2.1 Introduction

The purpose of the *Power Take-Off* (PTO) system is to convert linear motion into electrical power. Although the PTO ultimately is defined by its output power, it is more sensible to evaluate and rate the PTO based on the available damping force. As established by Equations 1.2 and 1.3, produced power equals wave force wave times speed. Since the wave speed is too low to impose any restrictions on the drive train, the PTO cost is mainly force driven. The rated force defines the dimensions of shafts, bearings and pulleys. The gearbox gives flexibility to utilize the speed capability of the generator, thus, power becomes and important factor for the high-speed components. However, the selected gear ratio also has strong impact on the moment of inertia, which may restrict the gearing. FO therefore uses force as the main parameter for PTO rating with the cost performance indicator N/€.

Linear reference frame

The PTO operates with both linear and rotational motion, and FO has selected linear motion as reference frame. The total gear ratio n is introduced to describe the relationship between generator rotational speed and the PTO linear speed, and is defined by Equation 2.1. Here, ω_{gen} refers to the generator speed in rad/s, and v_{pto} refers to the PTO linear speed in m/s. M_{gen} is the generator torque and F_{pto} is the linear PTO force, while n_{gear} and r_{drum} refers to the rotational drive train gear ratio and the radius of the winch drum, as illustrated in Fig. 2.1.

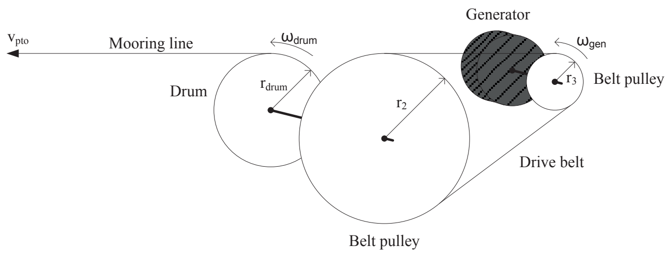


Figure 2.1: Illustration of the linear to rotational gear ratio

$$n = \frac{n_{gear}}{r_{drum}} = \frac{\omega_{gen}}{v_{pto}} = \frac{F_{pto}}{M_{gen}} \tag{2.1}$$

The effect of inertia is included by introducing the inertia mass equivalent parameter m_i, which is found by using the kinetic energy comparison described by Equations 2.2 and 2.3, where I denotes the rotational moment of inertia of the generator. By substituting $\frac{\omega_{gen}}{v_{pto}}$ by n, according to Equation 2.3, Equation 2.4 is found. The equation can be used for all parts of the drive train by using the correct inertia and gear ratio.

$$E_{k-lin} = E_{k-rot} \tag{2.2}$$

$$\frac{1}{2}m_i \cdot {v_{pto}}^2 = \frac{1}{2}I \cdot {\omega_{gen}}^2 \tag{2.3}$$

$$m_i = n^2 \cdot I \tag{2.4}$$

2.2 Mechanical configuration

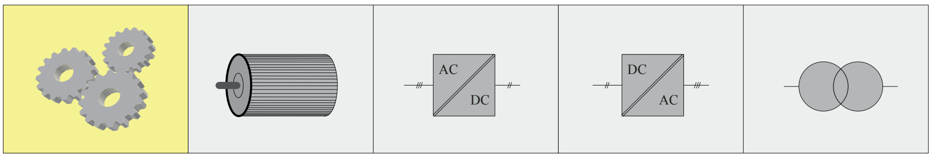


Figure 2.2: Power chain: Mechanical conversion

The FO PTO system is realized as a winch and rope system, as illustrated in Fig. 2.3. The generator can only produce power during upwards motion, and has to operate in motoring mode during downwards motion to wind the rope back on to the drum. The target force for the Bolt2Wavehub project was ten tons and resulted in the PTO configuration parameters listed in Table 2.1.

