Tampere University of Applied Sciences, Master of engineering
Electrical engineering; renewable energy
Hannes Stubbe

Final thesis

ESTIMATION OF THE POWERLOSSES IN THE ELECTRICAL PART OF A WAVE ENERGY CONVERTOR: ASWEC

Supervisor: Lauri Hietalahti
TAMK
Tampere 05/2010

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Thesis	Estimation of the powerlosses in the electrical part of a wave energy convertor: ASWEC
Pages	93
Graduation time	June 2010
Thesis supervisor	Lauri Hietalahti
Thesis orderer	TAMK

Abstract

This thesis is made for the department of electrical engineering of the University of Applied Sciences TAMK. The objective of this thesis is to find a electrical solution for the power production of their ASWEC machine and to estimate the losses of the electrical part by using Simulink.

The machine is a new concept of wave energy conversion. We use the linear movement of a buoy to turn a permanent magnet generator. Combining several devices together can stable the voltage, current and power output.

Keywords: WEC, ASWEC, wave energy, buoy, permanent magnet synchronous machine , bridge of diodes

Schrijver Hannes Stubbe
Thesis Schatting van the elektrische verliezen in een golf energie convertor: ASWEC

Bladzijden 93
Afstudeertijd Juni 2010
Thesis begeleider Lauri Hietalahti
Thesis aanvraag TAMK

Abstract (in Dutch)

Deze thesis is gemaakt voor het departement elektriciteit van the universiteit van toegepaste Wetenschappen TAMK. Het hoofddoel van deze thesis is het vinden van een elektrische oplossing voor de vermogen productie van de ASWEC-machine. Vervolgens moeten de verliezen bij deze oplossing geschat worden door gebruik te maken van Simulink, Matlab.

Deze machine is een nieuw concept van energieconversie. We zetten de lineaire beweging van een boei om in een rotatiebeweging. Deze rotatiebeweging gebruiken we om een synchrone permanente magneet generator aan te drijven. Door verschillende toestellen samen te koppelen kunnen we een stabiele spanning, stroom en vermogen verkrijgen.

.

Kernwoorden: WEC, ASWEC, golf energie, boei, permanente magneet synchrone generator, diodebrug

Preface

This work has been carried out at TAMK University of Applied Sciences in Tampere, Finland, during the second semester of the 2009/2010 academic course.

Writing this thesis was very challenging for me. I was aboard in Finland, miles away from my home country Belgium and English isn't my mother tongue.

This work is about a new wave energy application. We try to use the linear movement of the wave to turn a permanent magnet synchronous generator.

I thank my teacher Lauri Hietalahti for his help with the models and giving my advice in my report. I thank Leen Haesaert, who helped me with writing and spelling mistakes and many others that gave me useful tips and appropriate support.

Tampere May 2010

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Hannes Stubbe

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Abbreviations and symbols

symbol	*definition*
ASWEC	*'Aaltosorvi wave energy convertor' (Aalto=wave; sorvi= lathe)*
PTO	*power take off*
HVDC	*High voltage direct current*

Abbreviations and symbols waves		
symbol	*Unit*	*Definition*
λ	M	*wavelength*
T	S	*time period of the wave*
TA = A	M	*amplitude wave*
H = Hc	M	*peak to peak amplitude of the wave= 2A*
V	m/s	*horizontal velocity wave* $v = \frac{\lambda}{T} = \lambda f$
ω	Rad/s	*rotational speed*
N	rpm	*rotational speed*
f	rad/s	*frequency wave*
g	m/s^2	*gravity = 9.81* m/s^2
P	W/m	*total wave energy per unit crest width, under ideal conditions*
ρ	kg/m^3	*mass per volume*

Abbreviations and symbols generator		
Symbol	*Unit*	*definition*
D1	m	*diameter of the first gear of the gearbox*
ω 1	rad/s	*rotational speed of the first gear of the gearbox*
μ_e		*efficiency of mechanics and generator*
F_b	N	*force of buoy*
Va, Vb, Vc	V	*synchronous generator phase-to-phase voltages*
Ia, Ib, Ic	A	*synchronous generator phase-to-phase currents*
k1		*form factor*
k2		*winding factor*
$U_d = U_{average}$	V	*average DC voltage*
f	rad/s	*frequency generator*

PM		*permanent magnet*
BPM		*buried PM*
SMPM		*surface mounted PM*
P		*the amount of pole pairs*
φ_{max}		*total magnetic flux of a pole that passes a conductor completely while rotating*
B_{max}		*induction caused by* φ_{max}
$\bar{E}$	V	*average voltage:* $\bar{E} = \varphi_{max}\, 2pn2N$
E_{max}	V	$\frac{\pi}{2}\bar{E}$
E_{eff}	V	*effective voltage:* $E_{eff} = 4{,}44\, pn\varphi_{max}\, N$
R	Ω	resistance
Ld		*direct reluctance*
Lq		*quadrature reluctance*
φ_A		*flux induced by armature: armature flux*
φ_E		*flux induced by PM*
$\overline{E_{ae}}$	V	*average voltage induced by* φ_E
R_a	Ω	*average armature resistance*
$\bar{I_a}$	A	*average armature current*
$\bar{I_q}$	A	*average quadrature, resistive current*
$\bar{I_d}$	A	*average direct or reactive current*
$Pgen$	W	*generator losses in the windings*

Abbreviations and symbols diode bridge and grid		
Symbol	*Unit*	*Definition*
RD	Ω	*conducting resistance in the diode*
VF	V	*forward voltage drop in a diode*
$P_{D,conducting}$	W	*conducting losses through diode*
$P_{D,switch}$	W	*switching losses through diode*
$P_{D,inv}$	W	*inverse losses through diode*
U_D	V	*voltage diode*
I_D	A	*current diode*

$i_{inv}(t)$	A	*instantaneous inverse leakage current through diode*
I_{inv}	A	*inverse leakage current through diode*
t_{inv}	s	*time of the inverse polarization*
$u_{inv}(t)$	V	*instantaneous inverse voltage over diode*
$U_{av,inv}$	V	*average inverse voltage over diode during inverse polarized*

Introduction

This reporting guide consists of 5 chapters.

In the first part of my thesis I will explain how waves behave and what the potential of waves is in our energy production. After that I will also tell something about the mechanical devices of the wave energy project ASWEC. ASWEC stands for 'Aaltosorvi wave energy convertor'. Aaltosorvi is just the name of the device (aalto=wave; sorvi = lathe). In the third part I will explain the necessary theory for understanding my thesis, such as different kind of machines, the working principles of a bridge of diodes etc…

The 4th chapter is about the model that we use for all our simulations. I will introduce the working of the model and explain which input values we used. We will run the simulation to show what the outputs are.

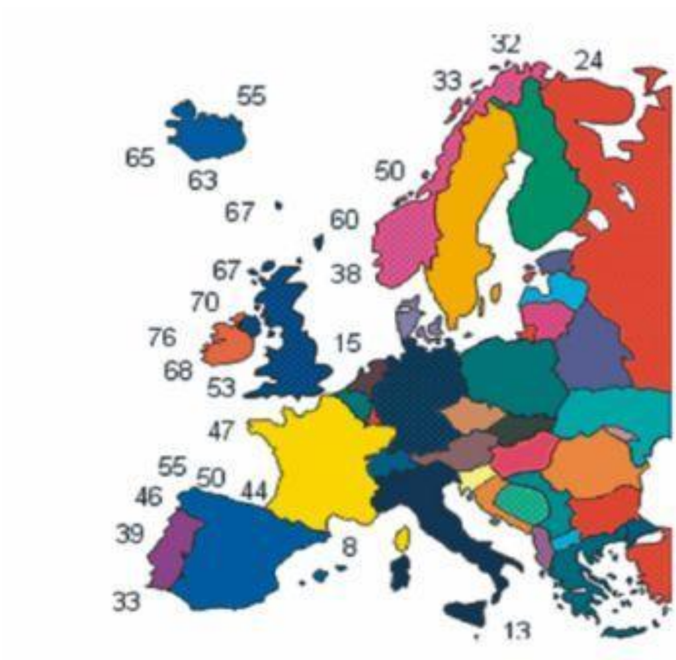
In the fifth part of my thesis I will make estimations of the losses of the electrical part of the ASWEC-machine. My estimations include the generator losses in the windings, the losses in bridge of diodes and I will also make a model to calculate the power losses in de DC circuit behind the rectification process.

1 Wave Energy and the ASWEC-project

1.1 Wave Energy around the world, and what about Belgium.

Ocean waves are generated by the wind. The wind energy is in turn produced by sun energy. So we can say that wave energy is a concentrated form of solar energy. An advantage of wave energy is that it doesn't fluctuate that much as wind energy. Variations in wind are compensated by the high inertia of the water.

Figure of estimated global annual average wave power in kW/m of wave front.



(Figure 1.1; Source: European Wave Energy Atlas, Average Theoretical Wave Power (kW))

The western coastline and the British coast is a favourable place to collect energy from waves. It is an interesting type of energy to make studies of in Belgium. Important are the possibilities to combine it with off-shore wind parks.

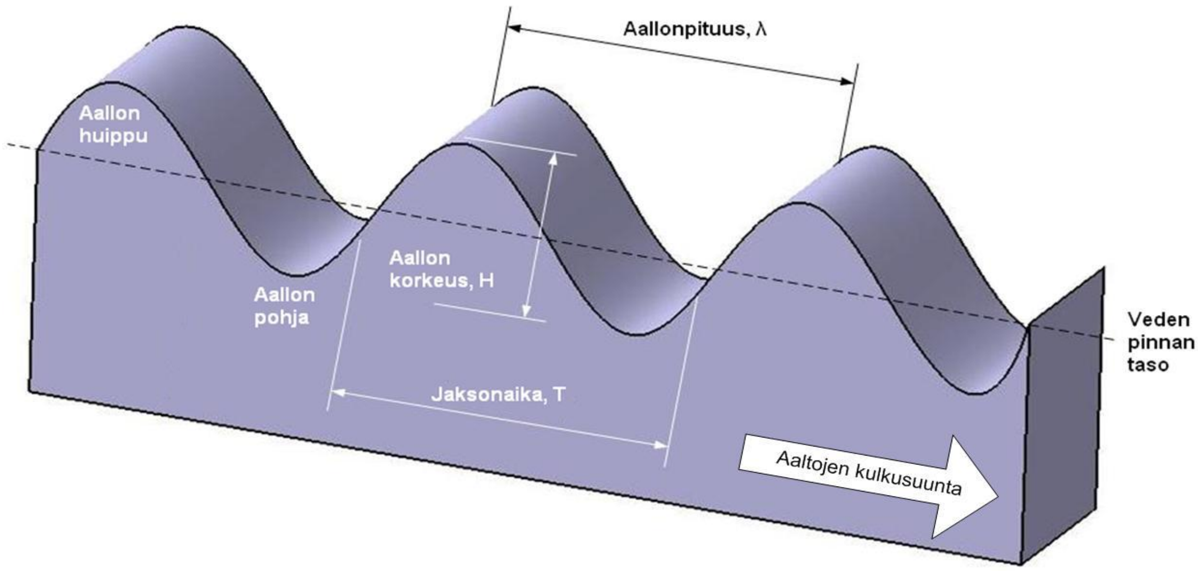
1.2 Basic properties of ideal-water waves

The energy density of waves in deep water is much higher than in undeep water areas. Off-coast wave parks are more favourable. But the height of the waves raises when they reach the shore which can be a very favourable characteristic, even if a part of the energy has been lost. Also the transportation cost of low power electricity is much lower with applications closer to the shore.

Deep-water is defined as places where the mean depth of the sea bed is greater than half a wavelength of the water wave. A typical wave length is 10 meters, so mean depths of more than 5 meters can be considered as ‘deep-water’ conditions. But, of course, this is depending on the occurring wave conditions.

The waves are sinusoidal in nature. Or a sum of sinusoidal, but mostly one sinus is dominating the others. To simplify the calculations in the models, we always use one sinus as a representation of the wave.

1.2.1 How much energy contains a wave



(Figure 1.2.1)

λ=wavelength (in m)

T= time period (s)

A= amplitude (in m)

H=Peak to peak amplitude=2A (in m)

Usually A< λ/10

v= wave progresses with a horizontal velocity v (individual particles describe circular paths) (Aaltojen kulkusuunta= travel direction of the waves).

Frequency f is related to the wavelength λ and the horizontal speed v.

$$v = \frac{\lambda}{T} = \lambda f \text{ (in m/s)} \qquad (1)$$

Angular frequency ω:

$$\omega = 2\pi f = \frac{2\pi}{T} \text{ (rad/s)} \qquad (2)$$

One can prove that the wavelength of a surface travelling wave is as follows:

$$\lambda = \frac{2\pi g}{\omega^2} \text{ (in m)} \qquad (3)$$

The last two expressions together give us:

$$T = \sqrt{\frac{2\pi\lambda}{g}} \text{ (s)} \qquad (4)$$

With g = 9.81 m/s²

In the Atlantic Ocean waves have periodic times of typical 10 seconds. So that gives a wavelength of approximately 156 meters.

- Horizontal speed.

$$v = \lambda f = \frac{\omega\lambda}{2\pi} \qquad (5)$$

$$v = \lambda f = \frac{2\pi g}{\omega^2} * f = \frac{2\pi g\omega}{\omega^2 2\pi} = \frac{g}{\omega} = \frac{g}{2\pi f} = \frac{gT}{2\pi} = g\sqrt{\frac{2\pi\lambda}{(2\pi)^2 g}} = \sqrt{\frac{\lambda g}{2\pi}} \qquad (6)$$

We see that the velocity v is independent of the wave amplitude H.

What is the total energy in the wave? This is important to know because we cannot extract more than maximum 50% of the energy the wave contains.

The total energy E (caused by potential and kinetic energy) in each wavelength, per unit width of wave crest of an individual wave is found to be (linear wave theory):

$$E = \frac{\rho g H^2}{8} \text{ (J/m/λ) (J/m}^2\text{)} \qquad (7)$$

For a certain wavelength per unit crest width:

$$E = \frac{\rho g H^2 \lambda}{8} \text{ (J/m)} \quad (8)$$

This is the energy per meter coast wave front length

And :

$$\lambda = \frac{2\pi g}{\omega^2} \quad (9)$$

$$E = \frac{\rho g H^2}{8} \frac{2\pi g}{\omega^2} \text{(J/m)} \quad (10)$$

$$E = \frac{\pi \rho g^2 H^2}{4\omega^2} \left(\frac{J}{m}\right) \quad (11)$$

And

$$\omega = \frac{2\pi}{T} \quad (12)$$

So:

$$E = \frac{1}{16\pi} \rho g^2 H^2 T^2 \left(\frac{J}{m}\right) \quad (13)$$

The theoretical maximum Power, P ideal, corresponding to de total energy content, per unit crest width, under ideal conditions (one sinus, deep water) is:

$$P\ ideal = \frac{1}{16\pi} \rho g^2 H^2 T \left(\frac{W}{m}\right) \quad (14)$$

Fill in with common values:

$$\rho = \frac{1000kg}{m^3}$$

$$g = 9{,}81 \frac{m}{s^2}$$

$$P\ ideal = 1915\ H^2 T \left(\frac{W}{m}\right) \quad (15)$$

1.2.2 Which part of P ideal is extractable?

In reality, a wave consists of more than one sinus, it is a complicated combination of waves having different wavelengths, directions and time-phase displacements.

Mathematically, one can show that the speed of the overall average wave motion, for random waves, is only one half of the power of an individual wave. The energy content of a group waves is transmitted at only one half of this velocity.

So the practical power extractable per meter of wave front is:

$$Ppract = \frac{1}{8}\rho g H^2 \frac{v}{2} \quad \text{(in W/m)} \qquad (16)$$

But even this value is not realistic. The best way to determine the overall effect is to measure it repeatedly and use statistical data based on measured previous performance.

To find exact information about a location scatter diagrams of wave heights are used.

An example:

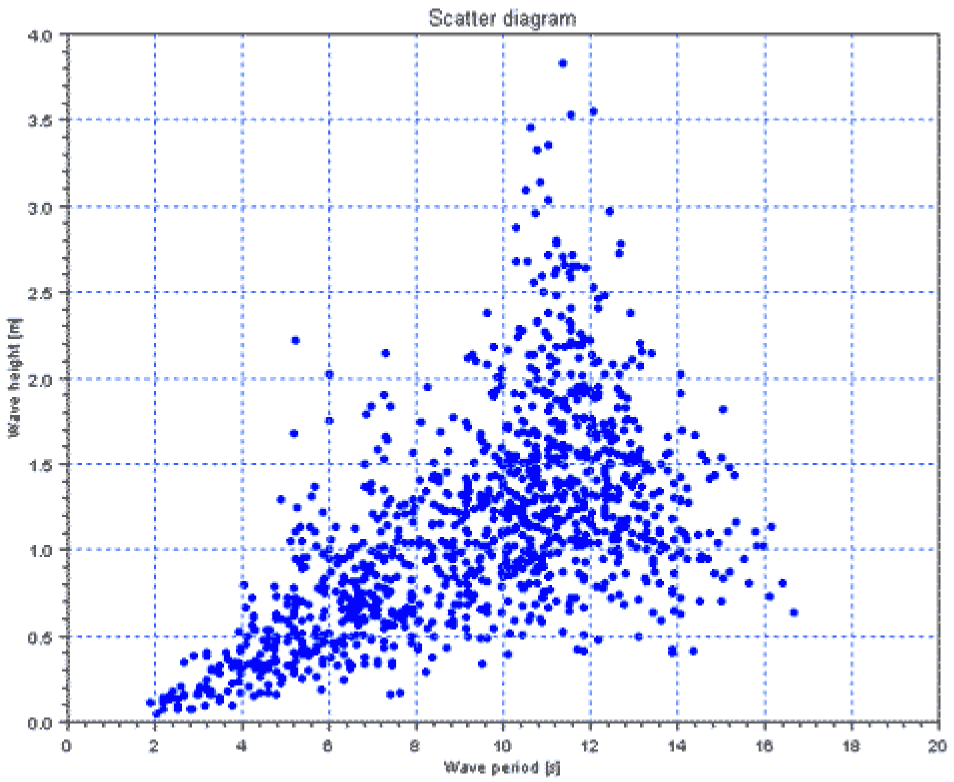


Figure 1.2.2: Scatter diagram for wave heights and periods detected within a time series acquired during a physical model test

Source: DHI-group, scatter diagram

You do 1,000 random measurements during one year and you look which time period and wave height occur. We should take this fact into consideration when building the ASWEC devices for a specific location.

1.2.3 Which part of P ideal can a buoy extract?

In the ASWEC project we use a buoy as a wave energy convertor. In our models we use another formula. As a buoy has a certain volume, it can only extract power within his reach. A formula has been developed for the energy that can be collected from a buoy:

$$P = \frac{Hc\ \pi\rho g}{T*4} = \frac{A\ \pi\rho g}{T*2}\ (\frac{watt}{m^3}) \quad (17)$$

This formula is use in all of our models.

You can recognise the formula of Archimedes in it.

1.2.4 What is the global estimated potential energy that we can extract from waves?

The theoretical potential is all wave energy there is on earth. As I mentioned before, waves are generated by the wind and the wind energy is produced by sun energy. So the theoretical potential is the amount of energy of the sun that is being used for making waves.

It is logical that we cannot extract it all. The technical potential is what we are able to extract. It takes the overall efficiency, and the available place into account.

And when we use economical potential, we look if it is a good investment in comparison with the other energy sources. The global commercial wave-energy potential is currently zero. Only if the price drops with factor 3 it would be economically responsible to use it.

sort potential	Unit	value
Global theoretical potential	TW	14
Global theoretical potential	TWh/year	18000
	TW	2
Global technical potential	Twhe/year	1460
	Gwe	556

Source: “Energie vandaag en morgen; W.D’haeseleer”

So let’s make some calculation with those values.

In 2005 the global electricity consumption was around 15 TW with a total energy consumption of 131400TWh/year.

$$15TW * 24 * 365 = 131400TWh/year$$

So the technical potential is estimated on 1.1% (1460/131400) of the total electrical energy production. This is not much, but all little efforts can help especially for local consumption and remote places.

According to the world energy council, the global wave energy resource is estimated to be 1-10 TW, we calculated with 2TW. The economical potential for future devices could rise up to 2000TW (1,5%). Nowadays the economical potential is 140-750 TWh/year (0,11% - 0,56%).

When waves move to shallower water, they lose a lot of their energy. But the sea-bed can collect those waves and focus them in so-called 'hot spots'. Those spots are the ideal areas for implementing our devices.

Properties of wave energy:

- Extractable at day and night-time
- Changes during the year. In Belgium, for example, waves are bigger and containing more energy during wintertime.
- Economical potential, only if the price drops with factor 3.

2 The project 'ASWEC'

*ASWEC is the name of the machine that we try to develop in the project in TAMK. ASWEC stands for '*Aaltosorvi wave energy convertor'.

In this chapter I would like to explain what already happened in previous investigations. My task in the project is trying to estimate the power losses in the rectification of the voltages and currents before we build the applications.

2.1 Mechanical device

The project is in research and the mechanical device is still not fully developed. There are a couple of prototypes that all more or less behave similarly. My task is to make estimations of the power losses that can be used as a guideline for each mechanical device.

There are two prototypes that I would like to explain in more in detail.

2.1.1 Mechanical device 1

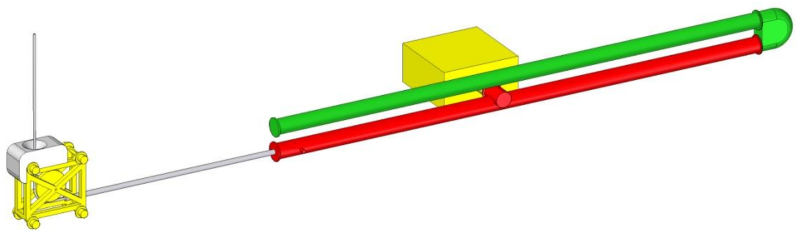


Figure 2.1.1a

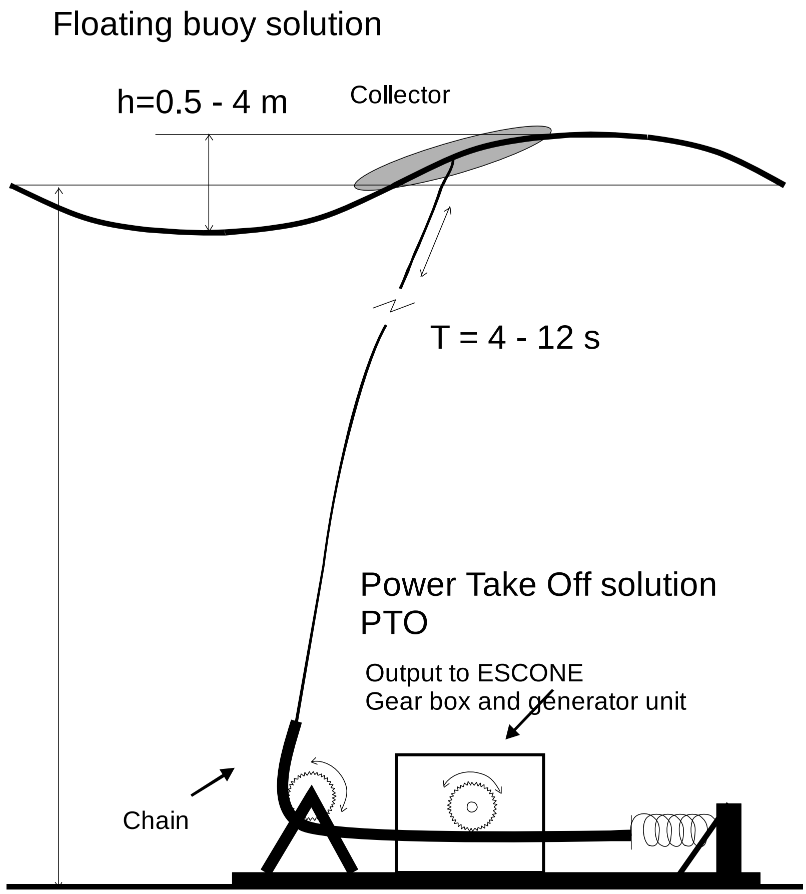


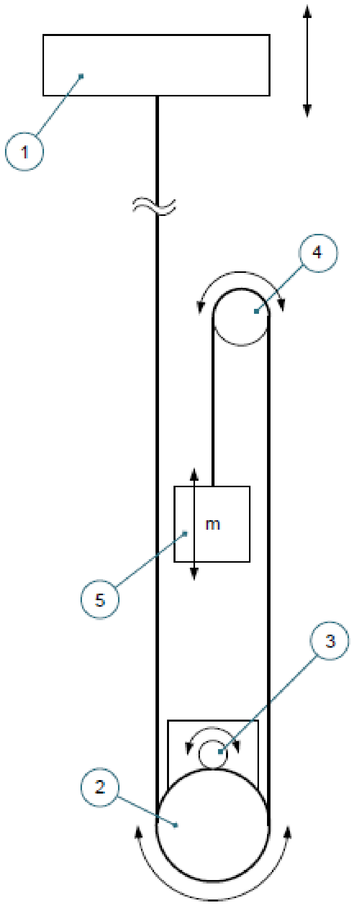
Figure 2.1.1b

The left part is connected to a buoy, which follows the rhythm of the wave. So a linear movement is created: a shaft moves in and out in the tube (red part). The green part is to bring the shaft back to the starting position with a spring. So we have two different movements: one is depending on the wave, the other is depending on the behaviour of the spring.

The translation movement is converted into a rotational movement in the yellow box in the middle. The rotation movement has two senses. To connect the device to a generator we convert the movement mechanically in one direction.

2.1.2 Mechanical device 2

Picture of the drawings:



Here the upward movement is caused by the buoy (1) and the downward movement is due to the mass (5). So we have two different behaviours when going up or down. The downward movement is always the same. The upward movement is depending on wave conditions. In the previous model there were problems to find a suitable spring, so they changed it by a more easy and predictable application. Also here we convert the movement mechanically in one direction.

Figure: 2.1.2

2.2 Conclusion

Both devices have a point in time where the speed becomes zero, and both mechanical devices make the rotational speed turn in one direction. A model to estimate power has already been made. The electrical behaviour of the two devices is very similar. The goal of this thesis is to find a way to connect the devices to the grid and to estimate the efficiency of the connection from gearbox until rectification.

2.3 The Simulink basic model

A model has been made which tries to show the behaviour of the machine. For a thorough explanation of the model I refer to the article “algorithm for the search of the secondary converter optimum impedance in a punctual wave energy converter” in my bibliography. I will shortly inform you about the outcome of the model

2.3.1 The model

It is an oscillating model that consists of several parts.

- The wave generator

One sinusoidal wave is created and it drives a buoy.

- The model for oscillating: buoy

The wave drives a buoy up and down. This part of the model calculated the acceleration, speed and position of the buoy.

- The model for oscillating: PTO unit

This part calculates the forces that the generator put on the buoy. This force tries to slow down the buoy.

- The gearbox

Because the speed of the buoy is not sufficient, we increase the speed a little for turning the generator. But the gearbox has also an important other function. We have a back and forth movement of the buoy. On our generator we prefer to have a one direction rotational movement. This can be solved mechanically, so this is implemented in the model.

- The generator + load

The generator is a PM generator.

