TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

JUHA KIVIMÄKI

EFFECTS OF ELECTRONICALLY COMMUTATED MOTORS USED IN PASSENGER CABIN AIR CONDITIONING ON LOW VOLTAGE NETWORK OF A CRUISE SHIP

Master of Science Thesis

Examiner: Assistant Professor Paavo Rasilo
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ABSTRACT

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In this thesis the target was to explore the cabin air conditioning system and especially then fan solution. The fan motor is an electronically commutated (EC) motor. The idea is to clarify the harmonic phenomenon and how the EC-motors affect to the electricity quality. First it is convenient to introduce the electricity network of a passenger cruise ship and give a basic understanding of the components included in the network. There are both medium voltage and low voltage networks in the ship. The used electricity network is modified from a Mein Schiff –ship with little modifications so that the important key figures are not compromised.

The EC-motor construction was introduced before the effects to ease the understanding why EC-motor produces harmonic currents and voltages which create harmonic distortion. The theory about harmonics is presented to the extent that is necessary for the thesis; sources of harmonics, effects of harmonics and different solution for harmonic mitigation. After the electricity network and harmonics are presented the focus is on the information of the certain EC-motor type that is installed in the cabin air conditioning module. An active power factor correction unit is used in series with the EC-motor and the goal is to figure out if the power factor correction is needed in the system. This was done with both analyzing the theoretical side of the motor and then with practical measurements on the sea trial of the ship.

The solution was that the power factor correction is not needed due the low harmonic currents and low electric power. This was also ensured by comparing total harmonic distortion measurements between the previous ship and the present ship because in the previous there was no power factor correction unit with the EC-motor. However the power factor correction improves the power factor almost by 0,5 (0,53 → 0,99) which means also better energy efficiency. To decide whether the power factor correction unit is needed one must evaluate the cost of the installation and the cost of the electrical energy.

TIIVISTELMÄ

JUHA KIVIMÄKI: Matkustajahyttien ilmastointiin käytettävien elektronisesti kommutoitujen moottorien vaikutukset risteilylaivan pienjänniteverkkoon
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Avainsanat: Elektronisesti kommutoitu moottori, Energia tehokkuus, Harmoninen särö, Harmoniset yliaallot, Ilmastointi, Laivan sähköverkko, Luotettava sähköverkko, Sähkönlaatu, Tehokerroin, Tehokertoimen korjaus

Tässä työssä oli tarkoitus tutkia matkustajahyttien ilmastointia isoissa risteilijöissä. Erityisesti ilmastoinnista kiinnostuksen kohteena olivat elektronisesti kommutoidut moottorit (EC-moottorit), joita käytetään puhaltimissa. Tarkoitus oli myös perehtyä sähkönlaatuun vaikuttaviin tekijöihin, kuten esimerkiksi harmonisiin yliaaltoihin, näiden EC-moottorien avulla. Aluksi esiteltiin kuitenkin laivan sähköverkko ja sen pääkomponentit, jotta voi saada käsityksen siitä, millainen on ja miten toimii matkustajalaivan sähköverkko. Sähköverkko koostuu keski- ja pienjänniteverkoista. Propulsio kuuluu keskijänniteverkkoon ja hotellipuoli pienjänniteverkkoon. Esimerkkinä on käytetty Mein Schiff –laivan sähköverkkoa, jota on muokattu niin, että tärkeät tiedot eivät paljastu.

Ennen EC-moottorien vaikutuksia sähköverkkoon ja sähkönlaatuun esiteltiin EC-moottorien yleiset rakenteet, ominaisuudet ja käyttökohteet, jotta vaikutusten tutkiminen olisi mahdollista. EC-moottorit aiheuttavat pääasiassa harmonisia yliaaltovirtoja ja siten myös harmonisia yliaaltojännitteitä. Harmoniset yliaallot aiheuttavat jännitteen ja virran säröytymistä, harmonista säröä. Harmonisten yliaaltojen teoria, niiden synty ja ehkäisy on esitetty niiltä osin, kun se on työn kannalta oleellista. Syvällisemmin keskitytään harmonisten yliaaltojen suodatukseen tehokerrointa parantamalla. Hyödyksi käytetään ilmastointilaitevalmistajan sekä moottorivalmistajan antamia esitteitä, joista selviää EC-moottorien vaikutukset ilman suodatusta ja suodatuksen kanssa. Suodatusmenetelmänä on käytetty aktiivista tehokertoimen korjausta. Tavoitteena on selvittää, onko aktiivinen tehokertoimen korjaus tarpeellista vai jäävätkö harmoniset yliaallot riittävän pieniksi myös ilman tehokertoimen korjausta. Laitevalmistajien tietoja tukemaan suoritettiin harmonisten yliaaltojen mittauksia laivan merikokeen aikana.

Ratkaisuksi saatiin todettua mittauksia hyödyntäen, että suodatus eli tässä tapauksessa tehokertoimen korjaus ei ole tarpeellista tämän teholuokan EC-moottorissa. Yliaaltovirrat jäävät pieniksi vaikka särö olisi suuri, koska moottorin teho on niin pieni. Tulos vahvistettiin vielä vertaamalla jakelumuuntajien pienjännitepuolelta mitattujen harmonisten säröjen eroja kahden laivan välillä, jossa toisessa on käytetty aktiivista tehokertoimen korjausta ja toisessa ei. Käytetty menetelmä kuitenkin parantaa tehokerrointa lähes 0,5:llä (0,53 $\rightarrow$ 0,99) verrattuna suodattamattomaan moottoriin, joten energiatehokkuuden kannalta käyttö on perusteltua. Kustannustehokkuus on huomioitava päätettäessä käytetäänkö tehokertoimen korjausta vai ei. Viime kädessä päätöksen tekee laivavarustamo.

PREFACE

This thesis is made in Turku for the Meyer Turku shipyard. The idea in this thesis was to clarify how EC-motor affects to the low voltage electricity network of a passenger cruise ship. The target was to find out is the present configuration of the cabin air conditioning needed. Also the electricity network and the main electrical components of the passenger cruise ship were introduced.

I would like to thank the examiner of the thesis, assistant professor Paavo Rasilo from the Department of Electrical Engineering in Tampere University of Technology. I would also like to thank the supervisor from the shipyard, M.Sc. (tech.) Harri Eriksson who has given me great advices for the thesis. Special thanks also to my former superior Atte Piiroinen for selecting the subject for the thesis and making the thesis possible.

I would also like to thank my parents Jaakko and Päivi Kivimäki for supporting me throughout the making of this thesis.

In Turku 10.10.2016

Juha Kivimäki

ALKUSANAT

Tämä työ tehtiin Meyer Turun telakalle Turussa. Työn ideana oli selvittää EC-moottorien vaikutuksia laivan pienjännite sähköverkkoon. Työn tarkoituksena oli tutkia, onko nykyinen matkustajahyttien ilmastointipuhaltimien rakenne tarpeellinen. Samalla esiteltiin myös matkustajalaivan sähköverkon rakenne sekä pääkomponentit.

Haluan kiittää työni tarkastajaa, assistant professor Paavo Rasiloa sähkötekniikan laitokselta Tampereen teknillisestä yliopistosta. Haluan myös kiittää työni ohjaajaa Meyer Turulta, diplomi-insinööri Harri Erikssonia, jolta sain hyviä neuvoja työhön liittyen. Erityiskiitokset haluan sanoa entiselle esimiehelleni Atte Piiroiselle aiheen valitsemisesta sekä työn toteutuksen mahdollistamisesta.

Haluan myös kiittää vanhempiani Jaakko ja Päivi Kivimäkeä, jotka ovat olleet tukena diplomityötä tehdessä.

Turussa 10.10.2016

Juha Kivimäki

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ABBREVIATIONS AND NOTATIONS

ABB	ASEA Brown Boveri, Swedish-Swiss multinational industrial corporation
ABS	American classification society, American Bureau of Shipping
AC	Alternating current
ANSI	American standardization institution, American National Standard Institute
AVR	Automatic voltage regulator
Azipod	Podded propulsion drive used by ABB
Boost-converter	DC-DC step up converter
BV	French classification society, Bureau Veritas
CFCU	Cabin fan coil unit
CSI	Current source inverter
DC	Direct current
DNV-GL	International classification society and certification body, a merge between Det Norske Veritas (Norway) and Germanischer Lloyd (Germany)
DOL	Type of motor connection to the electricity network, Direct-on-line
EC-motor	Electronically commutated motor
HFO	Heavy fuel oil
HVAC	Heat, ventilation and air conditioning
IAS	Integrated automation system
IEC	International standardization organization, International Electrotechnical Commission
IGBT	Insulated-gate bipolar transistor
IGCT	Insulated gate-commutated thyristor
IT	Type of electricity distribution system with no earthing

LCI	Load commutated inverter
LED	Light-emitting diode
LNG	Liquefied natural gas
LR	UK classification society, Lloyd's Register
LV	Low voltage
MCC	Motor control center
MDO	Marine diesel oil
MFZ	Main fire zone
MOSFET	Metal-oxide-semiconductor field-effect transistor
MV	Medium voltage
PF	Power factor
PFC	Power factor correction
PWM	Modulation technique, Pulse width modulation
RMS	Square root of mean square, Root mean square
RMU	Ring main unit
RPM	Rounds per minute
SMPS	Switched mode power supply
SOLAS	International organization for marine safety, International Convention for the Safety of Life at Sea
SRtP	Safe return to port
THD	Total harmonic distortion
TN-S	Five conductor electricity distribution system with separate neutral and protective earth conductors
UPS	Uninterruptable Power Supply
VSI	Voltage source inverter

α_n	Phase angle of the n^th^ harmonic
a_0	Fourier series coefficient for DC component
a_n	Fourier series coefficient for n^{th} harmonic order
b_n	Fourier series coefficient for n^{th} harmonic order
C	Capacitance
$\cos\varphi$	Power factor
$\cos\varphi_1$	Displacement factor
D	Distortion power
DF	Distortion factor
DPF	Displacement factor
F	Fourier series function
f	Frequency
f_1	Fundamental frequency
f_r	Resonance frequency
I	Current
I_1	Fundamental current
$I_{1,1\mathrm{EC}}$	Fundamental current of one air conditioning module
$I_{1,2\mathrm{EC}}$	Fundamental current of two air conditioning modules
$I_{EC,nominal}$	EC-motor nominal current used in Mein Schiff
I_n	Current of the n^{th} harmonic
$I_{primary}$	Primary side current
I_{RMS}	The total current RMS
$I_{secondary}$	Secondary side current
i_C	Capacitor current
i_{in}	Instantaneous input current

$\hat{\imath}_{in}$	Peak value of the input current
i_L	Inductor current
i_{load}	Load current
i_n	Relative harmonic current content
k	Positive integer
L	Inductance
$N_{primary}$	Primary side winding rounds
$N_{secondary}$	Secondary side winding rounds
n	nth harmonic order
ω	Angular speed
P	Active power
P_m	Mechanical power
PF	Power factor
$PF_{AC\text{-}module}$	Power factor of measured air conditioning module
$PF_{EC,tested}$	Power factor of factory tested EC-motor
p	Pulse number
φ	Phase shift between voltage and current
φ_1	Phase shift between fundamental voltage and current
Q_c	Reactive power of capacitor
S	Apparent power
S_k	Short-circuit power of the distribution network
T	Time period
T_{em}	Electromagnetic torque
T_m	Mechanical torque
THD_i	Current THD

THD_u	Voltage THD
t	Time
U	Voltage
U_1	Fundamental voltage
$U_{1,1\mathrm{EC}}$	Fundamental voltage of one air conditioning module
$U_{1,2\mathrm{EC}}$	Fundamental voltage of two air conditioning module
U_n	Voltage of the n^{th} harmonic
U_o	Voltage DC component in Fourier series
$U_{primary}$	Primary side voltage
U_{RMS}	The total voltage RMS
$U_{secondary}$	Secondary side voltage
u	Instantaneous voltage
u_{in}	Input voltage
u_o	Output voltage
u_n	Relative harmonic voltage content

1. INTRODUCTION

Electricity network and distribution system of a ship, especially passenger cruise ship, is an interesting entirety. On one hand it is very similar to the electricity network onshore but on the other hand it is totally different. It could be said that the passenger cruise ship nowadays is a little city floating on the ocean. In a ship the electricity generation and consumption are close to each other unlike onshore where the distribution network between generation and consumption can be several hundred kilometers. In a ship it is very important that the electricity supply is not interrupted and the electricity can be supplied even in emergency situations so that the passenger safety is not at risk. Also the quality of the electricity has an important role in ships so that the electrical devices are not interfered. In passenger cruise ships the passenger comfort and safety is the most important thing.

The main idea of the thesis is to explore the cabin air conditioning solution by analyzing the electricity quality and the things that affect to the quality. The example network is based on the electricity network of a Mein Schiff –ship. However no specific information about the electrical power and the implementation of the network are mentioned. The used air conditioning solution is an object of interest because it has not been used in the ships built by Meyer Turku before. The goal is to figure out if the new type of construction is needed.

The cabin air conditioning fans are electronically commutated (EC) motor fans. The electronic commutation affects to the quality of the electricity because of the voltage rectification. Voltage rectification creates harmonic distortion. In this thesis alongside the introduction of the electrical systems of the ship is also an introduction for the theory behind the harmonic voltages and currents. The understanding of harmonics is needed for the evaluation of the new type cabin air conditioning module configuration. In previous ships the harmonics produced by the EC-motor have not been filtered whereas in the present ship there is an active power factor correction circuit installed in series with the EC-motor. The idea is to evaluate if the power factor correction is needed. To verify the theory of harmonics also measurements were made in practical.

Chapter 2 is an introduction to the electricity network of the cruise ship with diesel-electric propulsion. The main components and the basic design of the network are described in Chapter 2. Chapters 3 and 4 are the introduction for the air conditioning systems and the EC-motor fan. In Chapter 5 are described the theory for harmonics and also the theory for the cabin air conditioning fan used in the present ship. Chapter 6 is the presentation of the THD measurements which were performed during the sea trial.

2. ELECTRICITY NETWORK IN A PASSENGER CRUISE SHIP

Every modern passenger cruise ship is run by electricity. Passenger cruise ships are large entities containing very complex electrical systems which all need to be considered when designing the ship. All systems from propulsion to passenger cabins require electricity. Nowadays passenger cruisers have a diesel-electric propulsion system which means that there is not mechanical connection between the propeller shaft and the diesel engines. Mechanical power produced by diesel engines is first transformed to electric power by generators and then again to mechanical power by propulsion motors. The diesel engine and generator combination produces also electricity for the rest of the ship.

The electricity network used in vessels is very similar to the power grid used onshore. Every vessel has its own electricity production, distribution and consumers. Electricity network in cruise vessels is a 3-phase alternating current (AC) network because electricity distribution and different voltage levels are easier to implement compared to direct current (DC) network. When direct current is needed it will be produced by rectifiers from alternating current.

There are also differences in offshore and onshore installations. The main differences between onshore and ship's power grid types are cable lengths and narrow spaces. Cable lengths are significantly shorter in a vessel than onshore and therefore management of the grid is easier. Maximum cable lengths in a vessel are about 300 m whereas transmission cables onshore could be several hundred kilometers long. Cruise ships also have a very limited space for installing all the required cables and this makes special requirements for the design of the electricity system. Also voltage levels in vessels are lower compared to onshore power grid voltages because the transferred electric power and transfer distance is less in vessels. In a large cruise vessel the total electric power of the generators is about 45 MW whereas onshore for example one nuclear power plant has an approximate total power of 800 MW. Difference in direct current usage is that onshore DC transmission is used for long distance electricity transmission whereas in vessels DC is used for control signals in automation, alarming systems, communication systems and emergency lighting. [4]

Because almost every system in a passenger cruiser requires electricity the functionality of the electricity network is absolutely necessary for secure operation. For example operation of the propulsion system and functionality of vital parts of the navigation system have to be ensured by redundant design. Also the network is designed redundantly and operation is secured for example by emergency generator and uninterruptible power supply (UPS). To ensure safety there are several directives and regulations set by different classification societies and national authorities. Classification societies are constantly monitoring and inspecting that everything is done correctly according to the rules and regulations. Different classification societies are for example *Det Norske Veritas - Germanischer Lloyd* (DNV-GL), *Bureau Veritas* (BV), *Lloyd's Register* (LR) and *American Bureau of Shipping* (ABS). National authorities control that the national regulations are fulfilled. [3; 7]

2.1 Configuration of electricity network

The electricity network in a ship is divided in medium voltage and low voltage networks. In marine business voltage levels less than 1 kV are low voltage and voltage levels above that are usually called medium voltages. Currently passenger cruise ships use 11 kV in medium voltage network. Low voltage levels vary a lot depending on the system using the low voltage. [3; 4]

Typical reference voltage levels in a passenger cruise ship are shown in Table 2.1. The voltage level also depends on the frequency as shown in Table 2.1. Also other voltages are used depending on the system, for example control systems use often 24 V. Usually phase voltage 110 V/60 Hz is used in North America and 230 V/50 Hz is used in Europe. The voltage levels shown in Table 2.1 are determined by different standards. Standards for European ships and North American ships are determined by *International Electrotechnical Commission* (IEC) and *American National Standards Institute* (ANSI). There are also exceptions in reference voltage levels, for example in the Tallink shuttle, which is built in the Meyer Turku shipyard alongside the Mein Schiff series, the used medium voltage is 11 kV but the frequency is still 50 Hz. [3; 8]

Table 2.1. *Typical voltage levels used in passenger cruise ships.* [3]

Frequency f (Hz)	Reference voltage level U (V)							
50	x	230	400	690	1000	3000	6000	10500
60	110	x	440	690	1100	3300	6600	11000

Table 2.2 shows guidelines when the different voltage levels should be used for the passenger cruise ship's electricity generation and distribution. The used voltage level depends on the total installed electric power generation and the electric power required by a certain consumer, for example a motor. The voltage level used by small consumers is determined separately. Fault currents and load currents also set some limitations to the used equipment so recommendations shown in Table 2.2 are not always applicable and voltage levels have to be adjusted. [8]

Table 2.2. *Voltage levels depending on the electric power.* [8]

Voltage level ***U*** **(V)**	**Total installed electricity generation** $P_{G,tot}$ **(MW)**	**Motor electric power** ***P*** **(kW)**
11 000	> 20	> 400
6 600	4-20	> 300
690	< 4	< 400

The frequency in the network is either 50 Hz or 60 Hz depending on the market area where the cruise vessel is going to operate. Usually in North America and in intercontinental cruises, ships use the higher frequency level but in some cases the higher level can also be used in other market areas. The used frequency level has to be taken into account on the design of motors, generators and transformers. [7]

Medium voltage electricity network in cruise ship is usually a modified IT network. IT network means that it is not earthed. In modified IT network the generator neutral point is earthed through high impedance resistor. The main advantage of IT network is that single earth fault does not immediately break the electric circuit and stop the operation of the network. IT network is used in systems which have a high need for uninterruptable electricity distribution for example hospitals, operating rooms, control circuits, industrial electricity distribution and cruise ships. In cruise ships, the network is earthed from generators' neutral points through high impedance resistor forming a highly resistive network. Earthing through the resistor increases the earth fault current, compared to unearthed network, to a detectable level and eases the earth fault control. Other advantages of the IT system are low earth fault currents and low risk for arcs caused by overvoltage. Low earth fault currents also reduce the risk for fire and failures in equipment. [1; 14; 18; 19; 20]

In the low voltage network different network types are often used. Usually the 690 V network is IT network and electricity networks with voltage under 690 V level TN-S networks. Unlike in IT network, in TN-S network a single earth fault interrupts the power supply. There are separate neutral and protective earth conductors in TN-S network and it is earthed directly of the neutral point on the supply, for example from transformer's neutral point. This forms a low impedance earth fault loop and high earth fault current. In case of insulation fault a circuit breaker interrupts the power supply instantly to protect humans, machine or device. The human protection is the most important. Exposed conductive parts and all device frames are connected to the provided protective earth conductor to ensure safety. One advantage in the TN-S network is that it enables direct use of one phase voltage, 230V or 110V, without separate voltage transformer. Other advantage in the TN-S network is that the locating of the fault is easier than in IT network because of the interrupted power supply. Because of separate conductors for neutral and protective earth, the protective earth conductor is free from harmonics and disturbances. Neutral conductor conducts possible harmonic currents, multiples of 3, which might occur in case of nonlinear electrical loads, for example rectifiers and inverters. Harmonics are described more precisely in Chapter 5. [1; 18; 19; 20]

A simplified single line diagram of the electricity distribution network is shown in Figure 2.1. The single line diagram in Figure 2.1 is based on the electricity network of the Mein Schiff –series passenger cruise ship.

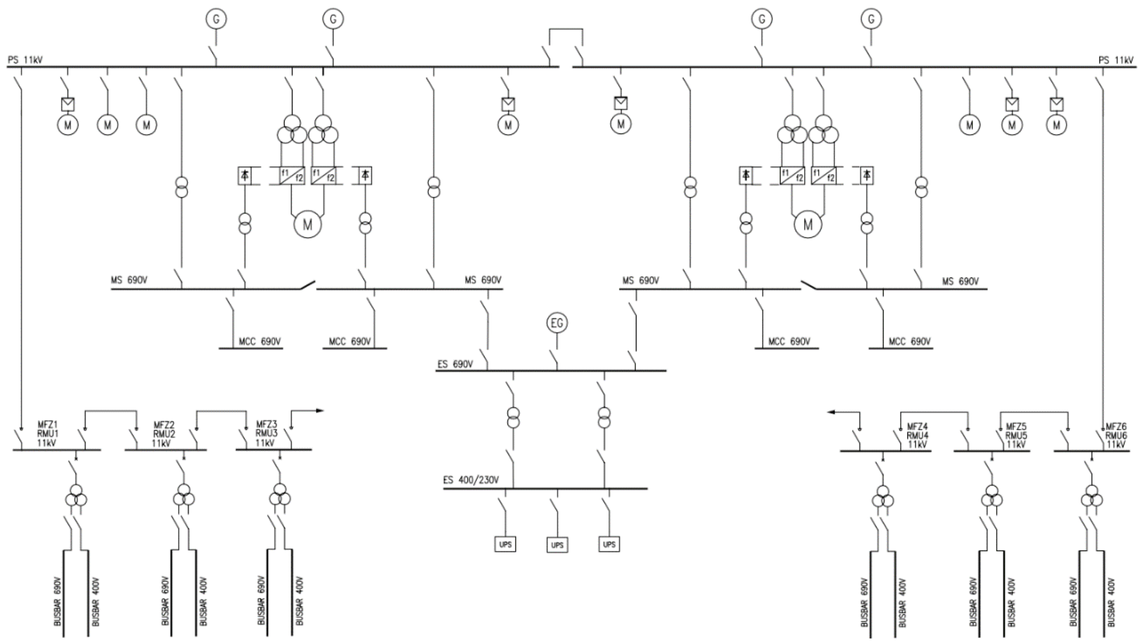


Figure 2.1. *Single line diagram of electricity distribution network in a passenger cruise ship.* [22]

Starting from the top there are generators which are feeding the electric power to the medium voltage (MV) switchboards. Thruster motors and air conditioning compressors are connected straight to the MV switchboards. The 3-winding propulsion transformers are connected to the MV switchboards and propulsion transformers are connected to propulsion frequency converters which control the propulsion motors. In addition to MV switchboard there are also other switchboards such as the main low voltage (LV) switchboard and the motor control center (MCC) to control for example propulsion system auxiliaries. The electric power for the hotel side of the ship is transferred through ring main units (RMU), distribution transformers and bus bars. For safe operation of the ship there are UPS systems, emergency switchboards and an emergency generator which are used in different emergency situations. More specific details of different networks and different components are described in the next chapters. [1; 2]

2.2 Normal operation

Normal operation means that there are no faults in the electricity network and the electrical load is almost equally distributed over the ship. In this case the bus-tie breaker between the two MV switchboards is closed and all the generators are connected parallel in the same network. In normal operation the medium voltage network is stable. The MV network is designed in such way that the total harmonic distortion (THD) is limited approximately to 5 % and in the low voltage network from 5 % to 8 %. Limits to the THD in the medium voltage and low voltage networks depend on the classification society [17]. The THD and other possible disturbances in the low voltage network caused by air conditioning motors are described in more detail in Chapter 5.

Passenger cruise ship's electricity network is used radially in normal operation although some parts of the network are built as meshed. Reasons for radial use are that protection is easier to implement in radial network than in meshed network and also disturbances are easier to restrict. In radial use the electric power is distributed from MV switchboards straightly to all over the ship via ring main units and distribution transformers. The electricity network is used as meshed only in situations where there are no possibility to supply electric power from the designated source and the electric load has to be transferred for example from one LV switchboard combination to another. [1; 2]

2.3 Emergency situations and redundancy

Emergency situations have to be carefully taken into account especially in marine business. For safe operation there are rules and regulations made by classification societies and also by *International Convention for the Safety of Life at Sea* (SOLAS). SOLAS regulations give minimum safety standards in construction, equipment and operation of the ship. These have to be fulfilled by all ships which operate under the flag of any of the states that have signed the convention. [23]

Nowadays there is also very strict Safe Return to Port (SRtP) rules for new building passenger ships and also for ships that are already in operation are more and more modified to fulfill these rules. The basic idea of the SRtP is that the ship itself is the best lifesaving boat and the actual lifesaving boats are only used in extreme emergency situations. This means that if there are not critical damages in the steel construction of the ship and the main systems of the ship are partially still working, the ship should be able to cruise back in to the closest harbor.

These different rules obligate that the most important electricity systems have to be designed to be redundant and some of them have to also be duplicated, for example some navigation systems. Redundant means that for example one machine has two alternative power supplies to ensure uninterruptible operation if for some reason one of the two supplies is out of operation. [1; 2] The ship is usually divided in different main fire zones (MFZ) and each fire zone has their own substation for electricity distribution. Design for safe operation is based on the idea that vital systems are divided in different parts of the ship. This means that it is still possible to use for example part of the propulsion and navigation even if one fire zone is isolated or not functioning properly due to fault in the electricity network, fire or flooding.

One example of redundancy can be seen in Figure 2.1, in the propulsion system. One propulsion motor is fed by two transformers and two frequency converters. Propulsion motor has a special construction with two stator windings for these two supplies. This construction also enables 24-pulse rectifier supply for propulsion frequency converters [3; 6; 18]. Construction and operation of the propulsion frequency converter and propulsion motors are described later in Chapter 2.4.

Operation in emergency situations also affects to the quality of the electricity in the network because only part of the electricity production can be used. This might for example increase harmonics in the network due to an uneven distribution and consumption in different parts of the network. Some part of the network might collapse if the harmonics or voltage dips increase too much. The use of electric power is limited during emergency situations so that the vital systems can be operated without interruptions, for example all the comforts in the hotel side are not in use.

