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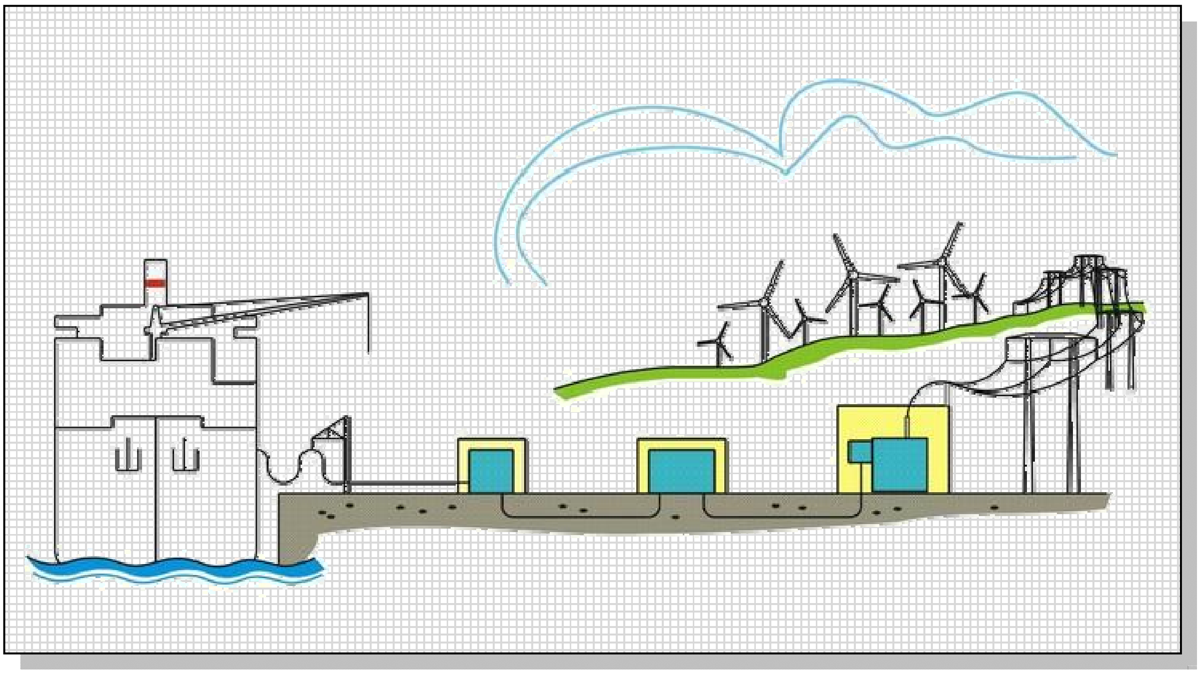

SHORE-SIDE POWER SUPPLY

A feasibility study and a technical solution for an on-shore electrical infrastructure to supply vessels with electric power while in port

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008

ABB

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Summary

While in port, ships use their diesel auxiliary engines to produce electricity for hotelling, unloading and loading activities. Main engines are usually switched off soon after berthing. The auxiliary engines today are running on cheap and low quality fuel, resulting in negative environmental impacts. The European Union has therefore entered into force a directive that limits the sulphur content in marine fuel from 4.5 % to 0.1 % in order to reduce the emission discharge from vessels. It has shown that this limit is a good start, but it is not good enough, therefore is shore-side power supply recommended.

There are currently 15 ports worldwide that have applied shore-side power supply in their electrical infrastructure, and they have experienced a radical improvement of the environment at their port. This has resulted in that ports worldwide have started to investigate the possibilities with shore-side power supply.

In order to make a technical design, the onboard electric system on the vessel had to be investigated. The study in the report has shown that the power demand varies depending on the type of vessel. This report shows that the minimal power demand that was made in the study was 1 MW and the maximum power demand was 11 MW for different types of vessels. The port must be aware of the vessels power demand, system voltage and system frequency when designing the shore-side power supply facility. The study made in report has shown that the majority of the vessels have a system frequency of 60 Hz and that the system voltage is low-voltage. This means that a frequency converter is needed in European harbours in order to supply 60 Hz vessels with electricity, and that the vessels need to be equipped with a transformer onboard in order to avoid great amount of parallel connection cables. Having two cables to connect instead of several cables in order to transfer the same amount of power will save great amount of time during the connection procedure, which is desirable. It has been shown during the thesis that a centrally placed frequency converter is mostly eligible in order to reduce the costs and also to save footprint on the berth where there is limited amount of space.

There are currently no standards available today regarding shore-side power supply, but is expected to be released in mid of 2009.

The recommended configuration in the report is implemented in a container terminal where five berths are to be supplied with shore-side power supply, 6.6 kV, 7.5 MVA and distribute both 50 Hz and 60 Hz. Each berth has to be equipped with an obligatory transformer to serve as galvanic separation between the harbours electric grid and the vessels electric system.

Having centrally placed frequency converters that can be dimensioned by the actual power demand of the harbour is the best way to reduce the cost, although it is not enough since the frequency converters correspond to 50 % of the total equipment cost. Therefore is module based frequency converters desirable, where the same module can be used as building block for different power need, and in that way increase the production volumes and reduce the costs. In order to retrieve module based frequency converter, development of today’s technology is needed.

Keywords: Alternative Maritime Power - AMP, High Voltage Shore-side Supply - HVSC, Onshore Power Supply – OPS, Cold Ironing

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Patrik Ericsson
Ismir Fazlagic´

Göteborg, 2008

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Part A - Introduction

A1 Introduction

Ocean-going marine vessels represent one of the largest, most difficult to regulate, source of air pollution in the world and are also an essential component of the international trade and goods movement process. It is estimated that in year 2025 the on-sea trading volume in the world will be tripled compared to year 2008 [9]. These vessels are similar to floating power plants in terms of power, and would surely be subjected to stricter regulations if their emissions had been generated onshore.

While in port, ships use their diesel auxiliary engines to produce electricity for hotelling, unloading and loading activities. Main engines are usually switched off soon after berthing. The auxiliary engines today are running on cheap and low quality fuel. It is known that ship's fuel contains 2 700 times more sulphur than the gasoline used in cars, and together with aviation, shipping is the biggest emitter of pollution in the European Union [54].

One measure to reduce emissions while at berth, is to provide electricity to the ships from the national grid instead of producing electricity by the ships own auxiliary diesel generators. To provide ships with electricity, a shore-side electricity supply arrangement is required. The electricity frequency in the European Union grid is 50 Hz. However, the frequency used onboard ships can be either 50 or 60 Hz. A ship designed for 60 Hz may be able to use 50 Hz for some equipment, such as lighting and heating, but this is a small fragment of the total power demand on the ship. Motor driven equipment, such as pumps and cranes, will not be able to run on their design speed, which will lead to damaging effects on the equipment. Therefore, a ship using 60 Hz electricity will require that the frequency in the European grid, needs to be converted to 60 Hz by a frequency converter, before connected.

This report includes both a feasibility study and a possible technical design for a shore-to-ship electrification. The idea of this report is that it should serve as guidance for future projects, concerning shore-side power supply, before a well-developed world standard is released.

A1.1 Background

Shore-to-ship electrification; also known as *Cold Ironing*, is an old expression from the shipping industry, that first came into use when all ships had coal fired iron clad engines. When a ship would tie up at port there was no need to continue to feed the fire and the iron engines would literally cool down eventually going completely cold, hence the term cold ironing. Cold ironing, in the meaning of shore-to-ship electrification, has been used by the military at naval bases for many years when ships are docked for long periods. As the world's vessel fleet is increasing, vessel calls to ports are becoming more frequent. In addition, hotelling power requirements have increased, and thus the concern of on-board generator emissions during docking periods has become an important air pollution issue.

The main background for this work is the upcoming European directive 2005/33/EG, limiting the air pollution contributed by ships while docked in harbours. From 2010 ships must use low sulphur fuels (0.1 %) or shut down their generators and use shore-side electricity [23].

A reduction of emission in the port by a power supply on the shore-side could be more cost-effective and favourable for the environment.

A1.2 Purpose

The purpose of the thesis is to:

- Examine the most common nominal voltages and frequencies for vessels that call European harbours, and their power demands.
- Determine the potential for harbours to supply vessels with electric power from the grid.
- Examine the specific needs of the shore to ship electrification for different types of harbours and different types of ships.
- From the data collected, evaluate different technical solutions to meet the needs from a technical point of view.
- Make a proposal for a modularized shore to ship electrification system which meets the needs from different size and type of harbours and ships and which fulfil the upcoming standard.

A1.3 Delimitation

The report will not consider how a reconstruction shall be made onboard the vessel in order to adapt to the shore-side power supply; this report concerns only the infrastructure on shore. Furthermore, the report doesn’t describe the communication and communication protocols between the shore and vessels, since there are no standards yet available regarding shore-side power supply communication. The report will not describe the electric system in detail onboard the vessel such as, how voltage and frequency synchronization is executed onboard, so that the voltage and frequency between the vessel and shore is adapted. Further, it is expected in the Simulations & Calculations chapter that the reader has some basic knowledge regarding electric power engineering in order to understand the models and the methods used for the handmade calculations.

A1.4 Method

Information has been gathered from the harbours homepages, books and internet, and scientific articles have been found in databases, such as IEEE. To make use of the knowledge inside ABB and learn more about the ships and the electrical system onboard the vessels, discussions and continuous meetings have been held with the personnel involved in the project. To get specified information about different components, the manufacturers were contacted trough e-mail and telephone.

To understand how it looks like in a harbour, several harbours were contacted, both in Europe and in the USA. The opportunity was given to visit some harbours to see what typical problem areas there are in ports. Port of Göteborg and Port of Stockholm, Port of Helsingborg, Port of Oslo and Port of Tallinn were visited to get a clearer picture of a harbour.

A1.5 Disposition

Part A - Introduction

Represents this part.

Part B - Market review

Contains the market survey. It describes the driving forces to shore-side power supply vessels, existing installations in the world, possible markets and actors in the market.

Part C - Technical survey

Describes the technical survey. It gives an introduction of power generation onboard vessels, onboard power demands, docking patterns for different types of vessels in port and describes the norms and standards available today.

Part D – Technical design

Contains the configuration of the technical design.

Part E – Calculations and simulations

Presents the simulations and calculation of the technical design.

Conclusion

Presents the conclusion of the master thesis.

Part B - Market review

B1 Driving forces

The shipping industry is an important link in the international system of goods movement and is increasing rapidly in size and power. Today, marine transport of goods is responsible for roughly 90 % of the world trade [25]. There is approximately a fleet of 30 000 commercial vessels over 1000 gross tonnage in the world, which are calling approximately 5 900 harbours worldwide. Among 5 900 worldwide harbours there is approximately 2 100 harbours located in Europe [50]. According to prognosis, it is estimated that in year 2025 the on-sea trading volume in the world will be tripled compared to year 2008. This is due to the rapid economic development in Asia [9]. Besides the transportation of goods, also a large increase in pleasure-travelling has just begun. Bigger and luxury cruise ships are constructed year after year and can carry thousands of passengers. The power demand for just one cruise ship can be compared with a small city. These floating power plants have almost been free from strict air-pollution regulations, compared to other transport sectors. The discussion in the past years concerning the greenhouse effect has created an extensive reaction from the public. This has caused an increased political pressure on ship-owners and port authorities' worldwide to improve the air quality in the cities and especially in ports, since they are often located in urban areas.

This chapter will concern the major driving forces for shore-side electrification of sea-going vessels.

B1.1 Directives and recommendations

One of the key forces behind shore-to-ship electrification is the EU directive *2005/33/EC* that will come into force the 1st of January 2010, and affects every single ship while at berth in a European port more then two hours. The directive requires that emissions from shipping should be limited by reducing the sulphur content in the marine fuels to 0.1 % by weight while docked [23]. Combustion of marine fuels with high sulphur content contribute to air pollution in the form of SO_X and particulate matter, harming human health and damaging the surrounding environment.

The global sulphur limit today in marine fuel, both at sea and in berth, is set to 4.5 % by weight excluding SO_X Emission Controlled Areas (SECA) - the North Sea, Baltic Sea and the English Channel, where the limit is set to 1.5 % sulphur by weight. This is according to the international directive *MARPOL Annex VI*, which is developed by The International Maritime Organisation (IMO). *MARPOL Annex VI* was formalized in 2004 and entered in force 19th of May 2005 [30].

The limits according to the European directive *2005/33/EC* and the International directive *MARPOL Annex VI* are summarized in *Figure B1*.

The European Union has also come with a recommendation *2006/339/EC,* to all member states, which propose an atmospheric reduction of emissions from seagoing ships, by urging the port authorities to require or facilitate ships to use land-based electricity while in port. In the recommendation there is a proposal saying that all member states should make a consideration regarding installation of shore-side electricity for ships at berth in ports, particularly in ports where air quality limit values are exceeded or where there is a public complaint about high levels of noise [35].

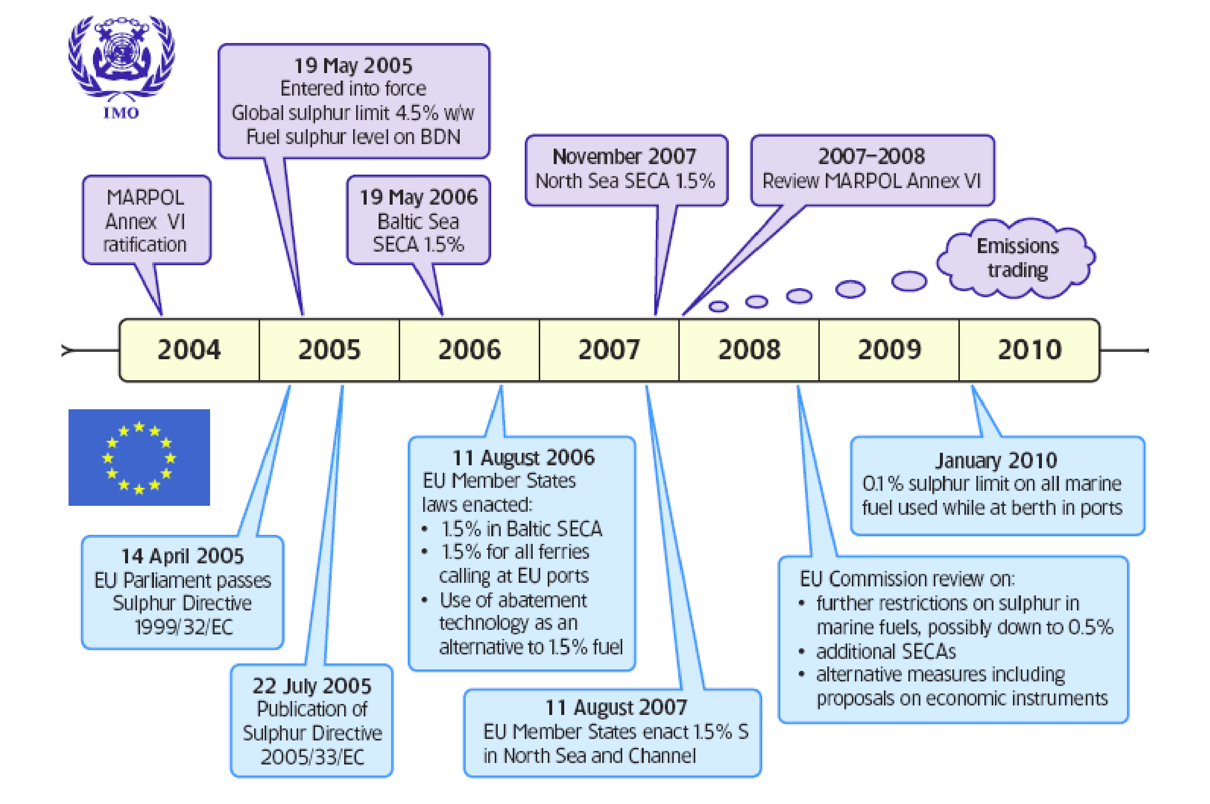


Figure B1 Legislative overview and timeline – IMO and European Union

B1.2 Environmental forces

Around the world, ports are considered as areas of high activity and profit generation that serve as a primary point for international goods import and export. They are also notorious for being major sources of air pollution, and will continue to be seen as such in the near future if something doesn't change. Ship engines are remarkably well designed as they remain in service for many years and are able to burn the cheapest and lowest quality fuel. While this is good from an operational or shipping owner's standpoint, an uncontrolled engine burning low quality fuel for decades is practically a nightmare for air quality and public health in any region where there are ships.

