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**TE<sup>4</sup>**      Technologie-Entwicklung für Erneuerbare Elektrische Energie  
(Development of technologies for renewable electric energy)

# Project "Generbine"

Underwater turbine for the production of electricity,  
of which the runner blades are at the same time  
permanent magnetic rotor poles of the generator

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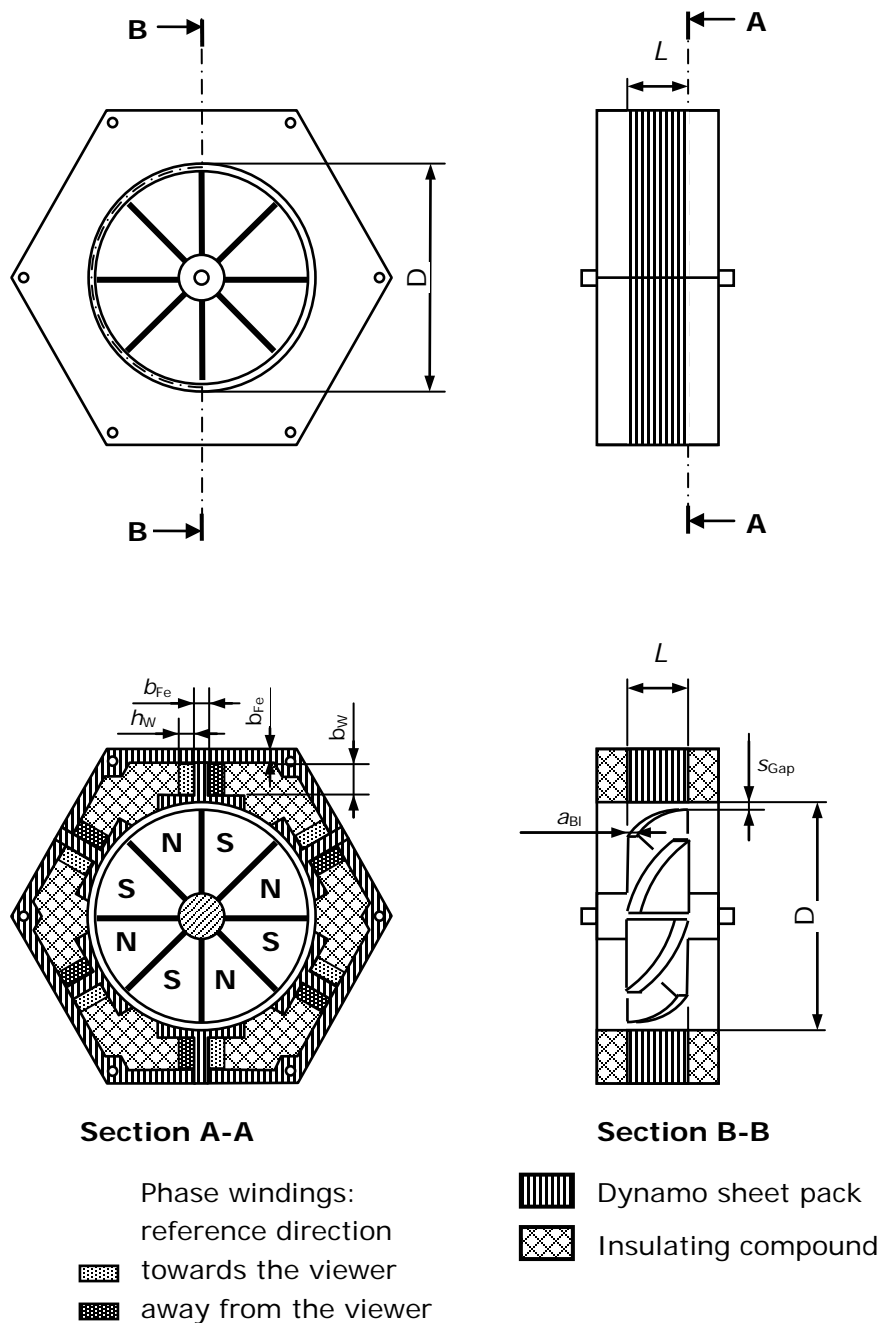
## **Abstract**

In a European patent application [1], an underwater turbine is proposed of which the blade wheel is made of hard-magnetic material and takes up the function as rotor of a permanent-excited generator. This documentation shows a conceptual draft of a prototype. It provides an analysis of its hydraulic, electrodynamic and electric properties on a conceptual basis. A prospect for the detailed analysis and the further steps of development are given as well.

This document has been translated from german without consulting a professional translator. The author therefore apologizes for any unusual or even incorrect formulations.

# 1. General concept

## 1.1 Mechanical construction



**Figure 1: Stator and rotor with their main dimensions**

Figure 1 shows the general design of the generbine. The stator of the generator consists as usual of a packet of punched soft-magnetic dynamo sheets that are insulated against each other to minimize eddy-current losses. The windings are slipped on the stator pole branches.

The rotor, however, is the true innovative element, combining the functions of the turbine's blade wheel and the generator's rotor. For that purpose, the rotor is manufactured of hard-

magnetic material, which can in principle be done by casting, sintering, or injection molding processes (the latter in the case of plastic bonded materials). The discrete segments serve on the one hand as turbine blades, for which purpose their shape is optimized, e.g. following the shapes of fixed propeller turbine blades. On the other hand, they constitute the magnetic poles, which means that their number must be even and they have to be adapted to the requirements of an optimal magnetic circuit as well.

