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Electrical systems in pod propulsion

Master of Science Thesis *of Electric Power Engineering*

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Abstract

Since the middle of the 1990´s pod propulsion in marine applications have become common. There are mainly two manufactures on the pod market. ABB is the biggest producer and has two types of pod-types, Azipod (5-30 MW) and Compact (0.4-5 MW). Rolls-Royce (RR) is the second biggest company on the market, producing a pod called Mermaid (5-25 MW).

The electrical system in pod propulsion normally consists of a transformer, a frequency converter and an electric motor. The transformer is used to divide the system into several parts in order to obtain different voltage levels but also for phase shift voltages for the used rectifiers. The purpose of the frequency converter is to control the speed and torque of the motor by changing a constant frequency from the main generator into variable frequency for the motor. The electric motor is used for conversion from electrical to mechanical power for the propeller.

Azipod has a synchronous motor controlled by a cyclo converter and dry type transformer. The non-drive end bearing is insulated and the shaft is grounded to earth in drive end and to the bearing housing in non-drive end. Mermaid has a dry type transformer and a synchronous motor controlled by a load commutated inverter (LCI). Both bearings are insulated and the shaft is grounded at the drive-end.

The biggest change in pod propulsion within the foreseeable future is a switch to voltage source inverter with pulse-width-modulation (VSI-PWM). Permanent magnet synchronous motors (PMSM) are an alternative in smaller pods and the development of magnets can make PMSM to an alternative for bigger pods. In addition, induction motors is an alternative motor in the future.

Acknowledgement

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Many thanks to all the people at SKF that have helped us during our project. We would like to thank the people at Rolls-Royce in Kristinehamn who made it possible for us to visit the cruise ship Constellation, but also for answering our questions. We would also like to thank Sofia Sauvageot, at Converteam, for the answers to our questions. At ABB we thank Jukka Varis and Jari Yllitalo for taking the time to answer questions that have come up during the last month of our work. Finally we would like to thank Anders Torstensson, at Chalmers, for help and support when we were short on time.

Dictionary

ABB	The biggest manufacturer on the pod market.
AC	Alternating current.
Azipod	The registered brand name of ABB’s pod.
BLSM	Brushless Synchronous Motor, synchronous motor with no brushes.
Cyclo	A frequency converter which converters AC waveform to another AC waveform with different frequency.
DC	Direct current.
DE	Drive end, the propeller side of the pod.
EMF	Electromagnetic field, physical field produced by electrically charged object.
IM	Induction motor, very common in industrial application.
LCI	Load Commutated Inverter, a frequency convert to control the current.
Mermaid	The registered brand name of RR’s pod.
NDE	Non drive end, the opposite side of the propeller.
SM	Synchronous Motor, the most common in pods.
PMSM	Permanent Magnet Synchronous Motor, synchronous motor with permanent magnet in the rotor.
PWM	Pulse width modulation, a way to control the VSI.
RR	Rolls-Royce, the second biggest manufacturer on the market.
VSI	Voltage Source Inverter, a frequency converter with controllable switches.

Table of contents

1 Introduction

This chapter presents an introduction to the Master thesis. First the background of the subject is explained to give a first description of the system to be analyzed in the report and the reason for performing this project. Moreover, to further explain the scope of this Master thesis the purpose, problem analysis and delimitations are described. The method is discussed and finally there is a presentation of the structure of the report.

1.1 Background

Since the middle 1990´s the use of electric motors for propulsion in marine applications has become very common. Different solutions are available when using an electric motor for marine propulsion, one of which is called pod. In this type of propulsion, the electric motor is placed under the ship´s hull in a pod shaped body. The market for pods is growing and it is expected to continue doing so in the future [28].

Typical applications where pods are used are offshore rigs, tankers, cruise ships, icebreakers and naval vessels among others [35e]. Many ships already have a large electricity generation system, usually diesel engines or gas turbines connected to generators, to fulfill the passengers' requirements of comfort, navigation and communication equipment and other applications on the boat. Conversion to electric propulsion is hence a natural step.

An electrical system in a vessel with electric propulsion normally consists of an electricity generation power plant, a distribution system and a motor for propulsion. The distribution system consists of switchboards, transformers and frequency converters. A simplified overview over the electrical installations in a vessel with electric propulsion is illustrated in Figure 1-1. This report will address the transformer, converter and motor, which are marked with a ring in the picture.

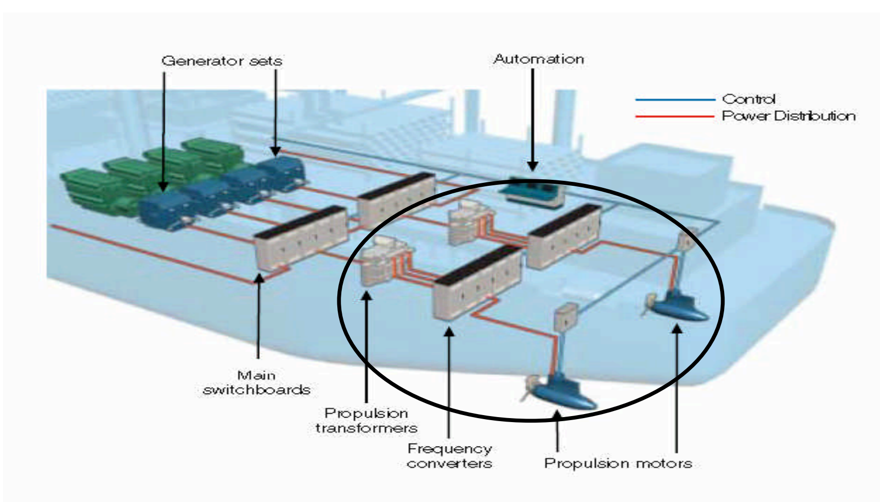


Figure 1-1 Overview of the electrical system on a vessel with electrical propulsion. The ring marks the transformer, converter and motor.

SKF delivers bearings for pods where one important production area is the large bearings needed in pods for big cruise ships. This is the main focus of this thesis report but also smaller pods will be considered as a complement. SKF have a sound knowledge regarding mechanical parts in pods, but intend to increase their insight into other areas. Therefore this Master thesis will focus on the electrical parts of the pod.

1.2 Purpose

The purpose of this thesis is to map, compare and present the electrical systems in Marine pods to further the knowledge of this application. Focus is to describe the various parts of the system and the effect on the bearing system as a result of the used electrical system. Moreover, the purpose is to compare different pod concepts.

1.3 Delimitation

The report will not consider the electricity generation power plant and the switchboards in the electrical system. Pod solutions from smaller manufacturers will only briefly be discussed; focus will be on the two main manufacturers. The thesis does not consider how electrical parts influence mechanical devices, such as bearings, from a mechanical point of view. Neither will the electrochemical processes between salt water and the hull be considered.

1.4 Method

Information has been gathered from the suppliers´ homepages, articles from databases, books and internet. To make use of the knowledge inside SKF and learn more about how this thesis can contribute, discussions and meetings have been held with SKF personnel. To get more specified information about the structure of the electrical system the pod-suppliers were contacted. A meeting with ABB took place at SKF, which was followed-up through e-mail contacts. A visit to the cruise ship Constellation (Celebrity Cruises) arranged by RR took place to see a pod installation (Mermaid). This gave a good understanding of how the systems look like in reality. Further conversation with RR and Converteam continued through e-mail and telephone.

1.5 Disposition

Chapter 2 contains a mechanical overview of a pod. It includes a short mechanical description of the pod and its functionalities.

Chapter 3 gives an introduction to the electrical system in pod propulsion. A brief overview of the devices used and advantages and disadvantages of them is presented.

Chapter 4 describes how a transformer works and different ways that it can be connected. How it is adapted to function together with a converter with various numbers of pulses is also illustrated.

Chapter 5 contains a description of the power semiconductors used in frequency converters and how these are controlled to obtain the required frequency and voltage. The chapter also presents cyclo converter, load commutated inverter and voltage source inverter with pulse width modulation which are the frequency converters normally used in marine applications. Harmonic distortion, which is an unwanted effect, is explained.

Chapter 6 describes the configurations and functionality of three types of electric motors which are of interest in pod propulsion. The motors types include: the brushless excitation synchronous motor, permanent magnet synchronous motor and induction motor.

Chapter 7 deals with the phenomena of current in shaft and bearings. The chapter points at some causes of this problem and explains different ways of trying to mitigate the damage.

Chapter 8 contains the system solutions for ABB's and Roll-Royce's pod propulsion.

Chapter 9 describes trends in the electrical system in pod propulsion

Chapter 10 gives suggestions on in which directions future work can be performed.

Chapter 11 presents the conclusion of the master thesis.

2 Introduction to pod propulsion

This chapter gives a brief introduction of the manufacturers on the pod-market but also a mechanical overview of the pod concept.

2.1 Manufacturers of pods

There are mainly two manufacturers on the pod market: ABB and Rolls-Royce. ABB is the company who has delivered the largest number of pods. They have two types of pod, Azipod which is their oldest pod and a newer concept called Compact. The power range of Azipod starts at around 5 MW and reaches approximately 30 MW and Compact is available in the range of 400 kW up to 5 MW [25]. RR is the second largest company on the market, producing the Mermaid pod. The Mermaid pod propulsion system is available in the power range from 5-25 MW [31]. ABB develops the whole pod solution within the company while RR cooperates with Converteam who develops the electrical parts.

Another player on the pod market is Schottel, they have one pod in the lower power range called SEP (Schottel Electric Propulsion), which they have produced themselves. Schottel has furthermore one pod in the higher power range called SSP (Siemens Schottel Propulsion) which is a joint venture between Siemens and Schottel (SS) [36e]. These two pods have been produced and sold in low numbers, but have not been sold at all in the recent years. There are also Japanese companies showing prototypes but they have not sold any pods so far [32]. The newest company in the pod business is Converteam who recently announced that they are developing a pod together with DCNS [37e].

2.2 Mechanical overview of a pod

Most of the pods sold today generally have the same design. As can be seen in Figure 2-1 ABB's Azipod and RR's Mermaid have similar outer appearance while Siemens-Schottel's SSP has a different design with two propellers. In the case of one propeller it is a pulling propeller. The pod is located outside the hull at the stern of the ship. The pod can rotate freely 360 degrees so the ships no longer need a rudder. This gives the ship improved maneuverability, useful especially in harbors and channels

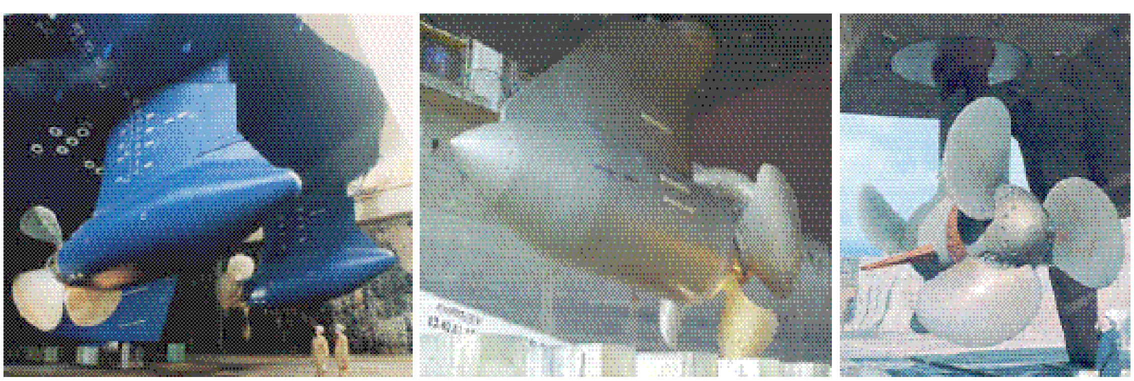


Figure 2-1 Three photos of pods, Azipod (left), Mermaid (middle) and SSP (right). Azipod and Mermaid have a pulling propeller while SSP has one pulling and one pushing.

Since the pod is mounted outside the hull, shaft lines and related equipment can be removed which gives more free volume or more compact ship size. Lower vibrations and noise are also a result of the location of the pod outside the hull. The fuel consumption is reduced because the generators can adjust the rotating speed that for that moment gives the highest efficiency. The hull resistance will be reduced when traditional shaft line and related brackets can be eliminated and optimum hull design can be utilized, which also results in lower fuel consumptions.

