Impact of the design method of permanent magnets synchronous generators for small direct drive wind turbines for battery operation

Mihai PREDESCU, Dr. eng.*, Aurelian CRĂCIUNESCU, Prof. Dr.**, Andrei BEJINARIU, Eng.*, Octavian MITROI, Eng.*, Adrian NEDELCU, Eng.*

**ICPE SICE Centre, Splaiul Unirii 313, Bucharest,Sector 3, RO-30138, Romania.*
Emails: predescu@icpe.ro, andrei.bejinariu@icpe.ro , octavian.mitroi@icpe.ro
***University Politehnica Bucharest, Splaiul Independenţei 313, Bucharest, Romania,*
Email: acraciunescu@netscape.net

Keywords : wind turbine, synchronous generator, direct drive, battery, airfoil

Abstract. In stand-alone direct drive wind turbine power generators, working on battery, the permanent magnets synchronous generators is the most common solution. The system can be analyzed as the combination of three subsystems: wind turbine, electric generator and the load, which is the battery for energy storage. For high energy transfer from wind to the battery, those components should be designed in a particular way.

The paper approaches the impact of the component parameters of each subsystem on power transfer from wind to the load.

1 Introduction

The direct coupling of synchronous generator to the wind turbine raises some problems in matching the mechanical output characteristic of the wind turbine to the characteristic of the synchronous generator for maximum power transfer.

In this power transmission chain the synchronous generator can be somehow easier to trim for maximum power transfer.

The paper describes the design method and experimental work done on a small power wind turbine, 1kW rated power, with a 400Ah battery storage unit.

The description of the experiments work gives the results of tests on rare earth, permanent magnets synchronous generator, according to the design method.

2 Energy transfer in a wind system

The block diagram of a small stand-alone wind turbine power source is in Figure 1 .

The generalised architecture of the wind power source is in Figure 2 in which the energy flow through the three main components. The kinetic energy of the wind is converted by the wind turbine into mechanical energy, then by the synchronous generator into electric energy which is stored in different ways: electrochemical, chemical, kinetic or mechanical potential energy. From the storage system, the load takes the requested amount of energy, regardless of the wind availability. Each component in Figure 2 has its own non linear efficiency curve, depending heavily on the design and working regime. A wind system is designed in such way to ensure an acceptable level of energy availability to the load and to capturing and storing the maximum energy of the wind, with minimum investment. Every component of the system: turbine, generator and storage unit have an appropriate design method. There are two objectives of the designer: designing each component for achieving maximum efficiency/cost and matching the components in such a way that the maximum energy is transferred through the system.

Two of the three wind system components of the Figure 2, the turbine and the storage unit interact with the environment: the turbine with the wind and the battery with the load. The design of those two components depend on wind resources and the load profile, respectively. The electric generator links the turbine with the battery.

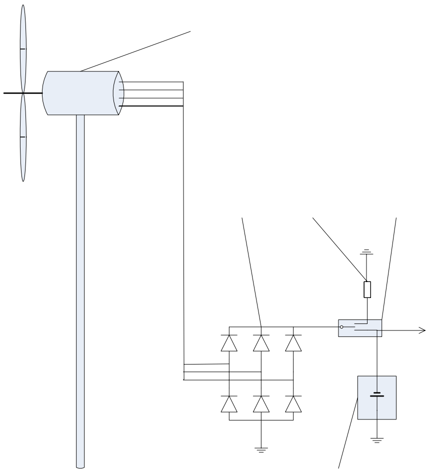

Figure 1-Architecture of a wind system

Therefore, the trimming of the energy chain for best overall efficiency can be easily achieved by an appropriate design procedure of the electric generator.