The most important dimensioning parameters are:

$D$	Aperture diameter of the stator
$L$	Stator length (thickness of the stator sheet pack; the term "length" is here meant as "dimension in the direction of fluid flow")
$Z_{\text{Stat}}$	Number of stator poles
$Z_{\text{Rot}}$	Number of rotor poles = number of turbine blades
$a_{\text{Bl}}$	Axial projection of the blade thickness
$s_{\text{Gap}}$	Gap width between stator and rotor
$b_{\text{Fe}}$	Width of the pole branches and the yokes of the stator
$b_{\text{W}}$	Width of the windings (= length of the stator pole branches)
$h_{\text{W}}$	Height of the windings

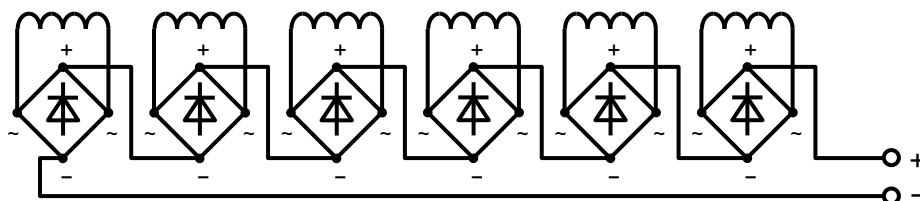
The parameters  $D$  and  $L$  can in principle be chosen arbitrarily; they determine the yield of the generator.

The number of stator poles and the number of rotor poles do not need to be equal. However, they must both be even, and it makes no sense that there would be less rotor poles than stator poles. Furthermore, the optimal width of one stator pole turns out to be equal to the width of one rotor pole (in radian measure), which means equal to  $\pi D / Z_{\text{Rot}}$  (see section 1.2).

The other parameters have to be determined according to the optimization of iron and copper losses, which is done in section 2.2.

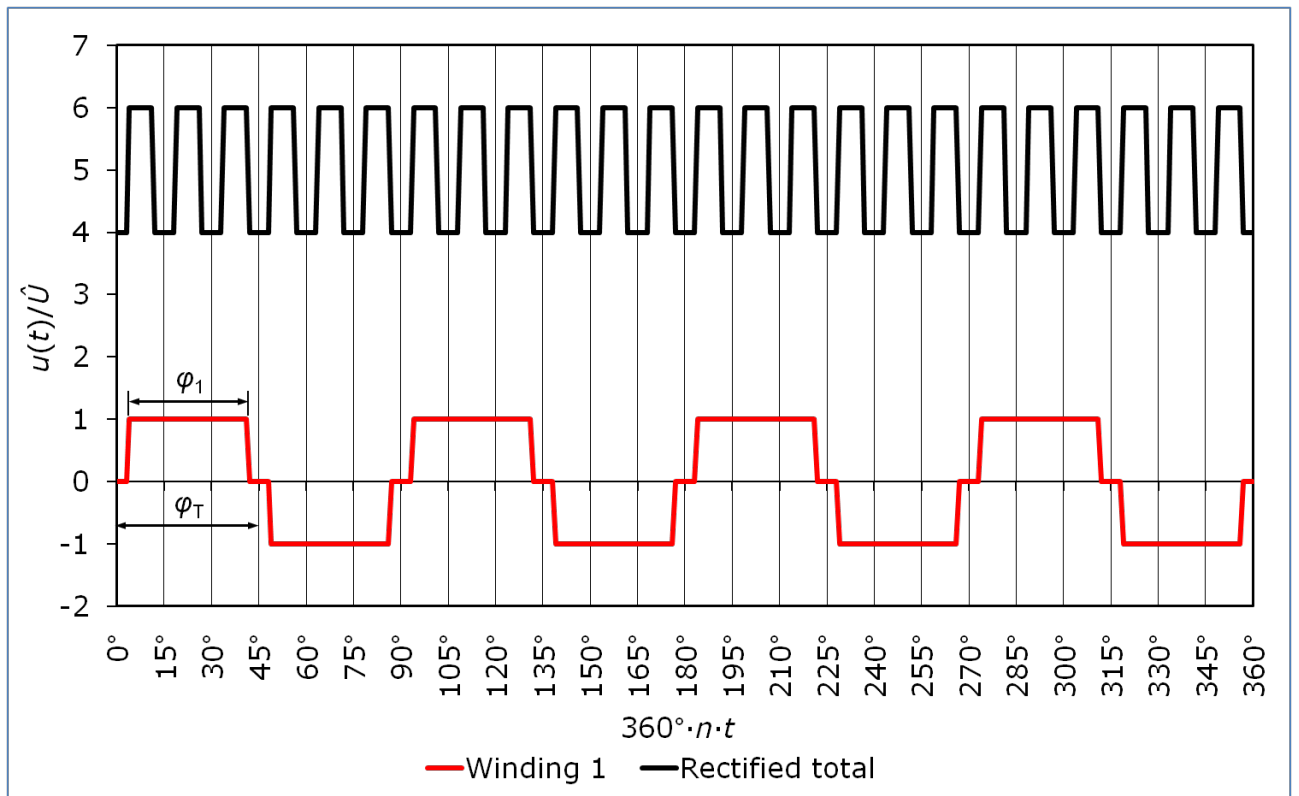
## 1.2 Electric circuit

In each of the stator windings an alternating voltage is induced, the frequency of which is determined by the rotational speed and by the number of rotor poles,  $Z_{\text{Rot}}$ . As the speed and hereby the frequency are variable, there is no sense in using the alternating voltages directly; they are rather to be rectified.



**Figure 2: Electric circuit of the stator windings**

The rectification is preferably done by a circuit according to figure 2, using one bridge rectifier for each winding. The rectifier outputs are then serially connected.

