Design of a PM generator for the Turby®, a wind turbine for the built environment

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Abstract – **This paper describes the design, the design optimization and testing of a direct-drive permanent-magnet generator for a wind turbine for use in the built environment. The application in urban areas leads to additional design criteria such as good aesthetic appearance, low audible noise, low speed and good performance in complex winds. Therefore, a vertical axis wind turbine with a Darrieus rotor is used. A direct-drive permanent-magnet generator is used to obtain a high efficiency, a good robustness and low maintenance. The design is optimized using a criterion that minimizes a compromise of both generator cost and generator losses. Measurements confirm the good performance of the generator.**

I. Introduction

This paper describes the development of the Turby®, a 2.5 kW wind turbine for the built environment depicted in Fig. 1, and focuses on the design and performance of the generator system.

Wind energy in western countries develops in two directions. On the one hand, the market for large wind turbines is growing roughly 30 % a year. The power levels of these wind turbines are continuously increasing and currently 4.5 MW wind turbines are commercially available [1]. In this field, the main focus is on cost reduction and improving performance. On the other hand, the interest in integrating wind energy into the built environment is increasing [2], [3]. Here, besides decreasing cost and improving performance, factors like aesthetic appearance and building a green image are very important. The Turby® [4] depicted in Fig. 1 is a wind turbine in the second category.

The first aim of this paper is to describe why the Turby®, a 2.5 kW wind turbine for the built environment, has been developed and what design choices have been made. The second aim of this paper is to describe in more detail how the generator has been designed and optimised. The resulting performance will be described, both from calculations and from measurements.

The original contribution of this paper is that it describes the design, the design optimisation and the testing of a direct-drive generator for a small wind turbine for use in urban areas, with other requirements and characteristics than wind turbines for rural areas or for offshore.

Figure 1. Photo of the Turby®.

II. Description and Design Choices

Fig. 2, 3 and 4 illustrate the use of the Turby® in the built environment.

The fact that the Turby® is intended for use in the built environment led to the following requirements.

1. Aesthetic appearance.
2. Good performance in complex winds.
3. Low audible noise level.
4. Safe operation in urban environments.
5. Easy installation in the built environment.
6. Robust and maintenance-free.

These criteria led to the choice of a vertical axis wind turbine with a Darrieus rotor. The Turby® rotor blades have a constant diameter. Although the aerodynamic efficiency (the power coefficient) of a vertical axis rotor is generally lower than for a horizontal axis wind turbine, a vertical axis turbine is chosen, mainly because it looks more attractive.

A vertical axis wind turbine also has the advantage that it does not need a yaw mechanism which rotates the rotor blades of the turbine on the wind. This makes the turbine more robust.

When the aerodynamic rotor was tested, an additional advantage was observed: the rotor was not only able to extract energy from wind in all horizontal directions, but also from vertical components of the wind [5], [6]. This is very useful when installed e.g. on the roof of a building, where the wind often has vertical components and where wind speeds are often higher than in free space because the wind has to go around these buildings. In other words: this rotor is more suitable for complex winds.

The aerodynamic rotor has three blades. These blades are skewed with respect to the vertical axis for a smooth and silent operation; for constant wind, the torque is more or less constant. This helps reducing mechanical loads and obtaining low audible noise levels.

The most important issue in reducing audible noise is the reduction of the turbine tip speed. Therefore, the rotor was designed specially for a high aerodynamic efficiency at low speeds. At maximum aerodynamic efficiency, the tip speed ratio (ratio of tip speed over wind speed) is as low as 3.

The requirement of easy installation in the built environment (e.g., on office roofs and residential buildings) led to the choice of a power rating of 2.5 kW. For this power level, the turbine consists of some parts with manageable dimensions and weights (see table I).

For power levels of a few kW, it is of course possible to buy off-the-shelf generators and converters. However, these components are generally not optimised for this application and less efficient than specially designed generators. On the long term, mass production is foreseen, and then custom-designed components may also become cheaper than standard components.