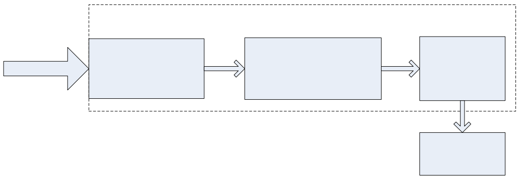

Figure 2 -Energy transmission chain

3 Optimal design of PM synchronous generator

A. Output power computation. Interaction with battery

For small wind turbines, direct drive permanent magnets generator is a common constructive solution for horizontal axis wind turbine. The old solution with mechanical speed multiplier is favourable for the generator that operates at high rotational speed. The dimensions are smaller and efficiency high. The mechanical multiplier, on the other hand, is a bulky piece of equipment which requires regular maintenance and it is a major source of failure.

The direct drive solution assembly is simpler, more reliable, but raises several design problems and needs a slightly different specific technology. In this case, the generator has large number of poles, and larger diameter. The cogging torque increases with the diameter of the generator, thus, special measures for diminishing this parasitic torque becomes very important.

The use of rare earth permanent magnets, due to their low price and high specific energy, improves the weight/power ratio of synchronous generators. Therefore, the method described refers to direct drive PM synchronous generators.

The design method is based on classic approach of the relationship between dimensions and transfer function of permanent magnets synchronous generators. The goal of the demonstration below is finding the parameters of the electric generator on which the designer can act upon for better matching the turbine and the load (battery) for maximum power transfer.
The phase electromotive force in a generator is computed as:

$$U_e = \frac{2\pi}{\sqrt{2}} w k_w \Phi \ f \qquad (1)$$

In which:

U_e-electromotive force;
w-number of turns of a phase winding;
k_w-winding factor;
Φ-pole magnetic flux;
f- frequency of the induced voltage.

$$f = n \cdot p \qquad (2)$$

n-rotational speed;
p-number of pole pairs.

From(1) and (2) we can define the voltage factor, k_f, as:

$$U_e = k_f n \qquad (3)$$

The k_f factor is constant parameter of a generator, depending on dimensions and materials used for constructing the generator. According to the simplified theory of synchronous electric generators, the phase equivalent impedance is:

$$Z = \sqrt{R^2 + X_s^2} \qquad (4)$$

In which:

R-winding phase resistance;
X_s-synchronous reactance.

The equivalent circuit is:

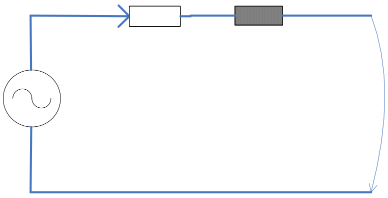

Figure 3-Equivalent circuit of PM generator

In which:

U_b-output DC voltage(battery voltage)
k_d- transfer coefficient of the rectifier bridge.

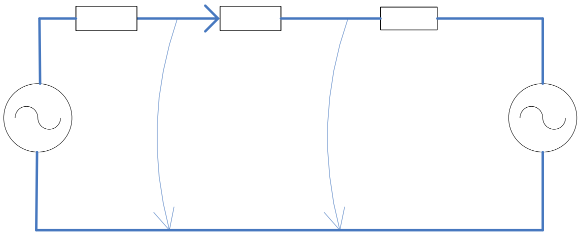

Figure 4 -Mono phase equivalent circuit

The computation of the power delivered to the battery by a AC generator can be explained on AC equivalent circuit of the generator-battery assembly, Figure 4 . The power injected into battery is:

$$P = m\frac{k_f \cdot \sqrt{3} \cdot n - U_b / k_d}{\sqrt{\left(\frac{R}{k_d}\right)^2 + n^2 k_s^2}} \frac{U_b}{k_d} \qquad (5)$$

$$k_s = \frac{X_s}{n} \qquad (6)$$

$$R = R_{cab} / kd + R_{bat} / kd \qquad (7)$$

In (5)-(7) we have:

P-active power;
m-number of phases of the generators-3;
k_s-synchronous reactance coefficient;
R_{cab}-Cable resistance;
R_{bat}-battery internal resistance.

