DESIGN OF SMALL WIND GENERATORS – GUIDELINES FOR AMATEURS

Lappeenranta–Lahti University of Technology LUT

Master`s program in Electrical Engineering, Master`s thesis

2022

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Examiners: Professor Juha Pyrhönen

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ABSTRACT

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76 pages, 43 figures, 8 tables, 1 appendix.

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Key words: Electric generator, axial flux, three-phase, low-speed wind generator, rotor Darrieus H-type, alternative energy, green energy, renewable sources, innovations, wind energy.

Master`s thesis is directed on detailed investigation of possibilities to build a small wind generator for domestic power supply application. The work contains two parts. The first part is a theoretical review of valid studies, related to household wind generators with comments based on the experience of the author. The purpose of the first part is to introduce typical parts of domestic wind generators, their calculation methods and selection logic for different components. The first part is aimed to help beginners to comprehend which type of wind generator is better for certain conditions. The second part’s purpose is a development of laboratory model of portable wind generator with an axial flux electric generator and a vertically oriented rotor for long hiking trips. The second part is a practical investigation of theory, given in the first part. Detailed ways for parameters calculation, physics explanation and assembling processes with visual accompaniment are given.

LIST OF SYMBOLS

Roman symbols

b	blade length	[m]
B_δ	magnetic flux density in airgap	[T]
B_r	remanence	[T]
c	blade chord	[m]
C	capacitance	[F]
d_{Cu}	stator winding wire diameter	[m]
d_{ws}	average diameter of stator coil	[m]
D_{mast}	wind turbine rotor mast diameter	[m]
D_{rot}	diameter of wind turbine blades	[m]
D_{avg}	average stator diameter	[m]
e	instantaneous back-emf	[V]
E_{nom}	phase rms of back-emf	[V]
f	electrical frequency	[Hz]
h_{yr}	thickness of rotor core	[m]
h_{ys}	thickness or stator core	[m]
h_{PM}	magnet height	[m]
h_{ws}	height of stator coil	[m]
F	Lorentz force	[N]
h_{rot}	wind turbine rotor height	[m]
H	magnetic field strength	[A/m]
I	current	[A]
l_a	active length of stator winding	[m]

l_{ws}	conductor length in one coil	[m]
l_{tot}	conductor length in phase	[m]
L_{ph}	phase inductance of stator winding	[H]
L_{ws}	inductance of one coil	[H]
n	rotational speed	[rpm]
P_{gen}	power of generator	[W]
P_{rot}	power of wind turbine	[W]
P_{air}	power of airflow	[W]
r	radius	[m]
r_{rot}	radius of wind turbine blades	[m]
r_{PM}	radius of permanent magnet	[m]
r_{yr}	radius of rotor	[m]
r_{ys}	radius of stator	[m]
$r_{ws.e}$	coil outer radius	[m]
$r_{ws.i}$	coil inner radius	[m]
R_{batt}	battery series resistance	[Ohm]
R_{ph}	phase resistance of stator winding	[Ohm]
R_{sll}	line-to-line resistance of stator winding	[Ohm]
S_{rot}	wind turbine rotor wind flow area	[m^2]
S_{Cu}	wire cross-sectional area	[m^2]
T	torque	[N·m]
U_{pb}	power bank (battery) voltage	[V]
U_{FT}	forward voltage drop on diodes	[V]
U_{rec}	voltage at rectifier output	[V]

U_{gen}	phase rms voltage at generator output	[V]
w_{PM}	width of magnet	[m]
w	wind turbine rotor width	[m]
X_L	inductive reactance	[Ohm]
X_C	capacitive reactance	[Ohm]

Greek symbols

δ_{eff}	effective airgap	[m]
δ	airgap	[m]
η_{gen}	efficiency of generator	[%]
θ_p	slot angle	[el.deg]
θ_m	angle between poles	[el.deg]
τ_p	pole pitch	[m]
v	wind speed	[m/s]
ω	electrical angular velocity	[rad/s]
Ω	mechanical angular velocity	[rad/s]
Θ	current linkage	[A/m]
Φ	magnetic flux	[Wb]

Constants

g	gravitational acceleration	9.81 m/s
ρ	air density	1.225 kg/m^3
μ_0	magnetic permeability	$4\pi\times10^{-7}$ H/m

Dimensionless quantities

c'	relative blade thickness
Re	Reynolds number
λ	tip speed ratio
q	number of slots per pole and per phase
C_p	power coefficient
C_T	torque coefficient
N	number of coil turns
Q_s	number of slots
$2p$	number of poles
p	number of pole pairs
k_w	winding factor
k_d	distribution factor
m	number of phases
z	blade elongation

Abbreviations

RPM	rotations per minute
RPS	rotations per second
DC	direct current
AC	alternating current
Nd	neodymium
AFPM	axial flux permanent magnet
RFPM	radial flux permanent magnet

TSR	tip speed ratio
HAWT	horizontal axis wind turbine
VAWT	vertical axis wind turbine

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1 Introduction

Nowadays mankind is facing probably one of the most significant problems through its whole history – enormous amount of carbon emissions into the atmosphere, which are still annually growing with unimaginable temps. Such a rapid increase in emissions is primarily due to the active use of fossil energy resources and growing consumption, which started to dramatically increase after the beginning of the industrialization era of the early 19th century. To extract energy for industry operation, people have learned to use fossil fuels – gas, oil and coal, which have proven their effectiveness due to cheapness, polished technological process of extraction and simplicity. However, together with all its seeming advantages, the use of such resources contributes to the development of a global catastrophe – it destroys the ozone layer of our planet, which carries a colossal problem that can result in the destruction of the planet and the deterioration of air quality to such an extent that the Earth will become uninhabitable.

From time immemorial, people have tried to use the energy of the sun and potential energy of water as energy sources, they have learned to convert the kinetic energy of water and wind flows into mechanical energy - the energy of rotation, which was involved, for example, in windmills for grinding grain. After the invention of electric generators in the 1830’s, the possibility of using wind energy to rotate electric machines became obvious, but at that time humanity was not yet aware of the problem of emissions, and fossil sources were cheaper, so people were in no hurry to increase the efficiency of solar energy and hydro power. In the middle of the 20th century, world leaders realized the seriousness of the coming consequences of burning fossil fuels and began to actively work on creating alternative energy supply routes and actively introducing other less harmful energy sources for the planet. This process led to the emergence of similar terms – Alternative Energy, Alternative Energy Sources or Renewable Energy.

One of the areas of research was the use of wind energy as the main source driving the rotor of an electric generator. Wind turbines have proven their effectiveness due to the clear principle of operation and high value of the efficiency coefficient. Now, the cost of using wind energy is falling dramatically along with ongoing research on optimizing processes in wind generation. Wind turbines have occupied a certain, significant niche in the global energy sector and the amount of electricity accounted for by wind turbines is growing every year. The active use of wind energy has also led to the popularization of wind generators among the world population, already now in developed countries most people know what a wind generator is, how it looks, and roughly understand the principle of its operation.

In 2022 world is on the threshold of a new energy crisis and this can cause serious anxiety among the population and cause great inconveniences. According to that, my project acquires an even more important meaning and can play a big role in stabilizing the situation. Enthusiastic engineers, inventors, scientists, craftsmen or just people who support green energy will be able to build their own domestic wind generators only by using this paper as a guideline

Efforts and time spent on the creation of your own wind turbine can easily pay off. Thanks to domestic wind generator with a capacity of 1 kW, it is possible to heat a room of 10 m^2 daily, while saving a considerable amount of money and contributing to the planet`s health. The cost of 1 kWh of household electricity in Finland in July 2021 is 0.17 Euro (Clausnitzer, 2021). However, the stock price has varied strongly during this winter and the peak prices have been close to 1000€/MWh.

If we expect the heater in the room works 18 hours a day in the cold season then for the whole season the cost of that kind of pleasure will exceed 400 euros, while the cost of assembling a 1 kW wind generator is about the same. That will allow the investment to pay off in less than a year even without taking into account the subsequent increase in electricity prices.

Working on the creation of my first wind turbine, I faced a big problem – the information needed was inaccurate, unverified and very different from source to source. Choosing the topic of my master's thesis, which in one way or another would be related to wind energy, I decided to create my own manual, a guide that would help people like me quickly find access to reliable and complete information related to the construction of a wind generator. My paper is primarily aimed on researching existing types of domestic wind turbines, reviewing various designs and types of wind turbines, comparing their pros and cons in relation to each other, assembly and calculation tips based on personal experience. Also, a concrete example of the assembly and testing of the optimal design of a wind generator with a Darrieus H-type rotor and a single-phase axial electric generator.

2 Review of possible constructions for domestic wind generators

The market of household wind generators offers a huge number of different models and types of various shapes and sizes. A wind generator usually consists of three equally important parts that should be paid attention to and treated with reverence for their design – an electric generator, a rotor and a power supply (rectifier and battery) for on-grid work. Before starting the process of creating a wind generator, the designer faces an important task – to determine the type of turbine rotor that will be used in the wind generator, as well as the type of electric generator that will convert wind turbine rotational energy into electricity. Usually, a turbine is selected first, and then, based on the aerodynamic characteristics of the rotor, an electric generator and a power supply are sized. However, it works only if the demand on the electric energy is not stated. If wind generator is created to serve one certain purpose and electric capabilities are defined, it is smart to design a generator and size a turbine to it. According to my own observations, people are often very limited in budget, and it is not always possible to choose between types of electric generators. Inexperienced designers do not size turbine and electric generator at all, which is often reflected in insufficient speed or weak torque developed by the wind generator, and as a result it does not work at full capacity or does not work at all.

To build a reliable and, most importantly, powerful wind generator, it is necessary to know exactly and understand well all possible shapes of rotors and types of electric generators and calculate the parameters of the rotor-generator as a pair based on finances, environmental conditions and available tools and equipment. As a rule, any type of electric generator can be paired with any type of rotor, however, the size and electrical characteristics (such as rated rotation speed, required torque, developed power and voltage) must be carefully selected for each specifically selected model. For example, a modified Automotive Alternator can be paired with a low-speed, but high-torque Savonius rotor, but a gear box will be required.

In this chapter, the main available types of electric generators and rotors will be considered, tips on their modifications and the processing and assembly process will be given, the necessary equipment will be provided. A critical review of mistakes from amateur articles in Internet will be given.

2.1 Calculation tools

Calculation processes for all kinds of wind generators do not differ too much. Basically same formulas can be used under the design of vertical or horizontal wind turbine with only small changes. In the chapter general formulas are given and a calculation example of wind generator is presented.

2.1.1 Basic equations

To build an effective wind generator, it is necessary first of all to analyze the wind speed in a specific area, determine the average annual and maximum wind speed, as well as its direction characteristic of a given territory. These parameters will directly affect the maximum achievable power of the wind generator.

> "Since Finland is located in the zone of westerly air disturbances, there are great variations in air pressure and winds, especially in winter. In the whole country, the wind blows most commonly from the southwest and least commonly from the northeast. The average wind speed is between 2.5 and 4 m/s inland, slightly higher on the coast and 5 to 7 m/s in maritime regions. Wind speeds are typically highest in winter and lowest in summer." (Finnish Meteorological Institute. 2017)

The wind speeds given above are measured at the height of 10 m. It means that forests are strongly limiting the wind speed. Domestic wind turbines, therefore, rarely have a place favourable for high wind power yield. However, according to Finnish Meteorological Institute, in Finland we can consider 5 m/s wind speed as an average, however it is always possible to make own research and define average wind speed by simply following weather forecasts every day. In the best case you might have an anemometer to measure the wind speeds in the location planned for the turbine.

Power of air flow can be considered as:

$$P_{\mathrm{air}} = \frac{\rho v^3 S_{\mathrm{rot}}}{2} = T\Omega \tag{1}$$

where ρ – air density (typically ρ = 1.225 kg/m^3), v – wind speed [m/s], S_{rot} – wind flow area towards the blade front plane [m^2], T – mechanical torque [N·m], Ω – mechanical angular velocity [rad/s].

The formula states, that the power of a wind generator depends on the wind speed in the third power and on the blade length in the second power. Double wind speed will increase power by a factor of eight and double length of horizontal turbine blades will increase power by a factor of four.

When wind meets any obstacle (in our case obstacles are blades), it brakes and a space air gap in front of obstacle is created. Another portion of wind bumps into the air gap and moves aside without affecting the blades. The useful percentage of wind that acts as a lifting force for blades is defined by power coefficient of wind turbine. Maximum value of turbine power coefficient is limited by Betz limit, which theoretically reaches the value of C_{p} = 16/27 = 0.59 (Grogg, 2005). Also, the efficiency η_{gen} of an electric generator itself should be taken into account (Galuschak et al, 2019). According to that, the power of wind generator can be found by:

$$P_{\mathrm{gen}} = \frac{\eta_{\mathrm{gen}} C_{\mathrm{p}} \rho v^3 S_{\mathrm{rot}}}{2} \tag{2}$$

The tip speed ratio of a wind turbine can be considered as:

$$\lambda = \frac{\Omega r_{\mathrm{rot}}}{v} \tag{3}$$

where Ω – rotor angular velocity [rad/s], v – wind speed [m/s], r_{rot} – radius of rotor blades [m].

Turbine tip speed ratio rated values are usually chosen in the range of 5-6 for a three-blade horizontal wind turbine. With formula (3) the speed of the turbine can be calculated $\Omega = \lambda v / r_{\mathrm{rot}}$. Torque of the wind turbine is calculated simply by power division on mechanical angular velocity:

$$T = \frac{P_{\mathrm{rot}}}{\Omega} \tag{4}$$

Figure 1 states that the highest turbine power coefficient in general can be reached with three-blades horizonal wind turbine, however, it is not always wise to use that kind of topology.

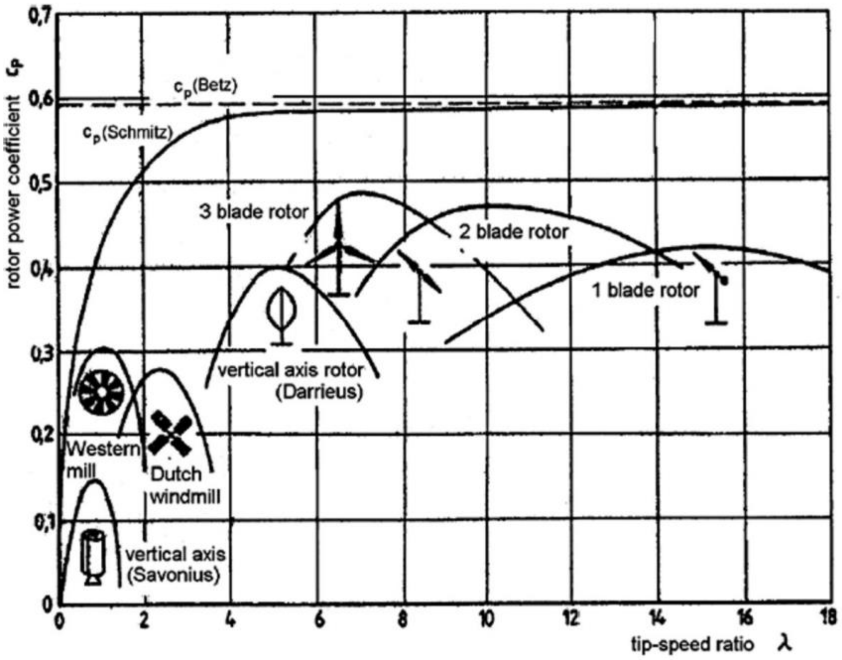


Figure 1. Rotor power coefficients for different types of rotors. (Stiebler, 2008)

As it was mentioned before, power dramatically increases with increasing wind speed, but it is not wise to consider wind will blow all the time with a constant speed. That is why it is usually a great idea to have a domestic power storage to keep your energy saved. Usually, it is smart to have a couple of spare batteries to be able to store energy and charge more than one accumulator simultaneously during periods when the wind speed happens to be high.

2.1.2 General calculation example

As an example, a three-blade horizontal rotor is considered. Turbine tip speed ratio $\lambda = 5$ is chosen and according to Figure 1 $C_p = 0.4$ (typically, good tip speed ratio for a three-blade horizontal rotor is in the range of 6-8, but here design's inaccuracy is taken into account).

Efficiency of electric generator depends on the type, construction and assembling quality, but it is taken $\eta_{gen} = 0.9$ as the highest possible in a low-power domestic application – three-phase axial flux generator. In Figure 2 using formula (2) different scenarios of power values depending on the wind speed and turbines diameter are shown.

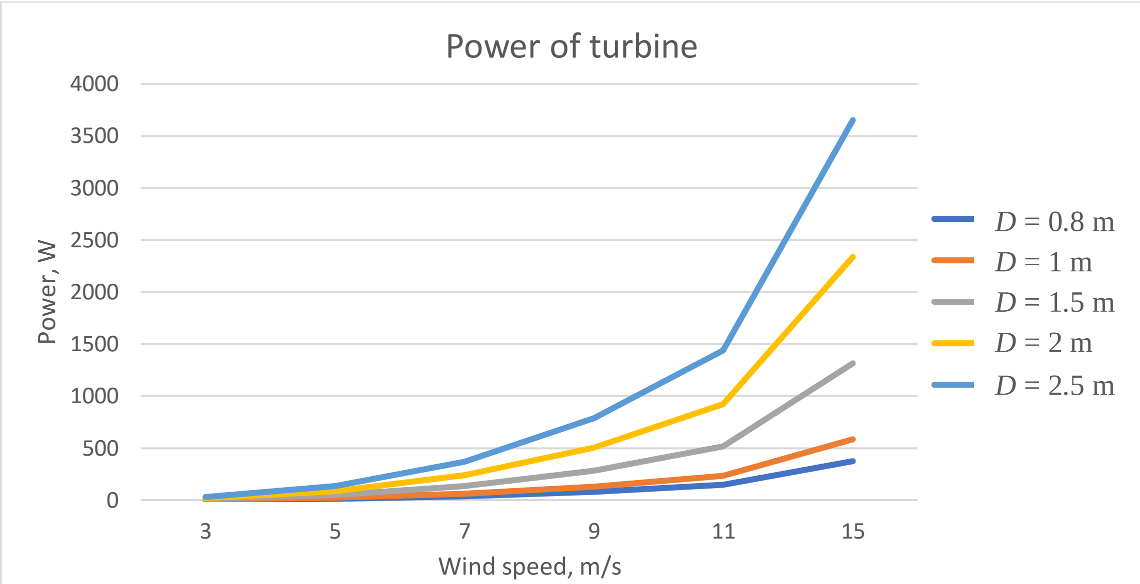


Figure 2. Dependence of power on wind speed and three-blade turbine diameter. (Galuschak et al, 2019)

For wind turbine rotor with diameter D_{rot} = 2.5 m, 1 kW is reached at wind speed v = 9 m/s (Table 1). To reduce the required wind speed for obtaining the same power, further wind turbine diameter increase is required.

