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Design of a Mean Power Wind Conversion Chain with a Magnetic Speed Multiplier

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Additional information is available at the end of the chapter

1. Introduction

When designing a wind turbine for power generation there are two methods of linking the wind sensor to the generator, as seen in figure 1.
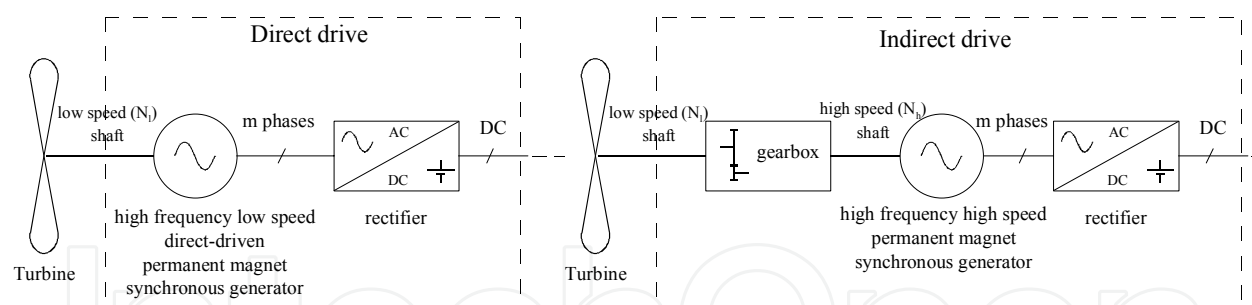

Figure 1. Linking the wind turbine to the generator

The first, the most common, links the turbine to the generator via a mechanical speed multiplier. In this configuration, the mechanical power is transmitted at high speed to the electrical machine. The size of the latter may then be easily reduced. This method has the major advantage of allowing the use of simply designed synchronous or asynchronous generators, which are readily available and inexpensive.

This first method is mainly used for high power wind turbines (above a few tens of kilowatts, to establish an order of magnitude) because at this power level, the large size of the generator becomes a problem, it becomes difficult to do without the speed multiplier.

The second, more recent, alternative is to link the generator directly to the turbine without a mechanical intermediary [8]. This method is known as "direct drive" and has become economically viable in recent years thanks to the progress made on permanent magnets. The cost of permanent magnets has dropped significantly while their performance has continued to improve. They have enabled the design of high performance, high power density, synchronous machines, well suited to the low speed operation imposed by the wind sensor, at reasonable cost.

The direct-drive method is attractive because it eliminates the weak element of the conversion chain: the speed multiplier gearbox. This is indeed a frequent source of failure, an additional noise source and may also require regular maintenance, resulting in high operating costs [8,9]. Finally, the multiplier can be the source of chemical pollution due to the lubricant oil. This explains why the latter option is widely preferred in the installation of small and medium size wind turbines for domestic applications, which are intended for operation over a long time without maintenance.

Above a certain power level, typically 10 kW, both methods become competitive in terms of cost; only a fine techno-economic study would tip the balance one way or the other.

As part of a medium-power design, there is a third method which offers an interesting alternative to the mechanical speed multiplier: the use of a magnetic gear [3-7]. This chapter, then, is devoted to the description of this device and shows the utility and feasibility of such a wind conversion chain. The different magnetic multiplier structures are presented and the design of this device will allow comparison with traditional solutions.

The advantage of the magnetic speed multiplier over its mechanical counterpart is clearly the contact-free force transmission that enables operation without any maintenance. We also show that the size and efficiency of magnetic speed multiplier are not prohibitive for the intended application.

2. Presentation of the magnetic speed multiplier

The principle of the magnetic speed reducer or multiplier is now well known, but the use of this type of converter is uncommon and usually reserved for low power [3-6]. We will show why the transmission of substantial power with very low wind turbine operating speed is useful.

The operation of the speed multiplier is based, firstly, on the principle of a Vernier type teeth coupling [1,2,10] between a series of alternating permanent magnets and a series of magnetic teeth. The following diagram, which represents a cylindrical or discoid developed structure, demonstrates the principle used in the calculation of the magnetic field in the air gap. In this device, a series of $2.N_r$ alternating permanent magnets, configured around a rotor, moves before a series of N_s magnetic teeth around a stator. The number N_s is different to N_r.
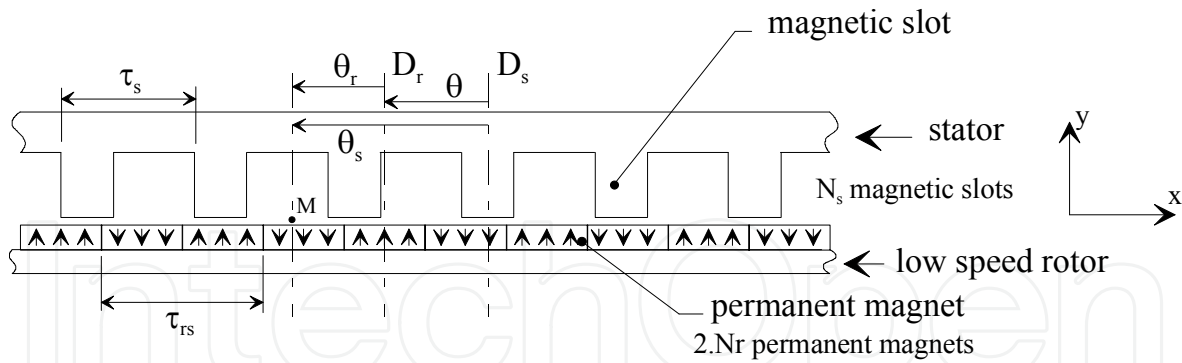
Figure 2. Cross-section of a Vernier machine with distributed windings

The calculation of the magnetic field at a point M, anywhere in the air gap, requires the azi‐muthal coordinates, θ_s and θ_r, identified respectively relative to the axis D_s, linked to the sta‐tor, and D_r, linked to the rotor. The angle, θ, between the two axes is a function of time.