B. Input power. Interaction turbine-generator Power curve of the turbine

For a designer it is very important to have a procedure for computing the power curve of the turbine or to have it measured in wind tunnel.
The computational method for output power curve *P(n)* at different wind speeds in the normal operating range of the wind turbine takes into consideration the following parameters:

a. the number of blades;
b. the airfoil profile of the blades;
c. the variation of the chord length along the blades;
d. the variation of the torsion angle of the blade along the length of the blade;
e. (the Reynolds number at different rotational and wind speeds).

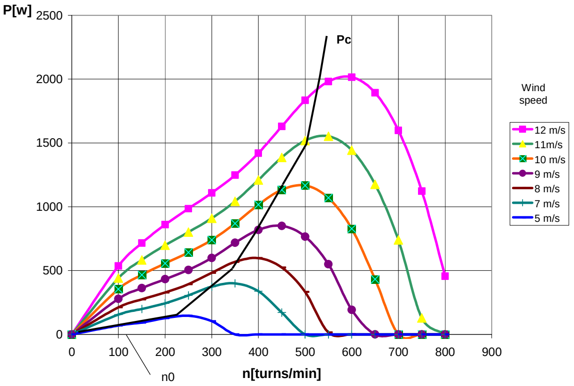

Figure 5-Sample of computed power curve of a small wind

For the specialists in aerodynamics of wind turbine, the power coefficient is computed in terms of tip speed ratio λ. For an electrical engineer is more common to have the power curve depending on rotational speed n which makes easier the connection with the phenomena within electric generator.

In Figure 5 is a computed power curve of a 1 kW wind turbine, using a developed procedure, which takes into consideration the above described parameters.

A good design of the electrical generator should have the input mechanical curve that links the peaks of the power curves at different wind speeds. That is the *Pc* curve in. In such manner, the wind turbine will extract the maximum available energy from wind. It is evident that the optimum designed generator should have the power curve fitted to *Pc*, in the operational wind speed range.
Another characteristic that should be considered in a design is that the generator starts injecting the power into the battery at a certain speed, n_0, at which the output voltage of the generator, eq. (1), equals the battery voltage, see Figure 5. In operation, the wind turbine speeds up until reaches n_0, during which the wind turbine is loaded only by frictional torque of the generator. Beyond n_0, the turbine is loaded mainly by the battery current. The speed n_0 cannot be lowered too much, because the number of turns of the winding will be very large, see (1), and it is impossible to make a generator with the power curve as described previously.

4 Design method of PM synchronous generator

The power curve *Pc* in Figure 5 can be approximated to a straight line on the most important region of the operating range of the wind turbine. Around nominal power, the power curve should approaches the line:

$$P(n) = k_f / k_s \; U_b / k_d (n - n_0) \qquad (8)$$

Equation (8) is the relationship of the power of the turbine with geometric characteristics of the generator (k_f, k_s) and the load (U_b).

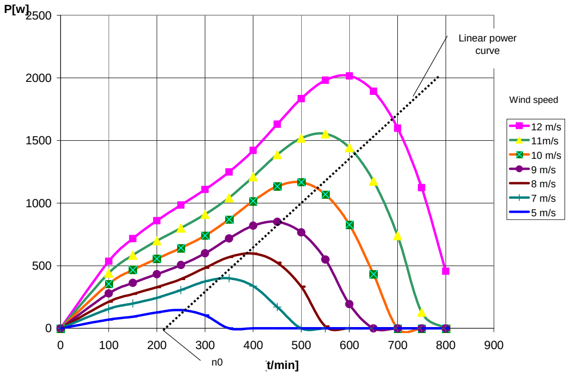

Figure 6-Approximation of generator power curve

Using the same output characteristics of the turbine as in Figure 5, and the approximated optimal curve (8) results the graphic representation in Figure 6.