2.4 Main electrical components

Electricity generation and main distribution is done with medium voltage. Medium voltage network in marine business means the network that contains the main electricity systems from generation of electricity to propulsion systems and transformers which distribute electricity for the rest of the ship. Medium voltage is used to these systems rather than low voltage because higher voltage level enables higher power transform with relatively low current whereas low voltage system with the same power generates higher current. With higher current losses are also higher due to impedance of the system and therefore higher current also requires bigger transmission cables.

To give a basic view about the medium voltage system, cruise ship's main electrical components are depicted in Figure 2.2. The main electrical components shown in Figure 2.2 are

1. Diesel engine
2. Generator
3. Propulsion switchboard (MV Switchboard)
4. Propulsion transformer
5. Propulsion frequency converter
6. Propulsion motor.

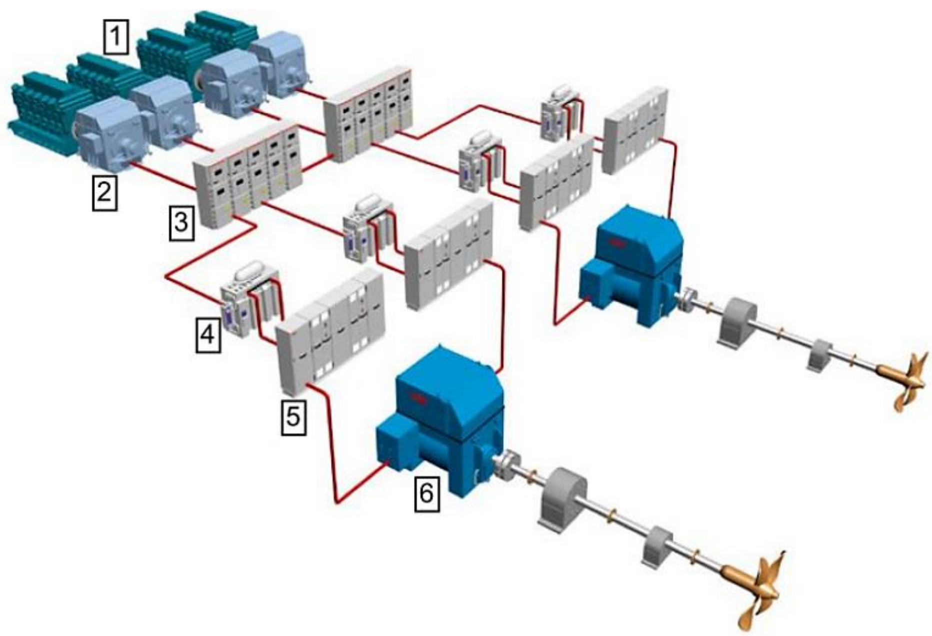


Figure 2.2. *Main electrical components in medium voltage electricity network.* [6]

The system shown in Figure 2.2 is the diesel-electric propulsion system. In addition to the components in Figure 2.2 there are also other type of electric devices connected to the medium voltage network, for example thruster motors, air conditioning compressors and ring main units [1; 2]. Thruster motors and air conditioning systems are described in more detail in later chapters. Depending on the design of the electricity distribution system and the size of the vessel, air conditioning compressors can be connected to the medium or low voltage network. In a large cruise ship, comprehensive air conditioning requires a lot of electric power and therefore the compressors are usually connected to the medium voltage network.

In large passenger cruise ships there are also ring main units in every main fire zone. The purpose of the ring main units is to enable the electricity network in a ship to operate similarly to a meshed network onshore if needed. In normal operation the electricity distribution is done radially but in abnormal situations it is possible to transfer electric power by different routes. The ring main units consist of medium voltage supply from the MV switchboards and two outputs; one for distribution transformer and one for the next ring main unit. The ring main units are located next to the distribution transformers in distribution substations in each fire zone. Distribution transformers transform the voltage level from medium voltage to low voltage, 690 V or 400 V depending on the consumers. [1; 2]

2.4.1 Main engines

Starting from the left in Figure 2.2 the first component is diesel engine and it is connected to a generator. Diesel engines and generators are the source of all electricity needed in a cruise ship. In a modern cruise ship the diesel engines can be dual fuel engines. This means that they can operate with both marine diesel oil (MDO) and liquefied natural gas (LNG). Traditional diesel engines use only marine diesel oil or heavy fuel oil (HFO) as fuel. LNG is used because it is more environmentally friendly than diesel oils. There is no sulphur in the fumes of LNG. When using diesel oil the sulphur has to be washed and filtered out according to the newest regulations. [1; 2]

Diesel engines are located at the bottom of the ship, usually on deck one or deck two. Engines are such large and heavy components that they need to be located as low as possible to keep the balance of the ship as good as possible. Usually in a passenger cruise ship diesel engines are located in separate engine rooms for example three engines in one room and two engines in the other. This is due to safety regulations; if one engine room is damaged the other engines in the other room can still operate.

2.4.2 Generators

Mechanical energy produced by the diesel engine is transformed to electrical energy by generator. Diesel engine is coupled to the generator rotor frame and the diesel engine rotates the rotor. Alternating magnetic field is generated when the rotor is rotating. Alternating magnetic field induces an alternating voltage to generator stator due to Faraday’s law of electromagnetic induction. The law states that when a loop made of conducting material is rotated in a magnetic field, voltage, an electromotive force, is induced between the two ends of the conductor loop. After the two ends are connected to a load, electric current starts to flow. [3; 5; 7]

Generators used in passenger cruise ships are synchronous machines. Synchronous means that the rotation frequency of the magnetic flux density in the air gap and induced voltage at stator winding are at the same phase as rotor’s electrical angular speed. This situation is shown in Figure 2.3. The speed is called the synchronous speed. [5]

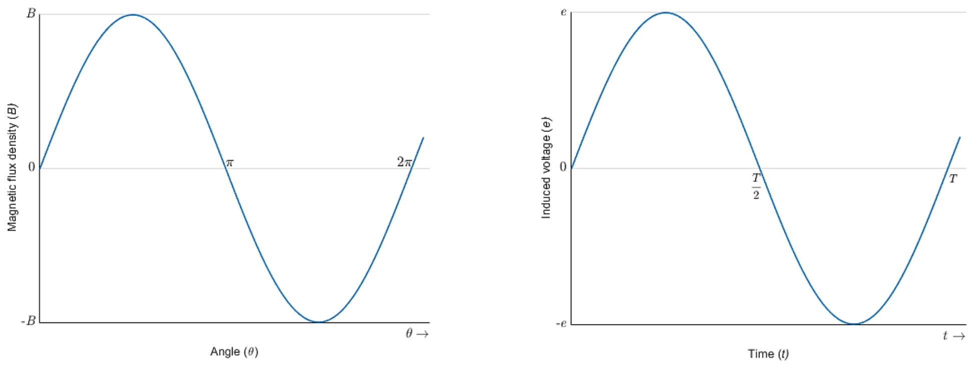


Figure 2.3. *Magnetic flux density with respect to angle and induced voltage with respect to time.* [5]

Figure 2.4 depicts a simple example of a two pole generator. The stator is the stationary part of the generator which consists of the generator frame, the stator core and the stator winding. The pair *a* and *-a* is the two sides of one winding which are perpendicular to the rotating magnetic field. Armature is the part of the synchronous machine where voltage is induced, in this case the stator. In three phase systems there are also windings for other phases; *b*, *-b* and *c*, *-c*. [5]

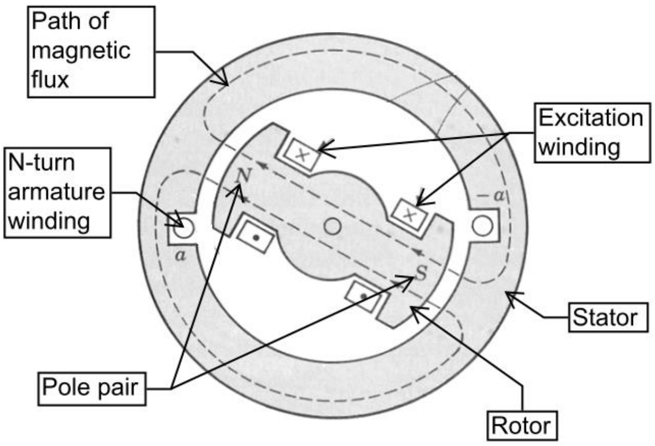


Figure 2.4. *An example of two pole synchronous generator.* [5]

The rotor is fitted inside the stator and it is supported by bearings in both ends of the rotor shaft. The rotor is built around the shaft and the diesel engine shaft is coupled to the rotor frame. The rotor has to be centered so that the air gap between the rotor's magnetic poles and stator is the same everywhere over the machine. The generators used in passenger cruise ships are self-excited. The self-excitation is used for the starting of the machine. There are permanent magnets to wake up the generator by inducing current in the excitation windings located around the rotor shaft inside the generator.

After the start the excitation current is used to control and maintain the terminal voltage of the generator when the load changes. Adjustment for keeping the right voltage level is done by Automatic Voltage Regulator (AVR) which adjusts voltage and reactive power of the generator. [3; 7; 9]

The synchronous rotating speed is determined by the frequency of the electricity network and the amount of pole pairs used in the synchronous machine. In Figure 2.4 was an example of two pole synchronous machine. With more pole pairs the desired frequency of the voltage will be achieved with less rotor speed. The synchronous speed can be calculated using equation

$$n_s = \frac{60 \cdot f}{p_n}, \tag{2.1}$$

where n_s is the synchronous speed (rpm), p_n is the amount of pole pairs and f is the frequency (Hz). [5; 9; 12]

Rotor speeds with different pole pair numbers have been calculated in Table 2.3 to clarify the relation between the pole pair number and the rotor speed. The used frequency level is 60 Hz.

Table 2.3. *Rotor speeds in relation to pole pairs at 60 Hz.*

Pole pairs	Synchronous speed (rpm)
1	3600
2	1800
3	1200
4	900
5	720
6	600
7	514
8	450

The reason why there is more than one pole pair in many applications is that the more pole pairs there is in the generator the less rpm is needed to create certain frequency. It can be calculated using (2.1) and Table 2.3 that for example using synchronous machine which has six pole pairs (12 poles) 600 rpm is needed to reach 60 Hz frequency. Because synchronous machine can only operate at the synchronous speed, in overload cases the machine may fall off the pace and it has to be disconnected to avoid any damages and failures. Classification societies have different regulations for this but usually the frequency is allowed to change ± 5 % before disconnecting. [3; 7; 17]

The generator is connected to the electricity network via a generator circuit breaker. To avoid any disturbances when connecting the generator to the network it has to be synchronized with the network. This means that the phase sequence, frequency and the amplitude of the voltage has to be the same in both sides of the breaker. The synchronization is done by relays located in the MV switchboard. Also the generator circuit breaker is located in the switchboard. If the generator is not synchronized properly before connecting there will be some switching currents and other disturbances which may damage the machine and the network. [3; 5; 7]

2.4.3 Switchboards

Switchboard controls the electricity distribution and protects the devices on both sides of the board. Switchboards are operating as a circuit breaker between electricity generation and distribution. Generators are usually directly connected to supply side of the switchboard and other devices, such as transformers and motors, are connected to the outputs. In addition to circuit breakers switchboards contain also protection relays, measuring units and separating devices. Protection relay protects the people, the network and the load equipment in case of malfunction and breaks the electrical circuit. [3; 7]

There are several different types of switchboards in a passenger cruise ship, for example MV switchboard, main LV switchboard, MCC switchboard which is used as a starter circuit for several motors and galley switchboard which is used for galleys. There are also emergency switchboards for emergency situations. Voltage levels in switchboards depend on the required power of the consumer and the total power of electricity generation. Voltage levels and a simplified configuration of the electricity network used in passenger cruise ships were introduced in Chapter 2.1.

MV switchboards distribute the electrical energy from generators to the whole ship via transformers and different types of distribution boards. Voltage level in MV switchboard is usually 6,6 kV or 11 kV. Main LV switchboard is connected to MV switchboard by transformers. Main LV switchboard controls consumers that need to be directly connected to switchboard but are not applicable for medium voltage, for example excitation transformers and propulsion auxiliary systems. Voltage level in main LV switchboard is usually 690 V but 400 V is also used in some cases. [3; 6; 11; 21]

2.4.4 Transformers

Transformers are used as a part of the electricity distribution system. Transformer enables an easy way to change voltage levels in electricity network when using AC voltage systems. Basic transformer consists of primary and secondary windings, iron core which is used for conducting the magnetic flux, insulation parts and different kind of constructional parts. Operation is based on the electromagnetic induction as in synchronous machines described in Chapter 2.4.2 except for the fact that there are no moving or rotating parts in a transformer. The fact that there are no moving parts in a transformer also makes them very reliable electrical devices. [3; 9; 12]

Primary AC voltage generates an alternating magnetic flux based on Faraday's law of electromagnetic induction. The alternating magnetic flux induces alternating voltage in the secondary windings. When a load, for example motor, is connected to secondary winding, current starts to flow to the load. Transforming voltage or current to another level is based on the ratio between winding rounds in the primary and secondary windings. [9] The dependence between voltage, current and winding round can be seen in the equation

$$\frac{U_{primary}}{U_{secondary}} = \frac{N_{primary}}{N_{secondary}} = \frac{I_{secondary}}{I_{primary}} , \tag{2.2}$$

where $U_{primary}$ is primary voltage (V), $I_{primary}$ is primary current (A), $N_{primary}$ is the amount of primary winding rounds, $U_{secondary}$ is secondary voltage (V), $I_{secondary}$ is secondary current (A) and $N_{secondary}$ is the amount of secondary winding rounds. [9]

The iron core is used to conduct the magnetic flux from the primary side through conductor loops on the secondary side. Because there is no galvanic connection between the primary and secondary windings, the transformer also isolates two parts of the electricity network from one and another. Basic diagram of a one phase transformer is shown in Figure 2.5. [3; 9; 12]

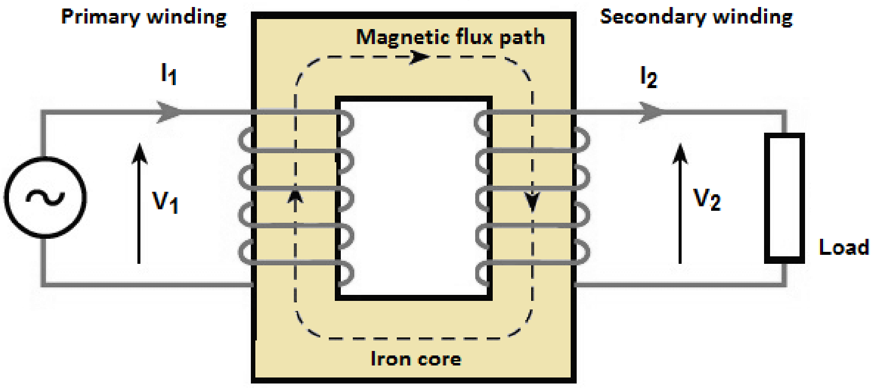


Figure 2.5. *Transformer operation diagram.* [24]

Different types of transformers are used in passenger cruise ships; from small transformers in electronic circuits to large propulsion transformers. Distribution transformers are used for electricity distribution system and their total electrical power varies from 1 000 to 2 000 kVA. Largest transformers in a ship are the propulsion transformers which transform the medium voltage to an applicable voltage level for propulsion frequency converter. Total electrical power of the propulsion transformers depends on the propulsion power and the power of a transformer can vary for example from 5 000 kVA to 12

000 kVA. There are also measuring transformers which are used for measuring voltage or current. [1; 22]

2.4.5 Frequency converters

Some applications that for example do not need variable rotating speed motors are equipped only with a starter circuit and the rotating speed is constant when the voltage and the frequency of the electricity are constant. However electric motors often need precise speed or torque control and then the control is done with different types of frequency converters. The type of the converter depends on the application. Frequency converters can control electric motors from small air conditioning motors to large propulsion motors. The range of the electric power in passenger cruise ships varies from few hundred watts to over 20 MW.

Frequency converter consists of power electronic components which can be controlled in a desired way to reach the right output values for the motor. Frequency converters consist of rectifier bridge, inverter bridge and DC-link, except cycloconverters. The basic operation principle of a frequency converter is that it first rectifies the AC voltage. Then the inverter bridge chops its output voltage in such frequency that the formed RMS output voltage wave is as sinusoidal as possible. Control of the electrical motor is based on the relation between the current, voltage, frequency, torque and rotating speed. The mechanical power of the motor can be calculated with equation

$$P_m = T \cdot \omega, \tag{2.3}$$

where P_m is the mechanical power (W), T is the torque (Nm) and ω is the angular speed of the rotor (rad/s). When the motor is running at constant speed the mechanical torque T_m and electromagnetic torque T_{em} are equal but opposite of each other $T_m = T_{em}$. If the motor speed is decreasing then the mechanical (load) torque is greater than the electromagnetic torque. When accelerating the motor the electromagnetic torque is greater than the mechanical torque. It can be noticed from the (2.3) that either the rotor angular speed or the torque has to be adjusted to achieve the desired mechanical power. Frequency converters can be used for either the adjustment of the angular speed or the torque. The torque of the machine is proportional to the magnetic flux created by the electromagnetic induction and therefore to the rotor current. Rotating speed is proportional to the frequency.

In torque control the current fed into the motor is changed according to the requested torque value. Then the torque is kept constant at the desired value and the rotating speed increases or decreases depending on the resisting torque of the load. When using the rotating speed control then the torque increases until the desired speed is achieved. After the desired rpm value is reached the torque decreases. The rpm value is then tried to keep constant. The rpm control is used in the passenger cruise ships. The desired rpm value is defined from the control system and then the torque increases step by step to achieve the desired rpm. When the ship leaves from the dock the required torque is very high because of the resistance of the water and it takes time to achieve the desired propeller rpm. When the propeller is stopped but the ship is still sailing the required torque is much smaller to achieve the desired rpm value again because the water resistance is much smaller.

There are several types of frequency converters available, for example cycloconverters, load commutated inverters (LCI), current source inverters (CSI) and voltage source inverters (VSI). Frequency converters operate as 6-pulse, 12-pulse and 24-pulse rectification depending on the application. The pulse number of the rectifier means the amount of unfiltered voltage pulses produced by the rectifier during one full period of the supply voltage. The pulse number depends on the configuration of the rectifier and the supply transformer. [6; 8; 11; 13; 21] In Figure 2.6 is shown an example of different configurations. The current waveform depicts the supply current.

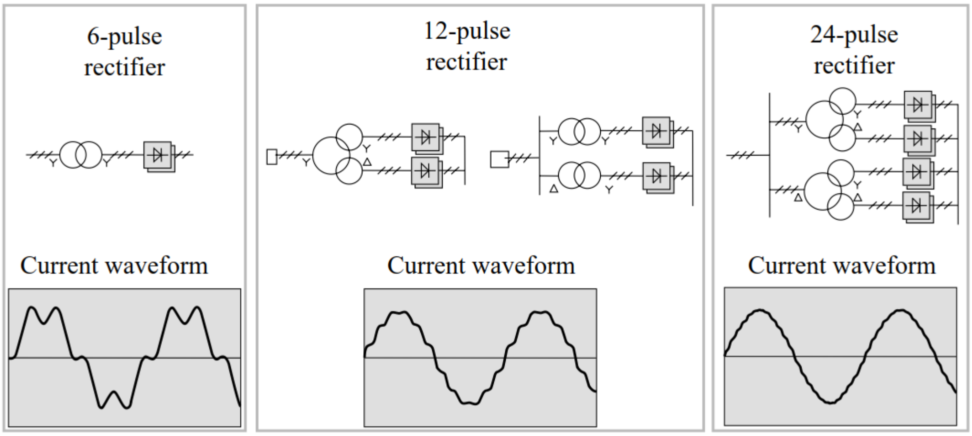


Figure 2.6. *Rectifier configurations with different pulse numbers.* [46]

It can be seen from Figure 2.6 that with 6-pulse rectification the current is highly distorted and with 24-pulse rectification the current is close to sinusoidal. Harmonics and harmonic currents are described more specific in Chapter 5. 12-pulse and 24-pulse configurations are most commonly used in the propulsion system because requirements for the THD are not reached with 6-pulse configuration without specific filtering. [46]

Cycloconverter has no DC link between the rectifier circuit and inverter circuit. It converts the original voltage and frequency to desired values directly. Operation is based on power electronics semiconductors, thyristors. Thyristors can be triggered to conductive state with certain phase angle of the AC voltage. Triggering is done by giving gate pulse for the thyristor. A simple 3-phase to 3-phase cycloconverter is shown in Figure 2.7. Cycloconverter in Figure 2.7 consists of supply transformers and six rectifying thyristor bridges. The main advantage of the cycloconverter is that it can provide high torque with a low speed to the motor. [8; 13; 15; 16]

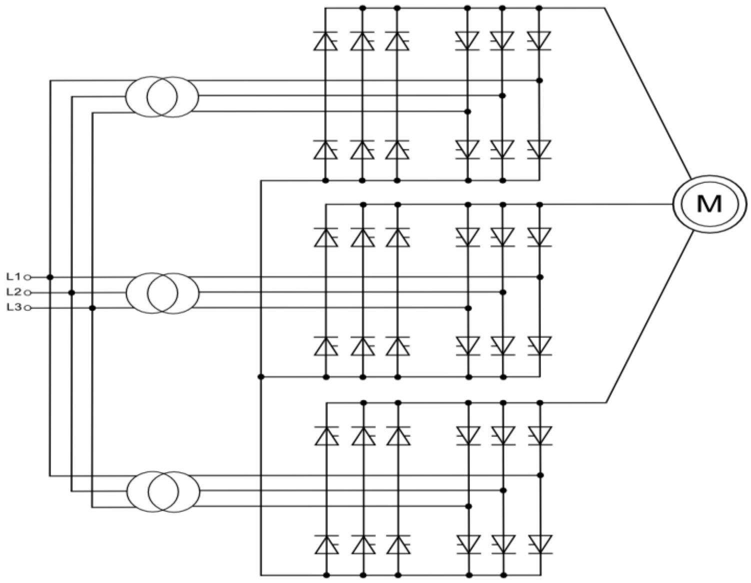


Figure 2.7. *3-phase to 3-phase cycloconverter.* [16]

Current source inverter or load commutated inverter consists of rectifier and inverter circuit and inductor between them. The inductor operates as energy storage between the rectifier and inverter to maintain the current in the circuit as constant as possible. The current source inverter can be used with fast operation of synchronous machines. Typical power electronic components used in CSI or LCI converters are thyristors. The motor provides the commutation voltage, induced voltages, for the inverter bridge in the LCI converter. The cycloconverter or the LCI are not widely used in passenger cruise ships. [8; 13]

Voltage source inverter consists of a rectifying bridge, an inverter bridge and the DC link capacitors between these bridges. Capacitors are used to store electric energy to converter circuit and to smooth the voltage ripple. In marine business and especially in passenger ships the voltage source inverter is used due its low level of disturbances, high efficiency and controllability. Almost all low voltage frequency converters are VSI type. Power factor of the voltage source inverter remains constant regardless of the motor speed, unlike in load commutated and current source inverters power factors vary due to motor rpm. Voltage source inverter can be controlled with pulse width modulation (PWM), vector modulation or for example direct torque control. Basic configuration of 12-pulse voltage source inverter is shown in Figure 2.8. 12-pulse frequency converter is achieved by two parallel 6-pulse circuits and three-winding transformer with two similar secondary side windings. 24-pulse configuration is achieved by two parallel 12-pulse circuits and two transformers as seen on Figure 2.6. [8; 11; 13; 21]

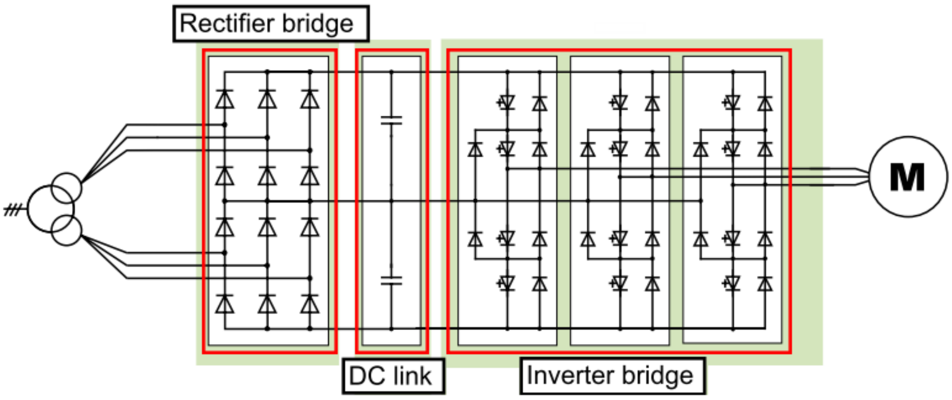


Figure 2.8. *12-pulse voltage source inverter configuration.* [11]

The most expensive frequency converter in the passenger cruise ships is the propulsion frequency converter. Propulsion frequency converter operates like a basic frequency converter and it is usually VSI type converter. VSI has replaced other types because of the benefits related to quality of the electricity and good energy efficiency. The converter is supplied by 3-winding propulsion transformers. The transformers transform the 11 kV voltage to lower voltage level (e.g. 3 kV) because the semiconductor components voltage ratings. In the propulsion frequency converter the semiconductors are usually integrated gate-commutated thyristors (IGCT). The rectifier bridge converts the original AC voltage to DC voltage then the inverter bridge converts the DC voltage back to AC voltage with applicable frequency for the end device, in this case the propulsion motor. This enables the desired propulsion control, rpm control. In marine applications an additional breaking resistor has to be installed parallel with the DC-link to waste the regenerative braking energy. Active rectifying is not commonly used in vessels because active front end drives are expensive and the regenerative braking energy is seldom generated in passenger cruise ships. [3; 8; 13]

2.4.6 Propulsion motors

Nowadays the propulsion system in passenger cruise ships is diesel-electric. The most of the electrical energy is consumed in the propulsion system. For example to get a large passenger cruise ship move with speed of approximately 21 knots requires electric power from 20 MW up to 40 MW depending on the size of the vessel. Propulsion motors are usually synchronous motors. Synchronous motors are used in propulsion systems more often than asynchronous motors because they are more applicable in high power propulsion systems. Synchronous motors are more expensive compared to asynchronous but they offer better power factor, efficiency and they are capable for high torque use. Efficiency of the combination of propulsion frequency converter (VSI type) and synchronous propulsion motor is high, approximately 95 % depending on the speed. [3; 6; 8]

Operation of synchronous motors is similar but opposite to the synchronous generators which were introduced in Chapter 2.4.2. In the synchronous motor the rotor is externally excited whereas the synchronous generators are self-excited. The alternating current is conducted to the stator. The alternating magnetic field generated by the alternating current in the stator windings gets the rotor to rotate. The rotor frame is coupled with the propeller by a shaft. The propulsion frequency converter controls the rotor rotation speed by controlling the frequency of the voltage supplied to motor. The relation between frequency and the rotation speed of the rotor was introduced in (2.1). [5]

Propulsion can be done either with different type azimuth propeller applications or direct drive shaft line propellers. Direct drive was introduced in Chapter 2.2 in Figure 2.2. The direct drive needs longs shaft lines. Long shaft line requires space which is already limited in the ship. Shafts also need bearings throughout the shaft line. A rudder is needed to steer the ship when the shaft line propulsion is used. [6]

Azimuth propulsion means that propeller is attached in a pod and the pod can be rotated horizontally. In Figure 2.9 is shown one azimuth application made by ABB. ABB uses the name Azipod (Azimuthing Podded Drive) for their azimuth propulsion units. Azimuth propulsion does not require a rudder because the podded drive is able to rotate. This also enables more precise steering of the ship. The propulsion motor is inside the pod and the parts shown in Figure 2.9 are all outside of the ship’s hull. Inside the ship are the steering gears that rotate the pod horizontally, cooling system, lubricating units and other auxiliaries needed by the podded drive. [6; 18]

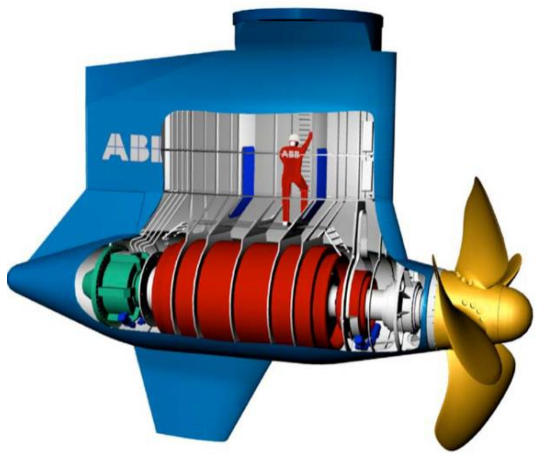


Figure 2.9. *Azipod propulsion unit made by ABB.* [6]

There are also applications where the propeller is coupled to the diesel engine via gear box. Mechanical propulsion requires more strength from the structure of the ship than electric propulsion. For example the vibration is much greater with mechanical propulsion than in diesel-electric propulsion systems. The diesel engines also have to be at same level with the propeller which sets some restrictions to the ship structure. When using the mechanical propulsion there are separate engines that are used in the electricity production. The energy efficiency and controllability is worse with mechanical propulsion compared to electrical propulsion. Nowadays the customer comfort is very important and the diesel-electric propulsion is silent and does not cause such vibrations that mechanical propulsion. Also the energy efficiency is on high priority in passenger cruise ships. [6]

2.4.7 Thruster motors

Thruster motors are also part of the medium voltage network and they are connected to the medium voltage switchboard. Thruster motors are used for sideways movement of the ship and thruster propellers are located in a tunnel at the keel of the ship. The amount of thruster motors varies depending on the size of the vessel and the type of propulsion used. If the ship uses direct drive propulsion there are thrusters both in bow and stern, usually two to three thrusters per side, but when azimuth propulsion is used stern thrusters are not needed. Thruster propeller is directly rotated by an electric motor which is located in the room above the tunnel. In a large passenger cruise ship the electric power of thruster motors can be up to 6 MW whereas in a ferry the electric power varies between 1 MW and 2 MW. For comparison the propulsion power is 20 – 40 MW. The thrust is controlled by hydraulically adjusting the blade angle of the thruster propeller. [1; 2] Tunnel thruster and installation is shown in Figure 2.10.