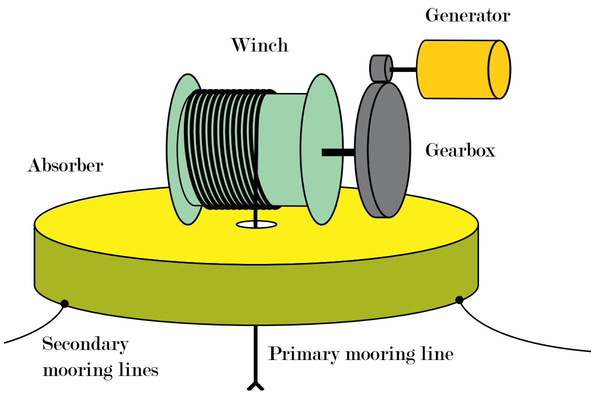


Figure 2.3: Principal sketch of the PTO and WEC

The PTO gearbox is realized as a belt drive system based on Gates® carbon fiber timing belts. The belt drive is very robust against shock loads and operates well with reciprocating motion. The belts are coated with polyurethane and are resistant against the highly corrosive environment at sea. FO has used the belt drive system for all the single body systems, and the gear concept has demonstrated excellent performance. The belt drive is also very flexible as belts and pulleys can be easily replaced. This is a highly valuable property for a prototype, since there is high risk of accidentally subjecting the drive train to excessive internal or external loads.

The Bolt2Wavehub drive train has been further developed from the original concept, and the balanced split drive configuration is a new design for the Bolt2Wavehub project developed and patented by FO. This has the advantage of better utilizing the first step, as torque is created on both sides. Secondly, it balances the forces over the main pulley and the generator so that the bearing loads are minimized. This allows the generator to be mounted with the pulley directly on the shaft, which avoids a complex setup with flexible coupling. The actual drive train design is shown in Fig. 2.4.

Property	Value	
Maximum production force	100	kN
Nominal generator speed	400	rpm
Maximum generator speed	1 800	rpm
PTO nominal production power	15	kW
Generator nominal power	80	kW
Inverter nominal power	120	kW
Gear ratio	38.5	1/m
Equivalent inertia (m_i)	3 000	kg

Table 2.1: PTO specifications

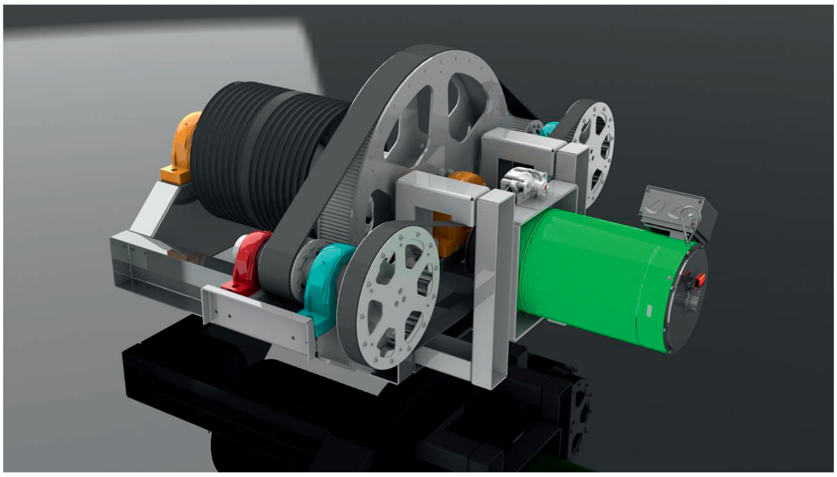


Figure 2.4: Actual PTO design

The total gear ratio of the drive train is 38.5, which is limited by the generator capacity and the resulting inertia. It has been found in simulations that a maximum speed of 6 m/s must be allowed. Since the drive train can carry full load at this speed, the power capacity is 600 kW, which leads to a very poor power utilization factor of 1/40 when compared to the nominal power output of 15 kW. This is the result of the large speed variations, and is exaggerated by the rope winch system that only allows for unidirectional production force. Bottom fixed or multi-body systems may operate with bi-directional damping force, which would double the PTO utilization factor. The FO system selection is based on total cost evaluation and concludes in favor of the unidirectional solution.

2.3 Generator selection

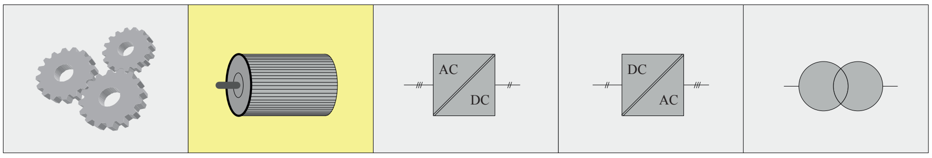


Figure 2.5: Power chain: Generator

For a dynamic drive system like the PTO, finding a suitable generator becomes very hard as there are many parameters that must be optimized. In this section, only the mechanical properties are discussed, as the electrical parameters are closely linked with the inverter configuration discussed in section 2.4. The main parameters are:

- Maximum mechanical speed
- Maximum torque
- Rotational inertia
- Efficiency
- Torque precision
- Cost