The number of pairs of poles of the generator, p, is related to the maximum rotational speed of the generator in normal operation. For building the generator, the magnetic materials are the same as for usual electric machines. The magnetic losses are low and efficiency is kept high when the output frequency is not to much beyond 50Hz.

$$p = 3000 / n_{max} \qquad (9)$$

According to the method, the voltage factor is :

$$k_f = U_b / (k_d n_0) \qquad (10)$$

If the winding resistance R is much lower than the synchronous impedance X_s, the k_s coefficient is:

$$k_s = \frac{1}{n_{\max}} \left[\frac{k_f (n_{\max} - n_0)}{P_{\max} k_d \, 1/3} \right] \qquad (11)$$

The pole magnetic flux is :

$$\Phi = \frac{\sqrt{2}}{p} \cdot \frac{k_f}{w \cdot k_w} \qquad (12)$$

The inner diameter of the generator is given by (13):

$$D_i = \left(\frac{0{,}3 \cdot p \cdot 60}{\pi^2 B_\delta A \cdot n_N} \right) \qquad (13)$$

in which:

D_i– inner diameter;
B_δ– air gap magnetic field density;
A-total current;
n_N-rated turning speed(usually $n_N = n_{\max}$).

The length of the magnetic core can be computed using the known expression:

$$l_i = \frac{2 \cdot p \cdot \Phi}{\pi \cdot D_i \cdot B_\delta} \qquad (14)$$

C. Influence of the winding

Once the overall dimensions, D and l, of the generator, the number of turns of the winding, w, plays a crucial role for reaching the optimal power curve (8), described in Figure 6.

The relationship between synchronous impedance X_s and the number of turns of the winding, w, is:

$$X_s = k_r \cdot w^2 \cdot n \qquad (15)$$

In which k_r is a constant depending only on the geometry of the generator.

If the geometry of the cross section of the generator is established, together with the length of the magnetic core, then the resistance of one phase winding is:

$$R(w) = \rho \cdot \frac{2 \cdot (l_f + l_i)}{\varsigma \cdot p \cdot s_c} \cdot w^2 = R_0 \cdot w^2 \qquad (16)$$

In which:

ρ-copper resistivity;
l_f-length of front section of the coils;
s_c-area of the stator slot;
ς-fill factor of the slots.

Given the cross section of the generator, R_0 is a constant for the generator, having the meaning of the resistance of a coil with one turn. Also, the phase resistance of the winding depends on square of the number of turns (16).

Based on equivalent circuit in Figure 4, the power delivered to the battery is:

$$P(w,n) = U_b \cdot \frac{0{,}675 \cdot \sqrt{3} \cdot k_b \cdot w \cdot n - \dfrac{U_b}{k_e}}{\sqrt{(k_b \cdot k)^2 \cdot (w^2 \cdot n^2) + \left(\dfrac{k_b R_0 \cdot w^2 + R_b + R_{cab}}{k_e} \right)}} \qquad (17)$$

k_b-1 for half bridge rectifier or 2 for full bridge.

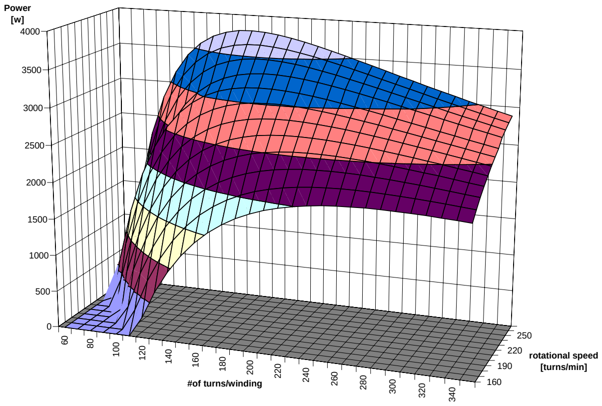

Figure 7-Output power vs. rotational speed and #turns/winding

In Figure 7 is the result of the computation of output power of a 3kW wind generator in relation to the winding (no of turns) and rotational speed. It is obvious that it is an well defined value of w for which the output power is optimum.