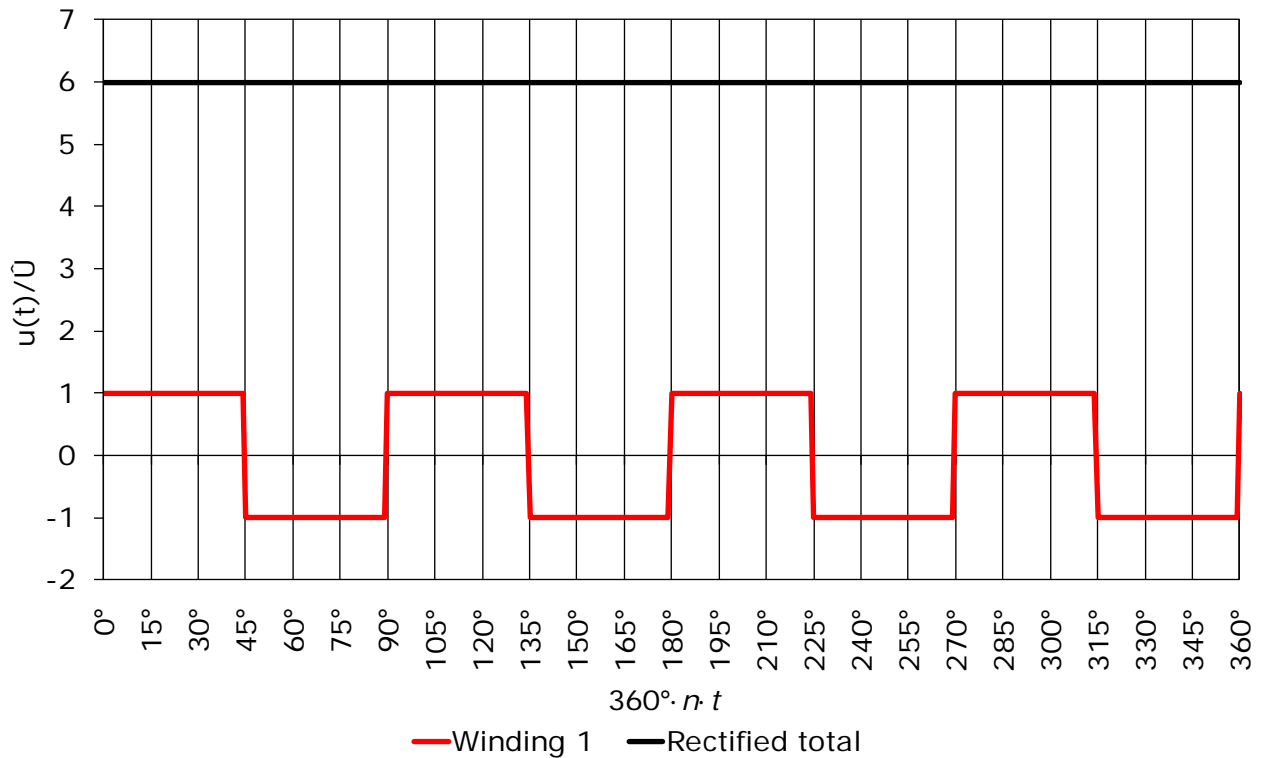


**Figure 3: Timing function of the induced voltage  
in the general case**

Figure 3 shows first, in red, the timing function of the induced voltage in winding 1. It has the shape of rectangular pulses, of which the duty factor  $\varphi_1/\varphi_T$  depends on the ratio of stator pole width to rotor pole width. The voltages on the other windings are not shown; they would be shifted by a phase angle of  $(k-1) \cdot 360^\circ/z_{\text{Stat}}$  ( $k$  being the winding number) with regard to winding 1.

Behind the serially connected rectifiers, the total direct voltage shown in black results. It contains a component that pulsates with a frequency corresponding to the rotational speed, multiplied with the least common multiple of  $z_{\text{Stat}}$  and  $z_{\text{Rot}}$ .

If the stator pole width is made equal to the rotor pole width (in radiant measure), the pulse duty factor of the induced voltage becomes  $\varphi_1/\varphi_T=1$ . Thus the pulsation of the total direct voltage is eliminated. This case, which is only possible with  $z_{\text{Stat}} < z_{\text{Rot}}$ , is shown in figure 4.



**Figure 4: Timing function of the induced voltage in the case of optimized stator pole width**

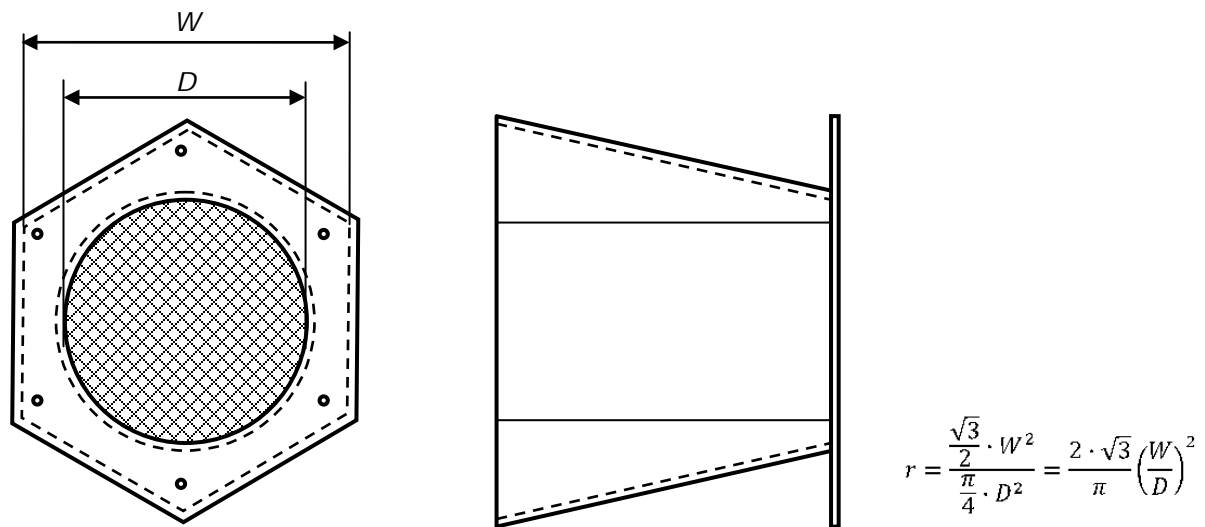
## 1.3 Balance of system

### 1.3.1 Inflow and outflow

At least on the inlet side, a grille should be provided that on the one hand protects the generbine from damage by solids floating in the water, and on the other hand prevents animals, especially fishes, from swimming in. This is also recommended on the outlet side.