Figure 2.10. *Tunnel thruster and thruster installation at the keel of the ship.* [25; 26]

Thruster motors are usually asynchronous motors. Asynchronous induction motors are the most common electric motors used in industrial and commercial applications because their construction is simple and they are rather cheap compared to synchronous motors. Due to simplicity, induction motors also are reliable and have low need for maintenance. Asynchronous means that the rotor is rotating with different speed than the magnetic flux in the air gap between the rotor and the stator. [5; 8; 12]

In induction motor there is no separate winding for excitation in the rotor. Rotor winding is a squirrel cage winding which consists of winding bars and the bars are short circuited by conducting rings at both ends. Squirrel cage bars are placed in slots in the rotor and they are not separately insulated from the rotor iron. Squirrel cage winding is shown in Figure 2.11. The induction motor stator is similar with the synchronous motor stator. [5; 12]

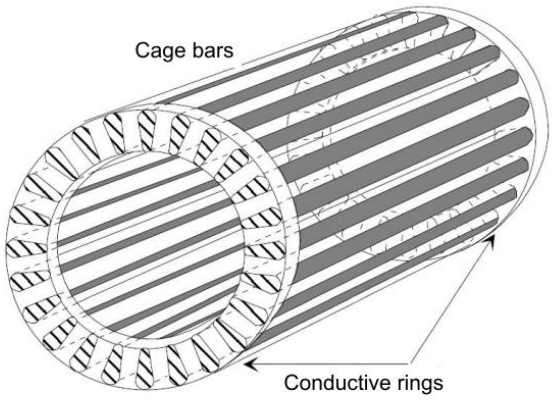


Figure 2.11. *Squirrel cage winding of induction motor.* [5]

Operation of the induction motor is based on rotating field produced by multiphase windings. Alternating voltage is conducted to stator windings which creates alternating magnetic flux. Due to Faraday's law this induces voltage to rotor bars. Rotor starts to rotate when the electric torque is greater than the breaking torque caused by the load. Rotation speed is lower than the speed of the magnetic flux. Difference in rotating speeds is called the slip [5; 9; 12]. The relation between synchronous speed and real rotating speed is defined by equation

$$s = \frac{(n_s - n_r)}{n_s}, \tag{2.4}$$

where n_s is the synchronous speed (Hz), n_r is the real rotating speed (Hz) and s is the slip. The slip depends on the load [5]. With heavy loads the slip is greater compared to lighter loads. Typical slip of induction motor is approximately 1 – 10 % in direct on line (DOL) use where the motor is straightly connected to the electricity network. Because the slip is dependent on the load also the rotating speed depends on it. [3; 5]

Induction motors are widely used in different marine applications because they are rather cheap and easy to control. However induction motors have major effects to electricity network if they are not started properly. Induction motors can be controlled by a simple starter circuit, frequency converter or DOL. If the motor is started and connected directly to electricity network the starting current might be from five to ten times the nominal current. This causes disturbances (voltage drop) to the network and may even harm other devices. For example thruster motors require a lot of electric power which means also great current and the effects might be dramatic to the ship's electricity network if motor starting and control are not done properly. Therefore different starting methods are used. Different methods are for example wye-delta starting, soft starter, frequency converter and adjustable starting transformer. [3; 5; 8; 9]

In wye-delta-starting the motor is started with wye configuration. After the rotation speed is high enough the configuration is changed to delta. This reduces the starting current and the torque for one third of the original values. Soft starter controls the RMS value of the fundamental wave of the voltage. With starting transformer the voltage is dropped to certain level when starting the motor. When the rotation speed increases the voltage is raised incrementally. Frequency converter is used for controlling the rotation speed due to the ability to change the frequency of the voltage fed to the motor. When frequency converter is used there is no need for separate starter because the starting current can be controlled with the frequency converter. [3; 5; 8; 9]

2.5 Low voltage electricity network

In cruise ship the low voltage network is very extensive although the total electric power in low voltage network is less compared to the medium voltage network. Low voltage network covers the engine room auxiliary devices needed by the medium voltage machines and main engines from the bottom decks all the way up on the top deck including crew cabins, passenger cabins, restaurants, shopping malls etc. Also the bridge is included in the low voltage network.

In low voltage network the voltage levels are 400 V, 440 V or 690 V depending on the type of the electricity consumers. In one phase systems usually 230 V or 110 V are applied depending on the market area, frequency and power. In a large ship the electricity distribution in low voltage network is done by using bus bar system and cabling together. Bus bars save space compared to cabling and electricity distribution is easier to implement by using bus bars. Bus bars are connected to distribution transformers and they are installed vertically through different decks. Cabling is used to distribute the electricity inside one deck and one MFZ. [1; 2; 4]

2.5.1 Power distribution boards

Different types of power distribution boards are commonly used between the bus bar and the end device. Power board includes electricity supply, fuses and circuit breakers. Power boards are used to add more power supplies to the network because all devices cannot be connected straight to bus bars; either cable length is too much or there are not enough space for all supplies in the bus bar. As mentioned power board shortens cable lengths and thereby reduces disturbances and power losses easing also protection of cable and devices from overload and short circuit situations. Number of fuses and also the number of devices connected to power board can vary from 3 up to 60. Some devices which require a lot of electric power have to be fed straight from the bus bar because it is not viable enough to manufacture power boards for these devices. [20]

Power boards are usually divided in galley power boards, lighting power boards, power boards for high electric power, dimming boards, emergency power boards and UPS power boards. Galley power boards are used for galley devices such as stoves, refrigerators, deep fat fryers etc. High electric power boards are mainly used for machinery in engine rooms which includes for example different kind of pumps. Dimming and lighting power boards are mainly used for lighting systems and sockets but occasionally also for other systems if there are not available supplies in other power boards. Important systems for example navigation and some of the lighting systems are connected to emergency and UPS power boards to ensure secure operation in different emergency situations. [1; 2; 20]

2.5.2 Lighting

There are many different types of lighting systems and lighting solutions in passenger cruise ships. Besides the normal lighting there are also navigation lights, theatre lights, other entertainment lights and emergency lights. Lighting has an important role of entertaining customers and increase comfort for the passengers but also ensure safety. Lighting systems have to be designed carefully and their effects to the electricity network have to be considered precisely. Some lighting systems are also connected to UPS units to ensure uninterruptible operation.

Previously incandescent and fluorescent lamps were widely used in marine applications but nowadays Light-Emitting Diode –lights (LED) have been gradually replacing them. LED-lights are more energy efficient compared to incandescent lamps but they produce more harmonics and other disturbances to the electricity network than incandescent lamps. Incandescent lamps are purely resistive load and therefore does not produce or consume reactive power. Fluorescent lamps produce reactive power which has to be compensated if the installed load is high enough. However fluorescent lamps are also more energy efficient compared to incandescent lamps which is the reason that they are still a popular solution for lighting systems although LED-lights are becoming more and more popular as the technology advances. [10]

The electric power of lighting varies depending on the ship. For example in cruise ship the total installed electric power of lighting systems might be up to 2 MW although only some of the total power is used simultaneously. The total installed electric power in the low voltage network is approximately 10 MW which means that lighting has a major role in electricity network especially because different lighting systems may be used rather unevenly. [20]

2.5.3 Other systems

Air conditioning has also an important role in passenger cruise ships. Air conditioning is used for cooling down and warming up the public areas and cabins but it is also used in machinery spaces to conduct fresh air to engine rooms and cooling them down. Air conditioning is also used for smoke extracting to extract harmful gases away in emergency situations if needed. Every room including a machine or device that heats up when operating, for example transformers in substations, needs to be cooled down with air conditioning for not overheating and breaking the device. Air conditioning is a very comprehensive system and therefore it is described in more detail in Chapter 3.

Galley systems include for example all the restaurants and bars in the ship. Galleys require a lot of electric power and the galley load is not always very constant. This is the main reason that galleys have their own switchboards and power distribution board in large ships. Some of the galley equipment are continuously switched on and off and without a separate transformer and distribution board this could cause disturbances to other parts of the low voltage network because of these radical changes in electricity consumption. The total installed electric load of the galley systems might be from 2 to 4 MW but as in lighting and air conditioning only a part of the whole system is used simultaneously.

One of the most important systems in ship's low voltage network is the navigation system. Navigation equipment is located all over the ship but navigation is controlled from the bridge or from the secondary bridge which is used in case of when the main bridge is out of operation. Also the propulsion and thrusters are controlled from the bridge. Important navigation systems are duplicated and they are also redundant to ensure safety. The bridge also has control and monitoring for other systems such as communication systems, fire alarm and sprinkler systems and for example automation and power management systems. Therefore it is very important to ensure uninterruptable power supply to the bridge and if needed to the secondary bridge also.

Other systems using low voltage are different type of communication, control and monitoring systems. For example information technology, including both computers and mobile phones, has become such popular and common nowadays that comprehensive data network is inevitable in passenger cruise ships for both passengers and staff. Also control circuits for different types of motors uses low voltage, usually 230 V. Control voltage is taken from the motor supply voltage with separate voltage transformer or straight between phase and neutral line. [1; 2]

3. IMPLEMENTATION OF AIR CONDITIONING

As mentioned earlier, in Chapter 2.5.3, air conditioning is very comprehensive system especially in a large passenger cruise ship. Air conditioning is used in almost every room in the ship with different purpose; for example for cooling down and warming up areas to keep the temperature in the desired level and for extraction of harmful gases and fumes. In the public spaces and in the cabins one of the main reasons for comprehensive air conditioning systems is the comfort and the coziness of the customers. In technical spaces air conditioning is used for cooling devices, fresh air supply, air exhaust and smoke extraction if needed. The electric power of the air conditioning devices varies a lot depending on the purpose and the space that needs to be air conditioned. The implementation of different air conditioning systems is explained in this chapter.

3.1 Main AC-components and public space air conditioning

Air conditioning in the whole ship is divided in different parts depending on the intended use. For example passenger cabins, crew cabins, medical center, public spaces such as theatres and shops, staircases, galleys, laundry stations and different types of technical rooms have its own type of air conditioning system. The whole air conditioning comprises of air conditioning compressor units which are the base for the cooling and warming the air, air handling units which are the main air conditioning units in each main fire zone and fan coil units in every place that needs to be air conditioned. Air conditioning systems also include ventilation grilles and fire or smoke dampers. [28]

The implementation of the air conditioning system differs from one ship to another but the basic operation is the same. The cooled or warmed water or other refrigerant fluid is circulated through different types of air conditioning units so that the air temperature can be changed in the heat exchanger. Air handling units supply the air for the certain area or space and fan coil units are circulating and further cooling the air. The air for the system is taken from the outside of the ship and therefore it has to be dehumidified and then either cooled down or warmed up depending on the outside conditions. [28; 35]

Usually there is a separate control system for heat, ventilation and air conditioning (HVAC) which is connected to the ship's integrated automation system (IAS). Air conditioning can be controlled remotely from the IAS but some parts of the system can also be controlled locally. In modern air conditioning systems there are also independent logic circuits that automatically control for example ventilation grilles. In emergency situation either the whole air conditioning system or some part of it can be shut down from the emergency shutdown system. Parts of the whole air conditioning can also be shut down in a situation where there is not enough generator capacity for running the propulsion and other vital electrical systems. [28; 30]

3.1.1 AC-compressors and the refrigerant system

The air conditioning system is based on the air conditioning compressor units. The compressor units are usually connected to the medium voltage switchboard because of the required great electric power. The units are located at the bottom decks near the switchboard. The amount of compressors and the total electric power depend on the size and on the design of the ship. Usual amount is from two to four compressors and electric power is approximately 600 – 800 kW each in passenger cruise ships. The units are usually installed in separate watertight compartments to ensure safe operation if one part of the ship has a black-out situation or otherwise is out of operation, for example flooding. Cooling capacity is usually few thousand kilowatts per unit. [29]

The compressors are used to change the temperature of the refrigerant fluid, in this case water. A basic schematic of air conditioning compressor unit is shown in Figure 3.1. The air conditioning compressor units in passenger cruise ships comprise of electric motor, compressor, evaporator, condenser and usually sea water heat exchange. [29]

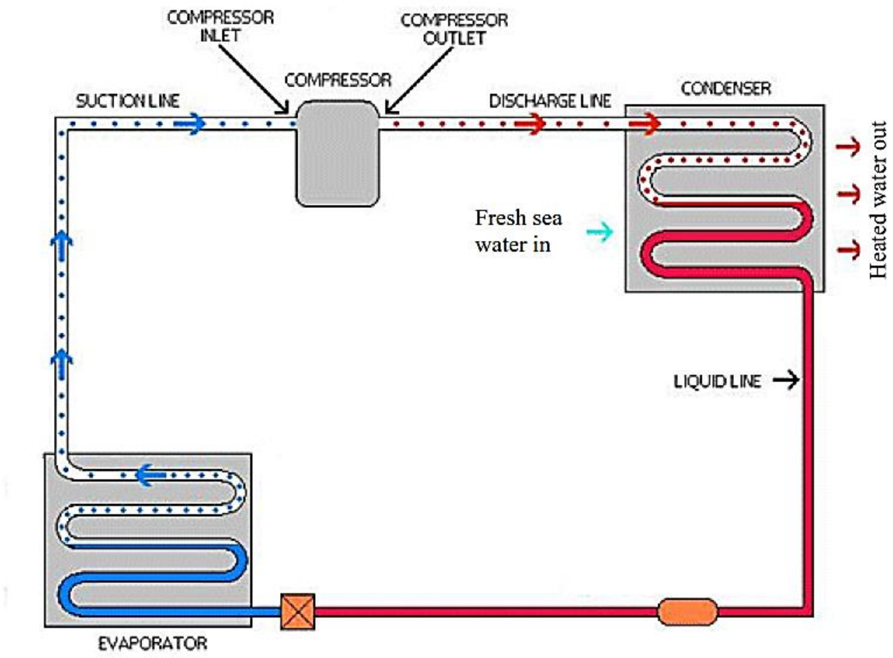


Figure 3.1. *Operation of an air conditioning compressor.* [27]

The refrigerant fluid is supplied in the compressor as vapor and liquid mixture. The compressor pressurizes the vapor which also increases the vapor temperature. The pressurized vapor passes through the condenser unit where the temperature is transferred to the surrounding areas. This process needs heat exchange which is done either by ambient air or water. The heat exchange for air conditioning compressors in passenger cruise ships is usually done by sea water. Sea water pumps are used to pump fresh sea water to the condenser for the heat exchange. Ambient water absorbs the heat from the vapor and the vapor condenses to liquid. The refrigerant fluid then passes an expansion valve which lowers the pressure and cools down the liquid. Heat is exchanged in the evaporator and the liquid turns in to vapor and liquid mixture. [27; 29]

Refrigerant water circulation through the air handling units is done by pumps and raising valves. In summer conditions the compressor cools down the water and in winter conditions the water is warmed up by a heating system located in the compressor unit. Even though the heating system is part of the compressor unit the refrigerant system and the heating system are separate circuits and can be controlled separately. In Figure 3.2 is shown a basic diagram of the refrigerant and heating water flows in the air conditioning system of the Mein Schiff. [28; 29; 35]

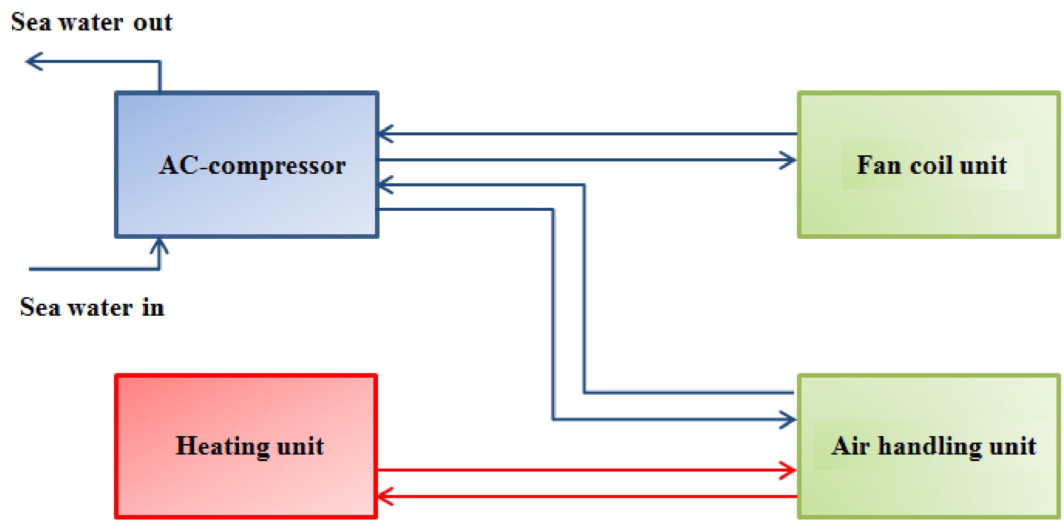


Figure 3.2. *Diagram of refrigerant and heating water flow.* [35]

The circulating water is used for heat exchanging in the air handling units and fan coil units located in different fire zones, areas and spaces in the ship. The solution in Mein Schiff is that heating water circuit is only used in air handling units. Air handling units supplies the air to the dedicated area and the fan coil units only circulate and cool down the air in the area if needed. Only fan coil units used in cabins have a separate heating system because of customer comfort. [28; 35]

3.1.2 Air handling units

Air handling units are the base of the air conditioning in one area of the ship and they are located in air conditioning rooms. There are separate air handling units for staircases, corridors, cabins, galleys and technical rooms. The electricity for the air handling units are usually supplied straight from the bus bars rather than the distribution power boards. The units require electric power of 15 – 40 kW and it is more efficient to arrange the supply from the bus bars because there is just one cable between the air handling unit and the bus bar. Distribution power boards are always connected to the bus bars with a cable which means that there are at least two cables between the end device and the bus bar. Cables limit the available current and therefore the available electric power. The used voltage level is either 690 V or 400 V. The total electric power of one unit includes the power of fan motors and the heating coils. [28]

Air handling units consist of fans and fan motors, a heat recovery wheel and pre-heating coils, air inlet and air outlet and air distribution sections. Air handling units also contain an electric section with power supply, starter circuits or frequency converters. A simple example of an air handling unit is shown in Figure 3.3. Air handling units can deviate from one to another but the parts shown in Figure 3.3 are the base of all the units. [28; 31] The different parts of the unit are

1. Supply air filter
2. Supply side silencer
3. Heat recovery wheel
4. Supply fan(s)
5. Section for inspection
6. Heat exchange section
7. Droplet elimination
8. Exhaust air filter
9. Exhaust fan(s)
10. Electrical section with control box and frequency converter.

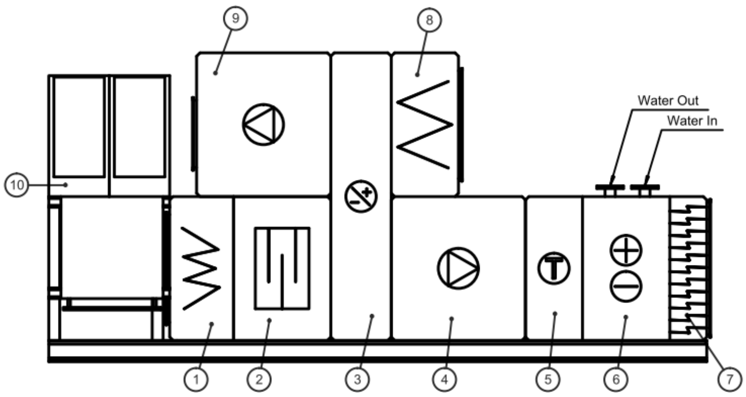


Figure 3.3. *Example of an air handling unit.* [31]

Operation of an air handling unit is based on the heat recovery wheel, heat exchangers and the fans distributing the air through the unit. In the air handling unit shown in Figure 3.3 the fresh air is taken into unit from the left side where the supply air filter is. Air flows through the silencer section to the heat recovery section. The heat recovery wheel is made from heat absorbing material and constructed as a honeycomb matrix. The wheel rotates slowly absorbing heat from the exhaust air and then returning the heat to the supply air. The wheel is usually rotated by a small electric motor. The heat recovery wheel also dehumidifies the fresh outside air that is supplied to the air handling unit. Recovering the heat from the exhaust air makes the system more energy efficient because then the supply air does not need to be heated with external heating coil. The external heating coil is then needed only in winter conditions. [28; 31]

After the heat recovery the supply fan pressurizes and distributes the air forward. There are separate filter and fan sections for supply and exhaust air. Exhaust side is also used for smoke extraction if needed. The fans are run by electric motors, usually induction motors. The electric power of fan motors depends on the amount of air handled by the unit and the size of the space that needs to be served by a single air handling unit. Fan motors are controlled by frequency converters and the frequency converters are connected to the automation system of the ship so that they can be remotely operated for example from the bridge. The pressurized supply air is distributed through the heat exchanging section where the air is either cooled or warmed by the water which is distributed from the compressor units. In winter conditions also an extra heating coil can be used for warming up the air. After the temperature changing section the droplet elimination section is used for eliminating the extra humidity before the air is supplied to the served area or space via ducting. [28; 31]

3.1.3 Other air conditioning components

Air conditioning in certain space is done with different types of fan coil units. Fan coil units are similar compared to air handling units but they are smaller and they have less air conditioning capacity. The total electric power of fan coil units varies a lot depending on the size and type of the served space. For example cabin fan coil units are a lot smaller (< 1 kW) than the units used for public space air conditioning (≤ 10 kW). As mentioned the electric power of a single fan coil unit is usually 1 – 10 kW and the used voltage level varies between 400 V and 690 V. Fan coil units are usually supplied from the distribution power boards but units which require ten or more kilowatts are supplied by the bus bars. [20; 28]

A simple example of a fan coil unit is shown in Figure 3.4. Fan coil unit shown in the figure is mounted horizontally but units can also be mounted vertically. The construction and the operation principle of the unit depend on the served area, for example public spaces and technical rooms have different types of units than passenger or crew cabins. [33] Basic fan coil unit consists of

1. Supply air filter
2. Heat exchange section for cooling
3. Droplet elimination
4. Supply fan.

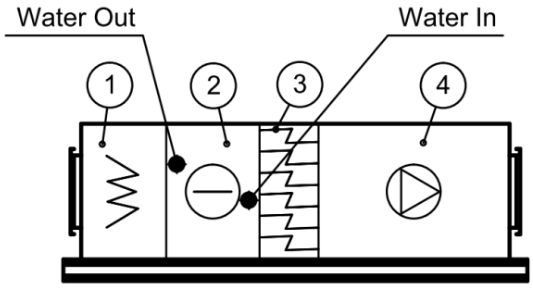


Figure 3.4. *Example of a fan coil unit.* [33]

The used air is taken from the operating area, with separate exhaust fan not shown in Figure 3.4, in the fan coil unit through the supply air filter. Then the air temperature is changed in the heat exchanging section if it is needed. Heat exchanging unit also dehumidifies the air and rest of the extra humidity is eliminated in the droplet elimination section. After the air is handled the supply fan distributes the air back into the served space. Exhaust of the used air from the served space is done with a separate fan or fan unit and then the exhausted air is conducted back to the fan coil unit. Some part of the used air is taken back into the air handling unit so that it can be replaced by fresh outside air. [28; 32; 33]

Principle of the air handling unit and the fan coil unit co-operation in general public spaces is shown in Figure 3.5. Operation of the cabin fan coil units are described in the next chapter. Base for this principle diagram is taken from the air conditioning system of the Mein Schiff.