It was decided to realize a dedicated generator system with good performance. This implies that variable speed is used to obtain the maximum aerodynamic efficiency and that a converter is needed for the grid connection.

To obtain a robust and efficient turbine with little maintenance, a brushless direct-drive PM generator was chosen. Using a direct-drive generator means no gearbox that might fail and needs lubrication. A PM generator has a good efficiency and has no mechanical contact between stator and rotor that wears.

The requirement of easy installation also led to the choice for a single-phase grid connection. Fig. 5 depicts the six-pulse diode bridge rectifier and a single phase PWM inverter used for the grid connection.

Table I. Turbine characteristics.

Rotor radius	1 m
Rotor height	3 m
Turbine weight (excluding tower)	90 kg
Rated power	2.5 kW
Rated speed	360 rpm
Tip speed ratio	3
Maximum aerodynamic efficiency (power coefficient)	0.3

Figure 2: The Turby® in an exposition.

Figure 3. The Turby® on the roof of an appartment building.

Figure 4: The Turby® on the roof of a flat from another position.

Figure 5. The converter for the grid connection.

III. GENERATOR DESIGN

Choices and starting points

As already mentioned in section II, it was decided to design a dedicated permanent magnet synchronous generator for this turbine.

To integrate the generator and the turbine, it appeared to be useful to use a generator with an outer rotor. At the bottom of the turbine, the blades are fixed to a rotating ring (see Fig. 1) with the rotor of the generator integrated.

NdFeB magnets are used because of their relatively low price and high energy product.

Low-loss laminations were used to obtain a good efficiency.

A single-layer winding is used in the stator.

To reduce cogging and to make it easier to start the turbine, the magnets are skewed over one slot-pitch and the stator slots are semi-closed.

The number of slots per pole per phase is chosen 1. Compared to machines where the number of slots per pole per phase is larger than 1, this leads to relatively thin yokes and a small risk of demagnetization. Compared to machines with a fractional pitch winding, (e.g., ¼ is often used as a number of slots per pole per phase in PM motors), this eliminates space harmonics that might lead to additional (eddy-current) losses in magnets and back-iron.

Control

Measuring wind speed is always a problem because of the wind complexity. Therefore, it is difficult to derive the power that has to be supplied to the grid from the wind speed. The rotational speed is much more useful for determining the power to be supplied to the grid. If this rotational speed is not optimal for the actual wind speed, the deviation in the power supplied to the grid forces the speed towards the optimal rotational speed. For example, when the rotational speed is higher than optimal, the power supplied to the grid is higher than optimal, and the turbine will slow down to the optimum.

Parameters

A set of equations has been derived that give the relations between the generator dimensions and the generator parameters. The machine parameters are calculated in simple and conventional ways [7], [8]. The following assumptions are used in the calculations.

- Space harmonics of the magnetic flux density distribution in the air gap are negligible, only the fundamental is considered.
- The magnetic flux density crosses the air-gap perpendicularly.
- The magnetic permeability of iron is assumed to be infinite.

Slot, air-gap and end-winding leakage inductances are calculated as in [8].

The effective air gap of the machine is calculated as

$$
\begin{aligned}
g_{eff} &= k_C g_1 \\
g_1 &= g + \frac{l_m}{\mu_{rm}} \\
k_C &= \frac{\tau_s}{\tau_s - g_1 \gamma} \\
\gamma &= \frac{4}{\pi}\left(\frac{b_s}{2g_1}\arctan\left(\frac{b_s}{2g_1}\right) - \log\sqrt{1+\left(\frac{b_s}{2g_1}\right)^2}\right)
\end{aligned}
\tag{1}
$$

where

k_C is the Carter factor [7,8],
g is the mechanical air gap,
l_m is the magnet length in the direction of the magnetization,
μ_{rm} is the relative recoil permeability of the magnets,
τ_s is the slot pitch,
b_s is the slot opening width.