While docked at berth, most ships turn of their propulsion engines but typically use the auxiliary diesel engines to provide power to the electrical equipment onboard the ship. The major emissions coming from the auxiliary engines are nitrogen oxides (NO_X), sulphur oxides (SO_X) and diesel particulate matter (PM) [20]. These emissions are currently uncontrolled for most vessels. A major description of the emissions from ships can be found in *Table B1*.

Table B1 Major emissions from ships and their environmental and health impacts

Emission	Description
NO_X	NO_X include various nitrogen compounds like nitrogen dioxide (NO_2) and nitric oxide (NO). These compounds play an important role in the atmospheric reactions that create harmful particulate matter, ground-level ozone (smog) and acid rain. Health impacts from NO_X are that they cause respiratory problems such as asthma, emphysema and bronchitis, aggravates existing heart disease, and contributes to extended damage to lung tissues, and causes premature death. [63]
SO_X	SO_X cause irritant effects by stimulating nerves in the lining of the nose and throat and the lung's airways. This causes a reflex cough, irritation, and a feeling of chest tightness, which may lead to narrowing of the airways. This later effect is particularly likely to occur in people suffering from asthma and chronic lung disease, whose airways are often inflamed and easily irritated. [65]
VOC	Volatile Organic Compounds (VOC) is a greenhouse gas and contributes eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment. [64]
PM	Particulate matter (PM) emissions contribute premature death, irritating asthma, increased respiratory symptoms' such as coughing and painful breathing, and they contribute to decreased lung function. [62]

Concluding, the major emissions have a negative impact on the human health and the surrounding environment, especially on the ozone contributing to the greenhouse gas.

A study was made by Port of Los Angeles and Port of Long Beach, looking at NO_X emissions that are contributed by ships at the port during the period of June 1, 2002 to May 31, 2003. In the study they looked at the emission contribution coming from main propulsion engines, auxiliary engines and boilers from 1 148 vessels making 2 913 calls. The primary type of vessels entering POLB was container vessels, tankers and dry bulk cargo vessels [21]. The results are shown in *Table B2*.

Table B2 NO_X emissions in Port of Los Angeles and Port of Long Beach combined [tons/day] [21]

Mode	Main Propulsion Engine	Auxiliary Engine	Boiler	Total
Cruise	16.2	1.4	-	17.6
Manoeuvring	2.0	0.7	0.1	2.8
Hotelling	0.7	11.0	1.0	12.7
Total	18.9	13.1	1.1	33.0

As can be seen 33 tons per day of NO_X emissions is contributed by vessels. Of these 33 tons, one-third of in port vessel emissions occur while the vessels are at berth. A comparison figure can be found for ordinary cars. It is said that 1 ton of NO_X is contributed by 1 000 000 cars per day [42]. Replacing the onboard generation with on-shore electric power could significantly reduce emissions.

The European Commission assigned *ENTEC*, which is an environmental and engineering consultancy firm, to investigate the amount of emissions contributed when producing one kWh of electricity by using the ships own auxiliary engine with 0.1 % sulphur fuel (EU 2010 limit) and also the amount of emissions contributed by land-base electricity connected to the ship. The emission factor for electrical generation in Europe is based from the Energy and Transport Trends to 2030. An average factor for electricity generation in 2010 was determined and is shown in *Table B3*. Also emission factors for auxiliary engine generation was calculated based on 0.1 % sulphur fuel and these figures are also shown in *Table B3* [20].

Table B3 Average emission factors for electricity production in Europe and onboard generation with 0,1 % sulphur fuel [20]

	NO_X [g/kWh]	SO_2 [g/kWh]	VOC [g/kWh]	PM [g/kWh]
Average emission factors for electricity production in Europe	0.35	0.46	0.02	0.03
Emission Factors from auxiliary engines using 0.1 % sulphur fuel (EU 2010 limit)	11.8	0.46	0.40	0.30

The reduction of emissions achieved by replacing onboard generated electricity with shore-side electricity is shown in *Table B4*. The table presents figures for tonnage/year/berth of emission reductions. They were calculated by assuming an utilisation at berths of 70 % of time.

Table B4 Emissions reduced per berth [t/year/berth] compared to engines using fuel with 0,1 % sulphur [20]

		Small [t/year]	Medium [t/year]	Large [t/year]
NO_X	Baseline emissions	15.3	42.4	109.1
	Emissions reduced	14.81	41.09	105.86
	Reduction efficiency	**97 %**	**97 %**	**97 %**
SO_2	Baseline emissions	0.62	1.72	4.44
	Emissions reduced	0.0	0.0	0.0
	Reduction efficiency	**0 %**	**0 %**	**0 %**
VOC	Baseline emissions	0.52	1.44	3.71
	Emissions reduced	0.49	1.36	3.49
	Reduction efficiency	**94 %**	**94 %**	**94 %**
PM	Baseline emissions	0.39	1.08	2.78
	Emissions reduced	0.35	0.96	2.48
	Reduction efficiency	**89 %**	**89 %**	**89 %**

As can be seen from the table it is a radical improvement of the total emission cut down by using shore-side power supply instead of using fuel with 0.1 % sulphur content according to the European directive *2005/33/EC*. There is a big profit margin for the environment when changing to shore-side electricity.

B1.3 The AMP Program

In 2001, the Los Angeles Mayor James Hahn initiated a No Net Emission Increase (NNEI) policy for the Port of Los Angeles [47]. The purpose of the policy was to hold back and maintain air emissions from the Port's activities. A task force was established to develop a plan to meet the NNEI goals, therefore the *Alternative Maritime Power* (AMP) program was introduced.

The AMP is a program in accordance with which shipping companies partners up with the Port of Los Angeles and the Los Angeles Department of Water and Power to develop an engineered solution, where a ship is provided electrical power via land. The program has been very successful since Port of Los Angeles set up a profitable strategy for the shipping owners. In order to gain the installation onboard the vessels, the port provided an incentive of 800 000 $ toward the cost to install the AMP necessary equipment on a port customer's first ship [40]. This means that the shipping companies will get paid for the installed shore-side electricity equipment onboard and use shore-side power and also traffic Port of Los Angeles for X number of years.

The success of the project has resulted in 52 new build container vessels equipped with shore side connection systems during 2005 – 2008, and also other ports in the US are taking the program into account, especially in the California region [43]. The AMP program will generate both reconstruction of ships and new build ships equipped with shore-side electricity systems onboard in the upcoming years. A major part of these vessels are also calling the European harbours.

B2 Existing installations

Shore-side power supply has been used since the 80s for supplying commercial vessels with electricity. Ferries were the first vessels to be shore-side connected. The reason for this was that they always docked in the same position making it easy for connection. Today, other types of commercial ships, such as, cruise-, container-, and Ro/Ro- vessels are connected to the electrical grid in ports around the world, see *Figure B2*.

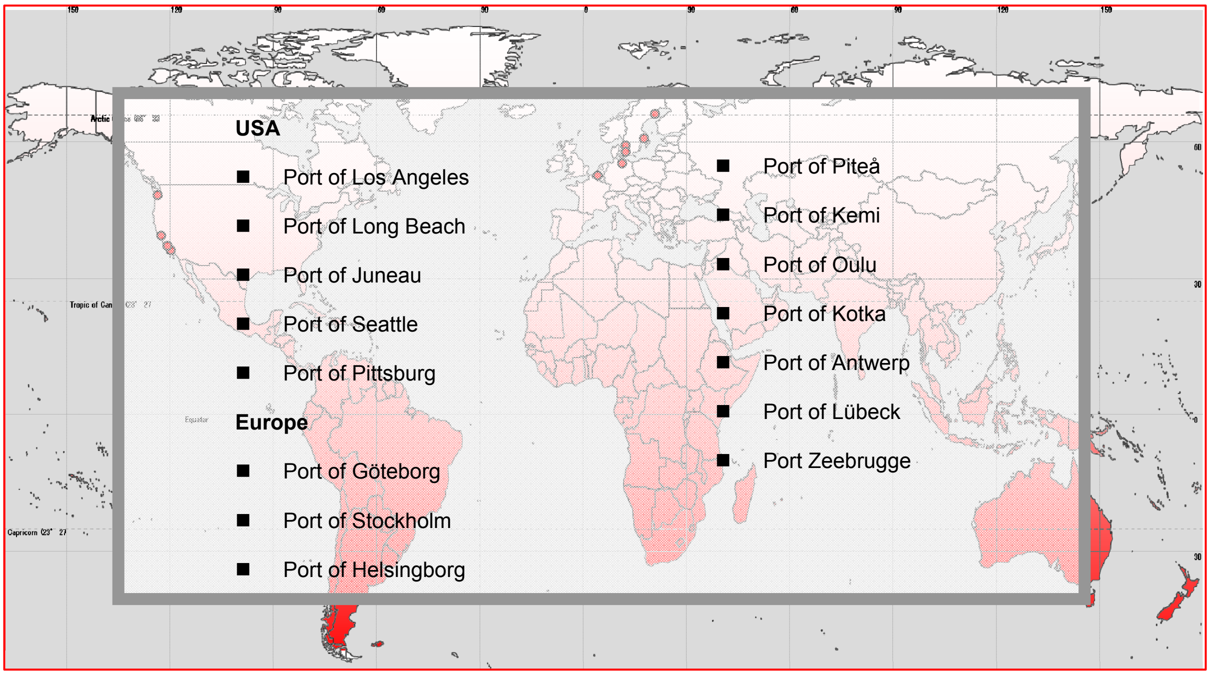


Figure B2 Existing shore-side power supplies in the world

The great need of power for existing vessels and the greater need for power for newer ships have substituted low-voltage connections with high-voltage connections. The reason for this is to get rid of a vast amount of parallel cables that take long time to connect during each dock. With a high-voltage connection you are able to transfer the same amount of power with fewer cables, which makes it easier during the connection process. A high-voltage cable makes it possible to transfer 25 times more power than with a normal 400 V cable of the same dimension.

In 2000, Port of Göteborg was the first port in the world to introduce a high-voltage connection, and since then many ports have replicated the connection, and today high-voltage connections are considered to be the most effective way to connect ships.

This chapter will present shore-side connections available today in the world. In the end of the chapter a summary of all existing shore-side connections can be found in *Table B5*.

B2.1 Port of Göteborg

The first step for shore side power supply in Port of Göteborg (Sweden) was taken in 1989. The port converted a terminal to service Stena Lines passenger ferries to Kiel with a low-voltage, 400 V, shore-side power supply system, see *Figure B3* and *Figure B4*. This service is run by the two combined passenger and Ro/Ro ferries Stena Scandinavica and Stena Germanica.

Figure B3 The first shore-connection in Port of Göteborg, installed in 1989 at the Kiel terminal. The building in the picture includes the transformer and cable arrangement equipment.

Figure B4 The 400 V cables are connected to Stena Scandinavica.

In January 2000 the next step for shore-side power supply was taken in Port of Göteborg. The world's first high-voltage shore-side connection was inaugurated. This project was in cooperation with Port of Göteborg, Stora Enso and ABB. It was the first time a shore-side connection was devoted for Ro/Ro-vessels. The power is distributed via a transformer substation 10 kV/6.6 kV 1250 kVA on the quay, see *Figure B5*. In between the vessel and the transformer substation, a 9ft container is equipped with control equipment and the power outlet for connection of the cable to the ship, see *Figure B5* and *Figure B6* [19].

Figure B5 The first high voltage installation in Port of Göteborg. The building in the top left contains a transformer and switchgears. The blue container building is the connection point.

Figure B6 The figure illustrates the interior of the blue 9ft container building. The main cable is connected to the outlet and, the manoeuvre cable is connected to the control panel where the person performing this action has an overview of the whole system.

Figure B7 A single main cable for the power supply and manoeuvre is all that is needed to connect the ship.

A single main cable for the power supply and manoeuvre is all that is needed to connect the ship, see *Figure B7*. The cable is provided by the ship and is mounted on a cable-wheel onboard. This means that the connection can be done by hand power; without cranes or other solutions. The cable is lowered down to the 9 ft container. Inside the container, where the equipment is protected from weather and wind, the actual connection is made. The manoeuvre cable is connected to the control panel where the person performing this action has an overview of the whole system. Another person on the bridge presses a button when the vessel is ready to be synchronized [19].

In 2003 an additional terminal was converted to use shore-side electricity. This terminal is similar to the previous facility, but with the exception of the transformer, taking out 10 kV directly from the Ports grid. This terminal was also devoted for servicing Ro/Ro vessels. Another difference between the terminals is that the cable now is provided by the Port [19].

Currently the two quays at the Ro/Ro terminal that offer high voltage shore-side electricity in Port of Göteborg connect six vessels operating for Stora Enso; three Transatlantic vessels and three Wagenborg vessels [44].

In 2006, an additional terminal was converted to service one of Stena Lines passenger ferries to Denmark, Stena Danica, using a high voltage connection, where the 10 kV power supply is transformed to 400 V onboard. This solution is used when the ship is at berth for more than three hours, in Port of Göteborg [19].

B2.2 Port of Stockholm

In 1985, Port of Stockholm (Sweden) inaugurated their first shore-side power supply facility for connection of bigger vessels. The connection is located in Stadsgården and connects ships that are operating to Aland Island - Viking Cinderella and Birger Jarl. These ships are connected with a low voltage connection, 400 V/50 Hz. To be able to deliver sufficient amount of power to the vessels (2.5 MW), 9 cables need to be connected before the electricity generators onboard the vessel are shutdown. To make the connection as smooth at possible a custom made cable arrangement was made at land, see *Figure B8* and *Figure B9*. The connection process takes approximately 5 minutes [57].