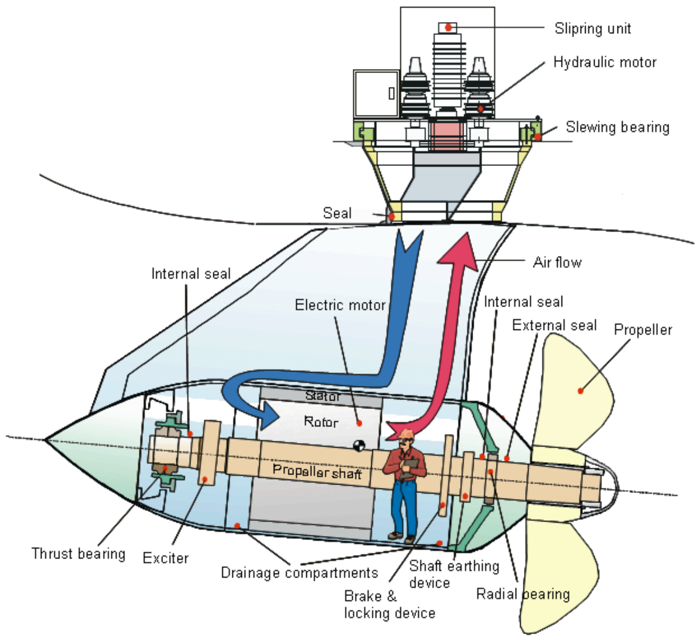


Figure 2-2 Cross section of a pod. The electric motor is placed in the pod. The slewing bearing makes the pod 360 degree rotational. The man shows the approximately size of the pod.

In pod propulsion the electric motor is placed inside the pod. In Figure 2-2 there is an illustration of a cross section of a Mermaid pod, this structure is used for the majority of pods constructed today. The rotor is placed on the same shaft as the propeller, there is therefore no need for gears. The shaft is held in place by a thrust bearing arrangement at the non drive end and a radial bearing arrangement at the drive end. SKF deliver both types of bearings to ABB and RR. The man in the figure shows the approximate size of a pod in the 20 MW power range. There are pods in the power range from 0.4 MW up to 30 MW, where pods between 0.4-5MW are referred to as smaller pods and the ones referred to as large pods in the range of 5-30 MW.

3 Electrical overview of pod propulsion

Electrical systems in pod propulsion usually consist of a power plant, switchboards, transformers, frequency converters and propulsion motors. Since the power plant and the switchboards are in the scope of this report the transformer, frequency converter and propulsion motor are from here on referred to as the electrical system. The transformer and converter are placed in the pod room in the ship and the motor in the pod. To transfer the electrical power from the converter to the freely rotating pod a slip ring is used. Figure 3-1 shows a single line diagram of a pod propulsion system. The system usually consists of sets of two pods each with exactly the same configuration independent of each other.

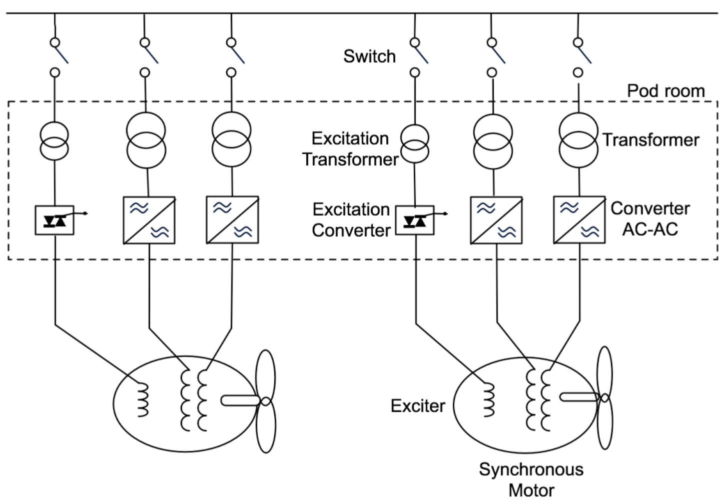


Figure 3-1 Single line diagram of a propulsion system with two sets of pods.

Originally, DC motors were the most practical alternative for propulsion. When power semiconductors became industrially available, the variable speed drives for AC motors became commercially competitive and today all electric propulsion systems are based on AC drive topology. DC machines have almost disappeared, certainly because of the complexity of their rotor. The upswing of electric motors in marine applications depends above all on the technology development in frequency converters which makes it easier to control the speed of the motors [34]. The technique in pod propulsion is often taken from an industrial application and adapted to marine propulsion.

3.1 Transformer

The transformer is used to divide the system into several parts in order to obtain different voltage levels but also for phase shifting. The transformer isolates the two sides electrically. In pod propulsion two types are most common, wet and dry type. ABB and RR use dry type. The output of a transformer, supplying a pod system, is adjusted to the input rectifier stage of the converter. Figure 3-2 shows a schematic illustration of transformers to be used for 6, 12, 18 and 24 pulses rectifiers.

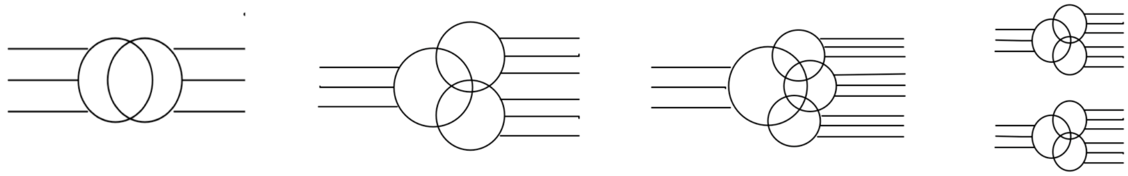


Figure 3-2 Schematic illustrations of transformers with 6, 12, 18 and 24 pulses.

3.2 Frequency converter

The purpose of the frequency converter is to control the speed and torque of the motor by changing constant frequency into variable frequency. The technical development of semiconductors has been important and made many different designs of converters possible. A converter has unwanted effects such as harmonic distortion that may disturb the system.

In pod propulsion there are three converters which are of current interest. These are illustrated in figure 3-3. The cyclo converter (Cyclo) and Load Commutated Inverter (LCI) are the most commonly used. They are direct descendants of DC drive technology and use the same thyristor, which only can be turned on [30]. ABB uses Cyclo and RR uses LCI.

Voltage Source Inverter (VSI) drives is the third converter type and differs from the two above by using controllable switches instead of thyristors. The VSI is a result of the technical development of power semiconductors. The power switches can be turned on and off, so the output voltage can be controlled by Pulse-Width-Modulation (PWM). The converter is therefore often referred as VSI-PWM. A wide range of controllable switches exists, ABB uses IGCT (integrated gate commutated thyristor) and RR uses IGBT (insulated gate bipolar transistor). The VSI converter is the most common frequency converter in industrial applications and will probably be the most common in marine application within a few years [34]. ABB uses VSI in their small pod Compact, and in some older small Azipods. RR uses it in some of their smaller Mermaid pods.

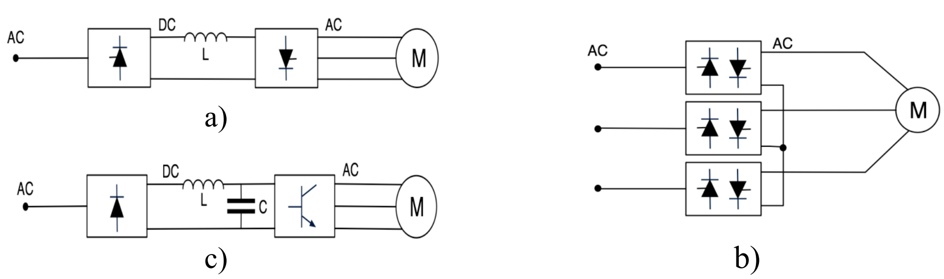


Figure 3-3 Simplified pictures of the three most commonly used converters in pod propulsion. a) An LCI converter used by RR b) Cyclo converter used by ABB c) VSI with new semiconductor technique, getting more common at both RR and ABB.

The LCI and VSI have a similar design. First there is a diode rectifier, then a DC link and finally an inverter that controls the frequency. The Cyclo converts the fixed frequency into variable frequency in one step. Table 3-1 shows the different converters, in which pod they are used, their advantages and disadvantages.

Table 3-1 Comparison of the different converters

	LCI	Cyclo	VSI – PWM
Pod (company)	Mermaid(RR)	Azipod(ABB)	Compact, Azipod(ABB), Mermaid(RR)
Advantage	Simple and reliable construction. Simplicity of the control system.	High torque at low speed.	Accurate, flexible and high performance.
Disadvantage	No high torque at low speed.	Complex construction.	Fast-switching semiconductor causes high frequency current flow and rapid voltage rise.

3.3 Electric motor

The electric motor is used for conversion from electrical to mechanical power. In pod propulsion three motors are used: synchronous-, permanent magnet- and induction motors.

The by far most common motor is the synchronous motor (SM), because of the high efficiency in high power range. The motor is called synchronous because the rotor runs at synchronous speed, meaning that the rotor is spins at the same rate as the oscillating field which drives it. The rotor in SM is supplied with current by an exciter which makes the construction complicated. The exciter is supplied from an excitation transformer and excitation converter. The exciter converter is a three phase converter with back to back thyristors which can regulate the power.

The permanent magnet synchronous motor (PMSM) has a magnet instead of windings in the rotor which gives no losses in the rotor and fewer components. The development of rare-earth magnets in just a few years has made PMSM available for high power applications. But still the magnets are a limitation in higher power applications.

The induction motor (IM) is the most common motor in industrial applications because of its robustness and simplicity in the construction. The motor is used in some pods with low power. Table 3-2 shows the different motors, in which pod it is used, their advantages and disadvantages.

Table 3-2 Comparison of the different electric motors used in pod propulsion

	Synchronous	Permanent	Induction
Pod (Company)	Mermaid(RR) Azipod(ABB)	Compact (ABB) SSP (SS)	Converteam SEP(Siemens)
Advantage	High efficiency at high power	No rotor losses Easy construction Compact design	Simple and robust construction
Disadvantage	Complicated construction	Not available at high power	Low efficiency at high power

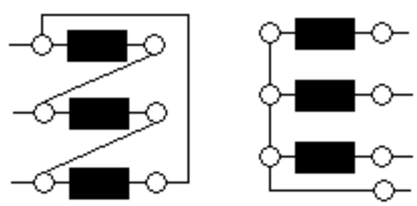
4 Transformer

The basic structure of a single phase transformer is two coils wrapped around an iron core. This means that they are galvanically isolated but magnetically connected. A 3-phase transformer has three legs, one for each phase. In a symmetrical three phase system the sum of the flux is zero, therefore a fourth leg is not needed. The windings in a transformer are normally connected in wye or delta connection. There are numerous different transformer designs, the most common used are air insulated dry type, resin insulated (cast or around) or oil/fluid insulated [34].

4.1 Wye and delta connection

In a wye connection the impedances is connected between a phase and zero and in delta connection the impedances are connected between the phases. When using a wye connection, the middle point can be connected to zero which is not possible for the delta case.

A delta connection can be seen in Figure 4-2 a) and wye connection with a zero point in Figure 4-2 b).



a) b)

Figure 4-2 Different connections for the windings in a transformer a) delta connection and b) wye connection where the middle point is connected to zero.

Generally are the primary side delta connected and the secondary side wye connected. This setup is the most common since there is no need for a ground connection on the primary side but on the secondary side a zero connection is often requested.

4.2 Non ideal transformer

Figure 4-1 shows an equivalent diagram of a non ideal transformer. The power losses in the windings are represented in R_1 and R_2. Flux leakage contributes to the induced voltage in the own coil without contributing to the mutual coupling. The leakage is represented with the inductances, jX_1 and jX_2. A core with finite permeability requires a magnetizing current, I_m, to maintain the mutual flux in the core. I_m is proportional to the induced voltage, while the flux is proportional to the voltage. The magnetic inductance can be modeled as a magnetizing reactance, jX_m. Iron losses are caused mostly by hysteresis and eddy current effects in the core and are proportional to the square of the core flux. The losses are represented by R_{Fe}. The secondary impedance R_2 and jX_2 is frequently moved to the primary side after multiplying the components by the impedance scaling factor $\left(\frac{N_1}{N_2}\right)^2$.

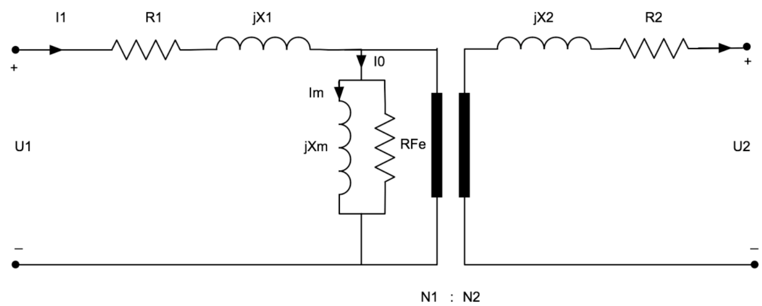
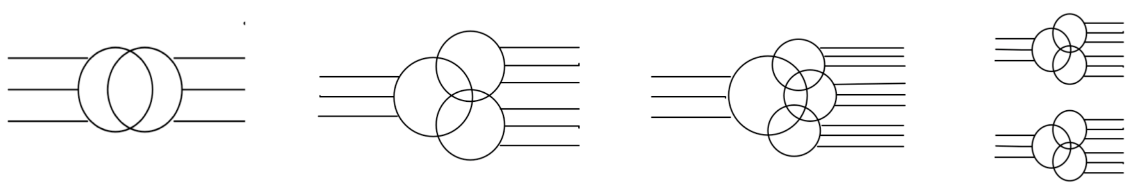


Figure 4-1 A not ideal transformer with resistive losses (R_1, R_2), flux leakage (jX_1, jX_2), magnetizing reactance (jX_m) and iron losses (R_{Fe}) indicated.