The maximum speed and torque must be matched with the PTO rating, and is typically an iterative process of finding a match between the drive train gear ratio and a specific generator system. Since this is a dynamic application, it is also important to keep the rotational inertia as low as possible. Fig 2.6 shows the linear equivalent of the drive system. To simplify the system, the PTO is used as the fixed reference frame, and the sea floor is thought to be moving as the equivalent of wave motion. On leftward motion, the PTO produces power, and on rightward motion, the PTO has to supply pullback force to rewind the PTO and maintain rope tension. As illustrated in the drawing, the major part of the dynamic mass will be in the generator, and is a significant challenge to the system. Firstly, the dynamic mass must be accelerated back and forth in each wave, causing unwanted power cycling in the drive train. This leads to reduced generator efficiency and utilization, and requires electric power to be cycled against the grid or an on-board energy storage. Secondly, high dynamic mass complicates the pull back regulation and

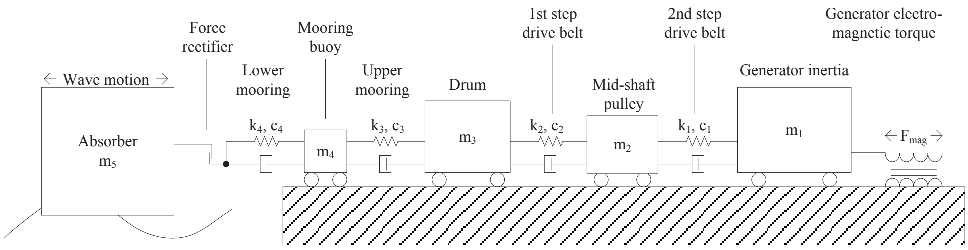


Figure 2.6: PTO dynamic model

makes the system more vulnerable to unwanted dynamic behavior, which will increase the risk of slack rope situations and require larger regulation margin. Thirdly, in slack rope situations, the impulse force that occurs during re-tensioning will be proportional to the dynamic mass. Hence, generator inertia is a crucial parameter that must be kept as low as possible.

The standard induction machine, which is the typical workhorse of industrial processes, is designed with little attention to inertia. It typically has a massive iron rotor, and is therefore unsuited for dynamic control applications. Machines that are optimized for this type of operation utilize other materials and clever design to reduce the rotor mass, and are usually based on permanent magnets since these provide higher torque density and lower inertia. Hence, the requirements seem to push toward servo machines, as opposed to standard generators.

Efficiency is also an important parameter, and although it is closely linked with the electrical configuration, the major parameters inflicting on efficiency are determined early in the design phase. The major loss factors in the generator are resistive loss in the windings, hysteresis loss and eddy currents in the iron, both due to stator and rotor magnetic field and bearing loss. It proved difficult to find generator systems that were designed with good dynamic performance that also showed good efficiency, but a suitable system were finally found in the extensive Siemens portfolio, that also allowed for customization to the customer needs. Siemens also supplied a detailed efficiency map, showed in Fig. 2.16, which also indicates the control boundaries, as discussed in section 2.5. Since the Siemens machine is optimized for accurate servo control it delivers much higher torque precision than would be required for a bulk power producer like the WEC, which results in an unnecessarily costly system.

2.4 Inverter and Generator configuration

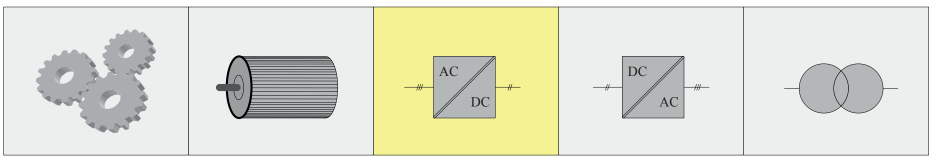


Figure 2.7: Power chain: Inverter

The mechanical properties of the generator were found in the previous section. The electrical parameters are given by the pole count, rotor configuration and winding properties. The electrical properties result in the torque/current relationship and the speed/voltage relationship, which links the mechanical and electrical properties.