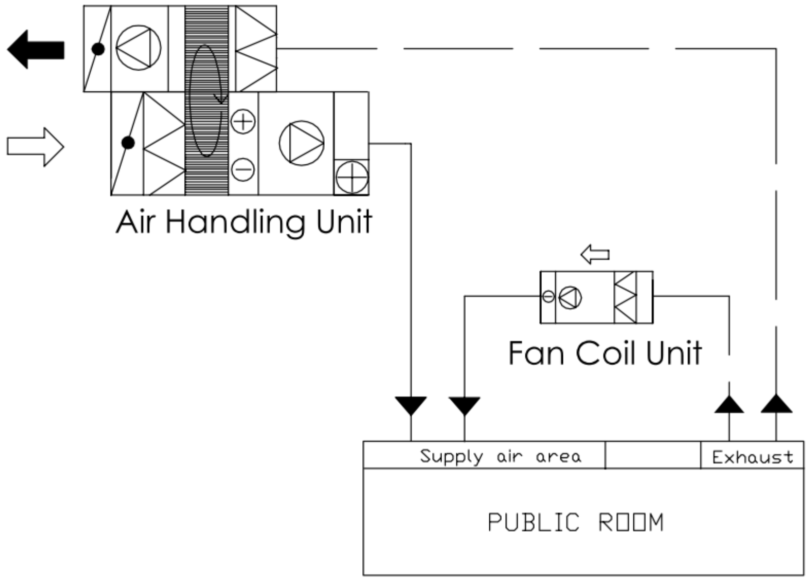


Figure 3.5. *Operation diagram of public space air conditioning.* [33; 35]

The air handling unit supplies the fresh, dehumidified and temperature controlled air to the space. The fan coil unit only circulates the air in the dedicated space. The air can be filtered and cooled in the fan coil unit but usually fan coil units do not contain a heating coil. In winter conditions when the air has to be heated it is done in the heat exchange section of the air handling unit. The air handling unit then supplies the warm air into the public space. The inside air temperature can then be controlled with the fan coil unit by adjusting the cooling air temperature. Therefore there is no need for heating coils in public space fan coil units. [28; 35]

As mentioned before also ventilation grilles and dampers are part of the air conditioning system. Ventilation grilles are grilles that are for example mounted into the fresh air intakes on the side of the hull of the ship. Grilles are also used when one air handling unit is supplying air to two separate spaces or more. The air handling unit supplies the air with certain quantity for both spaces and the air flow into the spaces is controlled by grilles because the needed air supply can deviate between the spaces. Grilles can be opened and closed remotely from the HVAC automation system or they can be independent and adjust the air flow locally by metering variables such as air humidity and temperature. [28; 35]

Dampers or fire dampers are used to prevent the spread of fire through the air conditioning ducting between two different areas. One example of a damper is shown in Figure 3.6. Damper in Figure 3.6 is a combination of fire and smoke damper. Smoke damper prevents the spread of smoke in to the air condition ducting. [34]

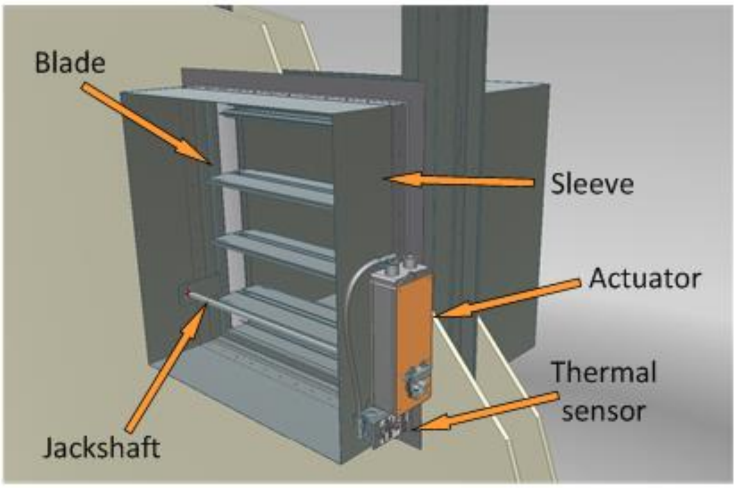


Figure 3.6. *Fire and smoke damper.* [34]

The damper consists of blades, shaft, sleeve, actuator and different types of sensors. The thermal sensor detects temperature changes and when the temperature is high enough a closing signal is given to the actuator. Actuator is a small electric motor which rotates the jackshaft. The electric power of the actuator is usually lower than 100 W. Blades are attached to the shaft and in case of a fire they are closed. Sensors are connected to the automation system and a signal of damper closing is given into the system. Dampers can also be remotely operated for example from the engine control room or from the bridge. [28; 30; 34]

3.2 Cabins and cabin air conditioning

The cabin manufacturing for passenger cruise ships is usually outsourced to an affiliated company. The reason for this is that there are not enough resources in the shipyard itself for manufacturing cabins and it is also more cost-effective to manufacture them in another company. For example in Meyer Turku shipyard the cabin manufacturer is Piikkiö Works which is a subsidiary for Meyer Turku. Because of this the air conditioning components and also electrical parts for cabins are installed by the other company.

The electricity for a single cabin is distributed from the cabin distribution box mounted inside the interior wall at the cabin corridor. Depending on the design of the ship there are two or three cabins connected to the same distribution box. The cabin distribution boxes are supplied from the bus bars. One distribution box from one deck and area is connected to the bus bar. Rest of the distribution boxes that are on the same side of the cabin corridor are linked with the one connected to bus bar. Electricity consumption of a cabin consists of lighting, sockets and air conditioning. The required electric power for a standard passenger cabin is approximately 1 – 2 kW. The voltage level used for cabin distribution boards is 400 V and inside the cabins the voltage is 230 V or 110 V depending on the market area. [36]

Each passenger cabin has its own air conditioning unit, a cabin fan coil unit (CFCU). The cabin fan coil unit is similar to the units used for public space air conditioning except there is a separate heating coil in cabin units. Therefore the air temperature can be changed individually in each cabin approximately on the scale of 20 – 30 ºC. This is necessary for maximizing the passenger comfort. Temperature scale depends on the design and the agreed specification of the ship. Compared to the fan coil unit shown in Figure 3.4 the heating coil is usually located after the supply fan and the droplet eliminator is after the heating coil. The construction of the fan coil unit depends on the air conditioning system supplier. [28; 32; 33]

Figure 3.7 shows an operation diagram of the cabin air conditioning. The air for the cabin fan coil unit is supplied from the air handling unit located in the same area with the cabin fan coil. The air handling unit is serving cabins on both side of the cabin corridor as shown in Figure 3.7. The amount of fresh air flow from the air handling unit to the cabin fan coil units is adjusted by the system operator and the flow set point is based on the outside temperature.

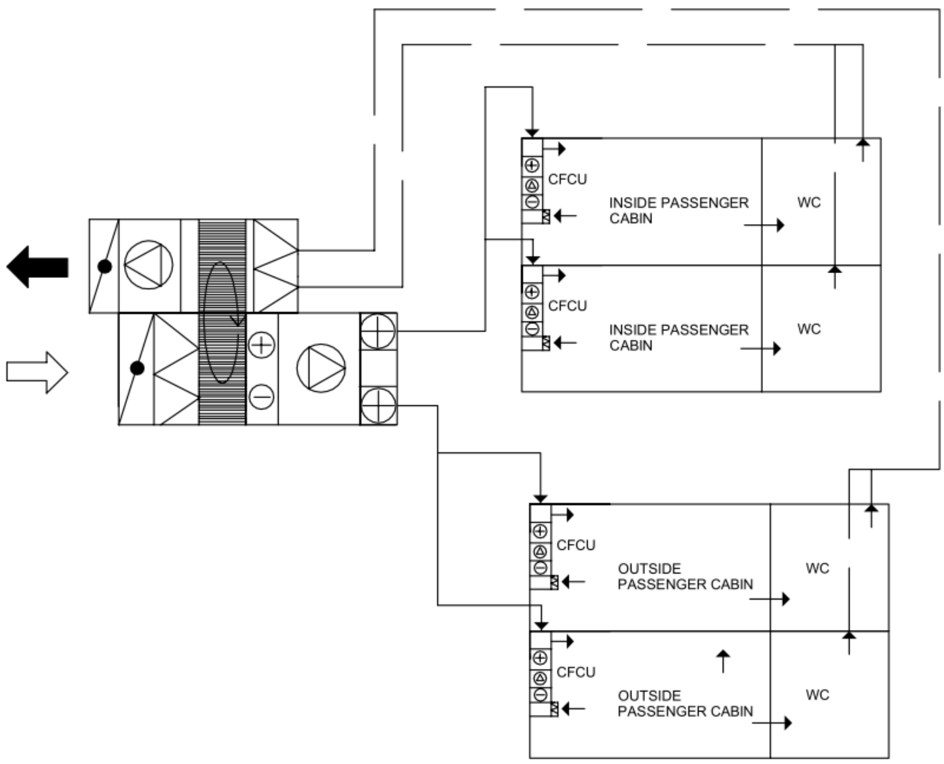


Figure 3.7. *Operation diagram of cabin air conditioning.* [28; 35]

Unlike in public space air conditioning where the air into the space was supplied by the air handling and then circulated by the dedicated fan coil unit, in passenger cabins the air is supplied inside to the cabin through the fan coil unit. The fan coil unit is located outside of the cabin and inside the cabin there are only a diffuser for air supply and exhaust ducting is located in the bathroom. [28; 35]

The fan in the fan coil unit is nowadays uses an electronically commutated motor (EC-motor). EC-motors are used because they do not require a separate frequency converter and they are more energy efficient compared to a traditional induction motor. EC-motors and their effects to the electricity network are described in more details in the next chapter. The cabin air conditioning is implemented by a module which includes the EC-motor, heating coil, cooling coil, controller inside the module, control unit inside the cabin and sensors which are monitoring if the cabin is occupied or the balcony door is open. The air conditioning module is shown in Figure 3.8.

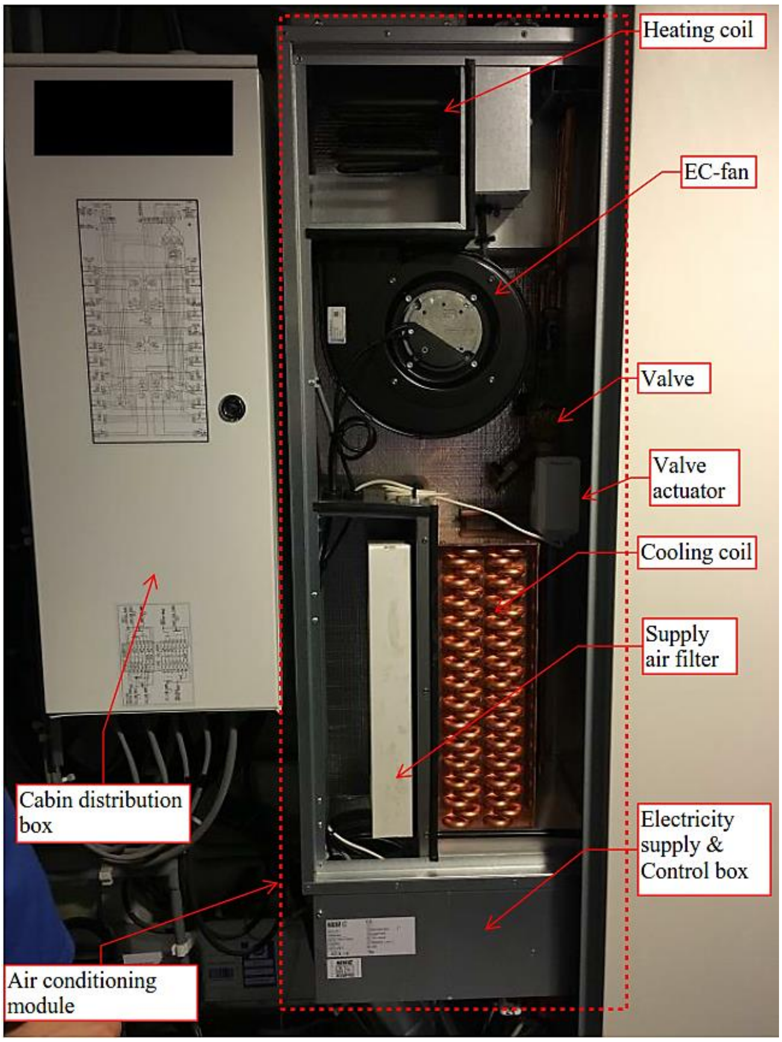


Figure 3.8. *Cabin air conditioning module.*

The EC-fan is a combination of EC-motor and centrifugal fan. The supply air is taken in from the bottom of the module and then the air goes through air filter and cooling unit. Cooling water flow is controlled by the valve. The cooled air is then supplied to the fan. After the fan there is the heating coil and the air is heated if necessary before it is supplied inside the cabin. All of these are pre-mounted in the cabin at the cabin factory and the shipyard's task is to connect the electricity supply and test the system. The air conditioning module is already connected to the cabin distribution box in the cabin factory.

4. ELECTRONICALLY COMMUTATED MOTOR

AC motors and especially induction motors are very popular in different types of electrical applications because of their simplicity and durability. However the energy efficiency of an induction motor is rather limited due to for example copper losses in the rotor. The need for better energy efficiency has driven motor manufactures to develop more and more efficient electric motors and one solution for rather small applications, for example air conditioning fans, is the EC-motor.

Briefly, the EC-motor is a brushless direct current motor, DC-motor, which has an electronic commutating unit integrated in the structure of the motor. EC-motor is more expensive and it has more complex structure than a basic induction motor but the energy efficiency is better. There are also other advantages and some disadvantages which are described in this chapter alongside the other features of the EC-motor. [39]

4.1 Construction

Construction of an EC motor is more complex compared squirrel cage induction motor mostly because of the need for commutation. Between EC-motors there are a few variations in the construction. The used construction depends on the field of application. Two different types of structures of the motor are shown in Figures 4.1 and 4.2.

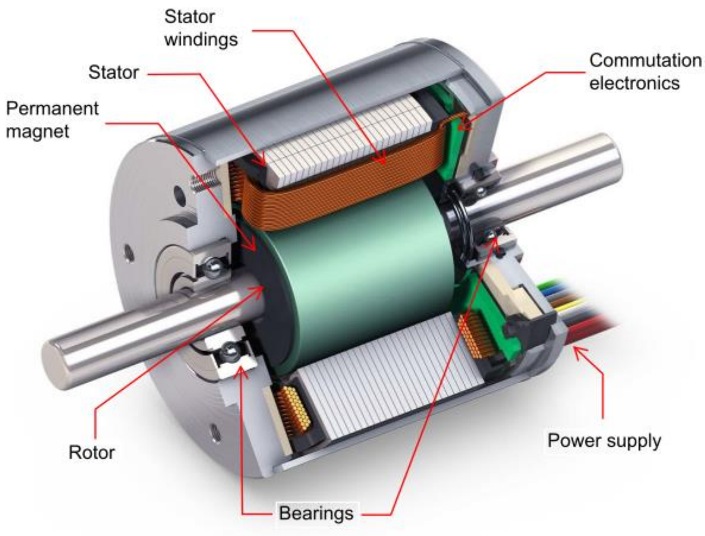


Figure 4.1. *Structure of an EC-motor with internal rotor.* [37; 38]

The EC-motor in Figure 4.1 is similar to a basic induction motor in some parts. The exceptions are that there is the electronic commutation unit mounted in to the motor housing and compared to an induction motor the rotor windings are replaced with a permanent magnet. The permanent magnet rotor disables the rotor copper losses which improves the total efficiency of the motor. In the construction shown in Figure 4.1 stator has similar windings as there is in the induction motor. The iron cores in the stator are constructed from laminated metal sheets. [38; 42]

The most commonly used type of the EC-motor is the construction with external rotor which is shown in Figure 4.2. This type of construction is especially used in air conditioning applications because of the small size and the fan is easy to mount on to the rotor housing.

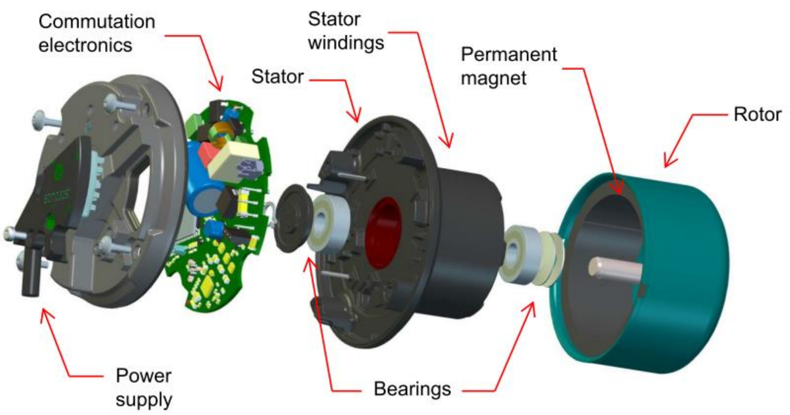


Figure 4.2. *Structure of an EC-motor with external rotor.* [40]

In this external rotor construction, the rotor itself is mounted outside from the stator and only the shaft is inside the stator. The shaft does not go through the whole construction, as in other motor types, which reduces the physical size of the motor. Also in this case the other end of the motor housing can be entirely reserved for the commutation electronics and power supply. The inner circle of the rotor housing is covered with permanent magnets. The stator has copper windings for creating the alternating magnetic field. Stator windings are located inside the middle part of the motor shown in Figure 4.2. [38; 42]

EC-motors are also equipped with different types of sensors depending on the field of application. Sensors are used for example in rotor speed detection for feedback to the control system. A Hall Effect sensor is used to determine the rotating speed of the rotor. The Hall Effect sensor is a transducer which varies its output voltage with respect of alternating magnetic field. Other sensors, for example pressure and temperature sensors, can be used to get information from the ambient conditions and this information is used to adjust the motor and fan speed. [39; 43]

4.2 Operation

Traditional brushed DC-motors have to be supplied with DC voltage. This means that for example in electricity distribution networks the AC voltage has to be converted to DC voltage with a rectifying unit before supplying the voltage to the motor. The DC voltage is supplied into the rotor windings through coal brushes and split ring. This combination of the split ring and the coal brushes are the commutation unit of the brushed DC-motor. [9; 12] Commutation unit is shown in Figure 4.3.

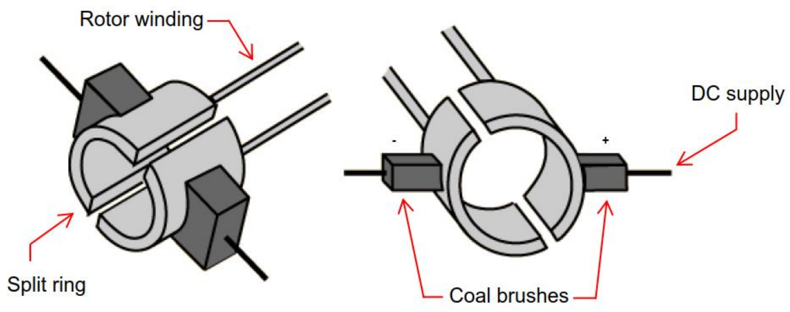


Figure 4.3. *Commutation of a DC-motor.* [41]

The split ring is a ring which is divided in two halves. The split ring is used to change the direction of the current flow in the rotor. Changing the current flow direction creates the alternating magnetic field which is needed for the operation of the motor. In a traditional DC-motor the stator can be constructed from two permanent magnets with different magnetic poles. In some applications there might also be windings in the stator and then the DC voltage has to be conducted to the stator windings alongside the rotor windings. The motor control can be done by varying the rotor or stator current or both at the same time. [9; 12]

In the EC-motor the commutation is done with commutation electronics. This means that the motor can be supplied with AC voltage and the electronics included in the motor first rectifies the AC voltage to DC voltage. The commutation is then done as DC voltage pulses (voltage steps) for the stator poles. Different pole pairs in the stator are excited at different time to create rotating magnetic field. Figure 4.4 shows the operation principle of the electronic commutation.

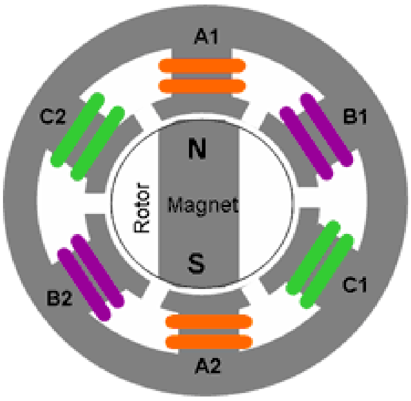


Figure 4.4. *Brushless DC-motor, EC-motor, commutation principle.* [64]

One pole pair, e.g. A1-A2, is fed with DC voltage pulse. The DC pulse excites the A1 as south pole and the A2 as north pole. This gets the rotor to rotate. After the permanent magnet passes the first pole pair then the second pole pair, B1-B2, is excited with DC pulse. Adjusting the sequence of the DC pulses the motor can be controlled in a desired way (rpm control). [64] With the commutation electronics the control of the speed is very precise if the control system is implemented carefully. The motor speed and the ambient conditions have to be continuously monitored to achieve the best control and thus the best efficiency. [39]

Usually the motor electronics are controlled either with 0 – 10 V voltage signal, pulse width modulation (PWM), 4 – 20 mA current control signal or with potentiometer. Potentiometer is adjustable resistor which operates as a voltage divider. Different voltage levels are then used for motor control. The feedback from the motor itself, rotating speed, is given by the Hall Effect sensor. The information about the rotating speed is then utilized in the controller circuit. The information from the external sensors, for example temperature, pressure and air flow sensors, is used to create reference value for the needed rotating speed. The controller circuit then compares the information about the actual rotating speed to the determined reference value and controls the switching frequency in the electronic commutator to achieve the desired rotating speed. EC-motors can even operate independently without any external automation system. [39; 44]

4.3 Efficiency

The efficiency of an EC-motor is much better compared to induction motor mainly because there are no copper losses in the rotor. [39] In Figure 4.5 is shown an efficiency comparison between an EC-motor, 3-phase induction motor and 1-phase induction motor. The efficiency of an induction motor is rather low especially in low electric power motors as seen on Figure 4.5. [42]

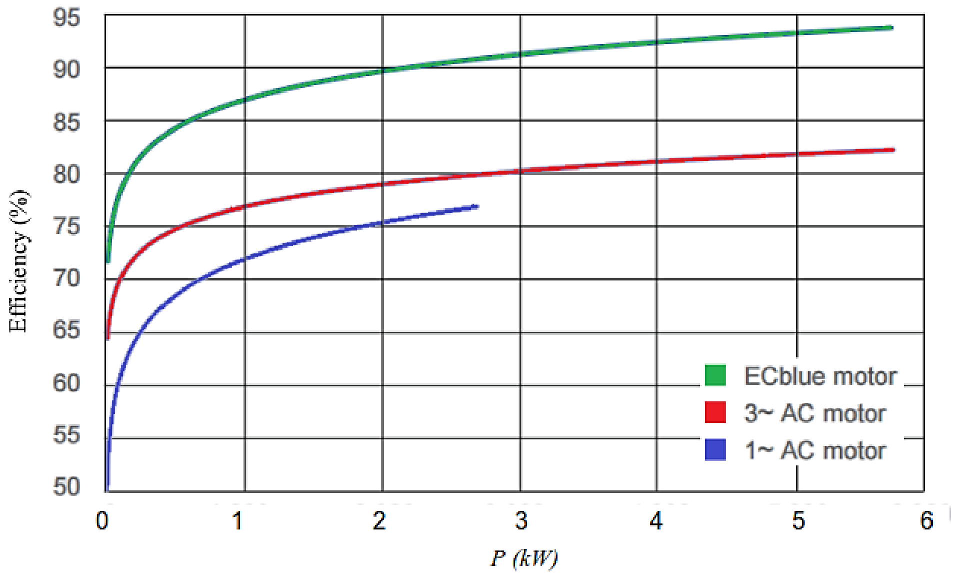


Figure 4.5. *Efficiency of an EC-motor compared to 1-phase and 3-phase induction motors.* [42]

With great electrical power, *P* > 100 kW, the efficiency of an induction motor is better but still not as good as in EC-motors. On the other hand EC-motors are not widely available with great electric power mainly because it is not so cost-effective compared to the combination of induction motor and frequency converter. Adding a frequency converter to the supply of the induction motor improves the power factor (PF), e.g. from *PF* = 0,75 to *PF* = 0,95, and therefore also the efficiency. [42]

A power consumption comparison between an EC-motor fan, voltage controlled AC-motor fan and AC-motor fan with frequency converter is shown in Figure 4.6. The fans' total electric power is 1 kW on the nominal speed in this example. The power consumption comparison is done with fan speed of 60 % of the nominal speed. [42] This example is based on one fan motor manufacturer's information about their motors and there might be some deviations between manufacturers but the basic idea is the same.