4.3 Adapted transformer

Harmonic distortion is an unwanted effect in electrical systems, as can be read more about in chapter 5. This can be reduced by increasing the number of pulses on the frequency converter, consequently the transformer must be adapted. A transformer adapted to 6 pulses is represented with two circles, as can be seen in Figure 4-3 a). A transformer adjusted to a 12 pulse converter has two 3 phase secondary windings and is mostly represented by three circles, which can be seen in Figure 4-3 b). A transformer adapted to 18- pulses has three small circles, as seen in Figure 4-3 c) and 24-pulses is a double 12 – pulses as seen in Figure 4-3 d).



a) b) c) d)

Figure 4-3 A transformer in a circuit diagram adapted to the number of pulses needed a) 6 pulses, b) 12 pulses, c) 18 pulses and d) 24 pulses.

5 Frequency converter

The frequency converters normally used in marine applications are Cyclo converters, voltage source inverters (VSI) and load commutated inverters (LCI). For switching devices in frequency converters diodes, thyristors and controllable switches are used. The technical development of power semiconductors has therefore been very important for the improvement of the frequency converter. This development has also improved the control of the frequency converter, where PWM (Pulse-width-modulation) is very common. Frequency converters contribute with negative effects on the rest of the electrical system known as harmonic distortion.

5.1 Power semiconductor device

The technical development of modern semiconductor devices have resulted in increased power capabilities, ease of control, and reduced cost. Power semiconductor devices operate on similar principles as the low-power counterpart but structural changes are made to accommodate the higher current density, higher power dissipation and higher reverse breakdown voltage.

Semiconductors can be divided into three categories according to their degree of controllability. The first one is diodes where the on and off states are controlled by the power circuit and no outer control is possible. The diodes´ most common main task is in the rectifier part of the converter. The second category is the thyristors which are turned on by a control signal and continue to conduct for as long as they are forward biased. Thyristors are used in LCI and Cyclo converters but also in more modern rectifiers. Controllable switches is the last group and they can be turned on and off by control signals. Controllable switches are used in VSI converter but also in more modern rectifiers. The circuit symbols for the power semiconductors used in frequency converters are shown in Figure 5-1.

Figure 5-1 Circuit symbols the diodes, thyristors and controllable switches.

The controllable switches group has enabled a number of new converter topologies. The controllable switches group includes several device types including GTO (gate turn off thyristor), IGBT (insulated gate bipolar transistor), and IGCT (integrated gate commutated thyristor). Table 5-1 shows the characteristics, the types and the applications of the different categories of power semiconductors. These devices dissipate power and too much dissipation can not only destroy them but also may damage other system components. Snubber circuits are used to modify the switching waveforms of controllable switches [27].

Table 5-1 Comparison of the different category of power semiconductors used in pod propulsion

	Diode	Thyristor	Controllable switches
Characteristics	On (not controllable)	On by signal	On and off by signal
Types	Diode	Thyristor	GTO IGBT(RR) IGCT(ABB)
Application	Rectifier	Rectifier LCI (RR) Cyclo (ABB)	Rectifier VSI (ABB, RR)

The IGCT is a special type of thyristor similar to a GTO but has lower conduction losses compared to GTOs. It can withstand higher rates of voltage rise, eliminating the need for a snubber circuit in most applications. The IGCT also manages much faster turn-off times than GTOs, which allows them to operate at higher frequencies, typically up to 500Hz [24]. IGCT is used by ABB in VSI-PWM.

The press pack IGBT is designed to carry larger currents by the connection of multiple IGBT chips and diode chips in parallel inside a package. A feature of the press pack IGBT is the low-power control, since it is a device of transistor type. This is a special advantage when operating at very high voltage levels, where the control circuit otherwise would have required higher power. A reduction of power needed results in a simpler control circuit and better efficiency of the complete system [15]. Press pack IGBT is used by RR in VSI-PWM.

5.2 Switching control

The motor is controlled by the output voltage from the converter, therefore the control of the converter is a vital part in the drive system. The purpose of the converter is to produce a plain sinusoidal output with variable amplitude and frequency which is more or less accomplished by using different types of control.

5.2.1 Control of cyclo converter

The control of the cyclo converter has two different modes of operation, sinusoidal and trapezoidal. The sinusoidal mode is used during the low speed range while the trapezoidal mode is employed in the upper speed range [30]. One drawback of the sinusoidal mode is the relatively high reactive power required which results in a correspondingly low power factor for the mains. The output voltage waveform is created by samples of the input voltages waveforms, an illustration of this can be seen in Figure 5-2 [28].

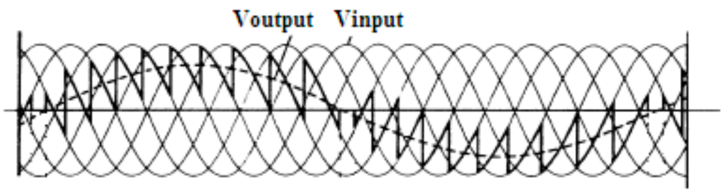


Figure 5-2 Output voltage from a cyclo converter constructed by samples from the input voltages waveforms.

5.2.2 Control of VSI

To control VSI converters, PWM is normally used. To create PWM controllable switches must be used. The desired waveform is created with a sinusoidal control signal at the desired frequency compared to a triangular waveform. When the value of the reference signal is higher than the modulation triangular waveform, the PWM signal is in the high state, otherwise it is in the low state as seen to the left in Figure 5-3. In three-phase PWM, the same triangular voltage waveform is compared with three sinusoidal waveforms that are 120^{o} out of phase as shown to the right in Figure 5-3 [27].

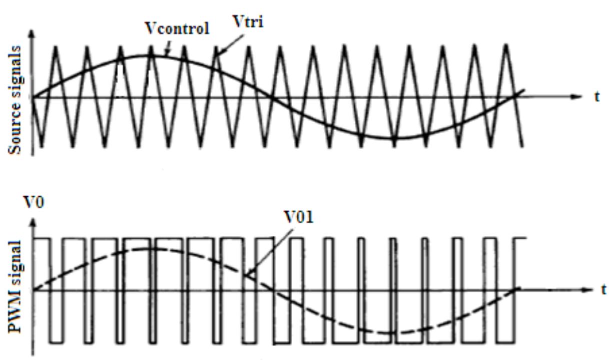


Figure 5-3 Basic principle of PWM in one-phase. A control signal is compared with sawtooth waveform. When the sawtooth is less than the control signal, the PWM signal is in high state. Otherwise it is in the low state.

The triangular waveform establishes the switching frequency. The control signal is used to modulate the switch duty ratio with the desired fundamental frequency of the converter output. The amplitude modulation ratio m_a is

$$m_a = \hat{V}_{control} / \hat{V}_{tri} \quad (5\text{-}1)$$

and the frequency modulation ratio m_f is

$$m_f = f_{tr} / f_{control} \ . \quad (5\text{-}2)$$

There are four cases in PWM to consider, low value of m_f, large value of m_f, overmodulation ($m_a > 1$) and linear modulation ($m_a <= 1$).

5.2.3 Control of LCI

To control a LCI converter square waves are used. The thyristors of the output bridge are fired in step with the rotation of the motor and act as an electronic commutator. This works by using the back emf (electromagnetic field) of the motor to also give natural load commutation of these thyristors. For speeds lower than 10% of the rated value the induced emf in the synchronous motor is not sufficient to provide current commutation in the output bridge. Under this condition the input bridge forces the current in the DC link to become zero and the previously conducting thyristors regain their blocking capability and the motor current can be transferred from one inverter leg to the other. The idealized motor current waveforms are shown in Figure 5-4 [5b].

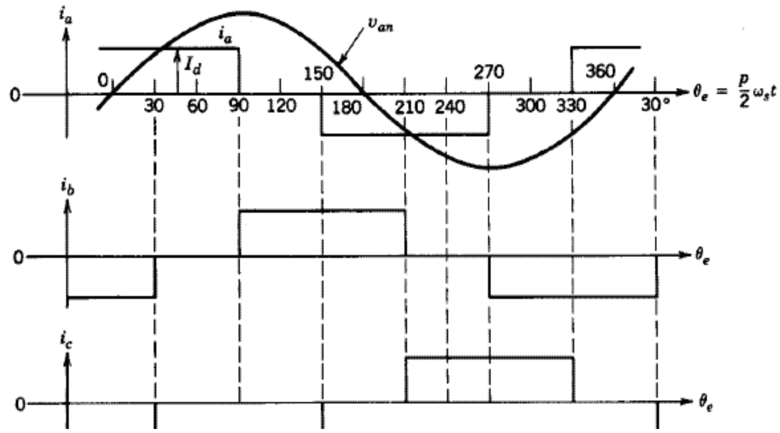


Figure 5-4 Idealized waveforms of motor currents from a LCI converter.

5.3 Harmonic distortion

Harmonic distortion, also referred to as power frequency effects, is the change in the waveform of the supply voltage from the ideal sinusoidal waveform. It occurs when a connected load in the network is nonlinear, i.e. does not draws sinusoidal currents. These load currents distort the sinusoidal voltages. AC variable frequency drives draw pulsed current from the supply. The power system has impedance which restricts the flow of current, this impedance is unavoidable and leads to a voltage drop between the supply substation and the connected load.

The supply frequency component is called the fundamental and the higher frequency components are multiples of the supply frequency and are called harmonics. The ratio of the harmonic frequency to the supply frequency is called harmonic order.

The harmonic currents causes increased power losses in the equipment connected to the network, which may lead to overheating of the insulation and reduced lifetime in the equipment. Especially the generators and power factor correction can be damaged. The distorted waveform may cause electromagnetic interference if the equipment is not designed for the actual distortion. These negative effects establish the importance of limiting the harmonic distortion [18].

One technique to reduce the harmonic effects is to increase the number of times current is drawn from the supply and therefore reduce the current drawn during each pulse. This affects the average current drawn and therefore reduces the harmonic delivered back to the supply. The basic converter has 6 pulses and with this method the converter has 12 pulses. The inverter utilizing 12-pulse control has two rectification units each with 6 rectifying devices as shown in Figure 5-5. The degree of harmonic cancellation increases with each addition of a 6-pulse rectifier. The disadvantage of this method is reduction of the efficiencies, primary due to the additional losses in the extra transformers. Even though 12-pulse is the most common solution there are converters with 18, 24, 36 and even 48 pulse design used [38e].

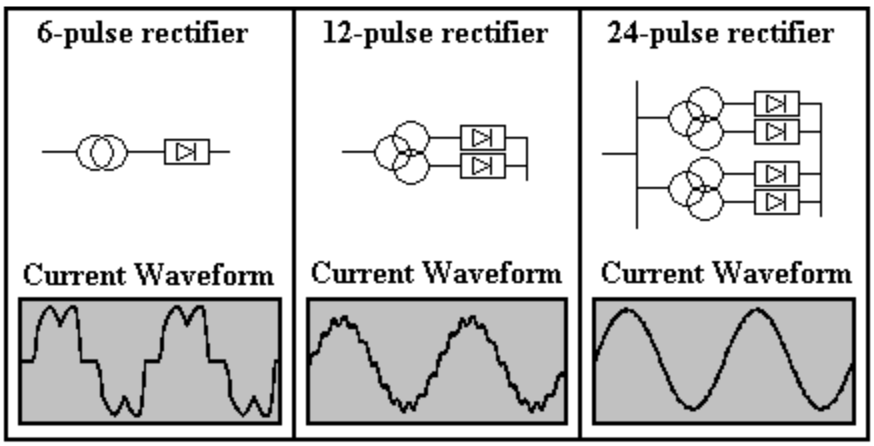


Figure 5-5 More pulses on the rectifier reduce the harmonic distortion. A 6-pulse rectifier draws not sinusoidal current from the supply voltage. A 12-pulse rectifier draws a little more cleanly sinusoidal current and a 24-pulse rectifier draws a even more cleaner sinusoidal

Another solution to reduce the distortion is to use passive and active filters. The active filter injects compensation current to compensate for the harmonic currents. Other methods are active front ends also known as sinusoidal rectifiers and lineators, which are designed for standard 6-pulse AC drives [14].

5.4 Load commutated inverter converter

LCI converters are used for synchronous motors, the corresponding converter for asynchronous motor is Current Source Inverter (CSI). LCI converters use thyristors as switching devices on both the input and output bridge. Figure 5-6 shows a simplified topology of a LCI converter.