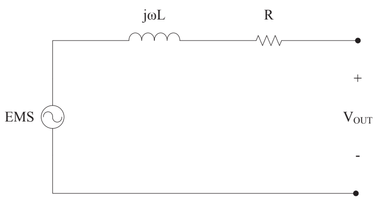


Figure 2.8: Equivalent circuit for PM generator

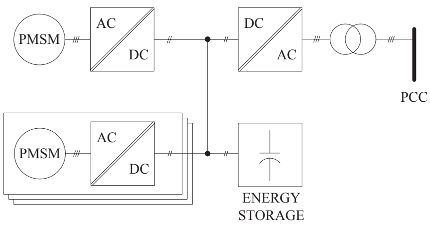


Figure 2.9: Principal diagram for BOLT2

Faradays' law of induction, as given in Equation 2.5 defines the relationship between the induced voltage ϵ, and rate of change in magnetic flux φ through a conductive loop. From this, Equation 2.6 can be derived which gives the induced voltage in n loops with area A that rotates with speed ω in magnetic field with constant flux density B. This shows the relationship between open circuit voltage and speed of a PMSM. Since the magnetic flux generated by the permanent magnets and the geometrical properties are constant, Equation 2.6 can be simplified into Equation 2.7 where v_{out} is the open circuit voltage and k is a constant. The equivalent circuit of the generator is shown in Fig. 2.8.

From this, and by including the electrical impedance of the machine, the nominal conditions can be expressed as given by Equation 2.8, where I_n is the nominal current and V_n is the nominal voltage. This shows that the number of pole windings works as a scaling factor between nominal current and voltage. However, the inverter that powers the machine has a fixed nominal voltage, and as shown in Equation 2.9, where P_n is the nominal power, ω_n is the nominal speed and M_n is the nominal torque, the pole winding count defines the nominal power and the nominal speed of the machine. Higher number of windings leads to lower nominal speed. The nominal torque is defined by the physical size and properties of the machine that were defined in the previous stage of the design process.

$$\epsilon = -\frac{d\varphi}{dt} \tag{2.5}$$

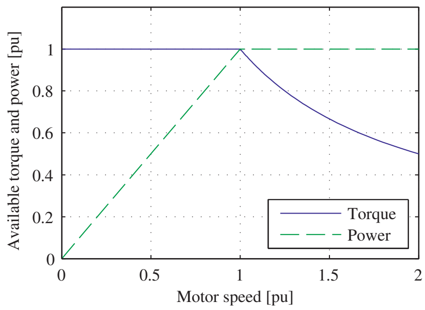
$$\epsilon\left(t\right) = n \cdot \omega \cdot B \cdot A \cdot \sin\left(\omega t\right) \tag{2.6}$$

$$v_{out}\left(t\right) = k \cdot n \cdot \sin\left(\omega t\right) \tag{2.7}$$

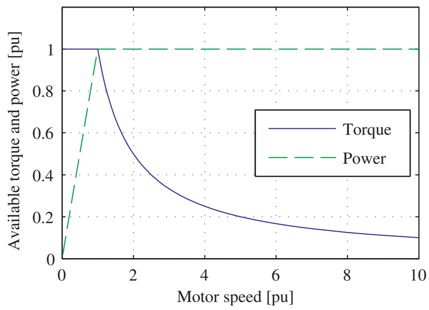
$$\frac{V_n}{I_n} = k \cdot n \tag{2.8}$$

$$P_n = V_n \cdot I_n = \omega_n \cdot M_n \tag{2.9}$$

Above nominal speed, the output voltage must be kept within limits by field weakening. For PMSMs, this leads to a reduction in available torque that is inversely proportional to the speed, and works as a constant power limit. Figure 2.10(a) illustrates this for a typical PMSM that allows for running with a mechanical speed of twice the nominal electrical speed. A more extreme design with ten times overspeed range is plotted in Fig. 2.10(b) and illustrates the power limiting effect with this approach. These plots show the ideal conditions, real systems would typically show less power for higher speeds due to reduced efficiency and limitations on the field-weakening control.



(a) Normal overspeed range



(b) High overspeed range

Figure 2.10: Ideal torque and power curves for PMSM

In context of the rather extreme peak to average speed ratio of the WECs it would be interesting to explore an extreme overspeed ratio of the generator. Bolt®, for instance, was operating with an average speed of 0.3 m/s in the most common wave state, but had to handle above 5 m/s in the most extreme wave state, which leads to a peak-to-average speed ratio of 16.7. The generator overspeed ratio is inversely proportional to installed power, and an increased overspeed ratio will therefore lead to cost reductions through the entire power chain and improve the capacity factor. Reduced installed power will also lead to lower power absorption from the high waves, and systems with very high maximum to nominal speed ratios are investigated to identify the optimal system configuration.