Figure B8 The cable arrangement building next to the berth for the first installation in 1985.

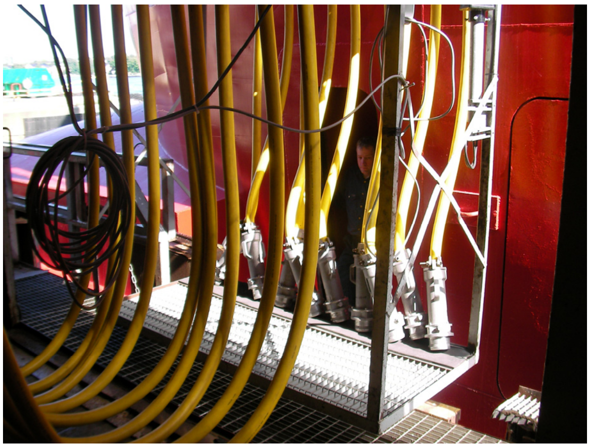


Figure B9 Nine cables are pushed out to Viking Cinderella and are ready to be connected.

During spring 2006 another shore-to ship low voltage connection, 690 V/50 Hz, was inaugurated to Tallink passenger ferries - Victoria I and Romantika - at Freeport terminal in Port of Stockholm. The power is distributed via a transformer substation on the quay. In between the vessel and the transformer substation a special flexible stand was made, see *Figure B10*. To be able to deliver sufficient amount of power to the vessels, 12 cables need to be connected before the electricity generators onboard the vessel are shutdown. Before departure the electricity generators are once again started and the shore-to-ship connection is disconnected. Also this connection process takes approximately 5 minutes. One of the power plugs can be seen in *Figure B11* [57].

Figure B10 The cable arrangement building next to the berth for the installation made in 2006.

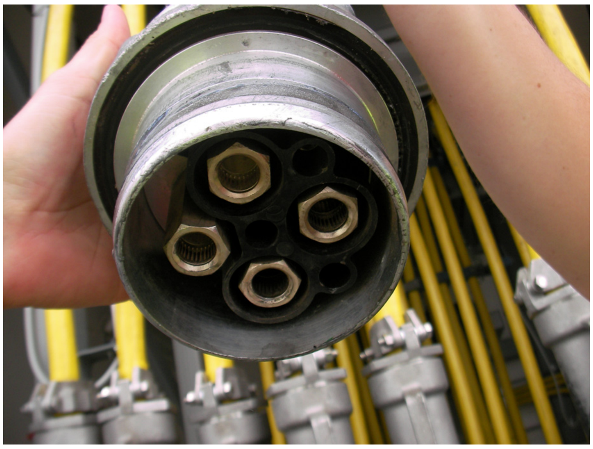


Figure B11 The connection plug (690 V).

B2.3 Port of Helsingborg

Port of Helsingborg (Sweden) is providing shore-side electricity to the ferries that stay at berth during night. The Scandlines ferries are connected via 400 V/50 Hz 2 x 250 A cables, which is sufficient for limited supply. Sundbussarna are connected with shore-side electricity 400 V/50 Hz 2 x 125 A. HH-Ferries are connected with 440 V/50 Hz [34].

B2.4 Port of Piteå

In Port of Piteå (Sweden), M/S Balticborg and M/S Bothniaborg are supplied with high voltage, 6 kV, shore-side electricity via a feeding and a control cable [34].

B2.5 Port of Kemi

In 2006, Stora Enso in cooperation with Port of Kemi (Finland) converted a terminal to service Stora Enso’s Ro/Ro vessels. The overall 6.6 kV electrical connections and designs are similar to Port of Göteborg, since it is the same vessel that is connected in Port of Göteborg [27].

B2.6 Port of Oulu

In 2006, Stora Enso in cooperation with Port of Oulu (Finland) converted a terminal to service Stora Enso’s Ro/Ro vessels. The overall 6.6 kV electrical connections and designs are similar to Port of Göteborg, since it is the same vessel that is connected in Port of Göteborg and Port of Kemi [27].

B2.7 Port of Antwerp

In 2008, Port of Antwerp (Belgium) in cooperation with ICL Holding of Hamburg installed the world's first 50/60 Hz shore-side electric supply system for the Independent Maritime Terminal (IMT) on Port of Antwerp. The facility will typically enable up to three container vessels to connect to it for approximately three days within one week while berthing. The on-shore supply facility is a high-voltage, 6.6 kV, facility and uses Pulse Width Modulated (PWM) technology for conversion of the frequency from 50 Hz to 60 Hz. The on-shore power supply is able to provide a power of 800 kVA trough one cable connected the ships cable drum [38]. The facility has not been taken in operation yet.

B2.8 Port of Lübeck

In 2008, Port of Lübeck (Germany) successfully installed a shore-side electric supply system. The system grid at the port is 10 kV. A transformer rated 2.5 MVA is installed in a concrete substation on the harbour site for separating the harbour grid and the ship grid electrically and to lower the voltage to 6 kV, see *Figure B12*. Another component of the shore-side connection is a smaller cabinet with a 6 kV/50 Hz outlet enabling power to be obtained from the berth via a cable supplied by the ship, see *Figure B13* and *Figure B14*. After connection, an automation system installed on-shore can automatically initiate the start up of the shore side power supply system. The auxiliary engines of the on-board power supply can then be shut down [38].

Figure B12 The transformer substation (10 / 6.6 kV 2.5 MVA) located on the harbour site next to the quay.

Figure B13 Cabinet with a 6.6 kV/50 Hz outlet enabling power to be obtained from the berth.

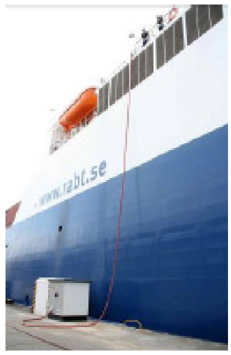


Figure B14 One cable, supplied by the ship, is connected to the cabinet.

B2.9 Port of Zeebrugge

The overall 6.6 kV electrical connection and designs are similar to Port of Göteborg. The connection is regularly used by Stora Enso vessels.

B2.10 Port of Los Angeles

In June 2004, the Port of Los Angeles in cooperation with China Shipping Container Line announced the opening of the West Basin container Terminal at berth 100. West Basin Terminal is the first container terminal in the world to be equipped with shore-side power supply. Two months later in August, the Port welcomed the world's first container vessel to be built with shore-side electricity equipment, NYK Atlas [47]. The West Basin terminal is supplied with 6.6 kV/60 Hz, but since NYK Atlas is operating with 440 V/60 Hz, the voltage needs to be transformed down to 440 V. A barge with the transformer and a cable reel is moored at the stern of the container vessel, see *Figure B15*. Nine heavy cables have to be hoisted into position, using cranes, before connecting the container vessel, see *Figure B16*. Manual power switchover is employed [56].

The connection procedure takes approximately 1 hour. The barge with the transformer will not be utilized at other terminals in the future due to logistics and cost [56].

Figure B17 illustrates the utility transformer that transforms the grid voltage 34.5 kV to 6.6 kV. *Figure B18* illustrates the main and metering facility.

Figure B15 A barge with the transformer and a cable reel is moored at the stern of the container vessel. Nine heavy cables are hoisted into position using a crane.

Figure B16 The 9 cables are connected to the vessel connection box.

Figure B17 The utility transformer (34.5/6.6 kV 7.5 MVA) located on the harbour site.

Figure B18 Main and Metering Equipment (6.6 kV)

Berth 212-216, Yusen Terminal, is also equipped with shore-side power supply since 2007. One electrical vault with two connectors is provided to supply 6.6 kV of electricity, see *Figure B19*. The system uses existing conduits to bring power to the wharf-side and provides direct cable connections between shore-side electric outlets and on-board receptacles see *Figure B20*. Automatic synchronization and power transfer systems is in use at this facility [56].

Figure B19 The electrical vault with two connectors located in the side of the quay.

Figure B20 The cables are provided by the ship and are lowered to the connection vault.

B2.11 Port of Long Beach

In 2005, cooperation between Port of Long Beach and British Petroleum (BP) voluntarily started to work with a shore-side power supply project on Berth T121. The purpose of the project was that the two BP tankers, which traffic Port of Long Beach, should use shore-power whenever they called at the Port. In 2008 the installation was finished and completed, but the testing stage took more time than expected, due to strict regulations for tanker vessels, so the official use of the shore-side power supply will be in year 2009. A transformer is used to step down the voltage from local power grid to 6.6 kV. The power transferred to the tankers is 10 MVA, and 3 cables are used for the power transfer [16]. The project can be seen in *Figure B21*.

Port of Long Beach, has an additional shore-side connection on the container terminal G323 at Pier G. The terminal was finished and ready for use in mid 2008. One electrical vault with two connectors is provided to supply 6.6 kV of electricity. The facility is going to be used to provide land-based electricity to four container vessels that call at port. The facility will provide a power of 7.5 MVA to the vessels [16].

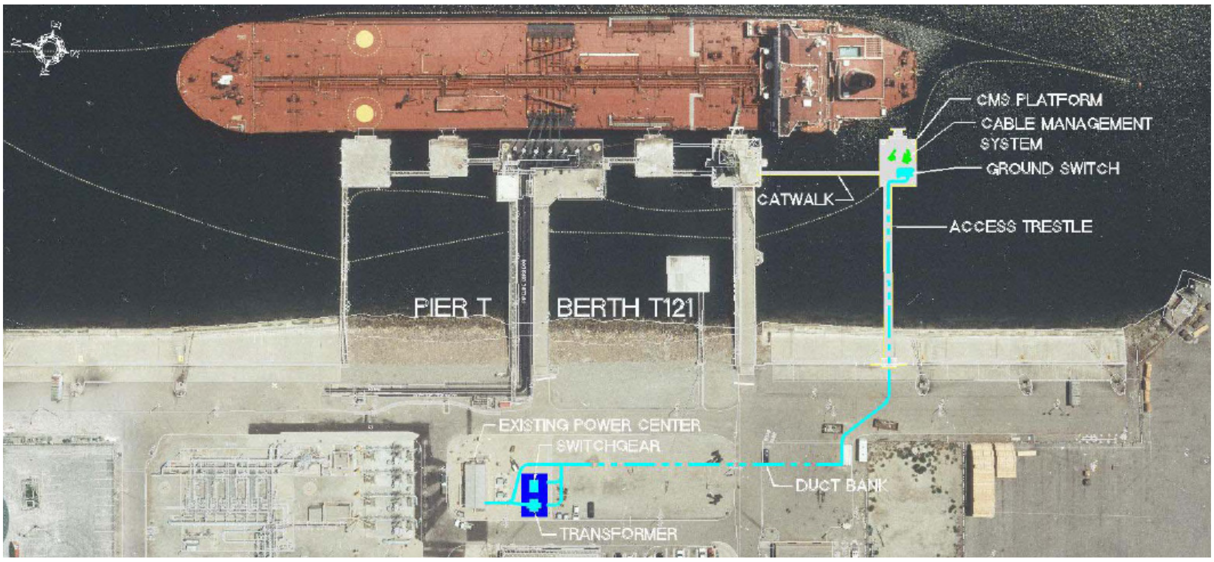


Figure B21 Shore-side power supply project on Berth T121.

B2.12 Port of Juneau

In June 2001, Port of Juneau (Alaska) in cooperation with Princess Cruise Lines installed the world's first high voltage shore-side power system for cruise ships docked at the Port. The shore-side electric system consists of cables and a substation to transfer electricity from the port grid. A dual-voltage transformer is used to step down the voltage from local power grid to 6.6 kV or 11 kV to provide different classes of ships, see *Figure B22.* A custom made dock-side gantry cable system was made for easier connection of the vessels. Four cables are used for the electric connection, each consisting of three cores for each phase, see *Figure B22* and *Figure B24*. On-board power management software is used to automatically synchronize, combine and transfer. Overall time required for cable connection, power synchronization and transfer is approximately 40 minutes, and the disconnection time is approximately 30 minutes. In 2002, five cruise vessels were converted to use shore-side electricity in Juneau. These vessels each require 7 MW. In 2004, a sixth princess cruise vessel was built with shore-side electricity equipment, with an expected electricity power demand of 8-9 MW. Currently, there are seven of nine cruise ships equipped with shore-power connection capabilities that dock in Port of Juneau [59].

Figure B22 A dual-voltage transformer is used to step down the voltage from the local power grid to 6.6 kV or 11 kV.

Figure B23 Four cables are used for the electric power connection and they're hoisted into position by the cable arrangement system.

Figure B24 The connection box on the ship connecting 4 power connectors, 1 neutral connection and the cables for controlling.

B2.13 Port of Seattle

In 2005, Princess Cruise Lines in cooperation with Port of Seattle installed a high-voltage shore-side power supply to one berth at Terminal 30, in Port of Seattle. Two of Princess Cruise Line's larger cruiser ships equipped with shore-power equipment was connected to the shore-side power supply. The overall electrical specifications and designs are similar to Port of Juneau. Shore-side cables were stored within a cable trench at the edge of the berth. When a cruise ship is at berth, cables are hoisted to the ship-side by a gantry and connected to the on-board electric system, see *Figure B25* and *Figure B26* [59].

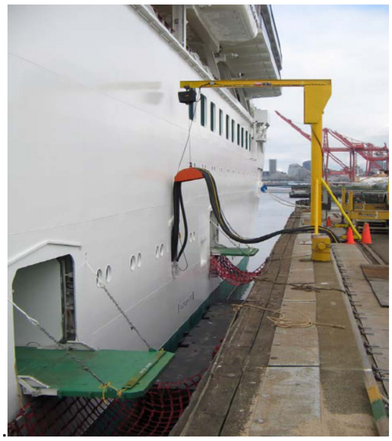


Figure B25 Cables are hoisted into position using a gantry.

Figure B26 Transformer, main and secondary metering equipment. Transformer capacity is 16 MW. Primary voltage 27 kV. Dual service delivery (secondary) voltage 6.6 or 11 kV.

In 2006, an additional berth at Terminal 30 was equipped and provided with shore-side power supply. This made Port of Seattle the only Port in North America capable of providing shore power for two vessels simultaneously at the same berth at year 2006. ABB prepared three vessels from Holland America Lines Vista class; Oosterdam, Westerdam and Noordam, for on-shore power supply (11 MW/ 11 kV). ABB provided the necessary 11 kV switchgear, automation hardware and software for the necessary changes in the power management system (PMS). The project also included the delivery and installation of all the high-voltage and low-voltage cables to connect the new shore panel to the existing main switchboard and PMS onboard the vessels [33].

The installation at the shore-side looks almost the same as the previous installation in Port of Seattle, see *Figure B27*. Cochran Electrical Inc. delivered and installed the shore side substation, step down transformer, grounding switch and flexible cable for the high-voltage connectors. ABB delivered the main components onshore such as transformer and circuit breaker, see *Figure B28* [33].