Table 1. Power dependence on wind speed with three-blade horizontal turbine having rotor diameter of 2.5 m

Wind speed v, m/s	3	5	7	9	11	15
Power P_{rot}, W	29	135	371	789	1440	3651

In order to select a correct type of generator, turbine speed must be known. According to formula (3) wind turbine speed can be calculated. Table 2 shows turbine speed depending on different wind speeds:

Table 2. 2.5 m diameter turbine speed dependence on wind speed

Wind speed *v*, m/s	3	5	7	9	11	15
Rotational speed *n*, rpm	115	191	268	344	420	573

Now after turbine diameter and power are known, electric generator can be sized. There is one necessary requirement for electric generator – it must be capable of operating at the maximum available power of the turbine rotor within working speed range without overloading. If generator`s power exceeds the turbine’s power at nominal point, the generator will break the rotor too effectively because of the electromagnetic torque generated and as a result rotor’s rotational speed will be reduced. The feature can be used to control turbine after reaching nominal speed to control overvoltage.

2.2 Selection of electric generator

Electric generator is one of the most important parts in a wind turbine. Correct selection of its type directly affects the power and efficiency of the whole installation. In domestic use the generator of the wind turbines must provide output voltage higher than the voltage of a battery. Available and most common types of batteries have voltage equal either 12 V, 24 V or 48 V, and after rectification generator must induce voltage slightly higher than these levels depending on which battery is going to be used. Suitable levels are 14 V, 28 V, 56 V.

2.2.1 Automotive Alternator

The chapter refers to study of Ani, Samuel Ofordile, “Small wind power generation using automotive alternator”, Renewable Energy, 2014, p. 185-195 (Ofordile et al, 2014).

In modern vehicles, alternators are used as electric generators (Figure 4). Most of them use the principle of interaction of the rotating magnetic field of the rotor and the stationary field of the armature, i.e. they are synchronous generators in terms of construction. For field excitation a simple single round coil is embedded in claw-shaped magnetic circuit halves (Figure 3). Typically, vehicle generators induce 14 V starting at 3000-4000 rpm and maintaining it until the maximum speed of the generator, which can be 20000 rpm, is reached. In a car there are electrical controllers used for keeping voltage value suitable. Typically, there is a step-up pulley (e.g. 1:3 step up) drive to reach suitable speed for the generator at all running speeds of the ICE. The generator must provide 14 V already at idle of the ICE. If idling takes place at 1000 rpm and the pulley gear ratio is 1:3 the generator must start delivering 14 V already at 3000 rpm. According to data presented in the previous chapter, a wind turbine typically operates at quite a low speed and using an automotive alternator needs a high step-up gear system. The gear ratio must be at least e.g. 1:10. Such a high gear-ratio system may have a very low efficiency. A V-belt system is not recommended. Instead, e.g. a multiple V-belt or a toothed belt can be used to improve efficiency

(a) (b) (c) (d)

Figure 3. Car alternator construction: a) Three-phase stator (armature) arrangement - side view; b) Stator arrangement – internal view; c) Claw-pole rotor core and excitation winding embedded between claw poles; d) Generator frame (Autocar-inspection blog, 2020)

The selection of an alternator for application in a wind turbine can have following advantages:

- Availability – automotive alternators are used everywhere across the globe, and it is easy to find either new or used ones almost for free;
- Reliability – alternators, that were specially designed for vehicle application possess high robustness and great performance in severe conditions;
- Design – there is no need to search for any special details and think about assembling part because everything is ready;
- Purpose – automotive alternators are created for charging batteries as they have an in-built excitation controller and a diode bridge to provide DC output.

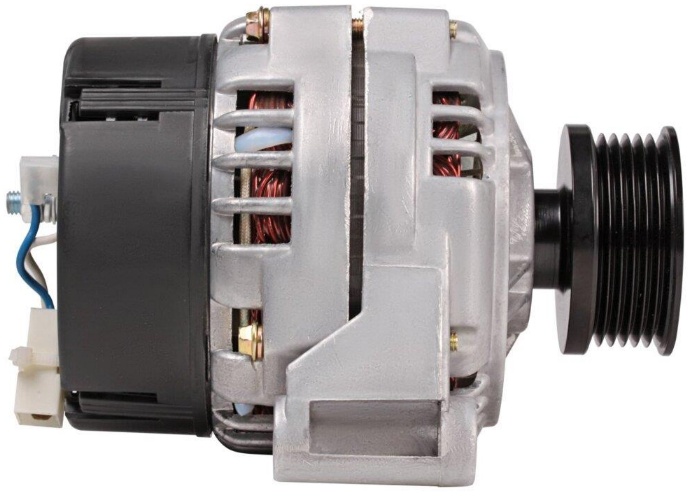


Figure 4. Car synchronous generator. (Samarins automobile journal, 2021)

In order to use an automotive alternator in a wind turbine application it must be optimized. Figure 5 shows electrical connection schema for car alternator. When ICE is not running, rotor winding (7) is supplied by battery (1) via indication lamp (3) and slip rings (8). When engine starts, battery excitation is turned off by switch (2) and generator goes to self-excitation mode via embedded three-diodes (5). Battery is charged via three-phase bridge rectifier (4). The same connection schema can be used if not willing to rebuilt generator.

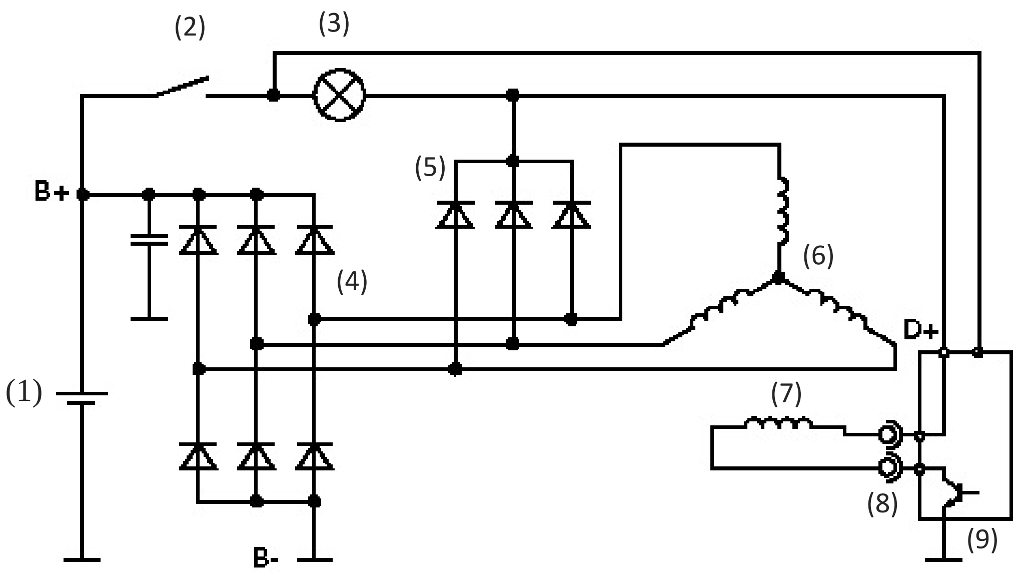


Figure 5. Car alternator excitation schema (Bengamin, 2005)

The controller (9) regulates the rotor excitation current in a way that the voltage at the stator terminals does not exceed a value of 14 V, depending on rotation speed of generator and connected load, the controller reduces or increases the values of the excitation current. In case when designer decides to keep an internal controller, connection is performed according to the same scheme as in the car. In case of regulator is being removed, the excitation winding is powered by a suitable value of current via a DC power supply. Using this method, it is possible to apply advanced control functions that allow loading the generator depending on the current rotation speed. According to the observations of And, Samuel Ofordile (Ani et al, 2014), exceeding the excitation current values of 3.5 A does not give a significant increase in power.

2.2.2 Squirrel cage induction motor conversion to a PMSM equipped with Nd magnets

One of the best and most appropriate types of electric machines for domestic wind turbines are squirrel cage asynchronous motors. The induction motor can be used as a generator itself if it can be connected to grid. If no grid is available, the induction generator can operate also as a self-excited generator by using suitable excitation capacitors in parallel to the motor. However, controlling the excitation is difficult and needs a suitable power electronic controller. It is, of course possible to adjust the self-excited induction generator by varying the capacitor values step by step and therefore get an output voltage that is close to the desired values. The excitation current of an induction generator can be roughly determined with the power factor of the motor. If $\cos\varphi = 0.8$, then $\sin\varphi = 0.6$ and the capacitors should provide the rated current times $\sin\varphi$ to excite the machine. The capacitor impedance is $Z_C = 1/(j\omega C)$ and therefore the capacitance C must be selected close to a value where $I_C = U_{ph}\omega C$ matches with the induction machine excitation current. For example, if 2 A excitation current is needed at U_{ph} = 230 V, about 28 μF capacitors should be needed to excite the machine.

The induction machine can also be modified to a permanent magnet generator using neodymium magnets. There is a variety of methods for rebuilding an asynchronous motor. The most popular and effective method consists of milling the rotor in a lathe to arrange a free space for rotor surfaced magnets, gluing the magnets onto the rotor according to a pre-

prepared template, and possibly rewinding the stator with less turns to lower the voltage to a suitable level. Without rewinding the modified generator will offer e.g. 230 V phase voltage. If the original winding is kept the rotor number of PM poles must match the stator number of poles.

Let us consider first the operating principle of a squirrel cage asynchronous motor. The rotor winding looks like a squirrel cage, and basically it is a cylinder mounted on a shaft. This cylinder consists of electrotechnical steel laminations with slots for cage bars made of highly conductive material, usually aluminium. Bars are connected to each other by an aluminium ring at both ends and are placed in cavities at a certain angle along the rotor axis (skewed rotor). Skewed position of bars reduces noise and minimizes torque fluctuations under variable load. The stator consists of windings placed in slots made of electrotechnical steel laminations. Three-phase alternating currents in stator windings create an alternating magnetic flux that rotates at a certain speed determined by the frequency f of the current and the number of pole pairs p of the machine. The speed in revolutions per second is $n = f/p$. Rotor in turn rotates at a slightly different speed. Due to the fact that in motoring the rotor is lagging the stator field, EMF e is induced in the bars according to the law of electromagnetic induction:

$$e = -k_{\mathrm{w}} N \mathrm{d}\Phi/\mathrm{d}t \tag{5}$$

where e – instantaneous electromotive force [V]; $\mathrm{d}\Phi/\mathrm{d}t$ – is a change of magnetic flux in the coil through the period of time; $k_w N$ – effective number of coil turns. Current, interacting with stator magnetic field is subjected to Lorentz Force, which rotates the shaft:

$$\mathrm{d}\boldsymbol{F} = i\mathrm{d}\boldsymbol{l} \times \boldsymbol{B} \tag{6}$$

where $\boldsymbol{F}$ – Lorentz force [N], i – current through the conductor [A], d$\boldsymbol{l}$ – length vector of conductor [m], $\boldsymbol{B}$ – magnetic flux density vector [T].

In typical IMs the air gap flux density follows about sinusoidal pattern with peak value of 0.8 T. When the torque production is considered, every conductor experiences its own Lorentz force, and the torque is produced by the forces of all possible conductors in the system. If the current in a conductor is 1 A and the flux density is 0.8 T and the length of the conductor is 0.1 m the force affecting the conductor is 1 A × 0.8 Vs/m^2 × 0.1 m = 0.08 VAs/m = 0.08 J/m = 0.08 N. If there are e.g. 100 turns in a slot the total force caused by the conductors in that slot is 80 N. One must keep in mind that, in practice, in different slots the conductors experience a different flux density. Therefore, calculating the final torque from the Lorentz force sentence is a challenging task.

Permanent magnet generators are reliable, highly efficient and do not require high rotational speeds to produce high power (Farooqui, 2012). Such generators do not have an excitation winding on the rotor, instead magnets with their permanent magnetic field excite the machine. The stator also consists of electrotechnical steel laminations with windings placed in slots. This arrangement of the stator and rotor resembles an asynchronous motor in terms of structure: no slip rings, no brushes and no physical contacts between rotor and stator, and that is why it can be converted into a permanent magnet generator. Rotor with permanent magnets according to the electromagnetic induction law (4) will induce back-EMF in the stator windings, as a result – electricity will be generated. Magnetic flux is a surface integral of magnetic flux density and the area it flows through. If the flux density is sinusoidal with certain peak value $\hat{B}_\delta$ of airgap, formula takes the following shape:

$$\Phi = \frac{2}{\pi}\hat{B}_\delta S \tag{7}$$

where $\hat{B}_\delta$ ⁀ – magnetic flux density peak scalar value, S – common cross-sectional area of coil and magnet. The fraction $\frac{2}{\pi}$ comes for the average value of sinusoidal flux density.

According to that, we obtain final formula, which allows to calculate emf of the generator (Pyrhönen, 2008):

$$e = k_w N \frac{2}{\pi}\hat{B}_\delta S\omega \tag{8}$$

where $K_w N$ – effective number of coil turns, ω – electrical angular velocity of rotor [rad/s] ($\omega = p\Omega$), $\hat{B}_\delta$ – peak scalar magnetic flux density in airgap [T] (0.6 – 1.0 T depending on magnets type and machine geometry), S – cross-sectional area of machine magnetic pole [m^2] (pole pitch times the machine length). The RMS voltage E is found as $e/\sqrt{2}$.

The number of poles in a PMG is simply the number of magnets (or groups of magnets with the same polarity). Magnets with N & S polarity are set next to each other, and the number of magnet poles must always be even. Usually, three phase-systems are utilized in PM systems, and there must be at least three coils on each pole pair in the generator. It means, that in case of distributed winding, with one pole pair system there must be at least six slots on stator, with two pole pairs – twelve stator slots etc.

It is possible to use the original IM in a way that the winding is replaced by a low number of turns and the number of poles is therefore maintained. In such a case the original rated synchronous speed of the motor dictates the number of poles. A 3000 rpm motor has two poles, 1500 rpm four, 1000 rpm six etc. If the slot number is suitable for a higher pole number, it can be used as the stator yoke will be large enough for any pole number equal or larger to the original one.

After finding a suitable type of asynchronous motor with appropriate number of stator poles or slots, it is possible to rebuild the machine into a PMG with desired number of poles. It is clever to keep in mind that if the original winding is used the machine can produce a low voltage value at a low speed which might suit for the wind turbine user. For example, in the original IM rated speed is 1500 rpm, it operates with 23 V phase voltage at 150 rpm which might suit well for a domestic wind turbine application. In this case, the original winding can be used and only the rotor needs to be modified to have four permanent magnet poles. Typically, the PM poles can cover 80 % of the rotor surface.

It is also necessary to consider height of permanent magnets h_{PM} to obtain desired value of magnetic flux density in airgap. The current linkage of PM Θ_{PM} can be found using following equation:

$$\Theta_{\mathrm{PM}} = H_{\mathrm{c}} h_{\mathrm{PM}} \tag{9}$$

where H_{c} – coercivity of permanent magnet.

Typical value of coercivity for PM is $H_{\mathrm{c}} = 800$ kA/m. A 6 mm magnet therefore gives Θ_{PM} = 4800 A. If the magnet length and physical airgap together are 8 mm and the effect of the iron circuit + 1 mm we get the average field strength H = 4800/0.009 = 533 kA/m. Magnetic flux density is therefore can be found using below stated equation:

$$B = H\mu_0 \tag{10}$$

where μ_0 – magnetic permeability of vacuum, equals to $\mu_0 = 4\pi\times10^{-7}$ H/m

In the airgap this field strength creates $B_\delta = 0.67$ T. As a result, varying height of the permanent magnet, desired magnetic flux density can be obtained.

If the machine winding is to be rebuilt, the required materials are copper wire of matching cross-section (or several parallel thinner wires), a set of NdFeB magnet (high remanence B_r and coercive force H_c), epoxy resin, super glue and glass-fibre or duct tape. Here is a sequence of actions for successful conversion:

1. Disassembling of Induction Motor (Figure 6):
   a. Remove rear cover and cooling fan (usually it takes some efforts).
   b. Unscrew front cover.
   c. Using a flat screwdriver, pull out front cover with rotor.
   d. In order to take off bearings, special equipment is required, but it is not necessary for rotor milling in a lathe, because bearings can remain untouched during milling. The alternative way is to mill a similar dimension rotor made of normal construction steel and replace the whole rotor
2. Rotor manufacturing:
   a. Define the height of magnets h_{PM} with the above given equations.
   b. Mill either the original rotor in a lathe according to suitable height of magnets h_{PM} + 1 mm as a spare space (spare height is defined by the form and sizes of magnets). Alternative option is to produce a solid rotor core, but that can be more expensive.
   c. Aluminium bars can either be removed or kept inside rotor. Removing of bars affects slightly higher performance. But rotor slotting somewhat reduces the PM flux in the machine and therefore it is recommended to make a new steel solid rotor.

Figure 6. Disassembling of an Induction motor (own photo). a) – Stator; b) – Cooling fan cover; c) – Cooling fan attached to rear cover; d) – Front cover; e) – Rotor.

3. Magnet arrangement:

    a. According to existing number of stator poles, the number of magnet poles are selected (Figure 7). Either the original number of poles is used, or the machine is wound to have a new number of poles.

    b. Then a template for attaching magnets is needed and one has to be prepared.

    c. First magnets are fixed with superglue to keep them in their position.

    d. After magnets are fixed, duct tape or rather glass-fibre tape is wound on the magnets and epoxy resin is poured inside to keep the magnets attached on the rotor.

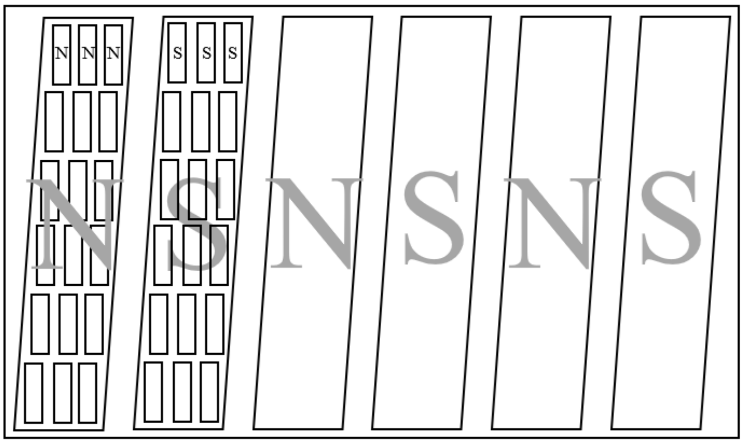


Figure 7. Example of six-pole magnet arrangement. Small 10×5×6 mm^3 magnets are placed in a skewed position to quench torque fluctuations.

4. Stator winding rearrangement in case of one slot per pole and phase q = 1:

   a. All previous windings are removed from stator slots.

   b. Slots are divided into groups, six slots in each group. Each group of slots consists of 3 windings, which intersects with 2 magnets of different poles (Figure 8).

   c. Windings of each phase are connected in series phase windings can have wye- or delta-connection. Wye-connection is preferable because of the possibility to vary voltage.