The overspeed optimization is performed by creating generator models for a list of different overspeed ratios. These models are then implemented into the simulation model described in Chapter 6, and a full simulation run for all the wave states in the scatter is performed for each of the generator models. The resulting annual energy production for the different overspeed ratios is listed in Table 2.2. Annual energy and load hours are shown in Fig. 2.13 and 2.12 respectively. The basis for the power normalization is 75 kW, which is the rated power for Lifesaver.

A first important observation is that the overspeed ratio can be raised to five without significant loss of annual production. This corresponds to a five times reduction in installed power. Further increase must be done as part of an economical optimization, and Fig. 2.11 shows the average power production for every hour through a year sorted in descending order, where each line represents a generator configuration with a given overspeed ratio. The figure is a good tool for sizing of the export system and clearly shows the effect of the overspeed ratio. A higher overspeed ratio results in a lower peak power rating, less fluctuation in power production and more load hours. This is mostly achieved by reducing production from the high sea states, but some energy is also lost in the low sea states due to the high irregularities of the waves.

It can be seen from Fig. 2.11 that the overspeed ratio does not appear as a constant power limit, but instead leads to a continuous reduction. This is because the overspeed ratio defines the peak instantaneous power while the exported energy is given by the average power over 20

Overspeed ratio	Annual energy [pu · hours]	Load hours [hours]	Peak power [pu]
1	5093	1840	2.77
3	5081	1928	2.64
5	5017	2180	2.3
7	4878	2511	1.94
10	4593	3026	1.52
15	4070	3690	1.1
20	3547	4128	0.859
30	2832	4773	0.593
40	2368	5244	0.452
50	2041	5611	0.364

Table 2.2: WEC performance with different overspeed ratios

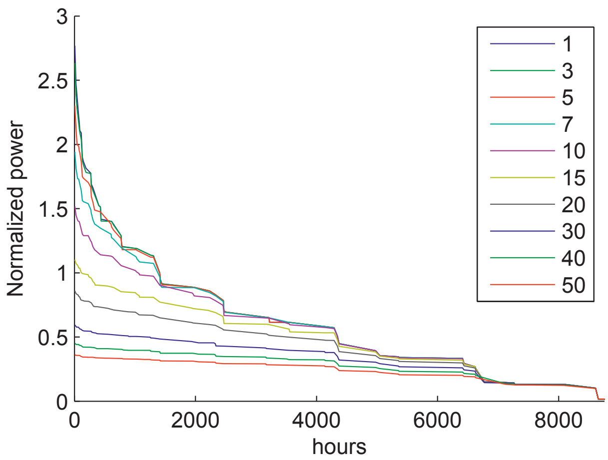


Figure 2.11: Annual power distribution per hour

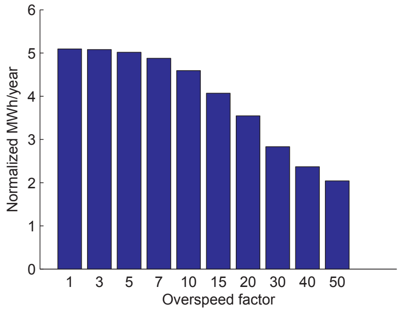


Figure 2.12: Annual energy production with different overspeed ratios

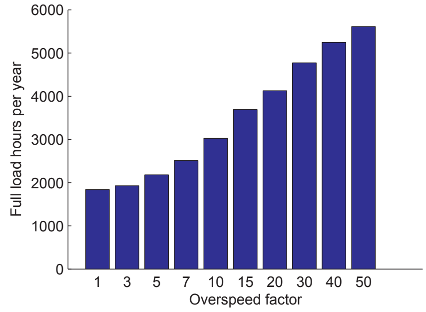


Figure 2.13: Annual load hours with different overspeed ratios

minutes. The goal is maximum utilization of the export capacity, and it is likely that other measures such as energy storage and averaging between groups of WECs also will be required.

There are, however, practical and physical limits to how high the overspeed ratio can be. The most important limitation for the Bolt2Wavehub system is that enough torque must be reserved to ensure adequate pull back force. For PM machines, the active field-weakening control also becomes very demanding for high speeds, and is limited by the magnetic properties of the machine. The Bolt2Wavehub generator is wound for a nominal speed of 400 rpm, while the maximum mechanical speed is 1800 rpm, which gives an overspeed ratio of 4.5. This generator has demonstrated very good performance, but has also suffered from minor issues at high speed. Hence, an overspeed ratio of five seems sensible for the Lifesaver system.

