiency (%)	88

Table 7. Electrical characteristics of the Vernier generator operating at cosΨ = 1, (active rectifier)

Dimensions	Values
External diameter (mm)	500
Airgap diameter (mm)	468
Stator length (mm)	187
Rotor length (mm)	127
Internal diameter of the rotor (mm)	454
Mass, rotor and stator (kg)	26

Table 8. Principal dimensions of the Vernier generator

loss, giving more latitude in the choice of rectifier. This is also a direct consequence of increased frequency.
Operating with a passive diode rectifier produces the waveforms represented in Fig. 11, very similar to Fig. 6.

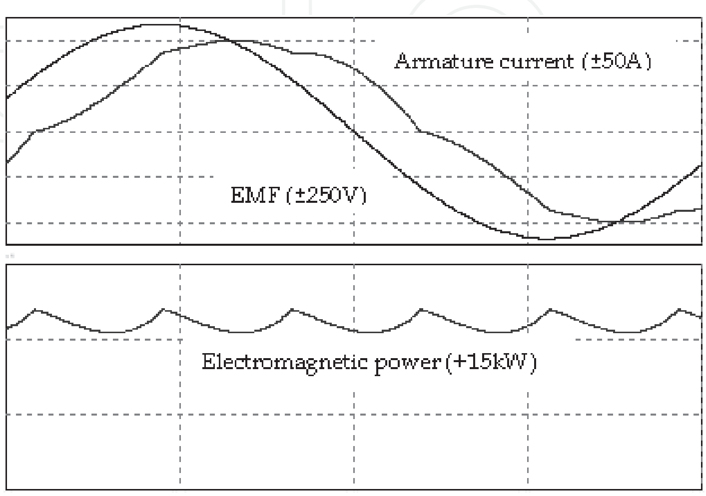


Fig. 11. Waveforms with a passive rectifier

The resulting characteristics are given in Table 9.

Characteristics	Values
Output power (kW)	10
EMF, E (V)	166
Armature current (RMS) (A)	28,5
Joule losses (W)	1072
Iron losses (W)	720
Efficiency (%)	85
Torque ripple (%)	14

Table 9. Operating with a diode rectifier

The main difference from a conventional generator is the efficiency obtained. Ohmic loss being weaker, the loss in efficiency is substantially reduced with a Vernier machine.
The rate of torque ripple stays the same, but, at a much higher frequency, above 1350 Hz, is far removed from the natural frequency of the structure of the wind turbine.
In conclusion, even if the theoretical configuration presented here is yet to be proved, we find that in terms of efficiency, power-weight ratio and torque ripple, the Vernier permanent magnet synchronous generator is extremely well-adapted to the type of use envisaged. The manufacturing costs of the Vernier probably hamper the development of this system in a very competitive market.

6. Operating with a synchronous generator with concentrated windings

The third structure presented is better known because it is used in many industrial applications (aeronautics, electric vehicles etc), but it has only recently appeared on the scene. This configuration uses concentrated windings, as shown in Fig. 12.
The operating principle is based on the coupling between a spatial harmonic component of the armature field and the first harmonic of the excitation field created by the magnets (Magnussen & Sadarangani, 2003). This configuration also allows a healthy increase in frequency at low speed rotation, because depending on the harmonic range, the number of slots can be divided by three or four compared to a conventional structure, for the same number of pairs of poles.
Furthermore, the phase distribution of the armature can be varied in order to adjust the electrical characteristics of the machine to the application under consideration.
Allowing for the different type of winding, the scaling of this type of machine is very similar to that of a conventional machine with Nr (number of pairs of magnets) pole-pairs.
Apart from the sizing, the structural characteristics of concentrated windings are numerous. We will mention a few of them.
Firstly, the structure of the winding allows the minimisation of Joule losses because the winding heads are very small (there are no overlapping windings in the stator extension). This phenomenon must be a little moderated, because the winding coefficient, relative to the harmonic range chosen for operation, is 5-10% weaker than in a conventional machine.
Secondly, the difference in slot and magnet numbers allows considerable reduction of torque ripple without slot tilt, as in the Vernier machine. This phenomenon is closely linked