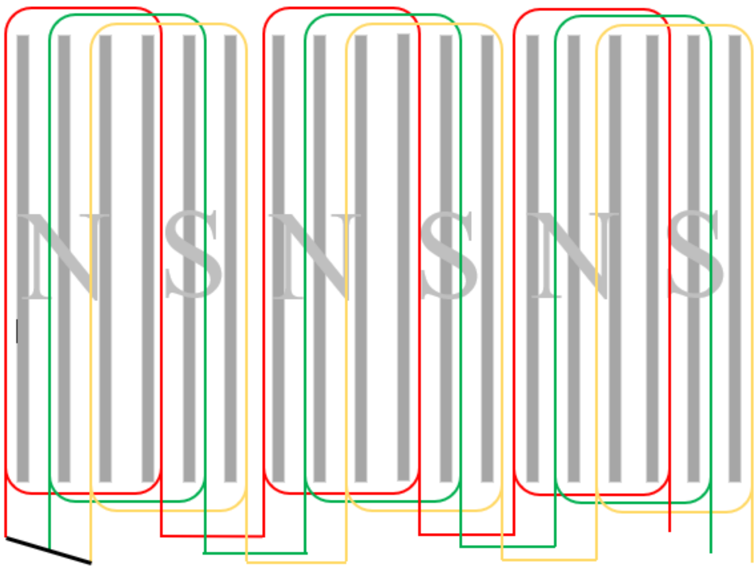


Figure 8. Windings arrangement for 18 stator slots, wye-connection.

After epoxy is dried (usually takes 24-48 hours), machine is assembled and tested.

2.2.3 Small axial flux permanent magnet generator

Axial flux generators with permanent magnets (AFPM) are considered to be one of the best options for smallest domestic wind turbines. Their operation principle is based on the interaction between permanent magnets attached to rotor and stator winding, which do not necessarily require an iron core for coils because of the specific magnet placement – north pole magnets are facing south pole magnets on the opposite side and create axial magnetic field so the stator yoke is unnecessary (Garrison et al, 2008). The flux path is depicted in Figure 9.

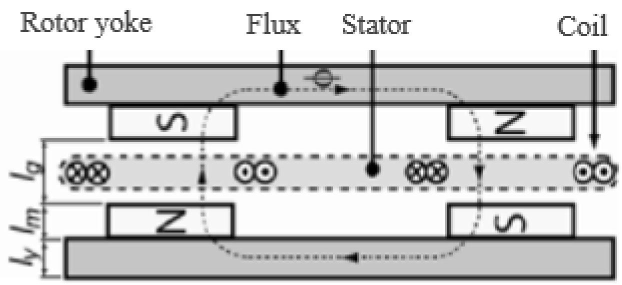


Figure 9. Axial magnetic flux path. (Garrison et al, 2008)

Both rotors have a steel yoke, but the armature can operate without a steel yoke. The air gap gets long. The magnetic air gap in this construction is a sum of the magnet heights ($2h_{PM}$) and the distance between the magnet surfaces. According to the drawing (Figure 9) the total air gap is in the range of $4h_{PM}$. As a result, the air gap flux density will be close to 50% of the PM remanence ($B_r/2$). The thickness of the yoke must be about 25% of the PM width w_{PM}.

Usually, small wind turbine designers prefer to use that kind of generator because of the possibility of direct coupling without any transmissions. That topology reduces the overall size and weight of the whole installation, eliminates gear-box losses as well as reduces excitation losses because magnetic field is excited by permanent magnets. Cost of the AFPM nowadays has decreased dramatically because of the lowering cost of NdFeB magnets during latest decade. The generator allows to avoid gear-coupling because it can operate with the rated speed from 200 to 600 rpm and develop frequency in the range of 25-70 Hz (Chan et al, 2007). Most of the stator arrangements are coreless, which simplifies turbine`s launch because of the absence of cogging torque. Diameter-to-length ratio is high, and it allows for better cooling for the machine. Typical industrial machine topology with slotted stator is depicted in Figure 10. Such a generator includes parts that need to be manufactured industrially. The only possibility to use such a machine in a domestic conversion application is to find the mechanical parts ready.

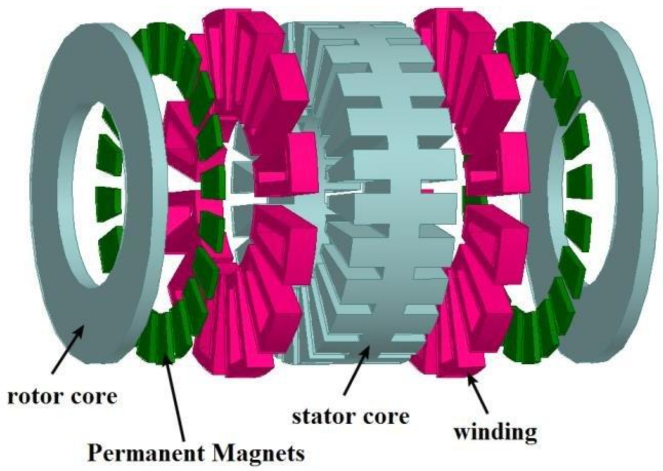


Figure 10. Axial Flux Permanent Magnet Generator with double-sided rotor and one stator (Taran et al, 2014).

Basic rotor and stator arrangement can be single- or double-sided. Single-sided rotor topology has a lower value of torque density and that is why double-sided topology is preferable for rotor application (Aydin et al, 2004). Stator windings can either be placed in stator slots, wound on the stator yoke (air-gap winding) or simply formed and drowned in epoxy resin without a yoke (Figure 11). All these arrangements take place and have their own pros and cons according to domestic power supply application. Winding coils drowned in epoxy resin is a preferable choice in terms of manufacturing – this is the simplest option which does not require any specific skills and equipment, moreover cogging torque is absolutely absent because of the slotless construction.

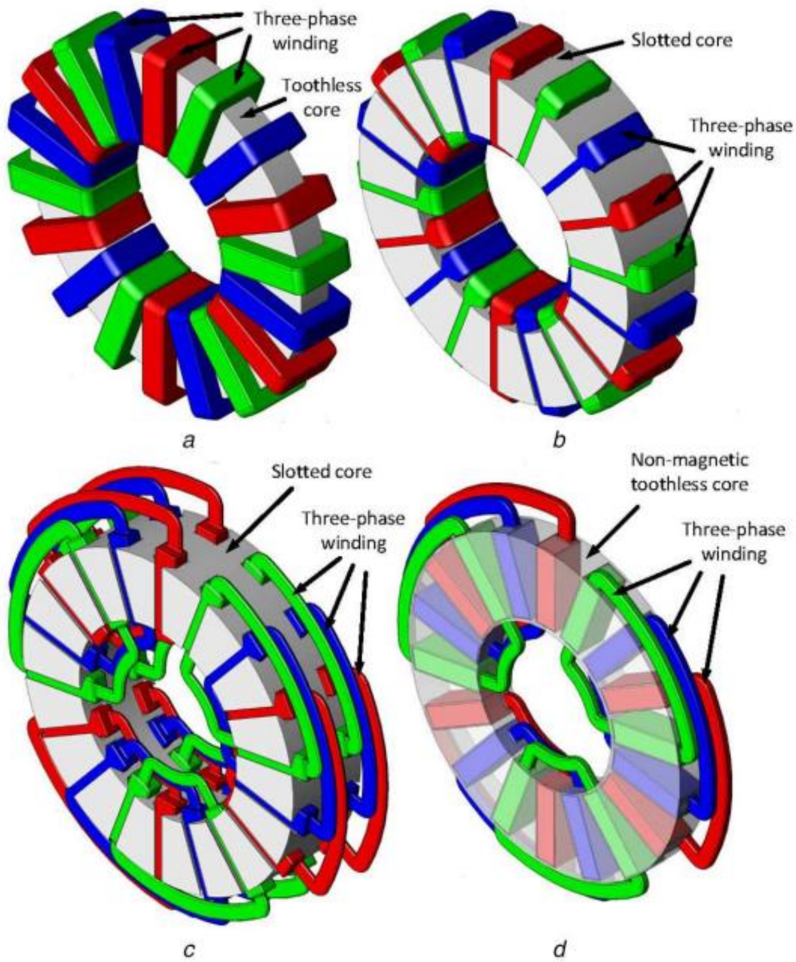


Figure 11. Possible stator winding arrangements for a double-rotor single-stator axial-flux generator: a) – slotless air-gap coils wound on stator core. b) – coils wound on core with slots. c) – slotted core with coils placed in slots. d) air-gap winding coils drowned in epoxy resin (Ghaheri et al, 2020).

Typically, stator winding is a three-phase one, but in small installation served as battery chargers (5 V) single-phase topology can take place because of the complexity and higher losses of three-phase bridge rectifier compared to one-phase bridge. In domestic Power Supply installations using single-phase windings connection will lead to increased noise and less voltage availiability.

Three-phase winding can be wye- or delta-connected (Figure 12) depending on the load type. In most cases domestic wind turbines work for battery charging via rectifiers and wye-connection is preferable.

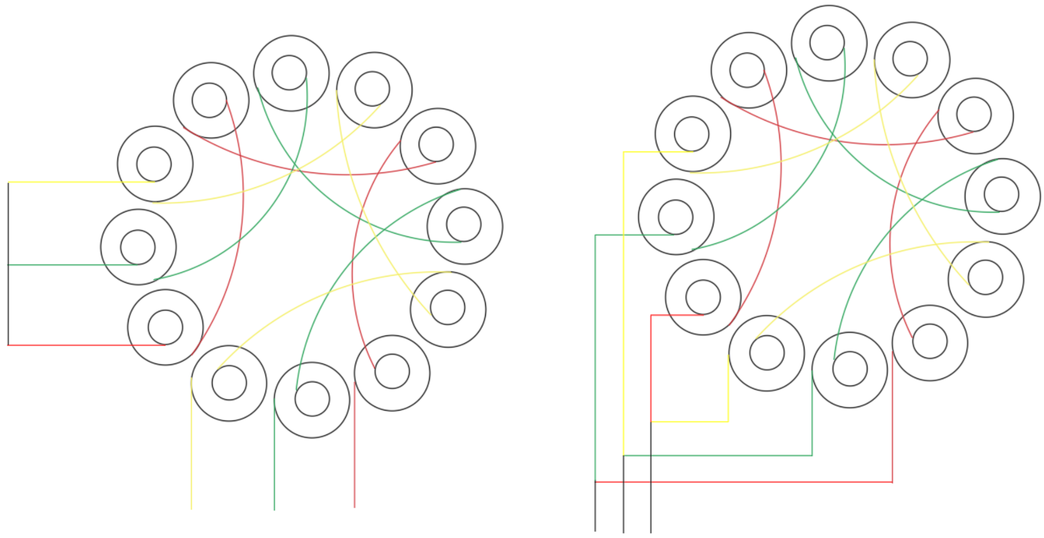


Figure 12. Wye- and delta-connection for three-phase single-sided non-overlapped stator.

According to the study of F.G.Rossouw (Rossouw, 2009), the peak EMF induced in stator of the AFPM is expressed by formula:

$$e = 2\sqrt{2}Q_s k_w N B_\delta r_{avg} l_a 2\pi n/p \tag{11}$$

where Q_s – number of coils per phase, $k_w N$ – effective number of turns in coil, B_δ – maximum magnetic flux density in airgap [T], r_{avg} – average radius of stator winding [m], l_a – active length of stator winding [m], n – machine`s rotational speed [rps], p – number of pole pairs.

In order to design an effective construction, a couple of requirements must be met. The shape of magnets has to be rectangular, and the coils are to be pulled in triangle form because in that arrangement magnetic field is distributed more evenly, which allows to increase intersection area between coils and magnets. Stator suspension can be either printed on 3D printer or formed with epoxy resin. Both ways do not affect the efficiency of the generator, but 3D-printing technology allows to more conveniently and reliably provide slotting for stator windings.

Assembling tips:

1. The most important thing is to size the rotor and stator. 3D-modelling in CAD systems allows to make a precise sizing and match virtual model with the physical one. It is further explained how to make precise 3D model and all the assemblies and couplings.

2. Coil windings can be made manually or with a help of special winding installation. Using special equipment is highly recommended because it allows to make more accurate windings and consequently improve current and voltage waveforms, but it is possible to make windings also with the simplest hand-drill.
3. Magnets must be surfaced on a ferromagnetic disk (rotor yoke) in order to improve the compatibility of magnetic flux of opposite magnets (see Figure 8). Usually, steel disks with glue form a sliding path and the permanent magnets will easily move towards each other. That is why it is recommended to use super glue and make special grooves on the disk surface for magnets if possible.
4. Wire connection can be done by simply twisting or by soldering. Soldering is advised if the wind generator is going to be used in severe conditions (for example – portable wind generators which are always moved from one place to another).
5. Try to avoid glue connection wherever possible (except magnets-to-yoke connection) because such an option allows to dissasemble the rotor and check problems under malfunctions.

2.3 Selection of rotor

Discussions about the most efficient type of rotor`s shape have been held since the first wind generator was created. Nowadays, there is a large number of different types and models of rotors. They differ in shape, size, efficiency and application purposes. The choice of blades still remains the most important task which is faced by designer of domestic wind generator. Considering high-power wind turbines exceeding hundreds of kilowatts, the choice obviously falls on the most popular three-blade horizontal rotors, which have the highest power coefficient comparing to other models. However, it should be noticed that industrial wind turbines have a large amount of additional equipment, which greatly assists the operation of the turbine. Sophisticated wind orientation systems, voltage stabilizers, multi-level transmissions of the highest quality with service personnel - this luxury allows horizontal turbines keep the rank of the most popular type among existing ones. However, the design of a household wind turbine is not much like the designs of industrial wind turbines in terms of scale and complexity, usually designers are aiming to construct the simplest and the most reliable installation, often with a limited budget and lack of time for constant maintenance, and in this case other models can compete with horizontal wind turbines.

Power characteristics, such as power coefficient, torque and torque coefficient can be defined by the following equations:

$$C_{\mathrm{p}} = \frac{P_{\mathrm{rot}}}{(1/2)pSv^3} \tag{12}$$

$$T = 60P_{\mathrm{rot}}/2\pi n \tag{13}$$

$$C_T = \frac{T}{(1/2)pSv^3D} \tag{14}$$

Blade type selection for domestic wind generators first of all must be based on the fundamental factors such as current wind speed and its direction. As it was mentioned previously, almost all electrical generators are compatible with any types of wind turbines, however, some features like availability of materials, presence of necessary equipment and possibility of home-assembling play sufficient role in rotor`s type selection.

The review of basic and the most popular types and shapes of wind turbines is presented in that chapter. Their general features, advantages and drawbacks as well as assembling methods and calculation ways are described using scientific articles and personal experience. This part will bring the full comprehension about the shapes and forms of rotor for the designer and will bring data about rotor selection based on the necessary parameters and assembler’s possibilities.

2.3.1 Darrieus rotor

Darrieus rotor – low pressure lift-force-based turbine with rotating axis perpendicular to fluid flow (in case of wind generation – perpendicular to the wind flow), consequently referred to the vertical axis wind turbine (VAWT). General advantage of that type of turbine is an independence on the wind flow direction. Darrieus turbine is considered to be a compromise between Savonius rotor and horizontal axis wind turbine (HAWT) because it is able to withstand high rotational speed with sufficient torque value.

General advantages of Darrieus type rotor:

- Darrieus rotor is characterized by relatively high tip speed ratio under small wind speed.
- Rotor`s operation is independent on flow direction and that is why Darrieus does not require any orientation systems, which are making construction more complex and bulkier.
- Relatively low noise level because of the uniform wind distribution on the blades with high rotation speed.
- Darrieus rotor possesses high power coefficient (which means high power coefficient, C_p), that might be even comparable to horizontal axis wind turbines.
- Rotation axis is an axis of mast.
- Some model’s construction appear to be the simplest one and does not cause any design and manufacturing troubles while prepared and assembled.

Under all claimed advantages, Darrieus rotor also has significant disadvantages, and design process must be done very accurate:

- Mast is subjected to high stress level because of the Magnus effect (Seifert, 2012), and that is why it requires durable and reliable materials and rugged design. One might say that Darrieus is not suitable for large turbines at all.
- Absence of full and accurate mathematical model of rotor`s aerodynamic behaviour, which complicates the design process and forces to rely on empirical data.
- Mass distribution limits efficiency and increases the stress on mast, which is reflected in short lifespan of moving mechanisms.
- No starting torque for conventional type.

There are three basic types of Darrieus wind turbines: helicoidal, traditional and H-type orthogonal (Figure 13)

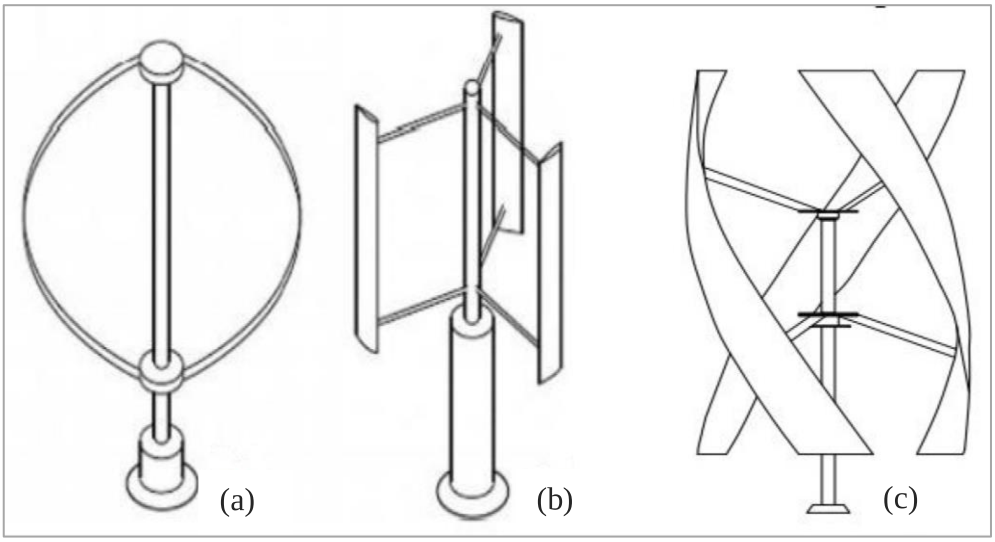


Figure 13. Basic types of Darrieus Rotors (Wind turbine catalogue, 2015):
a) – Conventional Darrieus; b) – H-type Darrieus; c) – Helicoidal Darrieus

Darrieus H-type orthogonal rotor seems to be the most promising option for domestic wind turbine application because of the reasonable ratio of cost to complexity (Figure 13 b). Straight blades of airplane wing's profile are mounted in parallel on rotation axis at some distance from it using traverses. That type of rotor is simple to manufacture, great in energy characteristics and can compete with horizontal types.

M.A. Singh in his study "Investigation of self-starting and high rotor solidity on the performance of a three S1210 blade H-type Darrieus rotor" (Singh et al, 2015)proves that H-type Darrieus rotor can develop a high starting torque with correct selection of *h/D* ratio.

Torque coefficient in that study is expressed through height h_{rot} and diameter D_{rot}:

$$C_T = \frac{4T}{\rho v^2 h_{\mathrm{rot}} D_{\mathrm{rot}}^2} \tag{15}$$

$$C_{\mathrm{p}} = \lambda C_{\mathrm{T}} \tag{16}$$

He claims that the highest possible $C_{\mathrm{p}} = 0.32$ is reached with 5.7 m/s wind velocity and $h/D = 1$ with S1210 (traditional drop-shaped) profile of blades.