An important side effect of operating PMSM beyond nominal speed is that the natural electromotive force of the machine, V_{EMF}, exceeds the nominal voltage rating. This relationship is linear with speed, with potential to cause damage at high overspeed. To overcome this, a *Voltage Protection Module* (VPM) is mounted directly on the generator terminals to short-circuit the generator in case of excessive voltage, as shown in Fig 2.14. This protects against failures in the electrical system and is important to avoid dangerous power surges into the electrical system. However, it should be noted that as long as the power circuitry is intact, the terminal voltage would be kept within range, even if active field-weakening control fails, since the generator will be short-circuited through the rectifier. Hence, the VPM module will only react against physical failures in the system.

2.5 Control principle

The amount of absorbed power from a point absorber is given by the control strategy applied on the PTO. In general, the optimal energy extraction is achieved when the point absorber is moving with a 90° phase shift to the waves. Several methods of approaching this production mode are described, the best known being *reactive control* [37–39] and *latching control* [19]. Fig. 2.15 shows an electrical equivalent circuit for the WEC where the dynamic behavior is modeled as an RLC circuit. The PTO is represented by a power extracting element (resistance) and a reactive element (reactance). The goal of reactive control is to tune the reactive element of the PTO so that it compensates for the reactive elements of the WEC to maximizes power extraction.

However, with the current design of Lifesaver, the PTO is too weak to have significant impact

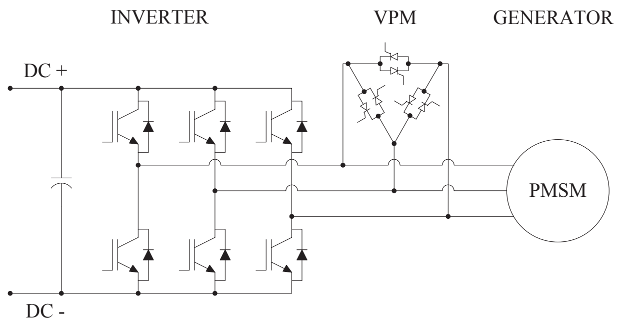


Figure 2.14: Generator frequency converter power circuit

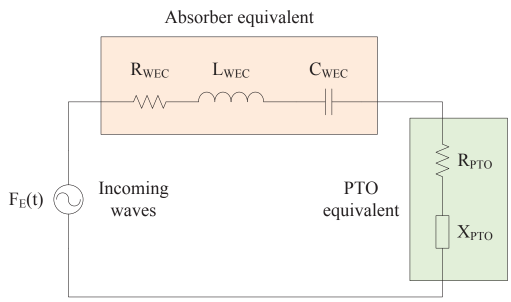


Figure 2.15: Equivalent circuit for Wave Energy Converter and Power Take Off

by advanced control, as demonstrated in Appendix J. This is a result of following the design guide lines specified in section 1.8. Passive damping therefore serves as the primary power extraction method. Nevertheless, in the lowest sea states, advanced control algorithms may improve output [37], but is not currently implemented on Lifesaver.

The PTO damping force F_{PTO} is defined in Equation 2.10 for the PTO speed v and implements passive damping with the damping coefficient B, while respecting the selected force limit F_{Lim} and the intrinsic generator power limit given by the nominal speed v_{nom} and the maximum force F_{Max}. The equation is referred to the linear reference frame with positive direction defined upwards. Thus, the damping coefficient B must be negative to extract power, and is optimized towards the highest efficiency region of the machine to produce the highest possible net power output. F_0 represents the pretension force required for pullback, and the damping function is limited to only react on positive motion. The resulting force and speed characteristics are plotted in Fig. 2.16, where the thick line shows the optimal force that results in maximum net power from the generator. Two saturation mechanisms limits the damping force, the first is the mechanical force limit of the gearbox and is reached already at 0.27 m/s. The second is the power limit of the generator, which is reached at 1.55 m/s. The linear region from 0 - 0.27 m/s corresponds to a damping coefficient of ca -350 kNs/m, which is the selected damping coefficient for Lifesaver.

$$F_{PTO}(v) = \begin{cases} \min\left(F_0 + Bv,\, F_{Max} \cdot v/v_{nom}\right) & : \quad v \geq v_{nom} \\ \min\left(F_0 + Bv,\, F_{Lim}\right) & : \quad v_{nom} \geq v \geq 0 \\ F_0 & : \quad v < 0 \end{cases} \tag{2.10}$$