The wave of flux density in the air gap, $b_a(\theta_s, \theta)$, created by the permanent magnets, is de‐duced from the following equation:

$$b_a(\theta_s, \theta) = P(\theta_s) \cdot \varepsilon_a(\theta_s, \theta) \tag{1}$$

where $\varepsilon_a(\theta_s, \theta)$ represents the scalar magnetic potential associated with the permanent mag‐nets and $P(\theta_s)$ represents the density of the air gap permeance modulated by the magnetic teeth. We retain only the initial harmonics of these waves.

$$\varepsilon_a(\theta_s, \theta) = \varepsilon_1 \cdot \cos N_r(\theta_s - \theta) \tag{2}$$

$$P = P_0 + P_{1s} \cdot \cos(N_s \theta_s) \tag{3}$$

The multiplication leads to:

$$b_a(\theta_s, \theta) = \tfrac{1}{2} \cdot \varepsilon_1 \cdot P_{1s} \cdot \cos((N_s - N_r) \cdot \theta_s + N_r \theta) + \tfrac{1}{2} \cdot \varepsilon_1 \cdot P_{1s} \cdot \cos((N_s + N_r) \cdot \theta_s - N_r \theta) + \varepsilon_1 \cdot P_0 \cdot \cos Nr(\theta_s - \theta) \tag{4}$$

The second term is without practical interest, its periodicity, $2\pi/|N_s+N_r|$, is too small for its implementation in a synchronous coupling with another magnetic field.

The third term, of a periodicity of $2\pi/N_r$, is quite simply linked to the distribution of the per‐manent magnets, and thus holds no interest for us in the mode of Vernier coupling as de‐fined here.

We shall consider, then, only the first term, which is in fact the fundamental. Its periodicity, $2\pi/|N_s-N_r|$, is characteristic of the Vernier effect:

$$b_a(\theta_s, \theta) = b_{a1} \cdot \cos\left((N_s - N_r) \cdot \theta_s + N_r\theta\right), \text{ with } b_{a1} = \tfrac{1}{2} \cdot \varepsilon_1 \cdot P_{1s} \tag{5}$$

Taking $\theta = \Omega_r.t$, the term appears as a wave rotating at a speed of $N_r.\Omega_r/|N_s\text{-}N_r| = k_v. \Omega_r$, the coefficient k_v is known as the Vernier ratio.

With small sized permanent magnets (N_r large) it is possible to have a high speed ratio between the magnetic field rotation speed and the rotor rotation speed. It is this phenomenon which is used to design the speed multiplier. The main physical limitation of the process is that the smaller the magnets, the smaller the field b_{a1}, as a result of not being able to reduce the air gap sufficiently.

In the Vernier structure, provided that the number of magnetic teeth or permanent magnets is large, the pitch τ_s, seems to be little different from pitch τ_{rs}, it is then possible to isolate a pseudo repeat pattern, characteristic of the magnetic interaction between a tooth and two magnets. This pattern is fully defined by four adimensional parameters, α, Λ, s, ε, as shown in the figure 3.
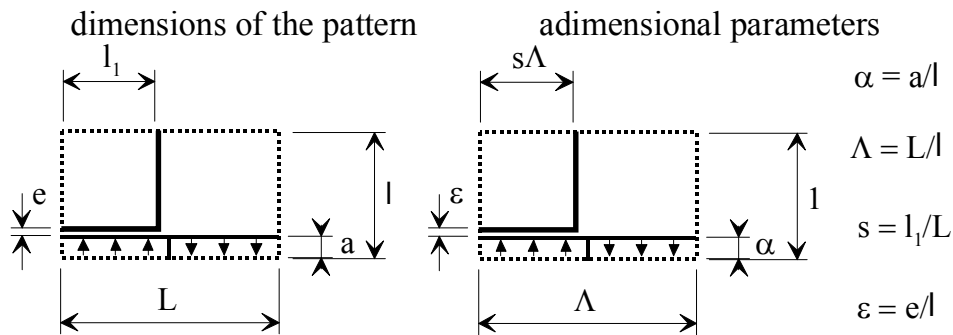

Figure 3. Elementary domain; tooth coupling

A parametric study conducted on the elementary pattern [1,10] allows us to quantify the amplitude of the first harmonic of the flux density, b_{a1}.

It is thus demonstrated, in [1], that b_{a1} that can be expressed as:

$$b_{a1} = \frac{\alpha \cdot \Lambda}{(\varepsilon + \alpha)^2} \cdot \frac{k_s}{\pi} \cdot B_{ar} \tag{6}$$

where B_{ar} represents the remanent magnetization of the permanent magnet.

A first approximation of the teeth coupling coefficient, k_s, obtained through numerical calculation of the magnetic fields, depends only on the adimensional parameters (α, Λ), and is given in the figure 4.
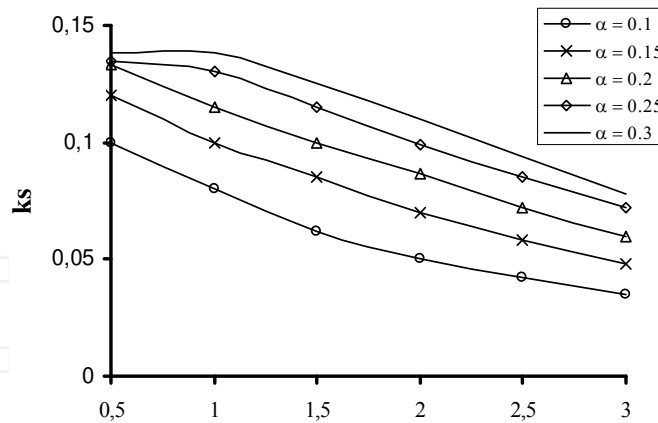
Figure 4. Variation of the coupling coefficient in terms of α and Λ

Taking the following typical values: $\Lambda = 1$, $\alpha = 0.2$, $\varepsilon = 0.05$, $B_{ar} = 1$ T, we obtain $k_s \approx 0.12$, i.e. $b_{a1} \approx 0.12$ T. It would appear that the magnetic field, b_a, is always weak, but in fact the field varies with time to a high frequency, becoming higher as N_r becomes greater. It is precisely this phenomenon which will be advantageously exploited in the transmission of mechanical force within the converter that we will describe.

The second principle used in the design of a magnetic speed multiplier is that of the magnetic coupler. This device combines two rotors through the magnetic field produced by permanent magnets.

