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# Wave energy converter test application

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This thesis was made for wave energy company Wello Oy. Given assignment was to find the suitable generator and frequency converter for a wave energy converter test application. The primary objective was to find a suitable generator for direct drive, in order to avoid the weight of the test application rising too high.

In this thesis the possible machine types for test application are presented and what are their advenatages and disadvantages. In addition, the operation of the frequency converter in generator use is presented.

Finding the suitable direct drive generator turned out to be challenging due to exceptional needed values of rotational speed and torque of the generator. Which in addition to, the high ratio of peak power to nominal power made it difficult to find a suitable generator. The supply of suitable generators for direct drive turned out to be low and also geared solution is presented as an alternative solution.

Some potential machines were found, but before the final selection can be made further information will be needed from the manufacturers.




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| Keywords | Wave Energy, Product Development, Direct Drive Generator |

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Tämä opinnäytetyö tehtiin suomalaiselle aaltoenergia yritykselle Wello Oy. Annettuna tehtävänä oli löytää soveltuva generaattori ja taajuusmuuttaja aaltoenergiamuuntimen testisovellukselle. Päätavoittena oli löytää soveltuva generaattori suorakäyttöön, jotta vältytään testisovelluksen painon nouseminen liian korkeaksi.

Opinnäytetyössä on esitetty mahdolliset konetyypit testilaitteistolle ja niiden edut ja huonot puolet. Sen lisäksi esitetään taajuusmuuttajan toiminta generaattorikäytössä.

Suorakäyttöön soveltuvan generaattorin löytäminen osoittautui haastavaksi johtuen generaattorilta tarvitun pyörimisnopeuden ja momentin arvoista. Sen lisäksi suuri huipputehon suhde nimellistehoon teki vaikeaksi löytää sopiva generaattori. Suorakäyttöön soveltuvien generaattorien tarjonta osoittautui pieneksi ja myös vaihteellinen ratkaisu on esitetty vaihtoehtona.

Joitakin potentiaalisia koneita löydettiin, mutta ennen kuin lopullinen valinta voidaan tehdä, tarvitaan lisätietoja valmistajilta.

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| Avainsanat | Aaltoenergia, Tuotekehitys, Suorakäyttöiset generaattorit |

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**Contents**

# 1 Introduction

Because of decreasing sources of fossil fuels and accelerated climate change, new ways to produce sustainable energy is searched all the time. Over 70 percent of the earth's surface is covered in water, but still this massive energy source have not been exploited. Wave energy is renewable source with a huge potential. Also its environmental impact is low. Interest in wave energy has increased lately when different wave-energy companies have manufactured full scale wave energy converters for testing. Results have been promising and it can be expected that wave energy redeem its potential in the near future. Wave energy can have significant role in future for reducing carbon dioxide emissions and mitigation of climate change. There are still some challenges of harnessing energy of waves effectively. Because of this product development has significant role that energy of waves can be harnessed seriously for energy production.

Several companies are developing wave energy converters and there are different approaches to the subject. It is interesting to see which one of these techniques will really make the breakthrough first. Some of the equipments are designed to operate on the sea surface while others are located near to cost to the seabed. This is interesting part of wave energy which also allows utilization of the wave energy in different circumstances. It is said that wave energy is now in same situation than wind energy was in seventies. However, estimations have done that wave energy could cover 10 % share of all produced energy in future.

There are also wave energy companies in Finland. Thesis was done for Finnish wave energy company Wello. The aim of this thesis was to find suitable generating system for wave energy test application.

## 2 Wave energy

Due to the decreasing resources of fossil fuels, the importance of developing the existing renewable resources and finding new ones has increased dramatically. Burning of fossil fuels creates carbon dioxide which is the main cause of greenhouse effect thereby it speeds up the process of global warming. There are couple different ways to produce electricity from water. The most common way to convert the energy of water to electricity is hydropower. Hydropower is also the most remarkable source of renewable energy with its around 16 percent share of all produced electricity included non-renewable sources. In hydropower the potential energy of the falling or fast flowing water is converted to mechanical energy of the turbine. Another one is tidal power which exploits the tidal action of the ocean. /3/ In wave energy, which is an object of interest in this thesis, kinetic and potential energy of waves are harnessed for power generation.

Despite that wave energy might be lesser-known form of energy production, earliest production concepts are over 100 years old. After the energy crisis of the 1970’s the possibilities of utilizing wave energy have been researched more thoroughly. /1/ Researchers have been trying to develop a technology with the help of which the ocean waves could be utilized in an efficient way as a resource for energy production, but the greater commercial breakthrough has not happened yet. Nevertheless, new concepts have been developed and tested with good results and wave energy converter can be worthy and competitive source of energy in next few years.

The estimated total energy contained in waves are something between 8000 – 80000 TWh annual. It is estimated that around 2000 TWh per year can be produced by wave energy, which means 10 percent of global electricity generation. /3/ Thus we can say that there is huge unused resource of energy and wave energy converters can make significant energy contribution in the future and reach its full potential. It is said that wave energy is now in same situation as wind energy was in 1970’s. Nowadays there are dozens of companies using several different techniques to extract the energy from waves. /1/

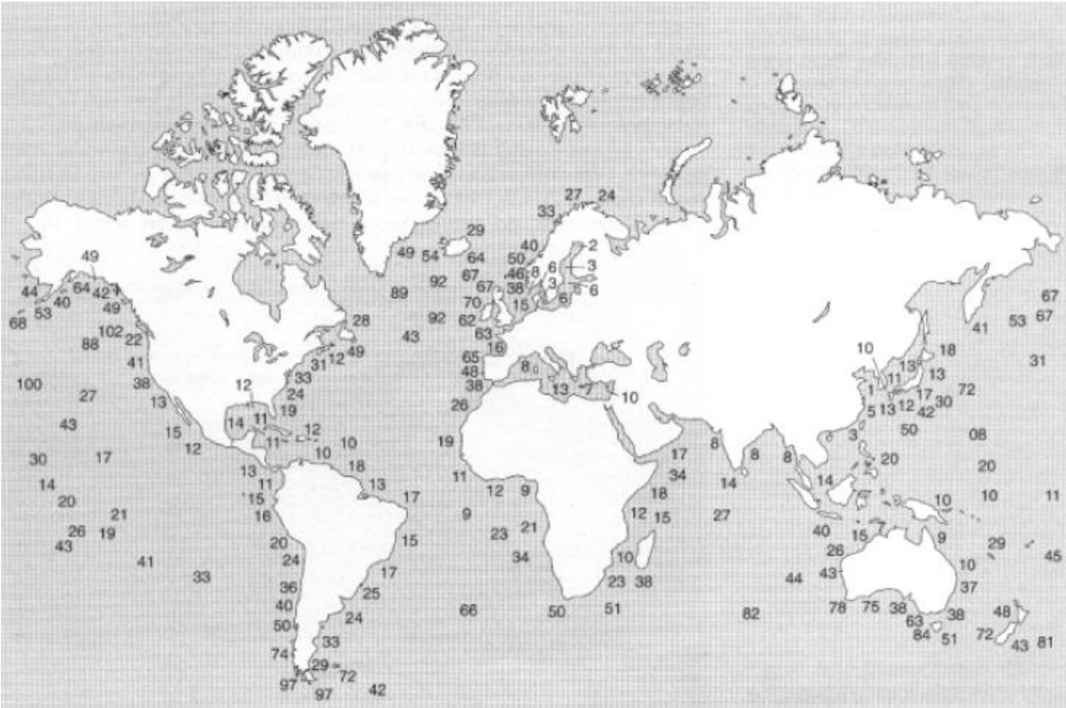

Figure 1. Wave energy resource around the world /1/

Geographically the most potential areas for maximum energy production are located to areas where highest winds occur. /3/ One of these are for example British Isles, so it is not surprise that the United Kingdom have had big role in wave energy research and there have been several government founded research projects related to wave energy technology. /1/ That can be seen also in figure 1, which illustrates the power content of waves in around the world. We can see that area of Baltic Sea does not seem to be that potential for wave energy production.