In the study of Gorelov D.N. "Review of energy characteristics of Darrieus rotor" energy characteristics of blades are investigated. Geometrical characteristics, such as h_{rot} – blade height, b_{rot} – blade chord, c_{rot} – blade thickness and r_{rot} – rotor radius are used to obtain optimal ratios of blade elongation z, relative blade thickness c', number of blades in one tier n_b, fill factor σ, which is the ratio between sum of all blade chords to the circumference along which they move, and the angle of installation of the blade ϕ.

$$z = l_{\mathrm{rot}}/b_{\mathrm{rot}} \tag{17}$$

$$c' = c_{\mathrm{rot}}/b_{\mathrm{rot}} \tag{18}$$

Reynolds number Re is a coefficient that helps to predict flow character is fluid dynamics:

$$Re = \Omega rb/v \tag{20}$$

where υ – kinematic air viscosity, equal to $\upsilon = 15.06 \cdot 10^{-6}$ m^2/s at 20℃.

In the study Gorelov investigated an ideal H-type Darrieus rotor, which is a rotor consisting only of blades and having neither a traverse nor a shaft (mast). The wind power coefficient of an ideal rotor is determined by the useful work of some blades without taking into account the losses introduced by the traverse, shaft and other elements of the wind wheel design. This virtual model can be studied theoretically in the framework of the nonlinear theory of the unsteady flow of an ideal incompressible fluid around a system of profiles rotating around a common axis with a given angular velocity. Currently, this task has not yet been solved. But the ideal Darrieus rotor can be studied experimentally, if the method of conducting the experiment allows you to allocate the useful power developed by the blades alone. The known results of systematic tests of orthogonal wind wheels were used to select the rotor parameters at which the C_p coefficient limits can be expected to be reached.

Based on the results of experiments, he achieved a model of a single-tier rotor with three straight blades placed between two parallel disks rigidly attached to the shaft. For an ideal rotor with parameters $\sigma = 0.3$, $z = 7$, $c' = 0.18$, $n_b = 3$, $\phi = 0$ the value of the coefficient $C_p = 0.72$ was obtained, which was higher than the previously known experimental data for all types of wind wheels, including the limit value $C_p = 0.593$ for an ideal propeller-type wind wheel. Such a high value of the power coefficient for an ideal Darrieus rotor, which exceeds the C_p limit value of a propeller-type wind wheel, he explained by the fundamental difference in the mechanism of torque generation between these wind wheels. These values, however, can be used for design of household wind turbine rotor to achieve maximum power coefficient.

The torque of a propeller-type wind wheel is created by the lifting forces acting on the blades. At the same time, the flow of the medium around the blades does not differ much from the stationary one. And around the rotor blades of the Darrieus rotor the flow of the medium is essentially non-stationary and is similar to the flow near the flapping wing of birds. Such a non-stationary flow generates a thrust force on the blades, which creates an aerodynamic torque (Gorelov, 2009). In that study the effect on the power coefficient of different geometrical parameters were also presented.

Wind turbine with H-type Darrieus rotor still remains the most mysterious type among the present kinds, but it also has the highest number of options for modifications and that is why it keeps being attractive for domestic wind generators enthusiasts.

2.3.2 Savonius rotor

Savonius rotor is a vertical axis drag-based wind turbine. As opposed to Darrieus lift based type, Savonius rotor rotates because wind is “pushing” blades forward around hub. The main advantages are high starting torque and independence on the wind direction. However, rotor cannot rotate faster than the wind speed and that is why it is characterized with relatively low rpm. Basically, turbine is represented by two semi-cylindrical surfaces (blades), which are mounted on the mast perpendicular to wind flow direction. Because of the inherent structure, wind generator with Savonius turbine cannot rotate with a speed higher than wind flow and much of the wind is crushing to the blades and does not participate in energy conversion. That is why turbine has the lowest power coefficient among existing types of VAWT and HAWT. The big advantage of Savonius is that it can be easily built at home while e.g. the Darrieus blades may be difficult to acquire.

In contrast to Darrieus type rotor, the mathematical model of Savonius rotor is well known and described in many papers, for example in the study of Bubenchikov A.A. “The study of aerodynamics and power characteristics of Savonius rotor” (Bubenchikov et al, 2016). He says that for aerodynamic investigation of Savonius averaged by Reynolds Navier-Stokes equations for uncompressible fluids are used. Application of the equations allows to research features of unsteady flow, structure of velocity fields and vortex processes around the rotor.

One of the most popular studies are directed on the improvement of Savonius rotor by changing its construction. Because of the simplicity of traditional Savonius type rotor there are many opportunities to develop its construction from adding additional blades to curving and twisting the blades in order to achieve more steady flow (Figure 14). Even Darrieus rotor, having an absolutely different rotation nature, was based on the Savonius type of rotor.

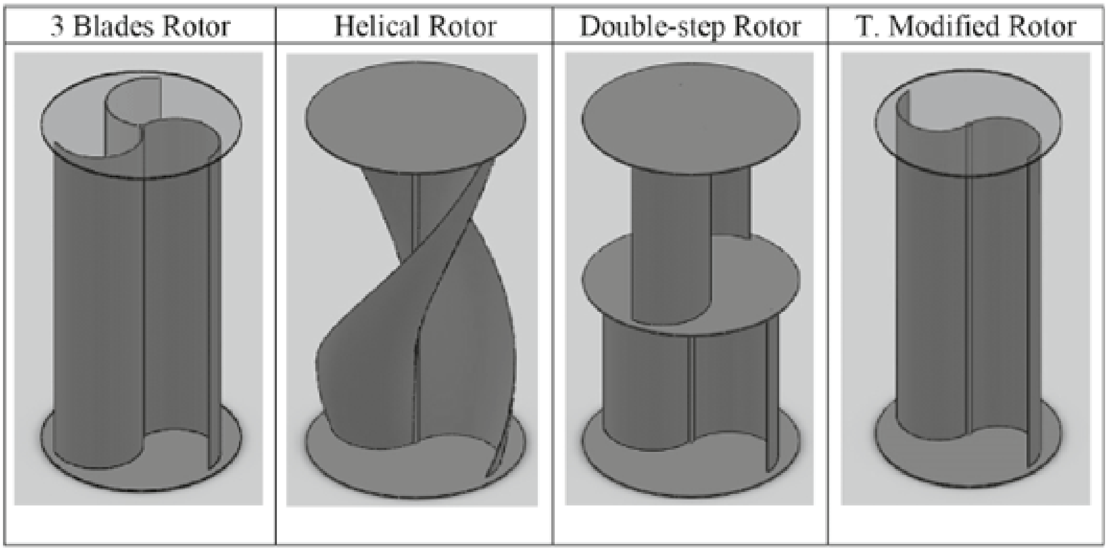


Figure 14. Savonius rotor modifications (Diaz et al, 2015)

Rotor can be modified by merging two rotors on the one shaft with 90° angle (Figure. 14 – Double-step Rotor). Double-step rotor has a greater static torque and consequently higher torque coefficient C_T.

Bubenchikov A.A. studied the effect of varying number of blades on the efficiency of rotor. he stated that rotor with four blades has a higher torque in comparison to three- or two-blades model. Three-blades models have better efficiency with higher speed of the blade tip, however, four-blades construction also shows a good efficiency under lower speed of blade tip.

The most popular and wide-spread material for plastic blades manufacturing is a traditional polyvinylchloride (PVC) tube. For almost all domestic applications this material is the best option. Advantages of the PVC-tube are low price, availability in any region, simplicity – it does not require any specific skills in material processing or any complex equipment.

Savonius rotor of a traditional (or conventional) type is considered to be the simplest one, but at the same time it has the lowest power coefficient, which can be improved by performing above mentioned modifications.

2.3.3 Horizonal propeller-type rotor

Horizontal axis wind turbines (HAWT) are still considered to be the best option in wind generator applications (Figure 15). This is the most popular and well-known type of turbines with the clearest mathematical description. There are many possible constructions for HAWT with different air foil profiles and number of blades. But almost all models follow classical construction for propeller type turbine implies three blades with equal pitch angle.

Basic advantage of HAWT is high efficiency – in the simplest three-blade model power coefficient is higher than in other types of vertical turbines with modifications because wind energy is digested much better according to aerodynamic features. However, horizontal turbines must be oriented by the wind direction with additional equipment (ball joint for auto rotation around the hub axis) and that makes construction more complex and heavier. Besides, propeller type turbines operate with higher wind speed and though they must be raised on high distance above the surface, which makes service and maintenance operations more complicated. Horizontal turbines also require generator and transmission to be installed in the nacelle, increasing the stress on the mast.

Operation principle of HAWT completely differs from vertical type rotors. When the wind flows towards the blade it is reflected from it and is thrown away under certain angle behind it. At the same time, another free wind flowing through the blade faces reflected flow and their interaction creates the pressure that lifts the blade. The higher that pressure is the stronger are the forces lifting the blades, that is why rotor`s rotational speed is not connected to the wind speed and depends on the pressure between reflected and free flows. Thus, blades’ edge speed can be much higher than the wind speed and TSR of HAWT are significantly higher than for vertical types.

An important role in power coefficient formation also plays ratio between wind flow area and total area of blades – the more blades – the lower amount of wind goes through them during certain time. Wind does not have time to fall through the blades and creates an air space in front of blade braking the next portions of wind which are reflected from the air space and do not take part in pressure creation. According to that, TSR of multi-blade horizontal rotors have lower power coefficients comparing to three- or -two blade models. Blade width also affects the efficiency – the thinner they are the less they resist the air flow.

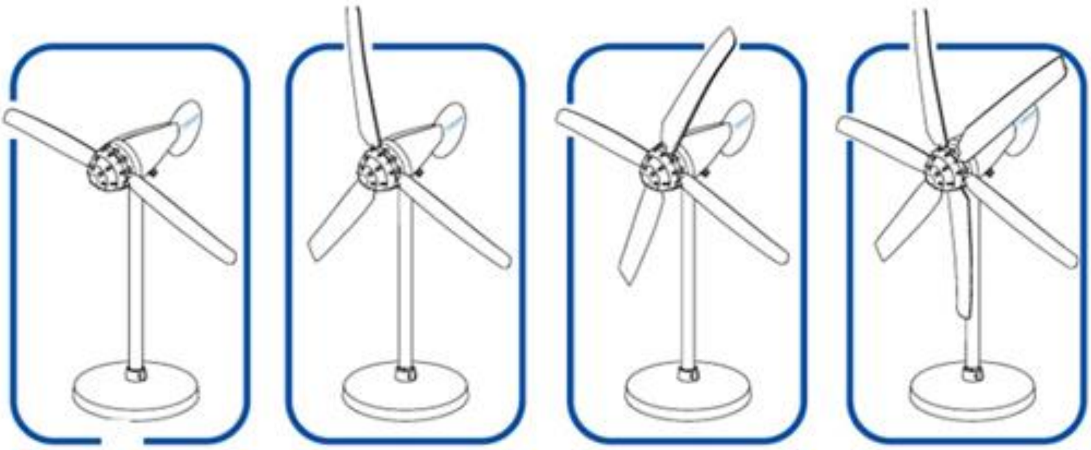


Figure 15. Different number of blades for HAWT (TCIP alternative energy blog, 2016)

Also, the number of blades does not affect the power production of the turbine. Power depends on the amount of energy that blades receive from the wind during a certain time – the faster a blade moves the higher is the amount of wind that it interacts with. For example, if the wind speed is low, blades interact with a small amount of air mass, and the number of blades can be increased in order to improve interaction with wind, but with increasing number of blades rotations will be decreased according to above mentioned mechanism, that is why power will not change. Rotation speed is also affected by the angle of blades in relation to wind flow direction. Apparently maximum torque will be created with 45% angle of blades, but it works only if blades do not move.

Aluminium is a light and durable metal. It is traditionally used for small wind generator blades. With correct blade shape aerodynamic features of the turbine will be very good according to its small weight. Even under normal operation conditions plastic tube will crack much faster than an aluminium turbine. The main drawback of aluminium details for wind generation is manufacture complexity. PVC-tube allows to cut appropriate blade shape that will be aerodynamically similar to existing air foil profiles, while aluminium can typically be found as a metal sheet only. After cutting the correct shape, detail should be rolled and form the curve. In domestic conditions and without special equipment it is a very hard task.

Comparing the efficiency of HAWT and VAWT it should be said, that even if HAWT has better efficiency with the same operation conditions, HAWT is more complicated type of turbine for domestic usage, and it brings more problems for everyday users in terms of installation, service and maintenance.

3 Design of portable wind generator

Thanks to the rapid development of electronics and the absence of electrical supply networks in unurbanized corners of the world a serious problem linked on the uninterrupted power supply of embedded batteries under appeared. Skilled hikers often face that problem – in long mountain travels power bank charge is not enough to supply all the electronic devices and portable lamps with power during the whole trip. This project is directed on the novel solution of the problem of power supply by the creation of wind generator with the features of portability, mobility and modularity.

In order to obtain needed features, requirements to the wind generator are stated below:

- Light-weightiness – total mass of the construction, which includes rotor, generator and battery must not exceed 1.5 kg.
- Size – height of the wind generator must not be more than 700 mm and width no more than 300 mm.
- Reliability and repairability – assembling of the system must be utilized in major with screw connections and minimum usage of glue in order to ensure possibilities for repair and modifications.
- Power – generator must be able to supply 5 V voltage and 1 A current to charge at least one lithium-ion portable battery during standard charging time of 1.5 - 2 hours.

The aim of the project is a development of an experimental layout of a portable wind generator. Creation of experimental sample will allow to better study ways of energy production of small wind generators and comprehend expediency and possibility of creation portable wind generators for entering the market and sells to customers.

The chapter appears to be an applied part of the master thesis and it is directed on the practical digestion of theory, given in the previous chapter. This part describes a logic process of type selection for electric generator, mostly suitable for portable wind generation application, calculation of its geometrical and physical parameters for sufficient level of power production, logic of rotor turbine selection according to the described features of existing types, its improvement to suit the requirements of portability and mobility. Brief tips for material selection and assembling process, as well as assembling stages with graphical explanations will also be given in the chapter.

3.1 Rotor selection

Selection of a wind turbine type is not an easy task, and the logic of selection is based on many factors. The objective of the project is to create a portable wind generator, which means that the design should occupy the minimum possible space in the backpack. Based primarily on the purpose of the project, as well as on the characteristics of the various types of turbines presented in the previous chapter, the main choice fell on the 3D – printed Darrieus H-type rotor. The design of this type of turbine is optimal in terms of simplicity, weight and the absence of needs in additional equipment, such as, for example, a wind direction device. Due to the properties of the generator, such as a low rotational speed, there is also no need for a transmission, since the H-type Darrieus rotor is capable of developing a sufficient rotational speed and the necessary torque, as shown below. The use of that type of rotor also allows to place electrical equipment at the base of the foundation, that is, on the ground, which is an undoubted advantage – the loads on the hub are reduced, and the centre of mass is located at lower point, which increases the reliability of fixing the structure and the chance of a wind generator fault on the ground under strong winds is reduced, and as is known, in conditions of constant movement and change of terrain during hiking it is not always possible to set the wind generator properly.

The novelty of the construction is based on the idea of using folding telescopic aluminium traverses, which are fixing the blades. This design allows to reduce the occupied volume in the user's backpack to a third, and the method of assembly and disassembly takes only a few seconds. When unfolded, the wind generator is a standard Darrieus H-type design capable of full-fledged operation.

3.2 Design of electric generator

Electric generator selection was based on the requirements of size and power for wind generator. According to the description, given in the chapter 2, the most suitable construction is an axial-flux permanent-magnet synchronous generator. Undoubtful advantage of the construction is relatively low rotation speed – axial-flux generator is capable of producing sufficient level of power under relatively low rotation speed, moreover, geometry of that type allows to reduce space and fit to the frames of required size. Simplicity of construction and understandable operation principles allow to create this type of electric generator at home without any help of skilled designer and without usage of professional equipment and installations. Furthermore, possibility to assemble the electric generator independently gives an opportunity to economize budget greatly – because all the expenditures are spent only on purchasing of materials, avoiding extra chargers of manufacturers. However, no doubts that creation of an axial-flux generator still requires great efforts, knowledge and engineering skills and definitely appears to be the most complicated and demanding part of the project.

According to the requirements and general aims of the project, calculation was based not as much on the reaching maximum power as on the possibility to fit required power in appropriate sizes. General dimensions for generator must not exceed 60 mm in height and 150 mm in diameter, moreover, mass must be no more than 1 kg, which imposes additional restraints in the area of metal usage and makes to pay careful attention to the used materials, searching for compromise between power, reliability and weight.

The generator is fully ironless and therefore has a magnetic circuit that closes via air. There are two rotor disks and a single stator between the rotors. The rotor disks have just 3D printed plastic placeholders for the magnets. The stator windings are round winding coils that are similarly placed in a 3D-printed plastic placeholder of the armature winding.

3.2.1 Charging battery application

The first step of design process basically includes the definition of connection schema for wind turbine application. There can be two possible operation modes – direct battery charge or grid-connection via inverter. For a household generator the first type seems to be a more promising idea because energy can be stored in the battery and used whenever needed. Direct battery charging scheme is presented in Figure 16.

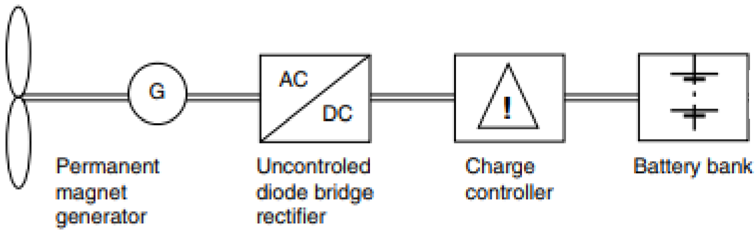


Figure 16. Direct battery charging connection scheme

Wind turbine rotor is directly coupled to a permanent magnet generator, which charges a battery via uncontrolled rectifier. Voltage control (charge controller) can be implemented by different means, which will be described later in the chapter. Voltage at battery output can be used as a source for an inverter and used for AC power supply of domestic consumers. In terms of hiking generator application, inverter is not considered because the primary load is a power bank (battery), which acts as an active resistive load for the generator. The voltage level of standard power bank is 5 V and therefore charging starts only when the rectified voltage at system output exceeds 5 V. Standard charging current for power bank is set to be 1 A. With 5 V and 1 A input power bank can be charged during normal time, usually 1.5 – 2 hours for Li-Ion battery type.

According to the Kirchhoff`s second law if the battery is considered to be a resistive load, charging current can be calculated using equation:

$$I = \frac{U_{\mathrm{rec}} - U_{\mathrm{pb}} - U_{\mathrm{FT}}}{R_{\mathrm{batt}}} \tag{21}$$

where U_{rec} – voltage at output terminals of rectifier [V], U_{pb} – power bank input voltage [V], U_{FT} – forward voltage drop of diode bridge [V], R_{batt} – battery resistance (connections resistances are neglected) [Ohm].

Active power of generator can be calculated:

$$P_{\mathrm{gen}} = IU_{\mathrm{rec}} \tag{22}$$

As it can be observed, it simply consists of charging current and voltage at rectifier output.

3.2.2 Generator sizing

In order to create a turbine that will produce sufficient amount of power and torque, generator and turbine must be sized. First, nominal wind v_{nom} speed for turbine must be defined. Average wind speed in Lappeenranta, Finland is 3 - 4 m/s. Assuming higher wind speeds at mountains height, for hiking generator 6 m/s wind speed is set to be nominal.