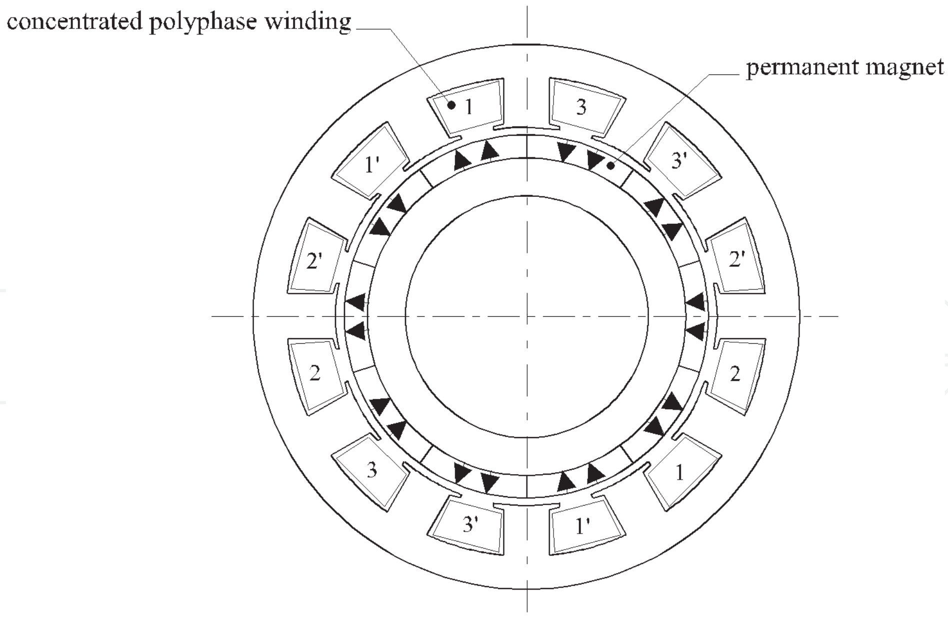


Fig. 12. Permanent Magnet Synchronous Generator with concentrated windings

to the configuration of the chosen winding. For the same reason, the electromotive forces of the machine tend to be devoid of harmonics.
Finally, the rustic nature of this machine (simple windings, open slots, large airgap ...) as opposed to the Vernier machine, and its high levels of performance, make it an ideal candidate for the envisaged use.
The following table summarises some of the most common configurations of this type of machine.

Type (N_s, N_b, N_r)	Windings structure (one pole-pair)	Coupling harmonic	Winding coefficient
9-9-4	[3′,1][1′,1′][1,1][1′,2][2′,2′][2,2][2′,3][3′,3′][3,3]	4	> 0,9
9-9-5	[3′,1][1′,1′][1,1][1′,2][2′,2′][2,2][2′,3][3′,3′][3,3]	5	> 0,8
12-6-5	[1][1′][2′][2][3][3′][1′][1][2][2′][3′][3]	5	> 0,9
12-6-7	[1][1′][2′][2][3][3′][1′][1][2][2′][3′][3]	7	≈ 0,9
12-12-5	[3′,1][1′,1′][1,2′][2,2][2′,3][3′,3′][3,1′][1,1][1′,2][2′,2′][2,3′][3,3]	5	≈ 0,9
12-12-7	[3′,1][1′,1′][1,2′][2,2][2′,3][3′,3′][3,1′][1,1][1′,2][2′,2′][2,3′][3,3]	7	> 0,8
6-3-2	[1][1′][2][2′][3][3′]	2	> 0,8
Legend: N_s, number of slot, N_b, number of windings, N_r, number of magnet-pair, [1,2′], phases 1 and 2′ in the same slot.			

Table 10. Different configurations of concentrated windings generators

The generator which we are going to study in this comparison is a commercial model which is very similar in scale to the two already studied. It is represented in Fig. 13.

The structure of this machine is of the type 12-6-5 (see Table 10).
This machine was sized with the aim of optimising efficiency and torque ripple without increasing the conversion frequency (for purely economic reasons).
Unlike the two preceding cases, the electromotive force is not perfectly sinusoidal, it contains some harmonics but these have little impact on the study undertaken. These harmonics will not be taken into account for the simulations.