## 2.1 Clean energy from waves

Ocean waves are generated by wind passing over the surface of water. Higher waves means greater energy as we can expect. The size of waves are proportional to the speed and duration of wind. These results the formation and growth of waves. For estimating power of waves we need to know its high and the wave period. The high of wave is from crest to trough and wave period is determined by the elapsed time from crest-to-crest. Power of the waves can be then calculated by the following formula

$$P\left[\frac{W}{m}\right] = \frac{\rho * g^2 * H^2 * T}{32\pi}$$

where ρ is the density of water, g the acceleration due to gravity, H the wave height and T the wave period. /1/

## 2.2 Advantages and challenges of wave energy

Research of wave energy is focused on marine areas which will not freeze and where the energy content of waves is highest. Wave energy does not seem to be that suitable for Finland since waves of Baltic Sea are small and the freezing sea does not help the situation. On the other hand, a wide range of applications is being developed and some of them might be suitable also for Finnish conditions and future can make it possible to produce energy also from Baltic Sea.

One significant advantage of wave energy is stable power generation compared for instance solar energy. Another advantage of wave energy is that it is easy to predict produced power even three to five days ahead. /26//27/ However these technologies do not compete with each other apart from financing and comparison between them are not meaningful and all of them has role in future energy production. Also environmental impacts of wave energy is said to be low, at least with wave energy converter which has sealed construction that for example fishes cannot end up inside the wave converter.

Although the future of wave energy seems bright, there is still challenges to beat before mass production can be achieved. In development phase when batch are small, building on the sea is quite expensive. However this will change when batches will increase. Also conditions in the open sea can sometimes be very challenging and construction of the converter needs to be robust in order to withstand big waves and storms.

## 2.3 Wello Penguin

Wello is Finnish wave-energy company which product is called Penguin. Power production of converter is based on rotating mass. It is patented technology and at the moment there is no other applications which operation is based on same principles.

Penguin is floating vessel which moves on the surface of the waves. Motion of waves rotates eccentric mass connected to the generator.

The company has made tests with full scale converter in Orkney Scotland. The converter has been tested in different conditions with smaller and bigger waves. The peak power of the converter has varied from 300 – 700 kW already in small waves. Penguin operates in open sea where depth of water can be 50 m and waves contains more energy. The developing of the converter has been rapid because of its simple construction and existing technology. Penguin is based on standard components of the industry. /2/

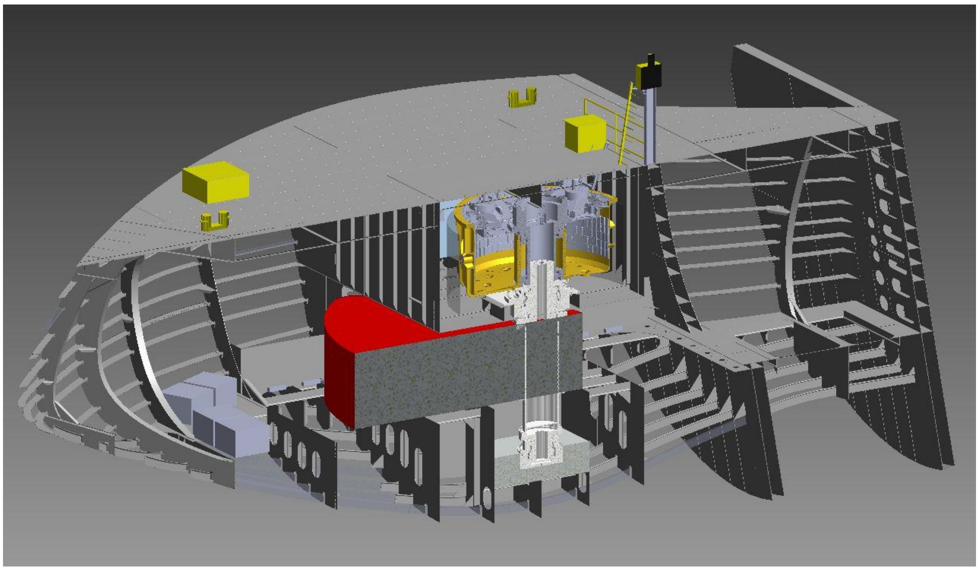

Figure 2. Wello Penguin /2/

## 3 Synchronous machine

Conventional synchronous machine is still the most used machine type in power production. Since it has great accuracy of speed and torque control it is used also as a motor, but that is more common only when remarkably high mechanical power is needed and it is not that usual nowadays, since control of induction machine has come more accurate and permanent magnet machine has raise it popularity. Set up of a synchronous machine is similar to other machine types. It consist a stator with three phase windings and rotor with excitation winding. Excitation of the rotor of the synchronous machine is implemented by external DC current source. Rotating magnetic flux of the rotor induces sinusoidal three phase back e.m.f. E to the stator, which frequency is directly proportional to rotational speed of the shaft and number of pole pairs of the machine. When rotational speed is constant, magnitude of induced voltage can be controlled by changing value of the excitation current and therefore increasing or decreasing the magnitude of the magnetic field. This can be seen in following equation: /4/

$$E = k * Im$$

where k is machine specific constant and $I_m$ is excitation current.

Separately excited synchronous machines are divided into two group according to the structure of the rotor. These are non-salient pole synchronous machines with distributed excitation rotor and salient-pole synchronous machines with concentrated excitation rotor. Non-salient pole synchronous machines are used for high speed applications such as turbo generators. Salient-pole synchronous machines are used for slow speed applications, where rotating speed can be less than 100 rpm, such as hydro generators. /6/ Because the excitation current is not a part of the stator current, synchronous machines have better efficiency and power factor compared to the induction machines. Also when rotor rotates same speed as the stator field, control of the synchronous machines are more accuracy.

The features of the synchronous machines are determined by the rotor construction, more precisely reactances. The rotor of the salient pole machine is magnetically asymmetrical, which means that it's direct axis air gap differs to air gap of quadrature axis. Therefore d-axis reactance $X_d$ differs to q-axis reactance $X_q$. Reactances of non-salient pole are approximately equal. /4/

Since the stator voltage is controlled separately with excitation winding, the ratio of the active power and reactive power can be controlled freely. The angular difference between induced voltage E and terminal voltage Us produces torque. When power angle rises the given active power of the generator rises. The active electrical power produced by salient pole generator can be expressed with the power angle equation /4/

$$P = [\frac{Us * E}{Xd} sin\delta + \frac{Us^2}{2}\left(\frac{1}{Xq} - \frac{1}{Xd}\right) sin\delta]$$

where E is electromotive force induced by phase and Us is phase voltage of the machine.