In case of battery charging application, turbine tip speed ratio λ (TSR) is not constant, but decreases with increasing wind speed. It happens because of the fact, that electromagnetic torque in stator limits the rotational speed of generator, slowing down the turbine and making ratio between rotational speed of turbine and wind speed (which is TSR) slightly fall. Considering TSR λ_{nom} = 2.1, turbine blade rotor size can be calculated. Additional parameters for size calculation are power coefficient, which is assumed to be C_p = 0.2 and nominal power of the wind turbine P_{rot} = 6 W, which must be assumed less than generator power from (22) in order to ensure control possibilities, described further. The efficiency of small generator is considered to be η = 75% due to the assembling inaccuracies and low power.

According to the equation (2), rotor wind flow area S_{rot} can be calculated:

$$S_{\mathrm{rot}} = \frac{2P_{\mathrm{rot}}}{\eta C_{\mathrm{p}} \rho v^3} \tag{23}$$

Wind flow area is also defined by following equation:

$$S_{\mathrm{rot}} = h_{\mathrm{rot}} w \tag{24}$$

where h_{rot} – Darrieus wind turbine rotor blades height [m], w – width of the front plane of wind turbine rotor [m] (Figure 17).

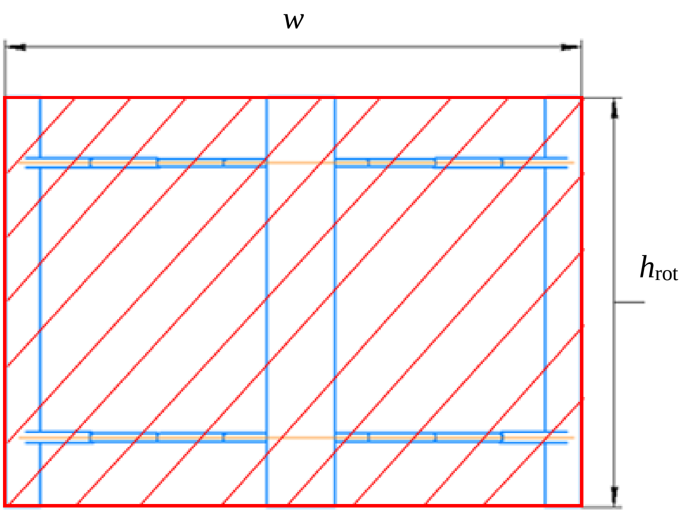


Figure 17. Wind flow area towards the blades

When width of the front plane is known, it is possible to calculate wind turbine rotor blade radius, considering the fact, that $h/D = 1$:

$$w = r_{\text{rot}} + D_{\text{mast}} + r_{\text{rot}}\cos(30°) \tag{25}$$

where r_{rot} – rotor radius [m], D_{mast} – mast diameter [m] (Figure 18).

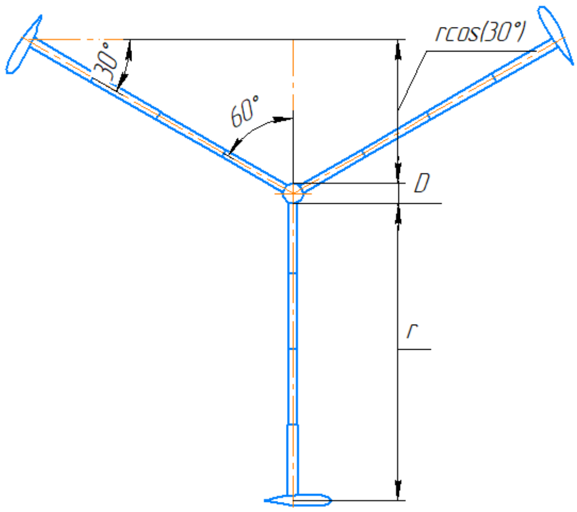


Figure 18. Definition of front plane width

Based on formula (3) angular velocity and working range for rotational speed of the turbine can be calculated with previously defined value of rotors radius:

$$n = \frac{60\lambda v}{2\pi r_{\mathrm{rot}}} \tag{26}$$

where n – wind turbine rotor rotational speed [rpm], v – wind speed [m/s], r_{rot} – radius of wind turbine rotor blades [m].

Nominal rotational speed of wind turbine is n_{nom} = 420 rpm.

3.2.3 Axial dimensions for generator

In order to define geometrical and electromagnetic parameters of the generator, initial value for induced back-emf must be presented. In case of the hiking generator project, nominal we assume phase rms value for back-emf E_{nom} = 5 V.

Number of pole pairs for generator defines the electrical frequency. Electrical energy generation (when the load is connected) is appeared itself while magnetic field of magnet go through the copper coil, forcing current to flow across the coil turns. Magnets on single rotor core are placed south and north in a row and two rotor disks are fixed in the way that south and north magnets lay opposite to each other. One pair of opposite magnets forms one pole. When one magnet pole moves near the coil it creates emf and if the loop is closed current starts to flow in certain direction. Coil in that case will have positive potential at one end and negative potential at another. When next magnet pole comes to the same coil positive and negative potential interchange and current flows in opposite direction. This process happens all the time in a circle creating AC current. Every single change of voltage/current direction is characterized by one Hertz (Hz) and if the generator has six pole pairs – one rotation per second creates 6 Hz frequency. Every coil on the stator is a unique voltage source which in series interacts with other coils of the phase and creates a total phase voltage of the generator.

There are still argues about the correct ratio between the number of poles and the number of coils, but in this project the number of stator slots per pole and per phase is considered to be q = 0.25. The following equation is used to calculate the number of slots per pole and per phase:

$$q = \frac{Q_{\mathrm{s}}}{m2p} \tag{27}$$

where Q_s – number of stator slots, m – number of phases, p - number of pole pairs. In order to suit q = 0.25 value, 6 pole pairs and 9 coils combination is used.

Axial dimensions for permanent magnet axial flux generator include height of magnets h_{PM}, thickness of rotor core h_{yr}, thickness of stator core h_{ys} and physical airgap δ. Since the rotor in the project is an air-cored rotor (rotor made of plastic), its thickness does not matter.

Calculation of iron rotor thickness can be roughly estimated using the width of the magnet $h_{yr} = w_{PM}/4$, as was described in 2.2.3. Basically, rotor ferromagnetic core is used to keep a closed loop for magnetic flux, so it does not travel in the air much. Thickness of rotor core can be checked by following rule – if any ferromagnetic thing is not attracted to the opposite side of rotor core, then rotor thickness is high enough. In order to improve the efficiency of the generator, even a thin ferromagnetic disk is recommended to use for rotor core. But be aware of using a too thin disk – it will possibly bend due to the high attractive forces between opposite magnets. Figure 19 presents the main axial dimensions' definition and flux path distribution for generators with or without rotor yokes.

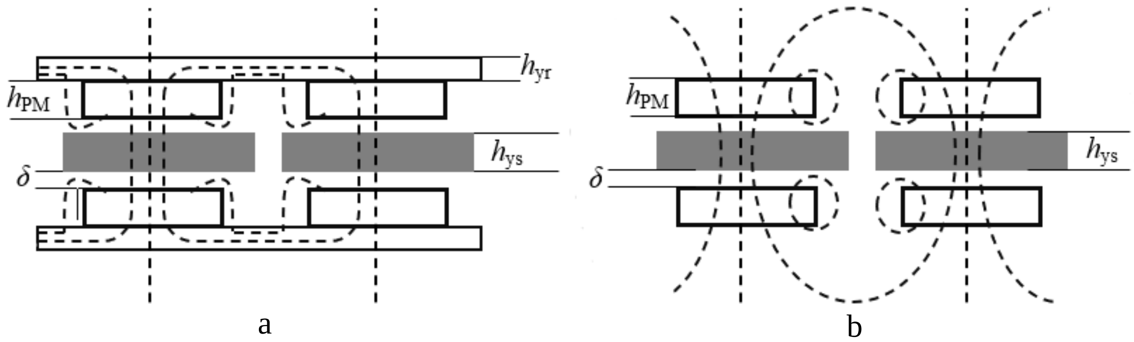


Figure 19. Generator axial dimensions and flux path a) – with rotor iron yoke b) – without rotor iron yoke

The best available magnets of N42 grade were selected for the project in order to compensate absence of rotor ferromagnetic core. The material coercivity is H_c = 1000 kA/m. The magnets have a round shape with 20 mm diameter and 10 mm height. The physical airgap is considered to be 1.5 mm due to the danger of assembling inaccuracies and to avoid possible friction of magnets and coils if some imbalance of generator occurs. Stator winding area thickness must be not more than magnets height, that is why h_{ys} is considered to be 10 mm.

Now, after axial dimensions are known, it is possible to calculate the airgap magnetic flux density. Figure 19 illustrates possible shape of the flux path. In case of iron yoke, the estimate for the total magnetic air gap δ_{eff} is the distance between the rotor yokes. In Figure 19 the magnetic air gap is therefore $\delta_{\mathrm{eff}} \approx 2h_{\mathrm{PM}} + 2\delta + h_{\mathrm{ys}}$. If the rotor steel yokes are omitted the effective air gap gets much longer. We might assume that the flux travels from magnet to magnet via a semicircle along the pole pitch $\tau_{\mathrm{p}} = \pi D_{\mathrm{avg}}/2p$. The yoke path is therefore $\tau_{\mathrm{p}}\pi/2$. Now the effective air gap becomes $\delta_{\mathrm{eff}} = 2h_{\mathrm{PM}} + 2\delta + h_{\mathrm{ys}} + \tau_{\mathrm{p}}\pi/2$. For one magnet we obtain:

$$\delta_{\mathrm{eff,PM}} = h_{\mathrm{PM}} + \delta + h_{\mathrm{ys}}/2 + \tau_{\mathrm{p}}\pi/4 \tag{28}$$

The air gap flux density can now be calculated:

$$B_{\delta} = h_{\mathrm{PM}} H_{\mathrm{c}} \cdot \mu_0 / \delta_{\mathrm{eff}} \tag{29}$$

High leakage flux of the PMs will be present. Estimating the leakage flux is challenging but with the dimensions selected in the work and with empirical knowledge it is possible to evaluate that 70% of the flux belongs to the main flux.

3.2.4 Winding calculation

The maximum flux per pole Φ_{max} can be found using airgap flux density and surface area of 1 magnet:

$$\Phi_{\mathrm{max}} = B_{\delta} \cdot 0.7\pi r_{\mathrm{PM}}^2 \tag{30}$$

where B_{δ} – magnetic flux density in airgap, r_{PM} – magnet radius. It is assumed that 70% of the PM flux will travel through the winding. Therefore, the factor 0.7 is used in (30).

Now, with equation (30) for maximum flux per pole, number of winding turns in one coil can be calculated using following equation:

$$N = \frac{\sqrt{2}E_{\mathrm{nom}}}{Q_{\mathrm{s}}k_{\mathrm{w}}\Phi_{\max}2\pi n_{\mathrm{nom}}p/60} \tag{31}$$

where N – number of turns per coil, E_{nom} – nominal phase RMS of back-emf [V], Q_s – number of coils, n_{nom} – rotational speed of generator [rpm], k_w – winding factor, B_δ – airgap flux density [T], p – number of pole pairs.

Winding factor is defined further. Basically, for single layer winding machine distribution factor is enough to calculate winding factor. For each radial layer of coil there is an offset between its actual position and position where it induces maximum back-emf. To get arithmetic mean of winding factor for all layers, slot angle for each layer should be defined. It is derived from proportion:

$$\frac{360 \cdot p}{\theta_{\mathrm{p}}} = \frac{2\pi r_{\mathrm{avg}}}{d_i} \Rightarrow \theta_{\mathrm{p}} = 360 \cdot p \cdot \frac{d_i}{2\pi r_{\mathrm{avg}}} \tag{32}$$

where θ_{p} – slot angle [el. deg], $2\pi r_{avg}$ – stator perimeter (trough the coil centres), d_i – layer diameter, p – number of pole pairs.

For each layer equation (32) turns out to be:

$$\theta_{\mathrm{p}.n} = 360 \cdot p \cdot \frac{d_{\mathrm{i.1}} + 2d_{\mathrm{Cu}} \cdot n}{2\pi r_{\mathrm{avg}}} \tag{33}$$

where $n \geq 0$, $2\pi r_{avg}$ – stator perimeter (through coil centres), d_{Cu} – wire diameter, on that stage can be selected freely.

Electrical angle between each pole is:

$$\theta_{\mathrm{m}} = \frac{360 \cdot p}{2p} \tag{34}$$

where $\theta_{\mathrm{m}} = 180°$ [el. deg] for any number of poles machine.

Now it is possible to derive distribution factor for each layer:

$$k_{\mathrm{w.n}} = k_{\mathrm{d}.n} = \cos\left(\frac{\theta_{\mathrm{p.n}} - \theta_{\mathrm{m}}}{2}\right) \tag{35}$$

And arithmetic mean for winding factor is defined by following equation:

$$k_{\mathrm{w}} = \sum_{n=0}^{i} k_{\mathrm{w}.n} \tag{36}$$

where $i = \frac{r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}}}{s_{\mathrm{Cu}}}$, k_{w} – wind factor of the machine (calculated in appendix A).

According to the purpose of the project, stator diameter is limited with the value of D_{ys} = 126 mm. Rotor diameter, in order to be assembled in the way that magnets are crossing coils in a right way, is set to be D_{yr} = 110 mm. Figure 20 depicts the radial dimensions for the generator rotor and stator.

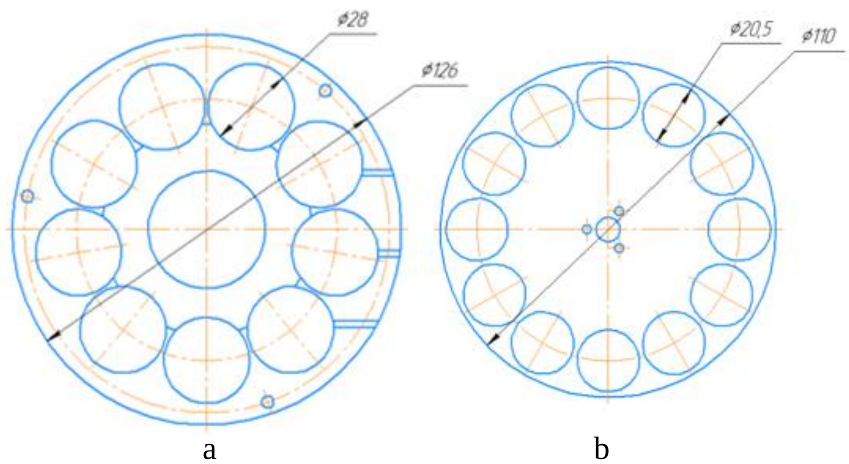


Figure 20. Radial dimensions for generator: a) – stator; b) - rotor

To reduce the stator phase resistance, and therefore increase efficiency, wire with maximum possible cross-section fitting to stator grooves can be selected according to the following equation:

$$s_{\mathrm{Cu}} = \frac{(r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}})h_{\mathrm{ys}}}{N} \tag{37}$$

where $r_{ws.e}$ and $r_{ws.i}$ – outer and inner radiuses of coil, h_{ys} – height of the stator, S_{Cu} – cross section of wire.

In order to correctly calculate the inner resistance of windings, one needs to know the length of the conductor in a phase. Typical length formula does not exist, and it varies much depending on the type of coil – triangular, rectangular or round coil. To find the length for each layer of round type coil the following equation is used:

$$l_{\mathrm{ws.n}} = 2\pi(r_{\mathrm{ws.i}} + d_{\mathrm{Cu}} \cdot n)\frac{h_{\mathrm{ws}}}{S} \tag{38}$$

where $n \geq 0$, h_{ws} – coil height.

After that, the length of all of the layers is summed up. Number *i* shows the number of layers to reach the outer diameter:

$$l_{\mathrm{ws}} = \sum_{n=1}^{i} l_{\mathrm{ws}.n} \tag{39}$$

where $i = \frac{r_{\mathrm{e}} - r_i}{s_{\mathrm{Cu}}}$, l_{ws} – wire length in one coil.

Length of coil then is multiplied on the number of coils per phase and total length of the phase l_{tot} is known. Resistance of the phase wire is calculated by formula:

$$R_{\mathrm{ph}} = \rho\frac{l_{\mathrm{tot}}}{S_{\mathrm{Cu}}} \tag{40}$$

Coil inductance can be estimated using the following equation:

$$L_{\mathrm{ws}} = \frac{d_{\mathrm{ws}}^2 N^2}{3d_{\mathrm{ws}} + 9h_{\mathrm{ws}} + 10(r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}})} \tag{41}$$

where L_{ws} – coil inductance [H]; d_{ws} – average diameter of coil [m]; h_{ws} – height of coil [m] ($h_{ws} = h_{ys}$). Due to 3 coils in every single phase, the inductance of one phase is $L_{ph} = 3L_{ws}$.

3.2.5 Rectifier calculation

To feed a power bank with DC current, a rectifier must be used. Optimal type for three-phase rectification is considered to be three-phase six pulse diode bridge, which is depicted in Figure 21. The price for rectifier appears to be enough descent to purchase ready-made model at the radio-electronic markets, however, construction simplicity allows to create one at home using diodes and electronic plates.

According to the fact, that hiking generator induces relatively small back-emf, forward voltage drop on the standard diodes will be very high, that is why it is recommended to use Schottky diodes, which have small forward voltage drop. In the project, diodes with 0.6 V forward voltage are selected.

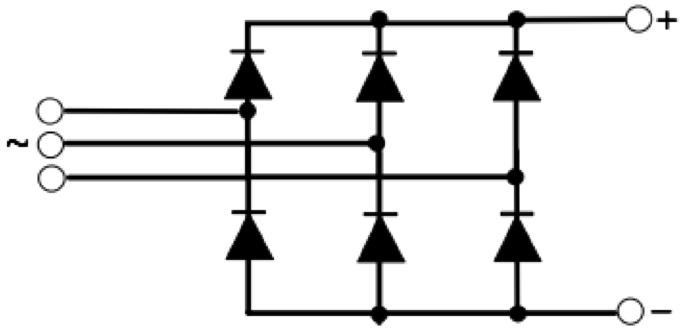


Figure 21. Six-pulse three-phase diode bridge

Diode bridge is not a rectifier yet because output current waveforms at the DC terminals are pulsating. To get rid of the pulses, C-filters are commonly used. To correctly calculate parameters for C-filter, below formulas are used. First, capacitive reactance is found:

$$X_{\mathrm{c}} = \frac{1}{2\pi f C} \tag{42}$$

where C – capacitance of the filter [F].

Efficiency of the capacitive filter increases under following below stated condition – active resistance of the load must be much higher than the capacitive reactance of the capacitor:

$$R_{\text{sll}} \gg X_c \tag{43}$$

According to the (30) and (31), capacitance can be found:

$$C \gg \frac{1}{2\pi f R_{\text{sll}}} \tag{44}$$

where R_{sll} – stator line-to-line resistance of generator stator winding [Ohm]. The value of capacitive impedance at the operating frequency must be at least 10 times as high as the calculated value. For project purposes, 1 mF value is chosen.