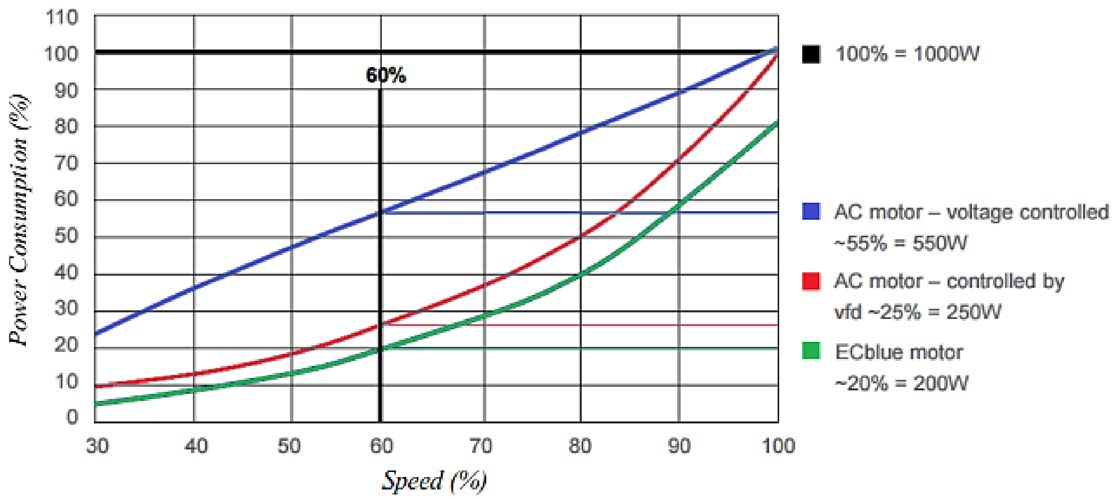


Figure 4.6. *Power consumption of the different types of motors.* [42]

It can be seen from Figure 4.6 that the EC-motor fan has the lowest power consumption and therefore also the best efficiency. The standard voltage controlled AC-motor fan has the most power consumption and so on also the worst efficiency. Voltage controlled AC-motor is connected to the electricity network by a simple starter circuit without any separate converter. Adding a frequency converter alongside of the AC-motor the power consumption reduces significantly. Therefore the variable frequency drive controlled AC-motors have almost as good efficiency as the EC-motors.

4.4 Applications

EC-motors are used in many applications nowadays and one of the most common fields of use is air conditioning systems. The popularity of the EC-motors in air conditioning systems is based on the small size of the motor construction and on the energy efficiency of the motor. There is also no need for separate frequency converter which increases the popularity. [39] For example room air conditioning can be done with EC-motor fan and a control module which is located in the room. Module controls the speed of the fan when temperature is adjusted from the module's buttons.

EC-motors are also used in automotive industry. For example engine cooling are easy to implement with EC-motor fan. There are also applications where the EC-motor can be used in the transmission systems and in different types of engine management applications. EC-motors are also developed to be used as a main motor of an electric car which could be a significant field of application for EC-motors in the future. [39; 45]

5. EFFECTS TO THE QUALITY OF ELECTRICITY

Quality of the electricity has a very important role in the electricity network of a ship. The increasing use of power electronic components affects to the quality of the electricity because these components are nonlinear. Nonlinear means that the load impedance changes due to applied voltage and current. Nonlinear load distorts the supply current and voltage waveforms and creates both current and voltage distortion back in to the electricity network. For example electric motors with frequency converters are nonlinear loads. [46]

Things that have an effect to quality of electricity are frequency, voltage level, slow and fast voltage level variation, voltage peaks, harmonics, asymmetry in the 3-phase system (uneven loading of phases), DC component of the voltage and interruptions. [47] All of these issues have to be taken in to account when designing a reliable electricity network. Harmonics are the main disturbance caused by EC-motors because of the voltage rectification [53].

5.1 Harmonics and harmonic distortion

The non-sinusoidal waveform of the voltage or the current consists of multiple sine waves with different frequencies summed together. The frequency of these additional waveforms is usually a whole multiple of the fundamental frequency (50 Hz or 60 Hz). The whole multiples are called harmonics and the distortion is called harmonic distortion. In Figure 5.1 is shown a few examples of distorted current waveform. The top two figures are examples of a distorted current in 1-phase systems and the bottom two are examples of 3-phase systems. [46]

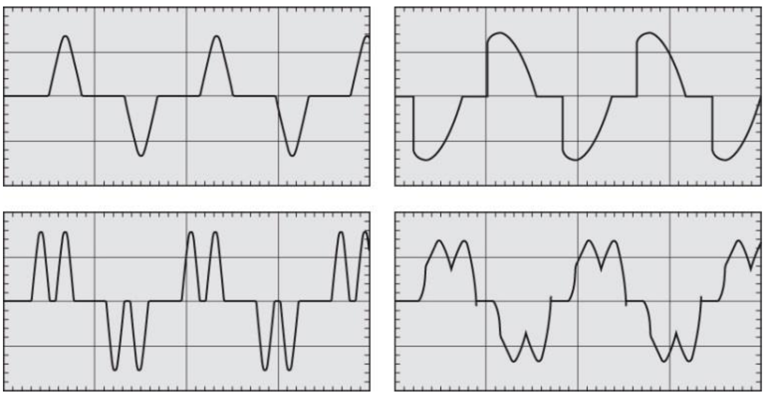


Figure 5.1. *Distorted current waveforms.* [46]

For example the left figures are 1- and 3-phase rectifiers. The supply current only flows from the network in to the load when the amplitude of the supply voltage exceeds the amplitude of the load side capacitor voltage. The right side figures can also be rectifiers but there is also some inductive reactance, choke inductor, included in to the circuit. [53; 54]

As seen on Figure 5.1 the harmonics generated by the nonlinear load distorts the waveform of the supply current. In Figure 5.2 is shown a simple example of the effects of the 3rd harmonic component to the total voltage waveform (resultant waveform).

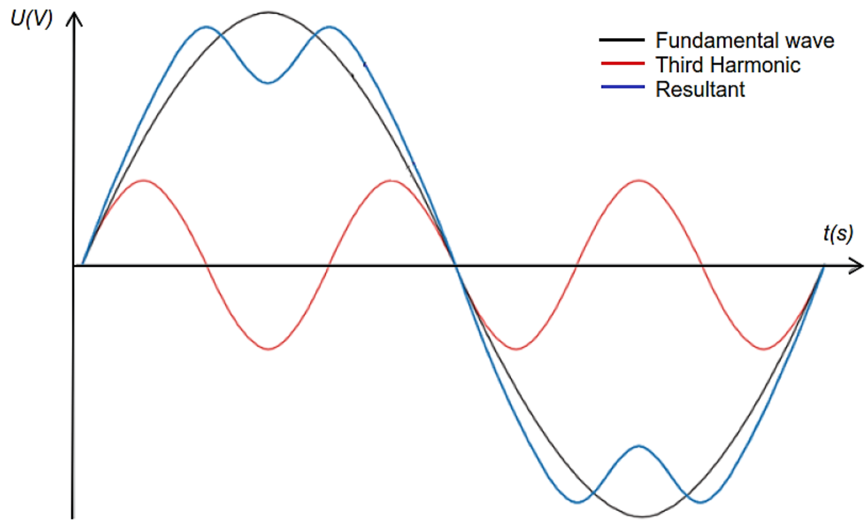


Figure 5.2. *The effect of the 3rd harmonic component to the voltage.* [49]

In Figure 5.2 the negative peak of the 3rd component and the positive peak of the fundamental wave are against each other during the first half period. On the second half period the situation is opposite. The result is a resultant waveform that has two peaks on both half periods. With more harmonic components the resultant wave would be more distorted. [49] There can also be interharmonic currents and voltages in electrical systems. These types of waves are not whole multiples of the fundamental wave frequency. [56] For example in Finland the fundamental frequency in the electricity network is 50 Hz and the multiple harmonic wave frequencies are 150 Hz (3rd harmonic), 250 Hz (5th harmonic), 350 Hz (7th harmonic) etc. The phase of the harmonic component affects to resultant waveform also.

5.1.1 Fourier theorem and harmonic series function

The distorted resultant waveform can be analyzed with the Fourier theorem which states that all periodic functions can be represented as the sum of the series made up from the sinusoidal fundamental wave (fundamental frequency), sinusoidal harmonic waves (frequencies that are whole multiples of the fundamental frequency) and the DC component which is the long term average of instantaneous voltage. The total wave function can be divided in series terms due to equation

$$F(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n \cdot \omega \cdot t) + \sum_{n=1}^{\infty} b_n \sin(n \cdot \omega \cdot t), \tag{5.1}$$

where the $F(t)$ is the periodical total wave function (voltage or current), n is a positive integer 1, 2, 3…, ω is the angular speed (rad/s) and t is the time (s). Coefficients a_0, a_n and b_n are defined in equations

$$a_0 = \frac{1}{T} \int_0^T F(t) dt \tag{5.2}$$

$$a_n = \frac{2}{T} \int_0^T F(t) \cos(n \cdot \omega \cdot t) dt \tag{5.3}$$

$$b_n = \frac{2}{T} \int_0^T F(t) \sin(n \cdot \omega \cdot t) dt, \tag{5.4}$$

where the T is the period of time of one full cycle (s). First term of the series ($n = 1$) is the fundamental wave. The a_0 depicts the DC component. The a_n and the b_n are the coefficients for the nth harmonic order. If the function $F(t)$ is symmetrical with respect the origin then the series contains only odd terms ($n = 3, 5, 7…$). [46; 48; 51]

Based on the Fourier theorem the instantaneous voltage can be calculated with simplified equation

$$\begin{aligned} u(t) &= U_0 + \sum_{n=1}^{\infty} \left[\sqrt{2} U_n \sin(n \cdot \omega \cdot t + \alpha_n) \right] \\ &= U_0 + \sum_{n=1}^{\infty} \left[\sqrt{2} U_n \sin(n \cdot 2 \cdot \pi \cdot f_1 \cdot t + \alpha_n) \right], \end{aligned} \tag{5.5}$$

where the $u(t)$ is the instantaneous voltage (V), U_0 is the voltage DC component (V), U_n is the nth harmonic order RMS phase voltage (V), f_1 is the fundamental frequency (Hz) and α_n is the phase angle of the nth harmonic order (rad). [47; 48]

The total RMS voltage U_{RMS} (V) and current I_{RMS} (A) can be calculated using equations

$$U_{RMS} = \sqrt{\sum_{n=0}^{\infty} U_n^2} \tag{5.6}$$

$$I_{RMS} = \sqrt{\sum_{n=0}^{\infty} I_n^2} \;, \tag{5.7}$$

where U_n is the n[th] harmonic order RMS phase voltage (V), I_n is the n[th] harmonic order RMS current (A). From (5.6) and (5.7) can be seen that harmonics increases the total RMS voltage and current which can be harmful for devices but also increases losses in the electricity network. [46; 47; 54]

Harmonics are divided in components due to their order. Each harmonic order has its own sequence in 3-phase systems i.e. the phasor rotation direction with respect to the fundamental wave. The components are positive sequence, negative sequence and zero sequence. [47] Table 5.1 shows the component definition of the first nine harmonic components.

Table 5.1. *Harmonic component definition.* [47]

Harmonic order	1	2	3	4	5	6	7	8	9
Frequency *f* (Hz)	50	100	150	200	250	300	350	400	450
Sequence	+	-	0	+	-	0	+	-	0

As seen in Table 5.1 the harmonic orders 4[th] and 7[th] are positive sequence which means that the vector rotation is in same sequence with the fundamental wave. Orders 2[nd], 5[th] and 8[th] are negative sequence harmonics which rotate in the opposite direction. The orders that are multiples of 3 are zero sequence. [47; 52]

5.1.2 Harmonic spectrum

Harmonics are usually presented in a line spectrum. Line spectrum or harmonic spectrum is a representation of the amplitude of each harmonic order with respect to its frequency and it is an easy way to compare the amount of harmonic contents to the fundamental wave. The spectrum is formed by comparing the harmonic order amplitudes to the amplitude of the fundamental wave as in equations

$$u_n = \frac{U_n}{U_1} \tag{5.8}$$

$$i_n = \frac{I_n}{I_1} \,, \tag{5.9}$$

where u_n (for voltage) and i_n (for current) are the relative values for the harmonic order content, U_1 is the RMS voltage (V) and I_1 is the RMS current (A) of the fundamental wave. The line spectrum is formed using (5.8) for voltage or (5.9) for current because fundamental frequency values for voltage U_1 or current I_1 are used in THD calculation which is introduced later. [46; 48]

In Figure 5.3 is an example of the harmonic spectrum. The relative values of the harmonic orders are on the y-axis and the frequency is on the x-axis. The fundamental frequency is 50 Hz and the harmonic frequencies are multiples of the fundamental value from 3rd to 11th order.

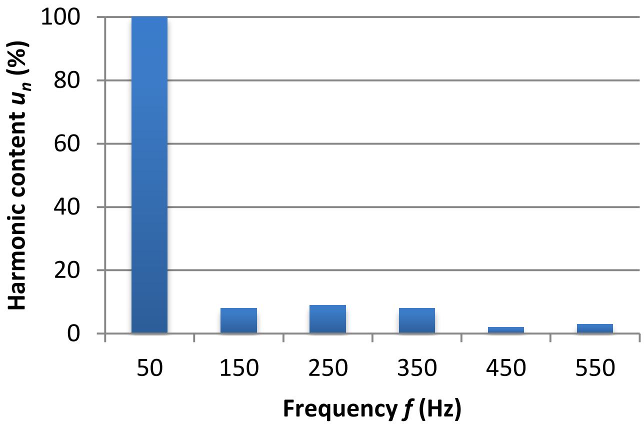


Figure 5.3. *Harmonic spectrum example with odd harmonic orders.*

From Figure 5.3 can be seen that the 3rd (u_3 = 8%), the 5th (u_5 = 9%) and the 7th (u_7 = 8%) harmonic order have greater amplitude than the rest. This is usually the case in the low voltage network because for example fluorescent lamps produce the 3th harmonic and simple 3-phase rectifiers produce the 5th and 7th harmonic most commonly. The electricity network from which the harmonic spectrum is formed in Figure 5.3 is rather well compensated because the total harmonic content seems to be low. [47; 48; 50]

Only the odd harmonic orders are shown in Figure 5.3 because usually the even harmonic orders are in a minor role if the system is assumed to be symmetrical with respect to origin; the loading is symmetrical. For example symmetrical full wave rectification in 3-phase systems produces only odd order harmonics whereas half wave rectification produces also even order harmonics.

5.1.3 Total harmonic distortion

Total harmonic distortion is used to inform, how much there are harmonics in the system in total. The THD is percentage of all harmonic orders with respect to the fundamental values of the voltage or the current. The THD can be calculated with equations

$$THD_u = \sqrt{\sum_{n=2}^{n=k} \left(\frac{U_n}{U_1} \right)^2} \tag{5.10}$$

$$THD_i = \sqrt{\sum_{n=2}^{n=k} \left(\frac{I_n}{I_1} \right)^2} , \tag{5.11}$$

where THD_u is the THD value for the voltage, THD_i is the THD value for the current and k is an integer. The maximum value of k varies from 25 to 50 depending on the requirements of the THD calculation. Usually calculations up to 25th order are enough to give sufficient knowledge about the harmonic content in the network. However harmonics are often calculated up to 50th order because it is required by standards and classification societies. [47; 48]

Electrical devices have to be built in such way that THD limits set by different standards, for example IEC 61000-2-3, are not exceeded. Examples of the current harmonics RMS values set by the IEC 61000-2-3 are shown in Table 5.2.

Table 5.2. *Allowed harmonic current RMS values according to the IEC 61000-3-2.* [53]

Harmonic order *n*	**Maximum RMS (A)**
2	1,08
3	2,30
4	0,43
5	1,14
6	0,30
7	0,77
9	0,40
11	0,33
13	0,21

Meeting the standards often requires adding filters alongside the device to reach the regulations considering the maximum THD values. Classification societies also have their own regulations for the maximum THD in the electricity network but they are based on the standards. For example DNV-GL requires that the voltage THD shall not exceed 8 % in the electricity distribution system and no single harmonic order shall exceed 5 %. This regulation is based on the standard IEC 61000-2-4 class 2. Also the ship building contract (the ship specification) includes the information about the maximum voltage THD in the medium voltage and in the low voltage network. Usually in medium voltage network the THD is limited to 5 % and in low voltage network to 8 % but still no single order harmonic shall exceed the 5 % because of the classification requirements. [17; 53]

5.2 Harmonics sources

Harmonics are caused by nonlinear electrical loads. Frequency converters and rectifiers contain power electronic components which makes them nonlinear. Also generators, electric motors and transformers are nonlinear. One major nonlinear load in a passenger cruise ship is the lighting which includes both fluorescent and LED-lights nowadays. Rectifiers are the most interesting source of harmonics in this thesis because EC-motors contain rectification circuit and therefore EC-motors also produce harmonics. Other sources are briefly described even though the diesel-electric propulsion system produces the most harmonics in medium voltage network. In low voltage network the electric load is much more complex due to so many different types of devices. [46; 47]

Harmonics can be analyzed with so called ideal harmonic theory. The ideal theory for harmonics is based on current source thinking which means that the harmonic source supplies the harmonic currents ideally to the AC network. Rectifiers can be thought as these kinds of harmonic sources. Other harmonic sources (e. g. transformers) can be thought as source of harmonic voltages rather than harmonic currents. Harmonic currents supplied to the network forms harmonic voltages when facing impedance. Harmonic voltages sum up to the fundamental voltage and form a distorted resultant voltage wave. [47; 50]

When using the ideal theory for harmonic source some assumptions have to be made for the network and rectifiers; the AC network is symmetric, the voltage is sinusoidal, the network impedance is 0 Ω, no commutating inductor installed in front of the rectifier, thyristor control angle is the same in all thyristors and the DC voltage produced by the rectifier is completely smooth (no ripple). [47; 50]

5.2.1 Rectifiers, inverters and frequency converters

As mentioned before electricity networks nowadays contain a lot of power electronic and electronic devices. Usually small electronic devices require DC voltage and therefore voltage conversion from AC to DC. Power electronics are used for example to precise motor control and switched mode power supply (SMPS). Rectifiers, inverters and frequency converters consist of semiconductor components, capacitors, inductors and resistors. The semiconductor components are diodes, thyristors and transistors. Thyristors and transistors can be controlled with separate control circuit which creates desired control signal for these components. Frequency converter is a combination of rectifier and inverter circuits as mentioned in Chapter 2.4.5. [46; 48; 50]

The ideal harmonic theory simplifies the calculations for the harmonic current content produced by a rectifier. In the ideal situation the harmonic orders produced by the rectifier can be calculated with the equation

$$n = k \cdot p \pm 1, \tag{5.12}$$

where n is the harmonic order, k is a positive integer and p is the pulse number of the rectifier. According to the (5.12) for example the 6-pulse rectifier produces harmonic orders n = 5, 7, 11, 13…, 12-pulse rectifier produces n = 11, 13, 23, 25… and 24-pulse rectifier produces n = 23, 25, 47, 49… Increasing the pulse number eliminates harmonics significantly. [47; 50]

In the ideal case the harmonic currents can be calculated with simplified equation [47]

$$I_n = \frac{I_1}{n}. \tag{5.13}$$

According to the ideal harmonic theory the pulse number defines the produced harmonic orders only. In this case the current taken from the electricity network to the rectifier is square wave. In reality there are always other harmonic orders as well. The impedance of the electricity network is never 0 Ω which means that commutation cannot be infinitely fast and the current waveform is not pure square wave. Also the DC voltage always contains ripple and is not completely smooth. The 3-phase electricity system is not completely symmetric in reality because usually the electric loads are not ideally divided between phases. Asymmetry causes even harmonics (n = 2, 4, 6…) and harmonics which are multiples of 3. [47; 50; 57]

In Figure 5.4 is shown an example of full wave diode bridge rectifier circuit. A basic 1-phase circuit consists of voltage source, four diodes and DC-link capacitor. In the figure i_{in} is the input current, u_{in} is the input voltage, C is the DC-link capacitor (smoothing capacitor), u_o is output voltage of the rectifier, i_C is the current charging the capacitor and i_{load} is the load current. [53; 54]

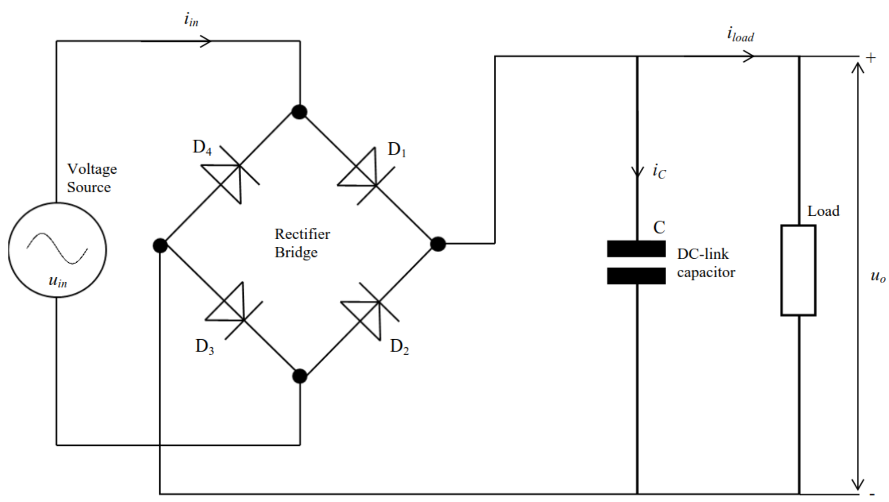


Figure 5.4. *1-phase full wave diode bridge rectifier.* [54]

The diodes D_1 and D_3 are forward biased and conduct the current during the positive half cycle of the supply. The diodes D_2 and D_4 are then reverse biased. During the negative half cycle the diodes D_2 and D_4 are forward biased and conduct the current. The diodes D_1 and D_3 are then reverse biased. The DC-link capacitor is used to even and increase the RMS value of the output voltage. Without the DC-link capacitor the rectifier forms only positive amplitudes to the output voltage with same peak values than in the input voltage. [54] In Figure 5.5 is shown the output voltage waveform of the rectifier without the DC-link capacitor and with the capacitor. The input current waveform is depicted with the capacitor. The electrical power of the load is 500 W. [54]

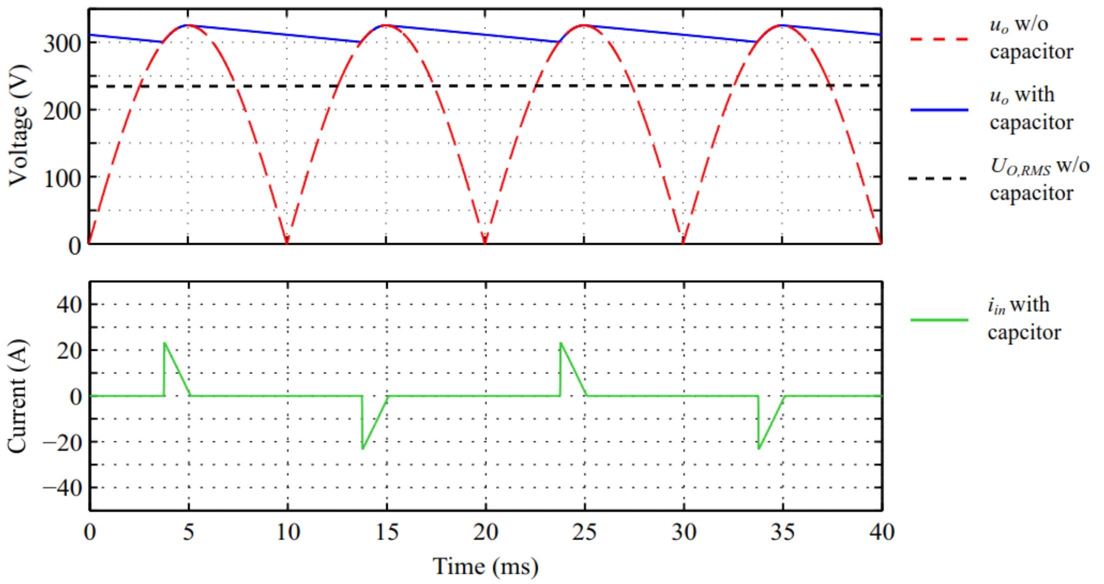


Figure 5.5. *Output voltage and input current of a full wave rectifier.* [54]

From Figure 5.5 can be seen that the DC-link capacitor smooths and also increases the RMS value of the output voltage; $U_{O,RMS} \approx 230$ V without the capacitor and when the capacitor is used $U_{O,RMS} \approx 320$ V. However installing the capacitor makes the input current non-sinusoidal. Without the capacitor the input current would be as close to sinusoidal as the input voltage is. Charging the capacitor causes the spikes in the input current. The current flows in to the rectifier bridge only when the input voltage instantaneous value is larger than the voltage of the capacitor. The capacitor is keeping the output voltage almost constant but discharging until the rectified input voltage is great enough. Then the capacitor is charged again and current flows in to the rectifier bridge. The difference between the lowest and highest value of the output voltage is called the ripple. Ripple can be reduced by increasing the capacitance of the DC-link capacitor but then the input current becomes more distorted because charging the capacitor requires more current and the current spikes increase. [52; 54; 55]

In Figure 5.6 is shown the harmonic spectrum of the rectifier introduced in Figure 5.4. The spectrum can be formed from the harmonic current orders using (5.9).

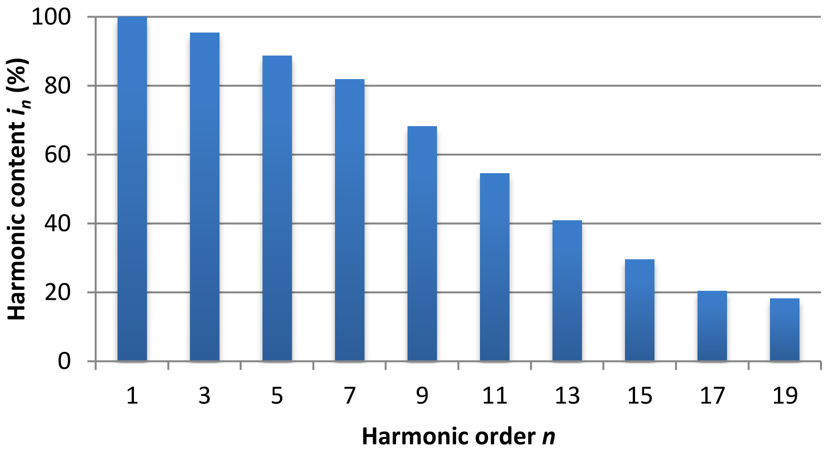


Figure 5.6. *The current harmonics caused by the rectifier shown in Figure 5.4.* [54]

From the spectrum can be seen that in this case there are a lot of harmonic content in the input current which means that the current is highly distorted. Harmonics are not compensated or filtered in this example and therefore the current THD is high. The current THD in this example is THD_i = 186% of the fundamental current. [54] Combining (5.6) and (5.10) or (5.7) and (5.11) the U_{RMS} and I_{RMS} of the resultant wave can be calculated from the THD values with equations

$$THD_i = \sqrt{\left(\frac{I_{RMS}}{I_1}\right)^2 - 1} \Leftrightarrow I_{RMS} = I_1\sqrt{1+THD_i^2} \tag{5.14}$$

$$THD_u = \sqrt{\left(\frac{U_{RMS}}{U_1}\right)^2 - 1} \Leftrightarrow U_{RMS} = U_1\sqrt{1+THD_u^2}\ , \tag{5.15}$$

where the THD_i and THD_u are ratios of harmonic current and voltage orders with respect to the fundamental value. [46; 48] For example if the fundamental input current for the rectifier in Figure 5.4 is I_1 = 2,2 A then the RMS value for the i_{in} is $I_{RMS} \approx$ 4,6 A. It can be noticed that the total RMS value is over twice as much as the fundamental value. High THD therefore increases losses due to increased current and high currents can also harm the electrical components.