In a magnetic speed multiplier, as shown in the figure below, an intermediate stator allows the decoupling of the velocity of the two rotors using the principle of teeth coupling as seen in the Vernier structure.
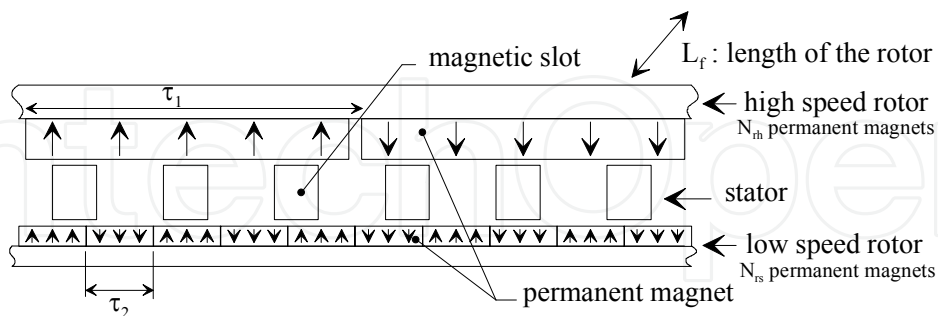

Figure 5. Magnetic gear: operating principle

The number of pairs of magnetic poles, p, of this structure, is defined by the number of pairs of permanent magnets linked to the high speed rotor, N_{rh}. This must correspond to the number of poles created by the coupling between the N_{rs} number of permanent magnet pairs on the low speed rotor, and the N_s stator teeth. The following formula must then be verified:

$$\left| N_s - N_{rs} \right| = p = N_{rh} \tag{7}$$

Operation is possible with $N_s > N_r$: the high speed rotor will then move in the opposite direction to the low speed rotor; or $N_r > N_s$: the two rotors will rotate in the same direction. Previous studies of Vernier structures [2] show however that the first configuration, $N_s > N_r$, is far better, giving higher force in relation to the air gap surface.

When the low speed rotor is displaced to the value of one small magnet pitch, τ_2, the high speed rotor will displace to the value of one large permanent magnet pitch, τ_1. The gear ratio is simply obtained by calculating the ratio of τ_1 and τ_2:

$$k_m = \left| N_{high} / N_{low} \right| = \tau_1 / \tau_2 = N_{rs} / N_{rh} = k_v \tag{8}$$

Operation in synchronous mode, characterized by the above equation, is possible only if the torque on the output shaft does not exceed a maximum value. We also show the consequences of a possible stall.

3. Intrinsic performance of magnetic speed multiplier

In a traditional speed multiplier gearbox, which transmits force via the intermediary of a mechanical contact, the sizing, in terms of transmissible torque, is dictated by considerations of wear and material strength. This is a good solution which allows compact structures, but the design must take into account many safety factors to reduce the risk of breakage, which is ultimately quite high [9].

The level of transmissible force without contact, via the intermediary of a magnetic field coupling within a magnetic gear, is obviously much weaker than with a traditional mechanical solution. On the other hand, it is not necessary to introduce safety factors that penalize the design, because there is no risk of breakage.

In order to quantify the performance level of the magnetic speed multiplier, we shall introduce tangential magnetic force density, defined by the following equation:

$$F_{st} = \frac{F_{max}}{S_e} \tag{9}$$

Maximum force on the low speed rotor, F_{max}, is obtained when the flux density fields created by the permanent magnets of both rotors are phase shifted at an electric angle of $\pi/2$, as shown in the figure 6.

The tangential force density can be calculated from the elementary domain of width τ_1 and depth L_f. The air gap surface, S_e, is equal to $\tau_1.L_f$.
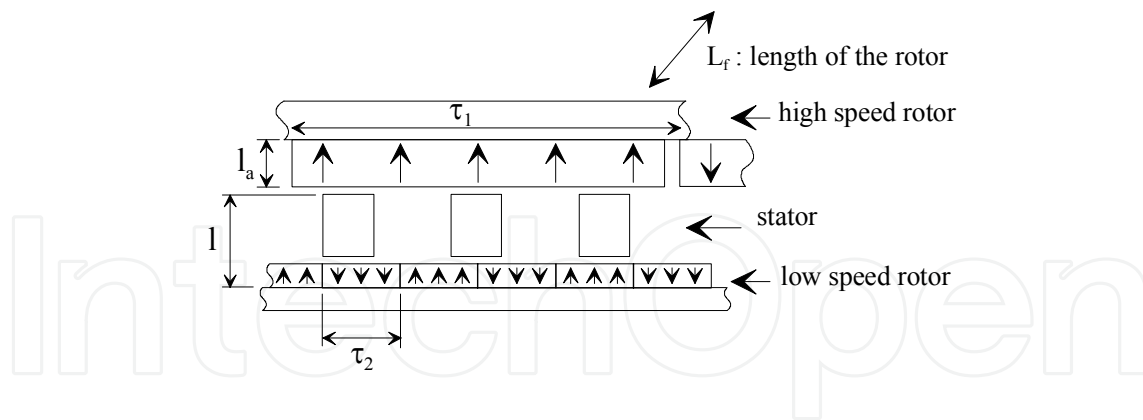
Figure 6. Position at maximum force

The calculation of F_{st} is made using a magnetic field, finite element, calculation software. Parameters are defined from the relative thickness of the main permanent magnet, $\beta = l_a/l$, and the multiplication ratio, k_v. The adimensional parameters of the magnetic pattern, relative to the low speed rotor, are arbitrarily assigned using the following values:

$\Lambda = 1$, $\alpha = 0.2$, $\varepsilon = 0.05$

These values generally give a good result in the Vernier machines design [1,10].

The air gap on the high speed rotor is defined as equal to one tenth of the thickness of the main magnet. This dimension, however, has less importance.

The following figure shows the flux lines within a configuration similar to that in figure 6, for a value of k_v equal to 5 and β equal to 1/2.

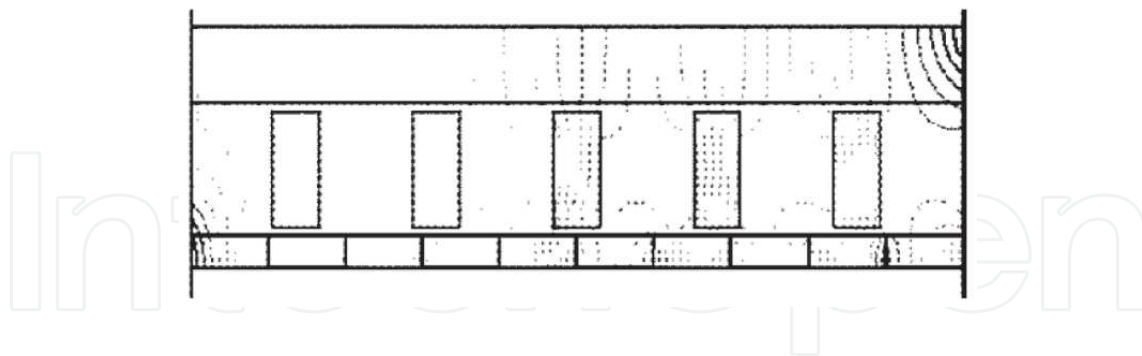**Figure 7.** Flux lines in maximum force position

The tangential force density, F_{st}, is represented in figure 8 versus the relative thickness, β. These are trend curves in linear mode.