The main part of the synchronous inductance can be calculated as

$$
L_{sm} = \frac{6\mu_0 l_s r_s (k_w N_s)^2}{p^2 g_{eff} \pi} \tag{2}
$$

where

l_s is the stack length of the machine perpendicular to the plane of the drawing,
r_s is the stator radius,
N_s is the number of turns of the phase winding,
k_w is the winding factor,
p is the number of pole pairs.

The fundamental space harmonic of the magnetic flux density in the air gap due to the magnets can be written as

$$
\hat{B}_g = \frac{l_m}{\mu_{rm} g_{eff}} B_{rm} \frac{4}{\pi} \sin\left(\frac{\pi b_p}{2\tau_p}\right) \tag{3}
$$

where

B_{rm} is the remanent flux density of the magnets,
τ_p is the pole pitch,
b_p is the width of the magnet.

The no-load voltage induced by this flux density in a stator winding can be calculated as

$$E_p = \sqrt{2} k_w k_{ws} N_s \omega_m r_s l_s \hat{B}_g \tag{4}$$

where

ω_m is the mechanical angular speed of the rotor.

k_{ws} is winding factor due to skewing, the skew factor.

The stator phase resistance is calculated from the dimensions of the machine, the number of turns in a slot and the cross-section of a slot:

$$R_s = \rho_{Cu} \frac{l_{Cus}}{A_{Cus}} \tag{5}$$

where

$$l_{Cus} = 2N_s (l_s + 2\tau_p) \tag{6}$$

$$A_{Cus} = \frac{p k_{sfil} b_{sav} h_s}{N_s} \tag{7}$$

k_{sfil} is the slot fill factor,

b_{sav} is the average slot width, and

h_s is the slot height.

Performance

If the turbine operates at a certain rotor speed, a certain amount of power has to be supplied to the grid. The no-load voltage induced by the magnets can be calculated with (4). It is assumed that the current of the generator loaded with a diode bridge rectifier is in phase with the terminal voltage. Especially at large loads, this is an optimistic assumption, because the current lags the terminal voltage. However, using this assumption, an easy indication for the current can be obtained.

The stator copper losses can then be calculated with

$$P_{Cus} = 3 R_s I_s^2 \tag{8}$$

The magnetic flux densities in the stator teeth and in the stator yoke are calculated as

$$\hat{B}_{Fest} = \hat{B}_g \frac{\tau_s}{b_t} \tag{9}$$

$$\hat{B}_{Fest} = \hat{B}_g \frac{\tau_p}{\pi h_{sy}} \tag{10}$$

With this, the stator iron losses are calculated as

$$P_{Fes} = 2 P_{Fe0} \left(\frac{f_e}{f_0} \right)^{\frac{3}{2}} \left(M_{Fest} \left(\frac{\hat{B}_{Fest}}{\hat{B}_{Fe0}} \right)^2 + M_{Fesy} \left(\frac{\hat{B}_{Fesy}}{\hat{B}_{Fe0}} \right)^2 \right) \tag{11}$$

where

P_{Fe0} is the iron loss per unit iron mass at the given angular frequency f_0 (50 Hz) and flux density B_0 (1.5 T),

M_{Fest} is the mass of the stator teeth,

M_{Fesy} is the mass of the stator yoke,

f_e is the frequency at the generator terminals,

b_t is the tooth width,

h_{sy} is the stator yoke height.

In this expression, the iron losses are assumed to be proportional to the frequency to the power of 3/2. Usually, iron losses are calculated as the sum of the hysteresis losses, which are proportional to the frequency, and the eddy-current losses, which are proportional to the square of the frequency. Taking the losses to be proportional to the frequency to the power of 3/2 is kind of an average approximation.

The factor 2 is included in this equation because the flux densities do not change sinusoidally and they are not sinusoidally distributed, which results in an extra increase of the iron losses.

IV. GENERATOR DESIGN OPTIMIZATION

Using these parameters, for each operating point of the turbine (depending on wind speed), the losses in the generator and the power supplied to the grid are calculated. Combination of this with the Weibull distribution of the wind (the fraction of time the wind has a certain speed for all wind speeds) leads to the annual energy supplied to the grid and the annual energy dissipated in the generator.