Because of power is product of torque and mechanical angular velocity, active power of the synchronous generator is determined by the prime mover. Therefore active power is controlled by controlling the kinetic energy of the prime mover. The amount of reactive power that synchronous generator feeds to grid depends on the excitation of the synchronous machine. The generator can be either over magnetized or sub-magnetized. Amount of reactive power can be controlled by controlling excitation current. The generator is over-magnetized when excitation is raised above no- load value. Over-magnetized generator feeds the grid with inductive reactive power. Correspondingly sub-magnetized generator takes reactive power from the grid to compensate inadequate excitation. The generating operation of separately excited salient pole machine is illustrated in Fig 1. /4/

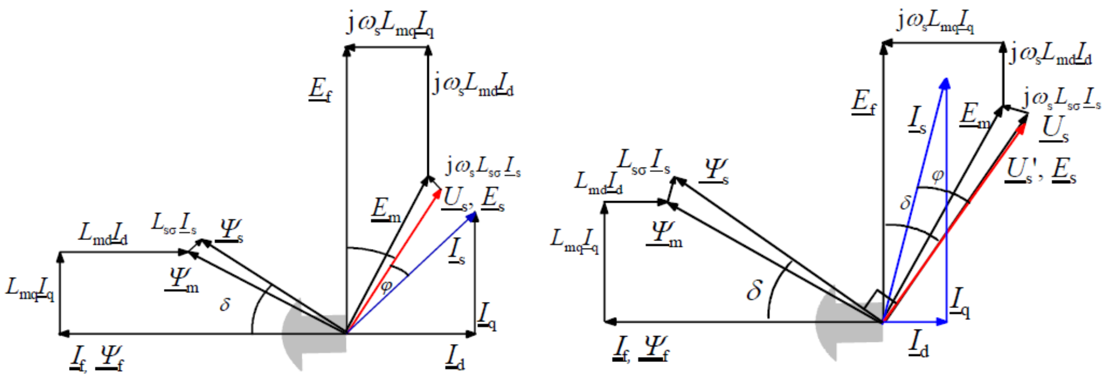

Figure 3. Sub-magnetized and over-magnetized salient pole generator /28/

The angle δ between induced voltage E and terminal voltage of stator Us is called inner load angle. For salient pole generator the highest torque and power is achieved when load δ angle is approximately 90 degrees, which can also be seen from power angle equation. /4/ The increased torque increases load angle δ and electrical power fed to the grid. If the torque is increased too much and load angle rises above 90 degrees, the connection between magnetic poles of stator and rotor cuts off and machine falls out of synchronism. /29/

When synchronous machine is started, its rotating speed of the rotor deviates from the frequency of the network. Because of that synchronous machine must be synchronized with the network. The generator is connected to the grid with switch which is closed when the voltage between the grid side and generator side is close to zero. Before switch can be closed, voltages of the grid side and generator side of the switch need to be almost equal, phase angles of the voltages are equal and the frequencies of voltages are equal. Synchronization is done in practice with automatic synchronization equipment. /7/

## 4 Permanent magnet synchronous machine

Use of permanent magnets in electrical machines has raised in recent decades with the availability of new better permanent magnet materials. Previously use of permanent magnet in electrical machines was lower because of low demagnetizing temperatures and sensitivity to external magnetic fields. The maximal value of remanence flux density for the best used magnetic materials are from 1,05 T to 1,4 T. When these magnetic materials with high flux density is used, bigger air-gap flux density is achieved which means higher torque. However these magnetic materials are quite expensive and choice of magnets is made based on needed performance of machine and there is also cheaper magnetic materials which can be used in many applications. On significant advantage of PMSMs is that number of the pole pairs can be freely selected in order to achieve wanted rotating speed and still have a good power factor and efficiency. Therefore PMSMs are natural choice for low speed gearless applications. /8/

Only small magnetization component of the stator component is needed because the air-gap flux is mainly produced by the magnets. In practice there is no copper losses in the rotor and excitation losses can be considered to be zero. The main source of losses in permanent magnet machines is copper losses in stator windings. Other sources for losses are hysteresis and eddy current losses which are called iron losses./12/.Other machine types have also rotor losses and higher efficiency is one advantage of permanent magnet machine.

Stator of PMSMs are similar with other machine types and many manufactures are using same standard stator for induction machines as well. Interesting part of PMSM is the rotor, which determines features of the machine. Several different rotor constructions are used and all of them offer their own advantages over other rotor constructions. Rotors can be divided in two main classes depending of the direction of the air gap; cylindrical rotors with radial air gap and disk rotors with axial air gap. Permanent magnets can be either mounted on rotor surface or inside the rotor construction when interior rotor is spoken. When rotor is cylindrical it can be internal or external to the stator, the first one is more common configuration. /11/

In axial flux machines usually more than one rotor is used. Construction with one rotor and stator causes large axial force between the rotor and stator and bearings need to handle that force, which makes it less attractive machine construction. /11/ The radial flux machines are more common and it has two fundamental rotor constructions. Magnets can be either glued on the surface of the rotor or they can be buried inside the rotor.

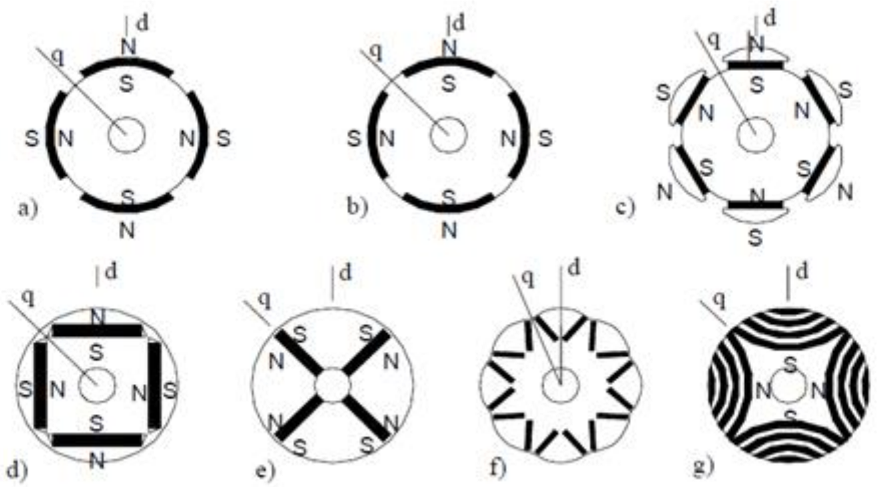


Figure 4. Different rotor constructions for permanent magnet machine /28/

When magnets are mounted on the surface of the rotor, non-salient pole rotors are spoken (SPM). With non-salient pole rotor the synchronous inductance of d- and q-axis are in practice equal. If magnets are mounted inside the rotor correspondingly salient pole rotors are spoken (IPM). That means that quadrature axis synchronous inductance differs to direct axis inductance. /6/

The surface mounted construction is more economical, because lower amount of produced flux is wasted in the leakage components of the rotor. Rotor construction with interior magnets can waste even 25 per cent of the flux for leakage components. /5/ Still rotor with interior magnets has some advantages over to surface magnet construction. When magnets are buried inside the rotor, they are sheltered against mechanical and electrical stress.