Furthermore, an inflow nozzle and an outflow diffuser should be provided (figure 5) to guide the flow and thus improve the hydraulic efficiency. By means of their conic narrowing, these construction parts also raise the flow velocity within the generbine by the factor  $r$  (figure 5). In slowly flowing waters, their aperture can be made significantly larger than the external dimensions of the generbine. Thus, the latter can work in the range of optimal flow velocity.

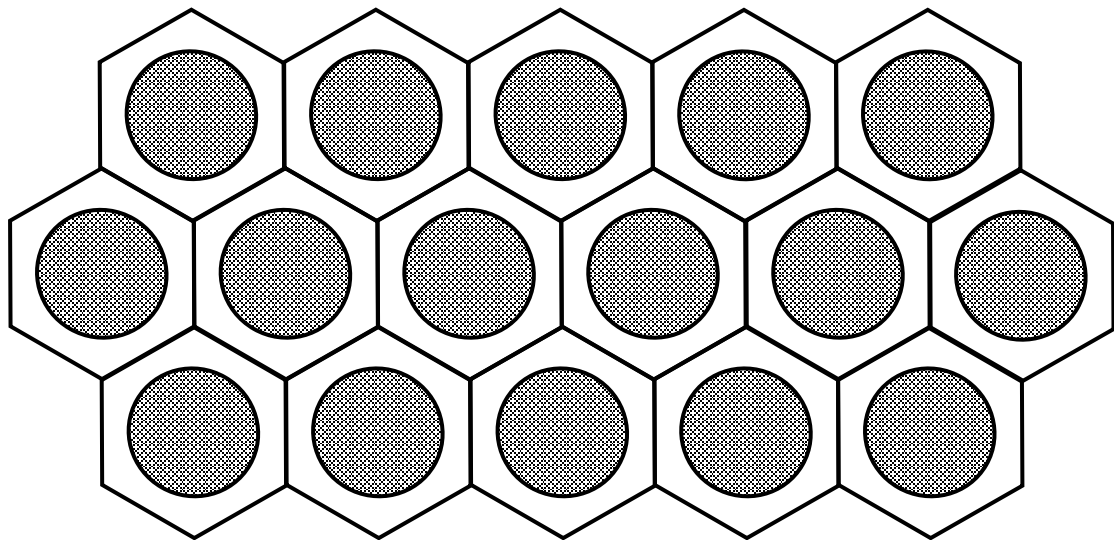
Optionally, the inflow nozzle can be provided with (fixed) guide vanes in order to further improve efficiency.



**Figure 5: Shape of the inflow nozzle and the outflow diffuser with integrated grille**

### 1.3.2 Lining-up and electric interconnection of generbines

According to the concept, greater hydroelectric plants are constructed in a modular way by lining up several generbines as shown in figure 6. As a result of the hexagonal shape, this is possible without gaps.



**Figure 6: Lining-up of generbines**

Concerning the electric interconnection, the generbine delivers a direct voltage, as seen in section 1.2. The voltage is varying with the rotational speed and hereby with the flow velocity. The best solution is to use one DC-DC converter per generbine or per group of generbines, which performs a maximum-power-point tracking as it is known from photovoltaic plants. The output is supplied to a DC bus, from which a further conversion to grid alternating voltage can take place. A corresponding concept is proposed in [2].

## 2. Conceptual analysis

As for the generbine prototype, the following dimensions are scheduled:

$D = 1 \text{ m}$  Aperture of the stator

$W = 1.47 \text{ m}$  Hexagonal inside width of the inflow nozzle and the outflow diffuser, according to section 1.3.1

$A_W = 1.87 \text{ m}^2$  Cross-sectional area of the inlet

$r = 2.38$  Nozzle throat (ratio of the sectional areas inlet to stator aperture)