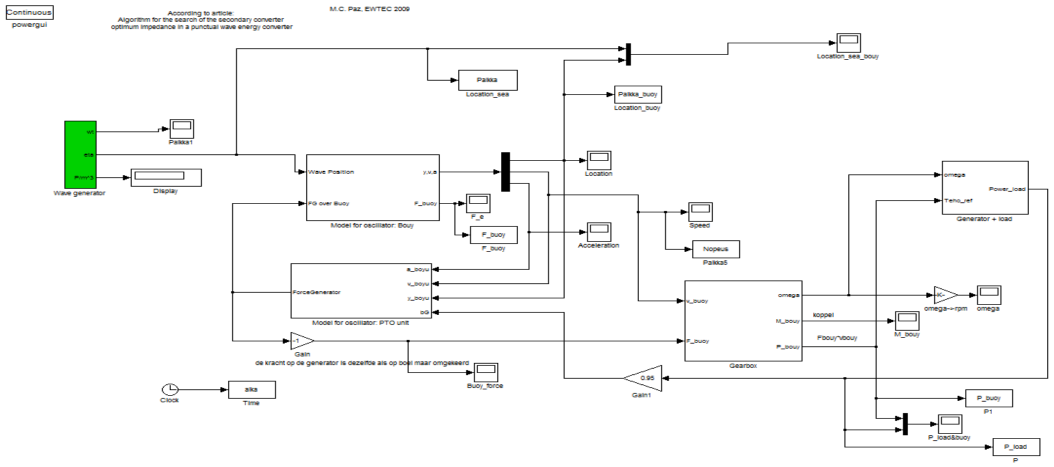


Figure 2.3.1

2.3.2 Measurements

We take waves with the following characteristics to see what the output is:

- Time period: 5sec
- Wave Height, Hc: 4m

This is not a fully realistic example, but the model goes very slowly with longer time periods. A more realistic example would be a longer time period, for example 10 seconds and wave height of 1.5 meters is a more realistic wave.

- Location sea and buoy

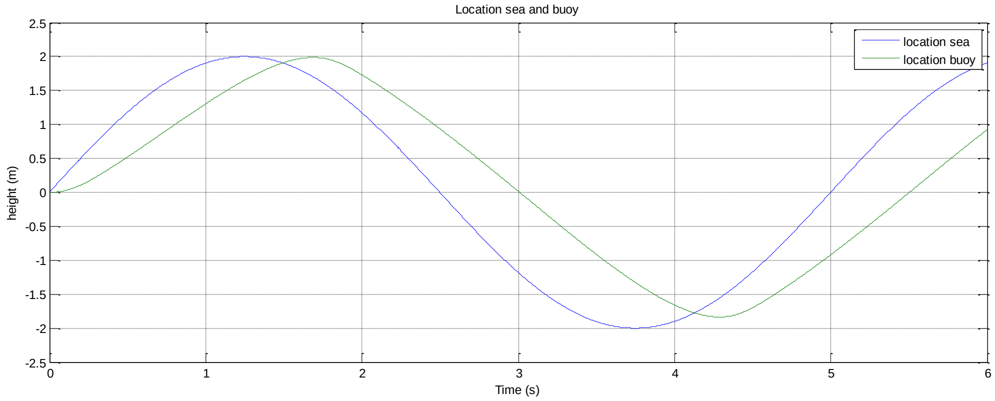


Figure 2.3.2a

You see that the buoy lacks behind on the sea. A reason for this is the force from the generator that the buoy encounters. After this the movement goes into a rotational movement and it gets mechanical rectified.

- Speed of rotation after gearbox

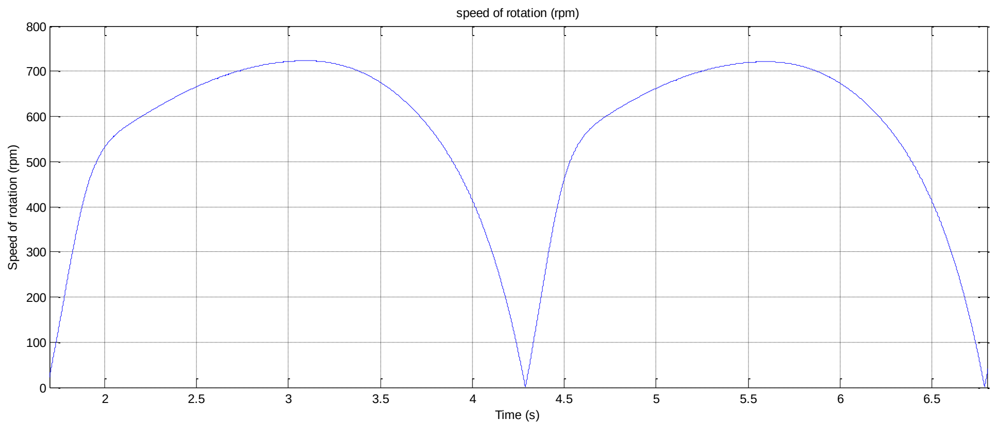


Figure 2.3.2b

We use this speed to turn a generator. We can clearly see that the speed drops to zero, when the buoy is on the top of the wave.

- The generator

    - Vabc (V): Va, Vb and Vc

This is the phase-to-phase voltages of the three lines that the generator of the wave device produces.

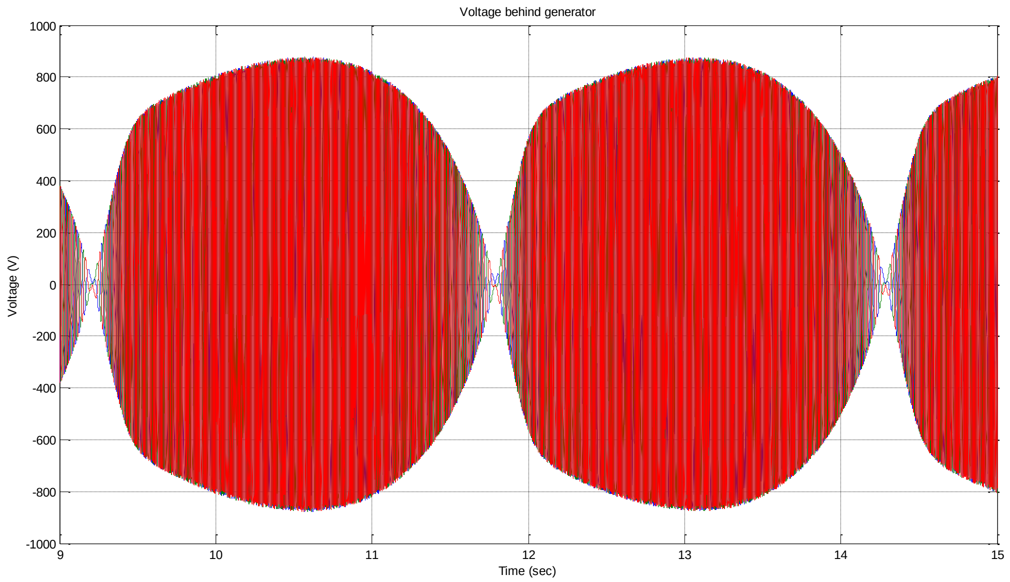


Figure 2.3.2c

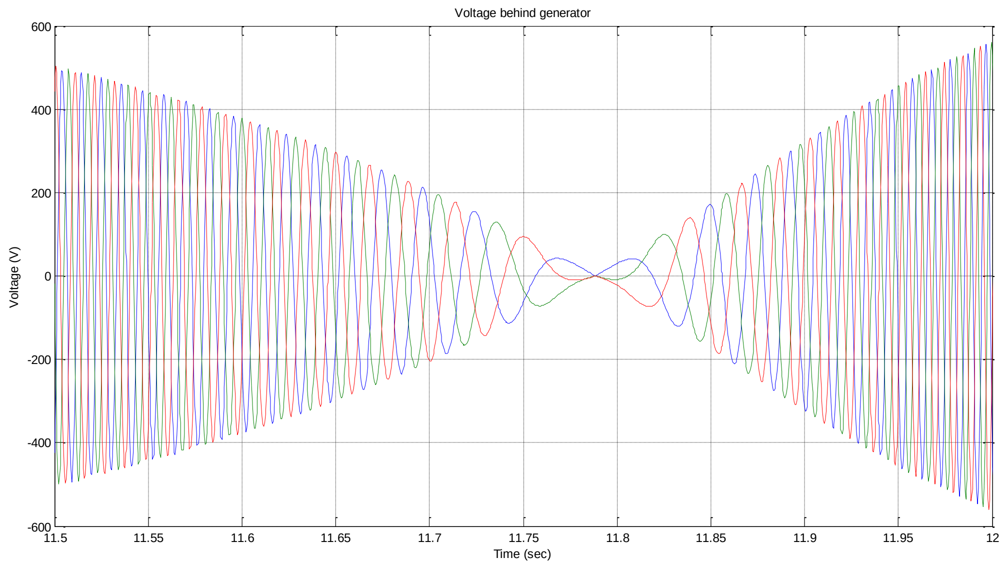


Figure 2.3.2d

For a certain input speed we see that the phase-to-phase voltages changes in:

- frequency
- amplitude

The reason for this is that the speed of rotation becomes zero on the top and bottom of the wave.

- Iabc (A):Ia, Ib and Ic

This is the current measurement of the 3 lines.

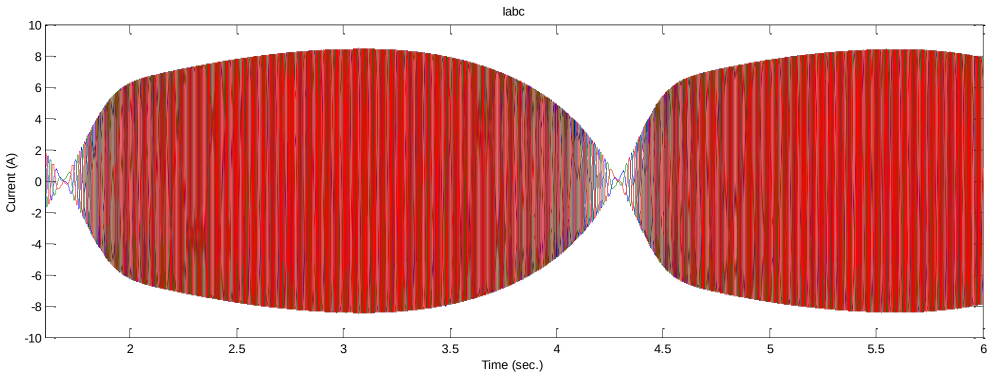


Figure 2.3.2e

The same problem occurs with the currents. The currents differ in:

- Amplitude
- Frequency

2.4 Conclusions:

We cannot connect the machine to the grid! The frequency and the amplitude are changing all the time (solutions, see part 2). We have big voids occurring in the voltage, current and hence also in the power production.

3 Theory about the electrical parts

3.1 The generator

3.1.1 What should be the characteristics of the generator?

Permanent magnet synchronous machines, behaves as an ordinary synchronous machines, but instead of excitation of the poles by a current, we use permanent magnets.

If we want to use a gear ratio as low as possible to avoid friction losses and design cost we need a low-speed generator, which means a lot of poles and a big diameter. Although the characteristics of permanent magnet materials have improved a lot over the past few years and the prices are decreasing, it is still less expensive to use a gearbox to raise the speed a little. We have to make a compromise. A gearbox decreases the efficiency and need maintenance. PM generators have good characteristics for low speed and high torque drives, which makes them very appropriate for our application.

Permanent magnet excitation gives us the possibility to use smaller pole pitch than conventional synchronous generators and the efficiency can also be higher. A PM machine can provide better performance and can be lighter than a traditional asynchronous machine with gearbox.

The magnets create a φE which is not controllable. The permanent magnets make it possible to design highly efficient machines, because there are no field windings, no excitation system, no field currents and hence no field losses. But the magnets are conductive, so joule losses take place. We also have no control over the power factor. Important is to keep in mind that the remanence of magnets decreases when the temperature increases. But we can use seawater to cool down our device.

3.1.2 Salient or non salient

- Non salient PM machines (Ld>>Lq)
    - PM machine with resistive/inductive load

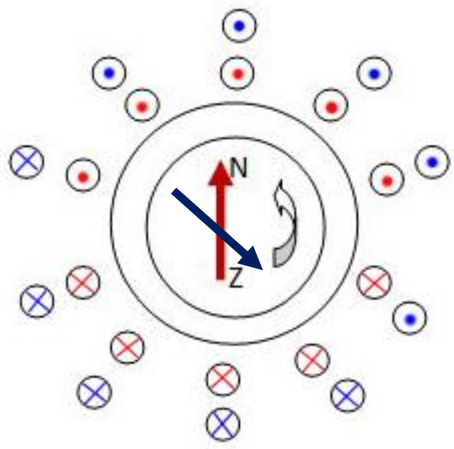
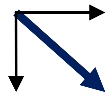


Figure 3.1.2a

The magnetic field φE of the permanent magnet (red arrow) will induce a voltage in the stator coils (see red dots and crosses). The current (blue dots and crosses) is lagging behind because it is both resistive and inductive.

The currents will induce a φA (blue arrow) that is called the armature flux, which consist of two components: the resistive current, also called quadrature current which induces a perpendicular component to the magnetic field φE and the inductive current, also called direct current and which induces a parallel component.



Both the components encounter the same reluctance in the non-salient PM machine because the air gab is always the same distance!

- Salient PM machines

Image that the rotor consists of one material with the same permeability:

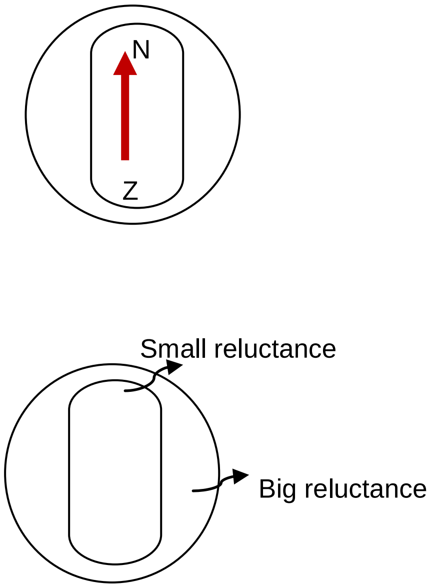


Figure 3.1.2b

The direct, or d-axis, is the magnetic axis of the rotor field and the quadrature, or q-axis, lags the d-axis behind by 90 electrical degrees. The magnetic inductance of the stator can vary in direct a quadrature direction because of the variation in air gap or permeability of the material. If you use permanent magnets, the permeability is approximately the same as air, so you still can have a non salient machine if the air gab is not the same.

φE will induce a voltage Eae and hence a current $\overline{I_a}$ will flow:

$$\overline{I_a} = \overline{I_q} + \overline{I_d} \tag{1}$$

With $\overline{I_q}$ the quadrature or resistive current component and with $\overline{I_d}$ the direct or reactive current component.

$$\overline{E_{ae}} = \overline{U} + R_a\overline{I_a} + jX_{a\sigma}\overline{I_a} + jX_{Aq}\overline{I_q} + jX_{Ad}\overline{I_d} \tag{2}$$

$$\overline{E_{ae}} = \overline{U} + R_a\overline{I_a} + j(X_{a\sigma} + X_{Aq})\overline{I_q} + j(X_{a\sigma} + X_{Ad})\overline{I_d} \tag{3}$$

$$\left(X_{a\sigma} + X_{Aq}\right) = X_q \tag{4}$$

$$(X_{a\sigma} + X_{Ad}) = X_d \tag{5}$$

$$\overline{E_{ae}} = \overline{U} + R_a\overline{I_a} + jX_q\,\overline{I_q} + jX_d\overline{I_d} \tag{6}$$

$X_d \gg X_q$, with salient PM machines

So we have a different equivalent scheme with the salient generator.

3.1.3 Brushes or brushless

- With brushes
  - The pm-poles are in the stator
  - The magnetic field stands still
  - We extract the power from the rotor. Therefore, we need brushes and slip rings.
- Brushless
  - The pm-poles are in the rotor
  - The poles move with the rotational speed (synchronous) of the generator
  - We can extract the power easily from the stator

We prefer to use the second type of generator because we like to extract the power without brushes and slip rings. The brushes are sensitive for wear, and need therefore much more maintenance.

3.1.4 Damper windings

Damper windings have the mission to reduce the swinging of the rotor. The damper windings behave like the cage rotor of an asynchronous machine. Swinging of the rotor can occur when the driving torque changes all the time. This behaviour is typical for our application. The rotor doesn't have a constant speed. When the speed deviates from the synchronic speed, voltages will be induced in the damper windings. If the speed tends to increase, induction occurs in the damper windings and tends to slow the machine down. If the speed tends to decrease, the damper windings are tending to increase the speed of the machine.

This characteristic can be very useful in our application to fill the voids in our power production.

3.1.5 Different kinds of permanent magnet synchronous machines.

The characteristics of permanent magnet machines are determined by the rotor construction.

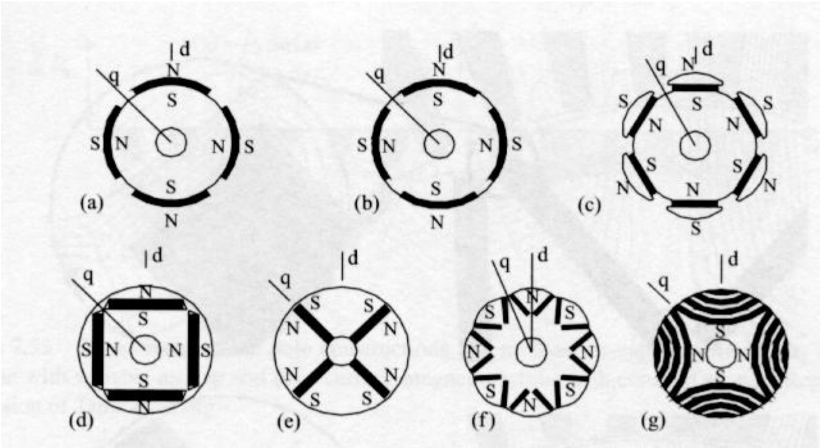


Figure 3.1.5; Source: design of rotating electrical machines, Pyrhönen, Juha.

a) Rotor-surface-mounted magnets (SMPM)

This generator is in principle non salient, because the relative permeability is mostly approximately one. Example: the neodymium-iron-boron permanent magnets have a relative permeability of μr=1.04-1.05. The PM material is best utilized in surface magnets machines. But they are exposed to mechanical and magnetic stresses and eddy currents losses. The magnets can be demagnetized and therefore it might be not appropriate to use it in our application: life expectance and operating hours are more important. The rotor can be provided with damper windings.

a) Magnets embedded in the surface (BPM –buried permanent magnets)

But when you embed the magnet in the surface the rotor is salient. Because the magnets have permeability around one, and the iron of the rotor has a much higher relative permeability.

Those machines produce a reluctance torque.

Embedding the magnets inside the rotor will typically result in waste a quarter of the flux produced by the magnets.

On the other hand the PM is protected mechanically and magnetically. This can be good to assure the life expectancy and it can reduce the maintenance cost.

b) Pole shoe rotor

They have similar inductance ratio as b. Damper windings can be used!

c) Tangentially embedded magnets

If the magnets are completely inside the rotor, a lot of the flux is consumed in leakage components of the rotor. On the other hand, the magnets are protected mechanically and magnetically. Here we use 2 poles to reach higher air-gap flux density

d) Radially embedded magnets

Here we have only one pole, but we can place damper windings

e) Two magnets per pole in the V position

As with Tangentially embedded magnets we can reach higher flux density in the air gap, and we have the possibility to place damper windings

f) A synchronous reluctance rotor equipped with permanents magnets.

3.1.6 Conclusion

SMPM are too sensitive to wear for our application. Pole shoe rotor, tangentially embedded magnets, radially embedded magnets and the V position can be constructed with damper windings, which is necessary in our design because the speed of rotation changes all the time.

Tangentially embedded and the V-position PM generator can offer us stronger flux density in the air gap, they can be constructed with damper windings and are not as sensitive for wear as the SMPM because of the embedded poles. Therefore I would suggest to design our application with a generator of this type.

3.1.7 Further generator specification

I send a couple of e-mails to producers of PM generators for extra information and they always asked me the same questions:

- What is the rotational speed of the generator?

In order to know how many poles there should be in the generator, we need to know what the rotational speed of the generator will be. The lower the speed, the more poles are necessary.

My colleagues of the mechanical design told me that the speed of rotation after the gearbox should be around 600 rpm. Of course we can optimize the mechanical part after we have chosen the generator.

- What are the voltages?

The peak values of the generator voltages should lower than 600 V peak to peak in order to find cheap and suitable bridges of diodes.

We have to overdimension the generator a little, so we can still operate in more strong sea states. We don't want to shut the generator down, when strong waves are appearing. We measure the time period and the wave height on a specific spot during one year to look what the strongest sea states are that occur. We can choose our generator so that it should be able to work for 95% of the time. After this we use this strong sea state to calculate the voltages that occur, using my models.

- What is the power production

The same can be done with the power production. I estimate that the generator should be around 10kW.

- What is the size

A compact size of generator is favourable. The price is highly depending on the size.

Our generator is very specific. There are companies that develop PM generators customized to the wishes of the clients, for instance PRECILEC. A specification request from can be asked by mailing to the sales manager of the company.

3.1.8 Losses in the generator

The permanent magnets makes it possible to design very high efficiency machines, because there are no field windings, no excitation system, no field currents and hence no field losses. But the magnets are conductive, so joule losses take place. The most important loss occurs in the armature of the stator. In my simulations I focused on that one, and neglected the joule losses.

3.2 The bridge of diodes

3.2.1 Working principles of the bridge

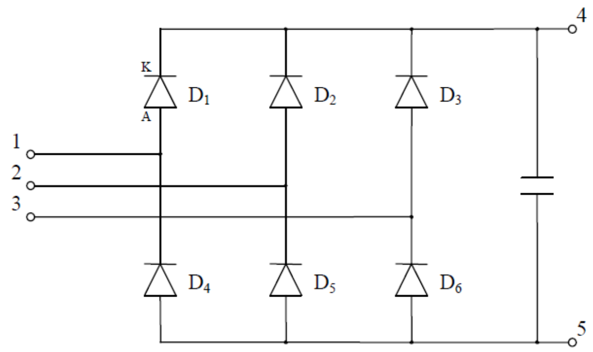


Figure 3.2.1a

A bridge of diodes is a power electronic device that is able to rectify a three-phase signal. A current will flow through one diode when the voltage of the anode is higher than the cathode. The three cathodes of the most upper diodes are connected and are on the same voltage level. Therefore the diode with the highest anode will conduct. The diode will conduct as long as the voltage before the diode is higher than the voltage behind the diode.

The cathode of the three lowest diodes is connected to the three-phase lines. The diode will conduct as long as the cathode is lower than the anode. So the diode that conducts is the one from which the cathode is connected with the lowest voltage!

I made a simulation in Matlab to show how this bridge behaves.

- The phase to ground voltage before the bridge: Vabc

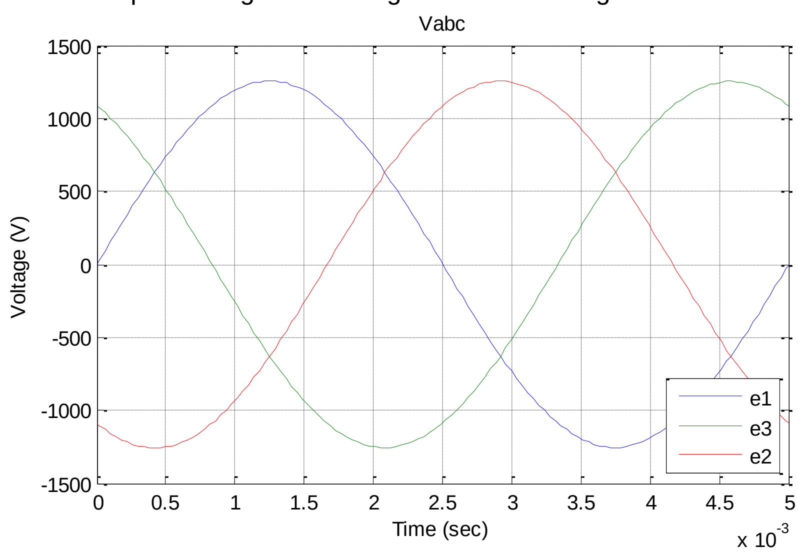


Figure 3.2.1b

- Phase-to-phase voltage

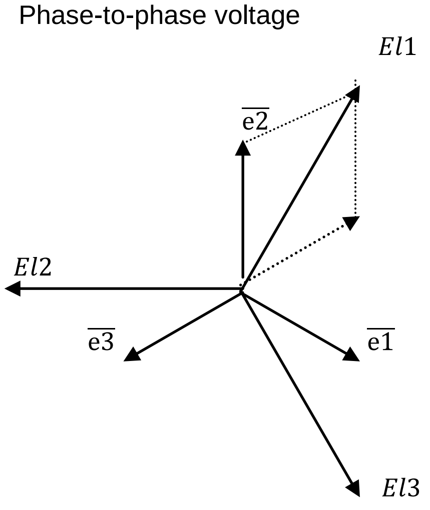


Figure 3.2.1c

$$\overline{El1} = \overline{e2} - \overline{e3}$$

$$\overline{El2} = \overline{e3} - \overline{e1}$$

$$\overline{El3} = \overline{e1} - \overline{e2}$$

$\overline{El1}$: 30° before $\overline{e2}$ in time and $\sqrt{3}$ bigger

$\overline{El2}$: 30° before $\overline{e3}$ in time $\sqrt{3}$ bigger

$\overline{El3}$: 30° before $\overline{e1}$ in time $\sqrt{3}$ bigger

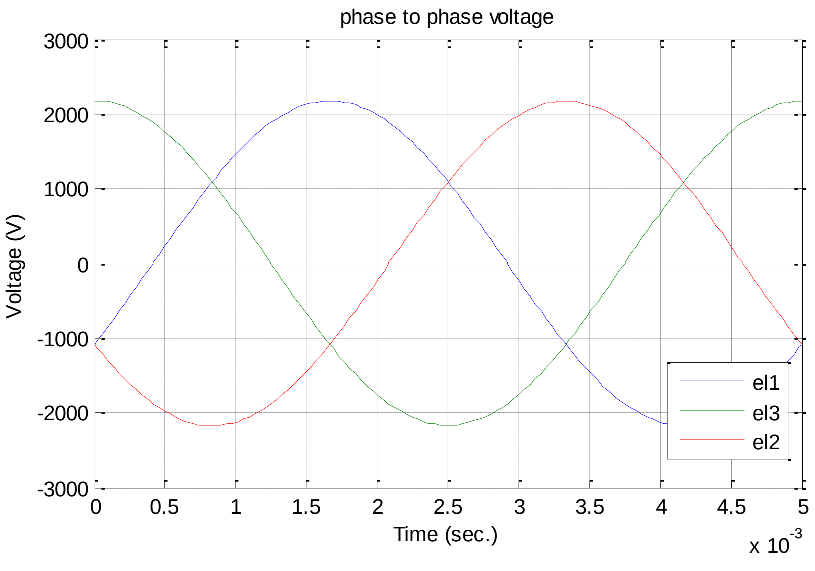


Figure 3.2.1d

- The rectifying process

If D1 and D6 are conducting, at time t1 the voltage of e2 becomes higher than e1 than diode D2 will conduct (see figure 2.2b). After another 30° e1 will become lower than e3 and then D6 goes out and D4 goes on. This process continues all the time. Each diode conducts two times 60 degrees. And every 30 degrees one diode goes off and another goes on.

conducting diodes	**D1 D5**	**D1 D6**	**D2 D6**	**D2 D4**	**D4 D3**	**D5 D3**
conducting phases	$\overline{e1} - \overline{e2}$	$\overline{e1}$-$\overline{e3}$	$\overline{e2} - \overline{e3}$	$\overline{e2}$-$\overline{e1}$	$\overline{e3} - \overline{e1}$	$\overline{e3}$-$\overline{e2}$
Phase-to-phase voltages	$\overline{El3}$	-$\overline{El2}$	$\overline{El1}$	-$\overline{El3}$	$\overline{El2}$	-$\overline{El1}$

As a result of this, we can see the regular phase-to-phase in the output, but also the inverse of this phase-to-phase output.

- Phase-to-phase signals and their inverse component

Figure 3.2.1e

Each of this lines conduct one sixth of a period.