The PMSMs are usually handled in rotor dq coordinate, where equivalent circuits of PM-machine is represented for d-axis and q-axis directions separately. One way to present the equivalent circuit of the permanent magnet synchronous machine is illustrated in Fig 5. In the equivalent circuit the permanent magnet is represented as a current source $i_{,PM}$, which produces the part of the air-gap flux linkage produced by permanent magnets. /8//10/

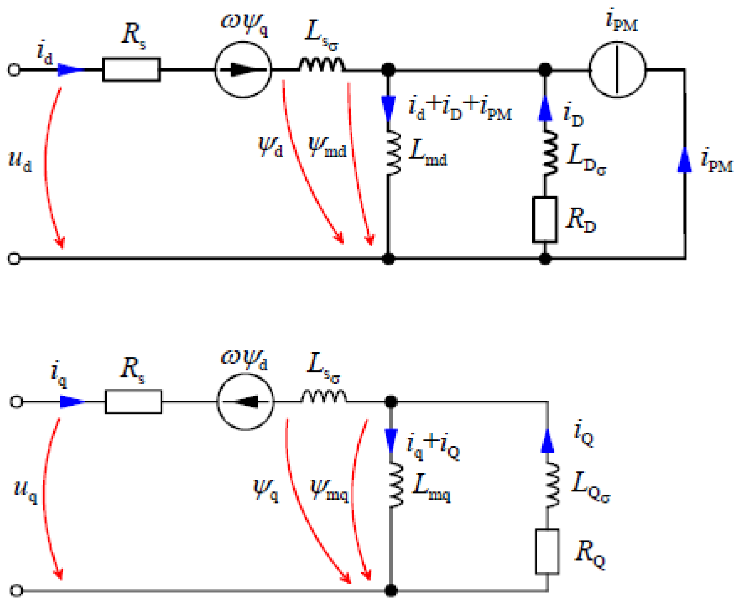


Figure 5. Equivalent circuit of the permanent magnet machine /10/

The equation of electrical torque for PM-machine can be written as following:

$$T,e = \frac{3}{2} p[\psi,\mathrm{PM} * \mathrm{i,sq} - (\mathrm{L,sq} - \mathrm{L,sd}) * i,sd * i,sq]$$

The torque equation above illustrates how torque is produced by the two terms when damping windings is not included. The first term represents torque produced by interaction between the flux linkage of permanent magnets and stator current. The second term is noteworthy for salient pole machine where there is noticeable difference between the quadrature axis inductance and direct-axis inductance. /10/

## 4.1 Permanent magnet synchronous generator

Permanent magnet generators is typically used in direct drive applications where slow rotational speed is needed. It is very common machine type in wind turbines for instance and also used in small hydropower plants. Let's take a look of generator operation of PM-machine.

The magnetic flux ψ,PM produced by permanent magnets is constant. Therefore the electromotive force E induced in the stator winding is proportional to the rotor speed. The equation for induced electromotive force E is represented in following formula:

$$E = \omega * \psi, \mathrm{PM}$$

Where ω is rotating speed of the rotor and Ψ, PM is magnetic flux produced by permanent magnets. The equivalent circuit of permanent magnet generator is represented in Fig 6. Angle between the stator voltage Us and induced voltage E is called load angle like in case of synchronous machine. Amount of produced active power can be controlled by controlling the load angle and thus either reduce or increase torque of the machine. /9/

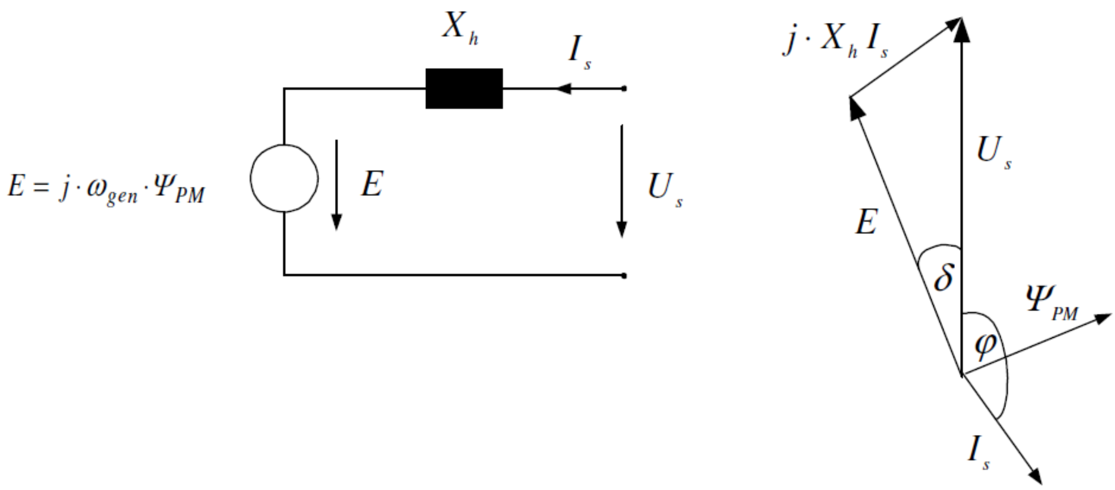


Figure 6. Equivalent circuit of PMG /9/

The permanent magnet machine has many advantages over to other machine types. Compared to the induction machine it has higher torque density for instance. The permanent magnet machine has also some advantages over to separately magnetized synchronous machine. Since excitation of generator is produced by permanent magnets the DC excitation system is not needed which reduces weight of the generating system and increases efficiency when rotor losses are basically zero. Slip rings of separately magnetized synchronous machine also need maintenance which can be eliminated with PMSMs. When there are less moving components, risk of malfunctions are also lower and generating system is more reliable. The most significant advantage is still that permanent magnet machines can be built for extremely low speeds which means that gearing can be omitted. The gear is most prone to failure in generating system and advantages of direct drive system especially for offshore applications is undisputed. In addition to gearless construction, PMSMs has few more advantage over induction generators. Induction machine need always external source for excitation. Also accurate control system is easier to do for PM machine than induction machine, because only torque producing component of stator current is need to control. /8//9//12/

Although permanent magnets offer many advantages they also have some disadvantages which other machine types do not have. Permanent magnets are expensive and best magnet materials are rare and their production is concentrated for a handful of manufacturers.  Also the fixed excitation is problematic in terms of a field weakening. Still the field weakening operation is also possible for PMSMs. Back-emf produced by magnets is directly proportional to the rotational speed of the machine. Then here for prevent rise of voltage too high, demagnetization current is needed from frequency converter to keep voltage under control./8//9//12/

# 5 Asynchronous machine

In asynchronous machine the rotor and rotating magnetic field of stator rotates always with different speed. The speed difference between rotor and magnetic field of stator is called slip speed. When asynchronous machine is used as generator slip is negative and rotor rotates faster than magnetic field produced by stator current. Operation of asynchronous machine is based on electromagnetic induction and speed difference is necessary for that. In asynchronous machines both, excitation current and work current is fed by stator. When flux lines of rotating magnetic field of stator cut rotor conductors, electromagnetic force is induced to the rotor windings and rotor is dragged along by the stator field. /16/