EC-motors create harmonics to the electricity network because they are nonlinear components. EC-motor is a DC-motor but can be supplied with AC voltage which means that there is a rectifier circuit either attached to the commutation unit or the rectifier is a separate unit from the motor. However the voltage rectification creates harmonics because the current which is taken from the electricity network is not pure sinusoidal form, as mentioned earlier. The construction of the cabin air conditioning module and the reason for this certain type of construction is described later in Chapter 6. [48; 53]

5.2.2 Transformers

Transformers are also a source of harmonics. Transformers produce harmonics because of the magnetic nonlinearity of the iron core. Magnetic flux density does not increase linearly when the magnetic field increases. The excitation current does not follow the supply voltage waveform because of the hysteresis of the iron core. Hysteresis is a phenomenon where the ferromagnetic material (e. g. iron) remains magnetized indefinitely after the magnetic field is taken away. [47]

Saturation is an issue when selecting and designing the right transformer. When the supply voltage is increased above the nominal the saturation region of the core is reached. This increases the amount of harmonics and also even harmonic order might occur in the system. Also if the electricity network where the transformer is connected contains a lot of harmonics the transformer cannot be loaded to nominal point anymore because of the increased current and losses. Effects of harmonics have to be taken into account especially when designing the transformer for DC motor or converter applications. [47; 48]

Transformer coupling, iron core construction and earth connection are the main things affecting to the creation and spreading of the harmonics. For economic reasons the iron core is usually made asymmetric which means that the reluctance is not the same throughout the core. The iron core for 3-phase transformer is usually constructed of three limbs as seen in Figure 5.7. The windings are wound around the limbs. [47; 48]

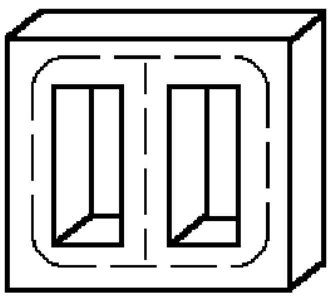


Figure 5.7. *Typical iron core of a 3-phase transformer.* [47]

In the type of the iron core seen in Figure 5.7 the reluctance and excitation current are smaller on the middle limb than on the side limbs which mean that also harmonic currents have different amplitudes in different phases. The reluctance means magnetic resistance. [47]

5.2.3 Other sources of harmonics

As mentioned earlier fluorescent lights are major source for harmonics in a passenger cruise ship. Also different types of energy saving lamps cause voltage distortion. Nowadays LED-lights are replacing the fluorescent lights but still the most of the lighting is implemented with fluorescent lights for example in machinery spaces. Fluorescent lights are nonlinear loads and they need both current limiter and shunt compensation. When using an inductor as a current limiter the power factor usually is low. Shunt compensation is used to improve the power factor. Electronic connecting devices which convert the network voltage with great frequency (≥ 20 kHz) are used nowadays to improve the efficiency of fluorescent lights. High frequency creates harmonics which have to be filtered. [47; 48]

Also generators and electric motors can be sources of harmonics. This is due to air gap asymmetry, winding structure and saturation of the iron core as in transformers. Magnetic flux is not always sinusoidal which creates harmonic currents. Magnitude of generator harmonic currents depends on the impedances of the electricity network. [47;48]

Computers, televisions and other entertainment electronics also create harmonic currents in to the electricity network. These devices operate with DC voltage so the AC voltage has to be rectified. In a large passenger cruise ship there is a lot of entertainment electronics and their effects to the quality of electricity has to be taken into account. For example passengers have their own computers and cell phone chargers which are not a problem in a single use but there are always several hundred or thousand passengers in the ship. [47; 48]

UPS-devices are used for emergency situations but also to filter harmonics in the network. Sometimes UPS devices can also cause harmonics for example when the battery is charging and discharging. Batteries operate with DC voltage so voltage conversion is needed. Battery charging should be designed as constant as possible so that there are no sudden spikes on the power consumption. [52]

5.3 Resonance

Harmonics have many undesirable effects to electricity systems such as power losses, overloading of components, errors in operations due to the distorted voltage. Harmonics also disturb communication by radio frequencies. Overloading and increased power losses age components faster compared to nominal operating life. However one of the most harmful effects from the electricity distribution network’s point of view is resonance. The resonance is formed when any harmonic frequency is close to the networks resonance frequency. Often resonance happens when the impedance between the input and output of the circuit is close to 0 Ω (series resonance). In this case the possible harmonics in the network multiplies. [47; 52]

In a circuit which includes both inductance and capacitance the resonance occurs when the decreasing magnetic field of the inductor generates current that charges the capacitor in the circuit. On the opposite the discharging capacitor provides current for the inductor and the magnetic field increases. This process is repeated continually. In other words electrical energy varies between the inductive reactance and capacitive reactance. At the resonance situation the parallel impedance of the inductor and capacitor is at maximum and the series impedance is at minimum. If the inductive and capacitive reactances are of equal magnitude, the resonance frequency for *LC*-circuit can be calculated with equation

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \tag{5.16}$$

where f_r is the resonance frequency (Hz), L is the inductance (H) and C is the capacitance (F). Because resonance frequency occurs with certain values of inductance and capacitance it can be used for tuning and filtering. For example signals can be strengthened by adjusting inductance or capacitance of the circuit to achieve resonance. Nonetheless resonance can be harmful if it is unwanted and not controlled because it can cause oscillation which causes noise, signal distortion and possible damages to the components. [47; 52; 56]

Resonance can be divided in series resonance and parallel resonance. Series resonance forms usually between a compensation capacitor and the transformer which is supplying the electricity distribution network. The resonance frequency can be calculated using (5.16). In series resonance the reactance in the network is close to 0 Ω and therefore the impedance is very low. Because of the low impedance in the medium voltage network the harmonic voltage with the certain frequency remains low. However, if the harmonics are close to resonance frequency the voltage is heavily distorted on the low voltage side because the harmonics are strengthened when passing through the distribution transformer. Series resonance is utilized for example in harmonic filtering applications due to the low impedance circuit for harmonic currents. [47; 52; 56]

Parallel resonance can be formed for example between a compensating capacitor, connected parallel to a rectifier, and distribution transformer or load inductances. The impedance is high in the resonance which means that also the voltage is heavily distorted. Then there is high current (multiple of the normal current) in the network which can harm components, especially compensating capacitors. Resonance frequency in parallel resonance can be calculated with equation

$$f_r = f_1\sqrt{\frac{S_k}{Q_c}}\,, \tag{5.17}$$

where f_r is the resonance frequency (Hz), f_1 the supplying network fundamental frequency (Hz), S_k is the short-circuit power of the network (VA) measured from the capacitor connection point and Q_c is the reactive power of the capacitor (var). According to the (5.17) increasing the short-circuit power also increases the resonance frequency. Increasing the compensation decreases the resonance frequency. Resistance has no effect to the resonance frequency which can be seen from (5.16) and (5.17) but it attenuates resonance currents significantly. [47; 52; 56]

5.4 Reduction of harmonics

Harmonics are unwanted because of their effects to the electricity distribution system. The component definition, which was introduced in Chapter 5.1, can be used to describe what kind of effects different harmonic orders have to electricity. Positive sequence harmonics overheats conductors and transformers due to the addition of the waveform amplitudes. Negative sequence harmonics rotate between phases in 3-phase systems. Negative sequence harmonics therefore creates problems for electric motors because the opposite phasor sequence weakens the magnetic field in the motor which leads to less available torque. Zero sequence harmonics, i.e. multiples of the 3rd harmonic order, do not rotate. They are all in the same phase and add up in the neutral wire creating currents as high as 3 times of the phase current. High current causes losses and overheating. The 3rd harmonic is produced in case of unbalanced load in the 3-phase system, for example in case of unbalanced 1-phase rectifiers. [47; 52; 57]

Harmonics can be reduced or eliminated in many different ways. Harmonics can be either filtered or the forming of harmonics can be reduced with reasonable design. The solution for harmonic reduction is selected based on economic and technical aspects; if it is necessary to build the equipment and network in such way that harmonics are not produced or is filtering effective enough. Structural changes for harmonics elimination are for example increasing the pulse number of rectifiers, strengthen the electricity supply, improving the internal filtering of components and installing compensation capacitors. Compensation capacitor banks are not widely used in passenger cruise ships but filters are installed near the consumption point. [47; 48; 50; 52]

5.4.1 Structural means in a ship

The most important structural way to reduce harmonics in a passenger cruise ship which is using diesel-electric propulsion is the design of the propulsion frequency converter. The frequency converter pulse number affects to the amount of harmonics. The rectifier unit in the frequency converter is constructed either as 6-pulse, 12-pulse or 24-pulse configuration. In Figure 5.8 is shown harmonic spectrum of different rectifier configurations. There are only shown those harmonic orders that can be determined from (5.12). [50]

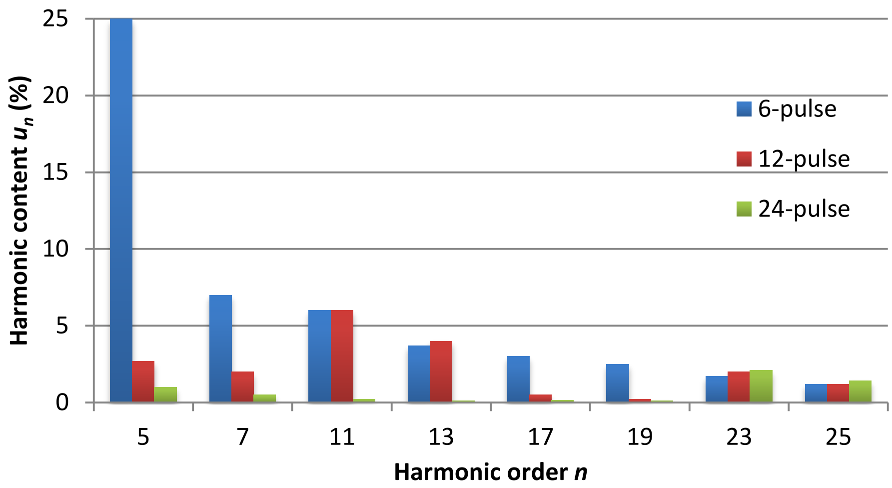


Figure 5.8. *Harmonic spectrum of 6-, 12- and 24-pulse rectifier configurations.* [50]

It can be seen from Figure 5.8 that 6-pulse rectifier configuration produces the most harmonics whereas 24-pulse the least. However the 6-pulse rectifier is the cheapest and simplest whereas 24-pulse rectifier is the most complex and expensive. Nowadays in passenger cruise ships the 24-pulse configuration is used in propulsion because of the low level of harmonics. Other ways to reduce harmonics produced by rectification is to change the diode bridges with thyristor (IGCT) or transistor (IGBT) bridges alongside of an active filter circuit. Thyristors and transistors can be controlled externally to conducting and non-conducting states. Construction of different converter configurations was introduced in Chapter 2.4.5. [50]

5.4.2 Filtering

In many applications harmonics are filtered. Filtering is used for example in situations where harmonic production is increased gradually during time period or filtering can be used also as a comprehensive solution of a new facility if it is more cost-effective than constructional means. Filters can be passive or active type and they can be tuned to filter one or more harmonic frequencies. [47; 50]

Passive filters are constructed of capacitor and inductor connected in parallel and the filters are usually located near the harmonic source to achieve the best filtering result. Passive filters attenuate harmonic orders above the tuned frequency and might strengthen orders below the tuned frequency. Passive filter with one tuned frequency is not used in new installations and often these filters should only be used for the first harmonic orders (n = 5, 7, 11, 13). Installing more capacitors in parallel with reactors allows tuning for multiple harmonic orders at the same time. With multiple tuning frequencies much better filtering and attenuation is achieved. When designing filters with multiple capacitors the strengthening of other harmonic orders have to be taken into account carefully. These branched passive filters are mostly used in high power DC applications where separate transformer supplies the whole application. [47; 48; 50]

Active filters are constructed from modern power electronic components and can be controlled to filter harmonics as desired. The basic idea of active filters is that they produce current signals which have opposite phases compared to the specific harmonic orders. Due to this the harmonic component is eliminated from the resultant wave. In Figure 5.9 is shown an example of active filter operation.

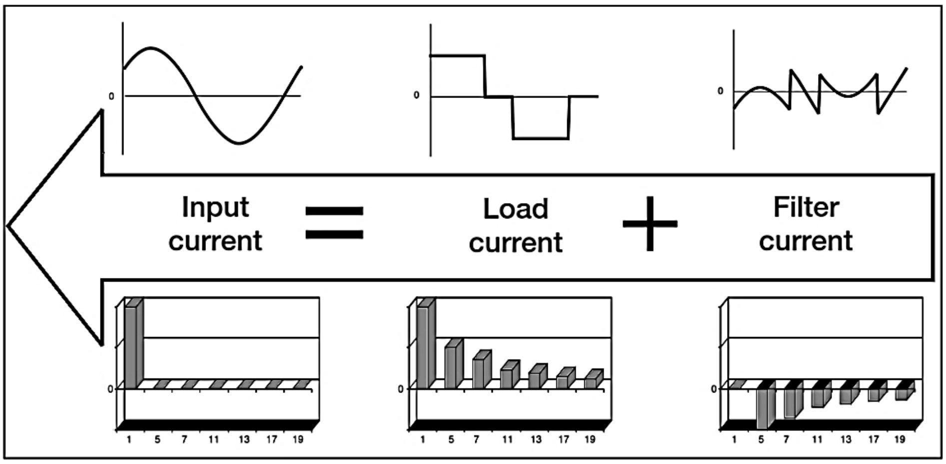


Figure 5.9. *An example of active filter operation.* [50]

The waveform of filter current is adjusted individually in each case to achieve optimum resultant wave for input current. Active filters are more expensive than passive filters so the best solution for decreasing harmonics depends on the total load, supply and the continuous harmonic distortion. [48; 50]

5.5 Power factor

The power factor is a ratio between the active power and apparent power in the system. Apparent power is the sum of active power, reactive power and, in case of non-sinusoidal current and voltage, also distortion power. The apparent power can be calculated with equation

$$S = \sqrt{P^2 + Q^2 + D^2}\ , \qquad (5.18)$$

where S is the apparent power (VA), P is the active power (W), Q is the reactive power (var) and related only in the fundamental waveform. The D is the power loss caused by distortion (VA). When the current and voltage waveforms are sinusoidal the distortion power is D = 0 VA. Also when the voltage is sinusoidal and the current is distorted the D is reactive power rather than distortion power. [54] Reactive power is the power that is either consumed by inductive reactance or produced by capacitive reactance. Reactive power does not do actual work in the system but it oscillates in the circuit between the load and the transmission system. Despite the fact that reactive power does not do work still the current caused by it increases power losses in the transmission system. Therefore the reactive power is usually compensated. As mentioned before, also distortion increases the current RMS value which increases power losses. [58; 59]

When the voltage and current are sinusoidal the power factor can be calculated with equation

$$PF = \cos\varphi = \frac{P}{S}, \tag{5.19}$$

where the angle φ is phase shift between the voltage and the current (rad). With purely resistive load there is no phase shift and $S = P$. The distortion and phase shift can be taken into account separately according to the equation

$$PF = \frac{I_1}{I_{RMS}}\cos\varphi_1, \tag{5.20}$$

where I_1 is the fundamental current (A), I_{RMS} is the total RMS current (A) and φ_1 is the phase shift between the fundamental voltage and current (rad). The term I_1/I_{RMS} is called the distortion factor (DF) and the $\cos\varphi_1$ is called the displacement factor (DPF). [48; 54; 58]

If the THD value in the system is known the power factor can be calculated with equation

$$PF = \frac{\cos\varphi_1}{\sqrt{1+THD^2}} = \frac{DPF}{\sqrt{1+THD^2}}, \tag{5.21}$$

where the THD value is a ratio between the harmonic content and the fundamental values. [48; 54; 58] It can be seen from (5.21) that eliminating harmonics ($THD \approx 0$) and compensating the reactive power ($\varphi_1 \approx 0$ rad, $\cos\varphi_1 \approx 1$) the power factor is $PF \approx 1$. The method to improve the power factor and reduce harmonics in the input current of the rectifier is called power factor correction (PFC). As seen on Figure 5.5 in Chapter 5.2.1 rectifying causes spikes to the input current which cause harmonic distortion and lower the power factor. Power factor correction (PFC) is based on the shaping of the input current as close to sinusoidal as possible. PFC is nowadays very popular method in small power 1-phase applications for example with air conditioning EC-motors. PFC is divided in passive and active correction. [53; 58]

5.5.1 Passive power factor correction

Passive PFC is simple and does not need a separate control circuit. In passive PFC, an inductor is used in the rectifying circuit between the rectifier bridge and DC-link capacitor to smoothen the current spikes reflected to the input current. The inductor's magnetic field resists the changes in the current which makes the current waveform smoother. With suitable selection of the inductor the current is smoothened enough to meet the regulations of harmonic emission in 3-phase rectification. In Figure 5.10 is shown an example of 1-phase passive PFC circuit. The rectifier operation principle is the same than in the rectifier shown in Figure 5.4 in Chapter 5.2.1 [53; 58]

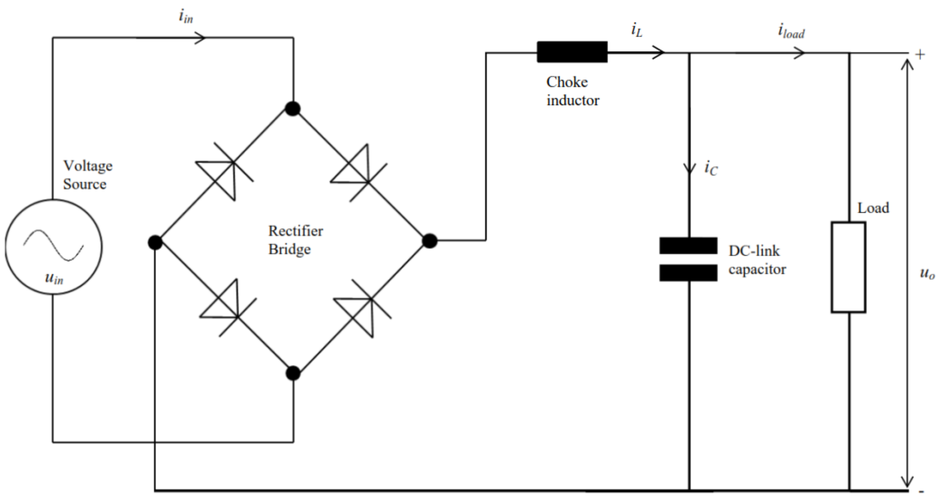


Figure 5.10. *1-phase passive PFC circuit.* [53]

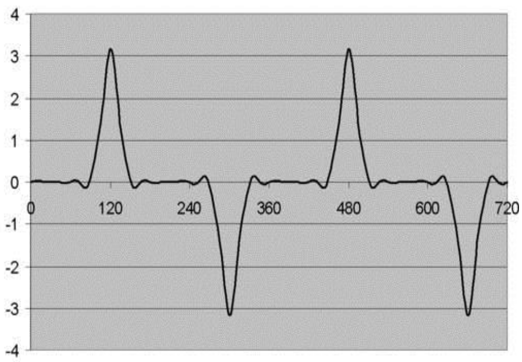
However the passive filtering is not very effective in 1-phase systems and the physical size of the passive components is the limiting factor in the 3-phase power systems. In Table 5.3 is shown a comparison of harmonic content without any PFC and with passive PFC. Values are referred to the fundamental wave. The load in this example a 1-phase EC-motor with the electrical power of P = 135 W. The values are collected from the material given by the air conditioning system supplier. [53]

Table 5.3. *Harmonic content without PFC and with passive PFC.* [53]

Harmonic order	Without PFC (%)	With passive PFC (%)
1	100	100
3	86	82
5	61	54
7	35	28
9	13	11
11	4	4
13	8	1
15	7	2
17	3	3
19	1	2

With passive PFC in 1-phase application the current THD is still THD_i = 104% whereas without any PFC the current THD is THD_i = 112 % in this example. Without PFC the total RMS current I_{RMS} is 150 % compared to the fundamental current I_1 whereas with passive PFC the I_{RMS} is still 144 %. [53] It can be noticed from Table 5.3 that the 13th and 15th harmonic orders are reduced the most in relation to the original value.

In Figure 5.11 is shown the input current waveforms of the rectifier circuit introduced in Figure 5.10. The left waveform is the input current without PFC and the right waveform is with passive PFC. [53]



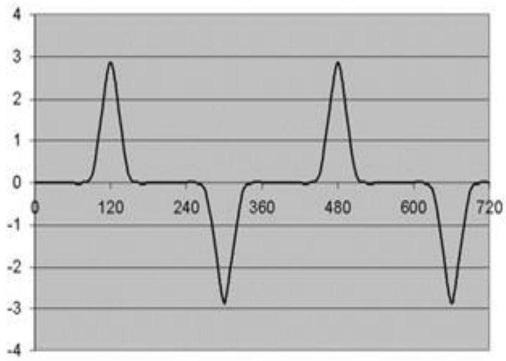


Figure 5.11. *Input current waveforms without PFC (left) and with passive PFC (right). The y-axis depicts the input current i_{in} (A) and the x-axis values are the time t (ms).* [53]

It can be seen from Figure 5.11 that the peak value of the input current $\hat{\imath}_{in}$ is reduced only approximately 0,2 A. The wave between the spikes is smoothened. The power factor without PFC is PF = 0,53 and with passive PFC is PF = 0,70. The current is still not close to sinusoidal so the passive PFC is not really effective in this case. [53]

For comparison the difference between 1-phase and 3-phase passive PFC is shown in Figure 5.12. The motor in this case is a 3-phase EC-motor with electrical power of P = 1,75 kW. The waveform on the left is the case without PFC and the right side waveform is the passive PFC. The sinewave in the right side figure is the input voltage. It is shown to give reference how the capacitor affects in the 3-phase system and how it is charged. [53]

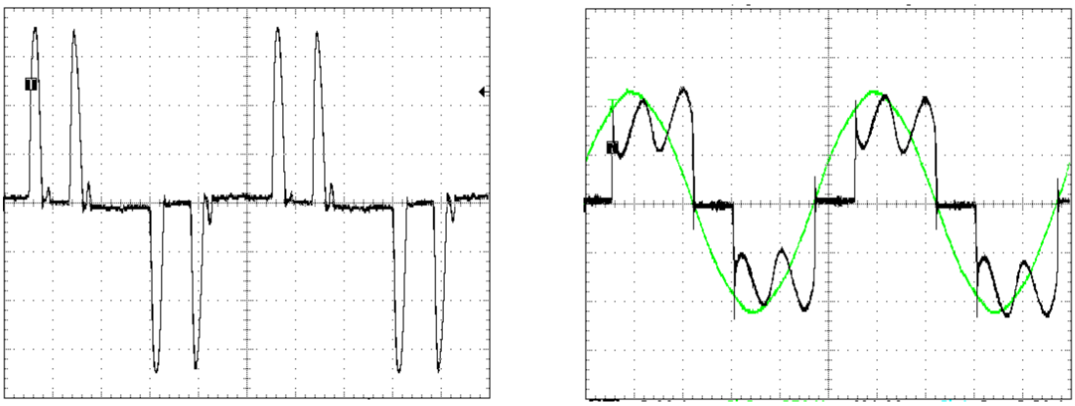


Figure 5.12. *Input current waveforms without PFC (left) and with passive PFC (right) in 3-phase system. The y-axis depicts the input current i_{in} (A) and x-axis the time t (ms).* [53]

The peak value for the input current $\hat{\imath}_{in}$ = 18 A and the I_{RMS} = 6 A without PFC whereas with passive PFC $\hat{\imath}_{in}$ = 5 A and the I_{RMS} = 2,8 A. Power factor is now PF = 0,54 without PFC and with passive PFC it is PF = 0,93. Even though the current is not purely sinusoidal with the passive PFC the power factor is significantly increased and the currents decreased. Therefore it can be stated the passive PFC is more effective in 3-phase systems where the load is symmetrical. [53]

5.5.2 Active power factor correction

In active PFC the principle is to control the current fed into DC-link capacitor so that the input current of the rectifier bridge is as sinusoidal as possible and in the same phase with the input voltage. Active PFC circuit is constructed from the rectifier bridge, high frequency bypass capacitor, inductor, switch (transistor), boost diode and DC-link capacitor. In other words there is a Boost converter included in the circuit. Active PFC is more complex than passive PFC because a separate control circuit is needed to control the transistor. Depending on the application the transistor is either MOSFET or IGBT type. [48; 53; 58]

In Figure 5.13 is shown an example of 1-phase active PFC circuit. The Boost converter part of the circuit is marked with dashed line. Boost converter is a DC to DC step-up converter which means that the Boost converter output voltage is greater than the input voltage. The Boost diode prevents the current flowing back in to the source when it is reverse biased, the transistor is conducting. Depending on the application also the bypass capacitor is optional. AC components or noise in the DC side voltage could cause interference for example in the control signal so the bypass capacitor is used as a filter. [53; 55; 58]

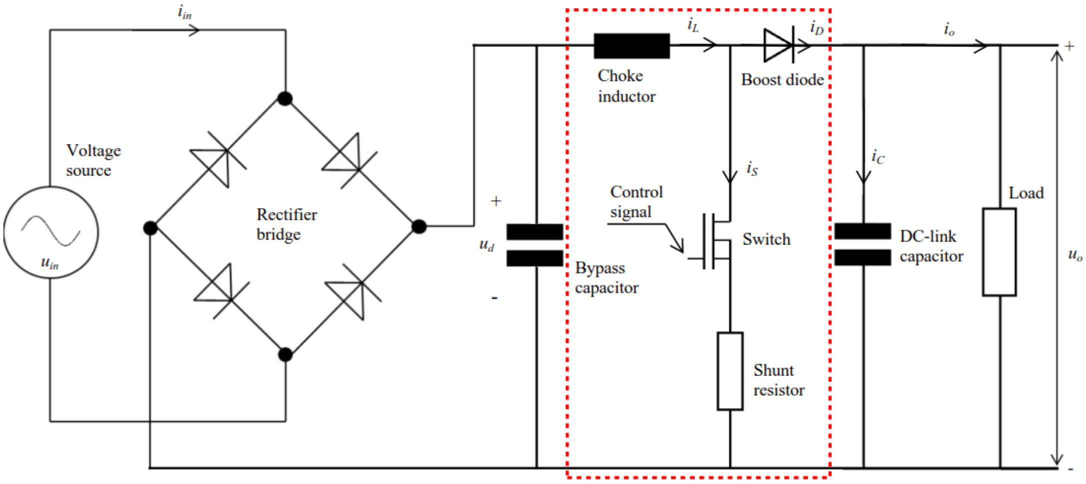


Figure 5.13. *1-phase active PFC circuit.* [53; 54]