The result of the rectification is shown in the following graph:

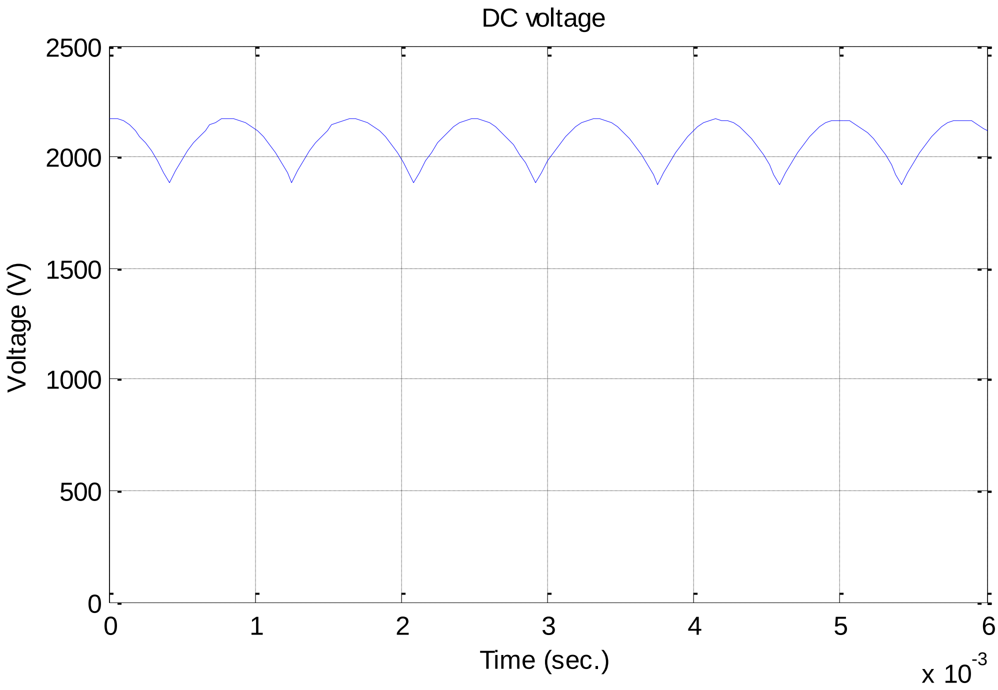


Figure 3.2.1d

Formula of the rectification:

$$U_d = U_{average} = \frac{3.\sqrt{3}\,\sqrt{2}}{\pi} . E_f \qquad (7)$$

3.2.2 Losses over bridge of diodes

The instantaneous power dissipated a diode is equal to the voltage multiplied with the current through the diode. The total loss can be divided into three parts:

- While conducting the effective diode current cause a power loss in the dynamic resistance. In this mode, there is a power loss due to threshold voltage (around 0.7V) and its corresponding average diode current.
- While the diode is not conducting, there still flows an inverse diode leakage current, which results in an inverse loss.
- Finally, there will be a switching loss at the start of the conduction of the diode.

3.2.2.1 Conducting losses

If you integrate the instantaneous power of the diode during the conduction of one period, you become the expression for the conduction losses. This instant power is equal to the instantaneous values of the voltage multiplied with the instantaneous values of the current through the diode.

$$P_D(t) = u_D(t) * i_D(t) \tag{8}$$

And:

$$u_D(t) = U_D + R_D i_D(t) \tag{9}$$

$$P_D(t) = U_D * i_D(t) + R_D i_D(t)^2 \tag{10}$$

So:

$$P_{D,conducting} = \frac{1}{T}\int_0^T P_D(t)dt = \frac{1}{T}\int_0^T U_D i_D(t) + R_D i_D(t)^2 . dt \tag{11}$$

$$P_{D,conducting} = \frac{1}{T}\int_0^T U_D i_D(t)dt + \frac{1}{T}\int_0^T R_D i_D(t)^2 . dt \tag{12}$$

$$P_{D,conducting} = U_D I_{Dav} + R_D I_{Drms}^2 \tag{13}$$

Figure 3.2.2a

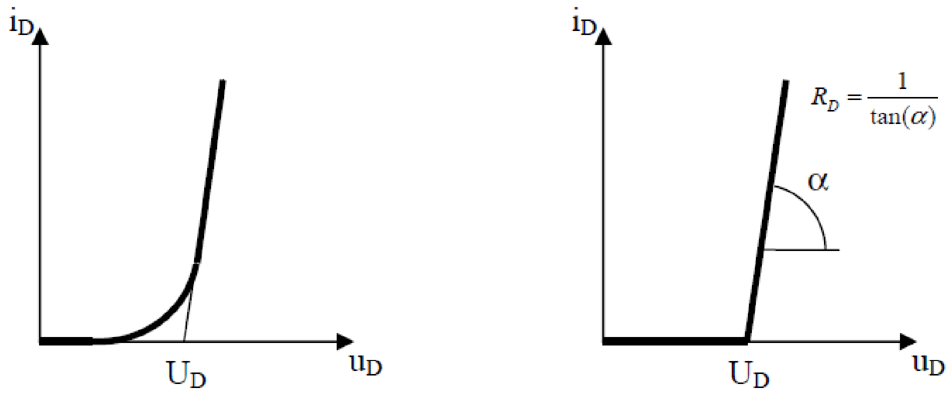


Figure 3.2.2b

Real and approximate characteristics of a diode.

All rectifier diodes that are made of silicon have a forward voltage drop U_D (or V_F) of around 0.7V. In the datasheets of ‘Shindengen Electric Mfg.Co.Ltd’, I find for all 3 Phase Diode bridges of 600V a maximum forward voltage drop of 1.05 V (0.7V+conducting voltage drop). In our models we will use the 0.6 V forwards voltage drop (explanation: see simulations).

3.2.2.2 Switching losses

When the diode stops conducting a reverse current will start to flow to rebuild the depletion layer. This inverse current is dependent of the previous forward current and the fall time. When you assume that the inverse voltage raises linear and the current drops linear, you find the following formula.

$$P_{D,switch}(t) = \frac{U_{switch}.t}{t_{rr}} . \frac{I_{rr}(t_{rr}-t)}{t_{rr}} \tag{14}$$

$$P_{D,switch} = \frac{1}{T} . \int_0^{t_{rr}} \frac{U_{switch}.t}{t_{rr}} . \frac{I_{rr}(t_{rr}-t)}{t_{rr}} dt = \frac{U_{switch}.I_{rr}}{t_{rr}^2.T} \int_0^{t_{rr}} (t.t_{rr} - t^2).dt \tag{15}$$

$$P_{D,switch} = \frac{U_{switch}.I_{rr}}{t_{rr}^2.T} \left(\frac{t^2.t_{rr}}{2} - \frac{t^3}{3}\right)_0^{t_{rr}} = \frac{U_{switch}.I_{rr}}{t_{rr}^2.T} \left(\frac{t_{rr}^2.t_{rr}}{2} - \frac{t_{rr}^3}{3}\right) \tag{16}$$

$$P_{D,switch} = \frac{U_{switch}.I_{rr}.t_{rr}}{6.T} \tag{17}$$

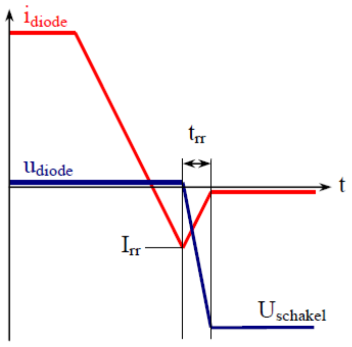


Figure 3.2.2c

3.2.2.3 Inverse losses

Because of the inverse voltage over the diode, there is a small inverse current through the diode. This inverse current is only there when the diode is inversely polarized.

$$P_{D,inv}(t) = u_{inv}(t).i_{inv}(t) \tag{18}$$

$$P_{D,inv}(t) = R * i_{inv}(t)^2 \tag{19}$$

$$P_{D,inv} = \frac{1}{T}\int_0^T u_{inv}(t).i_{inv}(t).dt \tag{20}$$

$$P_{D,inv} = \frac{U_{gem,inv}.I_{inv}.t_{inv}}{T} \tag{21}$$

With:

$i_{inv}(t)$ Instantaneous inverse leakage current through diode

I_{inv} Inverse leakage current through diode

t_{inv} Time of the inverse polarization

T Period of the grid

$u_{inv}(t)$ Instantaneous inverse voltage over diode

$U_{av,inv}$ Average inverse voltage over diode during inverse polarization

3.2.2.4 Conclusion

The biggest losses of the diode bridge are conducting losses. The voltage drop of the power diode is relatively big. In combination with the load current this can become a reasonable value.

When the diode stops conducting, the voltage and current values are already strongly decreased. These values define the switching loss. Furthermore, each diode of the bridge switches only one time each period. In a regular application this is only 50 times per second, so the switching loss of the bridge of diodes is negligible compared to the total loss.

While inversely polarized, there flows an inverse leakage current through the diode. This leakage current is very small, and can also be neglected.

3.2.3 Super capacitor

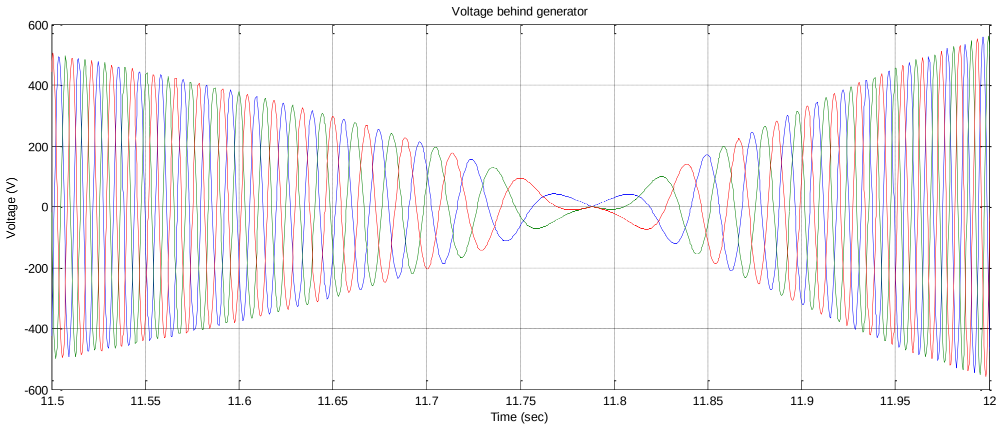


Figure 3.3

After a rectifying process of this signal, you still have a gap in the DC-voltage. These voids can be fixed by using a super capacitor. The use of a super capacitor gives us a technical solution for this problem, although this solution is economically not appropriate because the estimated life of the super capacitor is too short. The maintenance will increase and this is a big cost in off-shore applications. But we can implement the capacitor for extreme wave conditions. So we use it only in special occasions to assure the life time of the capacitor. Another solution is to implement the super capacitor on the shore. So we transport the voltages with a lot of ripple to the shore and before the frequency convertor we use the super capacitor. We can change the capacitors easily and save maintenance costs.

4 The Simulink simplified model

When we tried to rectify the basic model, we encountered a couple of problems. The model started to work really slowly. This is why we simplified the model. The oscillating model has been neglected. Now it’s also possible to connect several models together and see how we can connect them to each other. There are a couple of simplifications that makes it deviate from the real application:

- The movement of the wave is directly coupled to the generator

This leads in a symmetric movement. In the real application is the upward movement different from the downward movement. The upward movement is caused by the wave. The downward movement is caused by a spring or a mass.

- The driving torque on the generator is infinite

Imagine the load has a low resistive value. High currents will occur in the load and with the same voltage level you will have a very high power production. But high currents in load mean high currents in the generator coils and they will cause a very strong torque that wants to slow down the buoy and the generator, so the voltage and the current will drop again. They will drop until a steady state has been reached. We cannot put the information of the load back to the generator, which would be the most precise solution, because this will slow down the whole process. In order to find realistic simulations we have to estimate a realistic load value.

- The model is general and can be used for basic estimations for the different ASWEC designs.

The model exists of a wave generator that creates the waves (green block). Than we calculate the speed of the buoy depending on the wave conditions. With the speed of the buoy it is easy to calculate the rotational speed omega of the generator. After this we can rectify the generator output in the right Simulink block.

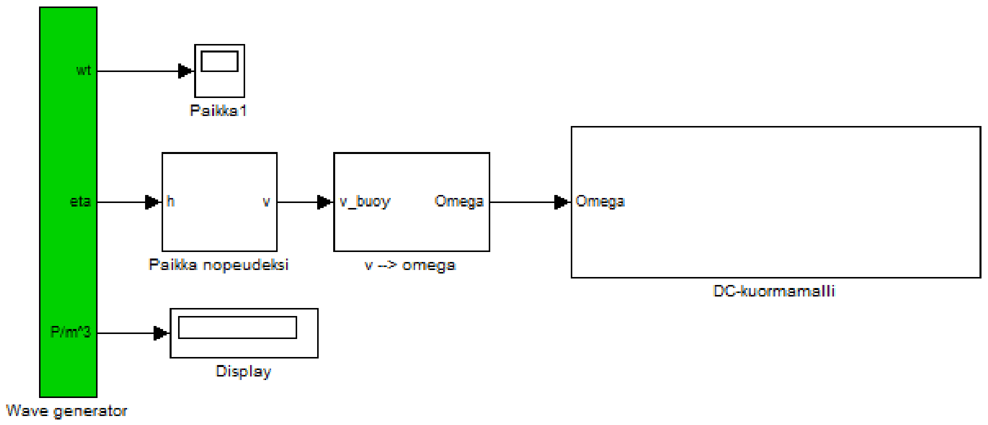


Figure 4

4.1 The wave generator

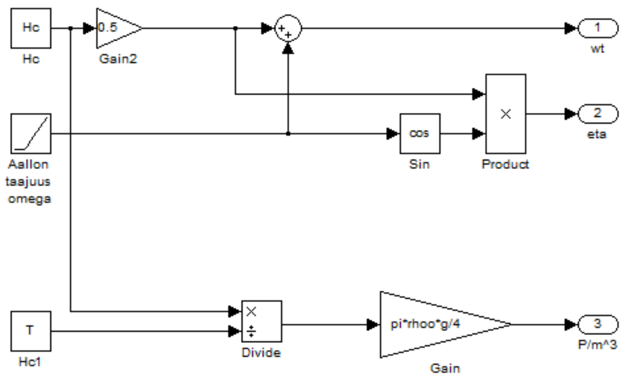


Figure 4.1

The basic equation of a wave:

$$y(x,t) = A * \cos\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right) = A\cos\left(\frac{2\pi}{\lambda}(x - vt)\right) \qquad (1)$$

If we look at only one buoy position:

$$y(0,t) = A * \cos\big((2\pi ft)\big) = A\cos\left(\frac{2\pi vt}{\lambda}\right) \qquad (2)$$

The last equation is been used in this model.

It doesn't matter if you take sinus-wave shape or cosines-wave shape. In the model we used the cosines-wave shape.

The wave generator creates waves which are simplified as normal sinus waves.

Location sea=A*cos(wt), with A=Hc/2

We can choose the density of the fluid (in this case seawater), the gravity factor, the time period of the wave and its height.

The output is the power of the wave, ωt and the position of the wave Eta = A. sin(ωt)

$$P = \frac{Hc\ \pi\rho g}{T*4} = \frac{A\ \pi\rho g}{T*2}\ (\frac{w}{m^3}) \quad (3)$$

We can use the power output of the wave to calculate realistic load values later on.

4.2 Rotational speed

The position of the wave on a certain place: Eta = A. cos(ωt).

The speed of the buoy is dependent of the derivative of the position of the wave, and it behaves as a first order transfer function.

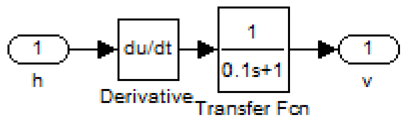


Figure 4.2a

In the gearbox we can calculate the rotational speed of the buoy with the gear ratio and the diameter of the first gear.

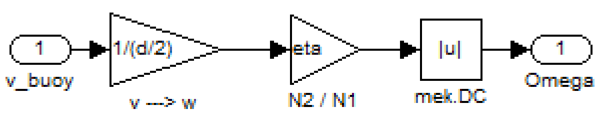


Figure 4.2b

$$v_{bouy} = \omega . R \quad (4)$$

$$\omega = \frac{v_{bouy}}{R} \quad (5)$$

We take the absolute value because the mechanical design of the machine makes the generator turn into one direction instead of back and forth. So now we have a simplified speed model which we can put on the generator.

Now we use the speed to turn the generator, consisting of two blocks. You can see that we put the same wave conditions in two different generators (the first two blocks on the left) with a time delay to simulate the difference in distance. A further explanation of this you can find in chapter 4.7. But first I will explain how we modelled the generator itself.

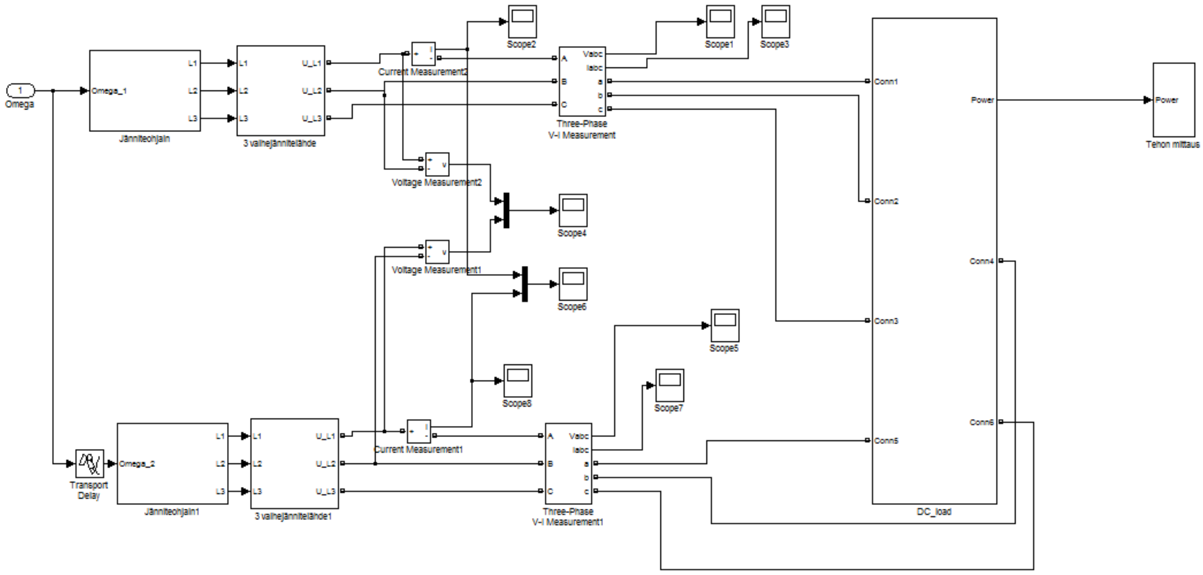


Figure 4.2c

4.3 The simplified generator

4.3.1 Properties of a PM machine

A 3-phase sinusoidal voltage is been induced in the stator because of the PMs in the rotor.

The instantaneous value of the induced voltage is:

$$e(t) = B(t)lv \qquad (6)$$

- The length l of the conductor is constant
- The speed v of the rotation field is also constant

The average induced voltage is:

$$\bar{e} = \bar{B}lv \qquad (7)$$

With $v = 2\pi rn$

- r is the radius of the rotor
- n is the rotation speed of the rotor in rps

So:

$$\bar{e} = \bar{B}l2\pi rn \qquad (8)$$

$$\bar{e} = \bar{B}\left(l\frac{2\pi r}{2\,p}\right)2p.n \quad (9)$$

p is the amount of pole pairs mounted in the rotor.

$$\bar{e} = \bar{B}(A_{pole})2pn \quad (10)$$

$$\bar{e} = \varphi_{max}\,2pn \quad (11)$$

The total magnetic flux of a pole that passes a conductor totally while rotating is the pole flux φ_{max} . This φ_{max} is equal to the average induction multiplied with the surface of the pole A_{pole} .

One coil has two coil sides with each N conductors in the stator. Hence, the total average voltage is:

$$\bar{E} = \varphi_{max}\,2pn\;2N \quad (12)$$

And:

$$E_{max} = \frac{\pi}{2}\bar{E} \quad (13)$$

$$E_{max} = 2\pi\varphi_{max}\,pnN \quad (14)$$

$$E_{eff} = \frac{2\pi}{\sqrt{2}}\varphi_{max}\,pnN \quad (15)$$

$$E_{eff} = 4{,}44pn\varphi_{max}\,N \quad (16)$$

Don't forget that this formula is only valid if the magnetic induction is perfect sinusoidal. This is never perfectly true. Therefore we use a correction k.

$$k = k_1k_2 \quad (17)$$

k_1= form factor; k_2=winding factor

$$E = 4{,}44kpn\varphi_{max}\,N \quad (18)$$

'4.44*k' is called the coefficient of Kapp and is usually between 3.75 and 4.25

p: pole pairs; N: amount of windings

- Interpretation
  - When the permanent magnets are stronger, there is a stronger induction B_{max} and φ_{max} . So the voltages in the stator are bigger.
  - B_{max} is constant because of the PM's and k, p and N are typical for one type of generator. Hence, the amplitude only depends on the speed of rotation. This is an important issue in modelling our system. We can say that:

$$E = cte.n \quad (19)$$

- The total flux φ_{max} is not only dependent on the induction of the magnetic field, the size of the poles are important too: the longer the radius r and the length l, the bigger the flux for the same induction:

$$\varphi_{max} = \frac{2}{\pi} B_{max} \frac{2\pi rl}{2p} \quad (20)$$

Now we can put this theory in the model! The generator part consists of two blocks.

4.3.2 First block: the voltage source input

The speed goes to a voltage controller and with the first block we produce a three phase voltage which has the same amplitude and frequency, but the phase angle is 120° shifted in time.

If we look behind the mask we see the following scheme:

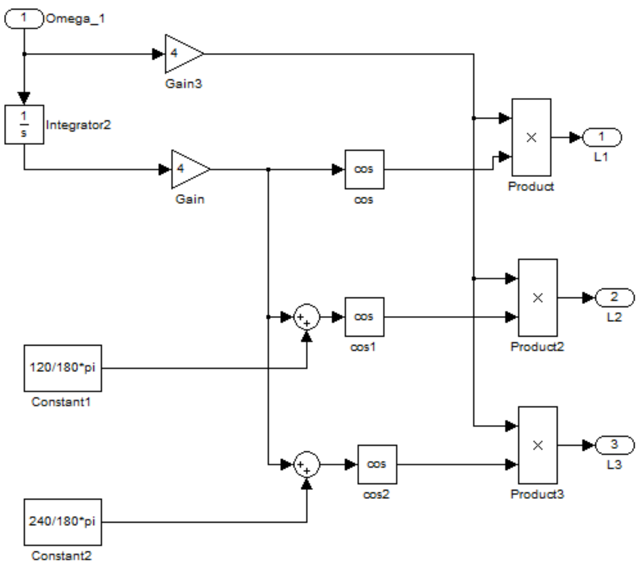


Figure 4.3.2a

The formula being used is:

$$L_1 = E_{max} * \cos(2\pi f t) \quad (21)$$

- The amplitude:

$$E = 4{,}44 k p n \varphi_{max} N \quad (18)$$

$$E_{max} = cte.n \quad (22)$$

$$\varphi_{max} = \frac{2}{\pi} B_{max} \frac{2\pi rl}{2p} \quad (23)$$

Be careful: the pole pairs don't influence the peak voltage!

We see the amplitude is:

- not depending on the amount of magnets being used
- depending on the revolutions per second
- depending on φ_{max} which is depending on the size and magnetic induction of the magnets

- The angular speed of the voltage

$$f = p * n \quad (24)$$

$$2\pi f t = 2\pi p n t \quad (25)$$

With:

- The rotation speed in revolutions per second
- p is the amount of pole pairs

$$n(rps) = \frac{\omega}{2\pi} \quad (26)$$

$$2\pi p n t = p\omega t \quad (27)$$

We can use this equation to make an appropriate voltage source which has similar characteristics as our device.

$$L = E_{max} * \cos(p\omega t) \quad (28)$$

$$L = cte * \omega * \cos(p\omega t) \quad (29)$$

- e.g.: $L = 4 * \omega * \cos(4\omega t)$ (30)

- We get 3 voltages of the form: L1,L2,L3=A*cos(ωt+ϕ)
- The same amplitude which is a function of omega.
- And the phase ϕ is leading with 0, 120 and 240 degrees

4.3.3 The second block: The generator: voltage source and generator windings

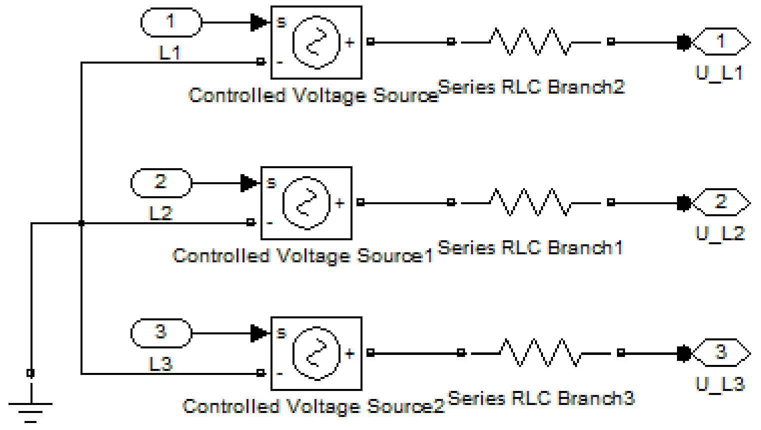


Figure 4.3.3a

We let the signals work as a voltage source, connected with the same zero-conductor. The series RLC branch are the windings of the generator. Due to the slow behaviour while using a more inductive value, we assume that it is purely resistive. This is an approximation.

Conclusion

Now we created a voltage source which is similar to the voltage source of our machine. But we have to realize that there is still a difference. The upward movement and the downward movement are the same. In the real application the upwards movement is depending on the wave and the downward movement is depending on the spring or mass.

Another difference is that there is no torque caused by the currents through the generator.

With a time delay we can connect two of those voltage sources together (see figure 1.2c). We have a tool to simulate how to connect several devices and how to estimate the power losses in the diode bridge.

4.4 The connection to the grid

4.4.1 The Problem

The problem with the devices is that the amplitude and frequency varies all the time. The rotational speed of the generator varies continuously as the buoy accelerates and decelerates near the turning points. The buoy accelerates upward because of the wave. When the buoy reaches the top of the wave the instantaneous speed will become zero and causes a drop in amplitude and frequency. We have the same problem in the downward movement. Several solutions are described in the book: Danielsson 2006: a number of connection solutions.

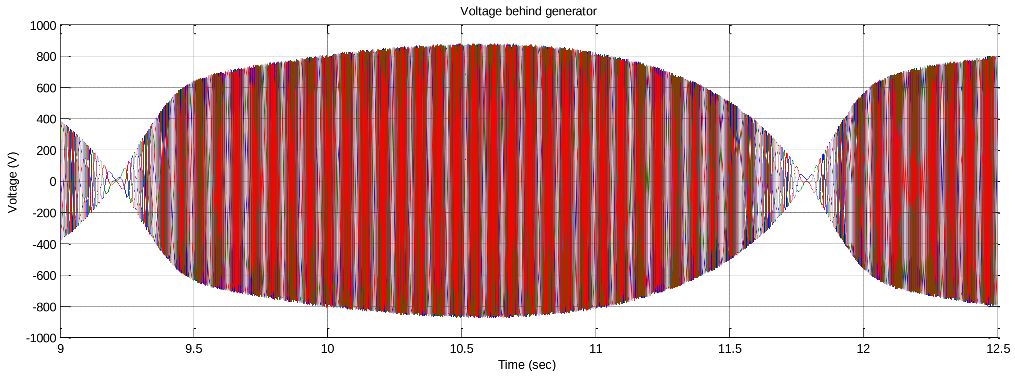


Figure 4.4.1

In order to make a three-phase sinusoidal signal of 50 Hz and with 120° phase difference between the signals we need to rectify this output. However this doesn't solve the voltage drop.

4.5 Statistical connection

If we can position the buoys in a way that the peaks of one device fill the gaps of the other device, than we can decrease the ripple on the DC-voltages, by adding the two voltages together. When the first buoy is on the top of the wave, the instantaneous speed becomes zero. We have to put a device on a place where the instantaneous speed is at a maximum, this is around the next zero-crossing of the sinusoidal-wave (see figure).