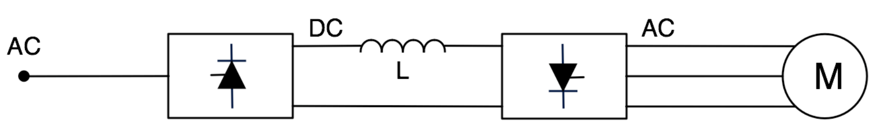


Figure 5-6 Simplified topology of a LCI converter. First is a rectifier, then a DC link to smoothen the current and finally an inverter that controls the frequency.

are fired using natural commutation, which means that they start to conduct once they have a forward current through them.

The thyristors of the input bridge controls the current to keep it at the required level in the DC-link. The thyristors of the output bridge are fired in step with the rotation of the motor and act as an electronic commutator. The rating of this converter is typically up to 30 MW per unit in marine applications. In an LCI the output frequency can exceed the AC supply frequency. To reduce the harmonic distortion a LCI can have different number of pulses, a 6-pulse configuration is shown in Figure 5-7 and a 12-pulse is illustrated in Figure 5-8. The DC-link between the input and output bridges consist of an inductor which opposes current changes and therefore smoothens the current.

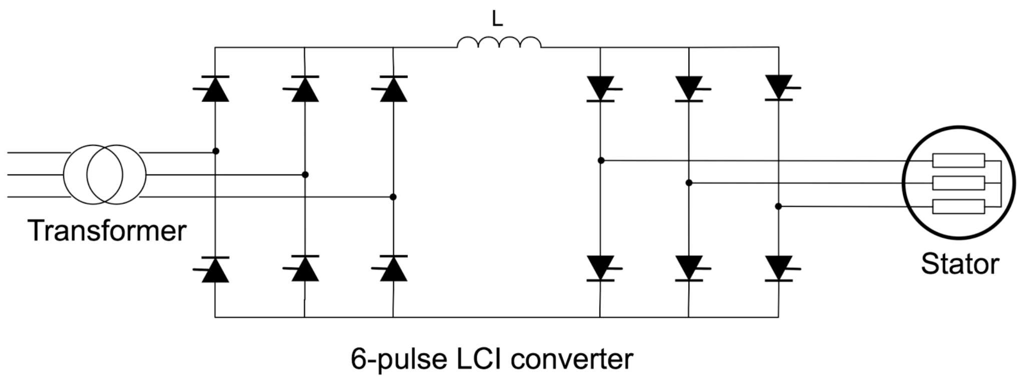


Figure 5-7 Topology of a 6-pulse LCI converter.

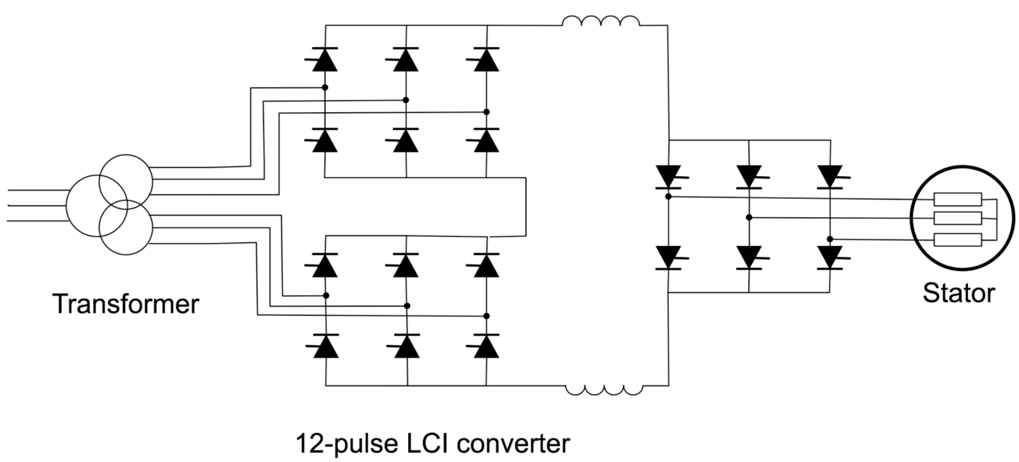


Figure 5-8 Topology of a 12-pulse LCI converter. 12-pulses are to reduce the harmonic distortion.

The LCI converters are capable of developing 100% full load torque over the entire speed range and develop considerably higher torques during the start. A main advantage is the simplicity of the control system. A further advantage is that it has a simple and reliable construction because of the fewer devices needed compared to the cyclo converter. The inductor in the DC link makes the dynamics slow.

5.5 Cyclo converter

The cyclo converter converts a fixed voltage and fixed frequency to a variable voltage and variable frequency in a single step without first rectifying the voltage. A simplified topology of a cyclo converter is illustrated in Figure 5-9.

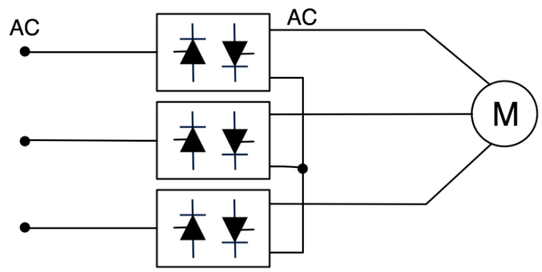


Figure 5-9 Simplified topology of a cyclo converter.

Cyclo converters can be used both for synchronous and asynchronous motors. ABB's cyclo is developed for synchronous motors while RR´s is able to operate with both [4],[6]. The power ratings are typically up to 30 MW per motor drive. The power semiconductors used for cyclo are thyristors. A detailed topology of a cyclo converter can be seen in Figure 5-10.

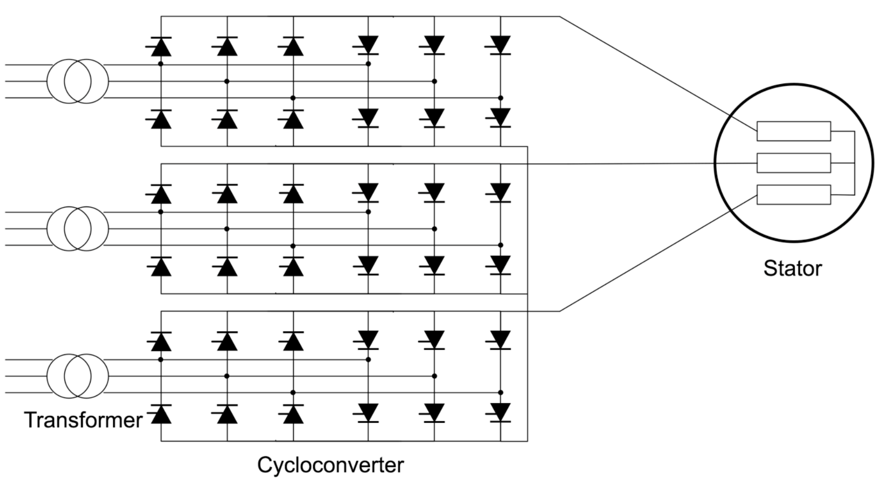


Figure 5-10 Topology of a 6-pulse cyclo converter.

The major advantage of the cyclo is that it can produce a high torque at a low speed with low torque pulsation and a good dynamic behavior. Other advantages are that the motor voltage contains a lower level of harmonics than the LCI and that it can operate down to zero speed.

One limitation is the low output frequency of about 25Hz, which is less than half of the output frequency of the VSI and LCI, this can be a drawback if high speed is required which is not the case in most pod applications. Another disadvantage is the complex AC supply effects, which mean that it does not draw a sinusoidal current from the network and will draw lagging reactive current.

5.6 Voltage source inverter

There are different topologies and control of VSI. The biggest advantage with VSI converter is that it can be controlled by PWM and therefore often referred to as VSI-PWM. The VSI has a DC voltage link which is supplied from the power system by a diode rectifier. The capacitors in the DC-link oppose changes in voltage and therefore smoothen out the voltage drawn from the supply. The power semiconductor devices used in the output bridge can either be IGBTs (RR) or IGCTs (ABB). Figure 5-11 illustrates a simplified topology of a VSI converter.

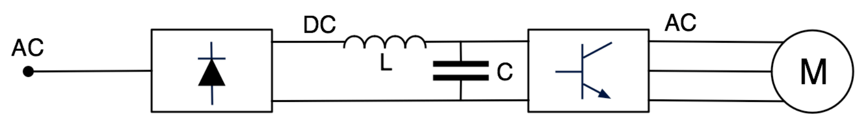


Figure 5-11 Simplified topology of VSI. The inverter starts with a diode rectifier and than a DC-link to smoothen the voltage. Finally a inverter to produce a controlled AC.

The VSI can have a 6, 12, 18 or 24 pulses rectifier. The main advantage of using a 12-pulse instead of a 6-pulse is the reduction of harmonics, where the 5^{th} and 7^{th} harmonics are completely cancelled out. A topology of a 6-pulse VSI converter is shown in Figure 5-12 and a topology of a 12-pulse rectifier can be seen in Figure 5-13.

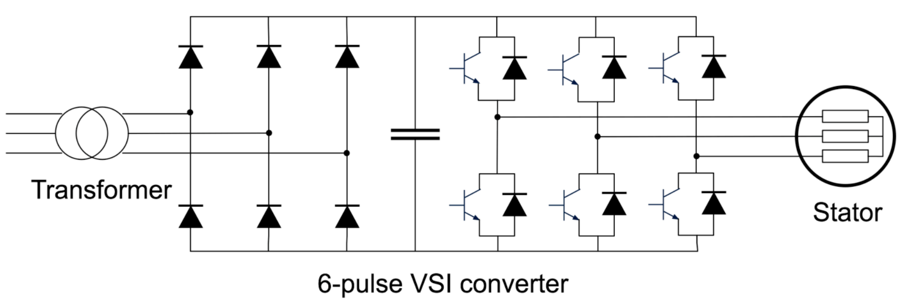


Figure 5-12 Topology of a 6-pulse VSI converter.

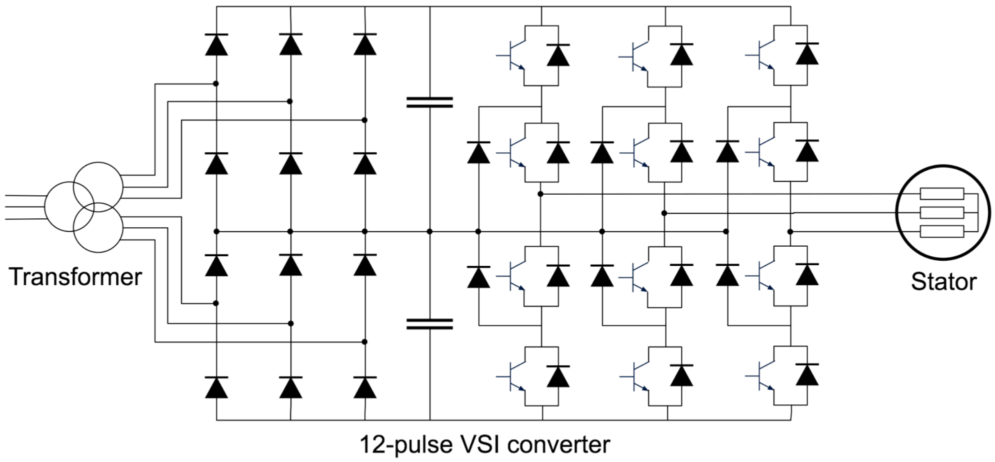


Figure 5.13 Topology of a 12-pulse VSI converter. 12-pulses are to reduce to harmonic distortion.

Since a minimum of current is drawn, the amount of line harmonics is lower than that of the LCI or Cyclo converter, and is proportional to motor speed. Further advantages of VSI are: good power factor throughout speed range, and low distortion of motor current, and it also has a fast transient response.

The high switching frequency in the VSI-PWM can cause bearing currents which cause damage in the bearing. This is handled in chapter 5.

5.7 Comparison of the different converters

VSI and LCI have the same design i.e. a rectifier, a DC-link and an inverter which generates the variable frequency and voltage for the motor. The cyclo has a slightly different design with a direct converter with no DC link. The cyclo has the most complicated construction while VSI and LCI have simpler construction.

A major difference between the three converters is their switching frequency, where the VSI has the highest output frequency at about 300Hz. The LCI have a maximum output frequency of approximately 120Hz while the cyclo only is able to give out 40% of the input frequency, 25Hz at 60Hz input.

All the converters are today available at higher power levels than required for pod propulsion.

6 Electric motor

The electric motor is an important part of the electric propulsion system. The brushless excitation synchronous motor (BLSM) is the most common in pod applications but induction motor (IM) and permanent magnet synchronous motors (PMSM) are becoming more common. In this chapter these three motors will be treated and if not specifically stated, they are all designed for a three-phase power supply.