It is important to note that the tangential force density level reached in the speed multiplier, from 40 to 50.10^3 N/m², is significantly higher than that obtained in a conventional electromechanical converter, which is closer from 10 to 20.10^3 N/m², at steady state and with air cooling [10]. This complex phenomenon is created by the fact that in an electromechanical converter, one of the magnetic field components, that interact to create the torque, is created

by currents, with less efficiency than with permanent magnets, as is the case in the speed multiplier. This is a general principle observed in all converters using magnets.
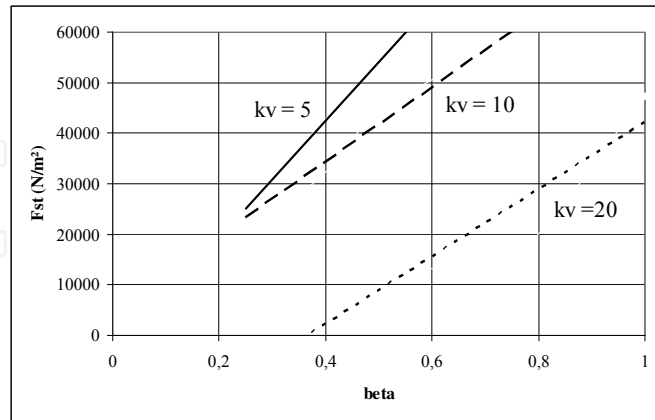

Figure 8. Tangential force density for different values of k_v (B_{ar} = 1.2 T)

Figure 9 shows, on the same basis, the evolution of the normal force density, F_{sn} = F/S_e, versus , for a value of k_v equal to 10.

The force F is perpendicular to the surfaces of the air gap; it produces no motive force but tends to introduce constraints on the bearings, as we shall see later. The normal force density is calculated for the low speed rotor and for the high speed rotor. It is much higher on the low speed rotor side, making it impossible to balance the force on the stator.

The normal force density level, which comes from the following relationship for flux density B, is, in most cases, still well above the level of tangential force density.
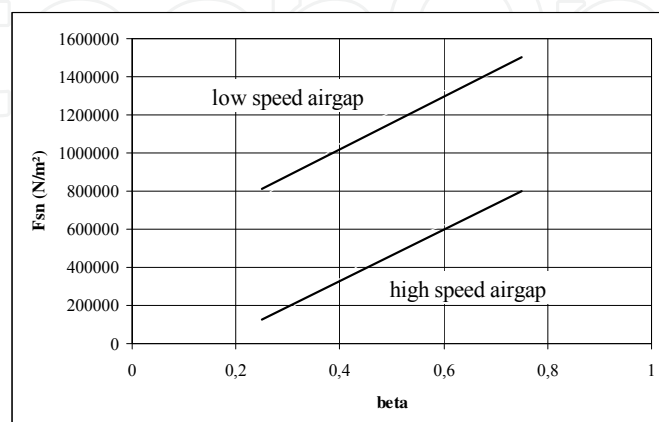
$$F_{sn} = \frac{B^2}{2 \cdot \mu_0}$$
(10)

Figure 9. Normal force density (k_v = 10)

4. Different configurations of magnetic speed multiplier systems

The device described above can be applied in numerous ways within a wind conversion chain.

It must be noted that Vernier-type interaction, of the magnetic teeth with small permanent magnets, can be achieved directly in an electric motor [1,8], which has the double advantage of being of a relatively simple design, with high performance at low speeds, for the given reasons (electromechanical conversion at high frequency). This shows its potential for direct drive use, without multiplier.

Figure 10 shows the design of such a machine, with $N_s = 12$, $N_r = 10$, $p = 2$, $k_v = 5$. This config‐uration will be a base to compare performance, in the next paragraph, for sizing at 10kW, corresponding to a medium power wind turbine/conversion system.

Despite its main problem, which is that it operates naturally with a low power factor (typi‐cally 0.4 to 0.7), this configuration lends itself admirably to wind turbine generator design because its mass power ratio is unrivalled in this kind of application [8].
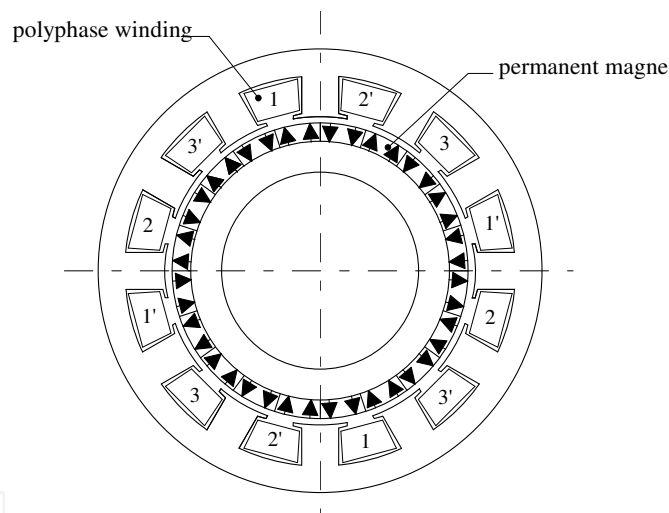

Figure 10. Vernier permanent magnet synchronous generator

The design of the magnetic speed multiplier conversion chain has the major advantage of allowing de-coupling between the electric problems (overheating, power factor …) and the problems arising from the Vernier effect in speed conversion.

We will also show that, given the high level of tangential force density attained in the multi‐plier, this solution may be more efficient in terms of weight and size than the more direct solution shown in Fig. 10.