Example: a wave with 10 meters wavelength and a height H of 2.5 meters.

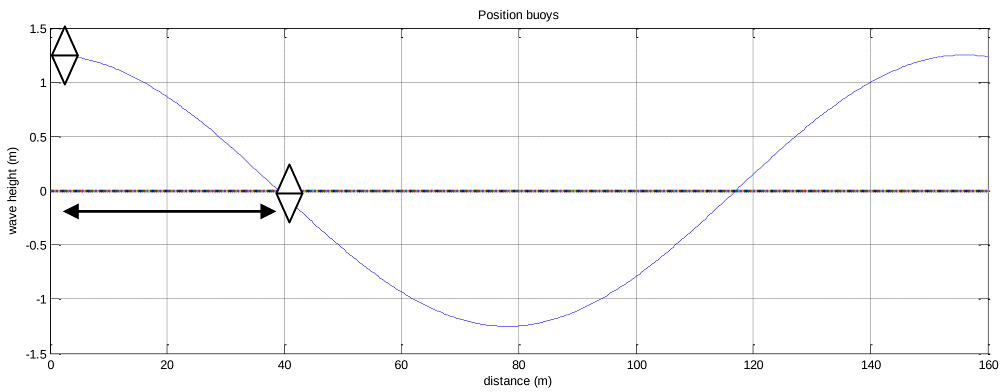


Figure 4.5

There are a lot of statistical models such as the Markov chain model and the Rayleigh probability density function to estimate scatter diagrams. But I think that the best information is from measurements at the place itself.

For information concerning the targeted location, one can consult the 'World Wave Atlas'. It provides atlases with accurate wind and wave climate statistics for any country or region worldwide.

Typical statistics include probabilities for wave height, extreme significant wave height, maximum wave height and crest height estimates, duration statistics , bivariate and trivariate statistics for wave heights, periods and directions (for example: scatter diagrams of wave height and period).

This typical data provides you with statistical information about the waves. Look for the most common frequency and use this to position your buoys. Now you can estimate the behaviour of the machine by putting the wave information into the model and see what happens.

4.6 Connection in parallel vs. connection in series.

In order to fill the gaps, we can add the voltage output of several devices to each other.

4.6.1 Parallel connection

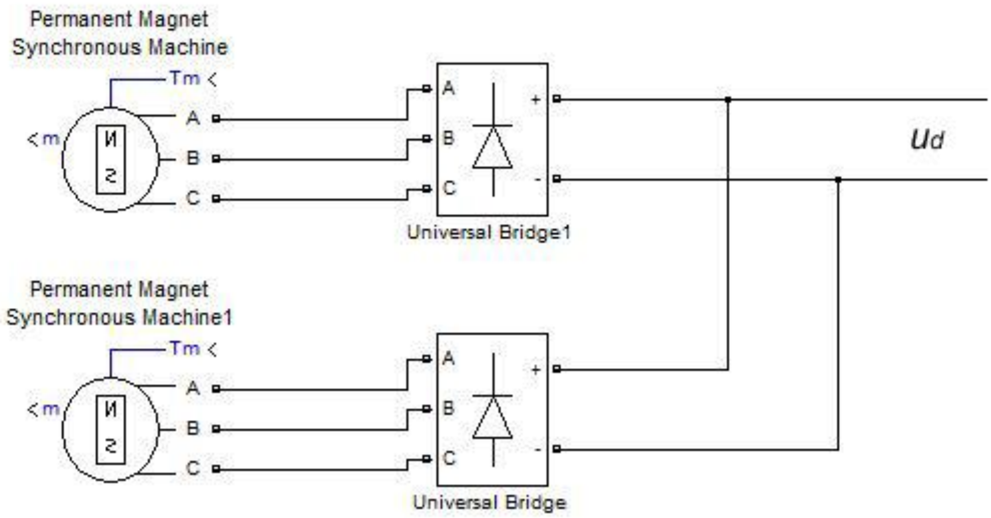
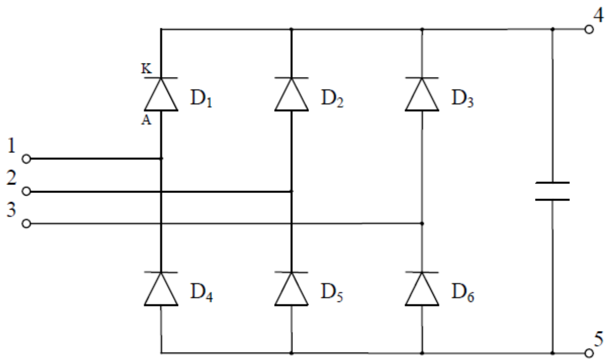


Figure 4.6.1a



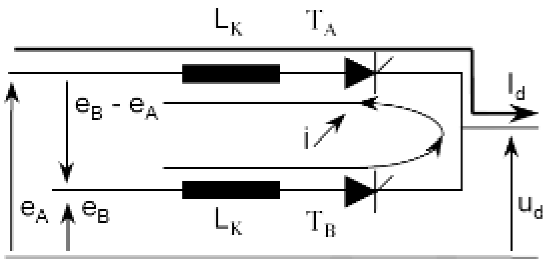


Figure 4.6.1c

Figure 4.6.1b

If Ud >eA:

- Diodes are always inversely polarized, and there’s no conduction.
- When you connect them in parallel the voltage after the bridge will be larger than the voltage before the bridge.

Conclusion: The connection in parallel is not appropriate for this application.

4.6.2 Connection in series

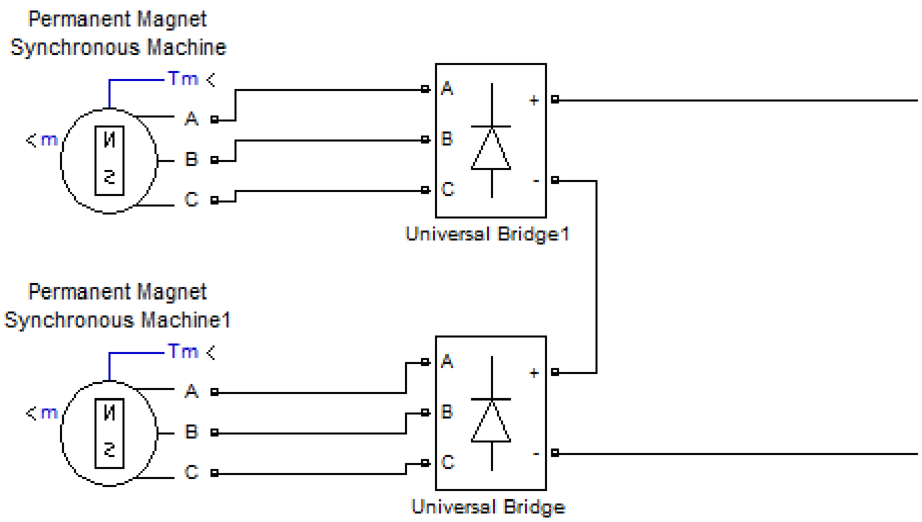


Figure 4.6.2

Because the parallel connection doesn’t work with a normal bridge of diodes, we use the series connection of the modules. The problem here is the high voltage. When you put too many devices together you will have problems with too high voltages. The voltage level cannot be higher than a certain value, because of the isolation with the sea.

Another problem is that the currents flow through all the diode bridges and generator windings. Hence, we have to keep the currents constant.

4.7 Positioning buoys

The aim is to find the correct time delay, which is one fourth of a Time period, corresponding to the right position, which is one fourth of a wavelength if we work with two buoys.

Travelling sinusoidal waves can be represented mathematically in terms of their velocity v (in the x direction, frequency and wavelength.

$$y(x,t) = A * \cos\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right) = A\cos(\frac{2\pi}{\lambda}(x - vt)) \quad (31)$$

Y is the value of the wave at a certain position and a certain time t.

$$y(x,t) = A * \cos\big((kx - \omega t)\big) = A\cos(k(x - vt)) \quad (32)$$

With: $k = \frac{2\pi}{\lambda}$ (33)

And

$$\lambda = \frac{v}{f} \quad (34)$$

So:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{v} = \frac{\omega}{v} \quad (35)$$

Or:

$$\lambda = \frac{2\pi}{k} = \frac{2\pi v}{\omega} = \frac{v}{f} \quad (36)$$

The relationship between ω and λ is called a dispersion relation. This is not a simple inverse relation because the wave velocity itself typically varies with frequency.

- Relationship between speed, wavelength and time for one period for deep water waves

$$\lambda = \frac{g * T^2}{2\,\pi} \quad (37)$$

$$\lambda = Tv = \frac{g * T^2}{2\,\pi} \quad (38)$$

$$v = \frac{g * T}{2\pi} \quad (39)$$

$$T = \frac{2\pi v}{g} = 0{,}641 * v \qquad (40)$$

You can measure the period of a wave very easily, but wavelength and speed not. So if we can measure the period and the wave height we know the most relevant information of the wave.

Example 1: T=10s

$$v = \frac{T}{0{,}641} = 1{,}56 * 10 = \frac{15{,}6m}{s} = 56km/hr$$

$$\lambda = \mathrm{Tv} = 156\mathrm{m}$$

Example 2: Tsunami goes at a speed of 200m/s

$$T = 0{,}641 * v = 128{,}2s$$

$$\lambda = \mathrm{Tv} = 128{,}2 * 200 = 25600\mathrm{m}$$

- Various depths

The depth of the ocean is not infinite. So the previous equation is not always valid.

  - the relation between the wave speed v and the period T
  - The relation between the wavelength λ and period.

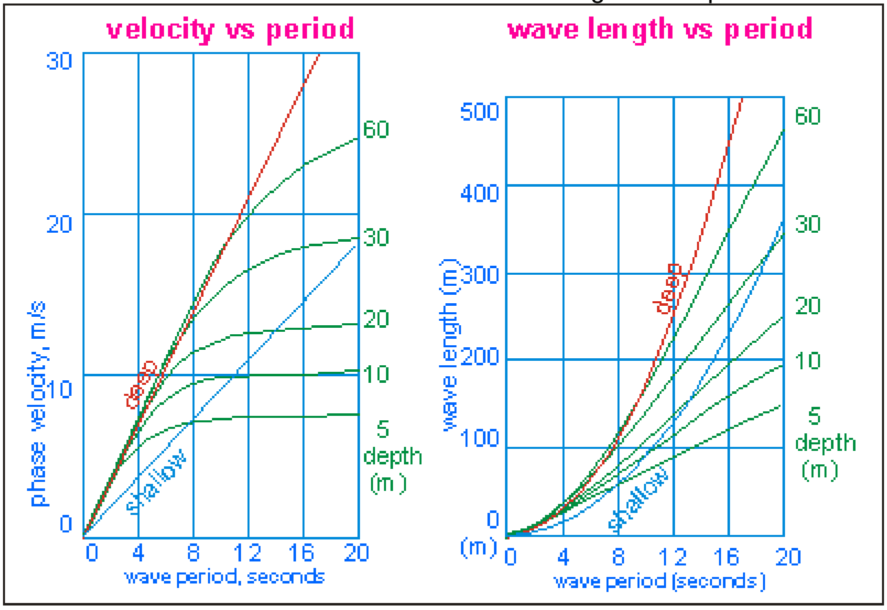


Figure 4.7a; source: *Van Dorn, 1974*

- Positioning buoys.

The question is where do you have to position the buoys? How far from each other? If we can position a buoy in a way that it fills the voids of the other device, we will have less ripple on our voltage, current and power. In the figure we see the output of one device, for a certain wave value, before we rectified the voltage. The figure is made by the simplified model.

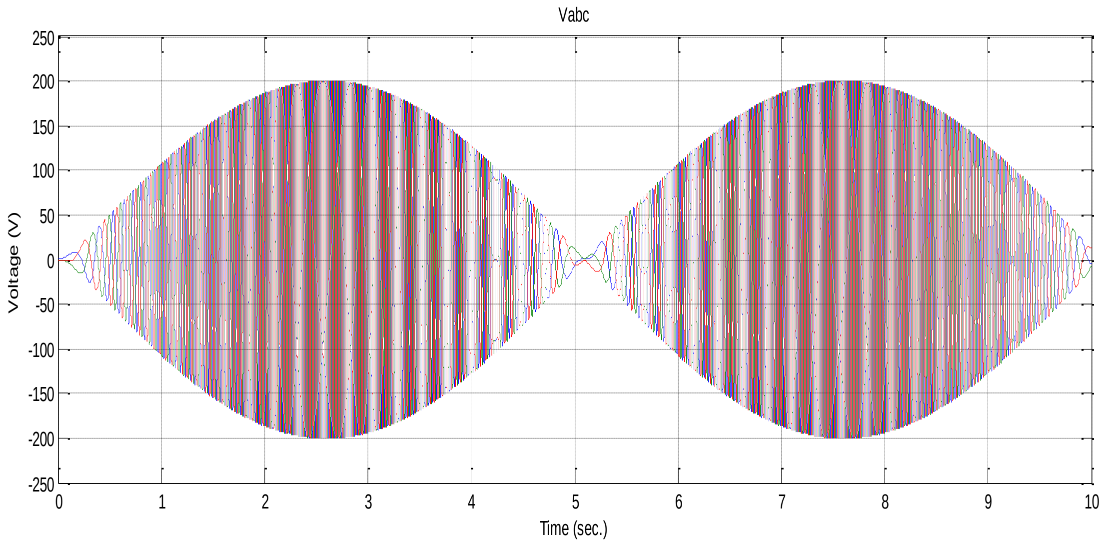


Figure 4.7b

The equation of the wave (32):

$$y(x,t) = A * \cos\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right) = A cos(\frac{2\pi}{\lambda}(x - vt))$$

We take for example a wave with:

$$T = 10s$$

$$v = \frac{T}{0,641} = 1,56 * 10 = \frac{15,6m}{s}$$

$$\lambda = \mathrm{Tv} = 156\mathrm{m}$$

$$H = 2.5m$$

$$A = 1.25m$$

$$y(x,t) = 1.25 * \cos\left(2\pi\left(\frac{x}{156\mathrm{m}} - 0,1t\right)\right)$$

and time=0

$$y(x,0) = 1.25 * \cos\left(2\pi\left(\frac{x}{156\mathrm{m}}\right)\right)$$

When y=1.25, on the top of the wave, the instantaneous speed is zero. So the speed on the generator is zero as well, and the amplitude of the voltage is very little.

We have to place the other buoy at a place where y=0, the buoy is at the highest speed and they compensate each other.

A few points to calculate:

1) $1.25 = 1.25 * \cos\left(2\pi\left(\frac{x}{156\,\mathrm{m}}\right)\right)$→x=156*n, with n=0,1,2,3… :x= 0meter, x=156 meter,…
2) $-1.25 = 1.25 * \cos\left(2\pi\left(\frac{x}{156\,\mathrm{m}}\right)\right)$→x=78*(2n-1),x=-78,x=78 meter
3) $0 = 1.25 * \cos\left(2\pi\left(\frac{x}{156\,\mathrm{m}}\right)\right)$→ 39(2n-1);x=-39meter;x=+39meter

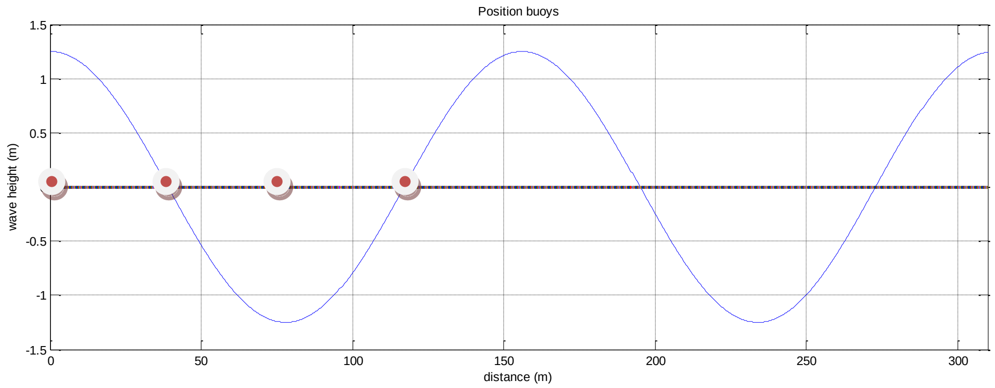


Figure 4.7c

4.8 Realistic simulations values

We use the simplified model and there are a couple of disadvantages:

- Upward movement and the downward movement are the same.
  - We put the characteristics from the wave directly to the generator
- The characteristics of the buoy are equal to those of the wave
- There is no Torque caused by the load

The first problems make the simulation less accurate. But the last one makes the model difficult make realistic estimations. Imagine the load after the rectifying process is very small. Than the currents through the load will be very high, while the voltages stay the same and the model will generate high power estimations. In fact this is not true! Also the currents through the generator will be very high and will cause a large torque that wants to slow down the movement. When the current is even too high, it is possible that the buoy will not move anymore. So the output voltage will drop, and the power production will drop too.

It is very important to find a right resistive load in order to be able to make appropriate estimations! The best way to find good values and estimations is to put the 'load' information back to the generator.

But this slows down the model and makes further work impossible. Therefore we have to find another way. I have to estimate realistic load values in order to have realistic results. So we have to make some restriction to our model.

According to following formula (17), in chapter one, the power of the waves will have a value of 5075 W/m^3 for a wave with T=6 and H=4.

$$P = \frac{Hc\ \pi\rho g}{T*4} = \frac{A\ \pi\rho g}{T*2}\left(\frac{w}{m^3}\right) = 5075\ (\frac{W}{m^3})$$

This is almost unrealistic heavy wave. If we take a volume of the buoy of 5m^3 and assume that the efficiency of the conversion wave to the buoy is 50%. Then we have a power value of 12.7 kW for the buoy. This is a very rough and optimistic situation, but we know now that we need a generator of arround10 kW. The efficiency of the conversion is not exact and experiments have to confirm more accurate values.

Let's take again the wave with following characteristics:

- Time period: 10
- Hc: 2 meter peak-to-peak

I found the catalogue of ALXION on the internet with some interesting PM-generators. They are specially developed for wind energy applications. For wind energy you also need low speed and high torque generators. Those types of generators come closest to our application, but there are still some things we have to consider.

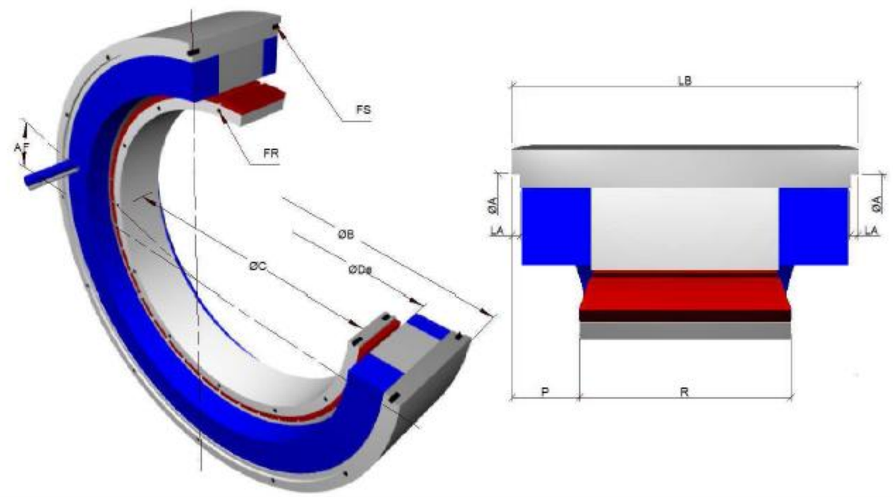


Figure 4.8a

All of them are PM generators:

TECHNICAL CHARACTERISTICS
300 STK ALTERNATORS

		300STK2M		300STK4M		300STK6M		300STK8M	
Rated speed	Rpm	350	800	350	800	350	800	350	600
Rated power (1)(2)	W	3174	8413	6627	13942	9573	17106	12683	19424
Current at rated speed (1)	Amps	7.9	21.1	16.6	34.9	24.0	42.9	31.8	48.7
Voltage at rated power (1)(2)(3)	V	133	133	133	133	133	133	133	133
Power at half speed (1)(2)	W	1297	3745	2729	7741	4136	11126	5506	10632
Phase resistance at 20℃	Ohm	2.41	0.47	0.99	0.15	0.53	0.08	0.37	0.11
Phase inductance	mH	15.1	3,04	8.5	1,28	5,08	0,78	3,86	1,11
Phase emf at 20℃ (4)	V	178.6	180.4	186.9	165.5	177.4	159. 8	178.6	164.1
Rotor inertia	10^{-3}Kg.m^2	52.7	52.7	105.5	105.5	158.2	158.2	211	211
Weight	Kg	18	18	31	31	44	44	57	57
Power cable square section	mm^2	4x1.5	4x2.5	4x1.5	4x6	4x4	4x10	4x6	4x10

300 STK Generators Power - Speed

Figure 4.8b

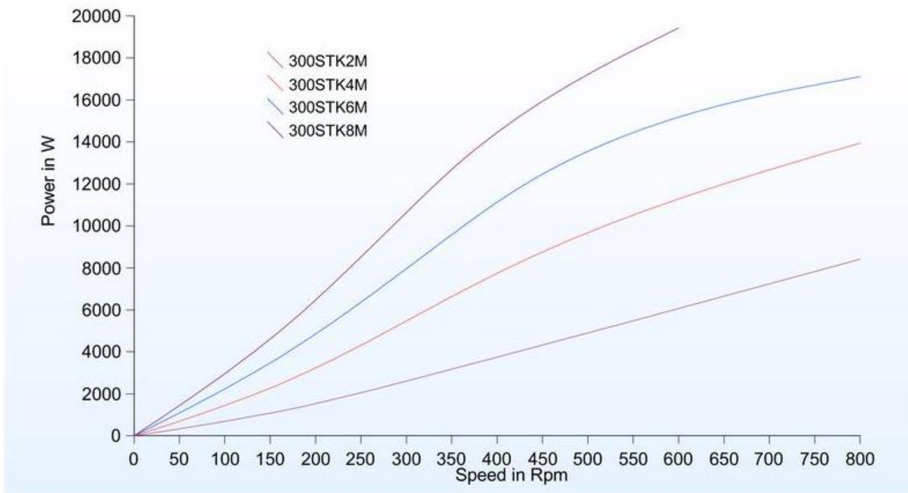


Figure 4.8c

4.8.1 The 300STK6M model with rated speed of 300.

At first I choose the 300STK6M model. This machine has a big disadvantage however. The losses in the generator are too big if you don't work in the nominal speed area all the time! I will explain why with my calculations.

- Speed of rotation and power production

In the first graph we see that until 350 rpm, we have a more or less linear area. Let's make the curve linear to find other values.

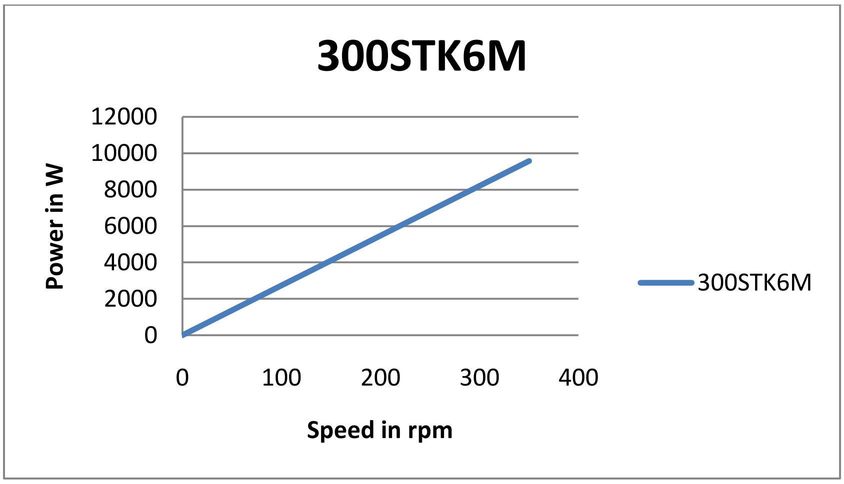


Figure 4.8.1a

Rico= 27.35

$$Power = 27.35 * speed\ (rmp) = T * \omega_1 * \mu_e \quad (41)$$

With:

$$\omega_1 = rotation\ speed\ before\ gearbox$$

$$\mu e = eficiency\ gearbox + generator$$

So the force on the buoy caused by the generator is approximately constant.

Now we can find the correct power output after the generator depending on the speed.

- The voltage production is linear with the speed of rotation

$$E = 4{,}44kpn\varphi_{max}\, N = cte * n \quad (42)$$

- The current production

If the power and the voltage are linear with the speed of rotation, then the currents must be more or less constant:

$$Current = \frac{Power}{3 * voltage} = 24\ A$$

This is the same value that we find in the table from ALXION.

- The losses in the generator

The currents are constant, and the phase resistance (see table ALXION) is 0.53. Hence, the losses in the generator are independent from the speed of rotation and power production. They are constant for each working point in the generator.

$$24^2 * 0,53 * 3 = 915,17Watt$$

- Table and graphs

rpm	power	voltage	currents	losses	%losses	Tot. R	R load
50	1367,5	19	23,99	915,17	66,9%	0,792	0,262
100	2735	38	23,99	915,17	33,5%	1,584	1,054
150	4102,5	57	23,99	915,17	22,3%	2,376	1,846
200	5470	76	23,99	915,17	16,7%	3,168	2,638
250	6837,5	95	23,99	915,17	13,4%	3,960	3,430
300	8205	114	23,99	915,17	11,2%	4,752	4,222
350	9572,5	133	23,99	915,17	9,6%	5,544	5,014

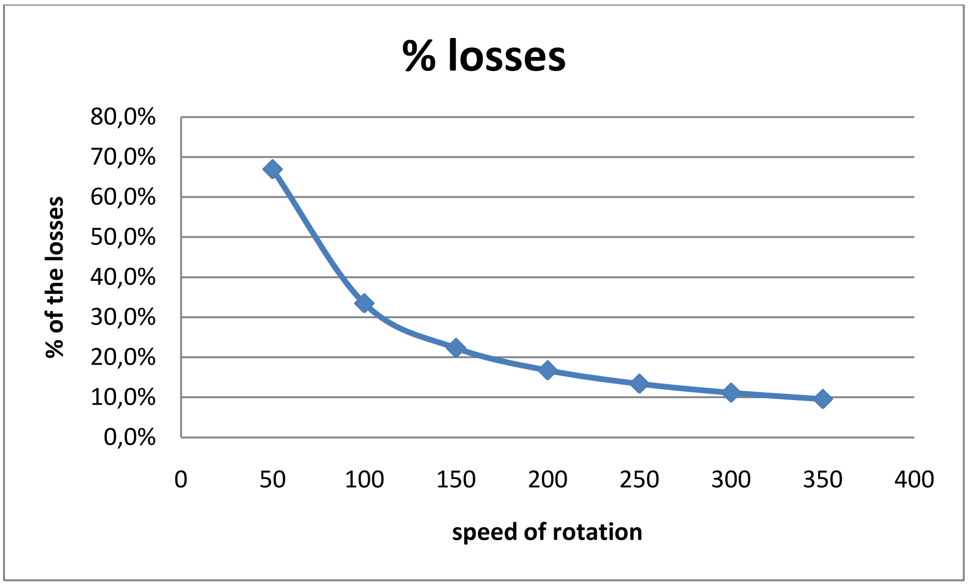


Figure 4.8.1b

You see that for all working points lower that the nominal power production, the losses in the generator raise really quickly, and the efficiency of the machine will drop fast.