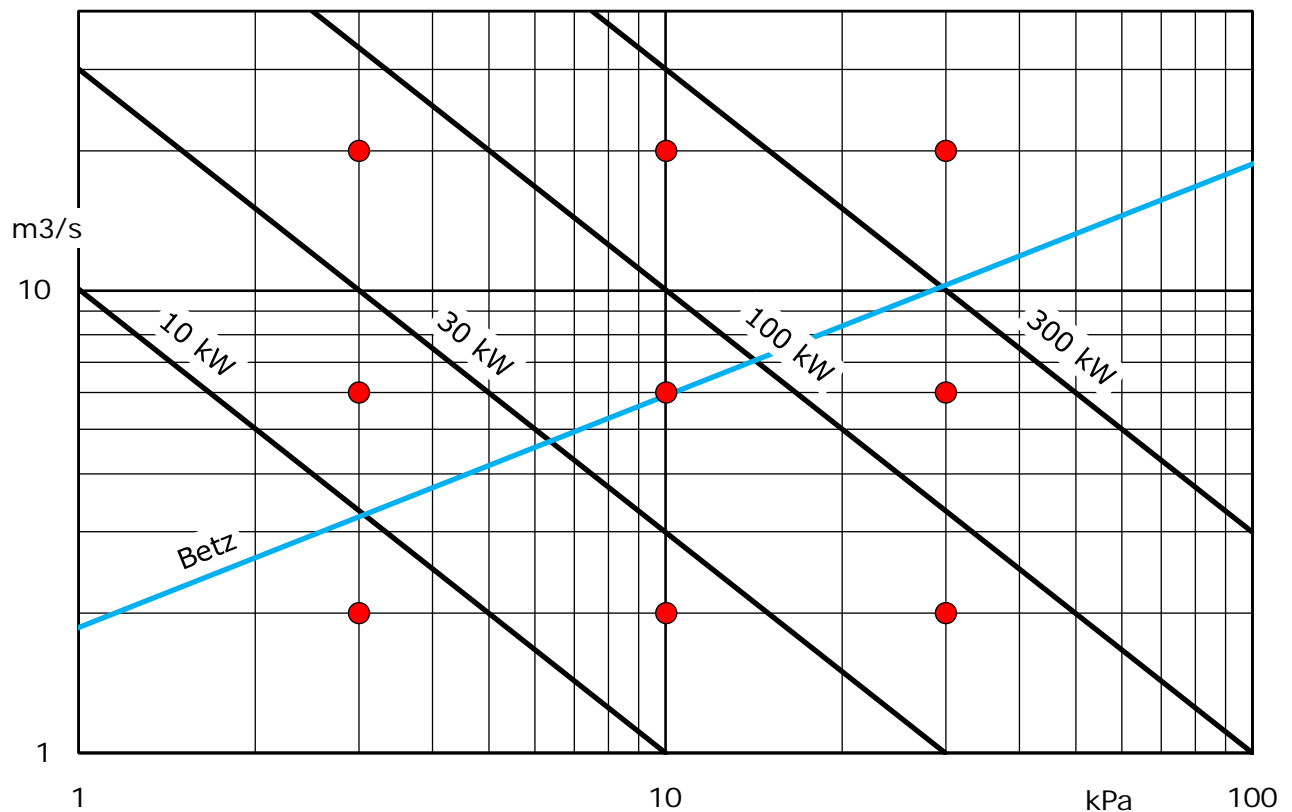
Figure 7 defines the hydraulic operating range of the generbine. The investigated working points (shown in red) include a volumetric flow range of

$Q = 2 \dots 20 \text{ m}^3/\text{s}$  according to an inlet flow velocity of  
 $c_W \approx 1.1 \dots 10.7 \text{ m/s}$ .

The pressure differences are located in the range

$\Delta p = 3 \dots 30 \text{ kPa}$  according to a fall of  
 $\Delta H \approx 0.3 \dots 3 \text{ m}$ .

### 2.1 Hydraulic dimensioning



**Figure 7: Considered operating points of the generbine in the volume flow / pressure difference diagram**

As an orientation, the diagram shows the lines of equal hydraulic power (in black). Furthermore, the blue line indicates the optimal energy utilization of a generbine that is placed in free circumfluent water. This line is calculated using the formula by Betz which has originally

been deduced for wind turbines. It says that, in the optimum working point, the inlet flow velocity is  $c_W = 2/3 \cdot c_0$  ( $c_0$  being the undisturbed flow velocity far upstream of the turbine). The hydraulic power then becomes  $P_{Hyd,Betz} = 8/27 \cdot \rho \cdot A_W \cdot c_0^3$  ( $\rho$  being the density of the medium).

The hydraulic behavior is determined by the dimensioning and the shaping of the blade wheel. The following of the quantities introduced in section 1.1 and figure 1 are important in this context:

- ◆ The blade wheel diameter  $D - 2 \cdot s_{Gap} \approx D$  ;
- ◆ The axial extension of the blades, which should be made equal to the stator length  $L$  ;
- ◆ The thickness of the blades, or its axial projection  $a_{Bl}$ , respectively. (In case of profiled blades, the average value over the profile length has to be used.) The choice of this quantity is determined by electrodynamic aspects (magnetic circuit) but has itself an effect on the hydraulic properties.
- ◆ The number of runner blades  $Z_{Rot}$ , which is identical with the number of rotor poles and must therefore be even.

For a conceptual analysis, the mechanical power is calculated first, by assuming a certain hydraulic efficiency. The rotational speed  $n$  is determined by the axial extension of the blades,  $L$ , and the number of blades,  $Z_{Rot}$ , considering an assumed slip.

## 2.2 *Electrodynamic and electric properties*

Following the hydraulic properties, the electrodynamic and electric performance has to be determined, which means calculating the value and timing function of the induced voltage as well as iron and copper losses. The most important of the quantities introduced in section 1.1 and figure 1 are:

- ◆ The gap width  $s_{Gap}$  that determines, together with the magnetic properties of the rotor, the magnetic flux density  $B_{Gap}$ .
- ◆ The sectional area of the gap,  $A_{Gap} = \pi D / Z_{Rot} \cdot a_{Bl}$ . Together with the magnetic flux density, it determines the magnetic flux that is maximally enclosed by the stator windings.
- ◆ The number of rotor poles  $Z_{Rot}$  which determines, together with the speed, frequency and value of the voltage that is induced in each of the stator windings.
- ◆ The effective iron mass and the effective sectional area ( $b_{Fe} \cdot L$ ) of the stator sheet pack. The latter has been fixed as equal to the sectional area of the gap, so that the flux densities in the gap and in the sheet pack become equal, too. This determines the value of  $b_{Fe}$ .
- ◆ The height  $h_W$  and the width  $b_W$  of the windings that determine, together with the copper filling factor, the effective sectional area of copper.
- ◆ The stator length  $L$  and the width of the pole branches  $b_{Fe}$  that determine, together with the height of the windings, the average turn length.