An optimisation program varied the dimensions in order to minimize the active material cost and to maximize the annual energy yield by minimizing the following criterion *C*:

$$C = C_{Fe} M_{Fe} + C_{Cu} M_{Cu} + C_{pm} M_{pm} - P C_E E_y \tag{12}$$

where

C_{Fe} is the cost of iron (3 euro/kg)

M_{Fe} is the iron mass

C_{Cu} is the cost of copper (10 euro/kg)

M_{Fe} is the copper mass

C_{pm} is the cost of magnets (20 euro/kg)

M_{pm} is the permanent magnet mass

P is a period (10 years)

C_E is the price of a kWh (0.1 euro) and

E_y is the annual energy yield (in kWh).

This criterion means that an additional investment in the generator efficiency (to increase the annual energy yield) has to be paid back within the period *P*. This period was taken rather long to obtain a good efficiency. A comparable criterion has been used in [9] for a generator for a wave energy converter and in [10] for an electrically excited synchronous direct-drive generator.

Fig. 6 depicts the stator and Fig. 7 depicts the rotor of the generator. Some of the resulting dimensions are given in table II.

Figure 6. The stator of the generator.

Figure 7. The rotor of the generator with skewed permanent magnets.

Table II. Some generator dimensions.

r_s	Stator radius	125 mm
l_s	Stack length	70 mm
p	Number of pole pairs	7
τ_p	Pole pitch	56 mm

V. CALCULATED PERFORMANCE

Fig. 8 gives some calculated characteristics of the generator as a function of the wind speed.

It is assumed that the controller controls the speed of the wind turbine. At low wind speeds, the turbine is switched off. From roughly 4 m/s up to 13 m/s, the controller keeps the rotor speed at the optimal tip speed ratio of 3 until the rated speed is reached (360 rpm). For higher wind speeds, the controller keeps the speed at roughly 360 rpm.

Fig. 9 depicts the Weibull distribution of the wind for an average wind speed of 7 m/s, the annual energy losses in iron and copper, the annual energy supplied to the grid, and the generator efficiency, considering only copper and iron losses. The Weibull distribution of the wind gives an indication of what part of the time there is a certain wind speed; the integral of this function over the wind speed is one. Combination of this distribution with losses and output power gives indications of the annual energy losses in copper and iron and of the annual energy supplied to the grid. By integrating the energy yield and energy dissipation over the wind speed, the total annual energy yield and the total annual energy dissipation of table III are obtained.

At high wind speeds, the copper losses are much larger than the iron losses. However, at the lower wind speeds that occur much more often, the iron losses are higher than the copper losses. This indicates that the choice for using low-loss laminations makes sense.

The sum of iron and copper losses is calculated to be well below 10% of the rated power in the most important part of the operating range.

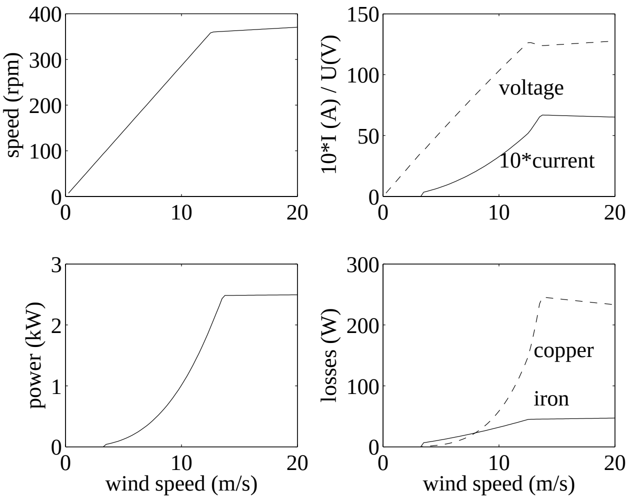

Figure 8. Generator speed, voltage, current, output power, and losses as a function of wind speed.