4.8.2 The 300STK4M with 800 rpm

If you have a look 300STK4M, the behaviour is different.

rpm	power	voltage	current	losses	losses	total	load
50	871,5	8,31	34,95	549,6	63,1%	0,238	0,088
100	1743	16,63	34,95	549,6	31,5%	0,476	0,326
150	2614,5	24,94	34,95	549,6	21,0%	0,714	0,564
200	3486	33,25	34,95	549,6	15,8%	0,951	0,801
250	4357,5	41,56	34,95	549,6	12,6%	1,189	1,039
300	5229	49,88	34,95	549,6	10,5%	1,427	1,277
350	6100,5	58,19	34,95	549,6	9,0%	1,665	1,515
400	6972	66,50	34,95	549,6	7,9%	1,903	1,753
450	7843,5	74,81	34,95	549,6	7,0%	2,140	1,990
500	8715	83,13	34,95	549,6	6,3%	2,379	2,229
550	9586,5	91,44	34,95	549,6	5,7%	2,616	2,466
600	10458	99,75	34,95	549,6	5,3%	2,854	2,704
650	11329,5	108,06	34,95	549,6	4,9%	3,092	2,942
700	12201	116,38	34,95	549,6	4,5%	3,330	3,180
750	13072,5	124,69	34,95	549,6	4,2%	3,568	3,418
800	13944	133	34,95	549,6	3,9%	3,805723	3,656

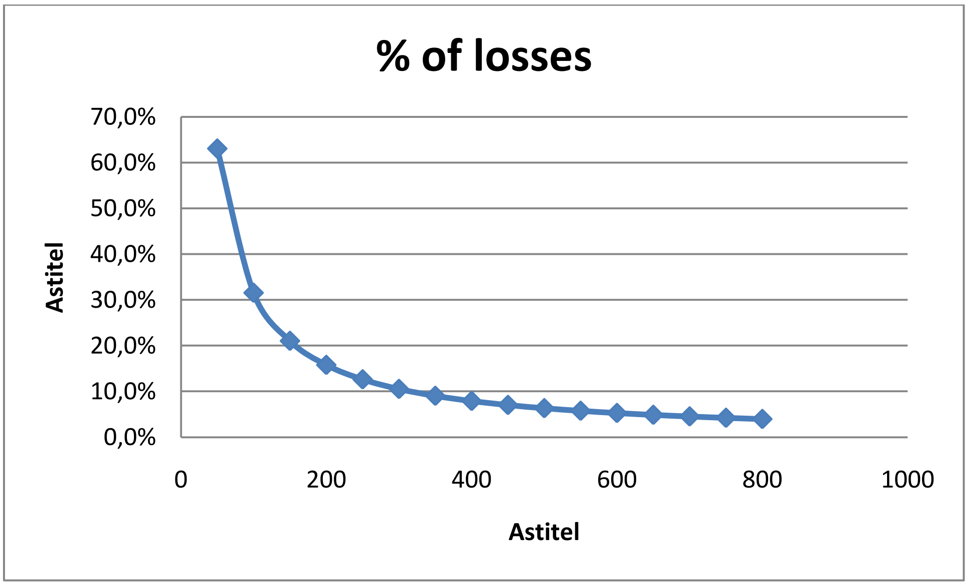


Figure 4.8.2a

4.8.3 300STK2M with 800 rpm

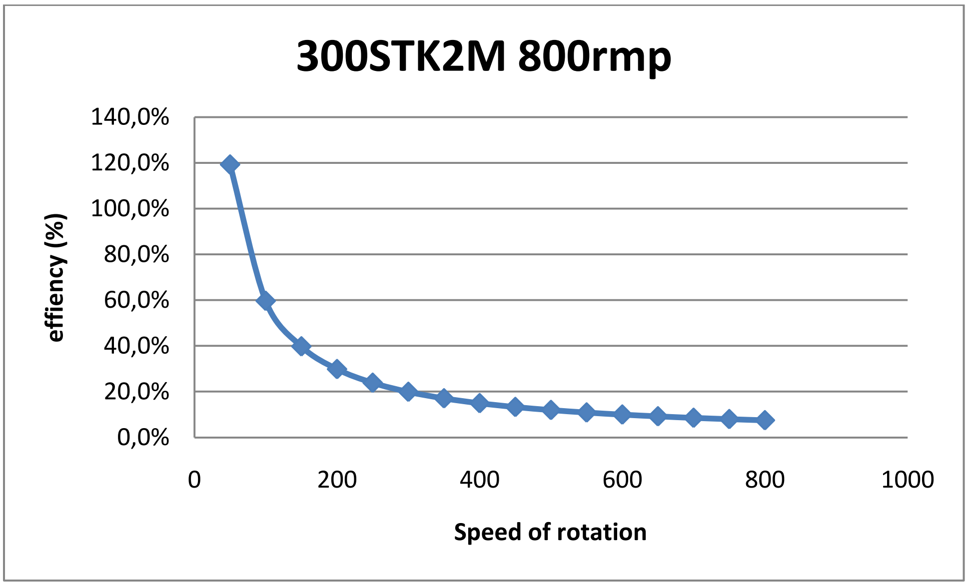


Figure 4.8.3a

4.8.4 Conclusion: comparison of the 3 models

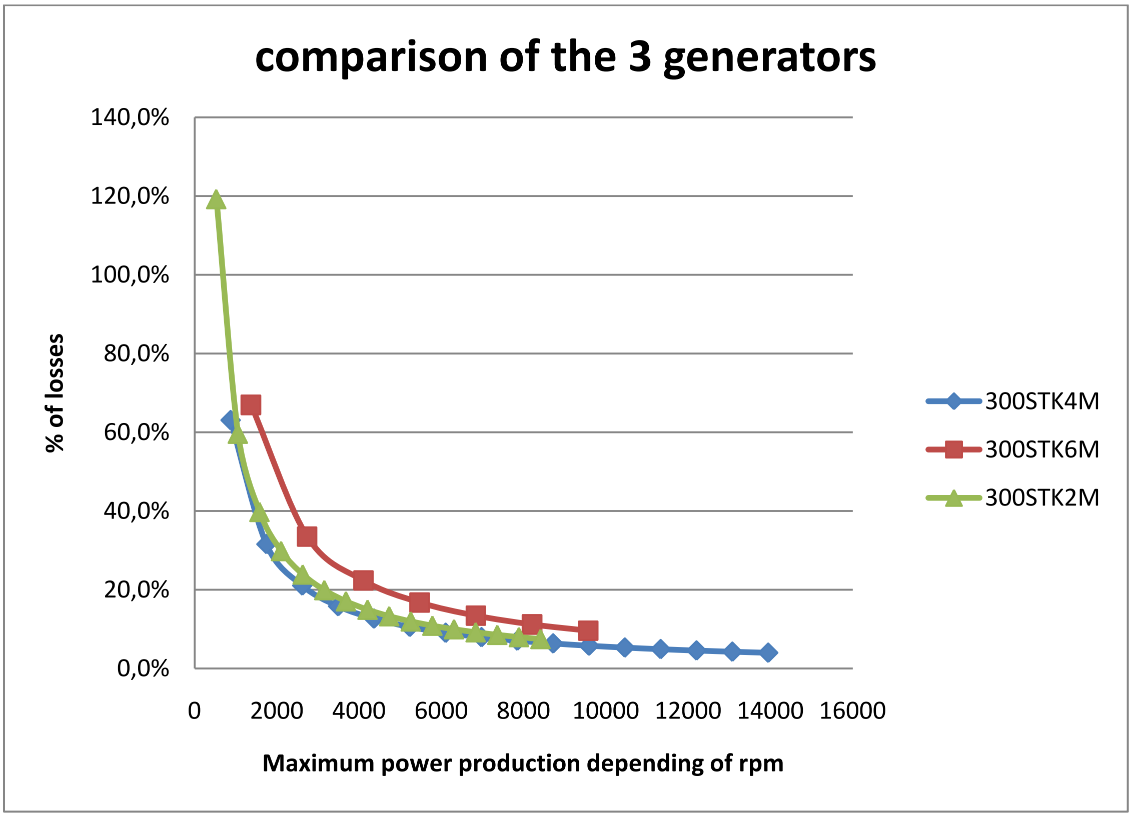


Figure 4.8.4a

In the rest of my thesis I will assume that we use a generator with similar characteristics as the 300STK2M. The best characteristics are the ones from the 300STK4M. We could choose the 300STK4M, but if you look in the table of AXION we see that the weight of the 300STK2M is 18 kg and the weight of the 300STK4M is 31 kg. I assume that the price of the 300STK2M is lower.

So we take the 300STK2M from ALXION with the 800 rpm. If we use a speed of 800rpm, we have to implement a gearbox. In the model with 350 rpm, it is maybe possible to skip the gearbox when we use just one small gear. If we choose the 300STK2M model we need a gearbox to raise up the speed.

It is good to note that all those generators, including 300STK2M, are developed for windmill applications. The phase-to-phase voltage is 230V ($\sqrt{3} * 133$). For our applications is this not necessary. If we can develop our own generator, with higher voltages and lower currents, we can accomplish higher efficiency.

A waterproof enclosure is also very important in our design.

Now we have to put all the characteristics in our model.

4.8.5 Determine the generator constants

We remove the wave generator in our model and we place a constant source of 800 rpm on our generator. We change the characteristics of the generator until we have approximately the same power production as in the ALXION table:

Power	8413
Voltage	133
current	21.1

Now we have to choose the resistive value of the load in order to have the right currents and power production:

After rectification we have a DC voltage of (see formula (7) in chapter 3):

$$U_d = U_{average} = \frac{3.\sqrt{3}\,\sqrt{2}}{\pi}.133 = 311.1V \quad \text{(7, chapter 4)}$$

So our current is (if we neglect the losses in the bridge of diodes):

$$\frac{8413}{311.1} = 27.04\text{A}$$

So we want to have 27.04 A. Now we can specify our resistive value.

$$R = \frac{P}{I^2} = 11.5\ Ohm$$

So we have to use a resistive value of 11.5 Ohm.

In order to have this voltage output we have to choose the correct generator constant. We can calculate this:

$$E_{max} = output\ voltage + voltage\ drop\ windings = 133 * \sqrt{2} + 9{,}917 = 191V$$

$$E = 4{,}44kp\varphi_{max} N.n \qquad (18,chapter4)$$

$$E_{max} = cte * \omega \qquad (19,chapter\ 4)$$

$$\omega = 800 * \frac{2\pi}{60} = 83.78\ rad/s$$

$$cte = \frac{191}{83.78} = 2.28$$

In our model we take 2.305 as a generator constant in order to have exactly the right value.

With the voltage drop of the generator windings we become:

$$133 * \sqrt{2} = 181.1V$$

- The second generator constant

$$L_1 = E_{max} * \cos(2\pi ft) \qquad (21,chapter\ 4)$$

$$2\pi pnt = p\omega t \qquad (27,\ chapter4)$$

With n in rps.

In the datasheets they don't mention the machine's amount of pole pares. So we have to figure this out. ALXION is a French company. Most applications in Europe work around 50 Hz. So with 800 rpm, we prefer 50 Hz.

$$f = p.n \qquad (24,chapter\ 4)$$

With n in rps

$$800rpm = 13{,}33rps$$

$$p = \frac{f}{n} = \frac{50}{13{,}33} = 3.75$$

So assume that the generator has 4 pole pairs, than we have a frequency of 53.33 Hz with 800 rpm.

$$f = 4 * 13{,}33 = 53{,}33Hz$$

We have a frequency of 50 Hz with 750 rpm.

$$n = \frac{f}{p} = \frac{50}{4} = 12{,}5rps = 750rpm$$

So the construction of the generator assumes that we have 4 pole pairs to use in our Matlab simulation.

- Let's put it in the model with the constant speed of rotation of 800 rpm and see what we get:

DC voltage:	295.2
DC current:	25.66
DC power:	7579

We see that the values are a little lower than usual, but not much. A reason for this can be the losses in the bridge of diodes.

Let's find the power output for other speed of rotations. On the first graph we see that until 800 rpm we have a more or less linear area. Let's make the curve linear to find other values.

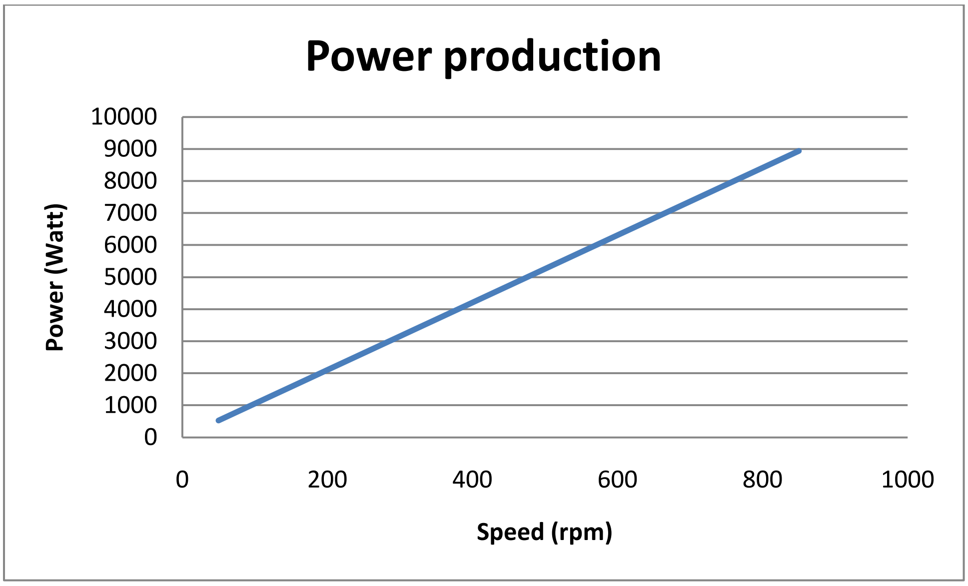


Figure 4.8.5a

Rico= 10.52

$$Power = 10.52 * speed\ (rmp) = T * \omega * \mu_e = Fb * \frac{D1}{2} * \omega_1 * \mu e \qquad (43)$$

With:

$$\omega_1 = rotation\ speed\ before\ gearbox$$

$$\mu e = efficiency\ gearbox + generator$$

$$Fb = force\ on\ the\ bouy$$

So the force Fb on the buoy, caused by the generator is approximately constant.

Now we can find the correct power output after the generator depending on the speed.

So now we are going to use the same characteristics but with the wave generator instead of the constant speed of rotation.

Now we have the right generator constants, so we don't change this anymore.

We choose one wave. Let's take for example this wave:

T (s)	H (m)	P/m^3
10	2.5	1965

This is a strong average wave. For all my simulations I will use this one.

And assume that the volume of the buoy is 6 cubic meter. Unlike the Betz-limit with wind energy, nowhere in the literature could I find an exact value for the efficiency of the conversion wave to buoy. So I assumed it to be 50%. Too high efficiency values will make the wave to stop after to buoy. Experiments have to confirm this value.

efficiency of the conversion wave to buoy	0,5
Volume of the buoy (m^3):	6
Power of the buoy (W):	5895
estimated total efficiency	0,45
Power of the load (W)	5305.5

If we take these assumptions into account, we can extract approximately 5.3 kW. Exact values will be obtained with future test devices and our models can be specified.

$$Power = 10.52 * speed\ (rpm)$$

$$5305.5 = 27.35 * speed(rpm)$$

$$average\ speed(rpm) = 504.5\ rpm$$

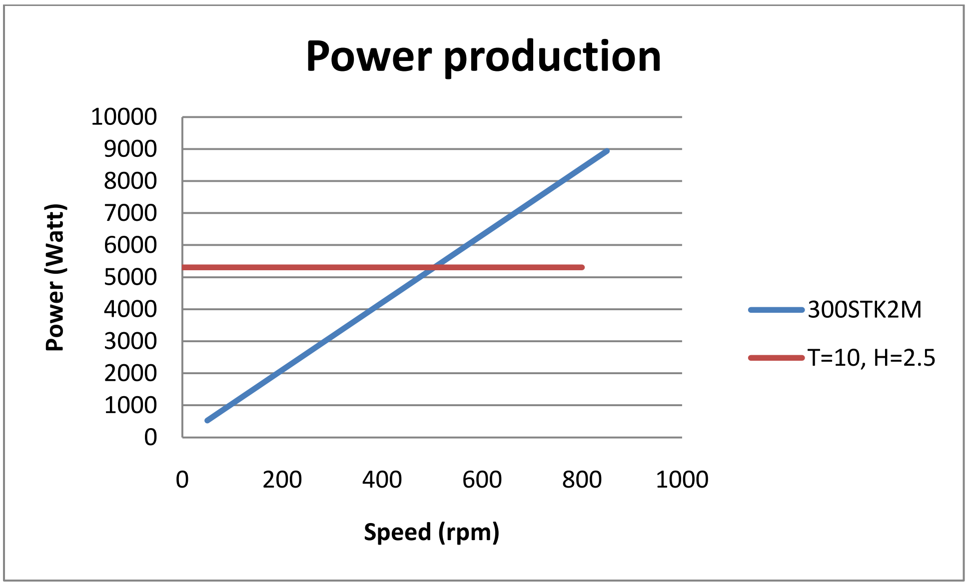


Figure 4.8.5b

In order to have this speed of rotation I put the gearbox on:

$$\frac{H*2*60}{T*D1\ \pi}(rpm) = 95.5 \quad (44)$$

D1 is the diameter of the first gear of the gearbox.

$$gear\ ratio = \frac{504.5}{95.5} = 5{,}285$$

Gear ratio	5.285
D1	0.1

If we look in Matlab we have a speed of rotation now of: 503.7 rpm

We can choose smaller values of D1 instead of a gearbox, but mechanical engineers have to calculate if smaller gears can hold the forces.

At the moment, we know the characteristics of the gearbox and the generator. Now we have to find realistic load values.

- Determine P load

$$P_{dc} = Udc\ x\ Idc \quad (45)$$

$$P_{dc} = Idc^2 x\ R \quad (46)$$

Now we have to select a correct resistive value to have the right currents to have the 5.3 kW of the load. The DC voltage is more or less fixed for a certain speed.

$$Idc = \frac{Pdc}{Udc} = 26.74\ A$$

$$R = \frac{Pdc}{Idc^2} = \frac{5305.5}{26.74^2} = 7.4\ Ohm$$

The results of this calculation:

The voltage value is experimental confirmed by Matlab.

DC volt RMS	198.4
Dc current	26.81
DC power	5321
R-value	7.4

So we can implement 7.4 Ohm for one device. For all the models that follow, we will use the same way to determine the load. If we use two devices we will see that the resistance value will be double this value (for further explanation, see later on).

4.9 Simulations

4.9.1 One device

So now let's put this concept into the model. We always use the same characteristics and the same generator inputs to compare our results. We always take the wave with the following characteristics:

$$T = 10s$$
$$v = \frac{T}{0,641} = 1,56 * 10 = \frac{15,6m}{s}$$
$$\lambda = \mathrm{Tv} = 156\mathrm{m}$$
$$A = 1.125m$$

$$y(x,t) = 1.125 * \cos\left(2\pi\left(\frac{x}{156\mathrm{m}} - 0,1t\right)\right)$$

Let’s first have a look at what we got out of one model:

- Vabc of one device before rectification

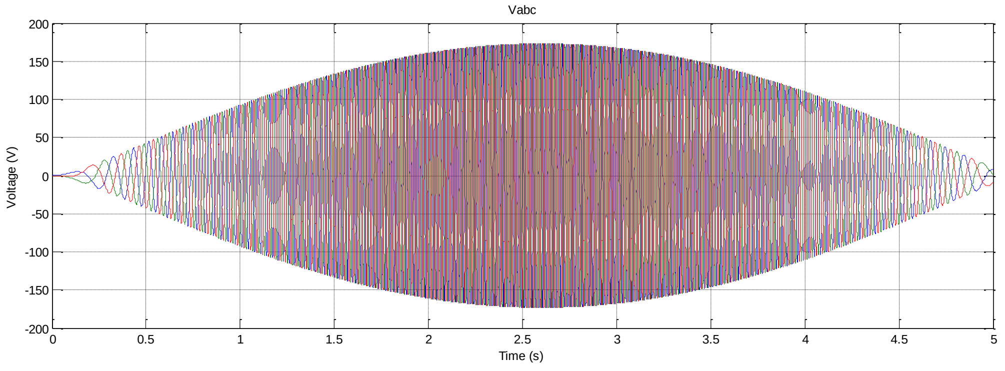


Figure 4.9.1a

- Power of 1 device after rectification

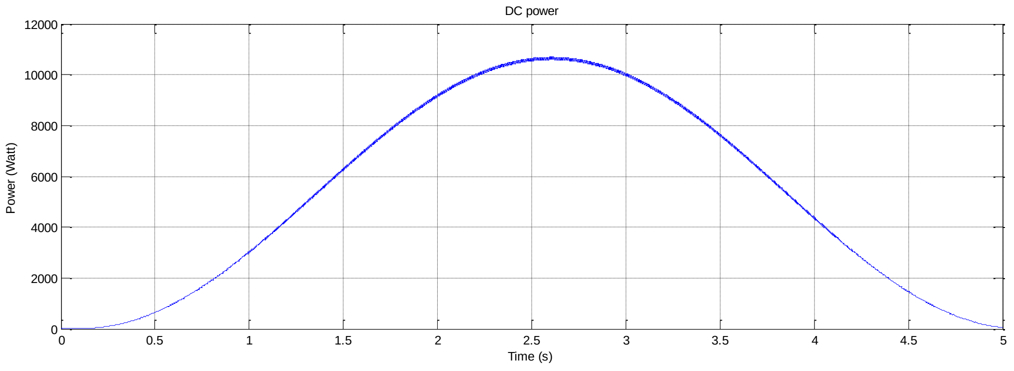


Figure 4.9.1b

Average power production:

$$Pdc = \frac{1}{T}\int_0^T Pdc(t) = 5321Watt$$

The line itself shows a lot of ripple, but this can easily be fixed by choosing the correct capacitor to put parallel of the load. The load is only resistive.

Now I took a RC-value of 0.006. With R=10 Ohm and C=0.0006, and we have already much less ripple.

- Voltage

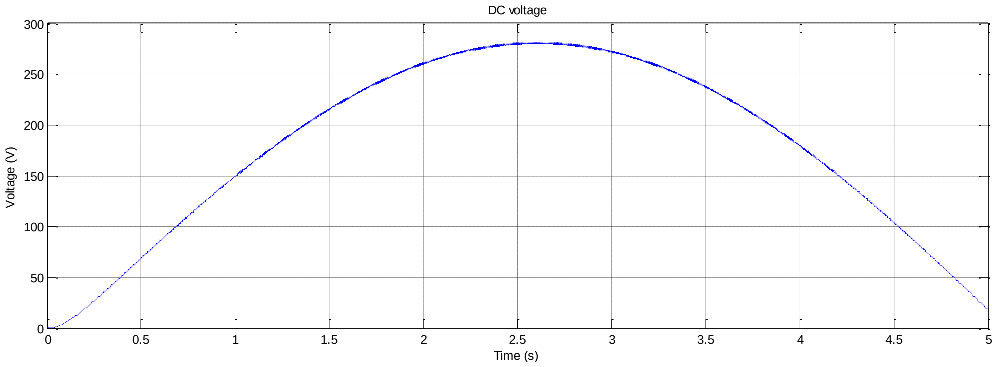


Figure 4.9.1c

$$Vd = \frac{1}{5}\int_0^5 V(t) = 178.6V$$

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T V_{dc}(t)^2.dt} = 198.4V$$

- Current

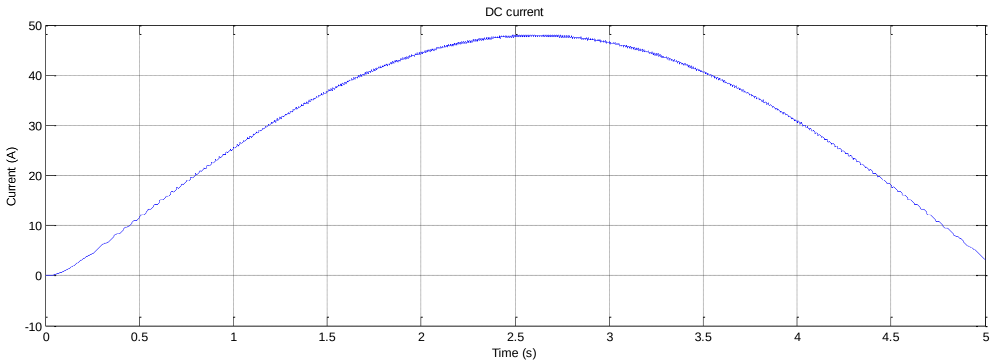


Figure 4.9.1d

$$Idc = \frac{1}{5}\int_0^5 I(t) = 24.14A$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T I_{dc}(t)^2.dt} = 26.81A$$

Conclusion: we only have to look at the behaviour of the first half of one period (1-5 seconds), because the second half has the same characteristics. It's important to know that this is only right in this model. In the real application there is a difference between the upward and downward movement. The upward movement was caused by the wave. The downward movement was a result of the spring or mass.

For fist calculations it is easy to put all the buoys just in one part of the wave.

4.9.2 Two devices

If you take the same resistive value, the model will not work because the currents are higher. Because of the series connection, the current will flow through the two generators, the current being much higher and creating a torque that wants to slow down the two generators. We need to have a resistive value that creates approximately the same current through the generator coils. A simple calculation shows how we can keep the currents through the coils of the generator constant. If you want to keep the same current through the coils you have to double the resistive value of the load in order to have approximately the same current through the diodes. (This is not a 100% true because if you combine several devices together with the aim to reduce the ripple on the current, the ripple through the coils of the generator will reduce too.)

$$P = RxI^2$$

If we put two generators in the application, the power output will double.

Hence we take a resistive value of 7.4*2= 14.8 Ohm to have the same currents.

$$2xP = (2xR)xI^2$$

Keeping the same currents is very important because due to the series connection, all the currents flow through all the generator coils!

We implement the difference in position as a difference in time. So in this example, if we want to make a difference in space of ¼ of a period of wavelength=39meter. We make a delay of ¼ of the time of a period= 2.5 seconds.

Distance (m)	0	**39**	78	117	156
Time delay (s)	0	**2.5**	5	7.5	10

So to simulate what happens 39 meter away from the buoy in the direction of the wave movement, we use a delay of 2.5 s.