The design generally adopted for the multiplier, based entirely on the principle described in figure 5, is thus the following:
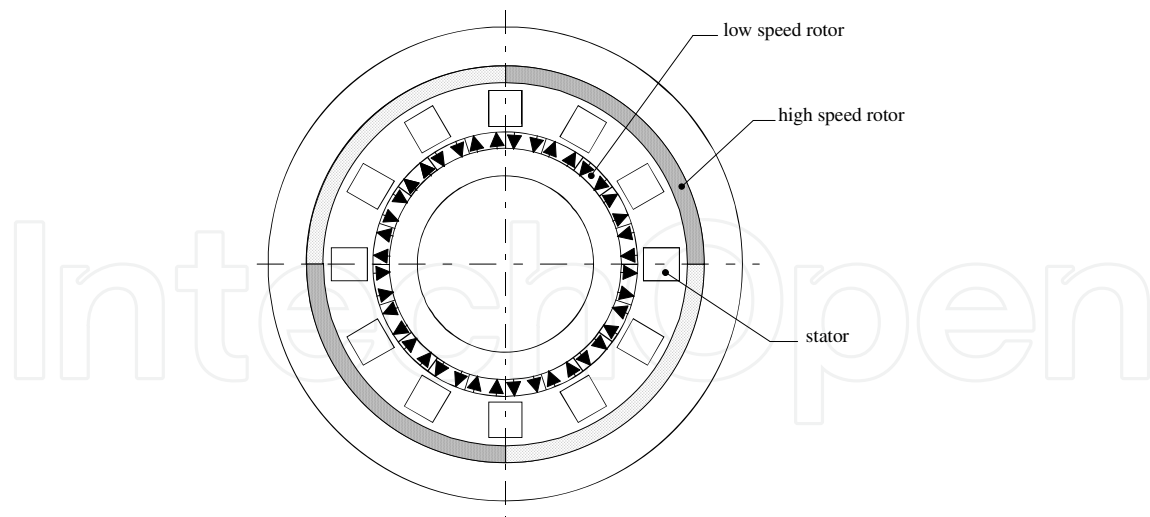
Figure 11. Magnetic speed multiplier with cylinder design

This figure immediately brings out a major difficulty in designing this type of device. This architecture is based on the overlap of three concentric cylinders, the two rotors and the stator, all rotating in relation to each other, the rotational guidance of the two rotors is necessarily delicate [3].
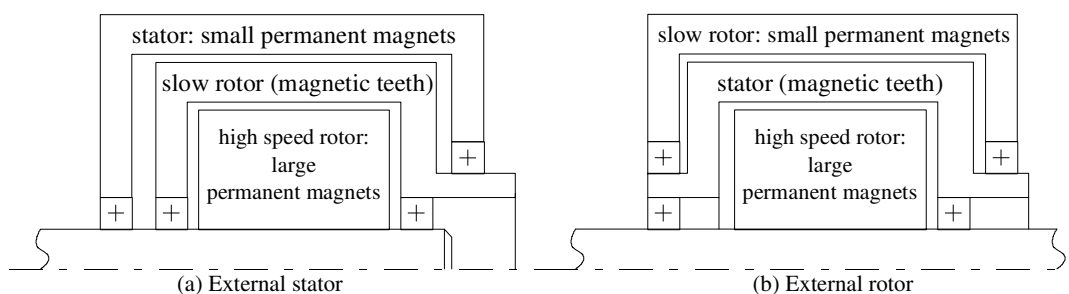

Figure 12. Arrangement of the bearings in cylindrical structure

The figure 12 shows two examples of bearing arrangement to solve the problem mentioned, but in all cases the additional constraints on by the bearings will be a source of accelerated aging of the structure.

In the first alternative arrangement (a), it is the magnetic teeth which act as low speed rotor. The small permanent magnets are on the stator. In the second arrangement (b), the magnetic teeth are fixed; the small permanent magnets are on the low speed rotor, which is external.

It should also be noted that the assembly consisting of alternating magnetic and nonmagnetic teeth is not easy to achieve because the magnetic teeth should be laminated or made with SMC material. The achievement of this complex, highly heterogeneous, structure, is still problematic.

The following photographs show an example of such a design. The magnetic teeth are secured using epoxy resin, the resulting assembly is reinforced by threaded rods visible in Figure 13(c).

(a) Virtual photography

(b) Stator   (c) Low speed rotor (magnetic teeth)   (d) High speed rotor
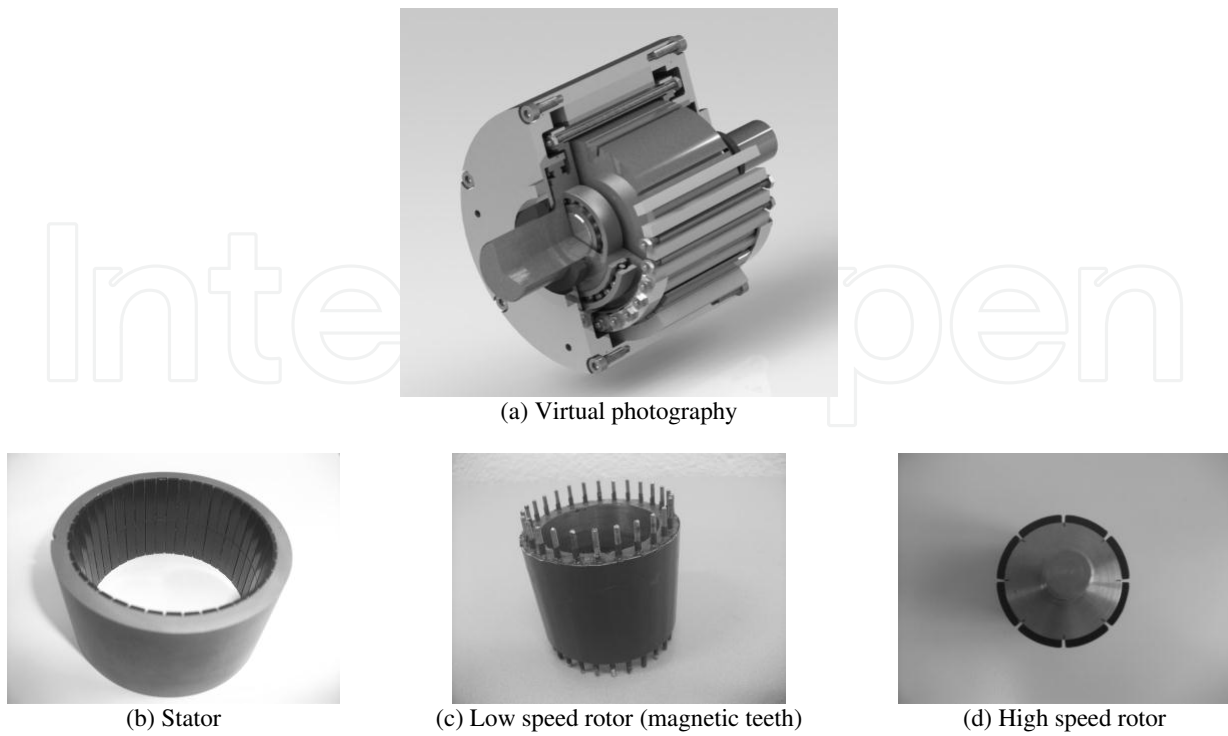
Figure 13. Prototype of a magnetic gear