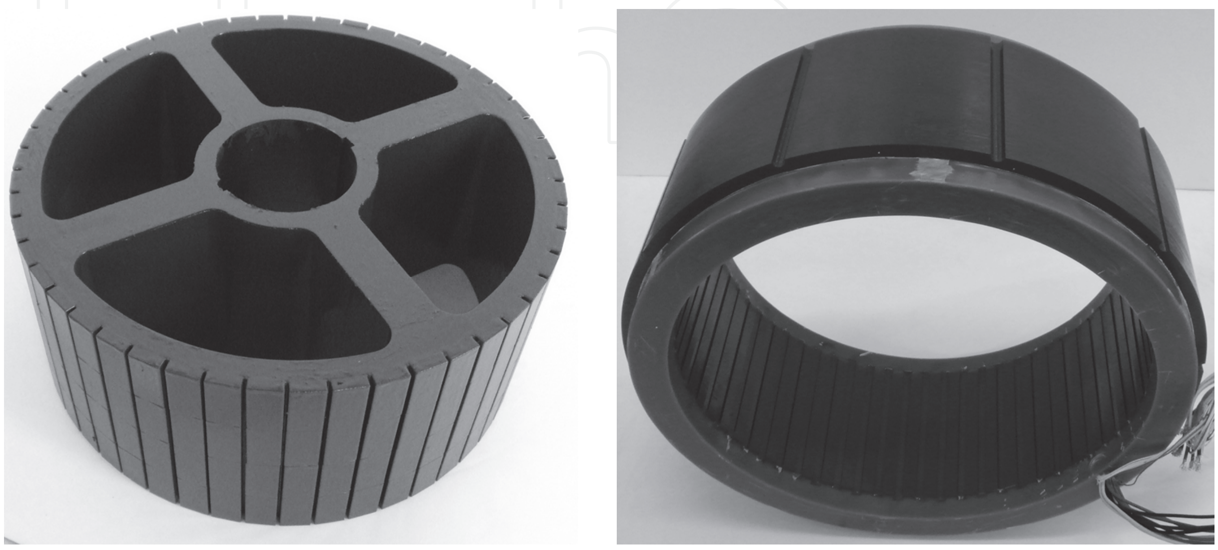


Fig. 13. Generator with concentrated windings for a wind turbine (photography ERNEO)

The following table presents the characteristics of a concentrated winding generator operating with an active rectifier.

Characteristics	Values
N_s / N_r	48 / 20
Number of pole-pairs	20
Nominal rotation speed (rpm)	150
f_e at nominal rotation speed (Hz)	50
Output power (kW)	10
E at nominal rotation speed (steady state) (V)	178
r (steady state) (Ω)	0,64
L_s (mH)	8,1
Joule losses (W)	800
Iron losses (W)	200
Torque ripple without load (cogging torque) (%)	1
Efficiency (%)	91

Table 11. Characteristics of a concentrated windings generator operating at $\cos\Psi = 1$

The main dimensions of this generator are shown in Table 12.
The waveforms obtained with a passive rectifier are represented in Fig. 14.
The resulting electrical characteristics are given in Table 13.

Dimensions	Values
External diameter (mm)	490
Airgap diameter (mm)	400
Stator length (mm)	170
Rotor length (mm)	115
Internal diameter of the rotor (mm)	353
Mass, rotor and stator (kg)	76

Table 12. Principal dimensions of a concentrated windings generator

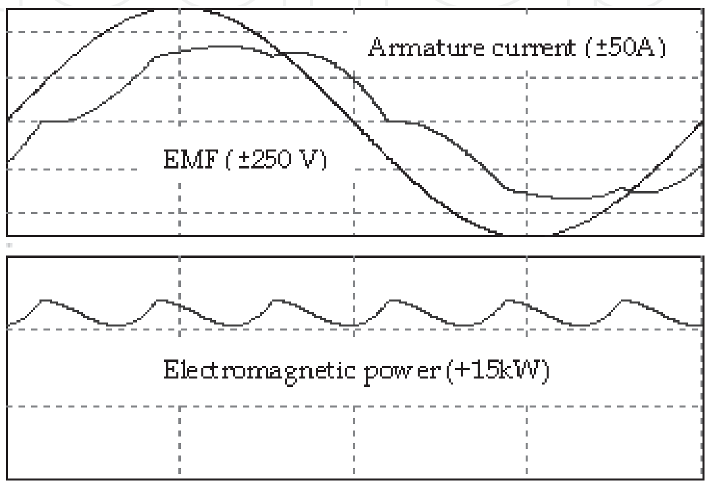


Fig. 14. Waveforms with a passive rectifier

Characteristics	Values
Output power (kW)	10
EMF, E (V)	178
Armature current (RMS) (A)	24,2
Joule losses (W)	1124
Iron losses (W)	200
Efficiency (%)	88
Torque ripple (%)	16

Table 13. Operation with a diode rectifier

This generator, which has a mass-power ratio comparable to that of the first configuration studied, mainly because their operating frequencies are almost identical, distinguishes itself by a very high efficiency, higher than that obtained by the Vernier machine. This is obviously due to the reduction in winding volume, obtained by the use of concentrated windings.
Torque ripple is slightly higher because the synchronous inductance, L_s. is quite weak. This is unique to concentrated windings.
In terms of the mass-power ratio, it is interesting to see what effect this concentrated winding configuration would have at higher frequencies. To do this, we rescale the machine, doubling the number of poles, without changing the other characteristics. The calculation is simple and relies essentially on the rules of proportionality.