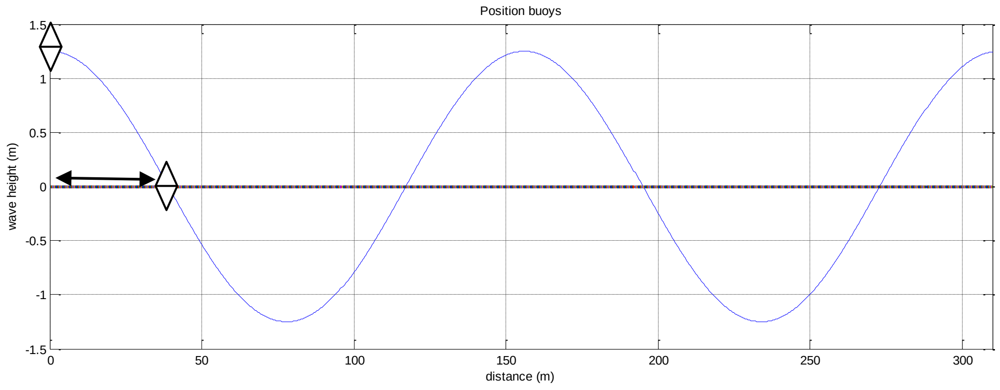


Figure 4.9.2a

- Output Power

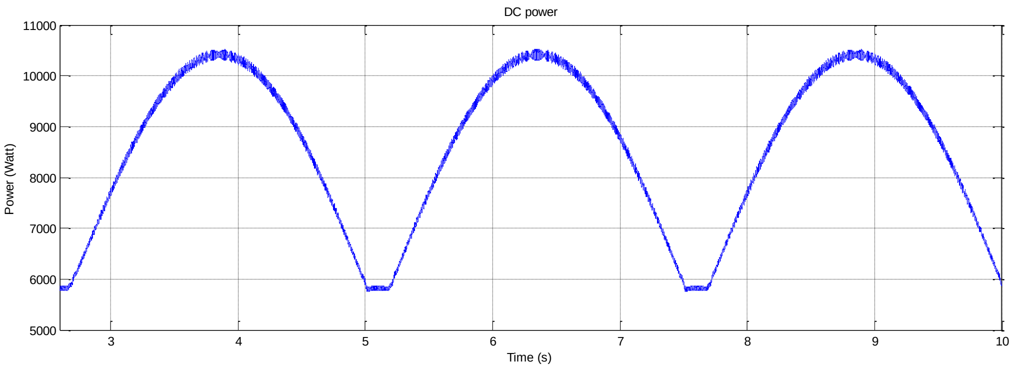


Figure 4.9.2b

With Matlab:

$$Pdc = \frac{1}{T}\int_{0}^{T} P_{dc}(t).dt = 8547Watt$$

- Output voltage

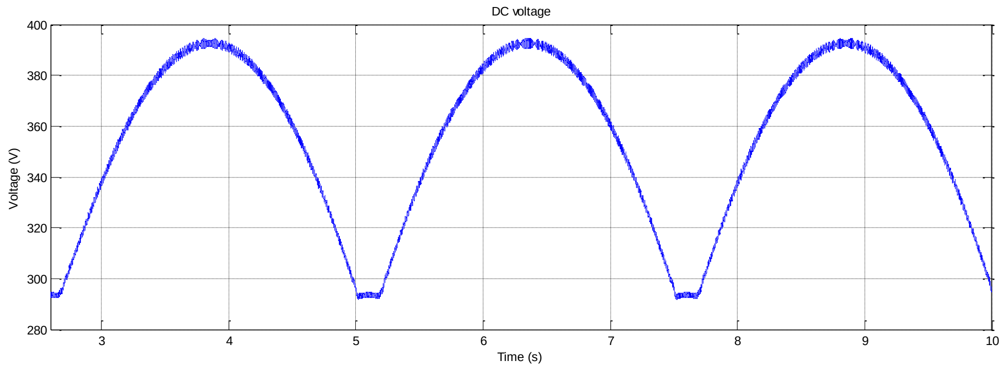


Figure 4.9.2c

With Matlab:

$$Udc = \frac{1}{7.5}\int_{2.5}^{10} V_{dc}(t).dt = 354.1\,V$$

$$U_{RMS} = \sqrt{\frac{1}{7.5}\int_{2.5}^{10} V_{dc}(t)^2.dt} = 355.7\,V$$

- Output current

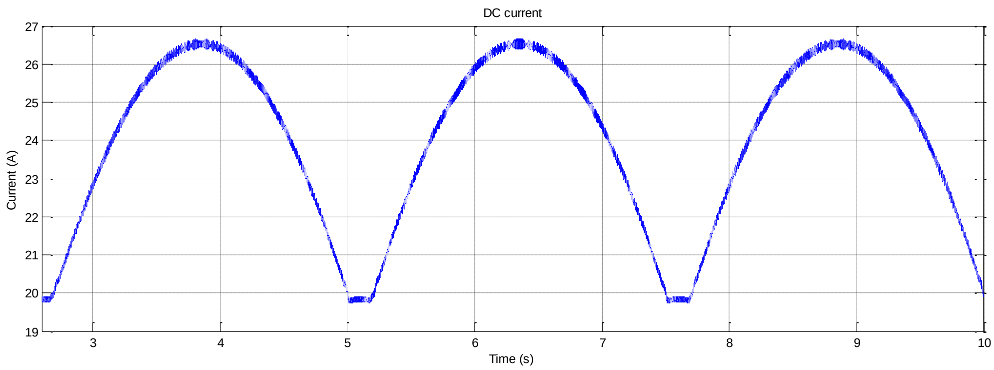


Figure 4.9.2d

$$Idc = \frac{1}{7.5}\int_{2.5}^{10} I(t) = 23.93A$$

$$I_{RMS} = \sqrt{\frac{1}{7.5}\int_{2.5}^{10} I_{dc}(t)^2.dt} = 24.3A$$

- Conclusion:

Because of the time delay we see in the first 2.5 seconds only the output caused by the first buoy. I erased this part, because this is not useful. After the 2.5 seconds the other buoy comes into action and we see that the voltage and power don't fall to zero anymore. There is still much ripple! Because of the series connection the voltage level approximately doubles. This can cause trouble for the design of the machine.

We see that the problem is still not solved.

4.9.3 4 devices

We use again (for all our simulations in the thesis) the same wave with following characteristics:

$$T = 10s$$
$$v = \frac{T}{0{,}641} = 1{,}56 * 10 = \frac{15{,}6m}{s}$$
$$\lambda = \mathrm{Tv} = 156\mathrm{m}$$
$$A = 1.125m$$

$$y(x,t) = 1.125 * \cos\left(2\pi\left(\frac{x}{156\mathrm{m}} - 0{,}1t\right)\right)$$

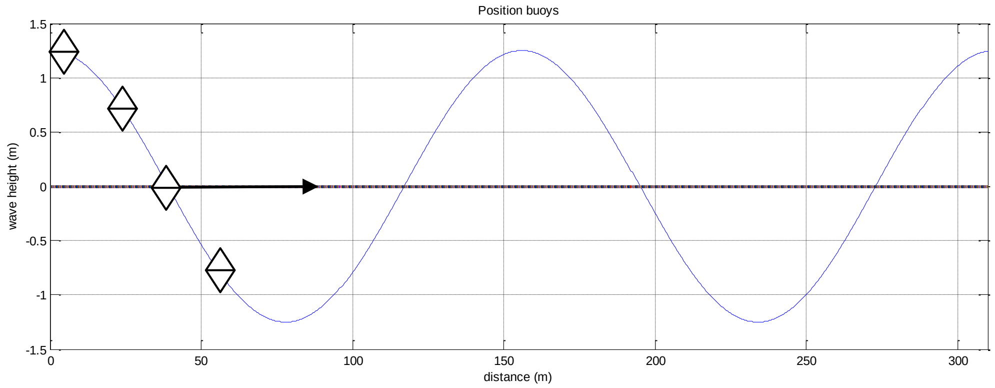


Figure 4.9.3.a

Wave length (m)	0	19.5	39	58.5
Time delay (s)	0	1.25	2.5	3.75

As the behaviour is similar in the second part of the wave we can put all buoys in the first half of the period. This is theoretical, because for practical applications this distance is to close. They will most likely affect each other. And if you put them out of the wave direction, you can have problems when the direction of the wave slightly changes. But for faster model behaviour we will put them closely behind each other for the first time.

Let's put a 3rd device at 19.5 meters from the first device and 4th at the distance of 58.5 meters, thus with a time delay of respectively 1.25 and 3.75 seconds.

To have the same currents through the generators we take a resistive value of 7.4*4= 29.6 Ohm.

- Power

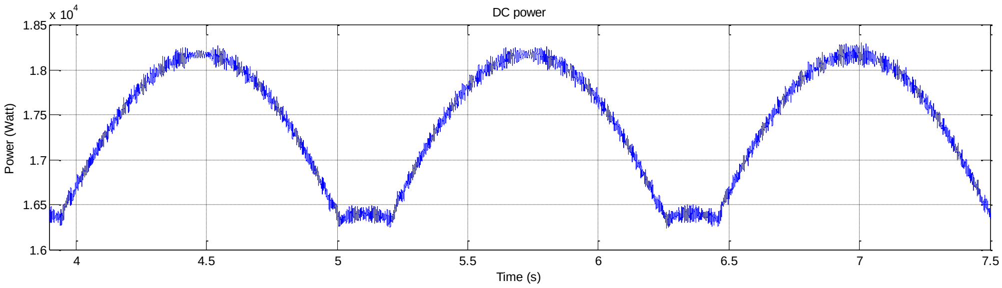


Figure 4.9.3.b

$$Pdc = \frac{1}{1.25}\int_{3.75}^{5} P_{dc}(t).dt = 17370Watt$$

This is almost exactly the double of the 2 devices together.

- Voltage

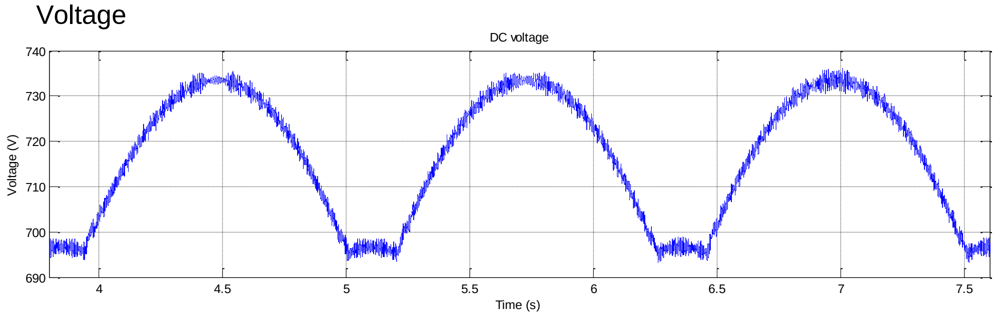


Figure 4.9.3.c

$$Udc = \frac{1}{1.25}\int_{3.75}^{1.25+3.75} V(t) * dt = 716.9V$$

$$U_{RMS} = \sqrt{\frac{1}{1.25}\int_{3.75}^{5} V_{dc}(t)^2.dt} = 717.1V$$

- Current

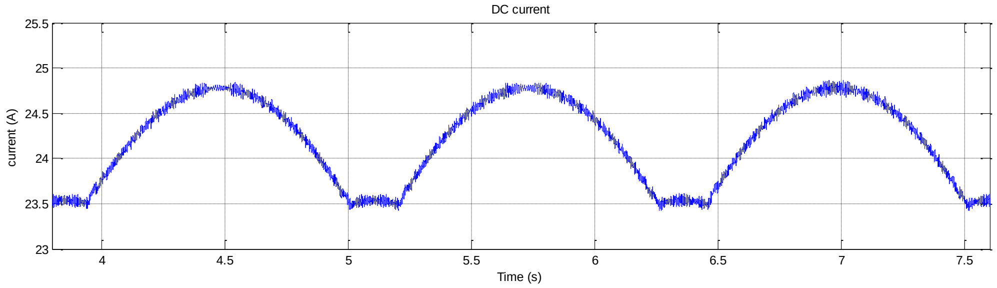


Figure 4.9.3.d

$$Idc = \frac{1}{1.25}\int_{3.75}^{5} I(t) = 24.22A$$

$$I_{RMS} = \sqrt{\frac{1}{1.25}\int_{3.75}^{5} V_{dc}(t)^2.dt} = 24.22A$$

The biggest ripple is on the power because current and voltage reinforce each other.

4.9.4 Devices but more distance between each other

- We can also use other time delays to achieve the same results:

Time delay1 (s)	Time delay 2 (s)
0	0
1.25	3.75
2.5	11.25
3.75	22.5

Imagine the wave flows to the right. You see the second buoy rising with a time delay of 3.75 seconds in comparison with the first buoy.

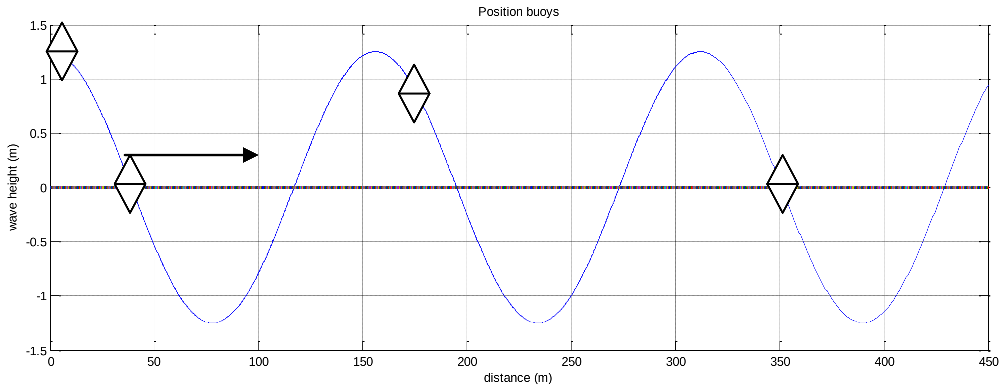


Figure 4.9.4a

If we run the simulation, we see exactly the same results as before! This is logical, because the buoys are at a place which has the same wave characteristics at the same time.

The only difference is that the simulation is much slower and it takes more time to have steady state behaviour.

This will not work sufficiently in the real application. The buoys are too close to each other. We also have to keep in mind that we use a simplified model. The upward movement is different from the downward movement in the real device. Hence, it is important to make a good balance by placing, for example, half of the buoys in the downward movement and the other half in the upward movement.

4.9.5 6 devices

For 6 devices we can use the following time-delays:

Time delay1 (s)
0
0.833
1.667
2.5
3.333
4.167

4.9.6 8 devices

time delay 1 (s)	time delay 2 (s)
0,000	0,000
0,625	10,625
1,250	21,250
1,875	31,875
2,500	42,500
3,125	53,125
3,750	63,750
4,375	74,375

Both time delays have the same result. Only the transition phenomenon in the model itself is much longer with the second time delays.

- Voltage

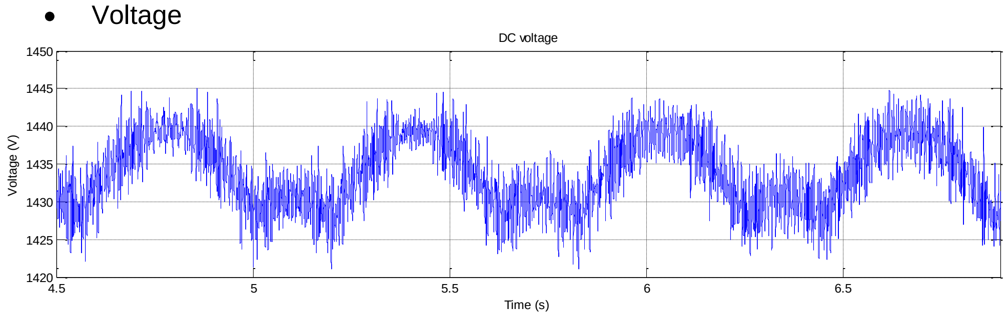


Figure 4.9.6a

$$Udc = \frac{1}{5.625}\int_{4.375}^{10} V(t).dt = 1434V$$

- Power

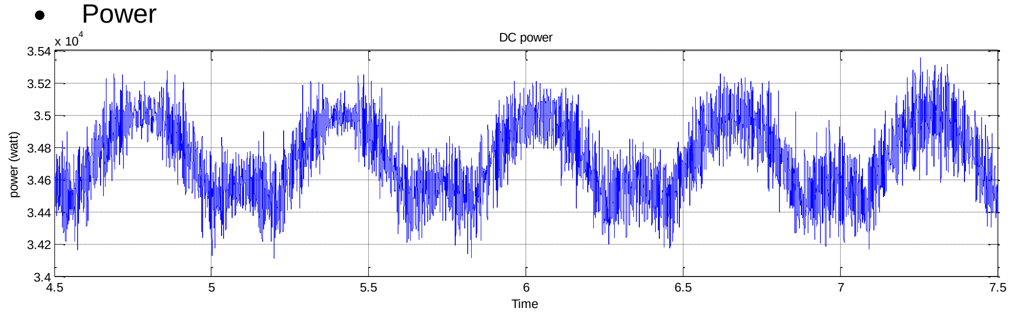


Figure 4.9.6b

$$Pdc = \frac{1}{5.625}\int_{4.375}^{10} P_{dc}(t).dt = 34720Watt$$

- DC current

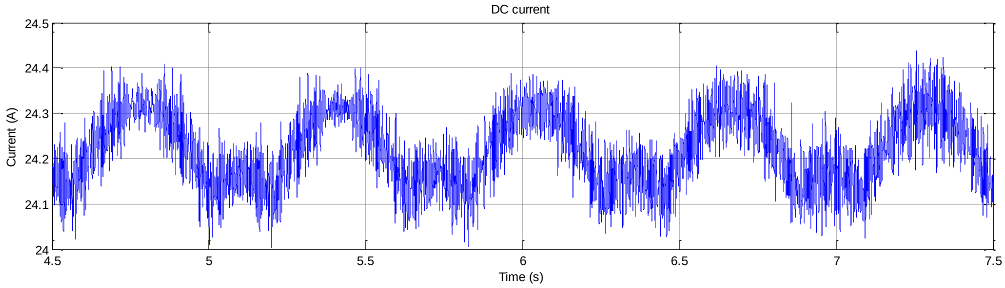


Figure 4.9.6c

$$Idc = \frac{1}{5.625}\int_{4.375}^{10} I(t) = 24.22A$$

The current is the same as the one with 4 devices. This ought to be like this, because we want to have the same currents in the generators.

4.9.7 10 devices

time delay (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

- DC power

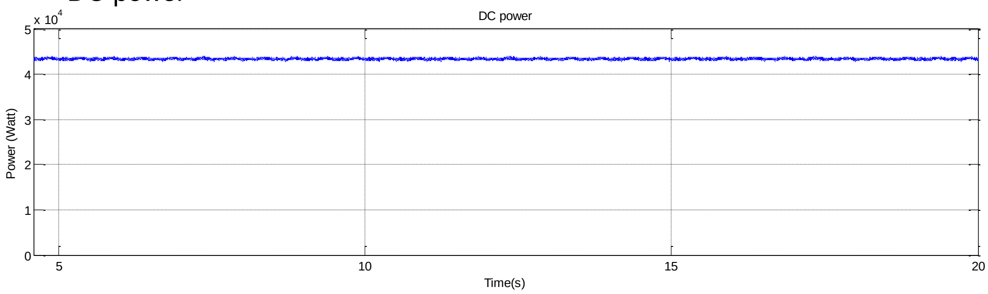


Figure 4.9.7a

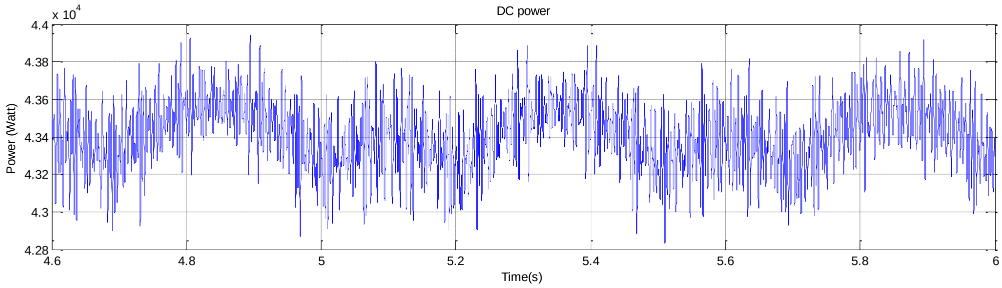


Figure 4.9.7b

$$Pdc = \frac{1}{4}\int_{4.5}^{8.5} P_{dc}(t).dt = 43400Watt$$

We see that we have exactly 5 times more power output than in the design with two devices.

- DC voltage

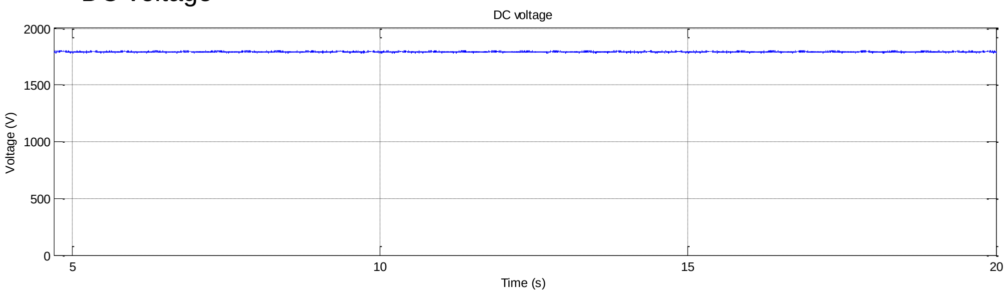


Figure 4.9.7c

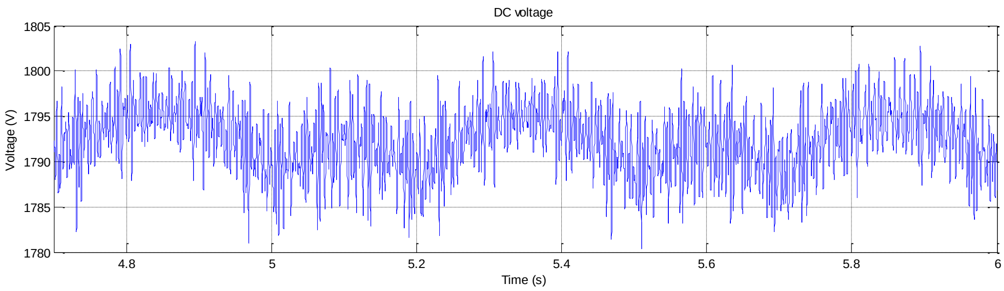


Figure 4.9.7d

Matlab:

$$U_{DC} = \frac{1}{4}\int_{4.5}^{8.5} V_{dc}(t).dt = 1792V$$

$$U_{RMS} = \sqrt{\frac{1}{4}\int_{4.5}^{8.5} V_{dc}(t)^2.dt} = 1792V$$

- DC current

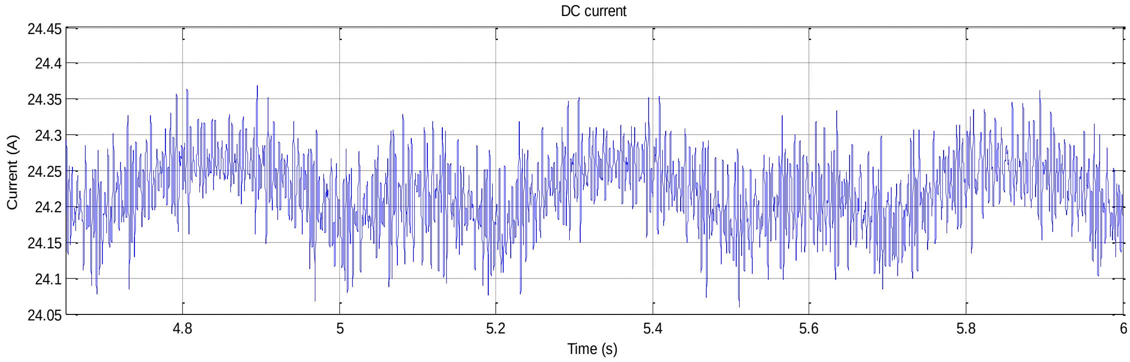


Figure 4.9.7e

$$Idc = \frac{1}{4}\int_{4.5}^{8.5} I(t) = 24.22A$$

4.9.8 Conclusion:

devices	Pout (Watt)
1	5321
2	8547
4	17370
8	34720
10	43400

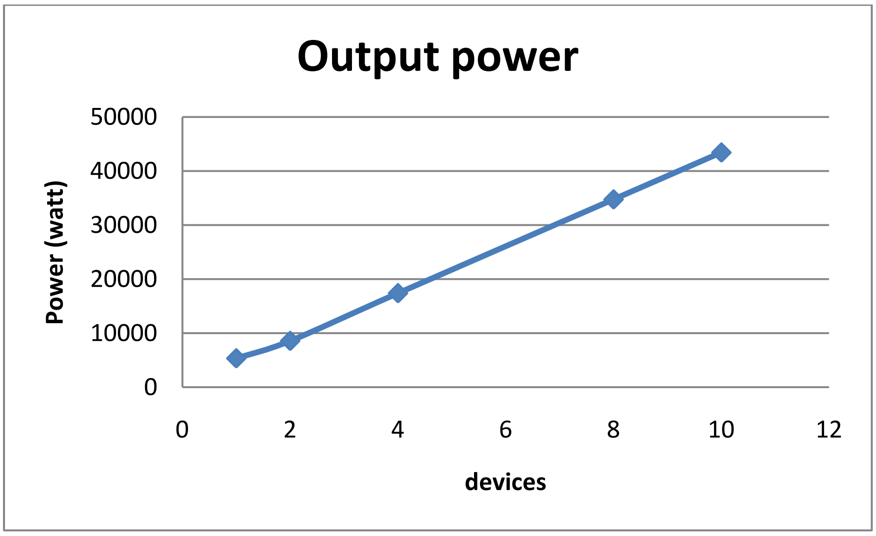


Figure 4.9.8

- Place enough buoys.

So that with extreme wave conditions or changes in wavelength the ripple will still be acceptable.

- Place of the buoys
    - Statistical analysis should be made to make sure that the power of a single device will not reinforce another.
    - Pay attention for oscillation.

A regular sea state is the addition of multiple wave sorts with different wavelengths and heights. We can never put the buoys in the perfect position for all the occurring wave types. We just chose a big occurring sinus wave. So it could be that one small wave makes the system oscillate. One solution is to use varying distances every time. Another is not to use distances that are a multiplication of one another in order to avoid this problem. Take for example primes.

- Super capacitor

We can implement a super capacitor and only use it in extreme or not appropriate wave conditions. Another solution is to transfer the power to the shore and then flatten the ripple, to avoid difficult off-shore maintenance cost.

- Asymmetric movement

We have to make test devices to see what happens in the ‘real’ devices. The upward and downward movement is not the same, and the results will be slightly different. We can construct two test applications. When you connect several devices together, one with the real 10kW PM generator and one test device with several smaller PM generators, you see what happens.

5 The efficiency of the connection: from gear-box to DC-current

5.1 Generator, bridge of diodes and DC-cables

The main goal of my thesis is to calculate the losses behind the gearbox until the rectified current and voltage.

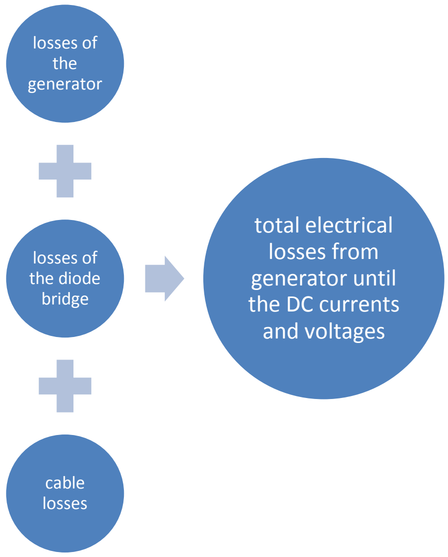


Figure 5.1

5.2 Losses in the generator coils

The same wave characteristics and load value are being used as in paragraph: 4.8.5

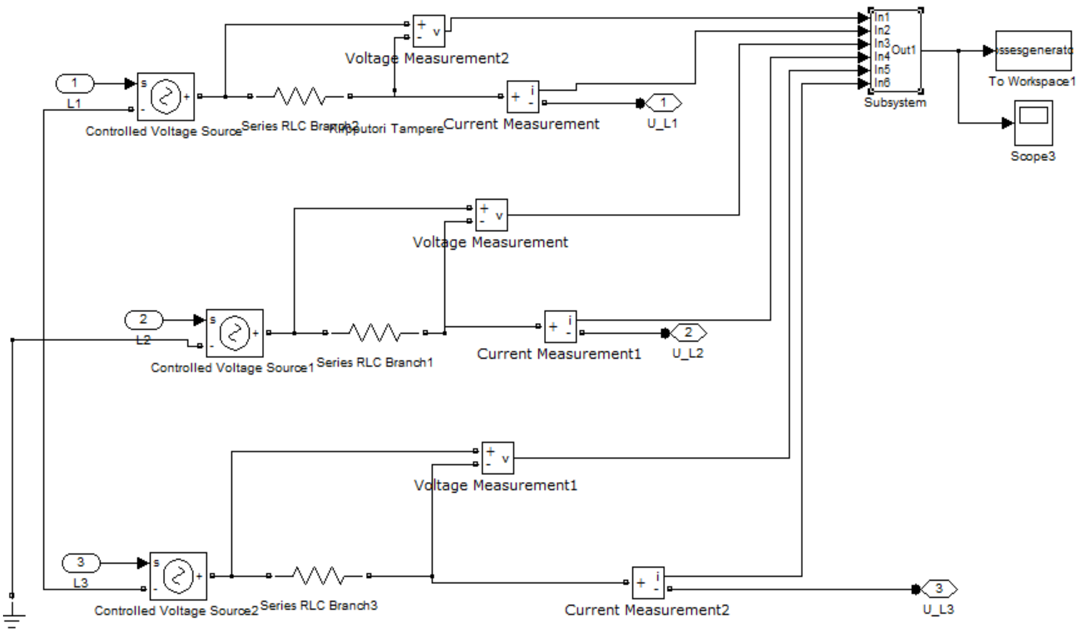


Figure5.2.1a

5.2.1 One device, usual values

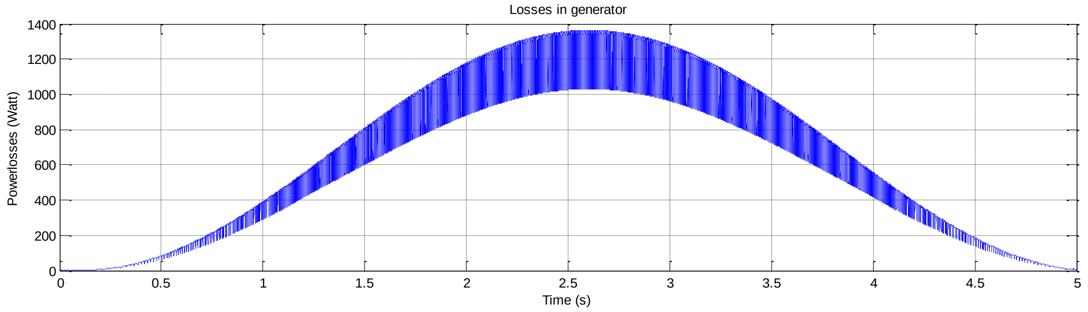


Figure 5.2.1b

$$P = \frac{1}{5}\int_0^5 P_{dc}(t).dt = 664.5\,Watt$$

5.2.2 Two devices, usual values

The following results are the losses in one generator, when we connect several devices together.