There are various control topologies for the active PFC rectifier but the main principle is the same. The control circuit monitors the output voltage u_o and the input voltage u_{in} to be able to shape the inductor current i_L as close to rectified sinusoidal current as possible as shown in Figure 5.14. The control signal is created with PWM and the signal is fed to transistor. The result is that the current spikes which were created due the charging of the DC-link capacitor are smoothened. [53; 54]

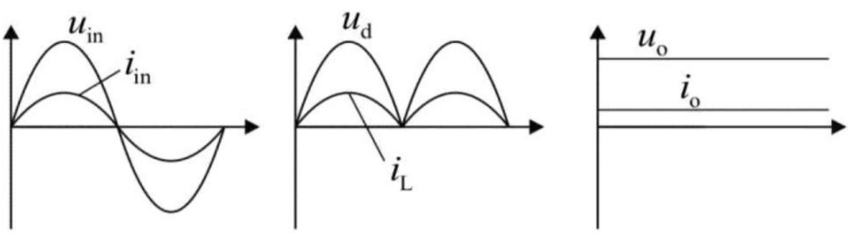
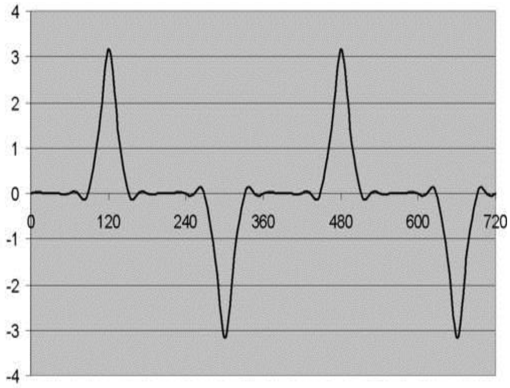


Figure 5.14. *Ideal current and voltage waveforms of the active PFC rectifier.* [54]

The situation in Figure 5.14 is ideal. In Figure 5.15 is shown the comparison of input current waveforms of the same application that was used in Chapter 5.5.1 with the passive PFC. It can be seen from Figure 5.15 that the input current is now very close to pure sinusoidal wave. There are always some deviations from the pure sine wave because of the component features and the switching frequency. [53]



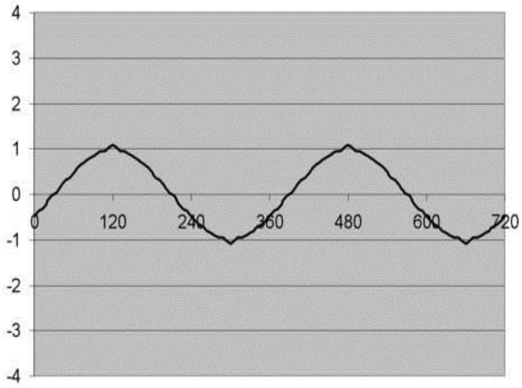


Figure 5.15. *Input current waveforms without PFC (left) and with active PFC (right). The y-axis depicts the input current i_{in} (A) and the x-axis values are the time t (ms).* [53]

Active PFC improves the power factor and reduces harmonics much more effective than passive PFC. In Table 5.4 is shown a comparison between the rectifiers without any PFC, with passive PFC and with active PFC. The load is the same EC-motor that was used in case of the passive PFC in 1-phase application. [53]

Table 5.4. *Comparison between rectifiers without PFC, passive PFC and active PFC.* [53]

Harmonic order	Without PFC (%)	Passive PFC (%)	Active PFC (%)
3	86	82	5
5	61	54	4
7	35	28	1
9	13	11	3
11	4	4	1
13	8	1	1
15	7	2	1
17	3	3	0
19	1	2	1

With active PFC in 1-phase application the current THD is THD_i = 7 % whereas without any PFC the current THD was THD_i = 112 % and with passive PFC the THD was THD_i = 104 %. Without PFC the total RMS current I_{RMS} was 150 % compared to the fundamental current I_1 whereas with active PFC the I_{RMS} is close 100 %. This means that the power factor is close to unity and as seen on Table 5.4 the THD is low. The corrected power factor is now PF = 0,99. [53] Compared to the unfiltered rectifier the power factor has improved by 0,46 which also means great improvement in the energy efficiency.

6. CABIN AIR CONDITIONING IN THE REFERENCE SHIP

The theory for cabin air conditioning motor solutions was given in the previous Chapters 4 and 5. Nowadays energy efficiency is very important thing especially in passenger cruisers. The energy is even necessary to save in the small power EC-motors if possible. Improving the efficiency and the power factor also reduces harmonics so that the motor values correspond to the IEC harmonic emission standards for electrical devices. The standards were mentioned in Chapter 5.

The idea of this thesis was to introduce and compare the different solutions of the EC-motor application for air conditioning and clarify the fact that is the filtering circuit needed. The cabin air conditioning is provided by a subcontractor and components are installed in the cabin factory before the cabins are delivered to shipyard and mounted in to the ship. Therefore the shipyard's own employees might not have a comprehensive knowledge about the system. Alongside the theory also some measurements was made during the sea trial of the ship where this problem was examined.

6.1 Air conditioning control for cabins

The electricity is supplied from the cabin distribution box to the control box of the module which was introduced in Chapter 3. The controller for the fan coil unit control is located in the bottom control box. In Figure 6.1 is shown an example of one type of control unit. The control unit used in this case is an independent automation device which is configurable for fan coil unit settings. The manufacturer is not shown. [60]

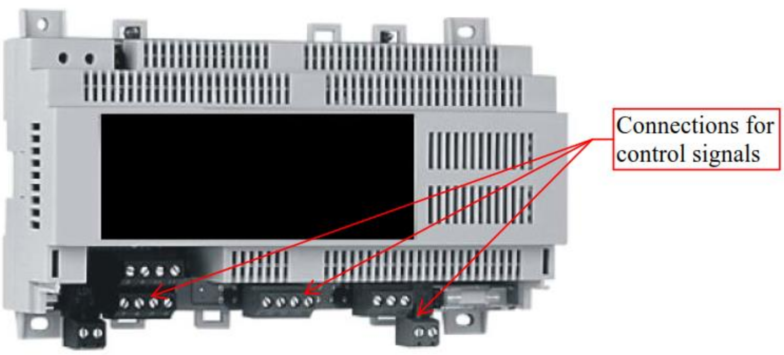


Figure 6.1. *One type of a fan coil control unit.* [60]

In each cabin the air conditioning is an independent system to achieve the maximum passenger comfort. The air conditioning can only be stopped remotely in case of an emergency. The cabin command module, balcony door switch and the possible occupation switch are connected to the controller. The balcony doors switch is used to inform if the balcony door is open or close. When the door is open the air conditioning is stopped. Occupation switch informs if there are passengers in the cabin. Otherwise the air conditioning is off or in an energy saving mode. The cabin control module allows the passenger choose the desired temperature setting for the cabin. The module varies along the manufacturer and supplier of the air conditioning system. In Figure 6.2 is an example of one type of cabin control module. [60]

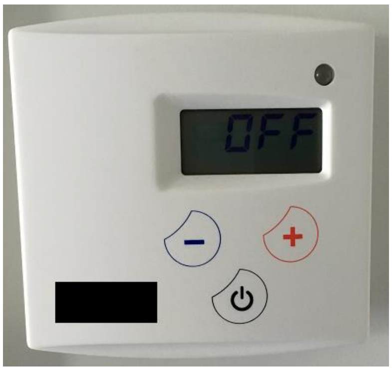


Figure 6.2. *Cabin control module for air conditioning.* [60]

The information from inside the cabin, e.g. balcony door position and desired temperature, is given to the controller in the air conditioning module. The controller processes the information and controls the fan speed, valve position and heating coil as needed. The heating coil and 3-way cooling water valve control are done with PWM. The EC-motor control is controlled by 0 – 10 V voltage signal. The EC-motor can be used as a variable speed motor. The fan starting point is usually set 1 – 5 % for the changeover of heating or cooling which means that if the set for heating is 5 % the fan starts only after the heating demand is 5 % above the present temperature. Then the fan speed increases with respect to the temperature demand. The EC-fan can also be 3-speed fan which means that there are only 3 available speed settings for the EC-motor. [60]

The cabin air conditioning has three different zones; cooling zone, zero energy band and heating zone. The zero energy band is a zone where there is no cooling or heating i.e. the temperature is on the desired level. The zero energy band range is usually 1 – 2 °C when the cabin is occupied and 2 – 5 °C when un-occupied. The nominal set point for cabin temperature is configured by the system operator (the ship owner). [60]

6.2 Electrical system

The electrical side of the cabin air conditioning is rather simple because there is only one power supply for the whole air conditioning module. The supply from the cabin distribution box is divided for two air conditioning modules because one distribution box supplies two cabins. The main supply for the module is then divided for the controller, EC-fan and electric heater. The electrical power of the heater and the EC-fan varies but in this case the heater power is P_{heater} = 800 W and the fan power is P_{fan} = 110 W. The cabin air conditioning system is a 1-phase system (230 V). [60]

The heater is controlled with PWM, as mentioned before, so it has both power supply and control circuit. Control is done with the controller and separate control relay. The heater is a resistive load which means that when heating is on, the heater immediately is on full power. With both cabins together the simultaneous electric power demand is then approximately 1,6 kW. The PWM control of the heaters also distorts the current and voltage even if the heater itself is a linear resistive load. The electrical power for 3-way valve is supplied from the controller as well as the control signal. [60]

The 1-phase EC-fan could be supplied straightly with 230 VAC voltage but for harmonic content reduction there is an active PFC module installed in series with the motor. In this case the AC voltage is first rectified and boosted to approximately 380 VDC and then supplied to the EC-motor. In Figure 6.3 is shown an example of the active PFC module used in passenger ships. On the AC side there are connection points for phase (L, 230 VAC), neutral (N) and protective earth (PE). On the DC side there are connection points for 380 VDC (+), GND VDC (-) and PE. The PFC module is installed in the supply box of the air conditioning module. The physical size of the PFC unit used in this application is approximately 170x80x55 mm. It requires quite a lot of installing space also. [61]

Figure 6.3. *Active PFC module.* [61]

EC-motor has to be especially designed for this kind of DC voltage use. The theory for active PFC was introduced in Chapter 5.5.2 and it is applicable for the present EC-motor application. With the active PFC the harmonics are well filtered from the input current and the power factor value is 0,46 better than without any PFC. [53; 61]

6.3 Measurements during the sea trial

To ensure that harmonic currents are filtered and the THD is low enough in reality some measurements were made during the sea trial and also afterwards on the dock. Measurements were made in situations where both air conditioning modules of one cabin distribution box were in use simultaneously and also when only one cabin was air conditioned. Measurements were also performed in different parts of the ship. For comparison there are THD measurements from distribution transformers low voltage side which were performed during the time full propulsion power. Then the THD in the medium voltage network should be at the greatest.

The measuring device in every measurement was *Fluke 435 Series II Power Quality and Energy Analyzer*. The analyzer is shown in Figure 6.4. The analyzer measures separately voltage and current from every phase and also the neutral conductor. Different measurements such as power, frequency, voltage, current, energy consumption can be selected from the menu. The measurement needed for this thesis is the THD for voltage and current. [62]

Figure 6.4. *Fluke 435 Series II Power Quality and Energy Analyzer.* [62]

The measurements were done from the cabin distribution box next to the fuse in which the air conditioning module is connected because there was no proper access next to the PFC module. Therefore other devices (heater, valve actuator, control electronics) in the module in addition to the EC-motor affects to the THD and current. Also the harmonics that already existing in the low voltage network are affecting to the measurement. The measurement point is shown in Figure 6.5.

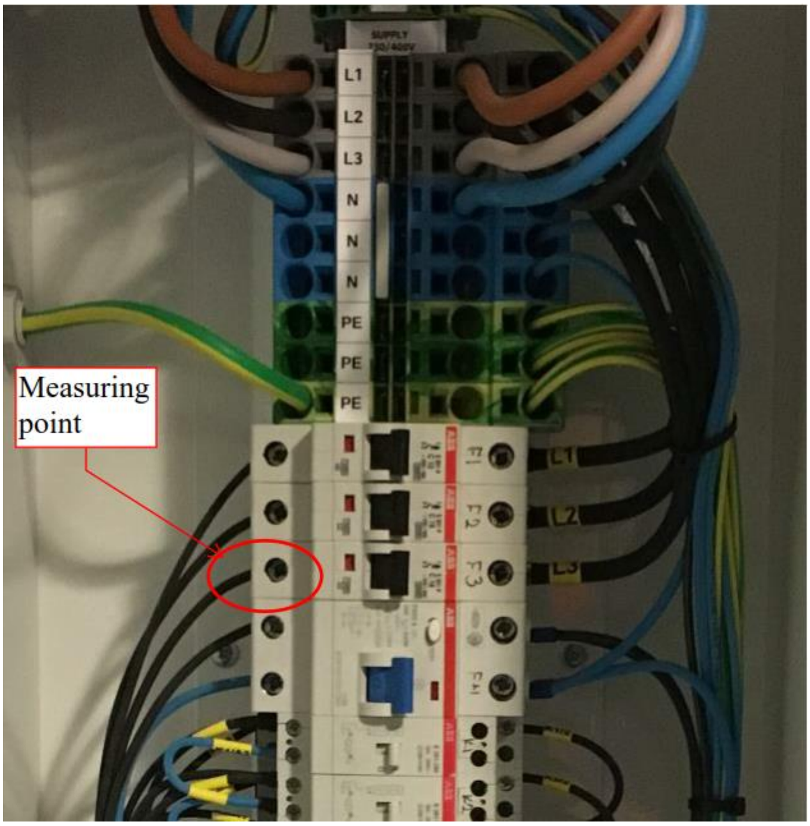


Figure 6.5. *Measuring point in the cabin distribution box.*

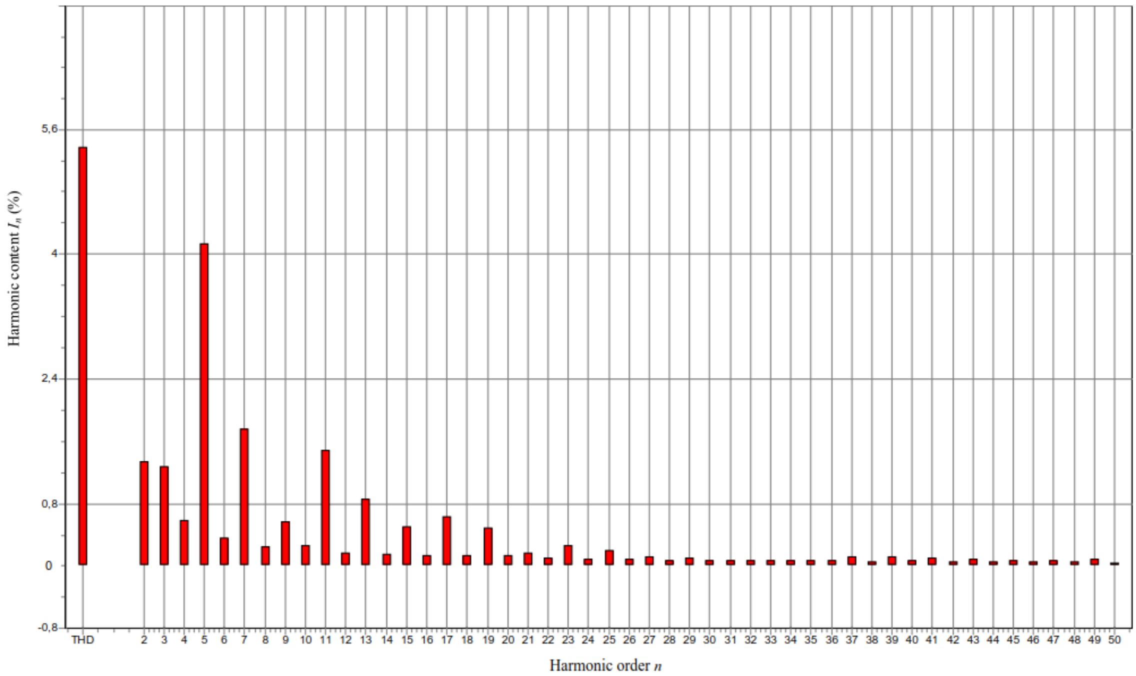
The conductor for current measuring was placed around of the phase conductor and the voltage was measured straight from the cable connection point in the fuse seen in Figure 6.5. The measuring was done in 2 minute periods for each case. The harmonics and THD measurement can be done simultaneously for current and voltage.

6.4 Results

After the measurements the results were analyzed with Fluke PowerLog –program and then printed out as relevant figure, harmonic spectrum. The y-axis is the percentage of the harmonic content, either current or voltage, with respect to the fundamental wave as defined in (5.8) and (5.9). The x-axis depicts the harmonic orders. The measuring situations were that only one air conditioning module was in operation and then two modules, connected in the same cabin distribution box, were operating simultaneously. The current and voltage THD was measured at same time.

In Figure 6.6 is shown the current harmonic spectrum and the THD_i in the both measuring cases.

a)



b)

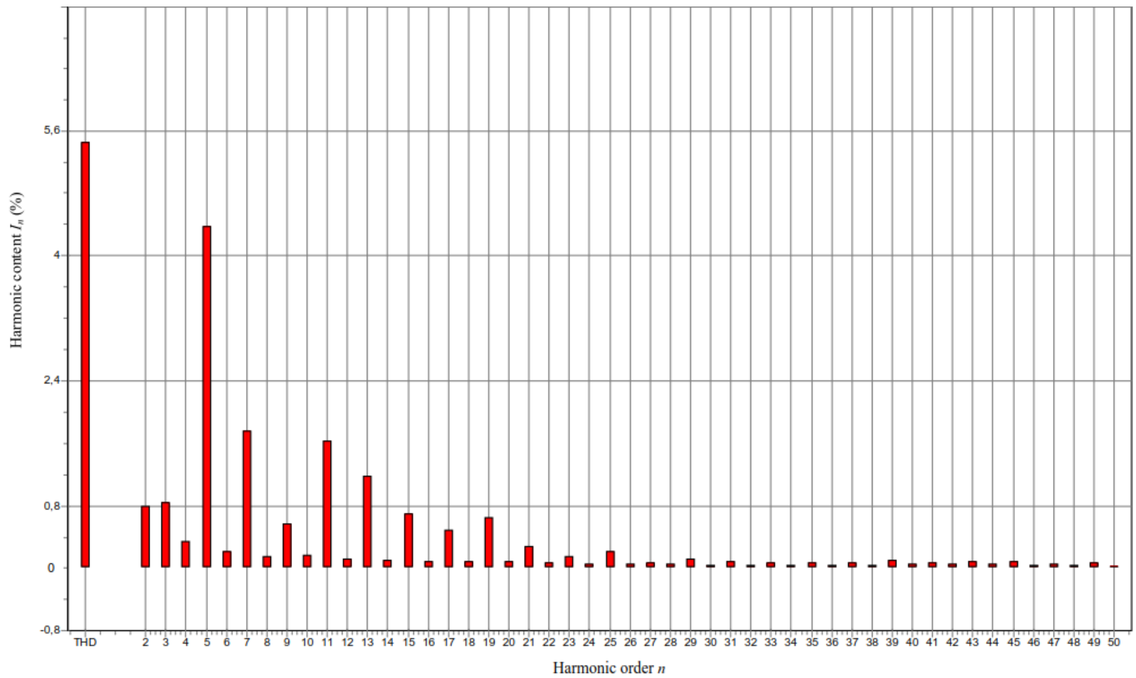


Figure 6.6. *Current THD_i a) 1 module in operation b) 2 modules in operation.*

The current THD_i and content of the harmonic orders are collected from Figure 6.6 in to Table 6.1. The values are approximate values. The harmonic orders above 25th are very close to 0 % and are not shown in the table. The current THD with one module is THD_i = 5,42 % and with two modules THD_i = 5,48 %.

Table 6.1. *THD_i and harmonic contents I_n (%).*

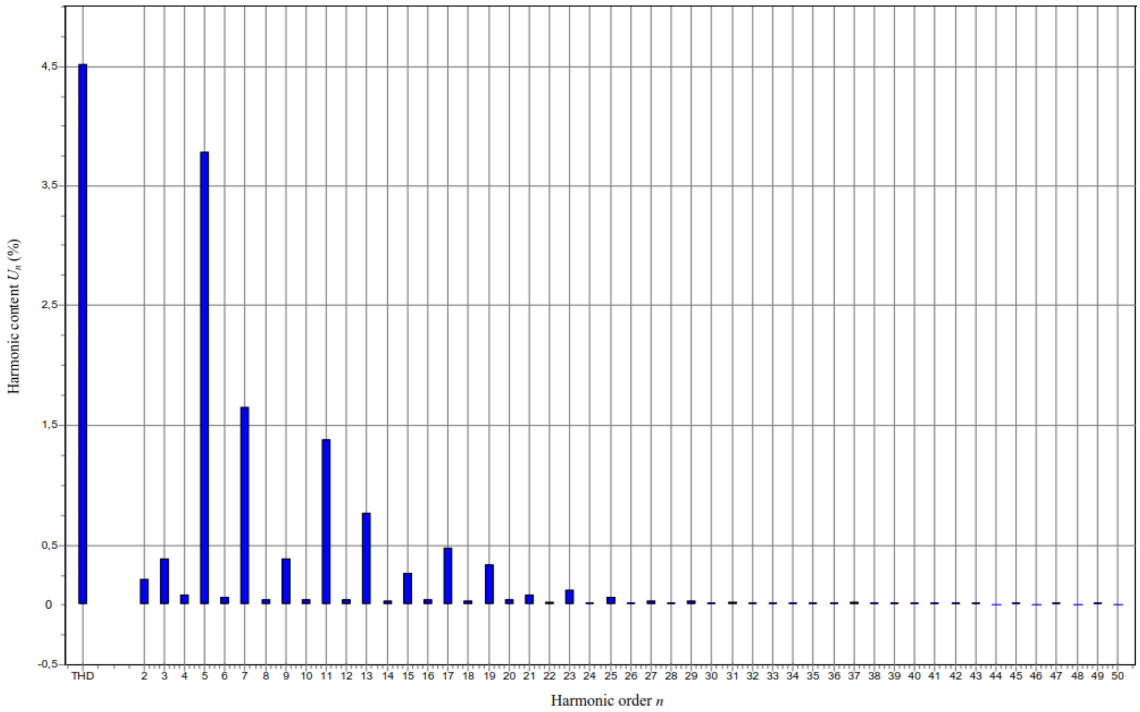
Harmonic order *n*	Harmonic content, 1 module (%)	Harmonic content, 2 modules (%)
2	1,35	0,80
3	1,29	0,83
4	0,55	0,34
5	4,12	4,37
6	0,37	0,18
7	1,72	1,75
8	0,25	0,12
9	0,55	0,55
10	0,25	0,15
11	1,48	1,60
12	0,15	0
13	0,86	1,17
15	0,49	0,68
17	0,62	0,49
19	0,49	0,65
21	0,18	0,25
23	0,25	0,12
25	0,18	0,18
> 25	0	0
Total harmonic distortion, THD_i	**5,42**	**5,48**

The 2nd harmonic order is rather great compared to for example the 3rd, 7th, 11th and 13th orders. It can be seen from Figure 6.6 and Table 6.1 that the 5th harmonic order is the most dominant in the measurement, i_5 > 4 % in both cases. On the other hand the THD_i is low and most of the harmonics are under 1 % of the fundamental wave. The origin of the harmonics is studied and reviewed in the next chapter.

The measured current RMS value is I_{RMS} = 3,75 A. The nominal current value for EC motor is $I_{nominal,EC}$ = 0,5 A and the RMS current is approximately $I_{RMS} \approx 0{,}3$ A when in operation depending on the rotating speed. The heater in the module requires the most electric power and because of the construction of the module the EC-motor and the active PFC component alone was not available for measuring. The fundamental currents for one whole module $I_{1,1EC}$ = 3,74 A and two modules $I_{1,2EC}$ = 3,74 A can be calculated with (5.14) with the I_{RMS} and THD_i values.

In Figure 6.7 is shown the voltage harmonic spectrum and the THD_u in the both measuring cases.

a)



b)

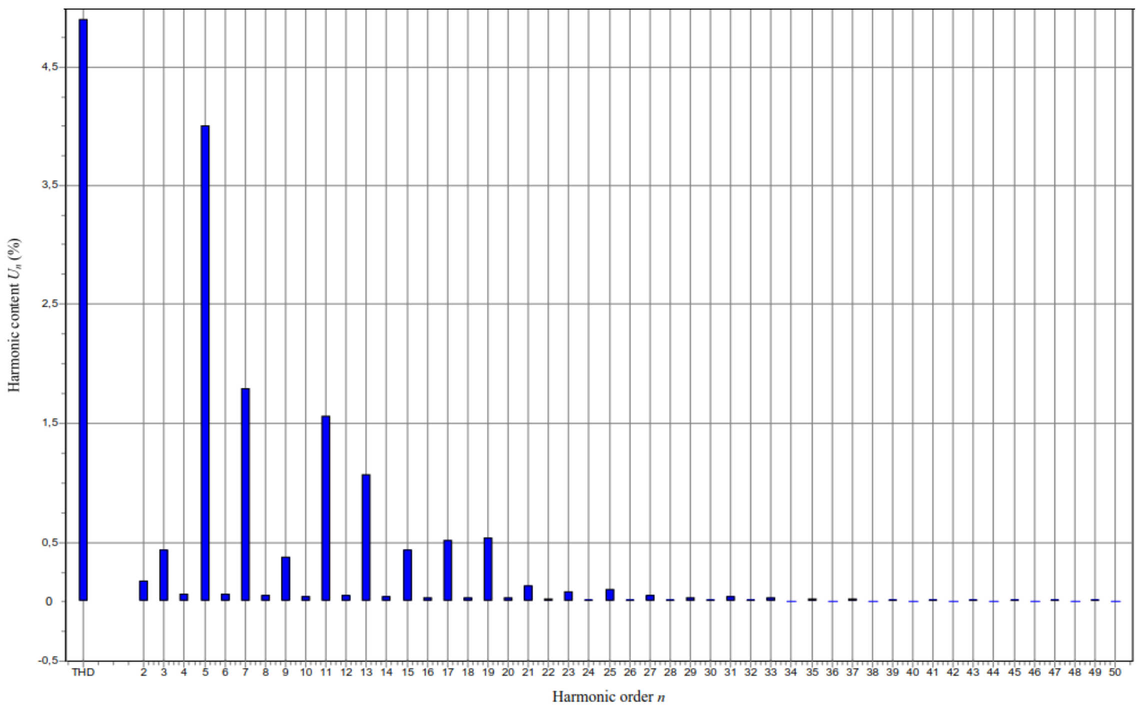


Figure 6.7. *Voltage THD_u a) 1 module in operation b) 2 modules in operation.*

The voltage THD and content of the harmonic orders are collected from Figure 6.7 in to Table 6.2. The values are approximate values. The voltage THD is THD_u = 4,54 % with one module and THD_u = 4,92 % with two modules.