6.1 Characteristics for motors in marine applications

Important characteristics for motors used in pods are high torque density, good power factor, low mass and volume and high reliability. The motor should work at low speed with high torque and high performance. The torque is calculated

$$T = \frac{P}{\omega}. \tag{6-1}$$

To achieve good reliability double windings are used in the stator. These windings each have their separate converter to make sure that the motor can keep on going, with less power, even if one system breaks down.

6.2 Brushless excitation synchronous motor

Synchronous motors are mainly used in high power applications [20]. In synchronous motors the rotor is supplied with DC from an external source, the exciter. There are two types of exciters, brushless and brushed. In pod propulsion brushless is used.

When using brushless excitation, a generator is mounted on the same shaft as the rotor and generates AC converted to a DC via a rotating diode rectifier. The rectifier is connected to the rotor in the synchronous motor via cables attached to the shaft. The total arrangement with a brushless exciter together with a synchronous motor can be seen in Figure 6-1. The exciter can be mounted on any side of the rotor [17]. In Azipods it is mounted in the drive end and in Mermaids it is mounted in the non drive end of the pod.

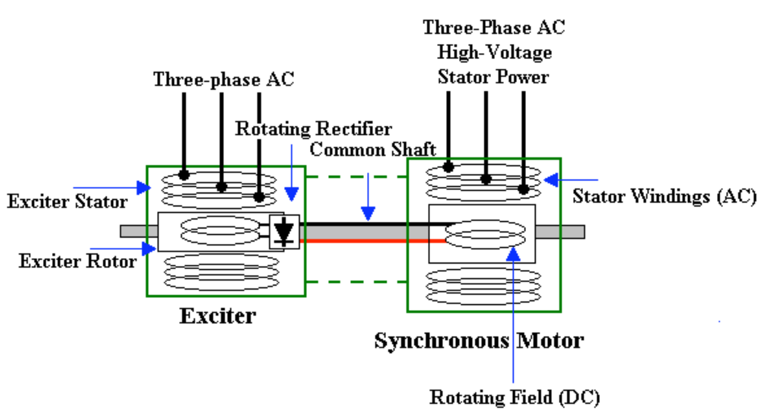


Figure 6-1 Brushless exciter mounted in the same shaft as the synchronous motor. The rotor in the synchronous motor consists of windings that are supplied with DC from the exciter.

In an exciter of brushed type the current is transferred from the exciter to the rotor via slip-ring brushes. The big disadvantage with this system is that the brushes require maintenance.

Synchronous motors run at synchronous speed which means that the rotor rotates in synchronism with the rotating magnetic field. The synchronous speed is calculated as

$$N_s = \frac{120 \cdot f}{p}, \tag{6-2}$$

where f is the supply frequency and p the number of poles per phase winding. The speed of the rotor is consequently proportional to the supply frequency. The rotor has the same number of poles as the stator. A per-phase equivalent circuit for a synchronous motor is shown in Figure 6-2. The stator windings are inductive and resistive which is represented by X_s and R_a respectively. The rotating field produced by the DC current in the rotor induces a voltage in the stator windings, a so called back-emf, E_a [20].

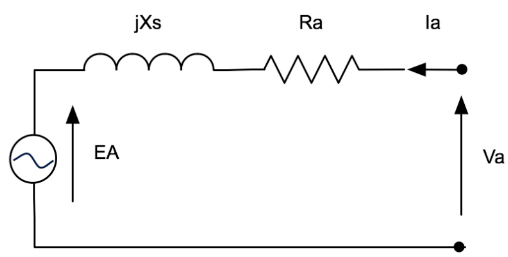


Figure 6-2 Equivalent circuit for a synchronous motor.

BLSM can produce high torque at low speed and it operates at an improved power factor. The cost of producing the synchronous motor is high because of the need for a wound rotor and an exciter.

6.3 Permanent magnet synchronous motor

The basic principle of a PMSM is that the windings in the rotor have been replaced with permanent magnets, an illustration of this can be seen in Figure 6-3. The rotor in this case has two poles but this can be adjusted according to the speed required.

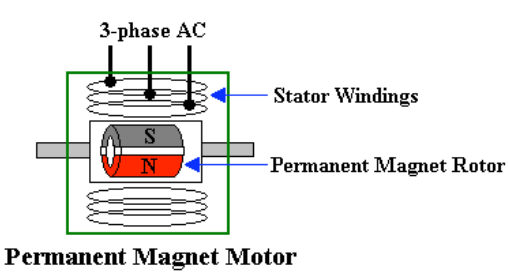


Figure 6-3 Basic illustration of a permanent magnet motor. The windings have been replaced with permanent magnets and therefore there is no need for exciter.

The PMSM motor is a synchronous motor and its stator works in the same way as the BLSM described above. This is why it can be represented with the same equivalent circuit as the BLSM in Figure 6-2. The difference is the back-emf which is in this case not controllable via the rotor since the flux from the magnets is constant.

PMSM normally have output ratings from about 100W to 100 kW and are not very common for high power applications, but in some pod applications there are permanent magnet motors for up to 11MW. Today the development is mainly in rare-earth magnets material, but these are still quite expensive [8].

The biggest advantage with the PMSM is the simple construction of the rotor since there is no need for windings and therefore no exciter, this gives a lower manufacturing cost and reduced size compared to the synchronous motor. Since there are no currents in the rotor there are no losses and no heat is generated. One drawback is the risk of demagnetization under high operating temperature [12].

6.4 Induction motor

IM is the most common motor used in industrial applications in low and medium power ranges because of its robustness and low manufacturing cost. It is not common in high power applications, since the synchronous motor has better efficiency for higher power. The IM can also be referred to as asynchronous motor.

The rotor currents in the IM are induced in the rotor which means that there is no need for outer connections to the rotor and consequently no need for an exciter. A basic illustration of an IM is shown in Figure 6-4, where the rotor is of cage type which is the most common of rotor types. The motor rotates slightly slower than synchronous speed since a slip is required for currents to be induced and thereby torque to be developed.

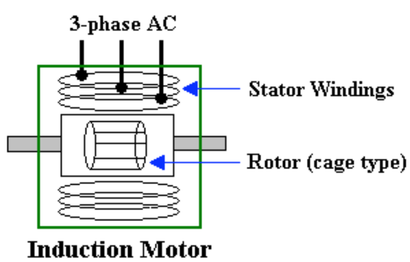


Figure 6-4 Basic illustration of an induction motor, where the rotor is of cage type.

A per-phase equivalent circuit of an IM with a stationary rotor is shown in Figure 6-5. The resistance in the windings in stator and rotor is represented with R_s respectively R_r. The leakage reactance X_{ls} is a consequence of that a part of the flux generated from the current in the stator windings will just go around the winding itself. For the same reason there is a leakage reactance X_{lr} present in the rotor. The magnetic field gives losses in the iron core, which is represented with the resistance R_c. A current is required to create a flux between the stator and the rotor, this is represented with a magnetizing reactance X_m.

E is not as in the synchronous motor the back-emf, it is phase to ground voltage in one stator phase.

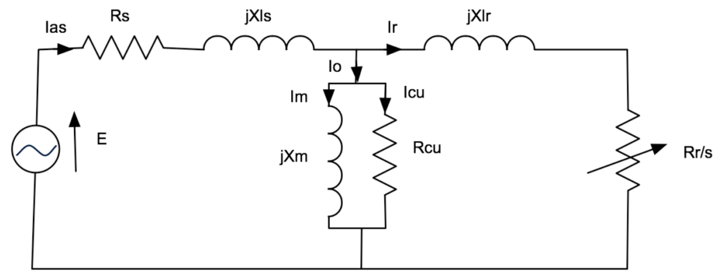


Figure 6-5 Equivalent circuit of induction motor. The rotor parameters have been referred to stator side.

An equivalent circuit of an IM with stationary rotor and the equivalent circuit of a transformer are very similar. The biggest difference is the value of the parameters. The induction machine has larger leakage reactance and smaller magnetizing reactance than the transformer.

Standard induction motors are normally not well suited for low-speed operations as their efficiency drops with the reduction in speed. They may also be unable to deliver sufficiently smooth torque across the lower speed range. This can be solved by a gearbox in the industry, but this is not very appropriate in the pod.

The major advantage of the IM is that it is robust and cheap to produce. Since there is no need for windings or exciter it can be more compact than the synchronous motor, which is an advantage in pod propulsion. The use of IM will increase in high power applications because of better frequency converters to control them [46o].

6.5 Comparison of the different motors

The BLSM has the big disadvantage that it needs electrical supply to the windings in the rotor which means more electric equipment but also losses in the rotor. The IM needs no electric supply to the rotor which makes it more robust and stabile compared to the BLSM but still bears rotor losses. The use of SM in large power ratings results in a few percentage points higher efficiency than what can be accomplished using the IM [27]. The higher efficiency and the simplicity to control the speed make the SM the most common choice in pods.

The PMSM is a motor which combines the high-quality performance of the SM with the robust design of the IM. The PMSM has a robust and reliable design and no rotor losses and also good power factor and high power density. If power range and the risk of demagnetization are not considered, PMSM would be the best choice.

7 Current in bearings

Current that travel from the shaft through the bearings is a phenomenon in many applications with electric motors. The current can cause damage in only a few months and the bearing must be replaced. There are two categories of causes of bearing currents treated in this chapter. The first is a classical problem where low frequency current, caused by asymmetry in the motor construction and asymmetrical and non-shielded cabling, travel through the bearings. The second category is high frequency current problems that occur when using PWM control which have high switching frequency and steep voltage surges. When trying to mitigate currents in bearings the two most common solutions are grounding and insulation.

7.1 Bearings in pods and their electrical representation

In a pod there is a bearing arrangement in the drive end which take care of the radial loads and one the in non drive end which take care of the axial loads. The bearing positions are shown in Figure 7-1.

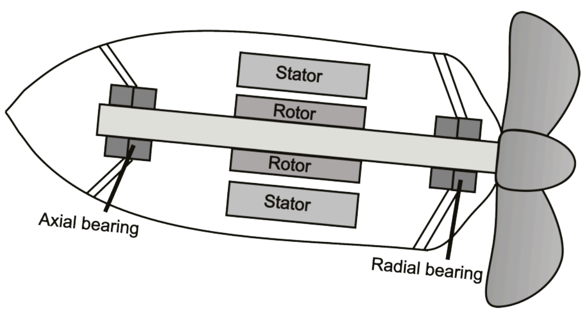


Figure 7-1 A pod with a thrust bearing arrangement in non drive end taking care of axial loads. The radial bearing arrangement carrying the radial loads is placed in drive end.

Pod bearings are usually lubricated with oil. Figure 7-2 shows the mechanical parts of the bearing for one rolling element. The inner and outer ring and the rolling element is maid of conductive material. The lubricant acts as a dielectric layer between the conductive parts, which gives the bearing its capacitive characteristics.

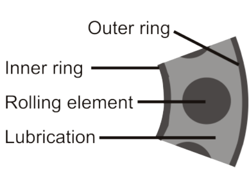


Figure 7-2 A cross section of a part of a bearing.

There are three states of electrical conductivity in a bearing; metallic conductive state, resistive state and capacitive state.

The metallic conductive state occurs when the bearing is still or rotates with a very low speed and there is no oil separating the conductive parts. This gives a purely resistive behavior of the bearing, resulting in that the bearing can be represented with a low resistance.

The resistive state occurs whit some higher speed than in the conductive state, then there is a thin oil film developed between the conductive parts. There are still some contacts between the conductive parts due to that the surface roughness is big compared to the thickness of the oil film. In this state the bearing can be represented with a linear and in some cases a non-linear resistance.

The third state is the capacitive state which occurs at high rotational speed. Now an oil film is built up between the conductive parts so that they are completely separated. In this state the bearing is represented with a capacitor. So as long as the threshold voltage is not reached the oil will have an insulating function. If the threshold voltage is reached an electrical discharge in form of a spark occurs.

When combining these three states the simplified circuit diagram in Figure 7-3 is used for the electrical representation of a bearing. R_b is a function the voltage and the current and C_b stands for the capacitance of the oil. Which one of the components that is dominating, depends on in which state the bearing is.

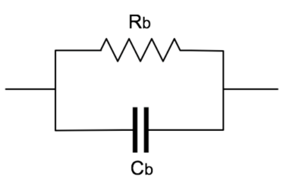


Figure 7-3 Electrical representation of a bearing.

When the electrical field strength in a finite region in one bearing reaches a threshold an EDM (Electrical Discharge Machining) current will flow through the bearing. The EDM current damages very small pieces in the metal, which can lead to that more EDM current might flow through the damage area.

Currents caused by dv/dt can pass through the capacitive coupling in the bearing, this current is calculated as

$$i = C\frac{dv}{dt}. \tag{7-1}$$

The dv/dt currents can contribute with voltage rice over the bearing which can lead to that it exceeds the threshold voltage and EDM current flow. It is not yet well known how the dv/dt currents influence the bearing.