An asynchronous machine is usually used as motor and it is most widely used machine type in industry. A basic induction motor can operate as generator and no modifications of its structure is needed to turn it into an induction generator. When rotor of asynchronous machine is rotated by the prime mover faster than synchronous speed, asynchronous machine operates as generator and asynchronous machine feeds power to the grid. Asynchronous generator can take its excitation current either from network or from capacitor bank connected to its terminals. Advantage of capacitor excited asynchronous generator is that it can be used also in locations where is not public network. Thank kind of operation is called island operation. /7/

Asynchronous generator needs reactive power from the grid for its excitation. Amount of reactive power taken from grid is determined by the power factor of the machine. Active power that the asynchronous generator feed to the grid is controlled by controlling slip speed. When torque increases also speed difference between rotor and rotating magnetic field of stator increases which leads higher amount of active power. The ratio of produced active power to the taken reactive power is constant, but amount of consumed reactive power can be compensated with capacitorbank connected to the terminals of the machine and therefore increases power factor of the generator. /14/

## 6 Frequency converter

Most common frequency converter type is two level voltage source inverter (VSI) with IGBT switches. Another common used topology of frequency converter is current source inverter (CSI). Voltage source inverter topology is also more common in generator applications so this thesis centralize to that topology.

The frequency converter can be divided into three main parts; the grid side unit which rectifies the alternative voltage of the mains supply to the intermediate DC-bus, the DC-bus which capacitors compensates the ripple of the rectified DC voltage and acts as an energy store for motor side inverter, and motor side inverter unit which produces wanted alternative voltage for motor. In addition to these there is control unit which based on measured values controls torque and speed of motor by controlling the switches of inverter unit. /18/

With typical motor drive the grid side converter is implemented with a passive diode bridge and the motor side inverter unit is equipped with active IGBT-bridge. When the motor is braked the regenerated power must be consumed in the frequency converter. The simplest this can be implemented with braking resistors. However, at higher power levels, this solution is no longer reasonable. The diode rectifier allows power to flow for one direction. When diode-bridge of the grid side converter are replaced by IGBT-bridge, the four-quadrant operation of the drive is possible. That means that power can flow in both directions, from the grid to the motor and vice versa. This solution is called Active front end (AFE). This is utilized, for example, with cranes and elevators which are braked on a regular basis. Naturally, active front end is needed for generator applications with frequency converter and it is used extensively in decentralized energy production where rotating speed of generator varies, for example in wind power. The structure of the frequency converter with active front end can be seen in Fig 7. /15//18/

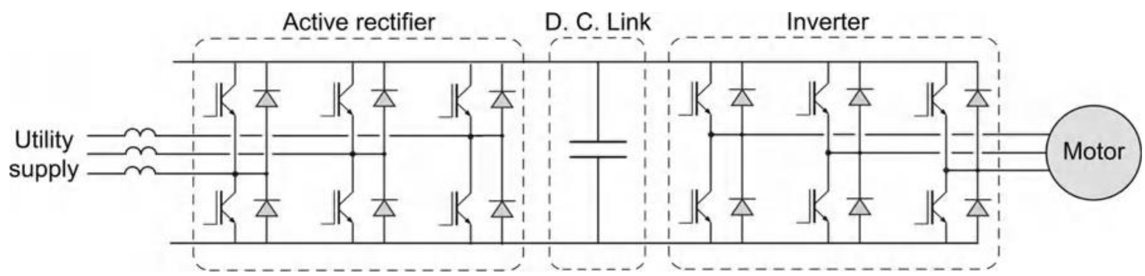


Figure 7. Frequency converter with active front end /15/

With generator the grid side converter must be active and equipped with IGBT-bridge so that the power supply to the network is possible. The generator side converter can be implemented either passive diode-bridge or active IGBT-bridge. The best controllability of the system is achieved when also the generator side converter includes IGBT-bridge. Thus, this chapter focuses on the implementation with active generator side converter.

With generator drives, the frequency converter consist of two converters; the grid side converter and the generator side converter. These converters are connected via DC-bus. The frequency converter in generator drives does not differ from one for motor drives. It has same hardware and main features. That means that inverter unit can be modified to AFE-unit by adding AFE-application software to it. In the case of a permanent magnet generator, the frequency converter must be compatible with PM-machine and includes PM-machines software. In addition to the special software, AFE-unit requires an external pre-charging circuit and LCL-filter. The pre-charging circuit is needed for increasing the intermediate voltage close to its nominal level. This must be done before AFE-unit can be connected to the distribution network. /9//17//19/

The control of the frequency converter is divided into two controlling loops: one for controlling the generator side converter and another for controlling the grid side converter. The generator side converter controls torque and rotational speed of generator and thus control and optimize amount of produced active power. The grid side converter feeds power from intermediate circuit to the grid and controls amount of produced reactive power. If the voltage of the intermediate DC-bus rises on its upper limit, the generator side converter reduces torque of the generator and therefore reduces amount of power fed to the intermediate circuit, causing the voltage decrease in DC-bus. The power fed into the grid reduces voltage of the DC-bus and if the generator cannot feed enough power to the DC-bus to keep its high enough and the voltage drops to the lower limit, the grid side converter reduces amount of the power transferred to the grid in order to keep the DC-bus voltage high enough. The voltage of the intermediate DC-link should be kept constant and voltage should be high enough that inverter is able to produce enough sinusoidal voltage to the grid. /9//17//18//31/

The function of the AFE-unit is keep the frequency converter synchronized with the grid and produce sinusoidal voltage to the distribution system. In order to do that AFE requires measurements of the DC-bus voltage and phase current between the grid and the AFE-unit. Measured phase currents are divided to active and reactive components. The control of AFE-unit can be divided in three main parts. The aim of the DC-bus voltage controller is to keep voltage of intermediate circuit on desired level. The DC-voltage controller compares measured voltage of intermediate circuit and compares it to reference value. Based on difference between measured value and reference value the DC-bus voltage is controlled to match with wanted value. The function of the active current controller is to control the voltage supplied to the network. The reactive current controller controls amount of reactive power fed to the grid and keeps the inverter synchroniced with the grid. /19/

The generator drive with frequency converter allows variable speed operation of the generator. The rotating speed of the generator can be selected that the highest possible efficiency is achieved. With frequency converter, the generator can be asynchronous- , conventional synchronous- or permanent magnet machine. When the generator is connected via frequency converter to the grid, there is no need for synchronize generator separately to the grid. With variable speed generator it is possible to control active and reactive power production independently and therefore support actively the grid. /9/ /17/

## 6.1 Field Oriented control

Field oriented control is also referred as vector control is widely used accurate control strategy for motors and generators. It uses two axial model which can be implemented in stator or rotor reference coordinate. Block diagram of the field oriented control consist of two mayor control loops. One for speed control and another for torque control. The speed control loop controls torque control loop. Measured values of voltage and stator current is converted based on motor model to wanted reference coordinate. Based on motor model and measured voltage and current values needed control variables are calculated and speed and torque is estimated. Vector modulator chooses correct switching positions for inverter. /8/