From these values, the losses and thus the electric efficiency can be calculated. (As for fundamental literature on the calculation of rotating electric machines, we refer e.g. to [4].)

## 2.3 Rough analysis

Quantity	Symbol	Unit	Operating point								
			1	2	3	4	5	6	7	8	9
Volume flow	$Q$	$\text{m}^3\text{s}^{-1}$	20.0	6.0	2.0	20.0	6.0	2.0	20.0	6.0	2.0
Pressure difference	$\Delta p_G$	kPa	30.0	30.0	30.0	10.0	10.0	10.0	3.0	3.0	3.0
Hydraulic power	$P_{\text{Hyd}}$	kW	600.0	180.0	60.0	200.0	60.0	20.0	60.0	18.0	6.0
Hydraulic efficiency	$\eta_{\text{Hyd}}$	1	0.90								
Mechanical power	$P_{\text{Mech}}$	kW	540.0	162.0	54.0	180.0	54.0	18.0	54.0	16.2	5.4
Stator diameter	$D$	m	1.00								
Stator length (axial)	$L$	m	0.35								
Number of stator poles	$Z_{\text{Stat}}$	1	6								
Number of rotor blades	$Z_{\text{Rot}}$	1	8								
Blade thickness (axial)	$a_{\text{Bl}}$	m	0.051								
Sectional area of the gap	$A_{\text{Gap}}$	$\text{m}^2$	0.0200								
Magn. flux density in the gap	$B_{\text{Gap}}$	T	1.0								
Iron filling factor	$k_{\text{Fe}}$	1	0.90								
Specif. loss of dynamo sheet	$p_{\text{Fe}1.5/50}$	W/kg	4.0								
Branch & yoke width (stator)	$b_{\text{Fe}}$	m	0.064	Determination: Sectional area of branch $A_{\text{Fe}} = A_{\text{Lift}}$							
Density of dynamo sheets	$\rho_{\text{Fe}}$	$\text{kgm}^{-3}$	7650								
Effective iron mass	$m_{\text{Fe}}$	kg	905								
Slip	$s$	1	0.10								
Relative peripheral speed	$u/c_G$	1	1.01								
Flow velocity	$c_G$	$\text{ms}^{-1}$	25.5	7.6	2.5	25.5	7.6	2.5	25.5	7.6	2.5
Peripheral rotor speed	$u$	$\text{ms}^{-1}$	25.7	7.7	2.6	25.7	7.7	2.6	25.7	7.7	2.6
Rotational speed	$n$	$\text{s}^{-1}$	8.19	2.46	0.82	8.19	2.46	0.82	8.19	2.46	0.82
Width of the winding	$b_W$	m	0.140								
Height of the winding	$h_W$	m	0.064	Determination: $h_W = b_{\text{Fe}}$							
Minimum turn length	$w_{\text{Cu,min}}$	m	0.83								
Maximum turn length	$w_{\text{Cu,max}}$	m	1.34								
Average turn length	$w_{\text{Cu}}$	m	1.08								
Copper filling factor	$k_{\text{Cu}}$	1	0.75								
Sectional area of copper	$A_{\text{Cu}}$	$\text{m}^2$	0.0067								
Density of copper	$\rho_{\text{Cu}}$	$\text{kgm}^{-3}$	8900								
Copper mass	$m_{\text{Cu}}$	kg	357								
Ins. compound: contact area	$A_{\text{th}}$	$\text{m}^2$	0.1158								
Insul. compound: thickness	$h_{\text{th}}$	m	0.0030								
Thermal conductivity	$\lambda_{\text{th}}$	$\text{Wm}^{-1}\text{K}^{-1}$	0.8000								
Temperature increase	$\Delta T$	K	96.8	96.8	96.8	10.8	10.8	10.8	1.0	1.0	1.0
Frequency per winding	$f_W$	Hz	32.74	9.82	3.27	32.74	9.82	3.27	32.74	9.82	3.27
Resulting pulse frequency	$f_{\text{Puls}}$	Hz	196.44	58.93	19.64	196.44	58.93	19.64	196.44	58.93	19.64
Number of turns per winding	$N_{\text{Cu}}$	1	40								
Induced voltage per winding	$\hat{U}_W$	V	105	31	10	105	31	10	105	31	10
Voltage drop per diode	$U_{\text{F,Diode}}$	V	0.70								
String current	$I_W$	A	857.8	857.8	857.8	285.9	285.9	285.9	85.8	85.8	85.8
Conductivity of copper, 120°C	$\kappa$	$\text{Sm}^{-1}$	4.08E+07								
Conductance of one winding	$G_{\text{Cu}}$	S	1.57E+02								
<b>Iron losses</b>	$P_{\text{V,Fe}}$	<b>kW</b>	<b>1.05</b>	<b>0.32</b>	<b>0.11</b>	<b>1.05</b>	<b>0.32</b>	<b>0.11</b>	<b>1.05</b>	<b>0.32</b>	<b>0.11</b>
<b>Copper losses</b>	$P_{\text{V,Cu}}$	<b>kW</b>	<b>28.03</b>	<b>28.03</b>	<b>28.03</b>	<b>3.11</b>	<b>3.11</b>	<b>3.11</b>	<b>0.28</b>	<b>0.28</b>	<b>0.28</b>
<b>Rectifier losses</b>	$P_{\text{Rect}}$	<b>kW</b>	<b>7.21</b>	<b>7.21</b>	<b>7.21</b>	<b>2.40</b>	<b>2.40</b>	<b>2.40</b>	<b>0.72</b>	<b>0.72</b>	<b>0.72</b>
<b>Electric efficiency</b>	$\eta_{\text{El}}$	<b>1</b>	<b>0.93</b>	<b>0.78</b>	<b>0.35</b>	<b>0.96</b>	<b>0.89</b>	<b>0.69</b>	<b>0.96</b>	<b>0.92</b>	<b>0.80</b>
Operating parameter											
Construction parameter											
Material or physical constant											
Others: Calculated values											

Table 1: Theoretically calculated operating points of the generbine prototype

Table 1 shows the calculation results for the investigated operating points. The construction parameters have been determined by numerous iteration steps according to the trial-and-error method. Thus, the electric losses as well as the copper and iron expenditure have already been optimized to a very large extent at the level of conceptual analysis.