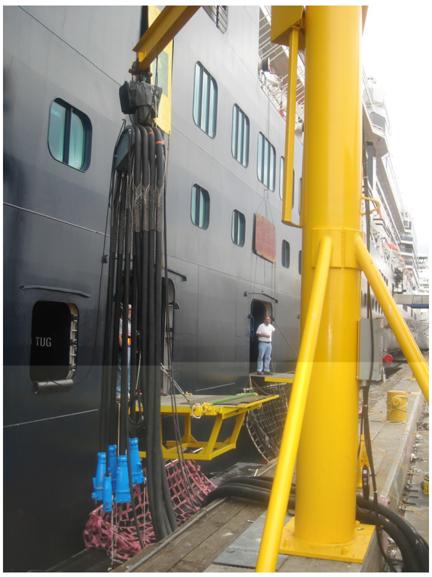


Figure B27 Cables are hoisted into position using a gantry. Each cable contains three cores (L1,L2,L3) and can carry 500 A per phase by 11 kV.

Figure B28 The pictures above show the incoming 27 kV power line and the substation, delivered and installed by Cochran Electrical Inc. (Main components such as the transformer and circuit breaker were provided by ABB.)

B2.14 Port of Pittsburg

In 1991, the Pohang Iron & Steel Company in Pittsburg established a shore-side electricity system to connect four dry bulk vessels at Port of Pittsburg. The vessels require a power supply of approximately 0.5 MW. The shore power is transmitted by two 440 V cables. After a ship docks the Port, two crewmembers pull the power cables on board and plug them into the onboard power system. This procedure takes approximately 20 minutes to complete [21].

B2.15 Summary of existing installations

Table B5 Existing Shore-side power supplies in the world applied for commercial vessels

Port	Country	Connection voltage	Frequency
Port of Göteborg	Sweden	400 V / 6.6 kV / 10 kV	50 Hz
Port of Stockholm	Sweden	400 V / 690 V	50 Hz
Port of Helsingborg	Sweden	400 V / 440 V	50 Hz
Port of Piteå	Sweden	6 kV	50 Hz
Port of Antwerp	Belgium	6.6 kV	50 Hz / 60 Hz
Port of Zeebrugge	Belgium	6.6 kV	50 Hz
Port of Lübeck	Germany	6 kV	50 Hz
Port of Kotka	Finland	6.6	50 Hz
Port of Oulu	Finland	6.6 kV	50 Hz
Port of Kemi	Finland	6.6 kV	50 Hz
Port of Los Angeles	USA	440 V / 6.6 kV	60 Hz
Port of Long Beach	USA	6.6 kV	60 Hz
Port of Seattle	USA	6.6 kV / 11 kV	60 Hz
Port of Pittsburg	USA	440 V	60 Hz
Port of Juneau	USA	6.6 / 11 kV	60 Hz

B3 Possible Markets

Shore-side connection is a hot topic around the world today. Many Ports are aware of their surrounding environment and the influence a vessel makes on it. The driving forces discussed in the previous chapter have made an accelerating impact for future shore-side connections, and many ports are ready to improve their reputation and the surrounding environment.

This chapter will present shore-side connection plans and new harbours that are considering shore-side electricity in their infrastructure.

B3.1 Ports planning for shore-side power supplies

This section will present harbours that have plans and which are investigating the possibilities to install shore-side power supply in their port.

B3.1.1 Port of Göteborg

Port of Göteborg is planning to supply shore-side electricity to two of their Ro/Ro-terminals, Älvsborg and Arendal. The port plans to supply electricity to both ships with 50 and 60 Hz. In total there are 5 berths in the Älvsborg terminal, two of them are already equipped with high-voltage power supply for 50 Hz vessels, as presented in the previous chapter. Two berths are being considered at the Arendal terminal.

Stena Line is planning to shore-side connect the majority of the vessels in the Scandinavian enterprise. In total they are prepared to invest between 7.5 to 10 million Euros. Stena Lines business in Port of Göteborg is going to be the first one to receive shore-side power supply. All vessels that aren't yet connected at Port of Göteborg will be retrofitted to be able to receive shore power [32].

B3.1.2 Port of Trelleborg

Port of Trelleborg is having plans to shore-side connect Scandlines ferries that traffic Germany. This concerns five ferries that are operating with low-voltage and 50 Hz. The port is as well planning to supply electricity to six of TT-lines ferries that also traffic Germany. Two of these ferries are operating with low-voltage and 60 Hz, and the remaining four ferries are 50 Hz vessels that operate with high-voltage. A summary of the power demand, voltage and frequency of the concerned vessels is presented in *Table B6* [33].

Table B6 Ferries concerned shore-side power supply in Port of Trelleborg [33]

Ferry	Voltage	Frequency	Power demand during hostelling
Scandlines			
M/S Götaland	380 V	50 Hz	1400 kW
M/S Mecklenburg	690 V	50 Hz	2600 kW
M/S Sassnitz	660 V	50 Hz	1500 kW
M/S Skåne	660 V	50 Hz	3300 kW
M/S Trelleborg	380 V	50 Hz	1500 kW
TT-Lines			
M/S Huckleberry Finn	440 V	60 Hz	1500 kW
M/S Nils Dacke	6.6 kV	50 Hz	2000 kW
M/S Nils Holgersson	6.6 kV	50 Hz	3600 kW
M/S Peter Pan	6.6 kV	50 Hz	3600 kW
M/S Robin Hood	6.6 kV	50 Hz	2000 kW
M/S Tom Sawyer	440 V	60 Hz	1500 kW

B3.1.3 Port of Oslo

Port of Oslo has plans to supply shore-side electricity to the arriving vessels that dock at their port. Today, they plan to facilitate Color Line ferry terminal with shore electricity. The ship owners of Color Line are positive for the shore-side connection and will take the economical responsibility to reconstruct the ferries to be able to connect to shore. This includes two vessels that traffic Kiel – Germany, together with the Stena Line ferry that traffic Denmark.

The Port of Oslo has the vision to connect the cruisers arriving to their port in the future [28].

B3.1.4 Port of Bergen

Port of Bergen has the vision to become Europe's cleanest port. The district of Bergen and the trade industry are pushing the question how to achieve this vision. One project shall give the opportunity to shore-side connect vessels at berth. The plans are to supply electricity to Koengen and Dokken terminals. Koengen terminal has berths for both ferries and cruiser ships. In the Dokken terminal there are berths for load ships as well as ferries and cruisers. Today, these terminals are called by 11 657 vessels per year, of which 250 of these are cruiser ships. The idea is to make it possible to connect vessels with 50 Hz and 60 Hz [12].

B3.1.5 Port of Tallinn

Port of Tallinn is investigating the possibilities to supply shore-side electricity connection for vessels. The ships that belong to Tallink and traffic Port of Stockholm have already the possibilities to receive land-based low-voltage electricity. There are also plans to connect cruiser and container ships, where there will be a need of a frequency converter that can convert 50 Hz to 60 Hz. To be able to cope with the great need of power, which for example cruiser ships need, there is a need for an upgrade of the existing grid. The ferry and the cruiser terminal are today fed by a substation which is able to supply 6 kV. There are plans to upgrade the substation to 10 kV. In the cargo port - Muuga, there is a 10 kV distribution network available, so an upgrade is not considered [31].

B3.1.6 Port of Rotterdam

Port of Rotterdam conducted a feasibility study for Euromax container terminal in 2006 [18]. The feasibility involved the shore-side electricity infrastructure into the container terminal design. For the feasibility study a survey of 53 container ships was made. It summarized the ships electric system characteristics, power requirements, fuel consumption and capability for shore-power connection while at port.

While it was technically possible to equip the terminal with land-based electricity, lack of international standards for shore-power supply and high investments costs, Port of Rotterdam choose not to recommend the terminal to be equipped with shore-power supply. The reason for the high investment costs were that Port of Rotterdam intended to connect vessels with 50 and 60 Hz, and at the same time supply two different voltages, 6.6 kV and 6.3 kV to the vessels. The intended configuration is shown in *Figure B29*. The calculated costs for the Euromax container terminal shore-side electricity is illustrated in *Table B7*. Despite the fact that they didn't equip the terminal, Port of Rotterdam is encouraging the shipping owners to equip the vessels with shore-power equipment for future use of land-based electricity [18].

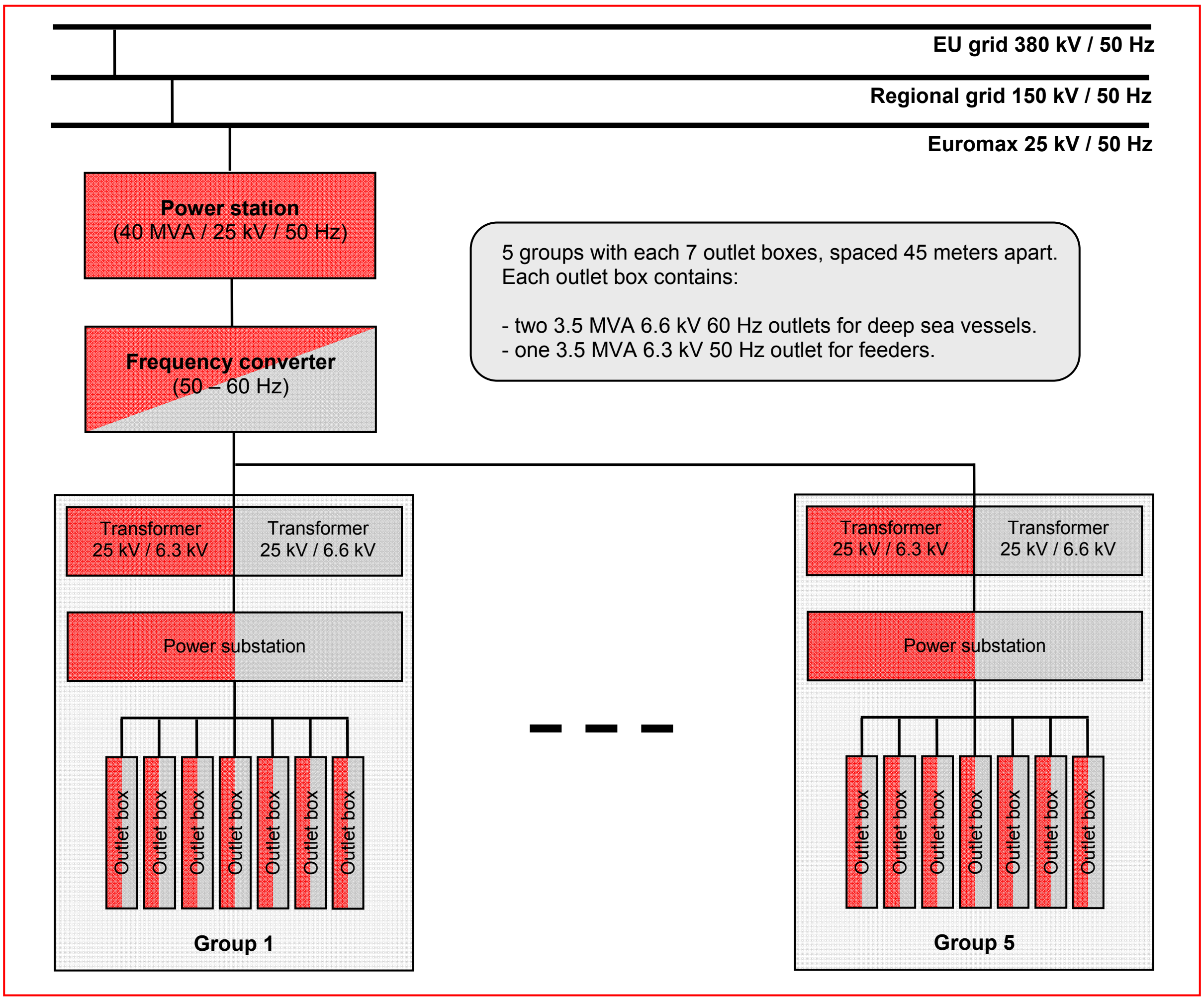


Figure B29 The intended configuration for shore-side power supply in Port of Rotterdam.

Table B7 Expected electrical installation costs in Port of Rotterdam [18]

Design	€
Power connection to grid	7 000 000
Main power station	2 000 000
Frequency convertor	2 500 000
Transformers	3 000 000
Power substations	1 500 000
Conduits	5 000 000
Cabling	2 000 000
Project management	2 500 000
Outlets	3 000 000
Total	**28 500 000**

Furthermore, it is expected that when the Maasvlakte II Terminal is under construction, the international standards for shore-side electricity will be finalized and adopted by the international communities. By then, shore-side power supply should be included in the terminal design [18].

B3.1.7 Port of Houston

Port of Houston evaluated the possibilities with a shore-side power supply on their port. Port of Houston is planning to equip Bayport Terminal with shore-power capabilities if shore-power becomes commercially available. It is estimated that the cost for the shore-power infrastructure at Bayport Terminal will be significantly higher since these facilities would have to be retrofitted for cable conduits and they may lack appropriate power supply in the substation feeding the port with power [59].

B3.1.8 Port of Los Angeles

As presented in the previous chapter, Port of Los Angeles is already supplying container terminals with low and high-voltage land-based electricity. Their primary goal is to provide electricity to all the container terminals, and further expand the shore-side electricity infrastructure. Port of Los Angeles future plans to provide shore-side electricity to berths is presented in *Table B7*. It is expected that all future shore-side power supply constructions will be high-voltage connected, 6.6 kV 60 Hz. Furthermore, Port of Los Angeles does not have any plans to connect 50 Hz vessels.