An alternative solution to figures 10 and 11, described in [5,7], consists of combining the high-speed generator and the speed multiplier within the same structure, by inserting a polyphase winding between the magnetic teeth, in accordance with the following figure:
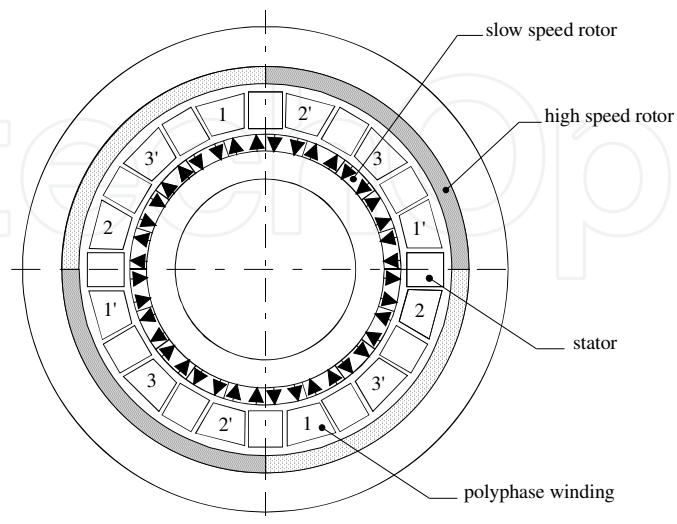

Figure 14. Combining the high-speed generator and the speed multiplier

This solution is attractive, but the technological design difficulties lead to sub-optimization (e.g. increase of air gap...), so it is highly unlikely that the result would be better than with the simplified solution seen in Figure 10.

The principle we have just described can be advantageously implemented in discoid structures, such as that in the figure 15, performing one or more multiplier stages.
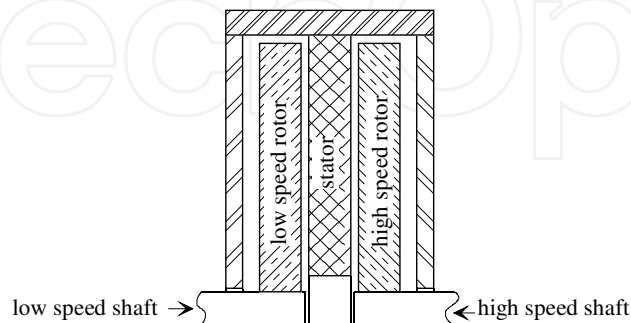

Figure 15. Magnetic speed multiplier: one stage discoid structure

This magnetic gear design has the advantage of being more compact than the cylindrical design for a higher level of torque, because it allows better use of the maximum radius. Above all, it has the advantage of being mechanically simpler; the rotors can be maintained by a simple bearing on each side of the stator.

On the other hand, in the structure shown in Figure 15, the rotors are subjected to huge axial forces that we will quantify, which will also constrain the bearings. This is typical of discoid structures and can be tricky to control. It is the main design problem.

5. Design of a magnetic gear

In order to clarify the potential uses of magnetic multipliers in the design of a wind conversion chain, we will size the electro mechanic device for an electric output power of 10 kW. This power output corresponds to an average power installation, for example for a small farm or a small group of isolated houses. This type of turbine has grown significantly.

To quantify the level of performance, we will compare the combination of multiplier and high-speed generator to a direct drive, low speed generator: a Vernier configuration like that in Figure 10. A study carried out in [1,8] shows that the power density of this configuration is significantly better than that obtained using a more conventional configuration with a large number of poles.

The nominal speed, N_{low}, of the wind turbine used for this study, is 150 RPM.

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

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 1. Electrical characteristics of a 10 kW Vernier generator

The main dimensions of this generator are shown in Table 2.

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 2. Principal dimensions of the Vernier generator

We observe that the high operating frequency, 225Hz, at low speed, 150 RPM, leads to a mass-power ratio of about 400 W/kg, taking into account only the weight of the active parts. The mass-power ratio of a conventional machine, with a large number of poles, would be in the order of 200W/kg. The efficiency of the Vernier machine is comparable to a conventional machine, under the same operating conditions, with more iron losses, but with less Joule loss. This is also a direct consequence of increased frequency.

The speed multiplier, which will be linked to a high speed machine, will be sized in operating conditions similar to that of the Vernier machine, in particular for the operating frequency of the low speed rotor, f_{rs}, which will be of the order of 225 Hz.

The low-speed rotor has N_{rs} permanent magnet pairs, the operating frequency, f_{rs}, is then equal to:

$$f_{rs} = \frac{N_{rs} \cdot N_{slow}}{60} \tag{11}$$

With f_{rs} = 225 Hz, we obtain N_{rs} = 90 pairs of permanent magnets for the entire low-speed rotor.

The choice of the multiplication ratio is an important parameter for optimizing the system; the higher the ratio the lower the size of the generator. On the other hand, in accordance with the results of Figure 8, the higher the ratio the lower the tangential force density within the multiplier, resulting in an increase of the size of the multiplier.

It is not within the scope of this chapter to optimize this system; we find simply that beyond k_v = 10, according to the results shown in Figure 8, the tangential force density decreases rapidly, so we will take k_v = 10 as the multiplication ratio, which leads to a nominal speed rotation of the generator, N_{high}, of 1500 RPM.