The following table gives the principal characteristics obtained with this rescaled concentrated winding generator.

Characteristics	Values
N_s / N_r	96 / 40
Number of pole-pairs	40
Nominal rotation speed (rpm)	150
f_e at nominal rotation speed (Hz)	100
Output power (kW)	10
E at nominal rotation speed (steady state) (V)	163
r (steady state) (Ω)	0,55
L_s (mH)	4,9
Joule losses (W)	870
Iron losses (W)	300
Torque ripple without load (cogging torque) (%)	1
Efficiency (%)	89

Table 14. Electrical characteristics at cosΨ=1

The main dimensions of this generator are given in Table 15.

Dimensions	Values
External diameter (mm)	490
Airgap diameter (mm)	417
Stator length (mm)	145
Rotor length (mm)	115
Internal diameter of the rotor (mm)	390
Mass, rotor and stator (kg)	48

Table 15. Principal dimensions

The waveforms obtained with a passive rectifier are represented in Fig. 15.

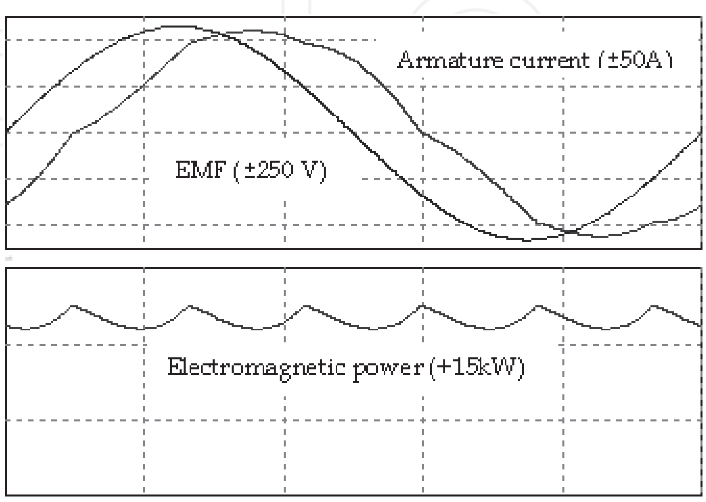


Fig. 15. Waveforms with a passive rectifier

The resulting electrical characteristics are given in Table 16.

Characteristics	Values
Output power (kW)	10
EMF, E (V)	163
Armature current (RMS) (A)	31,6
Joule losses (W)	1650
Iron losses (W)	200
Efficiency (%)	84
Torque ripple (%)	14

Table 16. Operation with a diode rectifier

The efficiency is slightly reduced, especially because of the relative increase in the synchronous reactance, but the power density is much higher. The frequency of torque ripple, a bit attenuated, is equal to 600 Hz. This solution is very satisfactory.

7. General conclusions

Three different generators, at the core of the passive conversion system for wind turbines, have been studied. We have shown that under the same operating conditions, two configurations which can be considered unconventional, the Vernier generator and the concentrated windings generator, operate very satisfactorily in terms of output, but do not allow complete control of the torque ripple resulting from the armature current waveform. However the impact of this ripple, in terms of noise pollution, can be reduced by increasing the operating frequency of the generator.

In this context, the concentrated windings configuration seems to be a good compromise in terms of output/cost, especially when compared to the conventional structure which we studied first which has relatively poor efficiency when combined with an active rectifier, and to the Vernier structure, which although unmatched in terms of mass-power ratio at very low speed, is expensive to manufacture.

8. References

Abdelli A. (2007). Optimisation multicritère d'une chaîne éolienne passive. Thesis, INPT, Toulouse, France, 2007

Gergaud, O; Multon, B; Ben Ahmed, H. (2001). Modélisation d'une chaîne de conversion éolienne de petite puissance, *Proceedings of Electrotechnique du futur 2001 (EF2001),* pp 17-22, Nancy, France, November 14-15, 2001.

Kharitonov, S. (2010). An Analytical Analysis of a Wind Power Generation System Including Synchronous Generator with Permanent Magnets, Active Rectifier and Voltage Source Inverter, In : *Wind Power*, InTech, S.M. Muyeen (Ed.), 23-72, ISBN: 978-953-7619-81-7.

Kolar, J. W., Ertl, H., Zach, F. C. (1998). Design and Experimental Investigation of a Three-Phase High Power Density High Efficiency Unity Power Factor PWM (Vienna) Rectifier Employing a Novel Integrated Power Semiconductor Module, *Proceedings* *of the 11th IEEE Applied Power Electronics Conference*, pp.514-523, San Jose, USA, March 1998.