Table B8 Port of Los Angeles Shore-power Infrastructure Plan for 2008-2011 [59]

Site	Number of berths	Expected year of operation
Berth 90-93 (Cruise terminal)	2	2008
Berths 101-102 (China shipping)	1	2009
Berths 121-131 (West Basin container terminal)	2	2011
Berths 136-147 (Trans Pacific container Service corp. TraPak	2	2009
Berths 175-181 (Pasha Group)	1	2011
Berths 206-209 (Long Term Tenant)	1	2011
Berths 224-235 (Evergreen)	1	2008
Pier 300 (American President Lines, APL)	1	2011
Pier 400 (AMP Terminals, Liquid Bulk)	2	2011
Total number of berths	**13**	

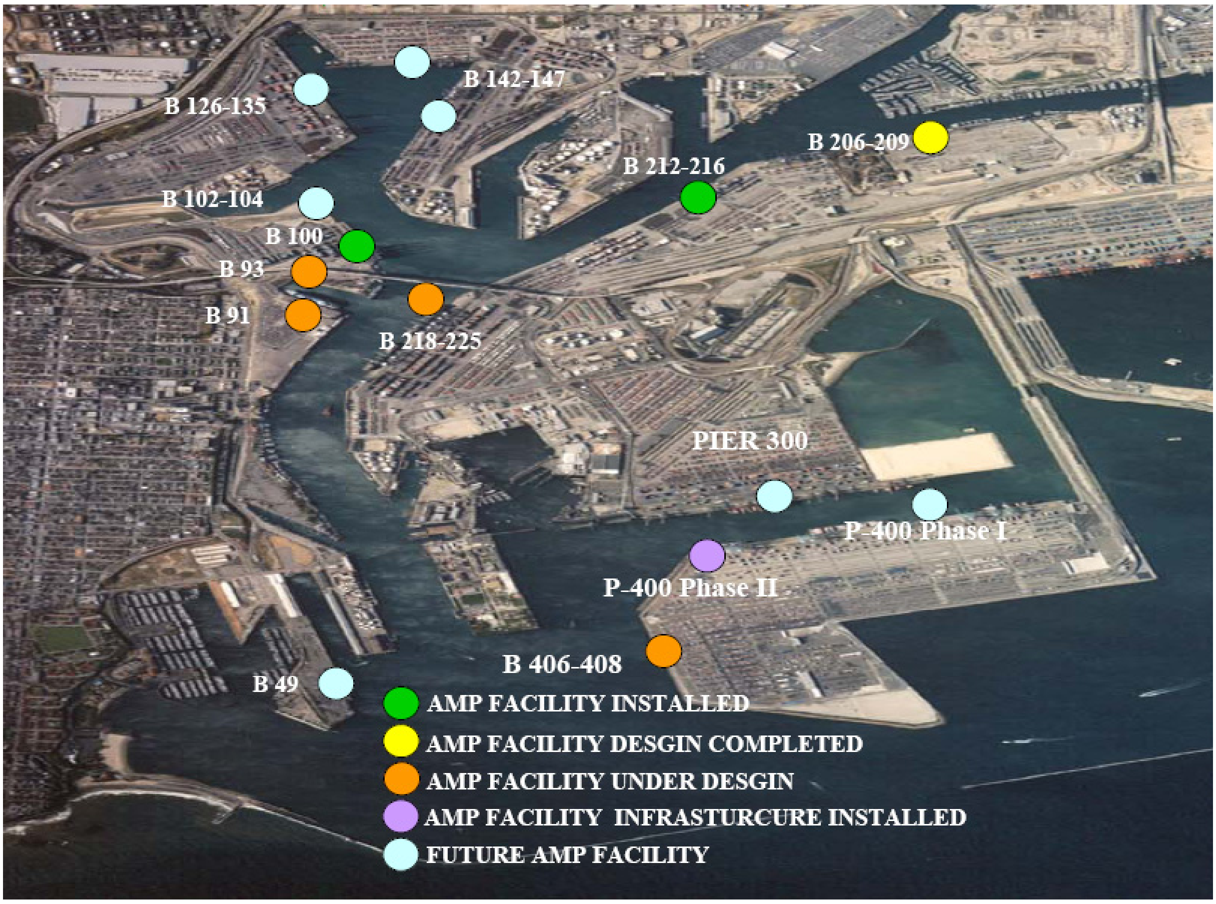


Figure B30 Port of Los Angeles Shore-power infrastructure installations and plans.

B3.1.9 Port of Long Beach

In 2004, Port of Long Beach made a shore-side power cost-effectiveness study to evaluate the feasibility of shore-side electricity. For the feasibility study a survey of 151 frequent port callers was made. It summarized the ships electric system characteristics, power requirements, fuel consumption and capability for shore-power connection while at port. 26 of these ships were identified as being potential candidates for shore-side power [21].

In 2005, Port of Long Beach distributed a preliminary standard design for shore-side power supply at their port. It is expected that the wharf outlet will be 6.6 kV, 3-phase, and 60 Hz with a grounding conductor, and a design load of 7.5 MVA for each ship [16].

The port's goal is to provide electrical infrastructure for shore-side power to 100 % of container terminals and at other major facilities. Port of Long Beach future plans to provide shore-side electricity to berths is presented in *Table B8*. The estimated cost for retrofitting the berths in *Table B8* is said to be a total of $129 millions. Additionally Port of Long Beach estimated the total cost of $201 millions, retrofitting an additional 31 berths at the port [58].

Table B9 Port of Long Beach Shore-Power Infrastructure Plan for 2007-2016 [59]

Site	Number of berths	Expected year of operation
Pier C (Matson)	2	2011
Pier D, E, F (Middle Harbour)	1	2011
Pier G (ITS)	2	2011
Pier S	3	2011
Pier A (SSA)	1	2011-2016
Pier H (Carnival)	1	2011-2016
Pier J (SSA)	1	2011-2016
Navy Mole (Sea-Launch)	2	2011-2016
Pier T (TTI)	1	2011-2016
Total number of berths	**16**	

B3.1.10 Port of San Francisco

The Port of San Francisco is investigating the possibility to include shore-side power supply to their new cruiser terminal at Piers 30-32. In 2005, Port of San Francisco contracted Environ Corporation to accomplish a shore-side power feasibility study. The study estimated a conceptual design and cost estimates for the shore-side facility [59].

B3.1.11 Port of Seattle

Port of Seattle has plans for two new construction projects in the port. The plan is to convert the current cruise terminal, Terminal 30, combined with Terminal 25, into a container terminal. The reason for the combination is that when these two terminals are combined, they will provide 75 acres of container use. The second plan is to expand Terminal 91, and use it as a base for cruise ship operations. Terminal 91 will have two berths providing shore-side power to cruisers [48].

B3.1.12 Port of Shanghai

Port of Shanghai conducted a shore-side power feasibility study for Chang-hua-bin terminal and Wai-guo-chiao container terminal. The focus of the feasibility study was on the technical aspects of electrical connections. However, the existing terminal infrastructure did not have power distribution, transmission, frequency conversion and cable connection facilities. The feasibility study concluded that, in order to utilize shore-power, power transformers and frequency converters will be required, since most of the vessels are operating with low-voltage and 60 Hz in Port of Shanghai. The key issue was the improvement of the terminal infrastructure to enable ships to use shore-side electricity. The study concluded that shore-power for ships at the Port of Shanghai were technically feasible. Nevertheless, there is no actual construction of shore-power infrastructure at this time [59].

B3.1.13 Summary of ports planning for shore-side power supply

Figure B31 summarizes all ports in the world that are currently planning or investigating for shore-side power supply.

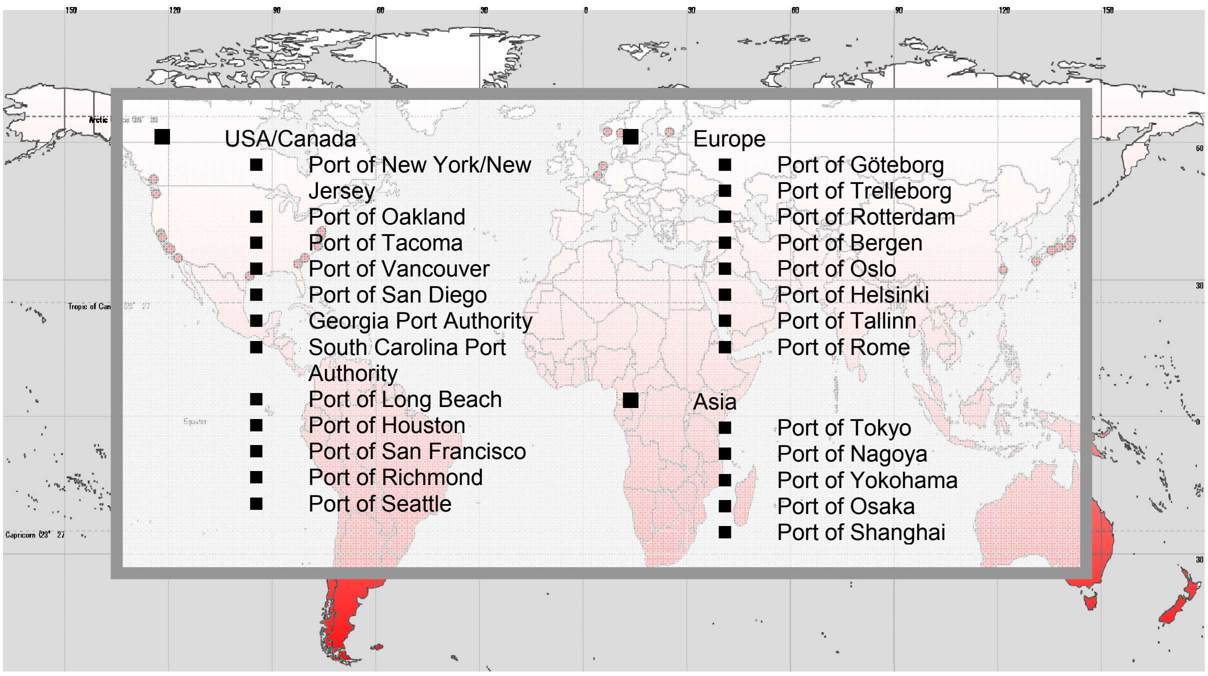


Figure B31 Ports in the world investigating shore-side power supply

B3.2 New Ports and Terminals

There are currently many ports around the world that have plans for extending their port or retrofitting new terminals, see *Table B9*. There is a possibility to erect shore-side power supply in the infrastructure in the beginning stage of the construction. This plan could save a vast amount of money and time for future shore-side power constructions.

Table B10 New Ports and Terminals planned around the world

Site	Country	Expected year of operation
Port of Nynäshamn	Sweden	2010
Port of Tallinn	Estonia	2009
3 new ports in the Murmansk Area: - Port of Pechenga - Port of Vidyaevo - Port of Teriberka	Russia	First port expected to be in operation year 2010
Port of Ust-Luga	Russia	2009
6 new ports in Shenzhen: - Liantang Port - Longhua Port - Fujian Guangzhou-Shenzhen-Hong Kong Port - Dachan Gulf Harbor Port - Nan'ao Port - Wenjindu Port	China	First port expected to be in operation year 2010
Houston Bayport Container Terminal	USA	-
The new Colombo Port	USA	2011

B4 Actors in the market

There are currently only a few actors in the market that have carried out shore-side power supply installations which are in service in ports around the world. There are even less actors in the market today that are able to supply systems for frequency conversion. This chapter will present the main actors in the market that have shore-side power supply systems, allowing vessels to be connected to the national grid.

B4.1 ABB

ABB is one of the major suppliers for vessels and harbours world wide. ABB is also on of the biggest suppliers in the world for main switchboards in vessels. When Port of Göteborg wanted to construct the world’s first high-voltage connection dedicated for Ro/Ro vessels, ABB was contracted to perform the installation and the design of the high-voltage shore-side supply. When Princess Cruise Lines wanted help to install the power management and monitoring system onboard the vessels, ABB installed the necessary equipment onboard.

B4.2 Siemens

SIHARBOR is the name of Siemens shore-side power supply system. The installation in Lübeck, as presented in a previous chapter, has been constructed by Siemens. This Port is the only reference for the SIHARBOR system today. Siemens has developed a shore connection system, called Siplink, which is used for connecting vessels that operate with 60 Hz to the European grid. According to Siemens, Siplink enables linking between a ship’s onboard power system to the existing onshore power grid even if the system frequencies are different. Nevertheless, Siplink has not yet been installed in any port. The only installation with the Siplink system is found in a shipyard in Flensburg. The shipyard utilizes the Siplink when installing a vessel's on-board electrical system. In this installation Siplink provides a 60 Hz power supply with adjustable voltage, which is also used as a test load when checking the electric system.

B4.3 Cavotec

Cavotec has 18 years of experience with shore-side connections. They have world leading systems for cable reels and their plugs and sockets have practically become a standard for shore-side connections. Cavotec has already equipped 14 vessels with cable reels or with plugs and sockets to be able to connect to shore, see *Figure B32, Figure B33* and *Figure B34.* The company has been involved in many shore-side power supply projects and supplied most equipment for the connection onboard the vessel.

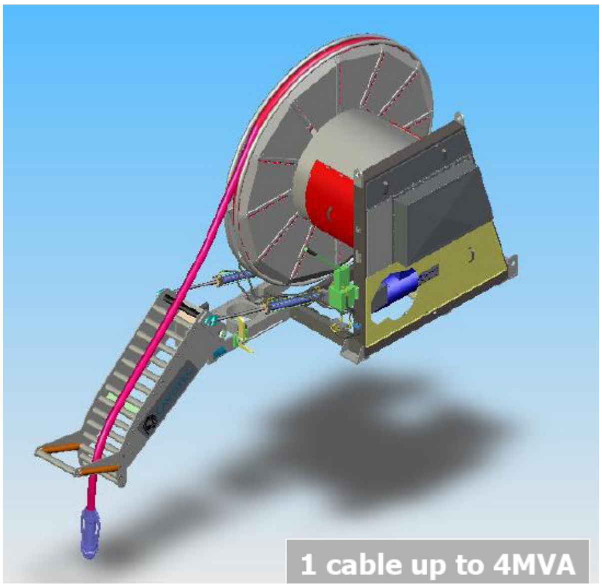


Figure B32 Cavotec cable reel arrangement for one cable up to 4MVA.

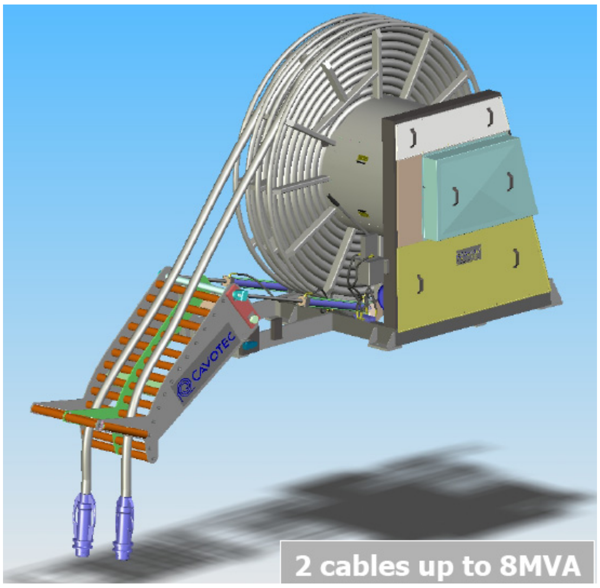


Figure B33 Cavotec cable reel arrangement for two cables up to 8MVA.

Figure B34 Cavotec plugs and sockets

B4.4 Sam Electronics

Since 2003 Sam Electronics has delivered twenty shore-side power supply equipment to both ships and ports. Sam Electronics was contracted by Port of Los Angeles to supply the necessary equipment for the first AMP terminal equipped in Port of Los Angeles. Sam Electronics has also been contracted by Port of Antwerp to construct the world's first terminal that can supply electricity to 50 and 60 Hz vessels. Nevertheless, Sam Electronics is the biggest actor on the market that has references for their low-voltage, 400 V, and high-voltage, 6.6 and 11 kV, solutions. They have also supplied container and barge systems outfitted with the necessary equipment for shore-side power supply, see *Figure B35* and *Figure B36*.

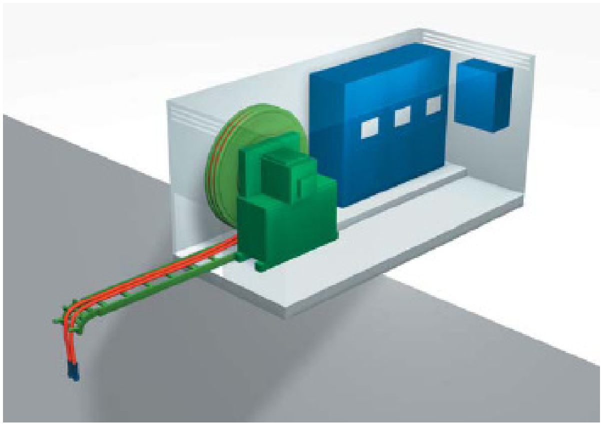


Figure B35 A container with the corresponding shore-side equipment located on the vessel.