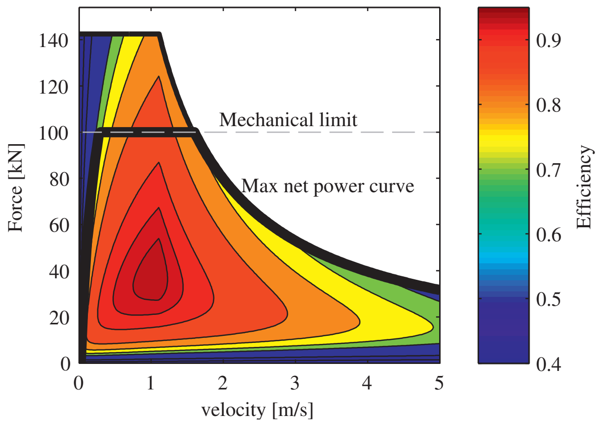


Figure 2.16: Efficiency plot for the generator used at Bolt2Wavehub

2.6 Drive train verification tests

As most of the uncertainty in the Bolt2Wavehub project was related to the PTO function, operation and control, two PTOs were built and assembled ahead of the WEC system. The two PTOs were connected against each other in a back-to-back configuration so that one could drive the other. The first PTO, referred to as the *driver*, was set to replicate the expected wave motions, while the second PTO, referred to as the *driven*, was operating according to its normal wave production program. Continuous tests for several days were performed at full load to verify the PTO function. Several issues emerged, both in the mechanical system and in the control system, which would cause damage if left unattended. It is much easier to perform repairs and system tests in a controlled environment, and this illustrates the importance of performing a thorough commissioning before launching sea trials. After the errors were corrected the PTOs showed excellent operation.

In addition to the wave production tests, a complete mapping of the drive train loss properties was also performed. This was done by running fixed speed runs with constant speed and torque. To allow for continuous unidirectional running, the drum and rope were replaced with a chain drive that connected the two PTOs together. Thus, the power transfer chain consisted of five gear steps when the chain drive was added to the two gear steps of each PTO. To estimate the loss on a single PTO, the loss was assumed to be evenly distributed over the gear steps, so that the PTO loss was 2/5 of the total loss. The chain drive was expected to have lower efficiency than the carbon belts, however, some friction is also introduced by the generator bearings, and these effects were expected cancel out to some extent.

$$M_{loss} = M_0 + c_M \cdot M_a + c_n \cdot n_a \tag{2.11}$$

The resulting torque loss and power efficiency is plotted in Table 2.3 and 2.4. The tables indicates three loss mechanisms, which is expressed in Equation 2.11, where M_0 denotes the static friction, c_M denotes friction constant due to torque load, c_n denotes the viscous friction and other loss effects linked to speed. M_a and n_a is the actual torque and speed.

The test plan also called for dynamic tests of the drive train to investigate the frequency response of the drive train. This was mainly planned by running frequency sweeps, where the driver set speed is super-positioned with a small fluctuating speed. The frequency of the fluctuating speed can then be gradually shifted to scan the drive train response to a range of frequencies. However, due to time constraints and concerns that the chain drive would not handle the dynamic behavior, these tests were omitted. The chain drive actually broke down later in the test program, which strengthened this view. However, in retrospect, it is clear that more time should have been spent on dynamic effects, as demonstrated in the next section.

2.7 Experience from sea trials

The PTOs have demonstrated successful operation through the sea trials, and have survived rough wave states up to 5.1 m Hs, with maximum waves of ca ten meters. However, several dynamic issues have been discovered that cause oscillations in the system and will lead to reduced lifetime if left unattended. Fig. 2.17 shows a typical case during normal production. In this example, the PTO is limited to 50 kN of damping force, and the pullback force is set to 10 kN. The figure shows how the PTO force follows the production force function on upward motion and maintains the pullback force on downward motion.

The concern is the oscillations that occur when the control model switches from a damped system to a saturated system. This cause a step response in the system behavior that leads to the observed ringing. Some distortion at this switchover was expected, but the measured fluctuations showed to be much more pronounced than anticipated, and must be caused by dynamic spring effects somewhere in the system. To further investigate this issue a research project was established in collaboration with NTNU to analyze the dynamic response of the system. The work concluded that spring effects in the primary mooring is the main contributor to the oscillations, and that the problem can be mitigated thorough active compensation control [24].