In Pm machine mounted permanent magnets of rotor produces rotor flux with constant magnitude. Stator windings produces its own rotating magnetic field, when stator current is fed. As Pm machine is synchronous machine, the magnetic fields of stator and rotor rotates in same frequency. Produced torque is based on interaction between these fluxes and torque production is controlled by controlling angle between these fluxes. The produced torque is cross product of stator field and rotor field, which means that the highest torque is achieved when angle between them is 90 degrees. Field oriented control needs feedback of the rotor position. That can be implemented with position sensor or if less accurate control is acceptable estimation of rotor position can be done without position sensor. Since the speed of the rotor is equal to the rotor flux speed, position of the rotor flux can be measured directly with position sensor. /20/

Phase stator current is separated into two current component, which are implemented in the rotor reference frame, direct axis current i,d and quadrature axis current iq. One for producing flux and another for producing torque. Direct axis component i,d is flux producing component of the stator current and quadrature axis component i,q is torque producing component of stator current. That means that both, flux and torque, can be controlled directly. In case of permanent magnet machine required air gap flux is produced by the magnets of rotor and there is no need for produce another, therefore reference value for flux producing component of stator current i,d is normally set to zero. Produced electrical torque is then

$$T,e = \frac{3}{2} * \frac{P}{2} * \lambda,\mathrm{m} * \mathrm{i},\mathrm{q}$$

Therefore in field oriented control of PM machine torque depends only the quadrature axis current. Field wakening is less common in case of PM machines, but that can be implemented by using also direct axis component of stator current for reducing increase of back e.m.f. over permissible limit. /24/

## 6.2 Direct torque control

Direct torque control is not used just for motor operation, but same principles is used also for generating. Direct torque control is widely used control strategy for example PM generator of wind turbines. In general with PMAC machines high accuracy of speed and torque control is achieved without position or speed feedback. Tough position feedback is required when torque is needed in zero speed or close to zero speed in longer periods. The strength of the direct torque control is that for calculating of the voltage of stator, conventional rotor parameters is not needed and hereby it is independent of machine type and can be used not only for induction machines but also for all type of synchronous machines. Direct torque control is widely used for PMAC machines without positon feedback sensor. As mentioned above, slow rotational speeds are challenging when position feedback is not used and there are some challenges for detection of rotor angle in slow rotational speeds. /21/

The initial value of the rotor position is needed. When position feedback is not used, the initial value of the rotor position is unknown which causes problems of synchronization for instance. That is because of the initial value of the stator flux is not zero like in case of induction machine but it depends on the rotor position. Still there are several solution for this problem. For instance scalar control can be used for accelerate rotor speed high enough that rotor angle can be detected. Also difference of the d- and q-axis inductances can be used for determination of rotor initial angle. This can be used only for salient pole machines where these inductances are not equal. Chosen method for determinate the initial value of rotor angle differs with different PM machine types. /8//21/

In direct torque control there is no predetermined switching frequency, therefore optimal switching is determined in every single control cycle. Block diagram of DTC consist of two mayor control loop, one for torque and another for speed. Needed measured values for estimating stator flux linkage and torque are phase currents, DC bus voltage and state of switches. For estimation of stator flux linkage accurate estimation of stator resistance is important. Torque is calculated based on estimated stator flux linkage and measured phase currents. Based on measured values the adaptive motor model can calculate estimated values of stator flux linkage and torque. /21/

As result of the estimated actual values of the stator flux linkage and torque, output signals of adaptive motor model is given to the flux linkage and torque comparator unit. Another inputs of comparator units are reference values of torque and rotating speed. These reference values come from speed controlling loop. Inner torque reference is determined in torque reference controller in speed control loop. Input of that controller comes either from speed controller or instead of that external torque reference determined by user can be used. In flux linkage and torque comparator units, hysteresis controller calculates status of flux linkage and torque by difference between the estimated actual values and reference values. The values obtained in comparators is input values of optimum pulse selector where switching combination is determined for inverter. /21/

Slow rotational speeds are problematic in controlling point of view especially for Permanent magnet machines. If sensorless control is not considered an option, accurate control can be achieved simple by adding feedback of rotor position. Here current model can be used alongside voltage model for correcting stator flux linkage estimations produced by voltage model. Voltage model calculates stator flux estimations which are then corrected by stator flux linkage estimations calculated by current model. Voltage model requires for stator flux estimations measured values of DC-bus voltage and positons of switches. Phase currents and rotor position is measured for current model. Also parameters of machines is required that current model can compute estimated values of stator fluxes. This operation can be seen in figure 8, which illustrates function block of DTC for PMAC with position feedback. /8/

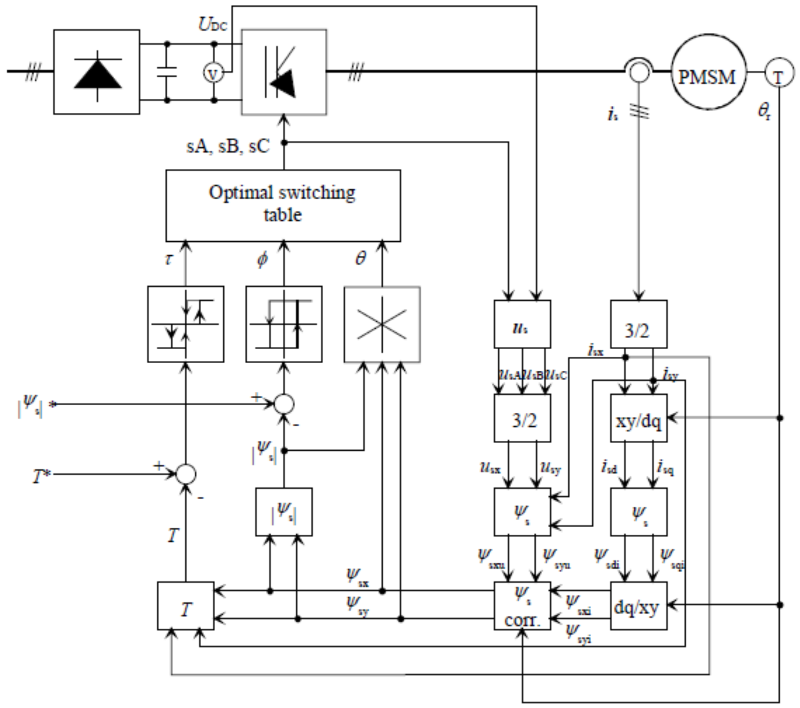


Figure 8. Function bloc of DTC /10/

## 6.3 Harmonic distortion

Non-linear loads connected to the power distribution system take non-sinusoidal current. This generates harmonic currents to the network and reduce quality of power in the distribution network. When these harmonic components are added to the fundamental current they causes distortion of the voltage waveform and the waveform become close to the rectangular waveform. The frequency of harmonic current is multiple of fundamental frequency of the electrical grid. Harmonics can be divided to components where first term is called fundamental wave and rest of them are called harmonics. Generated harmonics can be presented as shown in Fig 10. /22/