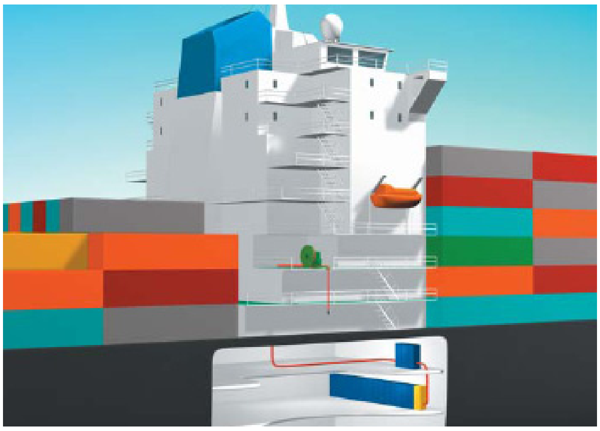


Figure B36 The container configuration fitted inside the vessel.

B4.5 Terasaki

Terasaki has been developing onboard marine systems since the 90s. Port of Los Angeles contacted Terasaki to design a high-voltage, 6.6 kV, AMP supply. The company offers a high-voltage shore-side power supply, 6.6 kV, similar to the installations in Port of Göteborg. Terasaki is also able to offer 50 Hz shore-side power supply equipment, but there is no indication that the company can supply equipment for 50 Hz and 60 Hz connections.

B4.6 Patton & Cooke

When Princess Cruise Lines needed a high-voltage shore-side power supply for their four Sun Class vessels in Port of Juneau, Patton & Cooke were contracted to perform the installation and design for the shore-side power system at Port of Juneau.

B4.7 Callenberg Engineering Inc

Callenberg Fläkt Marine, previously ABB Fläkt Marine, has developed, supplied and supported the Marine industry for seven decades. When Princess Cruise Lines wanted to connect their vessels to a high-voltage shore-side supply, Callenberg Engineering was contacted. Callenberg Engineering began to work on the means of delivering the power to the ships, and the main task was to identify and produce samples of candidate power cables that would safely transmit the required voltage and power to the ship. An additional gantry carrying the high-voltage cables together with custom made plugs was supplied by the company.

Part C - Technical survey

C1 Power generation onboard

Today's ships are like floating power plants. The electricity generated onboard is used to provide power for a wide range of applications. Lighting, heating, cooling, ventilation, pumps, navigation systems and cargo-related activities are example of such applications. Likewise, ships propulsion can be electrically reliant, depending on what type of propulsion manner the ship is using. Traditional vessels use diesel driven motors that are connect to the vessel's propeller by a shaft. Today, diesel electric vessels have become more popular where electric motors are being used to drive the ship. Therefore, these vessels are in need of higher electricity generation onboard.

This chapter will explain how electricity generation functions for the different propulsion matters when the vessel is on-sea and when it is at berth. Additionally the following chapter will present the power demand for the different types of vessels.

C1.1 Conventional propulsion vessels

Power generation onboard conventional propulsion vessels can be seen in *Figure C1*. A main generator that is coupled with the propulsion engine in combination with auxiliary engines generates the power needed while at sea. When the vessel arrives at the port, the power generation of the auxiliary engines is increased. The reason for the increased production is that the main engine runs at variable speeds while manoeuvring. At the berth the main engines are shutdown and the auxiliary generators take control of all the power generation onboard.

How the load factors for auxiliary engines vary by operating mode and ship type can be seen in *Table C1*. With help of the totally installed auxiliary power, the load factors illustrated in the table can be used to estimate the vessel power need during hotelling. A load factor of 1.0 means that the totally installed auxiliary generator capacity is used onboard the vessel. These load factors are commonly used to calculate the power need at berth when the hostelling power data is not available. The factors are determined by *Starcrest*, through interviews conducted with ship captains, chief engineers, and pilots during its vessel boarding programs. Previous reports have shown that the power generation was provided by propulsion engines in all modes but hotelling, but the *Starcrest* report shows that this is a false statement for most conventional propulsion vessels [29].

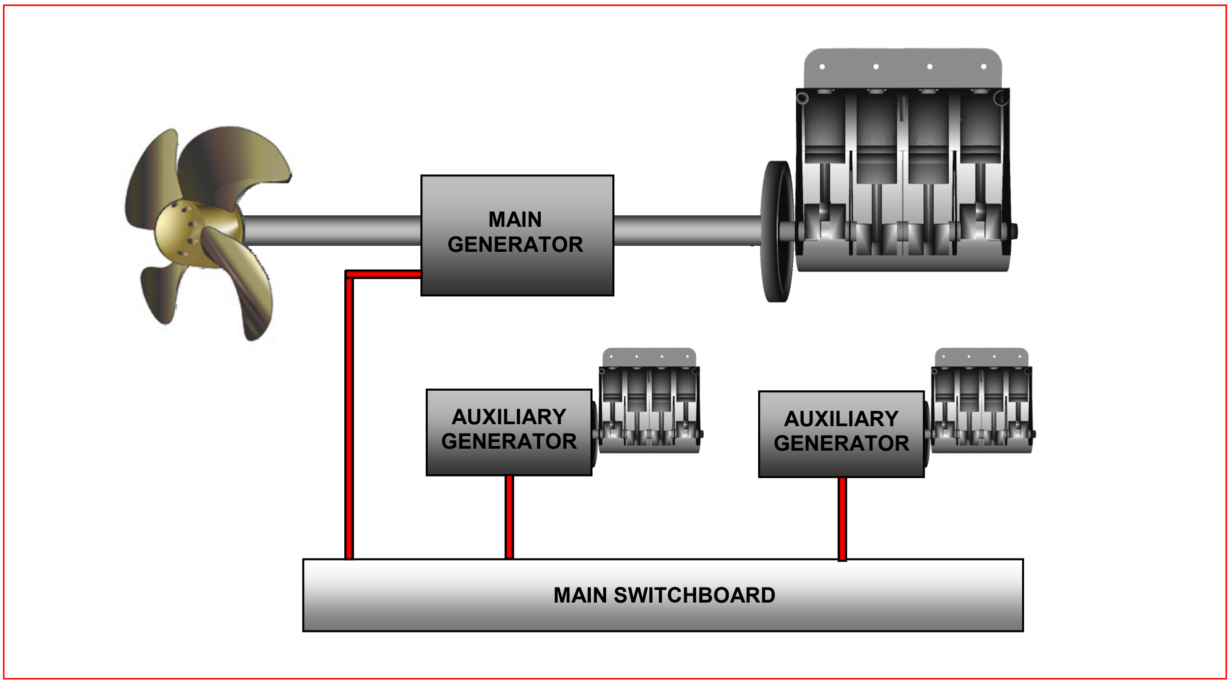


Figure C1 Power generation onboard conventional propulsion vessels.

Table C1 **Average load factors for auxiliary generators. A load factor of 1.0 means that the totally installed auxiliary generator capacity is used onboard the vessel. [29]**

Vessel Type	Cruise	Manoeuvre	Hotel
Container vessels	0.13	0.50	**0.17**
Ro/Ro vessels	0.15	0.45	**0.30**
Oil and product tankers	0.13	0.45	**0.67**
Cruise-/Passenger vessels	0.80	0.80	**0.64**

C1.2 Diesel Electric propulsion vessels

Newer and bigger ships like Cruise ships commonly use diesel electric propulsion systems. One reason for this is the easiness of manoeuvring, especially during docking. Propulsion is typically provided by several diesel engines coupled to the main generators, which drive the electric motor that runs the propeller on the vessel. The same generators that are used for propulsion are also used to generate auxiliary power onboard the vessel for lights, refrigeration, etc. A simplified overview of the electrical installations in a vessel with electric propulsion is illustrated in *Figure C2.*

The power needed while at sea can be up to 80 MW on a modern cruiser vessel. Most of the generators are therefore in use to manage the power need [8]. To be able to handle the big amount of power, high-voltage, 6-11 kV, is used onboard. When the vessel docks at the berth there is no need to produce the same quantity of power to drive the propulsion motors, so therefore a majority of the main generators are shut down and only a few generators are used to manage the power needed during hotelling.

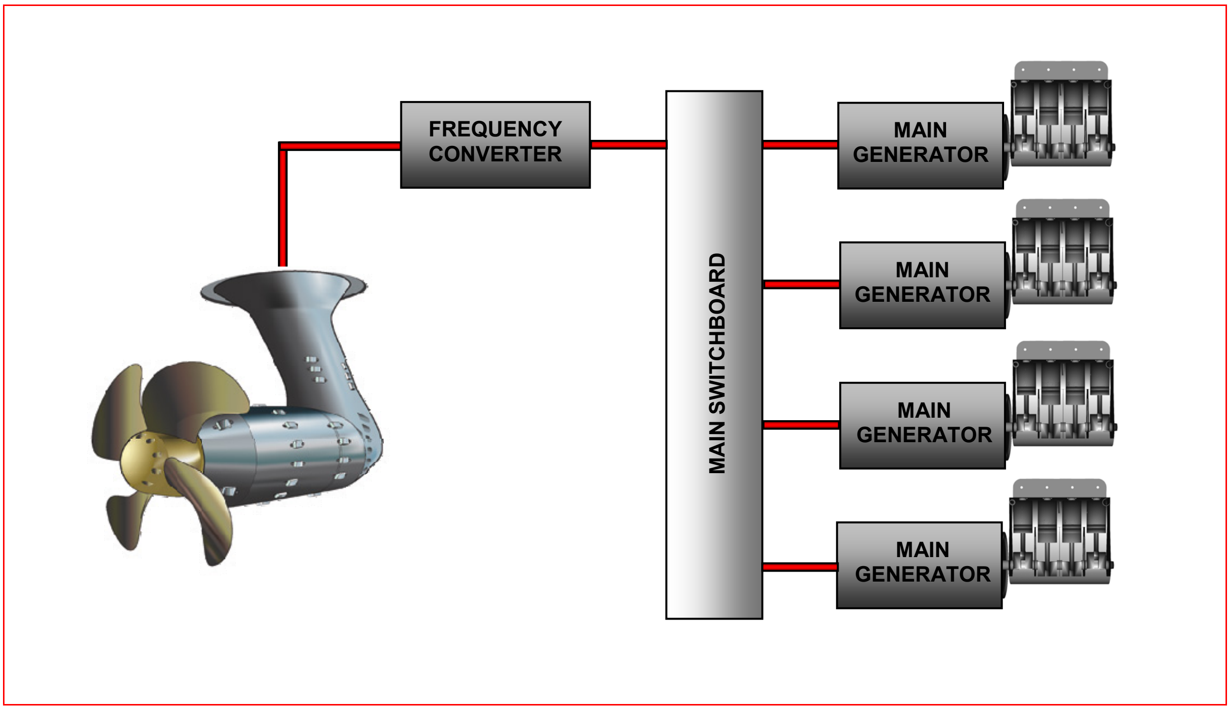


Figure C2 Power generation onboard diesel electric propulsion vessels.

C2 Onboard power demand analysis

This chapter's intention is to give an understanding of different onboard power demands, system voltages and system frequencies for vessels, when they are at berth. The vessel types treated are the ones illustrated in *Figure C3* – Container vessels, Ro/Ro-and Vehicle vessels, Oil and product tankers and finally cruisers. There are few previous similar studies and these touch only some of the mentioned vessel. This chapter will map all the parameters for the different vessels.

The thought of this chapter is that it shall be used as guidance for dimensioning of shore-side power supplies, to get an understanding for what power is needed. It is important to emphasize that the vessels concerned in the survey below, are such vessels that traffic European ports. Consequentially, the data, for example the system frequency onboard vessels, will appear differently in comparison if the study was made for vessels that traffic other continents. This concerns primarily the smaller vessels that don't traffic other continents.

In the end of this chapter a summary of the different power demand, system voltage and system frequencies for the vessels will be presented. The chapter will end with an illustration of the total power demand for two typical ports, as an indication of the total power need in port, to shore-side connect ships.

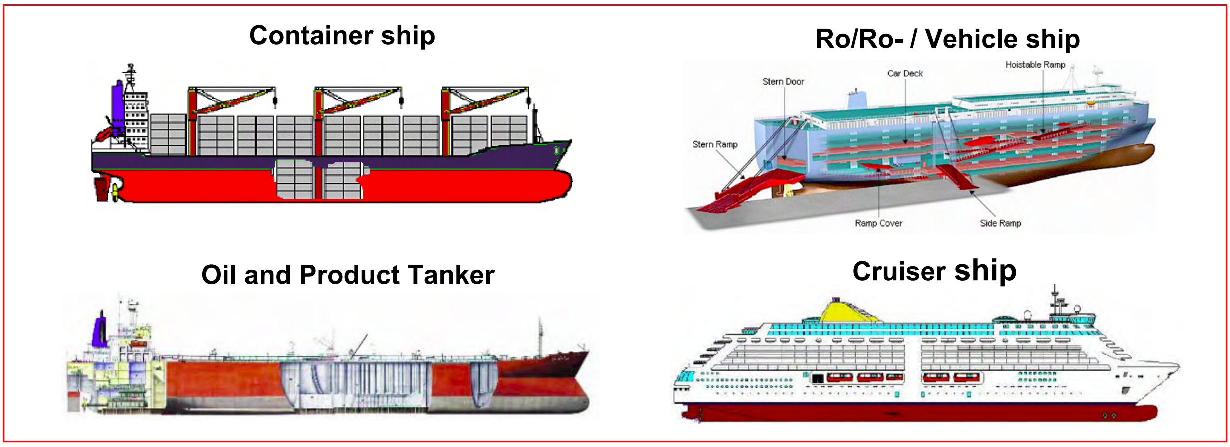


Figure C3 Different type of vessels.

C2.2 Container vessels

As the name says container vessels are used for transportation of containers. Most container vessels are constructed with single deck hull with an arrangement of hold, above and below deck fitted specifically, for containers. Container ships are designed so that no space is wasted. A container vessels load capacity is measured in Twenty-foot equivalent unit (TEU). Twenty-foot equivalent unit is the number of standard 20-foot (6.1 × 2.4 × 2.6 metres) containers a vessel can carry. Most containers used today measure 40 feet (12 metres) in length. Above a certain size, container ships do not carry their own loading gear, so loading and unloading can only be done at ports with the necessary cranes. However, smaller ships with capacities up to 2 900 TEU are often equipped with their own cranes. The world's largest container ship, M/V Emma Mærsk has a capacity of 15 200 containers (TEU) [66].

In 2006, Port of Rotterdam conducted a survey of 53 container ships for their electric system characteristics and power requirements while in port [18]. The containerships were divided into two groups - feeder and deep sea container vessels. Feeders are container vessels that traffic ports within the same continent and which don't traffic big open seas, and are classified in this survey as container vessel with a length less than 140 meters. Deep sea container vessels are most often used to traffic between different continents, for example trading between Europe, Asia and America, and are here classified as vessels larger than 140 meters.