In theory the losses should be almost the same in comparison to one device for the same sea state.

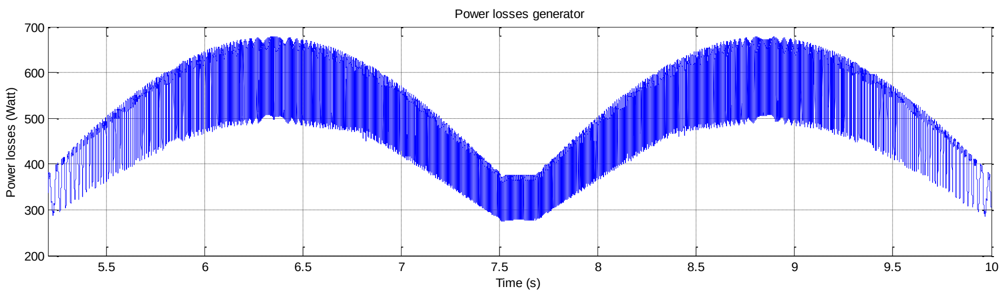


Figure 5.2.1c

$$Pgen = \frac{1}{7.5}\int_{2.5}^{10} P(t).dt = 524.2Watt$$

It seems that the losses are reduced for each machine. This is because there is much less ripple.

5.2.3 4 devices usual values

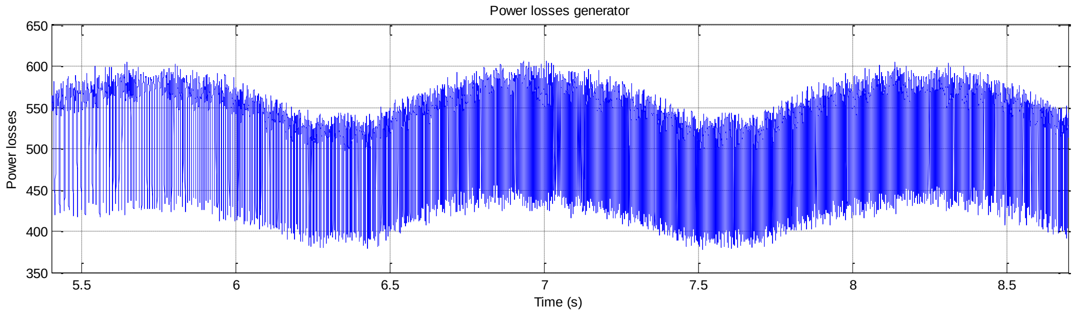


Figure 5.2.1c

$$Pgen = \frac{1}{7.5}\int_{2.5}^{10} P(t).dt = 523.6Watt$$

5.2.4 10 devices usual values

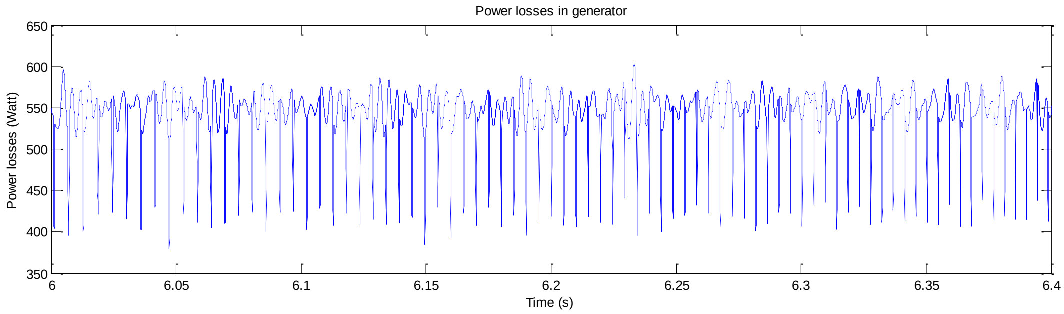


Figure 5.2.1d

$$Pgen = \frac{1}{4}\int_{4.5}^{8.5} P(t).dt = 517.6W$$

5.2.5 Conclusion

The losses over the generator are almost independent from the amount of devices that are connected. This is quit logical because I raised the resistive value of the load linear with the amount of connected devices. The currents flow through all the generators.

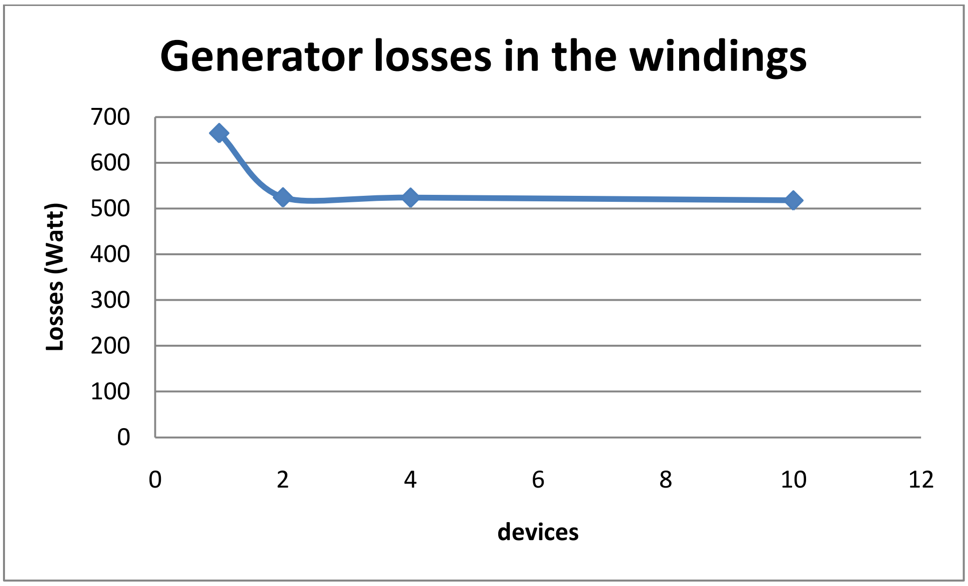


Figure 5.2.1e

Conclusion: we neglected the Joule losses. And the inductive part of the windings losses. We had to neglect the inductive behaviour of the coils, because Matlab cannot handle it. The model acts too slowly

Devices	Losses (watt)	Pout (watt)	Pout/device (watt)	efficiency
1	664,5	5321	5321	0,889
2	524,2	8547	4273,5	0,891
4	523,6	17370	4342,5	0,892
10	517,6	43400	4340	0,893

So we see that we have a fixed efficiency of 0.88. This is a high value for our application! A reason for this is the high currents through the system. We used a PM generator specially designed for wind energy production. If we look in the technical characteristics we see that we have a low voltage production of 133 V and a quiet high current production. In combination with the phase resistance of 0.47 Ohm, we lose a lot of energy.

TECHNICAL CHARACTERISTICS
300 STK ALTERNATORS

		300STK2M		300STK4M		300STK6M		300STK8M	
Rated speed	Rpm	350	800	350	800	350	800	350	600
Rated power (1)(2)	W	3174	8413	6627	13942	9573	17106	12683	19424
Current at rated speed (1)	Amps	7.9	21.1	16.6	34.9	24.0	42.9	31.8	48.7
Voltage at rated power (1)(2)(3)	V	133	133	133	133	133	133	133	133
Power at half speed (1)(2)	W	1297	3745	2729	7741	4136	11126	5506	10632
Phase resistance at 20℃	Ohm	2.41	0.47	0.99	0.15	0.53	0.08	0.37	0.11
Phase inductance	mH	15.1	3,04	8.5	1,28	5,08	0,78	3,86	1,11
Phase emf at 20℃ (4)	V	178.6	180.4	186.9	165.5	177.4	159. 8	178.6	164.1
Rotor inertia	10^{-3}Kg.m^2	52.7	52.7	105.5	105.5	158.2	158.2	211	211
Weight	Kg	18	18	31	31	44	44	57	57
Power cable square section	mm^2	4x1.5	4x2.5	4x1.5	4x6	4x4	4x10	4x6	4x10

300 STK Generators Power - Speed

Figure 5.2.1f

We can conclude that the most appropriate generator will be one especially designed for our wave energy collector. Companies such as PRECILEC can develop a more specific generator according to our design. If we can achieve higher voltage levels, the currents will drop and so will the losses. Hence, we can do some adaptations on this machine. The voltage level is depending on the following formula:

$$E = 4{,}44kpn\varphi_{max}N$$

- We can use stronger PMs to achieve a higher φ_{max} value
- We can use the V-shape position in order to achieve a higher φ_{max} value
- We can raise the amount of conductors in the stator (N)
- We can use more pole pairs, although this will raise the frequency of our generator too, and this is maybe not a good option.
- We can raise the rotational speed n (rps)

5.3 Simulations of the losses in the bridge of diodes

There are two ways to calculate the losses of the bridge. Fist we can measure the incoming and outgoing power. If we subtract the outgoing power from the incoming, we find the losses dissipated in the bridge of diodes. The efficiency can be easily calculated by dividing the outgoing power by the incoming power.

Another possibility is to measure the voltages and currents over the diode.

For all our simulations we use the same characteristics as in paragraph 4.8.5.

5.3.1 Diode characteristics

If we connect 10 devices together we see that our current is around 8 A, with a high average wave condition.

Let's take for example the following bridge:

S30VT60 - 3 Phase Bridge Diode (600V 30A) - Shindengen Electric Mfg.Co.Ltd

- Pulse measurement per diode of the datasheets of this bridge

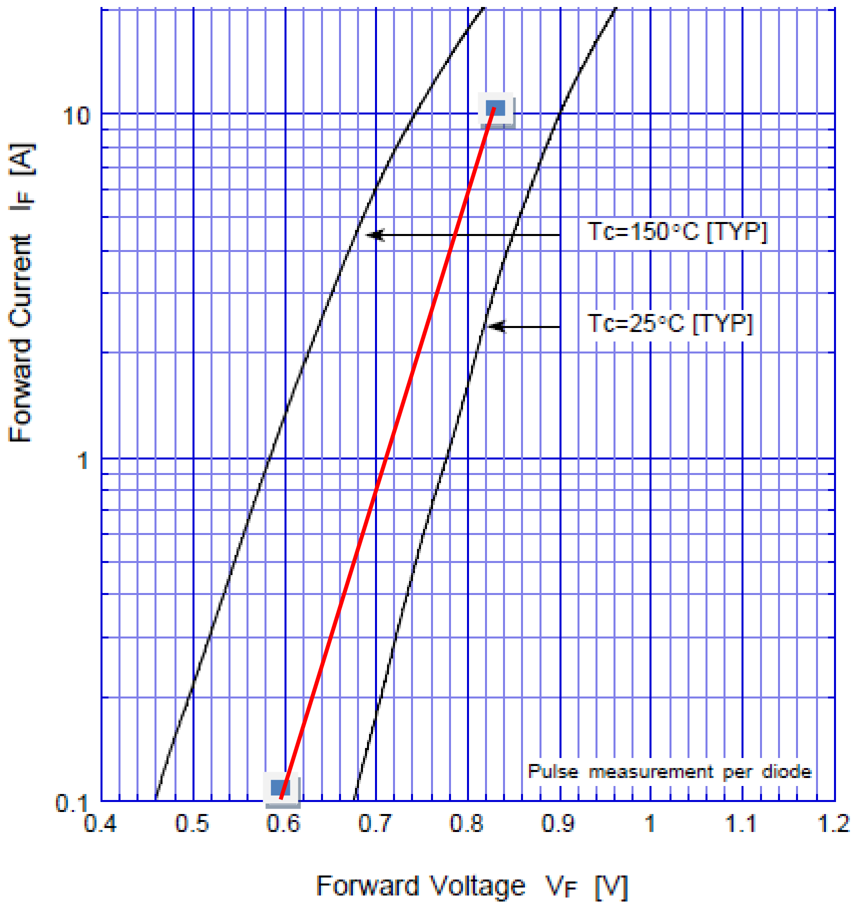


Figure 5.3.1a

If we simplify the curve we can find the following linear equation going through the points A (0.6; 0); B (0.82; 10)

$$Y = 45{,}45x - 27.27 \quad (1)$$

If you compare these characteristics to other three phase bridges with the same voltage and current range, you find very similar equations.

$$R_D = \frac{1}{\tan(\alpha)} = \frac{1}{45{,}45} = 0{,}022\Omega \quad (2)$$

5.3.2 Measurement of incoming and outgoing power to calculate efficiency

- Calculations of Pac

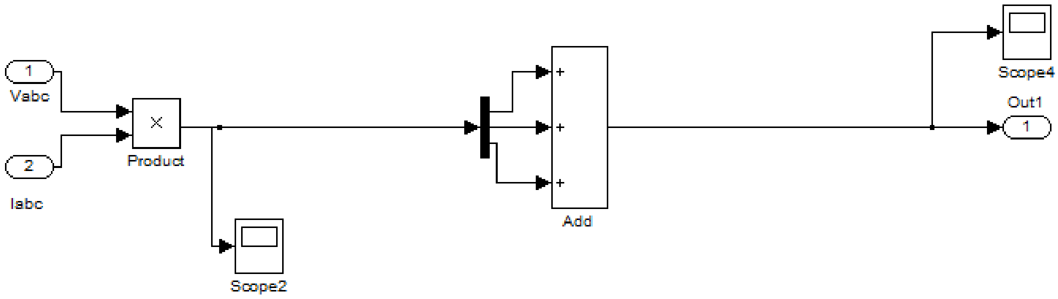


Figure 5.3.2a

- Calculations of Pdc

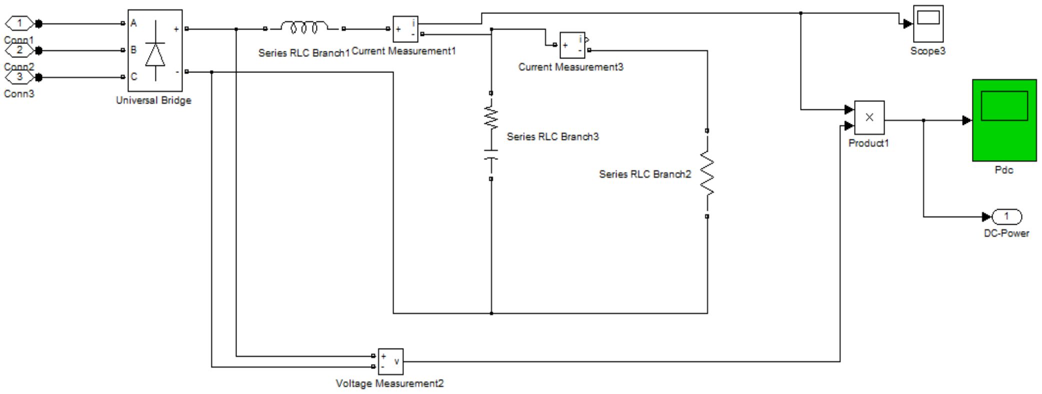


Figure 5.3.2b

- Calculations of efficiency and dissipated power

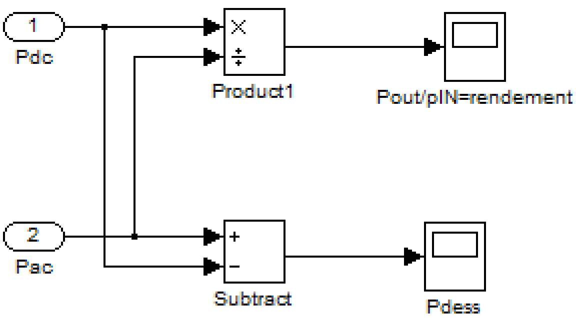


Figure 5.3.2c

- Results for 1 device
  - Power losses

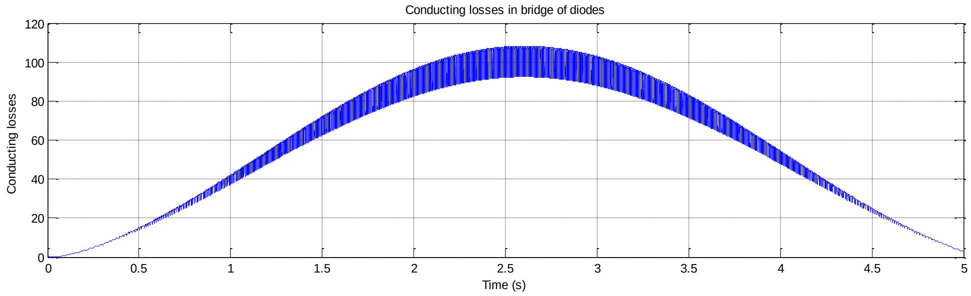


Figure 5.3.2d

$$Pgen = \frac{1}{5}\int_0^5 P(t).dt = 59.24$$

  - Efficiency

I use here again the snubber resistance of 1e6

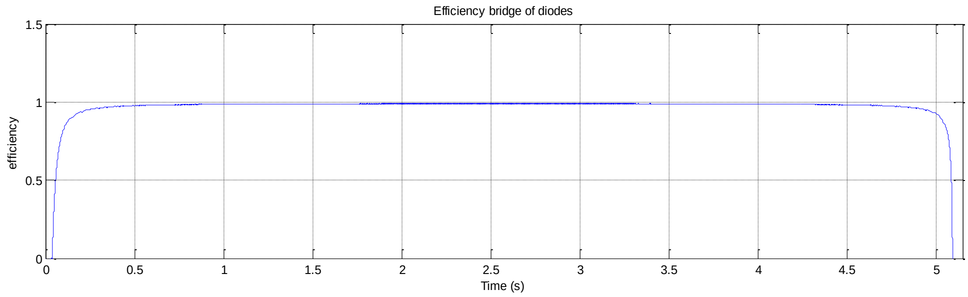


Figure 5.3.2e

$$\mu_{average} = \frac{1}{5}\int_0^5 \mu(t).dt = 0.976$$

These results are depending on the snubber resistance as well.

The snubber resistance is a bypass resistor over each diode. The second method doesn't take this into count, because there we only measure the currents through the diodes. The higher we chose the value of the snubber resistance, the more those two methods are similar.

If we take a snubber value of 1e5, the conducting losses are:

$$Pgen = \frac{1}{5}\int_0^5 P(t).dt = 60.18$$

The simulations run very slowly with this kind of measurements, that's why I decided to use the next method in the following simulations.

5.3.3 Efficiency by calculating dissipated power in bridge by measurement over the diode.

Out of my simulations it seems that inverse losses and switching losses can be neglected. The losses because of the snubber resistances are also neglected.

5.3.3.1 The model

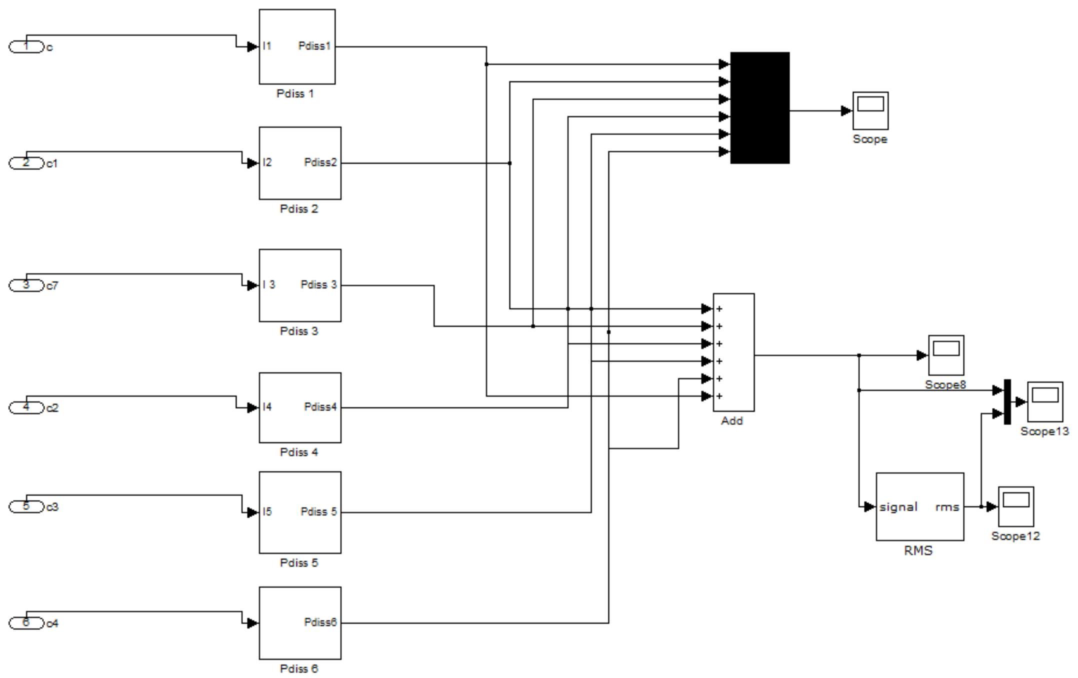


Figure 5.3.3a

There are 6 currents, for each diode one. I calculated the losses over each diode separately. If you look in the box you will find the following equation:

$$P_D(t) = U_D * i_D(t) + R_D i_D(t)^2 \tag{3}$$

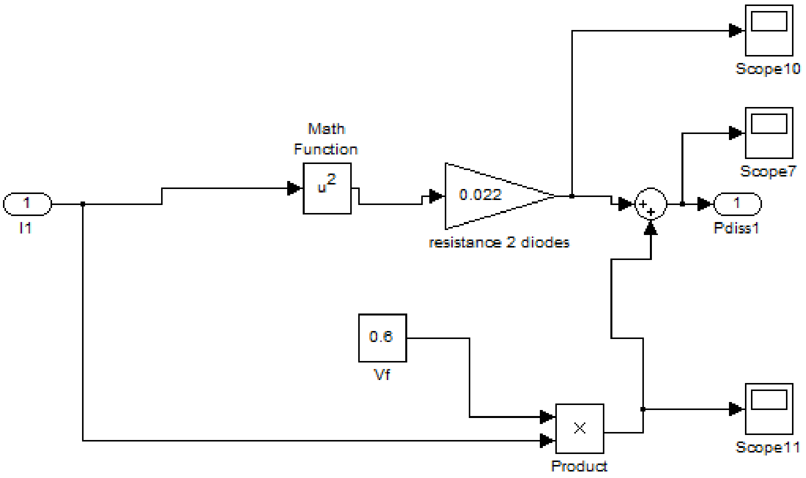


Figure 5.3.3b

Losses in one bridge when we connect several devices to each other.

It's important to know how the efficiency changes by connecting several devices together. In a series connection all the currents flow through both the bridges. The following results are the losses occurring in one bridge depending on the amount of devices that we connect together.

- One device

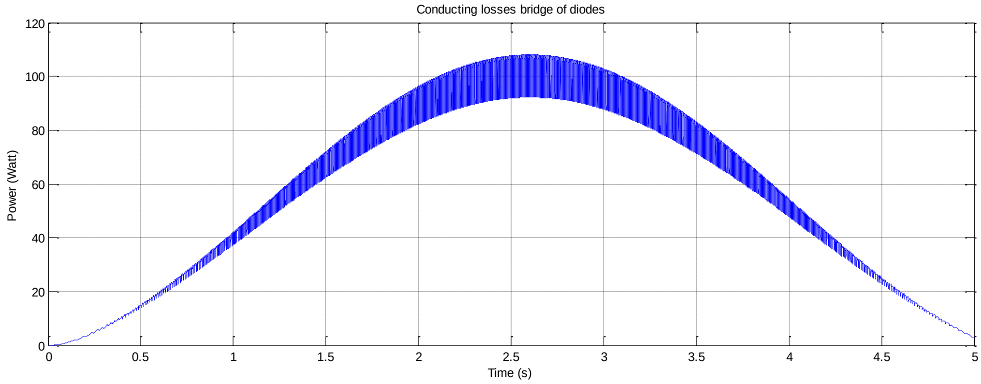


Figure 5.3.3c

$$P = \frac{1}{5}\int_0^5 P(t).dt = 59.14Watt$$

The value with this method is a little lower than the previous method. An explanation for this is that we only take the conducting losses into account. But as you see it is appropriate to do so.

- Two devices and measurement in one bridge

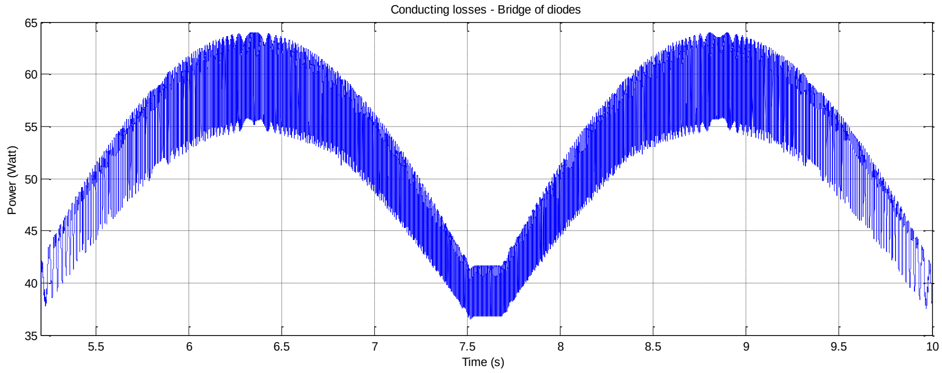


Figure 5.3.3d

$$P = \frac{1}{7.5}\int_{2.5}^{10} P(t).dt = 53.37Watt$$

- Four devices

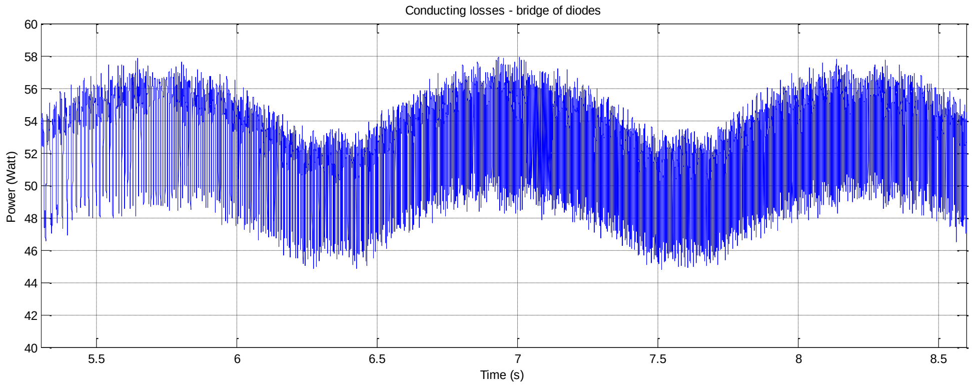


Figure 5.3.3e

$$P = \frac{1}{3.75}\int_{3.75}^{7.5} P(t).dt = 52.63\ Watt$$

- 10 devices

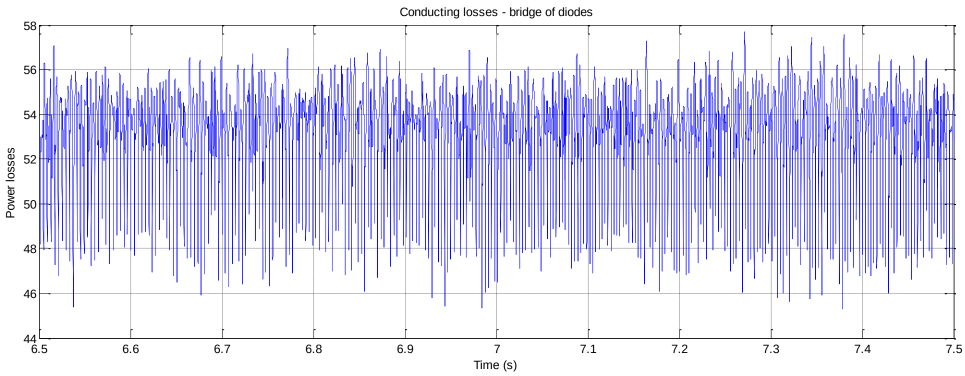


Figure 5.3.3f

$$P = \frac{1}{4}\int_{4.5}^{8.5} P(t).dt = 52.68\,Watt$$

We see that the amount of power dissipated in the bridge reduces only a little if we connect several devices together.