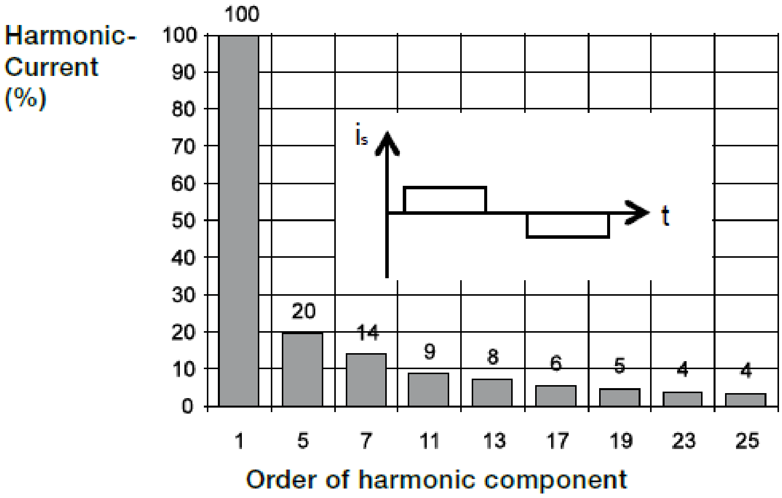


Figure 9. Harmonic content of six pulse diode rectifier /23/

One source of harmonic currents are frequency converter. Frequency converter generates harmonics because of high switching frequency of its rectifier. The high switching frequency of the frequency converter causes current and voltage peaks. Current and voltage peaks reduces power quality of the distribution system and causes shaft currents for motor or generator. /30/ The order numbers of harmonics currents generated by rectifier can be calculated by following formula:

$$n = pk \pm 1$$

where p is pulse number of the rectifier (6,12,24) and k has values from one to upwards 1,2,3..

Magnitudes of the harmonics are expressed by the ratio of harmonic current to the fundamental current. The RMS values of the harmonics currents can be calculated with following formula:

$$I, ni = \frac{I1}{n}$$

where I1 is the fundamental current and n is order number of the harmonic current. Harmonic content is can be described with total harmonics distortion index. /18/

$$THD(I) = \frac{\sqrt{I2^2 + I3^2 + I4^2 + \dots}}{I1}$$

Some harmful effects of harmonics have mentioned already above. Harmonics have also some another harmful effects for electrical grid. Harmonics cause redundant losses in the distribution system and non-sinusoidal voltage can cause malfunctions for devices connected to the grid with high harmonic content. Harmonics also reduce power factor of electrical drive and causes shaft current for motor. Another unwanted effect of harmonics is resonance. If frequency of harmonic component is close to the resonance frequency of the distribution network, harmonics are multiplied compared to normal due to resonance. /22/

Due to the numerous disadvantage of harmonics, the amount of harmonics is desired to be as small as possible. There are standards defining limits of harmonic content. The amount of harmonics generated by frequency converter can be reduced by replacing six pulse rectifier to 12 or 24 rectifier or by using active components in rectifier-bridge such as IGB-transistors. When frequency converter feeds power to the distribution network, voltage and current should be as sinusoidal as possible. Therefore the power fed to the grid needs to be well filtered. When active front end is used for generating power to the grid, the filter is basically always needed. LCL-filter is often used for this purpose. /18/

# 7 Possible setup for test application

The aim of this chapter is to find suitable components for generating system for wave energy converter test application. One possible configuration is presented and other possible generator-frequency converter combinations has been suggested for the company. Needed setup consist of a generator, frequency converter and filter. The starting point was to find suitable machine for direct drive, but due to needed high torque and very low rotating speed, also gearing may be needed. In addition to above mentioned components, needed protections and coupling are needed for the final test application setup, but these are not included the extent of the thesis. Due to this only suitable generator-frequency converter combination is represented in this chapter.

Challenges for producing energy from waves are related to that how well the energy contained in waves can be converted to the kinetic energy of the generator's shaft. Because the rotational speed of the generator varies all the time, also electrical values of the generator, such as voltage, current and power vary continually. This makes choice of the generator challenging in order to avoid unnecessary and expensive over-dimensioning. Due to the energy source, it is typical for wave energy converters that the ratio of produced maximum power to the average power is remarkably high compared to other form of renewably energy. /25/ That is illustrated in Fig 11. Large ratio of peak power to average power lead easily to over-dimensioning of the generator which decrease its efficiency and increase price. Respectively price of other components, such as frequency converter will increase.

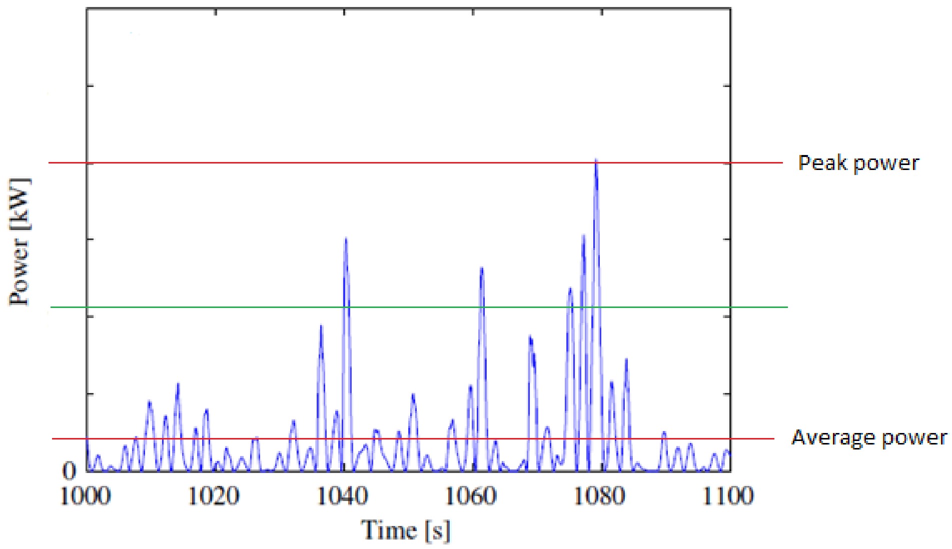


Figure 10. Typical power fluctuation of waves. Modified from: /25/

The Fig 10 illustrates how power can be produced from waves. It is not needed to dimensioning generator to available peak power produced by waves. The generator can be dimensioned between average power and peak power which green line on the Fig 10 illustrates. In case of highest peaks the output torque reference is limited and the rotator mass is instead given to accelerate. This does not reduce amount of produced power essentially and it is possible to get lighter and more economical generating unit.

The chosen machine type for test application not necessarily needs to be the best suitable for full scale wave energy converter, but it would be positive if similar setup would be applicable also for full scale converter. The most important is, that setup works as desired so that desired tests can be performed. Since wave energy converter can be located several kilometers from the coast, it is important that there is as less as possible source of failures. Gearing can be considered the most significant source of failure and failure of the gearing can cause long and costly interruption in production. In addition to the risk of failure, gearing cause additional noise which can be harmful to marine life. Because of the above mentioned reasons, the direct drive generator is appropriate for the purpose. Thus the aim was to find generator which is suitable to be used without gearing. In addition to the direct drive solution, it is desirable that the total mass of the system (generator and frequency converter), is less than 200 Kg. The induction machine cannot be build for speed-range low enough and also the mass limit does not support choice of it. Therefore the choice is made between external magnetized synchronous machine and permanent magnet synchronous machine. Synchronous machines can be build for slow rotational speed, which allows omission of the gear. The choice of the permanent magnet machines is supported by the fact that it has more simple construction, because it has fixed excitation and does not need any external equipment for that. It is desirable that the need for maintenance is minimal. Conventional synchronous machine needs maintenance because of its excitation system and the slip rings needs maintenance. In addition to the maintenance issues market supply is more comprehensive in permanent magnet machines when we are talking power rate under 10 kW. It was also stated that conventional synchronous machines is more complex and when there does not seem to be supply on markets, permanent magnet machine is most suitable for test application.