The generator prototype in its planned dimensions can handle a maximum hydraulic power of  $P_{Hyd} = 600$  kW. This requires about 900 kg of iron and 350 kg of copper in the stator. Additionally, the permanent-magnetic material of the rotor will have a mass of about 500 kg.

The loss analysis shows that the copper losses are predominant at high pressure differences. At low pressure differences, the rectifier losses become more important. The iron losses play a secondary role over the whole operating range. – The best efficiency is found at the working point with the highest volume flow and the lowest pressure difference. The highest pressure difference combined with the lowest volume flow, on the other hand, leads to the worst efficiency. This part of the operating range should therefore be avoided.

### ***3. Further design aspects***

In the following, an overview of the critical points is given that have to be considered in the construction design. A prototype is currently being planned, which will serve as a first fully functional basis for further optimization steps. These should be achieved by numerical simulations and/or scale model tests. Afterwards, a second full-size prototype should be constructed by considering the gained knowledge.

#### ***3.1 Hydraulic aspects***

##### ***3.1.1 Minimal requirements for the material of the blade wheel***

As the blade wheel constitutes at the same time the permanent-magnetic rotor, the material selection is mainly given by the magnetic properties. However, some requirements have to be met according to the hydraulic function:

- ◆ Resistance against chemical corrosion by the river- or sea-water, respectively.
- ◆ Resistance against erosion by suspended solids in the water.
- ◆ Resistance against possible erosion by cavitation<sup>1</sup>.

These requirements concern only the surface of the material. There may be the necessity of coating a base material that has been selected according to the magnetic properties.

##### ***3.1.2 Shape of the runner blades***

The most important design work to be done under hydraulic aspects is the optimization of the runner blade shaping. This can be achieved by simplified calculation methods (e.g. according to [3]), by numerical computer simulations, and/or by model tests.

A special aspect of the generbine is that the blade thickness is fixed according to the second function of the blades as magnetic rotor poles.

### ***3.2 Electric und electrodynamic aspects***

#### ***3.2.1 Thermal load of the windings***

Usually, the thermal load of the windings is one of the most critical points in the dimensioning of electric machines. This is not true to the same extent for the generbine, as on the one hand the short circuit power is limited to the hydraulic power in any case, and on the other hand an excellent heat removal is given by the flowing water.

Nevertheless, attention has to be paid to a good heat conduction from the windings to the stator sheet pack (sufficient thermal conductivity of the insulating compound, high copper filling factor.)

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<sup>1</sup> Cavitation means the building and collapsing of vapour bubbles by a local vacuum at points with increased flow velocity. Whether the danger of cavitation exists, depends on the hydraulic design (see e.g. [3]).

### 3.2.2 Material evaluation and dimensioning of the rotor and the gap

The selection of the rotor material is the most important task on the electrodynamic side of the project. The following points have to be considered:

- ◆ Magnetic properties:  
Remanent flux density  $B_r$  ( $> 1$  T), coercivity  $H_c$ , aging stability.
- ◆ Mechanical properties.
- ◆ Material costs.
- ◆ Effort for processing:  
Production in the desired size and shape by which processing steps?  
Costs depending on the production run?
- ◆ Possibilities of surface treatment or coating (see also section 3.1.1)

As the rotor is the true innovative element of the generbine, a careful evaluation and the search for the optimal compromise to meet the different requirements is most crucial.

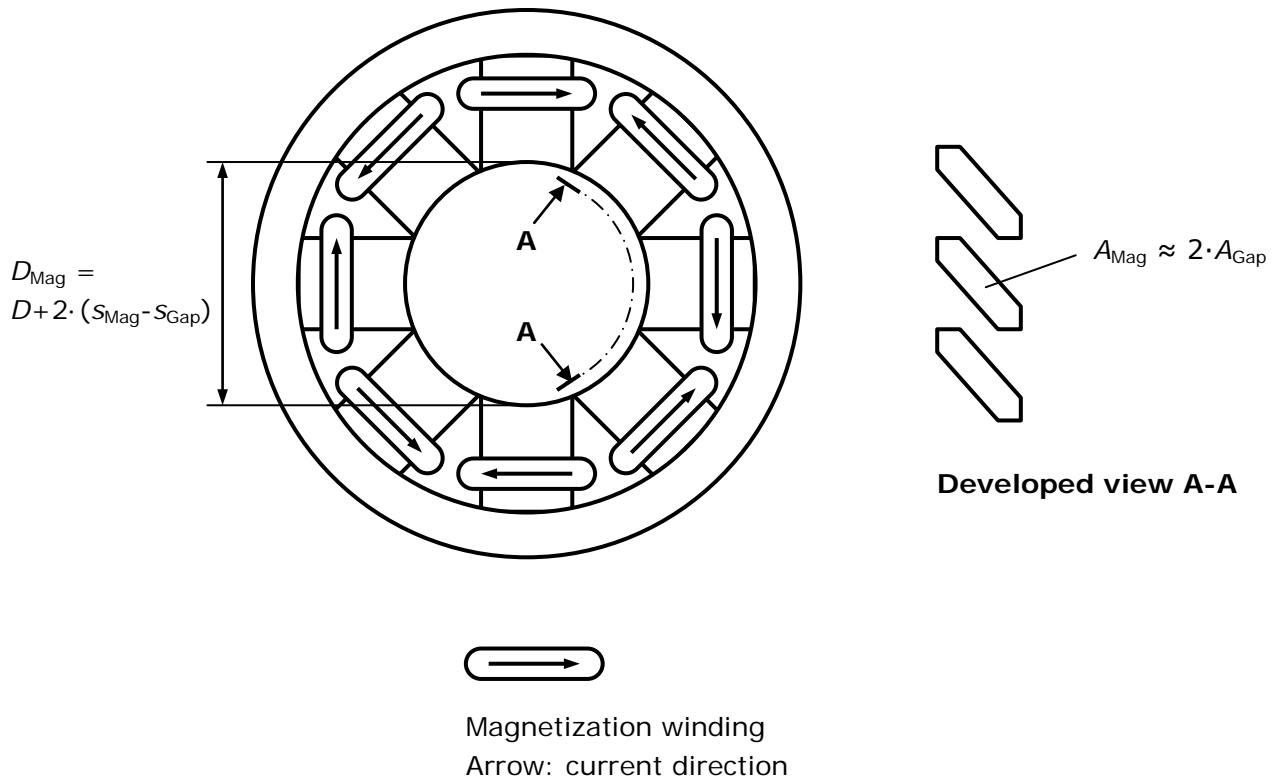
For the dimensioning of the rotor and the gap, the points to be considered are:

- ◆ The section area of the poles should be kept constant from the gap to the hub:  
 $A_{\text{Rot}} = a_{\text{Bl}} \cdot \pi D / z_{\text{Rot}}$   
The magnetic path length is approximately:  
 $w_{\text{Rot}} \approx \frac{1}{2} \cdot D - s_{\text{Gap}}$
- ◆ The gap should be, from the electrodynamic point of view, as small as possible. There are, of course, limits given by the production tolerances and the required mechanical ruggedness of the generbine. In any case, the gap width has to be small enough that the magnetic field strength in the permanent-magnetic material,  $H_{\text{Rot}}$ , is sufficiently far below the coercivity:  
 $H_{\text{Rot}} \ll H_c$   
As approximately  $H_{\text{Rot}} \cdot w_{\text{Rot}} \approx B_{\text{Gap}} / \mu_0 \cdot s_{\text{Gap}}$  is valid, it follows:  
 $s_{\text{Gap}} \ll H_c \cdot w_{\text{Rot}} \cdot \mu_0 / B_{\text{Gap}}$ ,  $\mu_0 = 4\pi \cdot 10^{-7}$  Vs/Am  
With  $H_c = 50$  kA/m,  $w_{\text{Rot}} = 0.49$  m,  $B_{\text{Gap}} = 1$  T as an example:  
 $s_{\text{Gap}} \ll 31$  mm; with a gap width of 5 mm there is a safety factor of about 6 left.

The actual flux density in the gap,  $B_{\text{Gap}}$ , follows from more detailed calculations based on the magnetization curve of the rotor material, or from experiments.

### 3.2.3 Magnetization of the rotor

For the magnetization of the rotor, an equipment must be available that is able to produce inside a sufficiently strong radial magnetic field with eight poles. Such an equipment is shown in figure 8. The dimensions are indicated depending on the dimensions of the generbine (see section 1.1).



**Figure 8: Equipment for the magnetization of the rotor**

The following material and design properties of the generbine have to be considered (see sections 1.1, 2.2 and 3.2.2):

- ◆ Saturation flux density  $B_s$  of the rotor material.
- ◆ Coercivity  $H_c$  of the rotor material.
- ◆ Number of rotor poles  $z_{Rot}$ .
- ◆ Magnetic path length in the rotor poles  $w_{Rot}$ .
- ◆ Magnetic section area of the rotor poles  $A_{Rot}$ .

From that follow the requirements to be met by the magnetization equipment:

- ◆ Sectional area of the magnetization poles,  $A_{Mag}$ :  
 $A_{Mag}$  should be chosen about twice  $A_{Gap}$  to make sure that the soft-magnetic material works far enough below the range of saturation.
- ◆ Gap between the magnetization poles and the rotor poles,  $s_{Mag}$ :  
 $s_{Mag}$  should not be too large (e.g. about equal to the gap of the generbine,  $s_{Gap}$ ), such that the main part of the magnetomotive force becomes active in the rotor poles.
- ◆ Magnetomotive force ("ampere turns") in the pole windings of the magnetization equipment,  $\Theta$ :  
 $\Theta$  should be chosen according to the manufacturer's data of the rotor material. Usually, the field strength in the rotor poles should reach about five times the coercivity. If the influence of the gap width can be neglected, it follows from that:  
 $\Theta > 5 \cdot H_c \cdot w_{Rot}$ ; at a coercivity of e.g.  $H_c = 60 \text{ kA/m}$  and a magnetic path length of  $w_{Rot} = 0.49 \text{ m}$ , this means  $\Theta > 147 \text{ kA}$  or about 150000 ampere turns.

The magnetization can be achieved by a short current pulse.

Depending on the hard-magnetic properties of the rotor material, an open storage of the rotor may no longer be admissible after the magnetization, because the rotor might be partly demagnetized if the magnetic circuit is not closed. It is recommended to move the rotor by a controlled spinning from the magnetization equipment into a magnetic short-circuit collar, such that the rotor poles are continuously enclosed by soft-magnetic material. The rotor can then be stored in the collar for a long time, until it is definitely mounted by shifting it from the collar directly into the stator.

## 4. *Reference publications*

- [1] European Patent Office, 1<sup>th</sup> September 2010  
Patent application EP10174933, Applicant: Max Blatter  
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Feeding into the grid of electric energy from distributed sources of variable power over a DC bus  
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