7.2 Low frequency current in bearings

Low frequency current in bearings is an old phenomenon, which has existed in electric motors for all time. The two sources of this current are asymmetry in motor construction and asymmetrical or non-shielded cables. The two causes and how they result in bearing current are described below. There are also descriptions of how to mitigate these problems.

7.2.1 Asymmetry in motor construction

Asymmetry in motor construction depends on the difficulty to make a motor with perfect electromagnetic symmetry. The asymmetry can arise if the rotor is not centered in the stator, if the stator laminations contain any dissymmetry or if the windings or slots of the stator are not symmetrical.

The motor asymmetry causes magnetic flux asymmetry, this means that the flux produced in the stator is not evenly distributed. In other words the stator will generate a circulating flux of alternating magnitude. These flux changes will induce an axial shaft voltage, which results in a low frequency current. The frequency of this current is the same as the supply frequency or a multiple of it [23]. The current, which is induced in the rotor, tries to seek a path to go round the stator and back to the rotor. A possible path is shown in Figure 7-4, where the current goes through the both bearings.

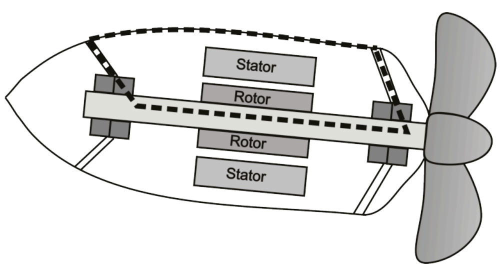


Figure 7-4 A possible path for the induced current to travel is from the rotor, through a bearing round the stator and back to the rotor through the other bearing.

Modern motor design and manufacturing practices have reduced bearing failures from this type of low frequency current. The best solution to mitigate this problem is to insulate the bearing in the non-drive end or both of the bearings. The reason for not only insulating the drive end is that the current might find a path through the propeller (driven machinery) and then through the bearing in the non drive end and therefore have a closed path. If the bearing is insulated in the non drive end the current can not find another path in this end and can therefore not have a closed loop round the stator. The two cases are illustrated in Figure 7-5 a) and b) respectively.

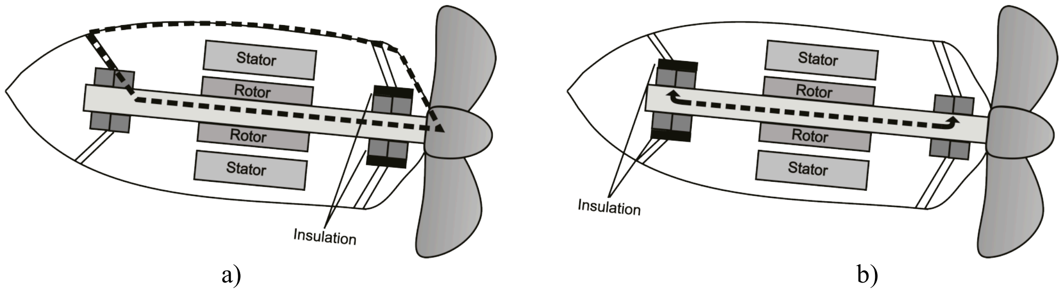


Figure 7-5a Illustration of a new path the current can take if only the bearing in the drive end is insulated.
Figure 7-5b The current can not establish a closed loop if the bearing in the non drive end is insulated.

7.2.2 Asymmetrical or non shielded cables

Currents in bearing can also be caused by asymmetrical or non-shielded cables. If the cable is asymmetric, a voltage is induced in the PE-lead (Protective Earth), which can generate a PE current. Figure 7-6 shows three types of cables where the two to the left are symmetric and shielded and the one to the right is shielded but not symmetrical. The PE-leads can either be distributed evenly in the cable or mounted with the shield round the cables in a symmetrical cable.

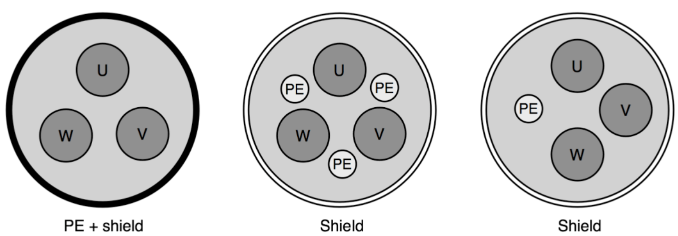


Figure 7-6 Three types of cables with PE, the two to the left are symmetrical but the one to the right will have problems with voltage induced in the PE-lead.

When current in the three-phase leads alternate, a voltage is induced in the PE-lead and this generates a PE current. There is therefore a risk for current flow from the point where the PE-lead is connected through a bearing to ground.

Using proper cabling with shield and a symmetrical arrangement can minimize this problem. It is not possible to have symmetrical cables in a pod because of the high power required and therefore the thick cables used. If insulation is used as a solution for this problem both bearings should be insulated since the current need just one path to ground and do not have to circulate.

It should be mentioned that this is a phenomenon that not all engineers agree up on. Some claim that cabling is not a problem when dealing with low frequency currents [45o].

7.3 High frequency current in bearings

The source of high frequency current in bearings is the fast switching converters, which produces common mode voltage. Common mode voltage occurs when the sum of the three phases is not zero in every instant. One other aspect is the fast switching devices used in today's converters with steep edged voltage pulses. The origin of common mode voltages and steep edged voltage pulses are explained below and after that it is clarified how these disturbances cause bearing currents.

7.3.1 Common mode voltage

If a three-phase voltage waveform is balanced and symmetrical it result in a vector sum of the three phases always equal to zero. Figure 7-7 shows a perfect symmetrical three phase sine wave, where the sum of the three phases is zero in every instant. If the sum is not zero, the neutral point is not zero and a common mode voltage is created.

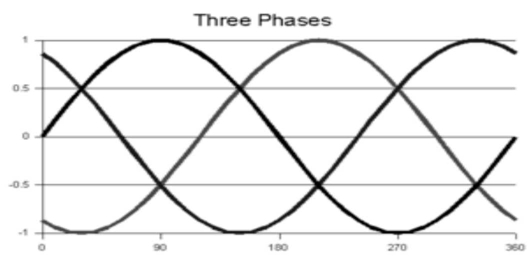


Figure 7-7 A symmetrical sine wave, where the sum of the three phases is instantaneously equal to zero.

Since no converters produce a pure sinusoidal output, common mode voltage is present in every system controlled by a converter. When considering how common mode disturbances affect the rest of the system, PWM switched converters are the ones treated. Other converters also produce a common mode voltage but these are never discussed in the literature and therefore conclusion that they produce much lower common mode voltage is drawn.

Because of the fast switching frequency, the PWM switched inverter can not produce three output voltages with the sum instantaneously equal to zero. Therefore PWM inverters have a common mode voltage. Three phases with PWM control are shown in Figure 7-8, which also illustrates the sum of the phases, the so-called common mode voltage.

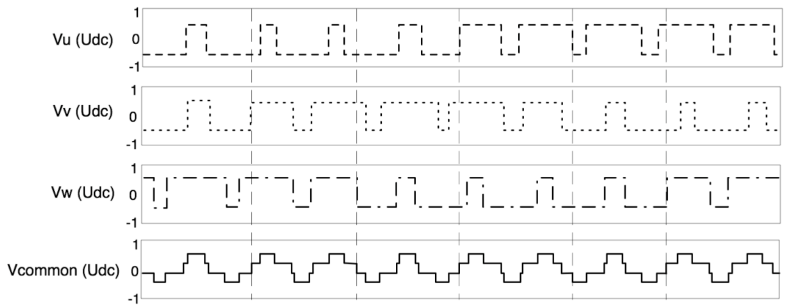


Figure 7-8 At the top three phases with PWM control are illustrated and at the bottom the sum of the phase voltages is drawn, as can be seen it is not equal to zero which gives common mode voltage.

7.3.2 Steep edged voltage pulses

When using PWM control on converters with newer semiconductors the pulses have very fast rise and fall times. These fast voltage switches, referred to as steep edged voltage pulses, create high frequency current transients. Figure 7-9 shows two pulses where the one to the left has a much lower rise time than the one to the right.

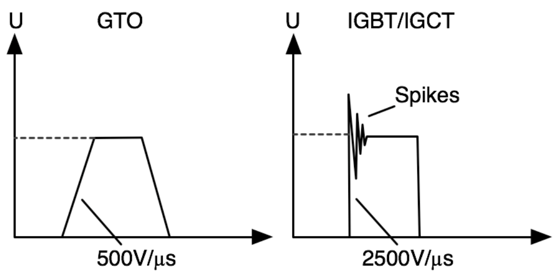


Figure 7-9 The voltage switching with the newer device (right), IGBT and IGCT is much faster than the switching with the old devices (left).

The common mode voltage together with the steep edged voltage pulses becomes a common mode voltage with very high frequency disturbances. An illustration of this is shown in Figure 7-10.

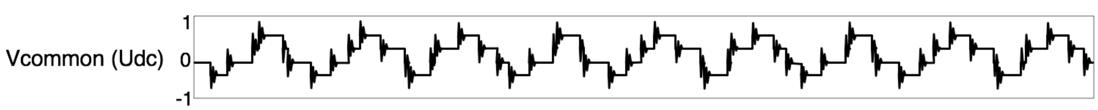


Figure 7-10 Common mode voltage combined with steep edged voltage pulses.

There are many ways of damping the source of the high frequency current. Different types of filters and common mode impedances are used for the converter to lower the common mode disturbances.

7.3.3 Bearing current caused by common mode disturbances

The common mode voltage disturbances can cause bearing current, in the large motors used in pods, in two ways:

- High frequency shaft grounding currents
- High frequency circulating currents

7.3.3.1 High frequency shaft grounding currents

The high frequency shaft grounding current is a similar problem to the poor cabling case described in Chapter 7.2.2. Here the PE voltage is caused by the common mode disturbances. If the impedance back via the PE lead to ground in the converter is too high the current will travel towards the motor and seek its way to ground. These currents arise in the grounding cable and travel from the motor frame to ground, via the path with the lowest impedance, this can in some cases be through the bearings.

As this problem is similar to the poor cabling described in Chapter 7.2.2 a way to mitigate it is to use asymmetric and shielded cables. But even if the cables are symmetrical the common mode disturbances will cause a current in the PE-leads so it is important to ground them in a correct way. The solution must be analyzed so that the placing of the grounding point will not lead to a current through the bearings to ground. If insulation is used both bearings should be insulated.

7.3.3.2 High frequency circulating currents

High frequency circulating currents is according to Jagenbrein (2005) still a problem, which needs to be investigated further. The capacitive couplings between the stator windings and the rest of the motor can explain the origin of these currents.

The relevance of considering the capacitive couplings between stator windings, rotor and frame increases with rising frequency. The capacitors illustrated in Figure 7-11 are not real capacitors but inherent stray capacitances. C_{SR} and C_{SG} are the stray capacitances for the stator to rotor coupling and the stator to ground coupling, respectively. The three stray capacitances between the shaft and ground are C_{RG}, the rotor to ground capacitance and C_{B1} and C_{B2}, the bearing capacitances, due to the lubricant within the rolling contacts (Jagenbrein, 2005).

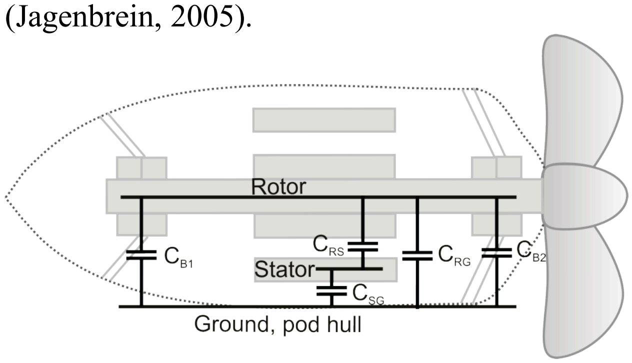


Figure 7-11 Equivalent circuit of the capacitive couplings in a motor, the capacitances are stray capacitances.

An illustration of the stray capacitances, with bearings and shaft represented with electrical components is shown in Figure 7-12. The ground is as earlier defined as the pod hull, which both bearings are connected to. The three broken lines with capacitors represent the stray capacitances between stator - rotor, stator - ground and rotor - ground.