The following mechanical values are required for the chosen machine. The required rotational speed for this application is approximately 40 rpm and the required torque is approximately 1000 Nm. However, values of chosen machine can differ a bit from above mentioned and dimensioning torque can be something between 800-900 Nm as well. The machine is chosen from standard series and speed can be a bit higher as long as it is capable to induce voltage high enough also at slower speeds. Even so, these values are quite challenging in this power rate when aim is to find machine suitable for direct drive. It seems that there is no greater demand for machine with these values and manufactures do not have brought them to the market.

Nevertheless some potential machines were found, but with many machines either rotational speed was too high or the torque producing capability of the machines was too low. Still there where couple potential machines which values were within the acceptable range. The final selection was done between 5-7 machines, which values were closest to desired values of speed and torque.

## 7.1 Selected generator

Because of its high torque density, high efficiency and power factor, and low need of maintenance permanent magnet machine was chosen for generator of the test application. The permanent magnet machine is good choice also for full scale wave converter which makes its choice justified. High power permanent magnet generators are used in applications where extremely low rotational speed is required, such as in wind turbines and small hydropower plants.

In general the choice of the generator is based on needed torque, power and wanted rotational speed. To optimize the produced power, nominal rotating speed of the generator needs to match with rotational speed of the prime mover. The needed basic values for choice of the generator are needed power, nominal rotational speed and wanted nominal voltage. Also torque-speed profile is needed to know. /17/

Now, however, the most important criterion for selection is torque producing capability and weight of the machine. Relative high torque peaks occur and ratio of nominal torque to peak torque is essential criterion for selection. Another necessary factor is that machine can induce adequate voltage, so value of the Volts/rpm of machines is important as well in order to produce power also in slower rotating speeds.

The cooling of the machine is important because temperature rise of machine determines after all the maximum power of the generator. /5/ However, heating issues is more important in case of full scale converter and heating of machine is not seen as problematic since machine is dimensioned that way that air cooling should be enough. Also temperature of the machine is measured and given torque reference is decreased if it seems that machine heats too much.

Permanent magnet machine from ETEL torque motor series was chosen as an example generator for test application. The most essential values of machine are represented in table below.

| ns [rpm] | Tn [Nm] | Tmax [Nm] | In [A] | Back emf constant [V/rpm] | Weight [Kg] |
|---|---|---|---|---|---|
| 45 | 992 | 3740 | 11 | 5.6 | 93.2 |

Table 1. Values of machine

Torque and rotating speed are suitable for test application. Given back emf constant would mean 256 V induced voltage in 45 rpm. That could be considered satisfactory. At least it was the best founded value of induced voltage in direct drive options.

### 7.2 Selected Frequency converter

After the generator is chosen it is time to choose suitable frequency converter. The power conversion hardware consist of two frequency converters. Frequency converter from Vacon NX-series would be suitable for this purpose, but it can be chosen for another manufacturer as well. Also either direct torque control or field oriented control is needed. Both converters, the grid side inverter unit and the generator side rectifier unit has same features and hardware. The difference between them is that the grid side unit requires additional active front end (AFE) application software and external loading circuit. When both inverter-bridges are equipped with IGB-transistors, power can flow in both directions and feeding power to the grid is possible.

When the frequency converter comes for generator use, the dimensioning is needed to do that way that the frequency converter is capable to receive continually power that generator feeds to it. /17/ For the test application dimensioning based on apparent power of the generator is not that suitable criteria of dimensioning, because of the needed over-loading of the generator. The frequency converter must be dimensioned based on peak torque. The value of continuous current of the frequency converter must be higher than peak current caused by the peak torque of the generator. Dimensioning of the frequency converter is needed to do carefully, because of the overload capacity of the frequency converter is essentially lower than generator's. That could be seen easily from them datasheets. Too high current heats power semiconductors of frequency converter and temperature of these components must not rise above given limits in the datasheet. Because of that it is important to know possible overloading situations of generator that the frequency converter does not break down. /17/ The company will do more accurate dimensioning of frequency converter when the final selection for setup is done. In Vacon NXI-series there are wide selection of frequency converters and rated values of continuous current are from couple to hundreds amps.

### 7.3 Geared solution

If chosen direct drive machine turns out to be unsuitable for some reason, drive with gearing is also shown as reference. The chosen reference machine is Axcomotor's axial flux permanent magnet generator, which has following values:

Electric power 7 kW, apparent power 7.5 kW, torque 420 Nm, nominal rotational speed 180 rpm, nominal frequency 24 Hz, voltage 400 V, PM excited voltage 400 V and phase current 10.5 A.

As we can see from values of the generator, rotational speed is too high and torque is too low. Therefore the gear is needed to fit these values to match with values of the load. The needed conversion ratio for gear can be determined from the ratio of the speed of the generator to the speed of the prime mover. This is represented in following equation:

$$i = \frac{180\ rpm}{40\ rpm} = 4.5$$

Now we can determine needed torque of the generator with following equation:

$$T, gen = \frac{1000\ Nm}{4.5} = 222\ Nm$$

The generator can produce 222 Nm easily. Also overload situations are taken into account because also higher values of torque occur. The secondary torque of the chosen gear needs to be higher than load torque. Choose of appropriate gear is done if company ends up to geared solution.

In order to connect the generator to the grid, certain protections is needed. Implementation of protections was not included in the scope of thesis, but it is good to have overview of them. The frequency converter can take care many of needed protections such as protections against overcurrent of the grid or generator and protection against voltage fluctuations of the grid. /32/ The active front end unit requires also filtering in order to produce voltage with quality high enough. The filtering is usually implemented with LCL-filter. Delivery of the filter is usually included to frequency converter delivery. /17/

## 8 Summary

Couple potential machines were found what could be suitable for direct drive solution. Though market supply is quite limited when rotational speed is as low as in test application. Only possible machines for this purpose seems to be so called torque motors. For these machines circular construction is typical and needed for producing torque in slow rotational speed. These machines are usually delivered only with electromagnetic parts and bearing for instance must buy separately. For test application this not problem, rather good thing. When suitable frequency converter was searched it was noticed that there was not that large supply for related low power rate. Nevertheless, suitable options were found also in frequency converters whom are capable to feed power to the grid.

The founded potential machines require further information from manufactures, because it might be that all of machines are not shown in the websites. Also some wanted technical data was not available. Making invitation for tenders was not included extend of the thesis and further studies about these machines is made by the company. The company also has accurate information about torque and power profile, which are not represented in this thesis, but which are necessary for accurate and cost-effective dimensioning.

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