The survey showed ship voltage ranged from 380 V to 6.6 kV, where the majority of the larger vessels used 440 V. 6.6 kV was only found on vessels built after 2001. The frequency was either 50 Hz or 60 Hz. The result of the survey can be illustrated below.

C2.2.1 Power demand

In *Figure C4* and *Figure C5* average-/maximum power consumption for feeders in port during hotelling is presented. The x-axis represents the length in meters of the feeder, and the y-axis represents the power consumption in kW. 19 of the total 53 vessels conducted in the survey represented feeder vessels. As seen from the figures all vessels in the range between 100 and 140 meters do not need higher peak power consumption than 1 MW and the average consumption is 200 kW.

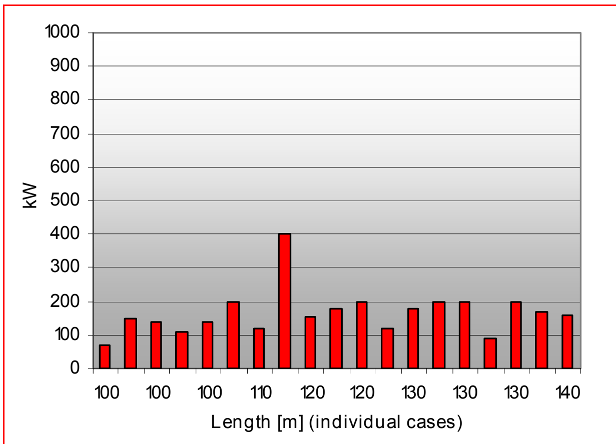


Figure C4 Average power consumption in port (feeders).

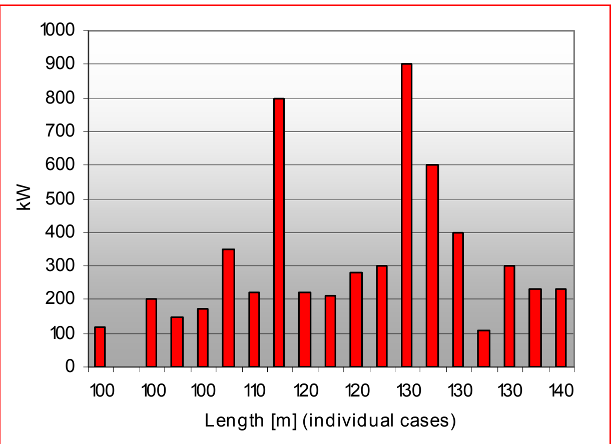


Figure C5 Maximum power consumption in port (feeders).

In *Figure C6* and *Figure C7* average-/maximum power consumption for deep sea container vessels in port during hotelling is presented. In this category the power demand is higher. The average power consumption is 2 MW, but with a peak power consumption of 8 MW.

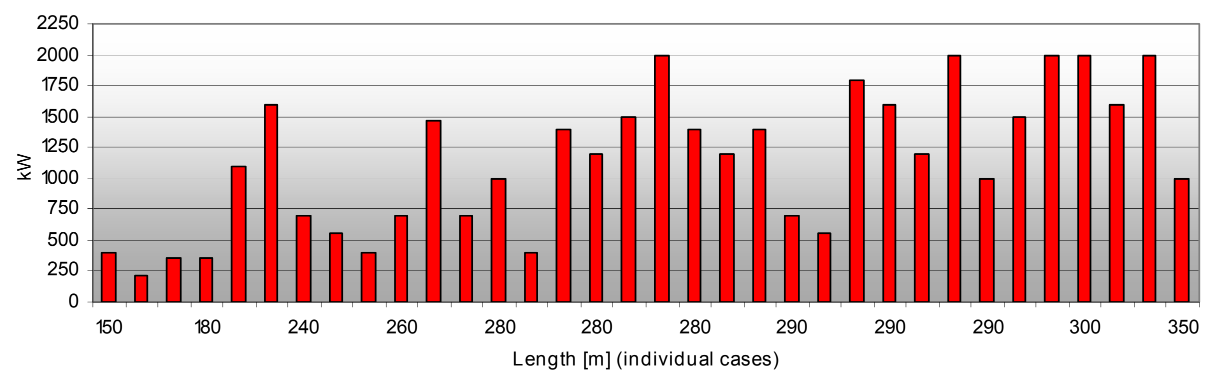


Figure C6 Average power consumption in port (deep sea container vessels).

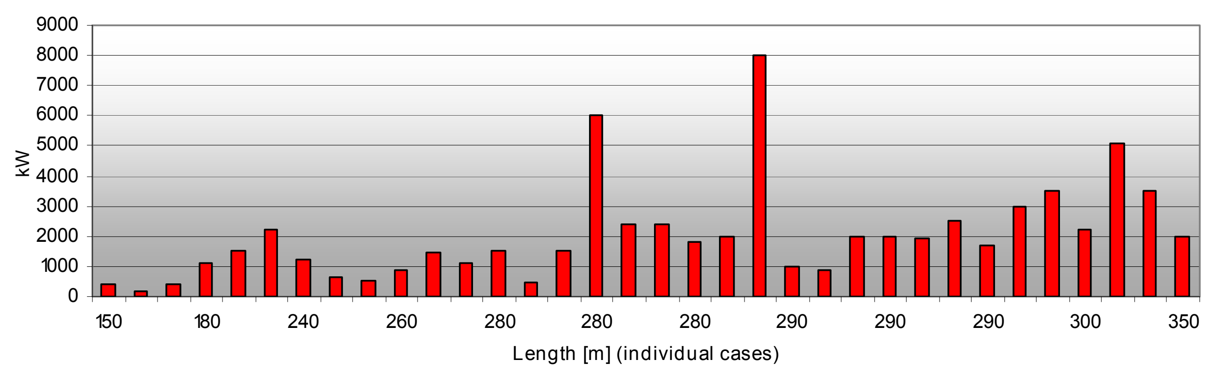


Figure C7 Maximum power consumption in port (deep sea container vessels).

C2.2.2 System voltage

As seen from *Figure C8* and *Figure C9*, the majority of the container vessels use a low-voltage as operation voltage. All of the feeders use low-voltage, and approximately 88 % of the deep sea container vessels use low-voltage. Only a small amount, 12 % use high-voltage, 6.6 kV as system voltage.

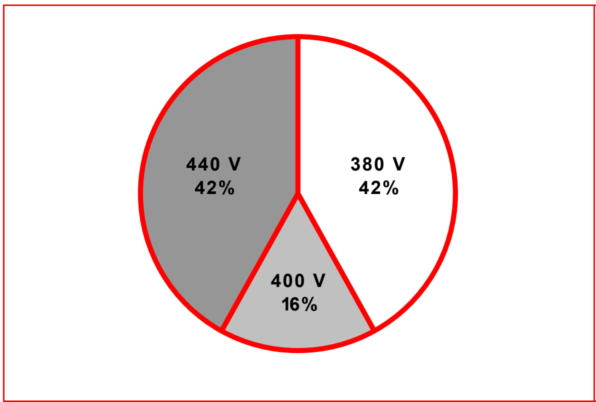


Figure C8 Main system voltage (feeders).

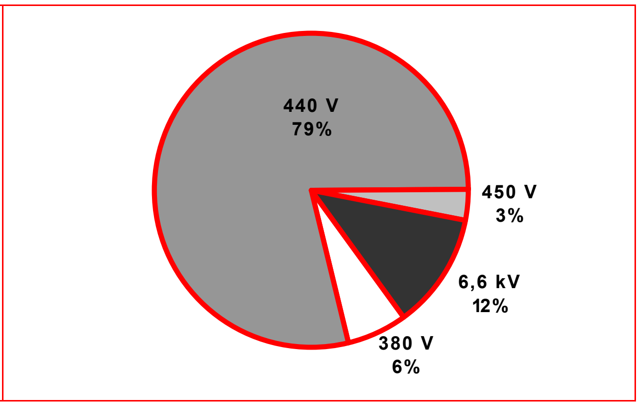


Figure C9 Main system voltage (deep sea container vessels).

C2.2.3 System frequency

Figure C10 illustrates that approximately 63 % of the feeders have an operation frequency of 50 Hz. While in *Figure C11* it is presented that approximately 94 % of deep sea vessel have an operational frequency of 60 Hz.

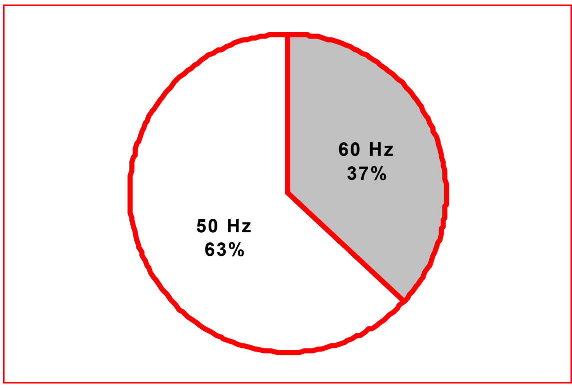


Figure C10 Main system frequency (feeders).

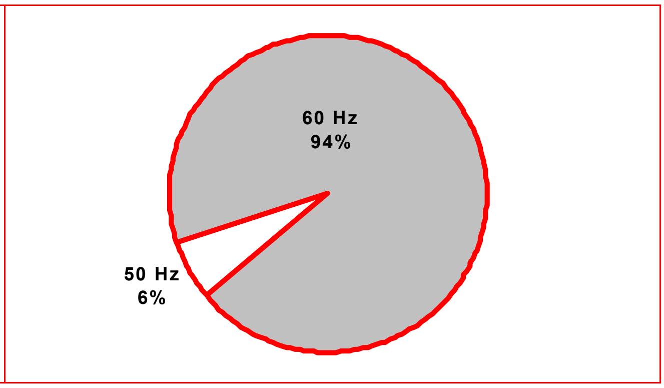


Figure C11 Main system frequency (deep sea container vessels).

C2.3 Ro/Ro- and Vehicle vessels

Ro/Ro stands for Roll-on/Roll-off, and Ro/Ro ships are vessels that are designed to carry wheeled cargo such as automobiles, trucks, semi-trailer trucks, trailers or railroad cars. This is in contrast to container vessels which use a crane to load and unload cargo. Ro/Ro vessels have built-in ramps which allow the cargo to be efficiently rolled on and rolled off the vessel when in port. The ramps and doors may be stern-only, or bow and stern for quick loading.

There are no previous studies made concerning power demand, system frequency and operation voltage for Ro/Ro vessels. By means of *Lloyds Register of Ships* an own study has been made concerning 30 vessels that traffic European ports [45]. The ships have been randomly chosen in the order of magnitude between 100 and 250 meter – which represents the smallest and the biggest Ro/Ro and vehicle vessels today. The complete list of vessels concerned in the survey can be found in *Appendix I*.

C2.3.1 Power demand

In *Figure C12* the maximum power generated onboard is represented. These values represent the total installed auxiliary generator capacity onboard. *Figure C13* illustrates the power needed during hotelling and is calculated according to *Table C1* in the previous chapter. The Ro/Ro vessels have an average power demand less than 2 MW during hotelling.

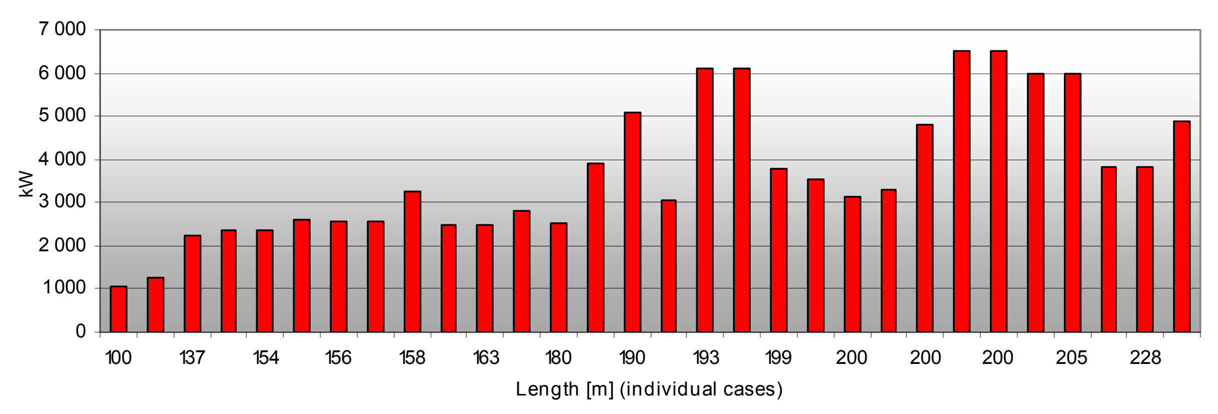


Figure C12 Totally installed generation capacity onboard.

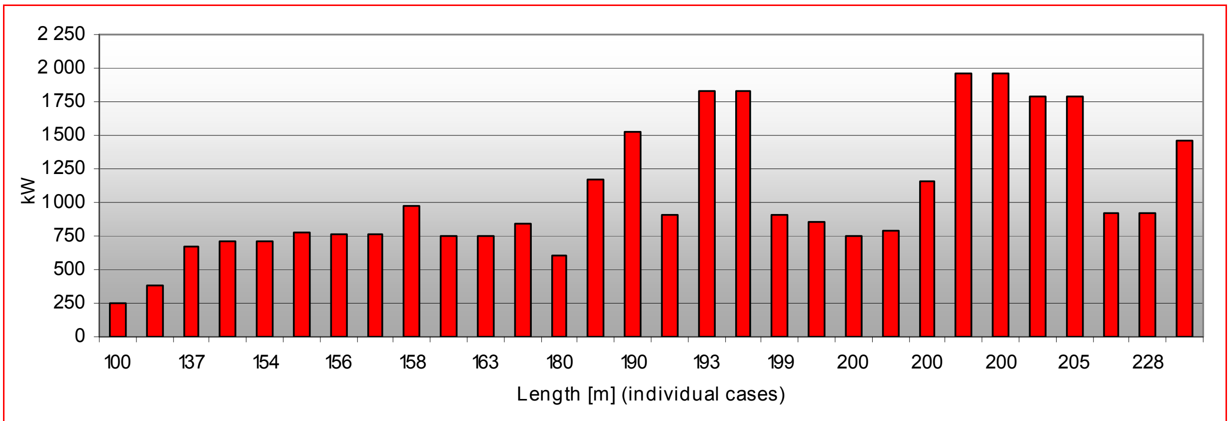


Figure C13 Average power consumption in port.

C2.3.2 System voltage

The system voltage for the Ro/Ro vessels concerned in the study is summarized and presented in *Figure C14*. As seen from the figure, all Ro/Ro vessels operate at low-voltage from 400 to 460 V.