Table 3 represents main stated and calculated parameters for three-phase axial flux generator.

Table 3. Main parameters for axial flux three-phase generator

Parameter	Value
Rotor higher radius $r_{\text{yr.e}}$, mm	60
Rotor lower radius $r_{\text{yr.i}}$, mm	40
Rotor average radius $r_{yr.\text{avg}}$, mm	50
Magnets height h_{PM}, mm	10
Magnets radial length $2r_{\text{PM}}$, mm	20
Rated rotational speed n_{nom}, rpm	420
Magnetic flux density in airgap B_{δ}, T	0.69
Winding factor k_{w}	0.87
Number of coil turns N	140
Number of coils per phase Q_{s}	3
Number of pole pairs p	6

After all parameters have been estimated, MATLAB Simulink software can be used to check wave-forms of current and voltage. Figure 22 presents a roughly-estimated equivalent circuit of three-phase axial flux generator.

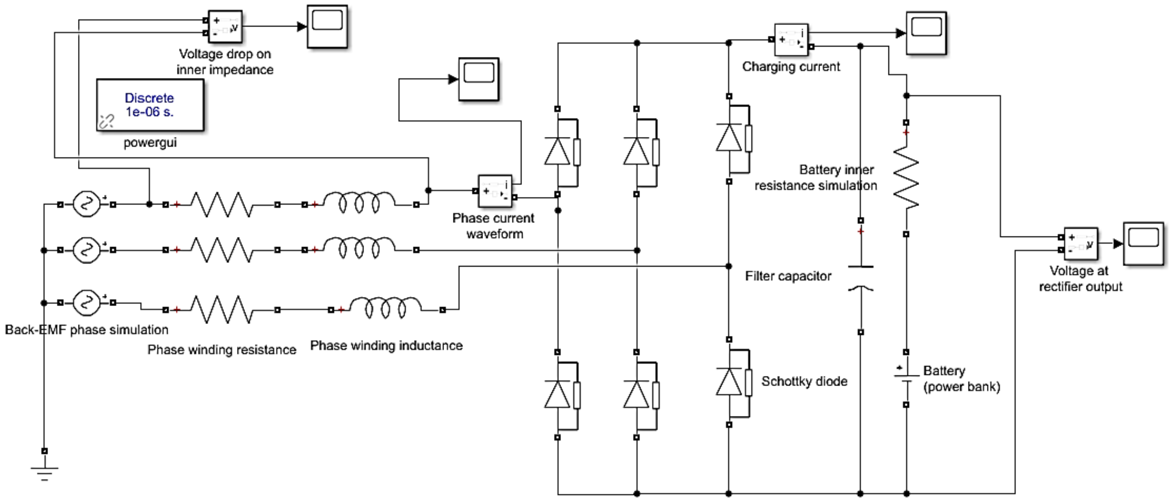


Figure 22. Simulation of diode bridge rectifier

Despite the current does not remain sinusoidal, in simplified form the phase-to-phase voltage at the terminals of generator is found using following phasor equation:

$$U_{\mathrm{gen}} = E_{\mathrm{nom}} - I_{\mathrm{rms}} R_{\mathrm{ph}} - jX_{\mathrm{L.ph}} I_{\mathrm{rms}} \tag{45}$$

where R_{ph} – phase resistance of windings [Ohm], $X_{L.ph}$ – phase reactance of windings [Ohm], I_{rms} – RMS value of phase current [A], which is $I_{\mathrm{rms}} = I/\sqrt{2}$, due to the fact, that current amplitude is 1 A and it will be DC charging current after rectification, but we need phase – RMS current value (wye-connection, phase current is equal to phase-to-phase current) to calculate voltage at terminals.

Line-to-line RMS voltage at the input of rectifier is 5.88 V, amplitude value will be 8.30 V and after rectification, slightly less DC voltage will be at filter's output.

To find a suitable value for battery internal resistance (here it is considered, that physical power bank has zero resistance), below stated equation is used:

$$R_{\mathrm{batt}} = \frac{U_{\mathrm{rec}} - U_{\mathrm{FT}} - U_{\mathrm{pb}}}{I} \tag{46}$$

Electrical parameters, used in simulation, are presented in the Table 4.

Table 4. Simulation electrical parameters.

Parameter	Value
Phase back-emf, E_{nom}, V	5
Phase resistance of winding, R_{ph}, Ohm	1.47
Phase inductance of winding, L_{ph}, mH	2.76
Diode bridge forward voltage drop, U_{FT}, V	0.7
Filter capacitance, C, mF	1
Internal battery resistance, R_{batt}, Ohm	1.9
DC voltage (power bank simulation), U_{pb}, V	5

Figures 23 - 26 represent simulation result for nominal point. Figure 23 represents voltage drop on the resistance and reactance. According to the figure, phase rms of voltage drop is approximately 1.55 V, which is also calculated from the equation (45).

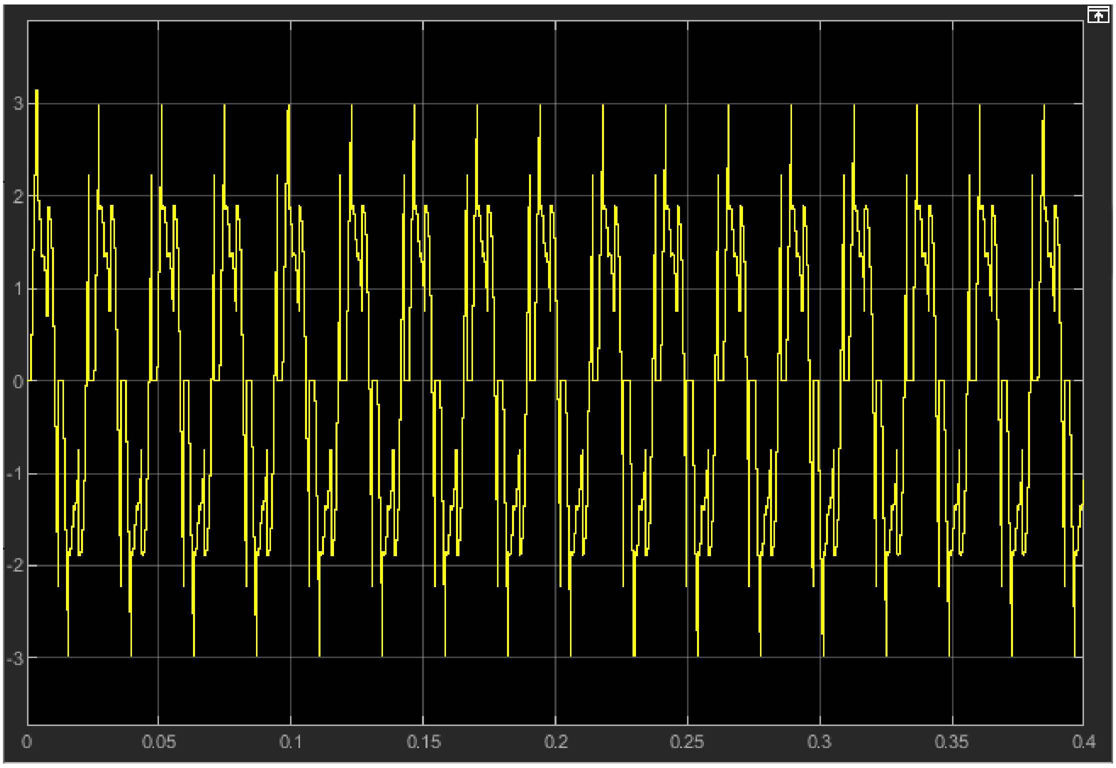


Figure 23. Phase voltage drop inside generator

Figure 24 shows generator output phase decurrent.

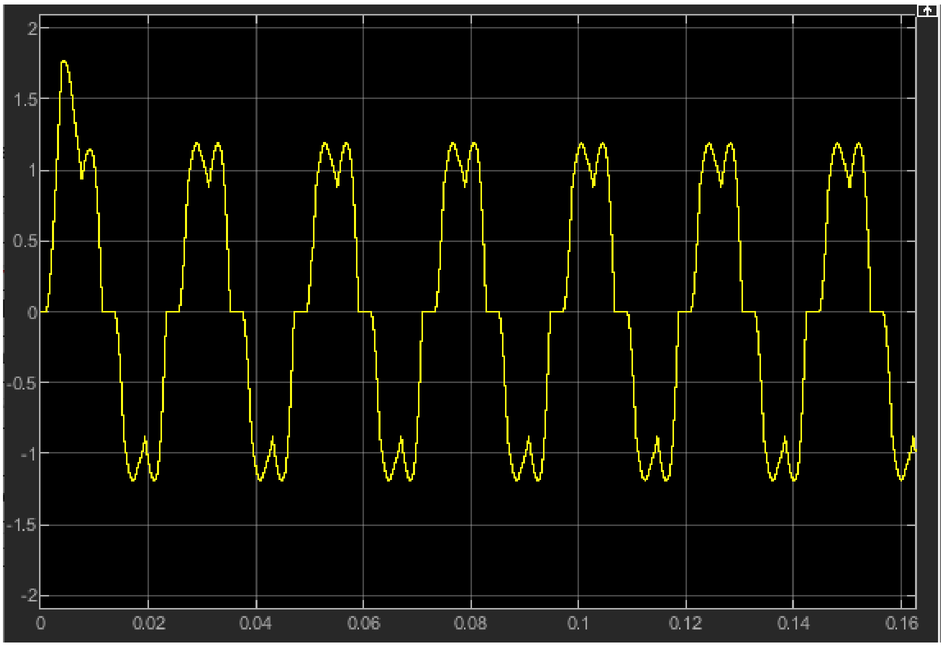


Figure 24. Generator output phase current

Rectified charging current is depicted in the Figure 25.

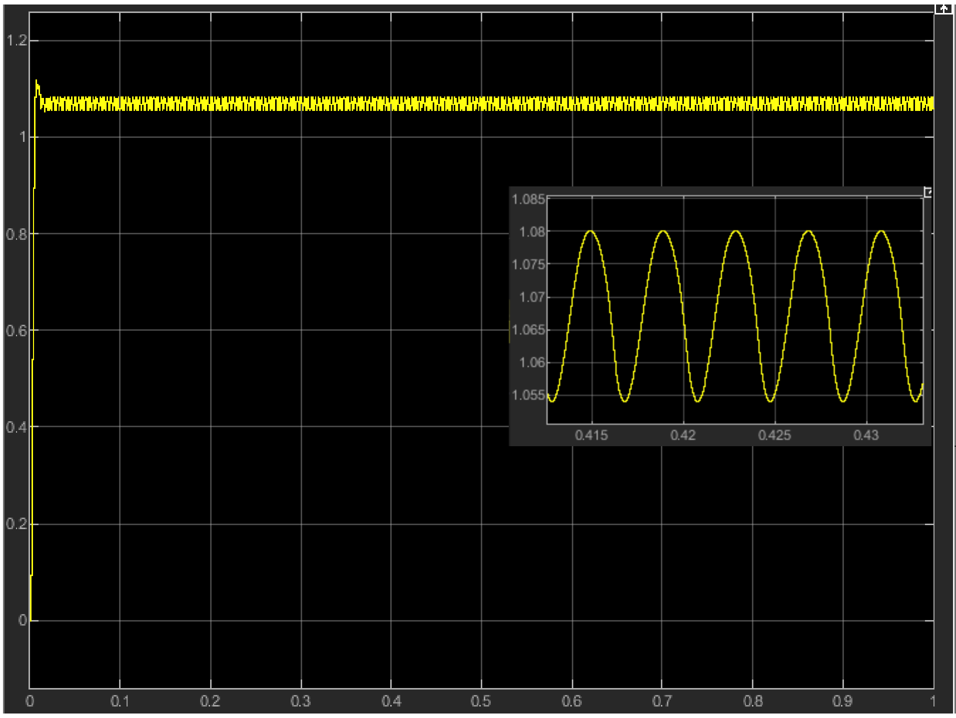


Figure 25. Rectified charging current

The voltage waveform at the output of filter is shown in Figure 26.

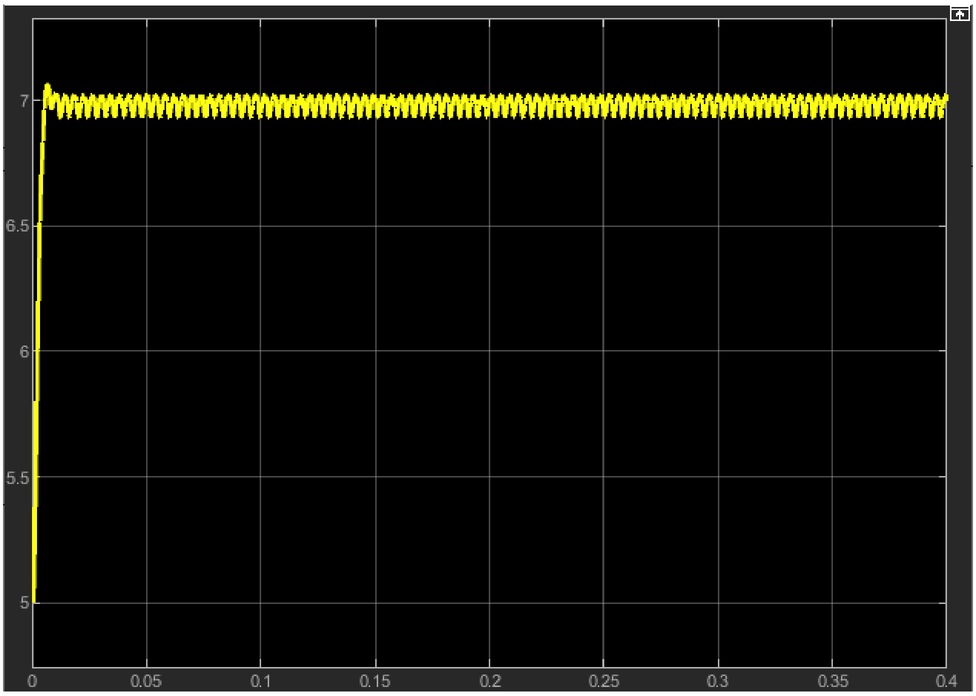


Figure 26. Voltage waveform at filter output

Next step is to perform open-circuit simulation in order to compare back-emf and voltage waveforms with real ones. Figure 27 represents open-circuit back-emf wave forms at 12 rps (720 rpm)

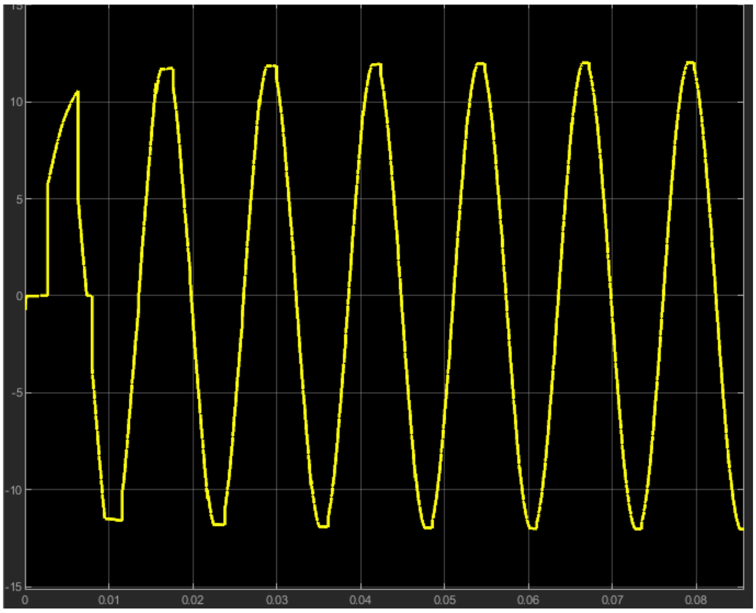


Figure 27. Back-emf open-circuit waveform at 12 rps

Figure 28 shows rectified and filtered voltage open-circuit test at 12 rps (720 rpm)

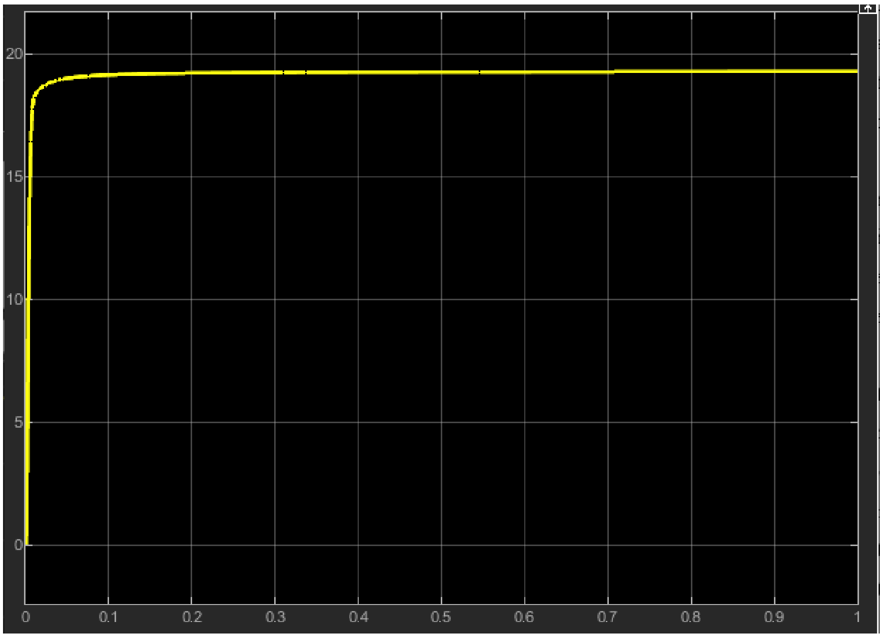


Figure 28. Rectified and filtered open-circuit voltage at 12 rps

3.2.6 Control possibilities

In case of big wind turbines, when the wind speed is below nominal, torque control is used to derive maximum power. When the wind speed is above nominal, pitch control is used to keep rotational speed constant. In case of a small wind turbine, usually control can be implemented by electrical braking: electromagnetic torque, created when current flows through the stator winding acts as a brake for wind turbine rotor. This electromagnetic brake reduces the turbine tip speed ratio. As a result, at the rated point electromagnetic torque brakes too actively and limits the rotational speed of turbine. Further increasing in wind speed will result in a higher torque production, but the speed will remain the same. Dependence of electromagnetic torque and turbine torque on the rotational speed is depicted in Figure 29.