From this value we deduce the number of pole pairs, p:

$$p = \frac{N_{rs}}{k_v} = 9 \tag{12}$$

These selected values of p and N_{rs} will allow us to calculate the main dimensions of the multiplier as defined in the figure 16:
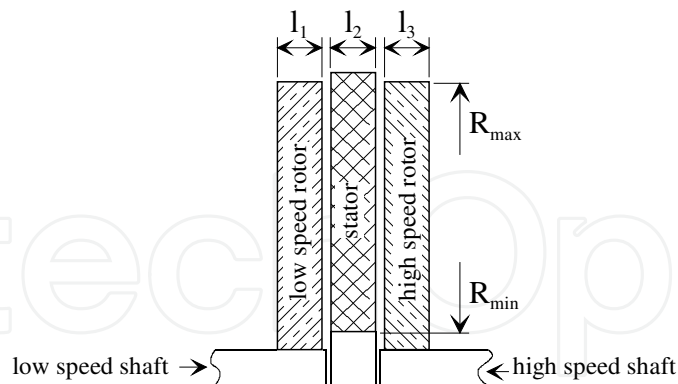

Figure 16. Main dimensions of the speed multiplier

The torque on the low-speed rotor is calculated from the discoid air gap surface and the tangential force density, F_{st}, as follows:

$$T_{low} = \frac{2}{3} \cdot \pi \le \cdot (R_{max}^3 - R_{min}^3) \cdot F_{st} \tag{13}$$

The generator should deliver an electrical power of 10 kW with 90% efficiency. The generator input power, P_m, is then equal to 11.1 kW. Ignoring the efficiency of the speed multiplier, we get a torque, T_{low}, equal to:

$$T_{low} = \frac{60 \cdot P_m}{2 \cdot \pi \cdot N_{low}} \approx 700 \text{ Nm} \tag{14}$$

The tangential force density, F_{st}, being fixed to an average value of 40.10^3 N/m² in accordance with the results of Figure 8, the radius R_{max} and R_{min} can be deduced from the above formulae. Taking a value for R_{max} that is slightly lower than the outer radius of the Vernier machine, $R_{max} = 210$ mm, the radius, R_{min}, is equal to 100 mm.

The thicknesses of the speed multiplier discs, l_1, l_2, l_3, can be deduced from the dimensions of the small permanent magnets in the elementary domain defined in Figure 3, by adopting the following values for the adimensional parameters: $\Lambda = 1$, $\alpha = 0.2$, $\varepsilon = 0.05$. The calculation is lengthy but not difficult. The following table summarizes the dimensions of the (speed) multiplier:

Dimensions (mm)	Values
Thickness of the small permanent magnets	3
Thickness of the low speed magnetic yoke	20
l_1	23
Low speed air gap	0,75
Thickness of the high speed permanent magnets	7,5
Thickness of the high speed magnetic yoke	20
l_3	27,5
High speed air gap	0,75
Thickness of the magnetic teeth, l_2	11
Total lenght	63
Weight of active parts (kg)	**50**

Table 3. Dimensions of the magnetic speed multiplier

The obtained result shows that the mass of the magnetic gear is substantially greater than that of the Vernier machine, counting only the active parts. The structure of the Vernier machine being hollow, unlike that of the speed multiplier, the addition of structural elements gives us the same result, i.e. about 50 kg (for the entire device). The technologies used being similar, this result is to be expected.

On the other hand, the extremely compact structure of the discoid multiplier gives a smaller size than the direct drive Vernier machine, the external diameter being slightly smaller, the length is reduced by almost a third.

The associated generator works at a nominal speed of 1500 RPM. It is driven with a torque equal to one tenth of the low-speed torque, i.e. 70 Nm. Designed on the principle of a permanent magnet synchronous machine, for which a torque per unit mass of 2 Nm/kg is possible [10], the mass of the associated generator would be about 30 to 40 kg. This leads to a total mass of less than 100 kg for the multiplier and generator combined.

The specific power of the system is then equal to 100 W/kg.

The efficiency of the magnetic gear is essentially related to losses in the small permanent magnets from the low-speed rotor, and to losses in the magnetic teeth, which are subject to a highly variable magnetic field. So efficiency will be calculated on the basis of these losses, ignoring the iron losses in the magnetic yokes.

The figure 17 shows the spatial evolution of the magnetic flux density in the permanent magnets of the low-speed rotor (configuration of Figure 7).

In a Vernier structure, the temporal evolution of the magnetic field is similar to the spatial evolution, therefore, we note from the figure that the amplitude, ΔB, of the temporal component, is approximately equal to 0.4 T, with a magnetic field of 1.2 T when the permanent magnets are polarized in the forward direction, and 0.4 T when they are polarized in the opposite direction.
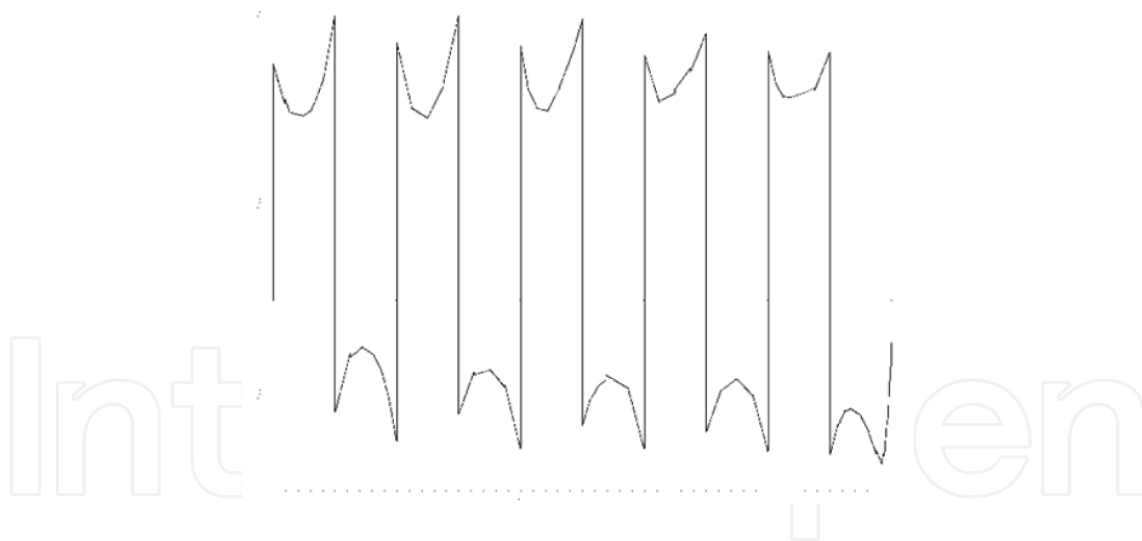

Figure 17. Flux density in the low-speed permanent magnets.