		Speed [rpm]									
		50	100	150	200	250	300	350	400	450	500
Torque [Nm]	0	42	48	49	49	54	58	58	58	57	57
	125	40	46	44	41	50	62	57	61	57	49
	250	48	52	52	50	49	61	57	59	62	63
	375	47	55	55	50	67	44	53	72	59	80
	500	54	56	59	61	45	64	68	73	52	71
	625	55	61	58	51	52	67	70	66	74	73
	750	54	63	51	54	54	77	65	72	82	73
	875	62	67	58	73	73	72	69	54	79	60
	1000	60	64	56	78	77	70	83	86	77	77
	1125	67	52	76	63	67	85	95	82	98	70
	1250	65	77	82	61	63	88	81	89	92	95
	1375	58	79	60	84	86	88	82	93	96	87
	1500	75	80	82	114	126	81	87	135	93	120
	1625	78	89	89	129	123	85	119	151	108	125
	1750	83	96	108	112	111	93	143	123	143	130
	1875	87	96	97	100	89	145	133	108	126	-
	2000	87	105	103	101	119	152	91	127	148	-

Table 2.3: Drive train torque loss [Nm]

		Speed [rpm]									
		50	100	150	200	250	300	350	400	450	500
Torque [Nm]	0	-	-	-	-	-	-	-	-	-	-
	125	81.8	79.6	79.7	81.1	77.8	74.6	75.7	74.2	75.1	76.8
	250	87.8	86.1	85.8	86.1	86.5	83.8	84.3	84.4	83.3	83.2
	375	91.8	89.8	89.1	90.3	87.2	91.2	89.2	86.1	88.1	84.8
	500	92.9	92	91	90.7	93.3	90.2	89.6	88.9	91.5	89.3
	625	93.8	93.1	93	94.2	93.5	91.7	91.2	91.7	90.7	90.7
	750	95	93.9	94.8	94.8	94.4	91.9	93	92	91	92
	875	95	94.4	95	93.4	93.6	93.7	93.6	94.9	92.7	94.3
	1000	96.7	95.6	96.6	93.9	93.8	94.4	93.1	93.1	93.8	93.5
	1125	96.3	97.7	94.7	96.2	95.4	93.9	93	94	92.9	94.9
	1250	96.7	95.5	94.8	96.5	95.9	94.5	94.9	94.1	93.9	93.5
	1375	98.7	95.8	97.5	95.3	95.1	94.9	95	94.5	94	94.7
	1500	97.3	96.2	96.2	94.1	93.4	95.5	95.1	92.6	94.6	93.3
	1625	97.6	96.1	96.1	93.6	94.4	95.9	94	92.4	94.3	93.5
	1750	98.5	96.2	95.3	95	95.1	95.6	93.3	94	93.2	93.9
	1875	97.7	97.5	96.4	95.8	96.1	93.6	94	95.2	94.3	-
	2000	98.3	96.4	96.3	96	95	93.7	96.2	94.6	93.8	-

Table 2.4: Drive train power efficiency [%]

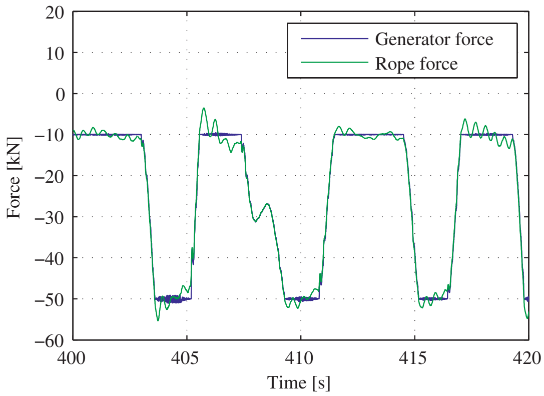


Figure 2.17: Force vibrations observed on mooring during normal operation

Another result of the same problem arises in high-speed cases. When the PTO reaches the nominal speed and has to saturate the production power due to field weakening, a system condition occurs where the damping coefficient becomes negative. This has a destabilizing effect on the system, and causes the PTO to accelerate due to positive feedback. This was expected during system design, as the force ramp down will reduce the floater submersion, but the effect was expected to decay as soon as the floater had reached its maximum speed. However, due to the dynamical softness of the system, this effect causes violent oscillations that have caused the PTO to trip on overspeed on a few occasions. This problem is believed to be easier to solve, as these occurrences are quite infrequent, so that more drastic approaches can be used without significantly affecting annual produced energy.

2.8 Concluding remarks

This chapter has described the PTO design in detail, and has addressed the many mechanisms affecting PTO performance. Important findings are the importance of inertia in the PTO system, both on dynamic behavior and on energy expenditure during pullback. It was also demonstrated that significant expenses can be saved on the inverter and power system by configuring the generator with nominal speed far below the maximum allowed speed. An overspeed ratio of around five has been found to be beneficial.