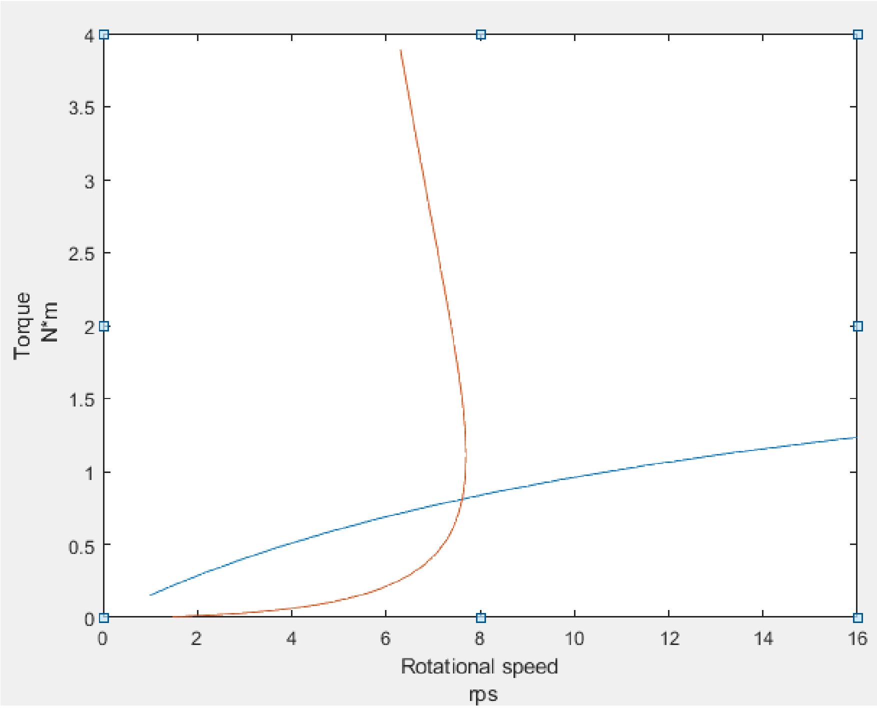


Figure 29. Torque: red – wind turbine rotor torque, blue – generator torque

As it can be observed, rotational speed of turbine starts to decrease after the rated point (7 rps).

3.3 Assembling process

The chapter explains how to correctly build a Darrieus-rotor hiking wind generator. Detailed explanation of electric generator and wind turbine rotor assembling are given.

3.3.1 Electrical generator assembling

Considering the small size of the generator, the main supports can be printed on a 3D printer. High-quality ABS plastic with 100% filling can be used for the rotor yoke. 100% filling is necessary to increase the endurance, since the force of attraction of magnets to each other is quite large and with an incomplete filling, the rotor yoke may crack or start bending. The Maxwell normal stress is $½\mu_0(H_n)^2 = ½\mu_0(B_n/\mu_0)^2$. If e.g. the air gap flux density is 0.69 T the attractive stress between the magnets is 189.5 kPa. If the magnet diameter is 0.02 m the maximum force is then 59 N which is not negligible. If there are e.g. 12 similar magnets the total force is 714 N. The mechanical system must tolerate this attractive force.

An alternative option is a sheet of plywood 3-5 mm thick, but the use of plywood or any other wood requires a high level of training from the part of the master and the use of additional professional equipment. Wood can also be processed in special carpentry workshops, which will be cheaper than 3D printing, but the weight of wood is still greater, which affects the inertial characteristics of the rotor. To greatly increase the airgap flux density, ferromagnetic steel should be used in rotor yoke. To achieve maximum efficiency, the thickness of the yoke should be equal to a quarter of the width of the magnets. It can be checked by bringing a nail closer to the back of the disc, if it is not attracted – the entire magnetic flux is distributed inside the rotor and flux leakage is very small. In any case, a steel structure of any thickness will increase the efficiency of the generator but will increase its mass. Magnets are sticked to the yoke surface with glue, the safest option is the usual momentum superglue. Its properties are good enough to securely fix the 20 mm diameter magnets with on the rotor, however, it is recommended to cut slots for magnets in the yoke. Figure 30 shows the design of the rotor with magnets.

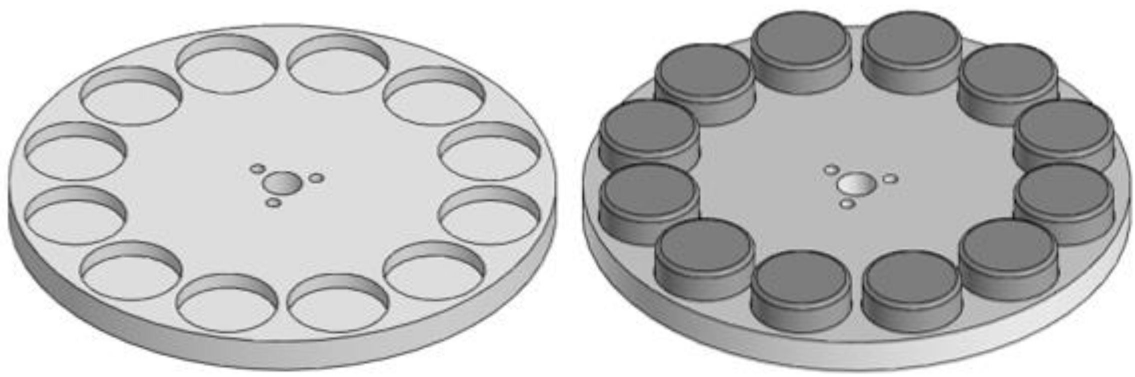


Figure 30. ABS-plastic rotor yoke

There are two main ways to create a stator. Steel structures are not used in the stator – this is one of the advantages of the axial-flux generator, described earlier. 3D printing with ABS plastic can be used to support the coils, filling at a minimum of 20% can be used, since the stator does not experience any serious stresses. The second option is to pour the pre-installed coils into a mould with epoxy glue. This option is considered much cheaper, but extremely unreliable – when pouring, there is a great chance of making a mistake and spoiling the coils as a result, so the recommendation to use 3D printing remains for both the stator and the rotor. Figure 31 shows the suspension for the stator.

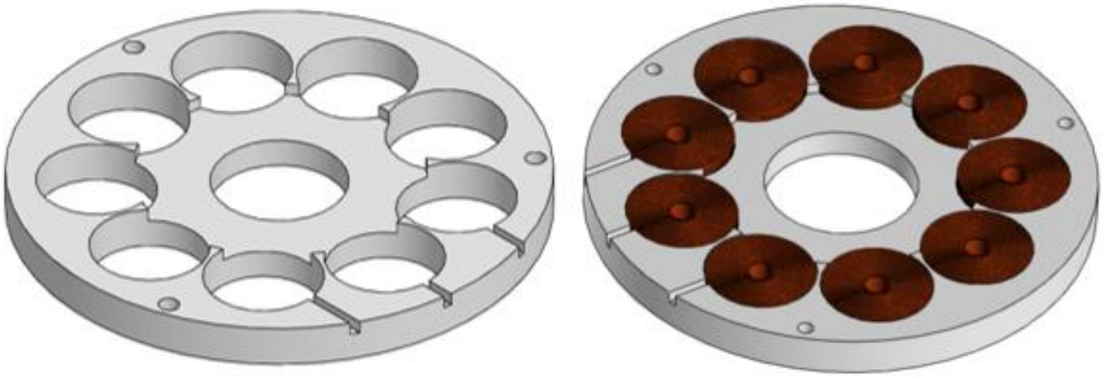


Figure 31. ABS-plastic stator suspension with and without coils

The hole inside must be made large enough to thread the shaft through the stator. A recess in the middle of the stator is made for laying the connections of the coils.

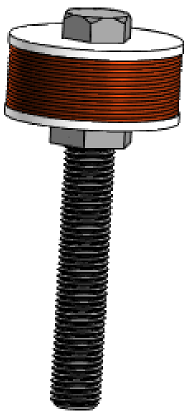


Figure 32. Layout for coil windings

The easiest way to wind the coils using a minimum amount of equipment is to wind the coils on a screw of the desired diameter with a drill. Special cardboard blanks with a coil diameter are mounted on the screw from two sides, the upper one is under the screw head, the lower one is fixed with a nut, a paper tape with a coil height is wound on the screw between the lower and upper blanks and secured with adhesive tape. The screw is inserted into a drill and winding starts. Figure 32 shows the template for winding a coil.

The shaft must be made of the most durable material, aluminium or steel is a good option, the shaft can also be made of ABS plastic with 100% filling, however, this option is not suitable for structures with a Darrieus rotor, since in this case the shaft experiences heavy loads and may break. A cylinder is installed in the middle of the shaft, which is fixed with a side screw or glue. The cylinder will play the role of fastener for opposite rotors.

Figure 33 shows assembling process in detail.

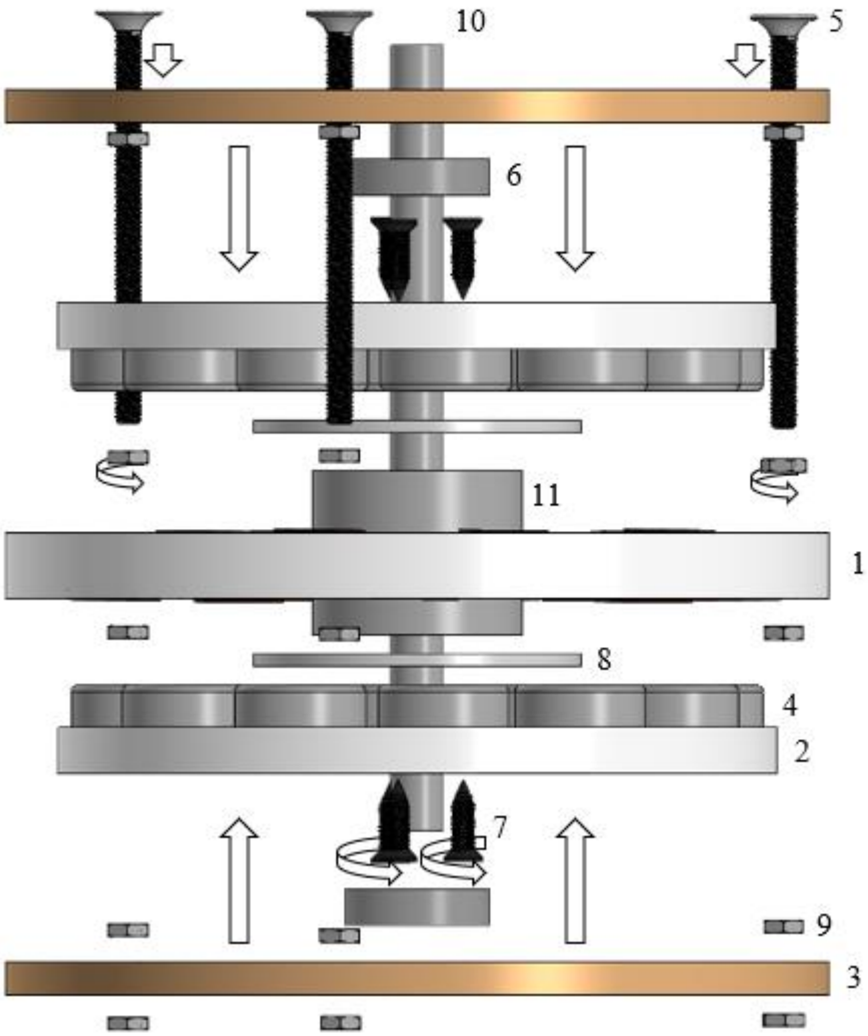


Figure 33. Generator assembling scheme

Magnets 4 are glued into the slots of the rotor support 2, for additional strengthening of the contact zone with the cylinder, a protection 8 with a hole slightly smaller than the stator hole is glued to the base. The rotor support is fixed by self-tapping screws 7 to the cylinder 11, previously fixed to the shaft 10, and the stator 1 is laid on the shaft, on the other side, the rotor support closes the stator. Bearings 6 are fixed with glue on the cover 3 and then the shaft is threaded into the bearings. The screws 5 are threaded into the holes on the lids and fixed with nuts 9. In perfect calculation, rotor must lay on the bearing with self-tapping screws, but if not – metallic spacer can be placed in between. An isometric view and a front view of the generator in assembled form are shown in Figure 34.

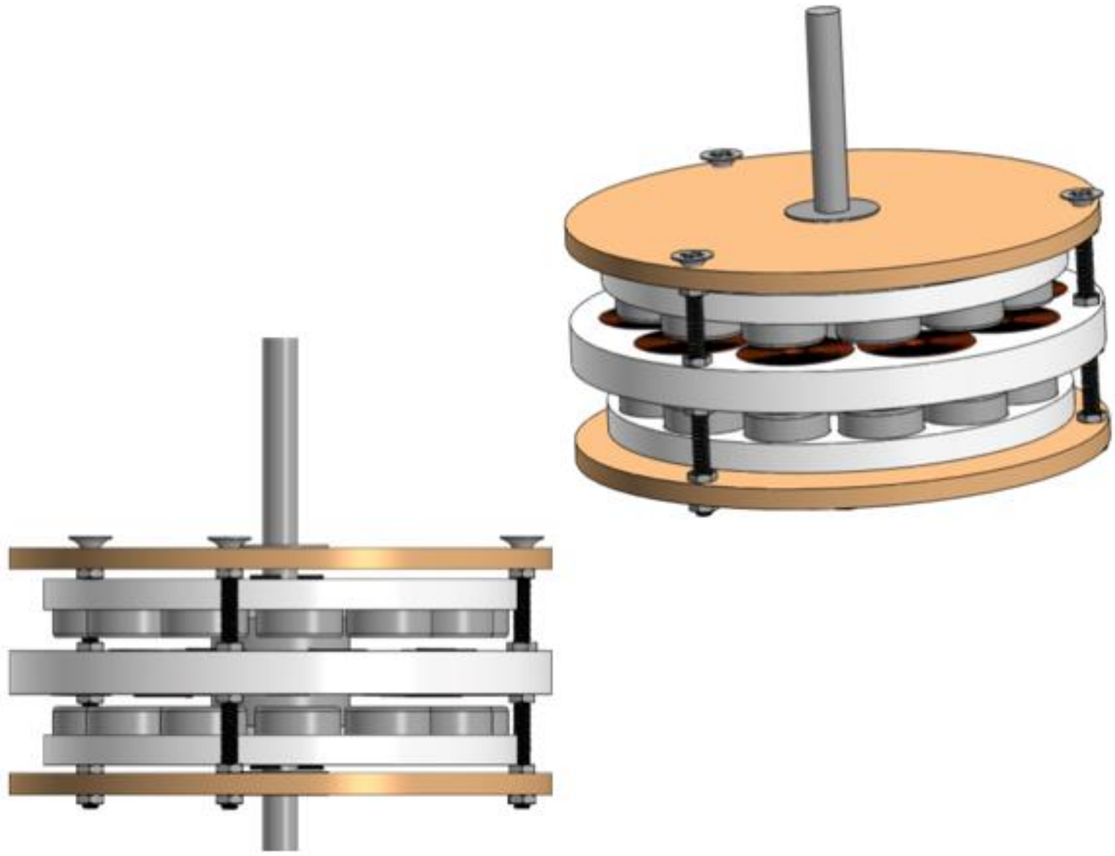


Figure 34. Axial flux generator 3D-model.

Suspension screws 5 and nuts 9 (see Figure 33) must be non-magnetic or mildly magnetic, for that purpose, stainless steels are perfect – most of them do not attract magnets and do not create additional cogging torque.

3.3.2 Wind turbine rotor assembling

Table 5 represents parameters for wind turbine rotor assembling.

Table 5 Main parameters for Darrieus H-type rotor

Parameter	Value for rotor
Nominal tip speed ratio	2.10
Nominal wind speed v, m/s	6
Rotor radius r_{rot}, m	0.27
n_n, rotation per minute	420
$n_{n,RPS}$, rotation per second	7
Front plane width w, m	0.55
Blade height h_{rot}, m	0.55
Blade elongation, z	7.5
Relative blade thickness, c'	0.175
Wind flow area S, m^2	0.302
Blade length b, m	0.08
Blade chord c, m	0.014
h/D ratio	1
Power coefficient	0.2
Nominal power of turbine P_{rot}, W	6

For the most efficient operation of the rotor in the wind and to reduce the starting torque, it is necessary to make the rotor from the lightest possible materials. The most vulnerable part of the Darrieus H-type rotor is the axial hub, since it is subjected to the main stresses during rotation. The choice of materials for creating a hub is quite large, it can be any light and durable tubular material – aluminum, PVC plastic, soft wood. A hub made of 3D ABS plastic with 100% filling is used for the project, this design provides sufficient reliability for such sizes of the wind generator and is relatively inexpensive in price, and also allows to make additional holes or recesses for the desired size.

The blades are made of NASA 0018 aerofoil profile, the simplest to manufacture. It allows to keep the right proportions. The material for the manufacture of blades is 3D ABS plastic with minimal filling, since the blades almost experience only moderate stresses during rotation, and their weight plays a key role in the efficiency of the system.

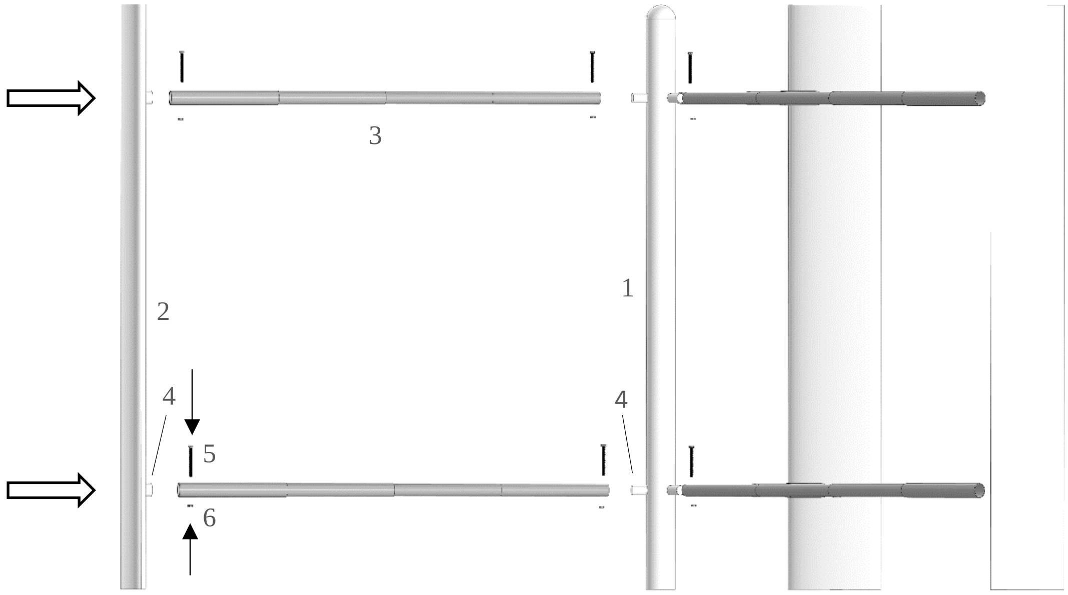


Figure 35. Assembling process of rotor

Folding telescopic traverses are made of aluminium rods for selfie sticks. Rods of the desired length are cut from two sides, a 30 cm long rod has four sections, and can be folded four times to a length of 7.5 cm, which is the most convenient and suitable solution for the size of the wind generator determined at the beginning of the project.

The assembly process is shown in Figure 35. Special cylinders 4 are used to attach the blades 2 and the hub 1 to the traverses 3. After assembly, bolts 5 are inserted into the holes previously made in both cylinders 4 and traverses 3 and fixed to nuts 6. This fastening is the only one that is as reliable as possible and moreover allows to replace broken parts, thus providing the modularity property. However, such a fastening has a drawback – the traverses do not fold completely, and the length when folded is 8.3 cm instead of 7.5 cm.