5 Experimental work

A. The problem

The methods described was used for designing a 1kW, 3 blade wind turbine, with rated wind speed 9,5 m/s. The wind turbine injects the energy in a 400Ah, 24V battery. The output characteristics of the wind turbine should fit the linear approximation in Figure 6.

Input data for the design method:

- Rated power: 1kW
- Rated wind speed: 9,5m/s
- n_0 220t/min
- Input power curve (linear aprox.):

$$P = 3{,}57 \cdot (n - n_0)$$

- Battery voltage: 24V
- Rectifier: 3 phase full bridge

B. The results

The geometry of the generator (see Figure 8) is:

Inner diameter:	157mm
Outer diameter:	230mm
Magnetic core length:	65mm
Number of pair poles:	8
Rare earth permanent magnets(N27H)	16

In Figure 8 is the cross section of the generator. Both stator and rotor are made of #0,5mm silicon iron using laser cutting machine. For prototyping it is cheaper to make the rotor in the same time with stator sheets.

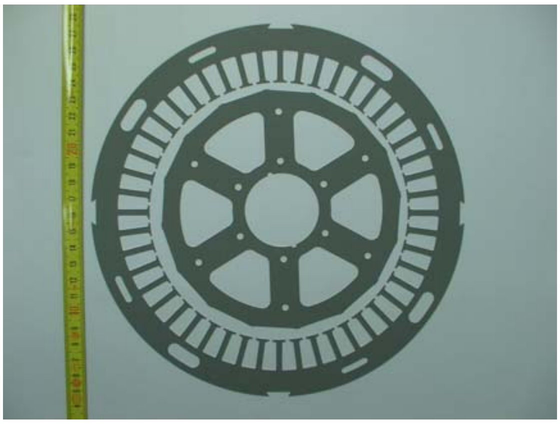

Figure 8-Magnetic sheets

In Figure 10 it is the experimental layout for measuring the power curve of the generators. The generator was tested using 12 batteries 2V, 400Ah seen in Figure 9.

Figure 9-Batteries used as load

Figure 10-Experimental layout

The Figure 11 is the measured input mechanical characteristic of the generator with load 24V battery. In the first region, at low turning speeds, the measured curve starts earlier than the linear approximation.

The starting turning speed n_0, depends on state of charge of the battery. At high turning speeds the measured curve becomes saturated and deviates from the approximated straight line.

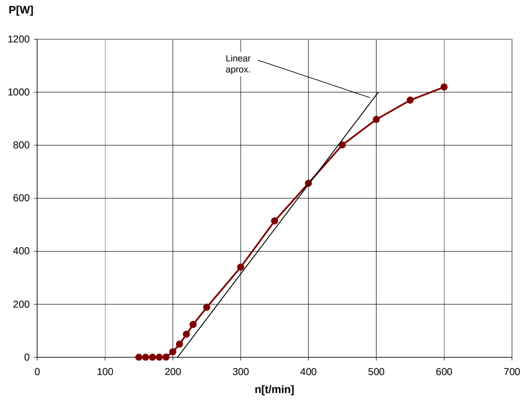

Figure 11-Measured output power curve of 1kW generator

6 Conclusions

The developed method for designing PM synchronous generators for low power direct drive wind turbine is based on the idea that the output mechanical characteristic of the turbine and the load should be matched by the electric generator. This concept comes from the fact that the turbine and the load (battery) are mainly conditioned by the environment (wind and load) and the generator is the linking piece between those two components that should play the role of trimming.
The method gives fairly good results for most of the operating range of the generator. Future refinements of the method could bring more accuracy in the results. Wind tunnel tests on turbines of different sizes could contribute to the validation of the concept.

References

[1]R.Gasch, J.Twele, Wind Power Plants, Solarpraxis, James&James-London
[2]G.L Johnson,Wind Energy Sytems, Englewoods kliffsm NJ 1985
[3]C. Bala, Masini electrice, Bucuresti, 1979-in Romanian