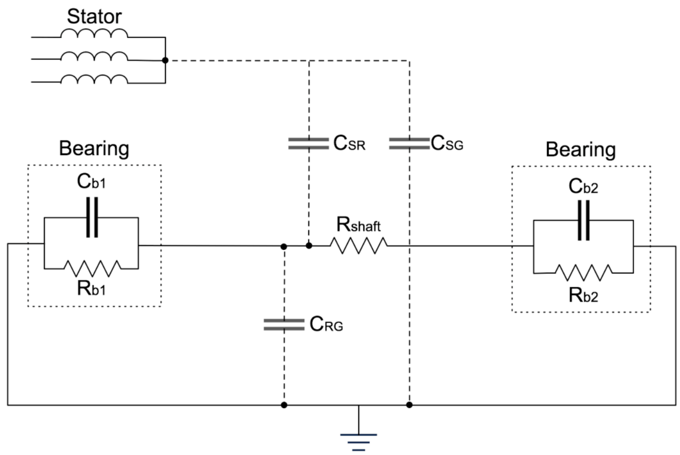


Figure 7-12 Equivalent circuit of shaft with bearings and stray capacitances between stator-rotor, stator-ground and rotor-ground, the ground is the pod hull.

The capacitive couplings provide paths for high frequency currents generated in the stator to travel to the rotor and frame. When current leaks trough the stator-to-frame stray capacitor there will be more current in one end and less in the next. The consequence of this is that a high frequency magnetic flux is generated and surrounds the rotor, producing a high frequency shaft end-to-end voltage. Where there is an induced voltage an equalizing current want to flow, in this case called high frequency circulating current [22]. A path the current can take is illustrated in Figure 7-13.

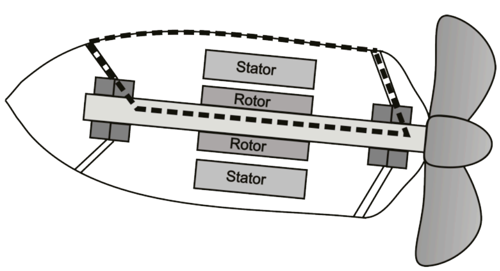


Figure 7-13 Motor with circulating high frequency current, same path as the low frequency currents.

As with the problem with low frequency circulating current a way to protect the bearings is to insulate the non-drive end bearing. The problem here is that there are very high frequencies, which might cause damage to the bearing even if insulation is used. It is important to have an insulation representing an as high impedance as required to protect the bearing.

7.4 Grounding and insulation solutions

As have been discussed in the previous chapters there are different ways of trying to mitigate the damage of the bearing currents. The most commonly used in pods are to ground the shaft and insulate the bearing.

7.4.1 Ground

Grounding of the shaft is used for most propeller shafts. In pod propulsion the hull is referred to as ground. By grounding the shaft, a path is established between the shafts and a grounding point, this path should have low impedance so that the current rather travel this way than through the bearings. Figure 7-14 shows two grounding rings mounted on the shaft. The right is connected to ground (hull) while the left is connected to the bearing housing inside the insulation. The connection to the bearing housing is a way of trying to eliminate voltage differences between the inner and outer ring of the bearing.

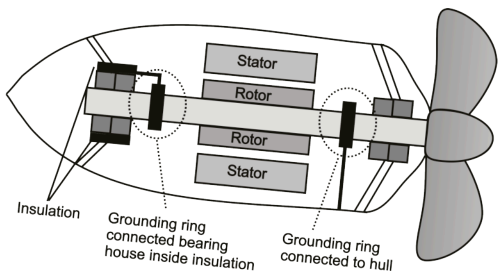


Figure 7-14 Placing of the grounding devices and the connection points in the pod.

The most common way to ground the shaft is to mount a ring on the shaft with two brushes transferring currents to ground. The ring is made of copper and has a silver track on it, which the brushes slide upon, this is illustrated in Figure 7-15. One other way of grounding the shaft is to mount brushes, which slide directly against the shaft.

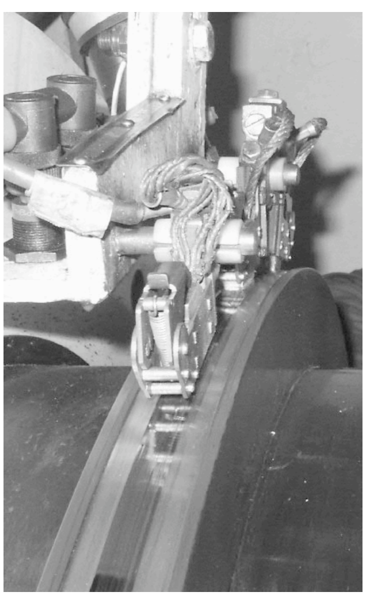


Figure 7-15 Grounding ring with a silver track and two brushes.

The brushes can be made of different materials such as copper-graphite, silver-graphite and silver-gold. The most commonly used brushes are copper- and silver-graphite since the silver-gold brush is much more expensive. An advantage of the copper-graphite brush is that its material is harder than silver-graphite and will therefore not be worn down as fast as the silver-graphite. This can also be seen as a disadvantage since the silver-graphite brush will form more easily and therefore have a better contact area.

RR uses the solution with a ring mounted on the shaft and two silver-graphite brushes sliding against it [42o]. ABB have used the same solution but with copper-graphite brushes. They did not find that this solution gave a satisfactory result so they changed to the solution with brushes sliding directly against the shaft [46o].

Table 7-1 Grounding solutions for RR and ABB

	Grounding contact on shaft	Type of brushes
RR	Copper ring with silver track	Silver-graphite
ABB before	Copper ring with silver track	Copper-graphite
ABB now	Directly on shaft	Copper-graphite

Cleaning of the brushes is a vital part for correct functioning. According to Higgins (2002) should the silver-graphite brushes be cleaned every week while the cleaning interval for the copper-graphite brushes should be every 24^{th} hour. RR state in their instruction manual that the brushes should be cleaned every week, this is in line with the recommendations from Higgins (2002). How often they are cleaned in reality is not known and varies from the different ships. The recommendation from ABB is that the brushes should be cleaned with a certain interval but not every 24^{th} hour.

The result of a test performed at Eskom’s Tutuka power station showed that the use of copper-graphite and silver-graphite brushes resulted in a non satisfactory result with bearing currents as a consequence. They recommended silver-gold brushes, which performed very well [19].

According to the company Carbex, who produces shaft grounding solutions and Costello (1993) are all graphite brushes sensitive to oily environment. An oil film is developed between the brushes and the shaft and this will result in behavior identical to that of a bearing. Since the brushes are made of graphite the material is a bit porous and oil can penetrate the brushes and reduce their functionality.

Grounding in the wrong place can be even worse than not grounding at all. For example if you insulate the non drive end bearing and put a grounding devices on the same side circulating currents will be able to flow trough the ground connection and back through the bearing in the drive end. This is illustrated in Figure 7-16.

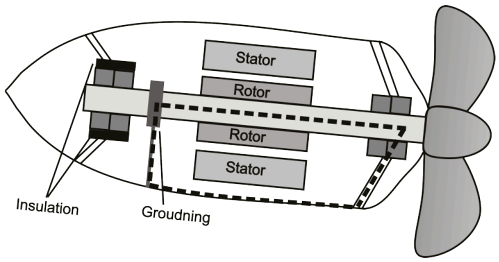


Figure 7-16 Grounding ring placed in wrong place provides a closed path round the stator.

Most grounding devices are built for low frequencies, which have to be considered when facing high frequency currents in the shaft. One other thing to have in mind is that the grounding devices will function as a capacitor if a layer of oil and dirt is present between the brush and the surface it slides against.

7.4.2 Insulation

A way to prevent current from passing through the bearings is to insulate the bearings so that no current will go through the bearing to the hull. Fiberglass epoxy and aluminum oxide are two types of insulation materials.

When adding insulation to a motor bearing the problem tends to appear elsewhere as the current searches for another way to ground. According to Oh (2007) high frequency currents can pass through the insulation and cause bearing failure.

The original solution in ABB's Azipod has a fiberglass epoxy insulation of the thrust bearings in the non-drive end (NDE) but no insulation of the bearing in the drive end (DE) [44o]. They are now changing their converter type and with this modification they install insulation in the drive end and keep the insulation in the non-drive end [47o].

RR's Mermaid has insulation of fiberglass epoxy in both the drive end and the non-drive end of the pods in their original concept. In some of their pods the insulation in the drive end has been removed and lager bearings have been mounted instead [40o].

Table 7-2 Insulation solutions for RR and ABB

	Fiberglass epoxy	Placing
RR	Yes	DE and NDE
ABB	Yes	NDE

The insulation will to some extent protect the bearings from alternating current but high frequencies might still cause damage to the bearings. When insulating the bearings either both ends or just the non drive end should be insulated. If only the drive end is insulated circulating currents can pass trough in the front of the pod, by the propeller and back through the bearing in the non-drive end.

7.5 Calculations of capacitances

As described earlier a capacitor consists of two conductive parts with a dielectric layer between. The capacitance of a capacitor can be calculated as

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{7-2}$$

where A is the contact area of the conductive parts, d is the width of the insulation, ε_0 and ε_r are the dielectric constant for vacuum and for the insulation material respectively.

Impedance is the electrical resistance for AC. If just considering how the capacitance and frequency affect the impedance it is calculated as

$$Z = \frac{1}{j\omega C} \tag{7-3}$$

where j shows that it is an imaginary number, ω is the angular frequency and C is the capacitance. This gives that a lower value on the capacitance result in higher impedance. So the lower the capacitance the higher frequency is possible for the same impedance.

As mentioned earlier there are a number of stray capacitances present in the system. The insulation of the bearings results in a capacitance and also the bearing itself with the oil layer acting as a dielectric layer. The grounding brush can have the behavior of a capacitor. This is since there is an oily environment in the pod and an oil layer can be developed between the grounding brush and its contact area which will make it function as a capacitor.

Rough approximations of the value of these capacitances are presented in Table 7-3. Take in consideration that all the values used when calculating these capacitances are approximations. The purpose of presenting this table is to show the magnitude of the values. The calculations are presented in Appendix 1.

Table 7-3 Values of the capacitances of different devices in the pod

	Capacitance
Insulation with 2mm thickness	40 nF
Bearing drive end	35 nF
Bearing non drive end	135 nF
Grounding brush	245 nF

7.6 Conclusion

The problem with low frequency currents in bearings has almost been eliminated because of better motor construction and proper cabling. To be sure that these currents will not affect the bearings, an insulation of at least the non-drive end should be present. The high frequency currents are a more complex problem since these can not be stopped with insulation. There have not been many tests on the grounding devices used so their functionality both for low and high frequency currents can be discussed.

8 System solutions

The electrical solutions in ABB's Azipod and RR's Mermaid are presented in this chapter. Circuit diagrams over the electrical devices gives an overview of the structure of the system. The insulation and grounding devices are represented with electrical components and illustrated together with bearings and shaft. Last the results are compiled in a table so that differences and similarities easily can be spotted.

8.1 ABB's Azipod propulsion system

ABB base their marine propulsion technology on ABB's industry leading technology. The first Azipod was produced 1990 to the service vessel Seili. The ship is a multipurpose vessel used mainly in the Gulf of Finland well suited for demanding purposes. From service vessel the step to icebreakers is not far. 1995 was the first Azipod to an icebreaker, Röthelstein, built. This is the history of the Azipod before it was used on a cruise ship, Elation, 1998.

Most of the produced Azipods have the same design, a synchronous motor controlled by a cyclo converter. A circuit diagram over the electrical components used in Azipods is illustrated in Figure 8-1. Transformers and converters are located inside the ship while the motor is positioned within the pod.

The transformer is dry type with a delta-wye coupling. The converter is a cyclo converter with 6 pulses. The synchronous motor has a brushless exciter for the rotor which is illustrated with the two rotors drawn on the same shaft. The three-phase supply to the exciter is controlled with a triac.

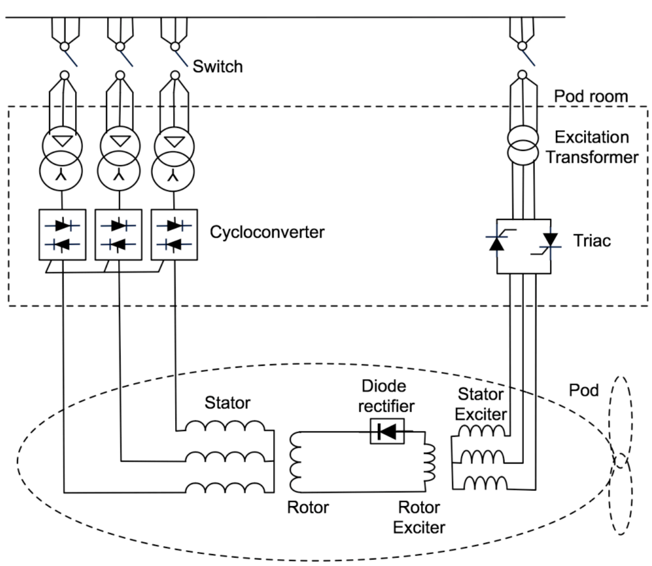


Figure 8-1 Circuit diagram of ABB's Azipod with the transformer, converter and motor.