5.3.4 Conclusions: Overall power losses; generator and bridge

devices	Generator losses (Watt)	Bridge losses (Watt)	total losses (Watt)	Pout/device (Watt)	µ
1	664,5	59,14	723,64	5321	0,880
2	524,2	53,37	577,57	4273,5	0,881
4	523,6	52,63	576,23	4342,5	0,883
10	517,6	52,68	570,28	4340	0,884

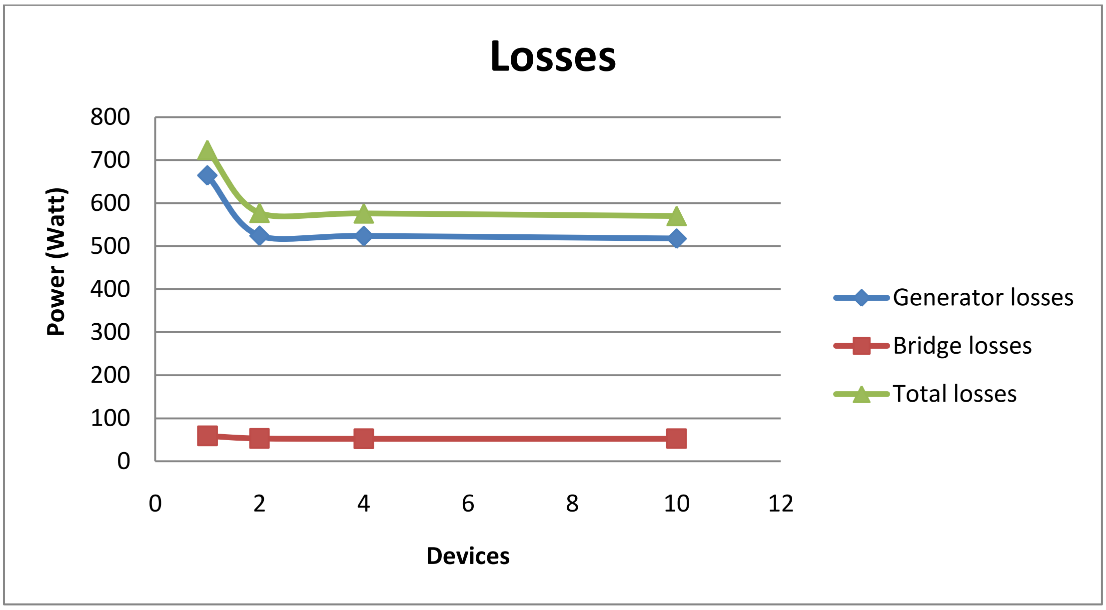


Figure 5.3.4a

Because the current becomes more and more constant, the losses will drop. After a certain amount of devices we see that the losses are more or less independent of the amount of machines.

- Total efficiency

$$\mu = \frac{Pout}{Pin} = \frac{Pout}{Pout + Pdiss} \qquad (4)$$

We see that the efficiency is fixed with a value around 88%!

5.4 Cable

Discussing the kind of cable is a difficult subject when practical tests are lacking. In the following text I will explain a couple of principles to take in mind when planning to design the cable.

After the bridge of diodes we get a DC current and voltage. When we combine several devices we can reduce the ripple. Losses of direct currents are much lower than losses of alternating currents. In order to reduce the losses it would be good to send the direct currents to the shore. To do so we need to have a low current and high voltage level, because the losses in the cable are depending on the current. With a boost convertor we can boost up the voltages, but they are expensive for high power applications. Studies have to show whether it is better to boost the DC voltage up with a DC-DC convertor before sending it to the coast or to make an alternative voltage and boost it up with a high power transformator before we send it to the coast.

I made a model to show the basic principles about cable losses.

The conducting losses in the cable are:

$$P_{loss;cable} = i(t)^2.R \quad (5)$$

$$R = \rho.\frac{l}{A} \ (in\ \Omega) \quad (6)$$

$$P_{loss;cable} = i(t)^2\rho.\frac{l}{A} \quad (7)$$

R= resistance (Ω)

l=length (in m)

A=surface (in m^2)

substance	Resistivity (Ohm x mm2/ m) by 20 °C (293 K)	Resistivity (Ohm x m) by 20 °C (293 K)
copper	0.0172	$1.72*10^{-8}$

$$P_{loss;cable} = i(t)^2\rho.\frac{l}{A}$$

I added the DC current to a new box in Simulink, and with the function block parameters, you can choose other values for resistivity ρ (in Ohm x m), length and diameter of the cable.

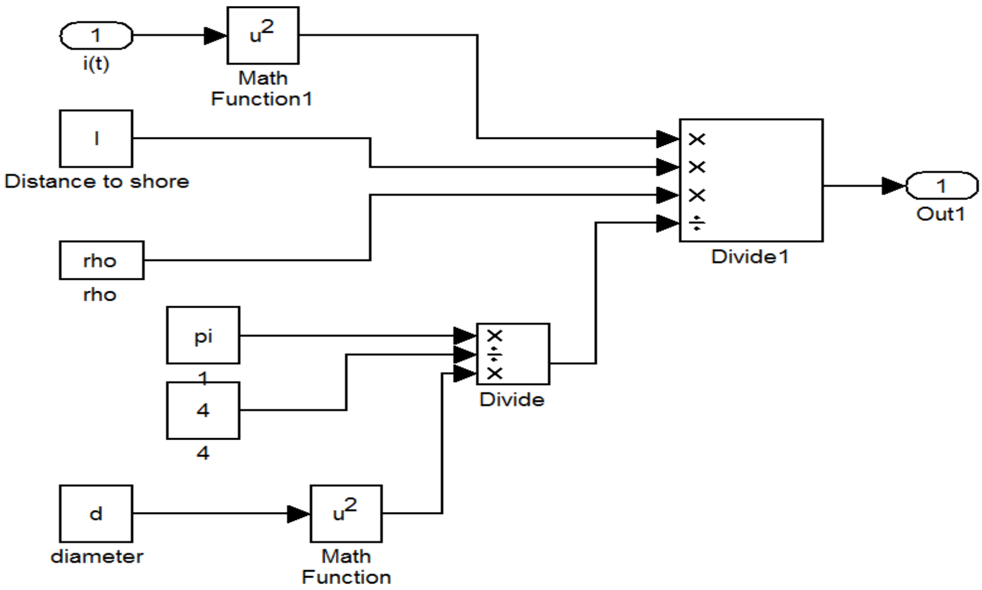


Figure 5.4

5.4.1 Simulations with 4 models

- Wave characteristics:

T (s)	H (m)	P/m^3
10	2.5	1965

- Input values
  - Same power, voltage and current productions as I used for all my previous simulations
  - Length of the cable: 50km
  - Diameter: 25mm
  - $\rho = 1.72 * 10^{-8}\ (\Omega * \mathrm{m})$

- Losses:

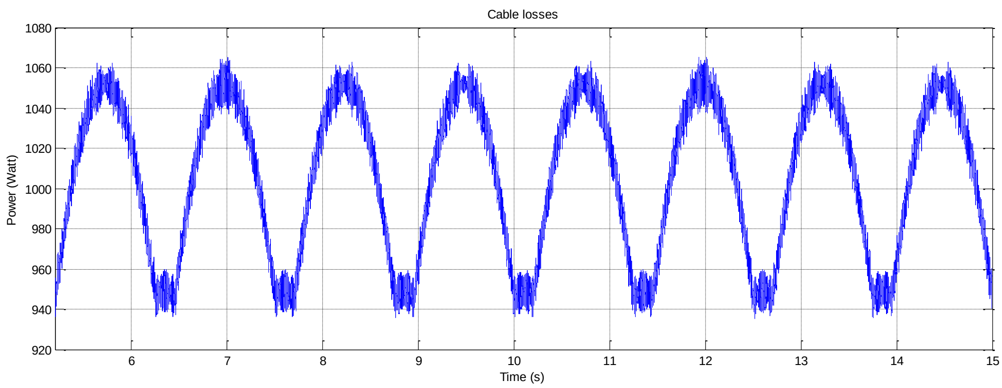


Figure 5.4.1a

$$P = \frac{1}{5}\int_{3.75}^{8.75} P(t).dt = 1005\ Watt$$

To be honest, this is an unrealistic example. It is economically irresponsible to make an application like this. If you have to transport a power of, for example, 1 MW, it is not appropriate to make a 50 km DC transport cable. I will show this with a simple calculation.

5.4.2 Cost of the cable and losses

In this calculation we use single wire earth return DC transportation cables, which mean that we can use only one cable. We can let the currents go back by the sea. There are a couple of other considerations you have to take into account while using this connection, but it is the cheapest way to transport power.

$$Total\ cost_{copper} = weight\ cable(kg)\ x\ cost_{copper}\ (per\ kg) \quad (8)$$

length (km)	diameter (cm)	Price (€/kg)	density (kg/m3)
50	4	5,16	8960

$$weight\ cable\ (kg) = \pi * 0.02^2 * 50000 * 8960 = 563000kg \quad (9)$$

$$Total\ cost_{copper} = 563000 * 5.16 = 2{,}9M€$$

From this point of view it is very important to have a high power output with offshore installations. You have to share this cost between several devices. And if you can boost the voltage level, the currents through the cable will drop and the cable can be thinner for the same power transport.

- Cost of the cable losses

If you take a cable of 50 km, you can calculate the resistive value of it with different diameters. For example:

$$Rkabel = \rho.\frac{l}{A} = 0.0172 * \frac{50000}{\pi * 20^2} = 0{,}68\ Ohm$$

$P_{loss\ ;cable} = i(t)^2 Rkabel$ (W)

All the energy you lost, you cannot sell.

$$E_{lost} = P_{loss\ ;cable} * \frac{8760}{1000}\,(kWh/year) \quad (10)$$

If you assume that you could sell the lost electricity for 0.08 €/kWh as green energy, than the money you lost in 20 years is approximately:

$$cost\ during\ 20 years = 0{,}08 * 20 * E_{lost}\ (\text{€}) \tag{11}$$

- Diameter?

Which is the perfect diameter for certain power transportation is another important question to answer?

If you assume that the life expectancy of the cables is 20 years:

$$cost\ of\ the\ transport = \frac{cost_{cable\ \ losses}}{year} + \frac{cost_{cable\ \ +installation}}{20\ year} \tag{12}$$

This equation has to be solved to find the minimum costs of transportation. If the diameter goes up, the cable costs will rise, but the losses will drop.

5.4.2.1 Calculations

- Cupper costs and losses

I transport 100 MW and calculate the losses and the costs of the cable for different diameters. For a certain distance and power, the cost of the cable is only depending on the diameter of the cable. The losses are depending on the diameter (resistive value) and the current/voltage ratio, for a certain distance and power.

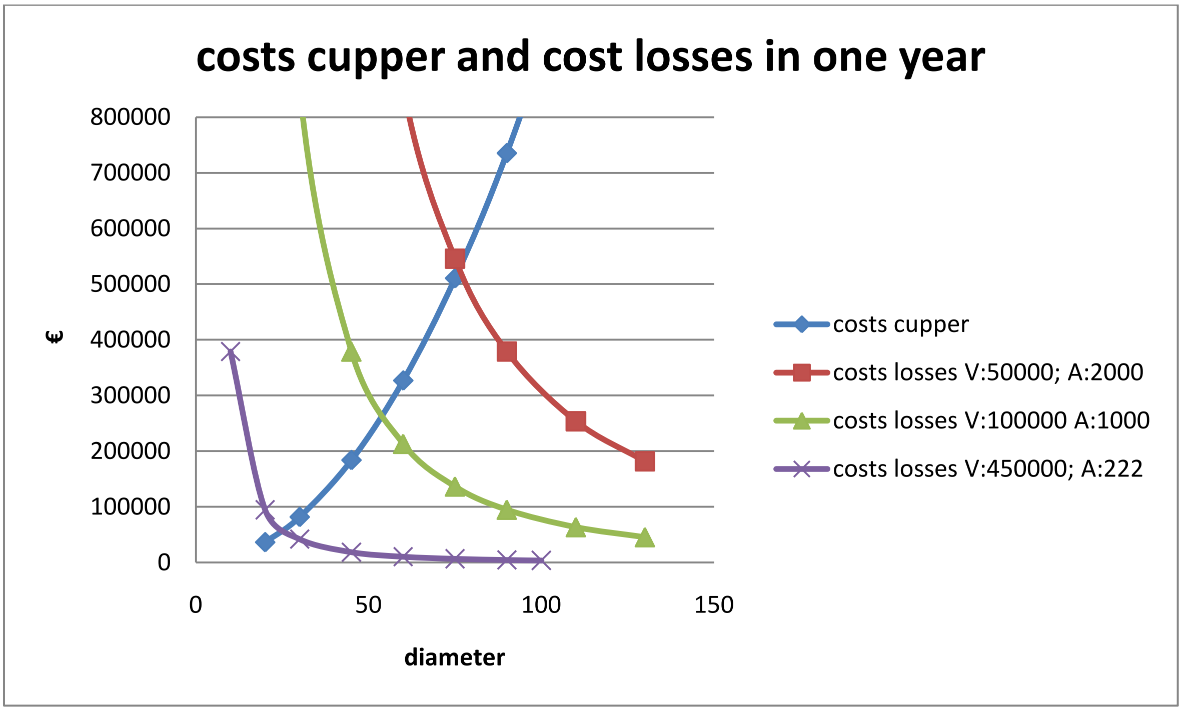


Figure 5.4.2a

- The sum of the cost gives us this graph:

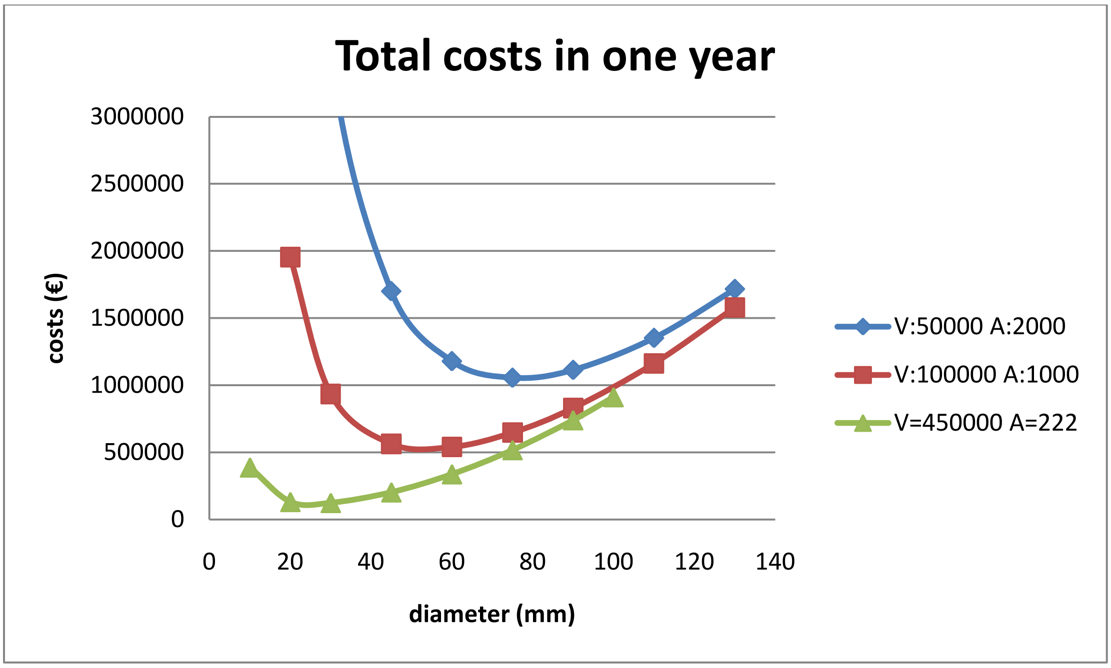


Figure 5.4.2b

You see a huge difference in cost between high voltage transport and low voltage.

- The cost is higher in reality for several reasons:
  - The installation costs and the cost of the power electronics are not included. They are less depending on the diameter, but they are also depending on the power production.
  - If we don't use single wire earth return, the costs will be higher too. Most applications are bipolar and then I have to double the cable cost price.
  - High voltage AC is more expensive than bipolar.
  - The price of cupper can still rise.

- The influence of the current/voltage ratio

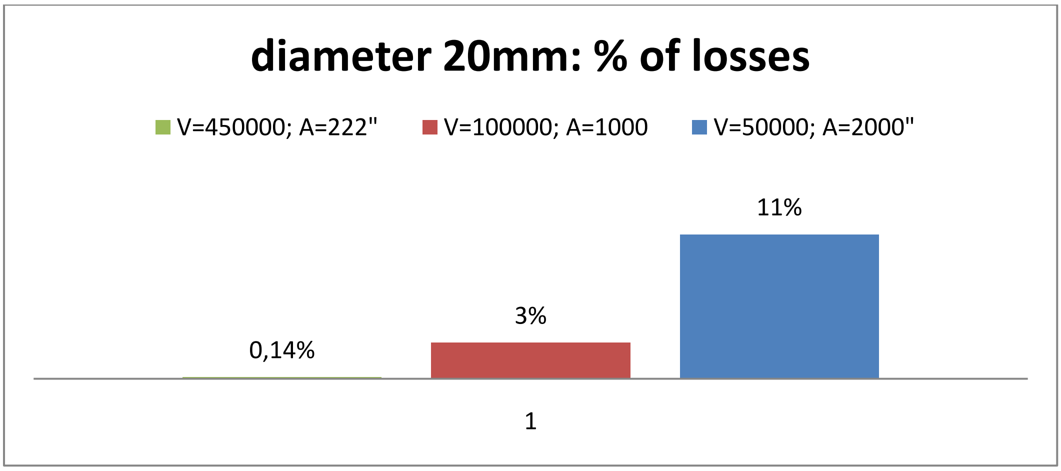


Figure 5.4.2

5.4.3 Conclusions

Transport low power application to the coast is not economically responsible. Even if we transport 100MW by using 450kV it costs, according to my calculations, 131,000 euro each year. So we have several options:

- Combine thousands of devices

We should combine thousands of devices to have a significant power and voltage output. Assume we have the full 8.4 kW output for each generator than we have to connect 10,000 devices in order to have 84MW. For applications far from the shore it is much more appropriate to use wind energy applications as you only need 17 windmills with a nominal power of 5MW for the same power production.

- Combining with wind parks

Most wind parks, even if the high power transport cables are DC, have an internal AC network were all the different windmills are connected. We could combine our devices with the wind parks and transform our DC power to AC and put it on the local AC grid. Combining wave and wind energy can gives us high power for transportation and can provide us a with more stable power production.

- Near shore applications

To reduce transportation costs we can place our wave parks closer to the shore or use this energy source in oil platforms. Visual pollution is also much lower than with windmills. When waves move to more shallow waters, the height of the waves will raise, this can be a very favourable characteristic, even if a part of the energy has been lost. The sea-bed can collect those waves and focus them in so called ‘hot spots’. Those spots are the ideal areas for implementing our devices. They can be implemented nearby harbours and there the buoys can even be used for multiple goals such as power production and helping to navigate the ships. They can be positioned on sandbanks where the waves are higher and the ships are not allowed to navigate.

- Other conclusions:

We really need high voltage in order to reduce our power losses. So we might have to use DC-DC convertors or when we connect it with a local AC grid we can use a transformator to get high voltages before we rectify it again.

For high power transportation the maximum voltage is nowadays 800kV (e.g. China). But usual voltages for HVDC are around 450kV. If we put around 1,500 devices together we reach this point. Because of the series connection we only have 24 A. In order to connect more to reach higher power we have to raise the currents and keep the voltage constant.

6 Conclusions

6.1 The Simulink simplified model

We created a simplified model to estimate the behaviour when connecting several devices together. The simplifications make it deviate from the real application:

- The upward movement and the downward movement are the same. In the real application the upwards movement is depending of the wave and the downward movement is depending on the spring or mass.
- Another difference is that there is no torque caused by the currents through the generator. The oscillating part of the model is deleted for faster behaviour.

With a time delay we can connect several voltage sources together.

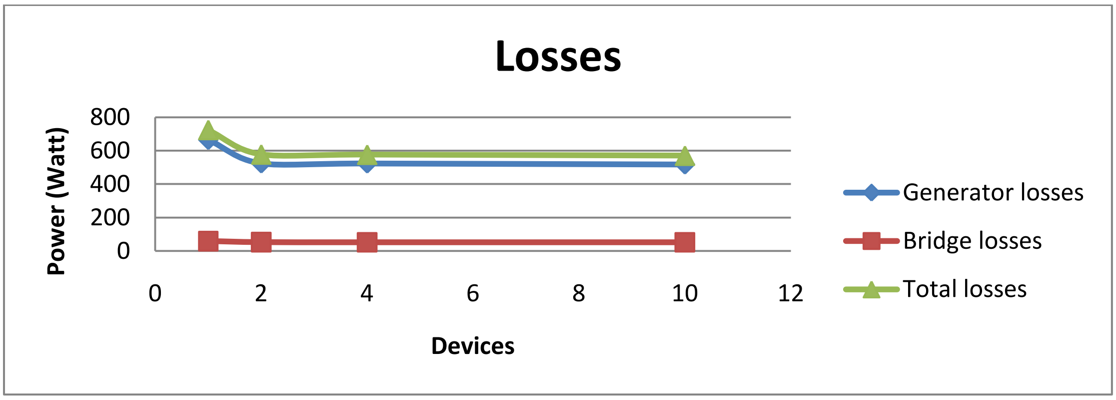
6.2 Conclusions about the generator and diode bridge

So we see that we have a fixed efficiency of 0.88. This is a high value for our application. A reason for this is the high currents through the system. We used a PM generator specially designed for wind energy production. If we look in the technical characteristics we see that we have a low voltage production of 133 V and a quiet high current production. In combination with the phase resistance of 0.47 Ohm, we lose a lot of energy.

Losses can be much smaller if we develop a PM machine that produces lower currents. The machines that we used are designed for wind energy applications and have a low voltage output so they can be connected directly to a 230V grid. In our application we can have higher voltages.

Because the current becomes more and more constant, the losses will drop. After a certain amount of devices we see that the losses are more or less independent of the amount of machines.

devices	Generator losses (Watt)	Bridge losses (Watt)	total losses (Watt)	Pout/device (Watt)	µ
1	664,5	59,14	723,64	5321	0,880
2	524,2	53,37	577,57	4273,5	0,881
4	523,6	52,63	576,23	4342,5	0,883
10	517,6	52,68	570,28	4340	0,884



6.2.1 Conclusions generator

We neglected the Joule losses and the inductive part of the windings losses. We had to neglect the inductive behaviour of the coils, because Matlab could not handle it. The model acts to slowly.

As you see in the graph, the losses over the generator are almost independent from the amount of devices that are connected. This is quite logical because I raised the resistive value of the load linear with the amount of connected devices. The same currents flow through all the generators.

SMPM are too sensitive to wear for our application, reducing maintenance is a priority. Pole shoe rotor, tangentially embedded magnets, radially embedded magnets and the V position can be constructed with damper windings, which is useful in our design because the speed of rotation changes all the time.

Tangentially embedded and the V-position PM generator can offer us stronger flux density in the air-gap, they can be constructed with damper windings and are not as sensitive for wear as the SMPM because of the embedded poles. Therefore I would suggest to design our application with a generator of this type.

In our applications we used a generator for wind mills, with a nominal voltage output of 230 V phase-to-phase. In our application this is not necessary. The production of higher voltages would be better because the losses will drop. The bridge of diodes allows us voltages up to 600V. Hence, it would be better to construct a generator with a nominal voltage output of 600V. We can do some adaptations on the generator to achieve higher voltages. The voltage level is depending on the following formula:

$$E = 4{,}44kpn\varphi_{max}N$$

- We can use stronger PMs to achieve a higher φ_{max} value
- We can use the V-shape position in order to achieve a higher φ_{max} value
- We can raise the amount of conductors in the stator (N)
- We can use more pole pairs, although this will raise the frequency of our generator too, and this is maybe not a good option.
- We can raise the rotational speed n (rps)

We can conclude that the most appropriate generator will be one especially designed for our wave energy collector. Companies such as PRECILEC can develop a more specific generator according to our design.

6.2.2 Conclusions about the bridge of diodes

The biggest losses of the diode bridge are conducting losses.

But as you can see from the graph, the losses in the bridge of diodes are much lower than the losses in the generator itself. Appropriate diode bridges can be found everywhere on the market and is not such a problem when compared to the PM generator.

6.3 Conclusions about the cable and the connection

Transport low power to the coast is not economical responsible. There are several options to be considered.

- Combine thousands of devices

For applications far from the shore it is much more appropriate to use wind energy applications: one does only need 17 windmills with a nominal power of 5MW for the same power production of 10,000 devices.

- Combining with wind parks

We could combine wind and wave energy to obtain high power and a more stable power production.

- Near shore applications

To reduce transportation cost we can place our wave parks closer to the shore or use this energy source in oil platforms. Visual pollution is also much lower than with windmills. When waves move to more shallow waters, the height of the waves will raise. This can be a very favourable characteristic, even if a part of the energy has been lost. The sea-bed can collect those waves and focus them in so called ‘hot spots’. Those spots are the ideal areas for implementing our devices. They can be implemented nearby harbours and there the buoys can even be used for multiple goals such as power production and helping to navigate the ships. They can be positioned on sandbanks where the waves are higher and the ships are not allowed to navigate.

- Other conclusions:

We really need high voltage in order to reduce our power losses. So we might have to use DC-DC convertors in order to achieve the ideal power for transportation.

6.4 What next?

Some work that should be done considering the electrical part: a more practical approach of the design.

- Test devices

A PM generator should be ordered. If you put a rotation movement on the generator similar to the behaviour of the wave, by using for instance a PLC that drives an asynchronous motor with a frequency convertor, you can see the actual output and find new conclusions.

  - To see how the system works in real live you can work with several smaller PM generators than the real application to reduce the costs of the research.
  - You can start by developing the actual device with diode bridge and load with a generator of a power output around 10 kW. The distance to the shore can be calculated by using my model of the cable losses and adding extra resistive value for longer distances.

- The current through the generators is approximately constant because of the connection of several devices, so the torque caused by the generator on the buoy is approximately constant, but the driving torque is not. Practical investigation of this problem can be useful.
- Better estimations of efficiency between wave and buoy are necessary for more precise modelling.
- Real waves conditions behave as the sum of multiple sinus waves. If we can make a model where the sea-state consists of the addition of more than one sinus, we can investigate further behaviour of the machines. Especially while deciding about the distances between each other. We have to make sure that no oscillation occurs.
- Mechanical design and electrical design have to be united. The mechanical part should drive the PM generator in the most ideal way.

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