As a result, rotor is assembled without any glue connections, and the mass is 450 grams.

3.4 Open-circuit back-emf trails

In order to explain rectification process and compare simulated waveforms with real ones, open-circuit back-emf tests have been performed. Figure 36 shows a laboratory layout for testing the generator's electrical parameters.

Figure 36. Experimental layout for electric generator measurement

Real line-to-line resistance of the phase coils turns out to be 2.6 Ohm which is acceptably close to before calculated value (R_{sll} = 2.51 Ohm)

First, generator peak AC back-emf is to be measured. Table 6 gives real peak back-emf of the generator and comparison to the calculated values.

Table 6. Real AC phase RMS back-emf of the generator

Rotation speed, rps	5	7	8	10	12
Phase RMS of back-emf, V	3.62	5.03	5.76	7.16	8.45
Calculated back-emf, V	3.59	5	5.73	7.15	8.41

Open-circuit back-emf waveforms for 5 rps and 12 rps are presented in the Figures 37 and 38 respectively.

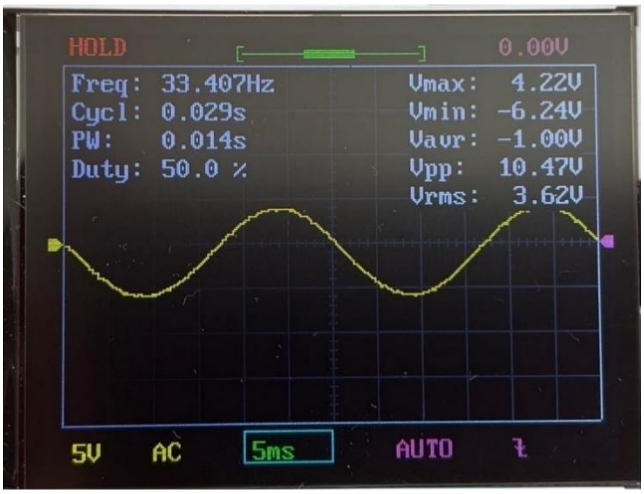


Figure 37. Back-emf waveform at 5 rps

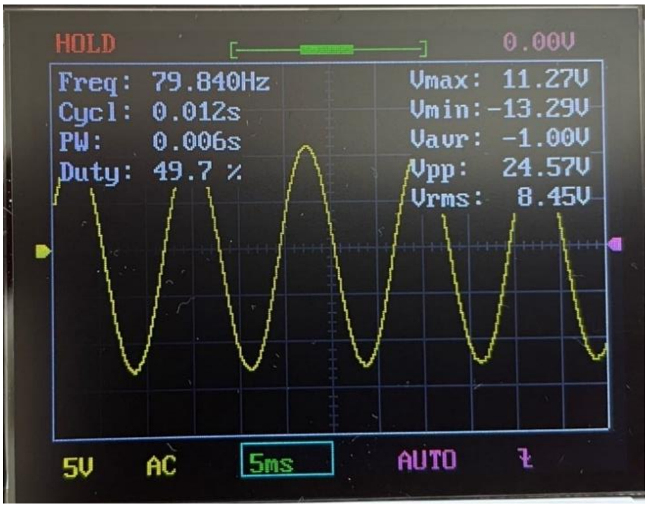


Figure 38. Back-emf waveform at 12 rps

Rectified back-emf without sinusoidal filter have been tested next. To compare the influence of the diodes – two diode bridges with different diodes have been compared. The first one is a standard bridge rectifier 26MT120 with 1.26 V forward voltage drop, the second one is a bridge rectifier made of Schottky diodes with 0.7 V forward voltage drop. Table 7 represents comparison of back-emf rectified by two different bridge rectifiers.

Table 7. Rectified open-circuit back-emf comparison for two types of diode bridges

Rotation speed, rps	5	7	8	10	12
26MT120 back-emf, V	4.11	6.37	7.46	9.28	12.85
Schottky diodes back-emf, V	5.23	7.23	8.61	10.33	13.89

Apparently, low forward voltage drop of Schottky diodes takes an advantage over usual diodes, but Schottky diodes are more expensive. Figure 39 and 40 depict the waveforms of the rectified back-emf with a Schottky diode-bridge. To improve the visibility of waveforms, oscilloscope polarity has been oppositely changed.

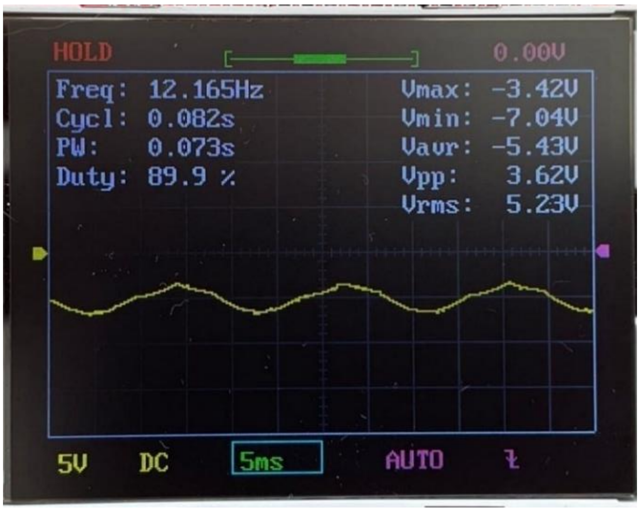


Figure 39. Rectified back-emf waveform at 5 rps

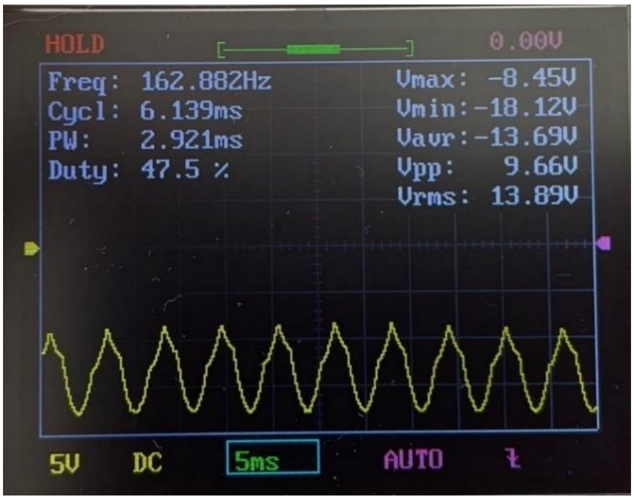


Figure 40. Rectified back-emf waveform at 12 rps

Next test provides information about the influence of filters capacity on the back-emf values. Four different values of capacitance have been chosen and test with diode bridge 26MT120 has been held. Table 8 represents related information about back-emf rectified and filtered values.

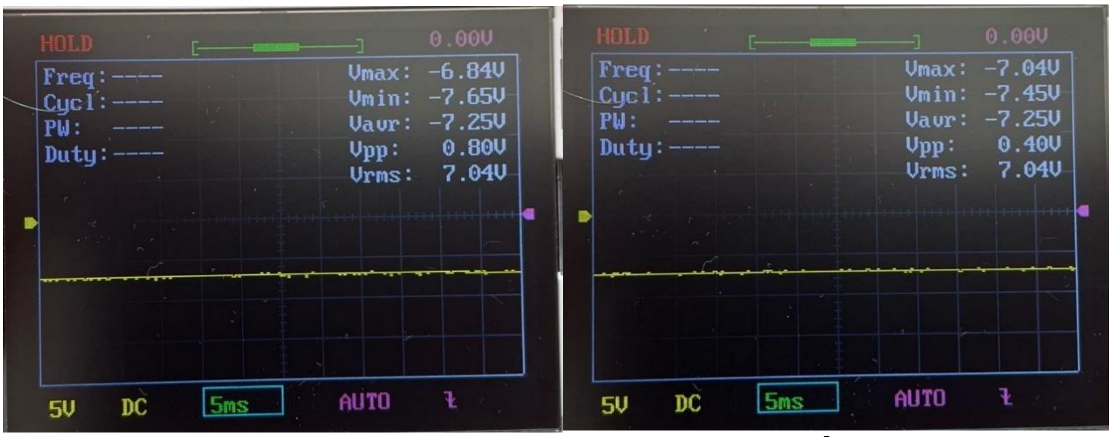
Table 8. Filtered rectified open-circuit back-emf

Rotation speed, rps	5	7	8	10	12
Back-emf for 1000 μF capacitor, V	7.04	8.32	10.4	12.48	15.61
Back-emf for 100 μF capacitor, V	7.11	9.17	11.53	13.62	16.90
Back-emf for 10 μF capacitor, V	7.41	9.19	11.59	13.54	17.31
Back-emf for 1 μF capacitor, V	7.89	9.42	11.73	13.67	17.92

As it states, back-emf voltage increases with lower values of capacitance which can be explained with faster charge-discharge time of the capacitors with lower capacitance values. Figures 41 and 42 represent rectified and filtered back-emf waveform comparison.

a b

Figure 41. Rectified and filtered back-emf waveform at 12 rps and 1000 μF capacitor: a) – Schottky diode; b) – 26MT120



a b

Figure 42. Rectified and filtered back-emf waveform at 5 rps and 1000 µF capacitor: a) – Schottky diode; b) – 26MT120

Picture of the wind generator layout is shown in Figure 43.

Figure 43. Hiking wind generator experimental layout

Further tests will include investigations of the wind generator aerodynamic characteristics in real life application under different wind speeds below and above nominal point.

Conclusion

The main goal of the project was to write a general guidance to design and creation of a small household wind generator. The first chapter gave a complete description of the existing parts of the wind turbine, their advantages and disadvantages under various conditions of use. The description and comparison of main types of electric generators led to the following conclusion – the most suitable type of a very small electric generator is a three-phase axial-flux electric generator. Although the assembly process is quite complex and time-consuming and even a simplified version of calculations requires certain skills, this type of electric generator is much more effective for use in hiking wind turbines. If a more powerful domestic system is needed the versions described in the beginning including induction generator or induction motor converted into a PMSM or even an ICE generator are more appropriate solutions.

Comparison of wind turbine rotors led to following conclusion – the advantages and disadvantages of different types overlap, and choice should be based on assessment of capabilities and skills of the designer. The Savonius rotor is the easiest to assemble, but it is not capable to develop high rotational speeds. The propeller-type rotor develops a high speed and torque but requires wind orientation devices and does not allow placing equipment on the ground, which complicates the maintenance and requires precise mechanical calculations of the ground-support. Darrieus rotor seems to be a good solution but requires special tools to be assembled.

The second chapter was a practical part of mastering the theory. A portable wind generator with an axial three-phase electric generator and an H-type Darrieus rotor were chosen for the experiments. Theoretical calculations slightly deviate with real ones, which can be explained by the structure of the electric generator – selection of $q = 0.25$, probably, reduced the active number of coils working on back-emf creation, besides, rough estimation of some parameters, such as airgap flux density, could also lead to inaccurate results.

Nominal rotation speed of the electric generator is 420 revolutions per minute, or 7 revolutions per second. The wind generator is capable of developing a nominal rotational speed with 6 m/s wind speed. Above nominal wind speed the basic control feature is implemented - generator slows down the turbine too effectively after reaching the nominal point and as a result, turbine rotational speed cannot become higher than nominal. At 7 revolutions per second, the generator develops 4.37 V of phase RMS and is able to charge the battery with a nominal charging current slightly less than 1 A.

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Appendix A. Back-emf calculation for axial flux three-phase generator

In order to summarize data, presented in chapter 3, here is a step-by-step back-emf calculation guide for the axial flux three-phase generator.

1. First, desired back-emf of generator is defined:

We want it to be $E_{nom} = 5$ V. This is phase RMS of back-emf.

2. Then, nominal wind speed, nominal tip speed ratio (TSR), nominal power coefficient C_p and desired nominal power of wind turbine P_{rot} is set to be:

$v_{nom} = 6$ m/s, $\lambda_{nom} = 2.10$, $C_p = 0.2$ and $P_{rot} = 6$ W.

3. Now, Darrieus H-type rotor radius can be defined through the wind flow area (eq. 23 – 24) and $h/D = 1$:

$$S_{\mathrm{rot}} = \frac{2P_{\mathrm{rot}}}{\eta C_p \rho v^3} = \frac{2 \cdot 6}{0.75 \cdot 0.2 \cdot 1.225 \cdot 6^3} = 0.302 \text{ m}^2$$

Considering $h/D = 1$:

$$S_{\mathrm{rot}} = h_{\mathrm{rot}} W = h_{\mathrm{rot}}(r_{\mathrm{rot}} + D_{\mathrm{mast}} + r_{\mathrm{rot}} \cos(30°))$$

$$=> r_{rot} = \frac{\frac{S_{\mathrm{rot}}}{h_{\mathrm{rot}}} - D_{\mathrm{mast}}}{(1 + \cos(30°))} = \frac{\frac{0.302}{0.58} - 0.03}{(1 + \cos(30°))} = 0.27 \text{ m}$$

4. Rotational speed according to (26) is calculated:

$$n = \frac{60\lambda v}{2\pi r_{\mathrm{rot}}} = \frac{60 \cdot 2.10 \cdot 6}{2 \cdot 3.14 \cdot 0.27} = 420 \text{ rpm}$$

5. The next step is to choose number of slots per pole and phase q. In case of the project, q is set to be 0.25 with 9 coils and 12 PM poles (6 pole pairs).

6. According to project needs, stator diameter cannot be no more than $D_{ys} = 128$ mm and rotor is therefore $D_{yr} = 110$ mm with magnets of N42 type with coercivity $H_c = 1000$ kA/m and diameter 20 mm. Coil diameter is 28 mm at maximum (Figure 20).

7. According to Figure 19, magnetic flux density in airgap can be calculated (eq. 28-29):

$$\delta_{\mathrm{eff,PM}} = h_{\mathrm{PM}} + \delta + \frac{h_{\mathrm{ys}}}{2} + \frac{\tau_{\mathrm{p}}\pi}{4} = 0.01 + 0.0015 + \frac{0.01}{2} + 0.026 \cdot \frac{\pi}{4} = 0.037\ \mathrm{m}$$

$$\tau_{\mathrm{p}} = \frac{\pi D_{\mathrm{yr.avg}}}{2p} = 3.14 \cdot \frac{0.1}{2 \cdot 6} = 26\ \mathrm{mm} = 0.026\ \mathrm{m}$$

$$B_{\delta} = \frac{h_{\mathrm{PM}} H_{\mathrm{c}} \cdot \mu_0}{\delta_{\mathrm{eff,PM}}} = \frac{0.01 \cdot 1000000 \cdot 4 \cdot 3.14 \cdot 10^{-7}}{0.037} = 0.34\ \mathrm{T}$$

8. Winding factor can be calculated according to equations (32-36):

Slot angle e.g. for inner layer:

$$\theta_{\mathrm{p}.n} = 360 \cdot p \cdot \frac{d_{\mathrm{i.1}} + 2d_{\mathrm{Cu}} \cdot 1}{2\pi r_{\mathrm{ys}}} = 360 \cdot p \cdot \frac{(8 + 2 \cdot 0.63 \cdot 0)}{2 \cdot 3.14 \cdot 42.15} = 65\ \mathrm{el.deg}$$

Electrical angle between each pole:

$$\theta_{\mathrm{m}} = \frac{360 \cdot p}{2p} = 180\ \mathrm{el.deg}$$

Winding factor for 1 layer:

$$k_{\mathrm{w.1}} = k_{\mathrm{d.1}} = \cos\left(\frac{\theta_{\mathrm{p.1}} - \theta_{\mathrm{m}}}{2}\right) = |\cos\left(\frac{65 - 180}{2}\right)| = 0.54$$

And summing up all layers:

$$k_{\mathrm{w}} = \sum_{n=0}^{i} k_{\mathrm{w}.n} = 0.869$$

$$i = \frac{r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}}}{S_{\mathrm{Cu}}} = \frac{14 - 4}{0.63} = 15\ \mathrm{layers}$$

9. Next, number of turns are calculated through the magnetic flux, assuming 70% of flux is a main flux (eq. 30-31):

$$\Phi_{\max} = B_{\delta} \cdot 0.7\pi r_{\mathrm{PM}}^2 = 0.34 \cdot 0.7 \cdot 3.14 \cdot 0.01^2 = 0.000075\ \mathrm{Wb}$$

$$N = \frac{\sqrt{2} E_{\mathrm{nom}}}{Q_{\mathrm{s}} \mathrm{k_w} \Phi_{\max} 2\pi n_{\mathrm{nom}} p/60} = \frac{5 \cdot \sqrt{2}}{3 \cdot 0.86 \cdot 0.000075 \cdot 2 \cdot 3.14 \cdot 420 \cdot 6/60} = 140$$

10. Inner phase resistance of stator windings is defined according to (37-40):

First is to define real cross-section of wire:

$$S_{\mathrm{Cu}} = \frac{(r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}})h_{\mathrm{ys}}}{N} = \frac{(14-4)\cdot 10}{140} \approx 0.63\ \mathrm{mm}^2$$

Then, layer length for round coil e.g. for inner layer:

$$l_{\mathrm{ws.n}} = 2\pi(r_{\mathrm{ws.i}} + d_{\mathrm{Cu}}\cdot \mathrm{n})\frac{h_{\mathrm{ws}}}{S} = 2\cdot 3.14(4 + 0.63\cdot 0)\frac{10}{0.63} = 0.398\ \mathrm{m}$$

Then, summing up all layers:

$$l_{\mathrm{ws}} = \sum_{n=1}^{i} l_{\mathrm{ws.n}} = 26.3\ \mathrm{m}$$

And phase resistance:

$$R_{\mathrm{ph}} = \rho\frac{l_{\mathrm{tot}}}{S_{\mathrm{Cu}}} = 0.0175\cdot\frac{26.3}{0.31} = 1.47\ \mathrm{Ohm}$$

11. Phase inductance can be defined with equation (41):

$$L_{\mathrm{ph}} = 3L_{\mathrm{ws}} = 3\frac{d_{\mathrm{ws}}^2 N^2}{3d_{\mathrm{ws}} + 9h_{\mathrm{ws}} + 10(r_{\mathrm{ws.e}} - r_{\mathrm{ws.i}})}$$

$$= 3\frac{0.018^2 140^2}{3\cdot 0.018 + 9\cdot 0.01 + 10(0.01)} = 2.76\ \mathrm{mH}$$

12. Voltage at generator terminals can be defined by (45):

$$U_{\mathrm{gen}} = E_{\mathrm{nom}} - I_{\mathrm{rms}}R_{\mathrm{ph}} - \mathrm{j}X_{\mathrm{L.ph}}I_{\mathrm{rms}} = 5 - 0.71\cdot 1.47 - 0.71\cdot 0.72 = 3.44\ \mathrm{V}$$

With that, line-to-line amplitude voltage is known:

$$\hat{u}_{\mathrm{ll}} = 8.30\ \mathrm{V} = U_{\mathrm{rec}}$$

and almost the same value will be at rectifiers output.

13. Resistance to be connected in series with battery can be defined with equation (46):

$$R_{\mathrm{batt}} = \frac{U_{\mathrm{rec}} - U_{\mathrm{FT}} - U_{\mathrm{pb}}}{I} = \frac{8.30 - 1.4 - 5}{1} = 1.90\ \mathrm{Ohm}.$$