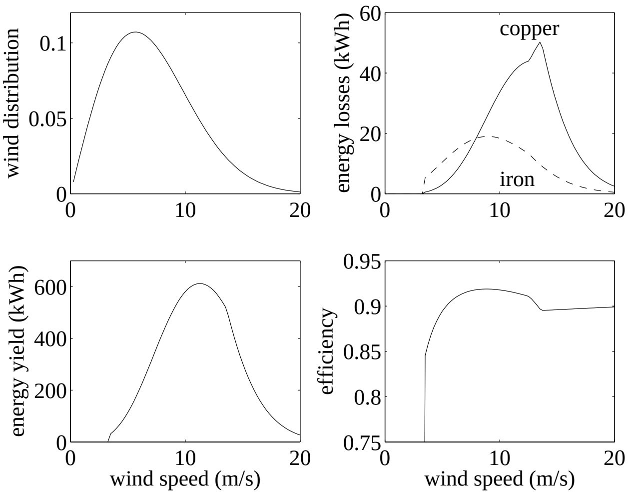

Figure 9. Wind distribution, annual energy losses, annual energy yield and generator efficiency as a function of wind speed.

Table III. Calculated annual energy.

Supplied to the grid	5200 kWh
Dissipation in copper	354 kWh
Dissipation in iron	170 kWh

VI. MEASURED PERFORMANCE

Figure 10 depicts measured phase current and line voltage waveforms of the generator loaded with a diode bridge rectifier and a large capacitor at slightly different speeds. One of the measurements is at a load of roughly 650 W, which is a typical operating condition. The other measurement is at roughly 3.3 kW, which is larger than rated. The measured voltage levels are lower than calculated because of a misalignment of stator and rotor, but that could easily be improved.

The measurement at 3.3 kW confirmed that the losses are so low that the generator remains rather cool. This implies that the generator could be built smaller, but it was chosen not to do that in order to have a good efficiency.

The inductance of the machine has such a value that the current properly commutates from one phase to another. It is not too large so that the current does not commutate within 60 degrees. It is also not too small so that the currents become rectangular current blocks, possibly resulting in additional (eddy-current) losses in the rotor.

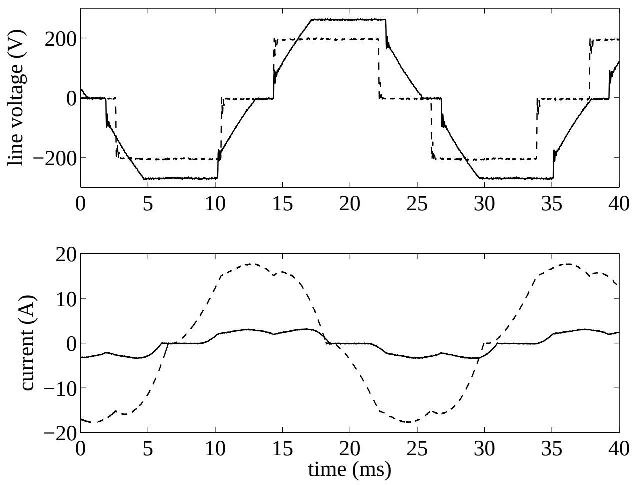

Figure 10. Measured line voltage and phase current at two different loads with a capacitor behind the rectifier.

VII. CONCLUSIONS

This paper describes the design, the design optimization and testing of a direct-drive permanent-magnet generator for a wind turbine for use in the built environment. The application in urban areas leads to additional design criteria such as good aesthetic appearance, low audible noise, low speed and good performance in complex winds. Therefore, a vertical axis wind turbine with a Darrieus rotor is used. A direct-drive permanent-magnet generator is used to obtain a high efficiency, a good robustness and low maintenance. The design is optimized using a criterion that minimizes a compromise of both generator cost and generator losses. Measurements confirm the good performance of the generator.

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