To protect the bearings from currents, various solutions can be applied. In the Azipod system ABB has chosen to insulate the bearing in the non drive end with an insulation of fiberglass epoxy. For grounding they have copper-graphite brushes sliding directly against the shaft. In the drive end the grounding device is connected to the pod hull (ground). In the non drive end the grounding device is connected to the bearing housing inside the insulation. An illustration of the shaft, bearings, insulation and grounding devices used is presented in Figure 8-2.

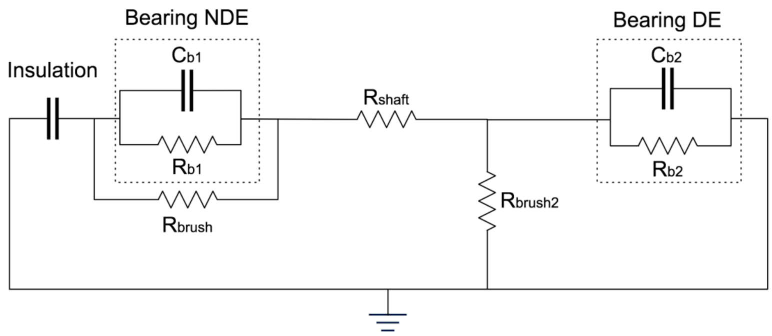


Figure 8-2 Electrical representation of shaft, bearings, insulation and grounding devices. Left is the non drive end and consequently right the drive end.

A summary of the Azipod system presented above is summarized in Table 8-1.

Table 8-1 Summary of the Azipod system

Azipod	
Power range	5-30 MW
Motor	Synchronous
Converter	Cyclo
Transformer	Dry type
Grounding contact on shaft	Directly on shaft
Grounding brushes	Copper-graphite
Insulation	Fiberglass epoxy NDE
Placing of insulation	Drive-end

8.2 Roll-Royce's Mermaid propulsion system

Roll-Royce produced the first Mermaid 1998 to the Millennium ships. Mermaid's concept is based on a synchronous motor controlled with a LCI converter. A circuit diagram of the electrical system in Mermaid pods is presented in Figure 8-3.

The motor is located in the pod and the converter and transformer in the ship in the pod room. The transformer is dry type and has delta-wye coupling. The converter is a LCI converter with a 12 pulses configuration. The synchronous motor has a brushless exciter for the rotor which is illustrated with the two rotors drawn on the same shaft. The three-phase supply to the exciter is controlled with a Gradathyr, which a brand name for a triac.

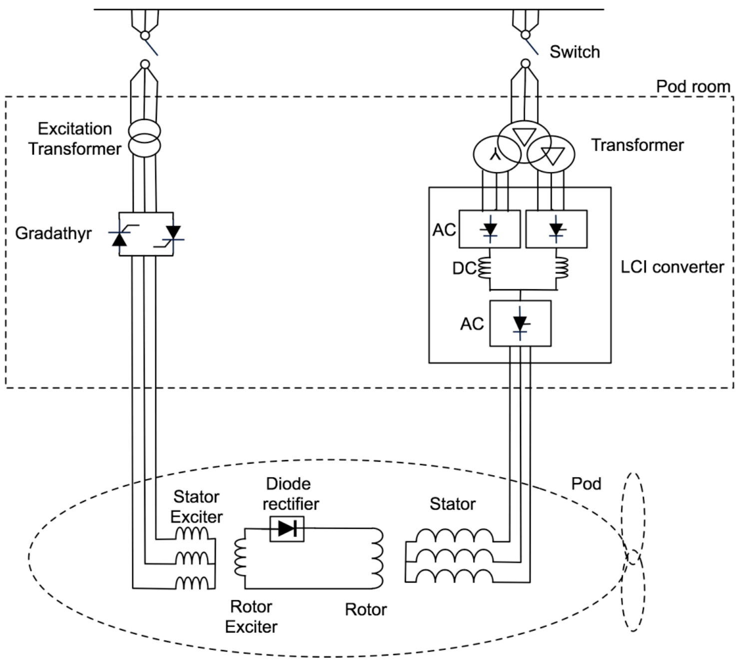


Figure 8-3 Circuit diagram of RR pod mermaid.

To protect the bearings from currents various solutions can be applied. In the Mermaid system RR has chosen to insulate both bearings. The insulation is made of fiberglass epoxy. For grounding they have silver-graphite brushes sliding against a ring mounted on the shaft. The grounding devices is mounted in the drive end and connected to the pod hull (ground). An illustration of the shaft, bearings, insulation and grounding devices used is presented in Figure 8-4.

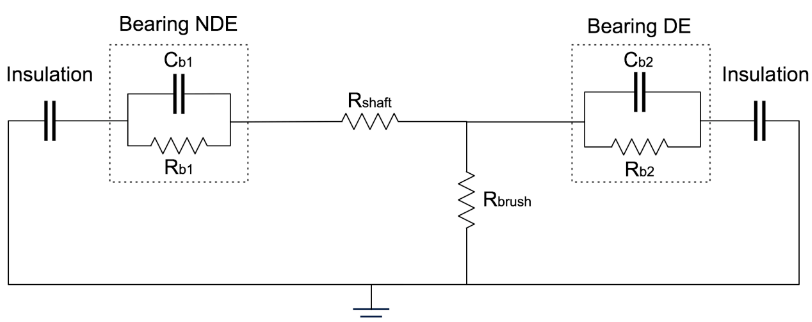


Figure 8-4 Electrical representation of shaft, bearings, insulation and grounding devices. The bearings are isolated in both drive-end and non drive-end. The shaft is grounded to the pod hull in drive-end. Left is the non drive end and consequently right the drive end.

A summary of the Mermaid system presented above is summarized in Table 8-1.

Table 8-2 Summary of the Mermaid system

Mermaid	
Power range	5-25 MW
Motor	Synchronous
Converter	LCI
Transformer	Dry type
Grounding contact on shaft	Copper ring with silver track
Grounding brushes	Silver-graphite
Insulation	Fiberglass epoxy DE and NDE
Placing of insulation	Drive-end and non drive-end

8.3 Comparison of the systems

The information about the different systems presented above is compiled in to Table 8-3. If there is a difference on the two systems the consequence of this difference is described.

	Mermaid (RR)	Azipod (ABB)	Difference	Consequence
Power range	5-25 MW	5-30 MW	No	–
Transformer	Dry type	Dry type	No	–
Motor	Synchronous	Synchronous	No	–
Exciter placing	Non drive end	Drive end	Yes	No known consequences presented in this report
Exciter converter	Gradathyr	Triac	No	Different names but same device
Converter (old)	LCI	Cyclo	Yes	LCI can not give high torque at low speed but has as simpler construction than the Cyclo
Semiconductor (old)	Thyristor	Thyristor	No	–
Converter (new)	VSI-PWM	VSI-PWM	No	–
Semiconductor (new)	IGCT	IGBT	Yes	No known consequences in this report
Grounding contact shaft	Copper ring with silver track	Directly on shaft	Yes	Less equipment could lead to lower impedance which is better
Grounding brushes	Silver-graphite	Copper-graphite	Yes	Silver-graphite brushes perform better [19]
Insulation material	Fiberglass epoxy	Fiberglass epoxy	No	–
Insulation placing	Drive-end and non drive-end	Drive-end	Yes	Insulation of one bearing should be satisfactory

9 Trends

The technology in pod propulsion is often taken from industrial applications and adapted to marine propulsion. So the equipment used in pods follows the development in industrial applications and therefore certain trends can be seen.

The biggest change in pod propulsion within a close future is the switch to VSI-PWM converters. The new technology change in converters has been in use in industrial applications for a while, but market penetration in marine propulsion has recently started.

When changing to VSI-PWM problems with induced shaft voltage and current can occur and therefore changes in insulation and grounding may take place. Insulation of both drive end and non drive end seems to be a solution. Even an extra grounding device in the drive end can be a result.

No such obvious trend can be found among the motors. The synchronous motors have earlier been the only good choice for high power applications. PMSM is today a viable alternative in smaller pods, for example ABB´s Compact pod. The development in magnets can make PMSM to an alternative also for larger pods. The induction motor has been used by Schottel´s small pod SEP (2MW) but could perhaps be more common in the future. Converteam recommends the induction motor and will use it in their new pod.

9.1 ABB

ABB are currently set to discontinue the use of cyclo converters, the new concept is based on VSI-PWM converters. This change might result in an adjustment of the insulation used. According to the department, at ABB, producing this converter it is recommended that both bearings should be insulated. This is not planed for all new Azipods with VSI-PWM, but in some cases it can be a possible outcome [47o]. The synchronous motor will still be a choice for big Azipods but if the technology allows it, maybe PMSM will be of interest in a few years. The transformers will be changed to match the new converter.

9.2 Rolls-Royce

The Mermaid pod is also facing a new era with VSI-PWM converter; some of the newest pods are equipped with these converters. To counteract bearing currents that the VSI-PWM might cause, a grounding ring is mounted on the shaft in the non drive end and connected to the bearing inside the insulation.

10 Future work

Further knowledge is required regarding the electrical systems in pods and the origin and mitigation of bearing currents. Some focus areas are suggested below.

10.1 Converter

The converter is a vital part in the electrical system in pod propulsion. It influences the design of the motor and the transformer. It controls the power drawn from the transformer and given to the motor and is in many cases the cause to a lot of unwanted effects.

The work that could be done regarding converters is to get a better understanding of how the new VSI-PWM converters will affect the bearing and try to find solutions that mitigate this problem. Have in mind that these large motors used for pods can act differently to the smaller ones that are often investigated. One area that is important for future work is the common mode voltage produced by the converter. Magnitude and frequency of these voltages are of interest.

10.2 Grounding

Grounding is an area where there have not been many tests or much analysis performed. Important question marks are how the grounding brushes respond to the oily environment in the pod and how much the functions of the grounding devices are reduced over time when not cleaned. Other questions are how big the expansion/contraction of the shaft is and how much reduction of contact area this will result in by the contact of the brushes.

To get further understanding it is suggested to test different kinds of grounding devices. The things to take in consideration if performing such a test are the following:

- Test both copper-graphite and silver-graphite brushes.
- If possible silver-gold brushes should be tested as well but this could be done if the results from the graphite brushes are not satisfactory.
- Test the brushes in an environment as similar to the pod as possible, oil leakage and the type of air ventilations are things to have in mind. The different temperature levels should also be tested.

One problem that has not been discussed in the report is the expansion/contraction of the shaft. When analyzing this problem no tests need to be performed, just calculations of the movement of the shaft and correct dimensions on the grounding devices are required to get a good picture of this problem.

10.3 Insulation

Regarding the insulation, it is proposed to examine the insulations when there has been a bearing breakdown, to see if the insulation too has been damaged. If the magnitude and frequency of the shaft currents can be estimated/measured calculations on suitable capacitance (thickness) of the insulation can be done. In these calculations the mounting arrangement and the screws and their insulation should be considered.

10.4 Model

To get a good understanding of the system, a model of the electrical system could be created and implemented, in for example Matlab, Simulink. To get an adequate model, the values of the parameters have to be carefully analyzed. Before setting up a model there have to be specifications on what to analyze and accomplish with the model. As a result of a satisfactory model it would be possible to specify the insulation thickness the required for protection of the bearings.

11 Conclusion

When mapping and comparing the electrical systems in pods, a conclusion is that the different systems have numerous of similarities. The synchronous motor is by far the most commonly used and differences in the transformers are hard to find. An area where the solution varied between the manufacturers is the converters used. The Cyclo- and LCI- converter are used in most pods but in the future the VSI-PWM will be the most common converter.

One other difference found between the various systems was the solution for mitigation of current in bearings. Both the thickness of the insulation and the type of grounding device, ring and brushes, varied. A conclusion drawn from reading information available on the subject is that knowledge on how to mitigate the problem with high frequency current is poor. As a result more information and knowledge on proper insulation and grounding needs to be collected.

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Appendix

The capacitances are calculated with

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}.$$

Bearings

The dimensions of the bearing are approximated with the following parameters:
Drive end:
A_1 = 991 mm^2
d_1 = 0,7 µm
Non drive end:
A_2 = 2759 mm^2
d_2 = 1 µm

The value of the dielectric constant of the oil which in this case is the insulation material is approximated to 5.5. Together with the dielectric constant of vacuum of $8{,}85 \cdot 10^{-12}$ the value of the capacitances can be calculated.

C_1 = 68 nF
C_2 = 134 nF

For the drive end there is one bearing but two oil layers, one on each side of the rolling element, so there are two capacitors in series which gives the total value:
C_{DE} = 34 nF

For the non drive end there are two bearings next to each other and two oil layers so the total capacitance is calculated by having two pairs of capacitors parallel connected. This gives the same value as for just one capacitor.
C_{NDE} = 134 nF

Grounding brush

The area and oil layer of the grounding brush are approximated to:
A_{brush} = 5 cm^2
d_{brush} = 0,1µm

If the dielectric constant of the oil is approximated to the same value as for the insulation the capacitance will be:

C_{brush} = 243 nF