Machmoum, M.; Moreau, L.; Zaïm, M.; Barakat, G.; Takorabet, N.; Chillet, Ch.; Matt, D.; Taïbi, S.;Tounzi, A.; Espanet, Ch.; Miraoui, A.; Zire, H. S. (2005). Comparaisons de structures électromagnétiques pour des applications à faible vitesse et fort couple. *Revue Internationale de Génie Electrique*, vol. 8, n°2, (2005), pp. 259-286, ISBN 2-7462-1159-9.

Magnussen, F; Sadarangani, C. (2003). Winding Factors and Joule Losses of Permanent Magnet Machines with Concentrated Windings, *Proceedings of IEEE International Electric Machines & Drives Conference (IEMDC)*, pp. 333–339, Madison, Wisconsin, June 2003.

Masoud Barakati, S. (2008). Modeling and Controller Design of a Wind Energy Conversion System Including a Matrix Converter, Thesis, Waterloo, Ontario, Canada, 2008.

Matt, D.; Enrici, P. (2005). Couplage par effet de denture dans les machines électriques synchrones. Synthèse et comparaison : machine à réluctance variable et machine à aimants. *Revue Internationale de Génie Electrique*, vol. 8, n°3/4, (2005), pp. 425-451, ISBN 2-7462-1094-0.

Matt, D., Nierlich, F., Enrici, P., Jac, J., Martire, T. (2007). Moteur électrique à fort couple massique pour l'aéronautique. *Revue Internationale de Génie Electrique*, vol. 10, n°3/4, (2007), pp. 403-427, ISBN 978-2-7462-1906-9.

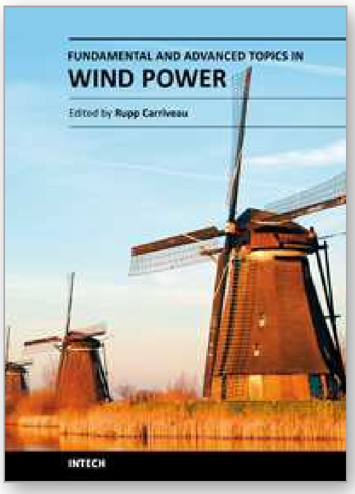
Matt, D.; Martire, T.; Enrici, P.; Jac, J.; Ziegler, N. (2008). Passive Wind Energy Conversion system Association of a direct-driven synchronous motor with vernier effect and a diode rectifier, *Proceedings of MELECON'2008, 14th IEEE Mediterranean Electrotechnical Conference*, ISBN 978-1-4244-1633-2, CD-ROM, Ajaccio, France, May 5-7, 2008.

Matt, D.; Tounzi, A.; Zaïm, M. (2011). Machines lentes à couplage dentaire, In : *Machines électriques non conventionnelles*, Hermes (Ed.) 39-97, 2011).

Meny, I.; Didat, J.R.; Enrici, P.; Matt, D. (2006). Use of a variable-reluctance magnet machine for a direct driven wind generator, *Proceedings of ICEM 2006, 17th International Conference on Electrical Machines*, CD-ROM, Crete Island, Greece, September 2-5, 2006.

Mirecki, S. (2005). Etude comparative de chaînes de conversion d'énergie dédiées à une éolienne de petite puissance. Thesis, INPT, Toulouse, France, 2005.

Toba, A.; Lipo, T.A. (2000). Generic Torque-Maximizing Design Methodology of Surface Permanent-Magnet Vernier Machine. *IEEE transactions on industry applications*, vol. 36, n°6, pp. 1539-1545, November-December 2000.



Fundamental and Advanced Topics in Wind Power

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As the fastest growing source of energy in the world, wind has a very important role to play in the global energy mix. This text covers a spectrum of leading edge topics critical to the rapidly evolving wind power industry. The reader is introduced to the fundamentals of wind energy aerodynamics; then essential structural, mechanical, and electrical subjects are discussed. The book is composed of three sections that include the Aerodynamics and Environmental Loading of Wind Turbines, Structural and Electromechanical Elements of Wind Power Conversion, and Wind Turbine Control and System Integration. In addition to the fundamental rudiments illustrated, the reader will be exposed to specialized applied and advanced topics including magnetic suspension bearing systems, structural health monitoring, and the optimized integration of wind power into micro and smart grids.

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Unit 405, Office Block, Hotel Equatorial Shanghai
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Phone: +86-21-62489820
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