The permanent magnets are parallelepipeds 3 mm thick (in the direction of magnetization), 110 mm high and 5.4 mm wide on average; the volume, V_a, is equal to 1782 mm3. The following equation then allows the calculation of losses in a permanent magnet:

$$P_f = \frac{\pi^2 \cdot f^2 \cdot \Delta B^2 \cdot t_a^2}{6 \cdot \rho} \cdot V_a \tag{15}$$

Total losses in the permanent magnets are equal to $2\,N_{rs}\,P_f = 156$ W.

The figure 18 shows the spatial evolution of the magnetic field in the magnetic teeth (config‐uration of Figure 7).

The amplitude of variation of the magnetic field in the teeth is 1 T. The calculation of losses depends on the nature of the material used to make the teeth, and on the thickness of the lamination, if these teeth are made of stacked plates, so it is not possible to quantify the level of loss. However, taking an average value of specific loss, at 225 Hz and 1T, i.e. 15W/kg for a common material, with 2.75 kg of magnetic teeth, the losses are in the order of 40 W.

The efficiency of the magnetic gear, which follows from the previous calculation of losses, is close to 98%. Taking into account the additional iron losses and mechanical losses induced by stress on the bearings, efficiency remains well above 90%.
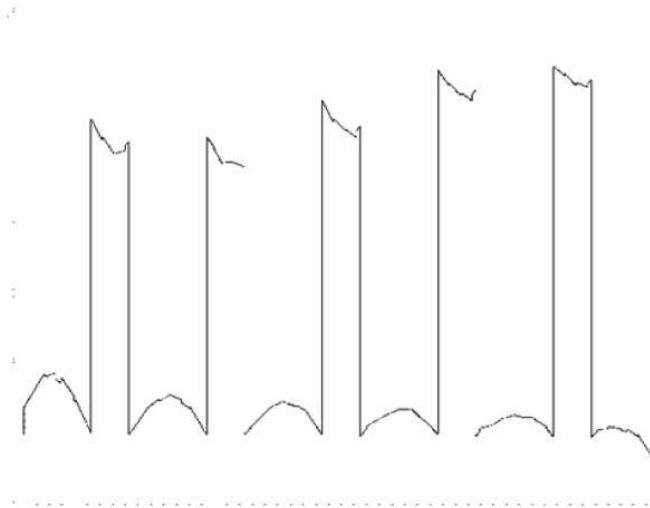

Figure 18. Flux density in the magnetic teeth

The final problem to consider in the design of the device lies in taking into account normal forces, F_1 and F_2, which act on the discs. These forces are calculated from the air gap surface and from the results of Figure 9. They are shown in Figure 19.

$F_1 = 130$ kN   low speed rotor   stator   high speed rotor $F_2 = 54$ kN

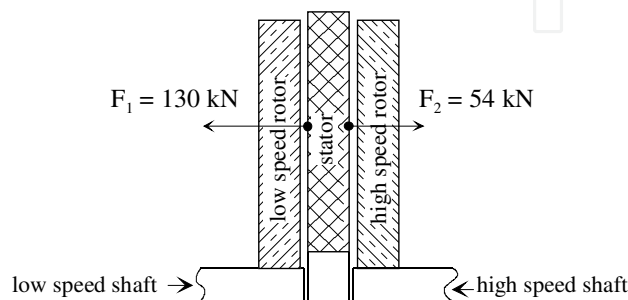low speed shaft →   ← high speed shaft

Figure 19. Normal forces

These forces are very high and are a major problem in bearing design. The axial force on the bearings is equal to the resultant force exerted on the stator, i.e. 76 kN. This problem exists in most discoid machines and hampers their development.

6. Stability in operation

The operation of the speed multiplier is of synchronous type, with no possibility of direct control, so there is a risk of stalling one rotor relative to the other. A precise study of this phenomenon is yet to be done (because, oddly, there is nothing definite on this subject in the bibliography). It goes without saying that this issue is delicate.

In the absence of a comprehensive study, the main solution to this problem in the design of the wind system is to monitor the electrical angle, ψ, between the magnetic fields from the two rotors through position sensors placed on the two shafts, or by indirect measurement through the voltage produced by a detection coil placed at the magnetic teeth.

When ψ tends to become greater than 90°, especially during rapid changes in the mechanical power from the wind turbine due to gusts, it is possible to influence the level of electrical power delivered by the generator in order to act on the dynamics of the driven load, allowing it to follow more easily the variations in speed.

However, the system becomes more stable as the maximum torque level transmitted by the multiplier is distanced from the maximum torque absorbed by the generator. This necessarily leads to oversizing of the speed multiplier.

The consequences of a possible stall are not really problematic for the intended application, provided that there is an electrical method of slowing down the wind turbine to allow mechanical braking or pitch control of the blades.

The addition of electrical conductors at the high speed rotor, intended to act as electrical shock absorbers and allowing the transmission of high asynchronous torque, makes the operation safer.

7. Conclusion

It has been shown that a system combining a magnetic speed multiplier and a high-speed generator is an interesting alternative to the use of a direct drive generator. The high performance level of the magnetic gear discoid structure allows the design of a more compact system with better efficiency.

In this context, despite its limited capacity in the transmission of torque, the magnetic speed multiplier has many advantages over its mechanical counterpart, but the cost will inevitably be higher because of the use of expensive materials.

The absence of maintenance of the magnetic device could nevertheless tip the economic balance towards the latter.

The magnetic gear discoid structure is particularly suitable for power levels of tens of kilowatts. The design made in paragraph 5, for a 10 kW wind turbine, confirms this. The same calculations show that a speed multiplier for a wind turbine of 40 kW (approx. 4000 Nm at 100 RPM), would have an external diameter of 800 mm, which is reasonable considering the mechanical structure.

For significantly higher powers, above 100 kilowatts, the design of a large diameter discoid structure becomes difficult, particularly because of the axial forces acting on the discs, according to what was discussed in Section 5. The solution is no longer economically viable.

At the opposite side of the power scale, for a wind turbine of a few hundred watts to several kilowatts, the use of a multiplier, mechanical or magnetic, is unwise. A structure of direct-drive generator, like that of Figure 10, for example, allows a more economical and more reliable design.

Magnetic gear technology is not yet fully developed and many of the mechanical problems in cylindrical or discoid design are yet to be resolved.

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