Table 6.2. *THD_u and odd harmonic contents U_n (%).*

Harmonic order *n*	**Harmonic content, 1 module (%)**	**Harmonic content, 2 modules (%)**
2	0,21	0,17
3	0,38	0,42
5	3,81	4,00
7	1,65	1,81
9	0,38	0,38
11	1,38	1,58
13	0,77	1,08
15	0,27	0,42
17	0,46	0,50
19	0,35	0,54
21	0,08	0,12
23	0,12	0,08
25	0,04	0,08
> 25	0	0
Total harmonic distortion, THD_u	**4,54**	**4,92**

It can be seen from Figure 6.7 that the harmonic voltage orders are similar to the corresponding current values except that the even harmonics are smaller with respect to the other harmonics than they were with current. The 5th is also the most dominant harmonic in the voltage as it was in the current. The measured voltage RMS value is U_{RMS} = 235,5 V. The fundamental voltage U_1 can be calculated with (5.15). Using (5.15), the fundamental values for voltage are $U_{1,1EC}$ = 235,3 V and $U_{1,2EC}$ = 235,2 V.

6.5 Review and comparison of the results

The theory about the active PFC rectifier that is used alongside EC-motors is based on the information which was given from the air conditioning supplier and the motor manufacturer. The measurements were performed to verify the theory. The values that were given by the manufacturer are results of testing which was performed in the fan coil factory and for a little different type of EC-motor with different electrical power. Also, as mentioned before, the measurements were difficult to perform straight from the EC-motor and active PFC rectifier which affects to the quality of the measurements. The electric heater requires much more electric power compared to the EC-motor; for the heater I_{RMS} = 3,5 A and for the EC-motor I_{RMS} = 0,3 A depending on the rotating speed. It could not be confirmed that the motors were rotating at the same speed so the RMS current is therefore not really differentiating between one motor and two motor uses.

The measurements were made for different cabins in different parts of the ship and the required current could vary because of the different speed settings. When reviewing the results of the measurements it has to be considered that also the PWM control of the heater creates harmonics even though the heater itself is a linear load.

Also the harmonic which are present in the low voltage network of the certain main fire zone appears in the measurement. For example the 3rd harmonic order shown in Figures 6.6 and 6.7 is not produced all by the rectifying but also e.g. fluorescent lamps. There are also a lot of other rectifiers in the low voltage network that are not used for air conditioning. LED-lights are more and more popular in passenger cruise ships nowadays and they need voltage rectification. For example in the studied case the major part of lighting is implemented with LED-lights in the hotel side of the ship. The high content of even harmonics in the current (2nd and 4th in both cases) can be explained by the fact that there is asymmetry in the loading of phases. There are also a lot of other nonlinear components in the low voltage network, e.g. computers and entertainment electronics, in addition to the air conditioning and LED-lights. Unbalanced loading and nonlinear components causes the even harmonics.

The current harmonics between the factory testing and the measuring are compared in Table 6.3. The tested values which were given from the manufacturer are only shown in accuracy of one digit so the measured values from Figure 6.6 and Table 6.3 are also rounded to accuracy of one decimal. The first odd harmonics (from 3rd to 19th) are shown in the table. The measured values are for both one module and two module cases.

Table 6.3. *The tested and measured current harmonics.* [53]

Harmonic order *n*	**Harmonic content, Tested (%)**	**Harmonic content, Measured 1 (%)**	**Harmonic content, Measured 2 (%)**
3	5	1,3	0,8
5	4	4,1	4,4
7	1	1,7	1,8
9	3	0,6	0,6
11	1	1,5	1,6
13	1	0,9	1,2
15	1	0,5	0,7
17	0	0,6	0,5
19	1	0,5	0,7
Total harmonic distortion, THD_i	**7,4**	**5,4**	**5,5**

It can be seen from Table 6.3 that there are not very much difference between the two measuring cases. The differences between the measurements are so low (0,1 – 0,5 %) that the even the inaccuracy in the measurement and the measurement device can cause that. Also the measuring point was different between the two situations because access to cabins to adjust the air conditioning was limited. It can be also noticed from the table

6.3 that the both measuring cases have lower current THD level than the tested one. But it has to be considered that the tested values from the manufacturer are for one EC-motor and the measurements were performed for the whole air conditioning modules. The power factor can be calculated with (5.21) when the THD_i is known. If assumed that the phase shift between the voltage and current, φ_1, is close to zero then the power factor of the module $PF_{AC\text{-}module} \approx 0{,}99$. In the manufacturer tested EC-motor the power factor with active PFC was also $PF_{tested} = 0{,}99$.

When estimating the effects of the harmonics it is more convenient to observe the voltage harmonics. The current varies a lot depending on the application and high current THD causes losses and heats up the systems but it is also important that voltage remains as sinusoidal as possible to ensure the right kind of operation of different devices. For example some small electronic devices (e.g. controllers) do not require a lot of current but the voltage has to be sinusoidal. The voltage waveforms and harmonics were not given from the manufacturer. When analyzing the harmonic spectrum shown in the figure 6.7 and the collected values in Table 6.2 it can be seen that the voltage THD fulfills the requirements of the classification society and the standards considering harmonics for class A-devices; no single order harmonic is over 5 % of the fundamental wave and the total voltage THD is also THD_u < 8%. The voltage THD in measuring point was THD_u = 4,54 % with one module in operation and THD_u = 4,92 % with two modules.

As mentioned before in this thesis the greatest source of harmonics in a ship is the propulsion system. However if the design of the propulsion frequency converter is done carefully the harmonics can be almost all eliminated and they do not multiply in to the low voltage network. In Figure 6.8 is shown an example of the voltage waveform and voltage harmonic spectrum of a propulsion system. The THD in this case is THD_u = 2,8 % in medium voltage network. [63]

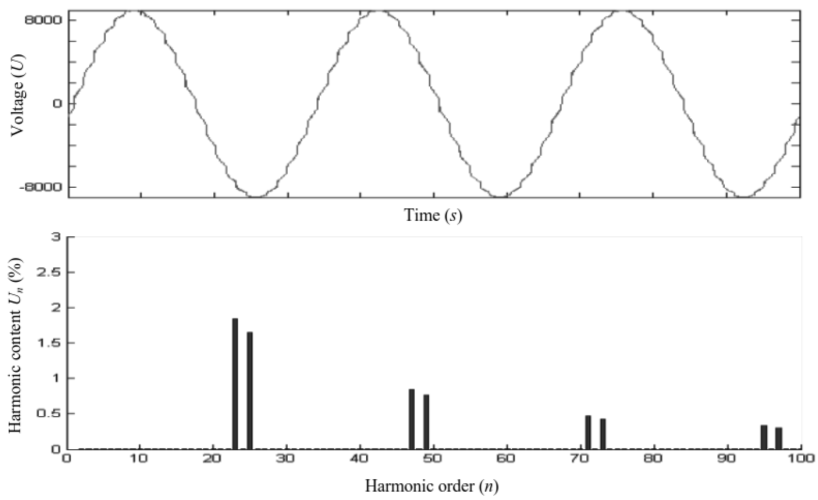


Figure 6.8. *Voltage waveform and harmonics in the medium voltage network.* [63]

It can be seen from Figure 6.8 that the harmonics that are produced by the 24-pulse rectification is equivalent to the theoretical 24-pulse rectifier which was introduced in Chapter 5.4.1. The harmonics can be calculated in this case with (5.12). When comparing Figures 6.7 and 6.8 to each other it can be noticed that the 23^{th} and the 25^{th} order, which are the greatest on the medium voltage network, are very small on the low voltage network and the orders above 25^{th} are zero. The conclusion is that the propulsion system has almost no effect to the harmonics in the low voltage network.

7. CONCLUSION

The purpose in this chapter is to evaluate if the PFC rectification is needed considering the effects and the costs. To back up the facts that were presented in the previous chapter there are also voltage THD measurements made from the distribution transformers' secondary side of two main fire zones in the previous and in the present ship.

7.1 Evaluation of the need for active PFC

The classification society requires that the voltage THD in the distribution network should not exceed 8 % and a single voltage harmonic should not exceed 5 %. Also the standard IEC 61000-3-2 defines harmonic current RMS limits for different types of devices with the supply lower than 16 A. As seen on the measuring results and the manufacturer testing results the regulations and standards are fulfilled with active PFC. However the EC-motor in the case studied is such small that the standard limits for current are not exceeded even if there were not any kind of filtering. The nominal current for the EC-motor used in the cabin air conditioning is only $I_{EC,nominal}$ = 0,5 A and the total RMS current is I_{RMS} = 0,3 A. For example the limit for the 3rd harmonic current is 2,3 A and for the 5th the limit is 1,14 A.

There is no measuring data of the cabin air conditioning available from the previous ships. It is known that in the previous ship there was no active or passive filtering installed alongside of the EC-motor. For comparison the voltage THD values of two different main fire zones measured from the distribution transformers secondary side (400 V) is shown in Table 7.1. The measurements were made with the same Fluke 435 Series II –meter on the sea trial. The transformers are from those main fire zones which have the most cabins.

Table 7.1. *Voltage THD measured from the distribution transformers secondary side (400 V) in two different ships.*

Transformer	THD_u (%), previous ship	THD_u (%), present ship
MFZ 4	2,6	2,4
MFZ 5	2,6	2,5

From Table 7.1 can be seen that the voltage THD values are almost equivalent. The little variations from the results are caused by variations in the loading of the distribution network and measuring errors. It can also be seen that the THD is well below the required limits.

Based on the THD values measured from the transformers distribution boxes there should be no need for active PFC in the cabin air conditioning. The previous installations demonstrate that there have been no interruptions or interferences in the low voltage distribution networks in this kind of passenger cruise ships. For backing up the conclusions there is the fact that the total electric power of cabin air conditioning EC-motors in one main fire zone is approximately $P \approx 30$ kW and the distribution transformer electrical power is approximately $S \approx 1700$ kVA. Transformers are double sized because of safety regulations which mean that one transformer can supply two main fire zones in case of an emergency. There are types of loads in the low voltage network which create higher harmonic RMS values (e.g. lighting installations, entertainment electronics and larger air conditioning devices) than the EC-motors. The EC-motor load is only 2 % of the nominal transformer electric power in the case that the motors are all at full speed.

Dropping out the active PFC should be still considered carefully. Even if there is no technical need for the filter it still improves the power factor of the EC-motor significantly, 0,46 improvement in the value in theory. Better power factor means better energy efficiency even though the total electric power is low. The total cost of one active PFC module is approximately one third of the fan price so some savings in the installation costs could be made if the filter is not installed.

7.2 Further actions

For more accurate result the measurements should be done straight from the combination of the EC-motor and the PFC module. Then the possible harmonics that are present in the low voltage network and also the effects the heater control could be eliminated from the results. More accurate measurements could be done during the building phase of the next ship and also on the sea trial again.

One interesting point considering the operation of cabin air conditioning that came out in the measurements was the control of the heaters. Even though the air conditioning modules operate independently the heaters are switched on almost at the same time. Then the heater is on a period of time which depends on the heating demand. The simultaneous switching creates major power variations because the electric power of one heater is 800 W. The total electric power of all heaters in the ship is then approximately $P \approx 1$ MW. The heater control should be under more investigation to solve the power variations. The current waveform drawn by the heater is shown in Appendix A. It can be seen that the both heaters that are connected to one cabin distribution box are switched on at the same time even if the systems are independent. The same situation is repeated in whole ship which creates major power variations.

8. SUMMARY

The purpose of this thesis was to introduce the electricity network of a passenger cruise ship and to become familiar with the quality of the electricity by exploring the effects of an EC-motor. The main goal was to explore the cabin air conditioning system and find out if the configuration, which is used at the moment, is needed. Alongside the study of EC-motors also the harmonic voltages and current were clarified; their sources, effects and how the harmonics are defined. It was essential for completion of the thesis to figure out the phenomena behind the harmonics.

The main components of the electricity network and their basic operation principles were introduced at first to give understanding about the operation of the ship. Nowadays everything is run by electricity in passenger cruise ships from the propulsion to the movie theaters. The electricity is produced in the ship using combustion engines. The electricity network is divided in medium voltage and in low voltage network and the used voltage levels were introduced alongside the example network that was used in this thesis. Also some basic information about the rules and regulations for marine business were necessary to look over to understand the different design requirements in land applications and marine applications. For example that the ship has to be divided in different fire zones which places requirements to the electricity distribution system also. Knowledge of the electricity network is needed to back the theory of harmonics in the network.

The basic operation scheme and the main components of the air condition system were also described. The air conditioning consists of several different phases before the fresh air is supplied from outside of the ship in to the passenger cabin. The air conditioning devices are part of the low voltage network except the air conditioning compressor which requires medium voltage and is located at bottom decks of the ship. Every main fire zone usually has its own air handling units which operate as main air conditioning units for fresh air distribution. The cabin fan coil unit is an independent air conditioning device that is controlled by the passenger. The fan motor in the cabin fan coil is an EC-motor and the effects of the motor to the electricity network were being examined. The EC-motor construction and operation principle was examined in theory.

The main effect that EC-motors cause to the electricity network is the harmonic distortion of current and voltage. The harmonics were first examined in theory and then the harmonic theory was combined to the information about the EC-motor which was given by the manufacturer. The harmonics created by the EC-motor are the result of the voltage rectification in the motor. In this case the rectification was made before the motor in the active PFC module which is also used to lower the harmonic distortion. The PFC unit operates as a Boost DC-DC converter in the system. The idea of harmonic analysis was to figure out if the active PFC module is needed to decrease the THD in the low voltage network. To verify the theory, the harmonics were also measured during the sea trial of the Mein Schiff and afterwards on the dock. The measurements were impossible to perform straight from the supply of the active PFC module due to the construction of the cabin air conditioning module. Therefore the measurements are only indicative because of the interference of other components in the low voltage network. However it could be noted that the harmonics in the low voltage network are well within the required limits.

For comparison also the harmonic distortion measurement from the previous ship is brought out because there were no active or passive PFC alongside the EC-motors used in the cabin air conditioning. It could be stated that the harmonics produced by the EC-motor have no effect to the voltage THD in the low voltage network because the values were practically the same between the two ships. The total electric power of the EC-motors is such small compared to the total electric power of the distribution transformer so that there is no effect to the voltage even if no PFC is used. Also using the active PFC increases the installation costs of the cabin air conditioning module.

However the use of active PFC improves the power factor of the motor from 0,53 to 0,99 which means better energy efficiency. When deciding if the PFC is needed the effects and the cost should be evaluated. Nowadays energy efficiency is very important and also the customers appreciate energy efficient ships. One other effect that the active PFC has is that it lowers the noise level created by the motor which is important in these kinds of passenger cruise ships.

REFERENCES

[1] Meyer Turku, Electrical Design, Electric Power Generation and Distribution – General Description, Mein Schiff.

[2] Meyer Turku, Electrical Design, Electric Power Generation and Distribution – General Description, Tallink.

[3] K. Hyytiä, Laivan sähköverkon simulointi, Aalto University, Master of Science Thesis, 2012, 71 p.

[4] P. Häkkinen, Laivan konejärjestelmät, Aalto University, Otaniemi, Espoo, Finland, 1993, 238 p.

[5] J. Bastman, Sähkökoneet, Tampere University of Technology, Tampere, Finland, 2014, lecture handout, 194 p.

[6] ABB Oy Marine, System Project Guide for Passenger Vessels, Helsinki, 2011, Project Guide, 268 p. Available (referred 1.2.2016): https://library.e.abb.com/public/608df0ae42ea2ce8c1257abd004ff506/ABB_System_Project_Guide_ Passenger_Vessels.pdf

[7] O. Ståhle, Laivan sähköverkon yliaaltojen tarkastelu Neplan-ohjelmiston avulla, Tampere University of Technology, Master of Science Thesis, 2016, 95 p.

[8] A.K. Ådnanes, Marine Electrical Installations and Diesel Electric Propulsion, ABB AS Marine, Oslo, 2003, 86 p.

[9] A.E. Fitzgerald, Electric Machinery Sixth Edition, New York, NY, USA, 2003, 703 p.

[10] W. Maes, Marine Electrical Knowledge, Antwerp Maritime Academy, Antwerpen, 2013, 52 p. Available (referred 5.2.2016): http://magelhaes.hzs.be/willem/assorted/marine_electrical_knowledge.pdf

[11] ABB Oy Drives, Product Brochure, Medium voltage AC drive ACS 6000, 3-36 MW, up to 3,3 kV, 20 p. Available (referred 1.2.2016): http://www04.abb.com/global/seitp/seitp202.nsf/e308f3e92d9a8fc5c1257c9f00349c99/9e85af04443f562448257c14001d261d/$FILE/ACS+6000+EN+Rev+F_lowres.pdf

[12] L. Korpinen, Sähkövoimatekniikkaopus, Tampere University of Technology, Tampere, 1998. Available (referred 10.2.2016): http://www.leenakorpinen.fi/node/158

[13] D. Radar, Power Electronic Converters for Ship Propulsion Electric Motors, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 23 p. Available (referred 12.2.2016): http://www.fpp.uni-lj.si/mma_bin.php?id=2011111019030187

[14] J. Saastamoinen, Jännitetasojen vertailu laivan sähköverkossa, Metropolia University of Applied Sciences, Thesis, 2013, 58 p.

[15] B. Ozpineci, Cycloconverters, Department of Electrical and Computer Engineering, University of Tennessee-Knoxville, Knoxville, USA, 17 p. Available (referred 15.2.2016): http://www.uv.es/emaset/iep00/cycloconvertertutorial.pdf

[16] Elprocus, Cycloconverters – Types & Applications, [WWW], Available (referred 15.2.2016): https://www.elprocus.com/cycloconverters-types-applications/

[17] DNV-GL, Rules and Standards, Rules for Classification: Ships, [WWW], Available (referred 19.2.2016): https://rules.dnvgl.com/ServiceDocuments/dnvgl/#!/industry/1/Maritime/1/DNV%20GL%20rules%20for%20classification:%20Ships%20(RU-SHIP)

[18] H. Eriksson, M.Sc., System Responsible, Meyer Turku, Turku, Interview, 17.2.2016.

[19] K. Hyytiä, M. Sc., Project Coordinator, Meyer Turku, Turku, Interview, 18.2.2016.

[20] A. Törne, Electrical Engineer, Designer, Meyer Turku, Turku, Interview, 22.2.2016.

[21] ABB Oy Drives, Product Brochure, ABB Drives for Marine Medium Voltage Drives for Reliable and Efficient Operations at Sea, 16 p. Available (referred 15.2.2016): https://library.e.abb.com/public/2e7b508ea530471ac125785b00446c95/Marine%20brochure%20RevB_lowres.pdf

[22] Meyer Turku, Electrical Design, Electric Power Distribution Single Line Diagram Mein Schiff, 2015.

[23] IMO, International Maritime Organization, International Convention for the Safety of Life at Sea (SOLAS), [WWW], Available (referred 7.3.2016): http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

[24] myElectrical Engineering, Power Transformers – An Introduction, [WWW], Available (referred 26.2.2106): http://myelectrical.com/notes/entryid/199/power-transformers-an-introduction

[25] Rolls-Royce, Tunnel Thrusters, Product Brochure, [WWW], Available (referred 12.2.2016): http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents /customers/%20marine/tunnel-thrusters.pdf

[26] Maritime-Connector, Press release: Drydocks World launches AHTS built for Swire Pacific, [WWW], Availble (referred 12.2.2016): http://maritime-connector .com/news/port-and-shipbuilding/press-release-drydocks-world-launches-ahts-built-for-swire-pacific/

[27] IHS Engineering 360, Refrigeration Compressors and Air Conditioning Compressors Information, [WWW], Available (referred 31.3.2016): http://www. globalspec.com/learnmore/building_construction/hvac/ventilation/refrigeration _compressors_air_conditioning_compressors

[28] Meyer Turku, HVAC Design, Description of Air Conditioning system, Mein Schiff, 2015.

[29] Meyer Turku, HVAC Design, Description of AC Pre- and Reheating system, Mein Schiff, 2015.

[30] Meyer Turku, HVAC Design, HVAC Automation system - Description, Mein Schiff, 2015.

[31] Meyer Turku, HVAC Design, Air Handling Unit Register, Mein Schiff, 2015.

[32] Meyer Turku, HVAC Design, AC Air Devices Register, Mein Schiff, 2015.

[33] Meyer Turku, HVAC Design, Fan Coil Unit Register, Mein Schiff, 2015.

[34] Belimo US, Blog, Code Required Testing of Fire, Smoke, and Combination Dampers, [WWW], Available (referred 5.4.2016): http://blog.belimo.com/Blog /bid/71397/Code-Required-Testing-of-Fire-Smoke-and-Combination-Dampers

[35] V. Heikkilä, M.Sc., System Responsible, Meyer Turku, Turku, Interview, 7.4.2016.

[36] Meyer Turku, Electric Design, Power distribution system for cabins - Principle, Mein Schiff, 2015.

[37] Maxon precision motors, High Dynamic Brushless DC motors, [WWW], Available (referred 9.5.2016): https://maxonmotorusa.wordpress.com/2013/12/13/max on-ec-i40/

[38] airtècnics, ECfans: Overview, [WWW], Available (referred 9.5): http://www. airtecnics.com/technology/ec-fans-overview

[39] ebm-papst, EC-puhaltimet, Mitä erikoista on EC-puhaltimissa, [WWW], Available (referred 9.5.2016): http://www.ebmpapst.fi/fi/dat/media_manager/news/8/news-files/Tietoisku__Mita_erikoista_EC-puhaltimissa.pdf

[40] ebm-papst, ebm-papst Fans, Blowers and Technology, [WWW], Available (referred (9.5.2016): http://info.ebmpapst.us/ebm-papst/topic/brushless-motor

[41] Hyperphysics, Commutator and Brushes on DC Motor, [WWW], Available (referred 11.5.2016): http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/comtat.html

[42] Elta Select, Information Centre, EC vs. AC, [WWW], Available (referred 11.5.2016): http://www.fantech.com.vn/mydata/mce/news/ec_vs_ac.pdf

[43] ebm-papst, Yleistä ebmpapst-puhaltimista, [WWW], Available (referred 9.5.2016): http://www.ebmpapst.fi/fi/dat/media_manager/news/3/news-files/yleistapuhaltimista.pdf

[44] ebm-papst, data sheet, EC-motor type G3G146ED1919, Not available in public

[45] ebm-papst, EC Fans and Motors, [WWW], Available (referred 11.5.2016): http://www.ebmpapst.com.au/en/ec_technology/ec_fans_and_motors/ec-technology_special.html

[46] Schneider Electric, Electrical Installation wiki, Power harmonics management, [WWW], Available (referred 2.8.2016): http://www.electrical-installation.org/enwiki/Power_harmonics_management

[47] L. Korpinen, M. Mikkola, T. Keikko, E. Falck, Yliaalto-opus, Available (referred 2.8.2016): http://www.leenakorpinen.fi/archive/opukset/yliaalto-opus.pdf

[48] A. Baggini, Handbook of Power Quality, John Wiley & Sons, Chichester, West Sussex, England, 2008, 642 p.

[49] Power Monitors, Inc, Understanding IEEE 1159 Definitions, [WWW], Available (referred 4.8.2016): http://blog.powermonitors.com/blog/understanding-ieee-1159-definitions

[50] ABB Oy, Tekninen opas nro.6: Vaihtovirtakäyttöjen yliaalto-opas, Available (referred 4.8.2016): https://library.e.abb.com/public/9aaf3178627952c7c1256d2800411f8d/Tekninen_opas_nro_6.pdf

[51] M. Laaksonen, Fourier'n menetelmät, Tampere University of Technology, Tampere, Finland, 2013, lecture handout, 84 p.

[52] American Bureau of Shipping, ABS, Rules and Guides, Guidance notes on control of harmonics in electrical power systems, May 2006, [WWW], Available (referred 16.8.2016): https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/150_CtrlofHarmonicsinElecPowerSystems/Pub150_ElHarmonics

[53] ebm-papst, EC-motor, Harmonics and Power Factor Correction, Research

[54] T. Suntio, Power Electronic Converters, Tampere University of Technology, Tampere, Finland, 2014, lecture notes

[55] T. Messo, Introduction to Power Electronics, Tampere University of Technology, Tampere, Finland, 2014, lecture notes

[56] A. Mäkinen, Sähköverkon häiriöt ja sähkön laatu, Tampere University of Techonology, Tampere, Finland, 2013, lecture handout 63 p.

[57] J. Schonek, Schneider Electric, Cahier technique no. 202, The singularities of the third harmonic, 2001, 20 p.

[58] ON Semiconductor, Power Factor Correction (PFC) Handbook, 2014, [WWW], Available (referred 22.8.2016): http://www.onsemi.com/pub_link/Collateral/HBD853-D.PDF

[59] K. Nousiainen, Sähkövoimajärjestelmän perusteet, Tampere University of Technology, Tampere, Finland, 2012, lecture handout

[60] Air conditioning supplier, Technical presentation of cabin fan coil

[61] Air conditioning supplier, PFC unit, technical specification

[62] Fluke, Fluke 435 Series II Power Quality and Energy Analyzer, [WWW], Available (referred 30.8.2016): http://en-us.fluke.com/products/power-quality-analyzers/fluke-435-ii-power-quality.html

[63] Meyer Turku, Electrical Design, ABB – Harmonic distortion calculation, Mein Schiff

[64] Elektropaedia, Battery and Energy Technologies, Electric Drives – Brushless DC/AC and Reluctance Motors, [WWW], Available (referred 12.9.2016): http://www.mpoweruk.com/motorsbrushless.htm

APPENDIX A: THE CURRENT WAVEFORM DRAWN BY THE HEATER IN THE AIR CONDITIONING MODULE