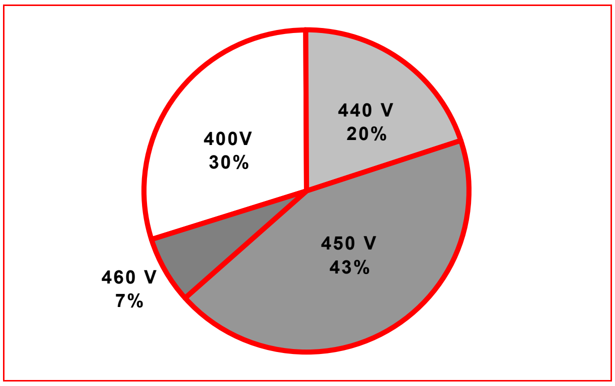


Figure C14 Main system voltage

C2.3.3 System frequency

Figure C15 illustrates the system frequency for the Ro/Ro vessels.

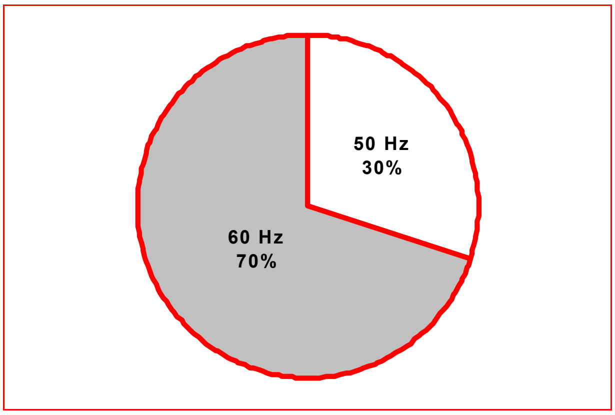


Figure C15 Main system frequency

C2.4 Oil- and product tankers

An oil tanker, also known as a petroleum tanker, is a ship designed for the bulk transport of oil. There are two basic types of oil tankers: the crude tanker and the product tanker. Crude tankers move large quantities of unrefined crude oil from its point of extraction to refineries. Product tankers, generally much smaller, are designed to move petrochemicals from refineries to points near consuming markets.

There are no previous studies made concerning power demand, system frequency and operation voltage for oil- and product tankers available. As for Ro/Ro vessels an own survey has been made with the same selection criteria concerning oil- and product tankers with the length between 100 and 250 meters. The complete list of vessels concerned in the survey can be found in *Appendix II.*

It is important to emphasize that no Liquefied Natural Gas (LNG) vessels are concerned in this survey. LNG vessels are out of scope in the study. These vessels have a power demand in the same range as cruse ships discussed in the next section and are usually diesel-electric vessels.

C2.4.1 Power demand

In *Figure C16* the maximum power generated onboard is represented. These values represent the total installed auxiliary generator capacity onboard. *Figure C17* illustrates the power needed during hotelling and is calculated according to *Table C1* in the previous chapter. The oil- and product tankers have an average power demand less than 3 MW during hotelling.

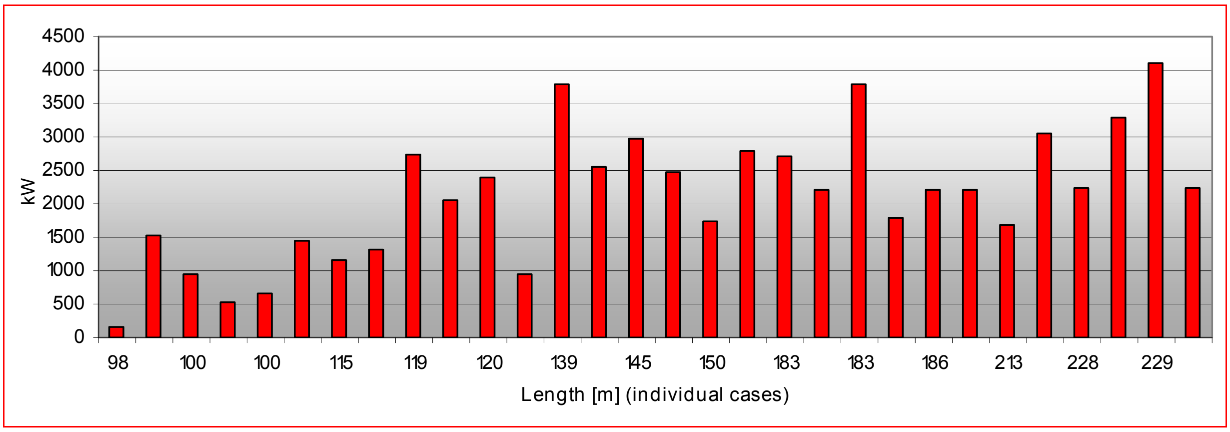


Figure C16 Totally installed generation capacity onboard.

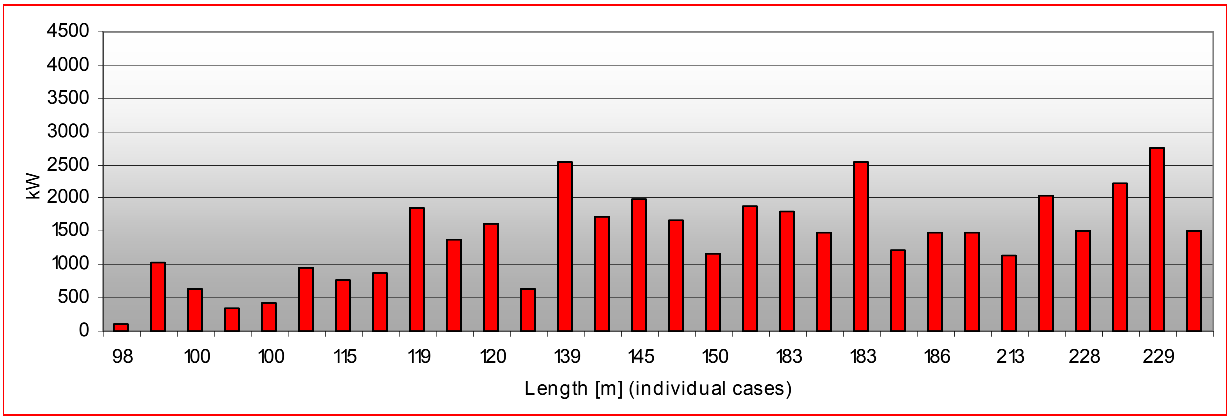


Figure C17 Average power consumption in port.

C2.4.2 System voltage

As seen in *Figure C18*, all the vessels concerned in the study are operating with low-voltage.

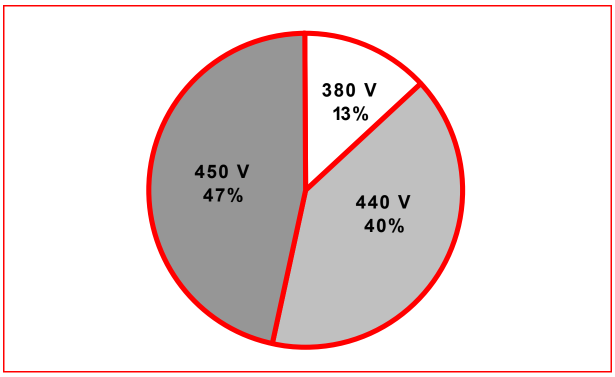


Figure C18 Main system voltage.

C2.4.3 System frequency

Figure C19 illustrates the system frequency for the oil- and product tankers. As seen from the figure approximately 80 % of the vessels have a system frequency of 60 Hz.

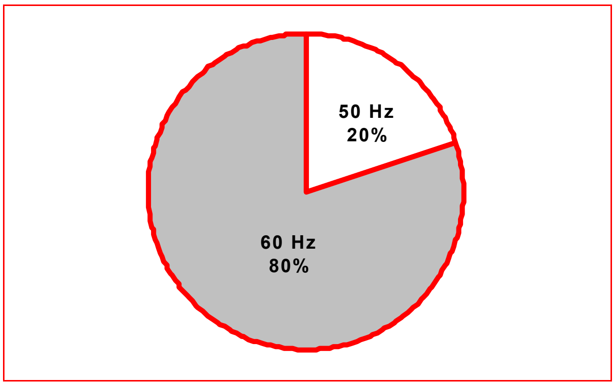


Figure C19 Main system frequency.

C2.5 Cruise ships

A cruise ship or cruise liner is a passenger ship used for pleasure voyages, where the voyage itself and the ship's amenities are part of the experience. Cruising has become a major part of the tourism industry, with millions of passengers each year. Cruise ships operate mostly on routes that return passengers to their originating port. Passenger ships typically dock in the morning and set sail in the evening. The average time in dock is about ten hours. Since the short docking time occurs only during the day, utility rates are usually at peak or near-peak rates. Cruiser ships have the highest power consumption while hotelling of any vessel type. As mentioned in the previous chapter cruiser ships mostly use diesel-electric power systems.

Some details regarding power demand are collected from a previous study made by Environ [22]. This study is complemented with additional vessels and totally 40 vessels are included. 47 cruiser vessels are included in the survey regarding system frequency and system voltage. More details concerning the ships included can be found in *Appendix III* and *Appendix IV*.

C2.5.1 Power demand

As mentioned in the previous chapter diesel-electric vessels have a higher need of power. *Figure C20* indicates that this statement is correct. The average power generated in port is calculated according to *Table C1,* and the average peak power is approximately 11 MW. A mean average power is approximately 7 MW for most cruisers.

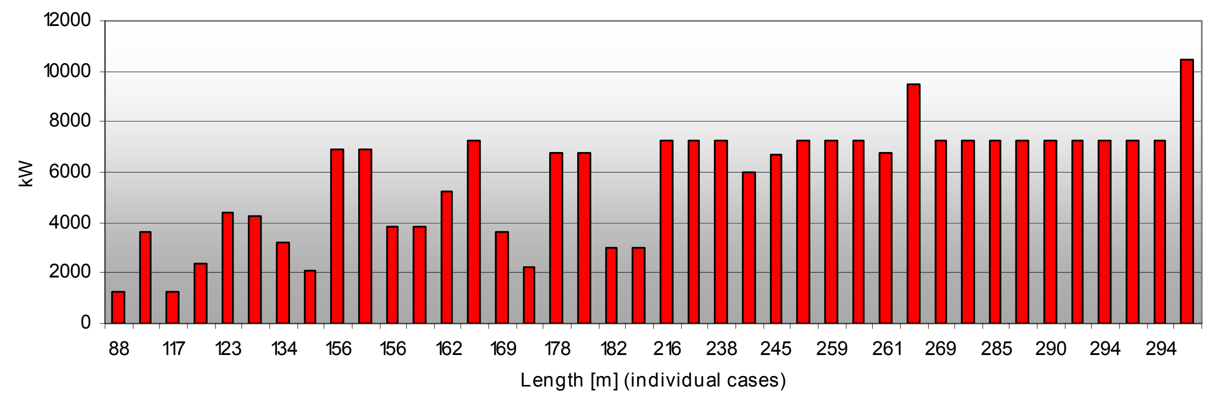


Figure C20 Average power consumption in port

C2.5.2 System voltage

As seen from *Figure C21* most cruisers with a length below 200 meters operate with low-voltage. *Figure C22* shows that most of the cruisers with the length larger than 200 m operate with high-voltage, due to the high power demand and the fact that they use diesel-electric propulsion. A summary of all cruiser system voltages is shown in *Figure C23*.

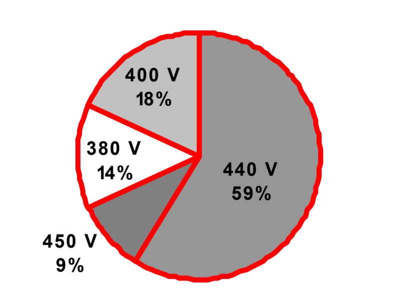


Figure C21 Main system voltage (< 200 m)

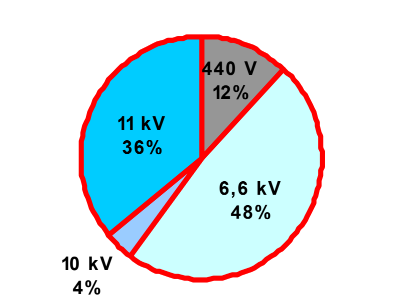


Figure C22 Main system voltage (> 200 m)

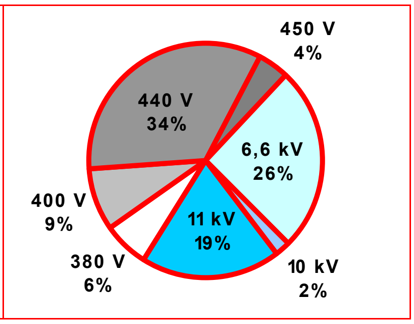


Figure C23 Main system voltage (total)

C2.5.3 System frequency

For cruiser vessels larger than 200 meters, all the vessels are operating with 60 Hz, see *Figure C25*. As seen in *Figure C24* a majority of the cruiser vessels operate with 60 Hz. A summary of all cruisers system frequencies is shown in *Figure C26*.

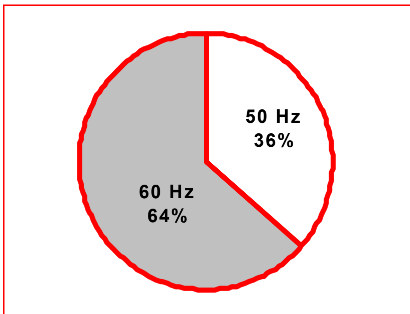


Figure C24 Main system frequency (<200m)

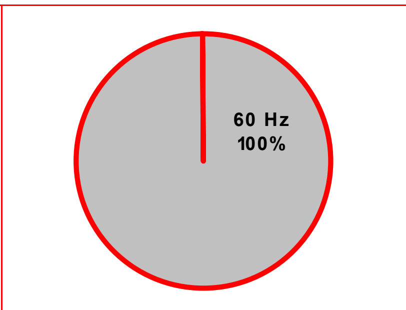


Figure C25 Main system frequency (>200 m)

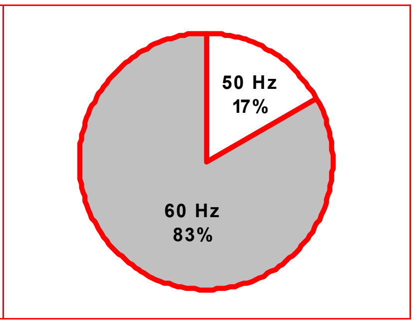


Figure C26 Main system frequency (total)

C2.6 Summary – Power demand onboard

In the following tables a summary of power demand, system voltage and system frequency is shown.

Table C2 Summary of Power Demand

	Average Power Demand	Peak Power Demand	Peak Power Demand for 95 % of the vessels
Container vessels (< 140 m)	170 kW	1 000 kW	800 kW
Container vessels (> 140 m)	1 200 kW	8 000 kW	5 000 kW
Container vessels (total)	800 kW	8 000 kW	4 000 kW
Ro/Ro- and Vehicle vessels	1 500 kW	2 000 kW	1 800 kW
Oil- and Product tankers	1 400 kW	2 700 kW	2 500 kW
Cruise ships (< 200 m)	4 100 kW	7 300 kW	6 700 kW
Cruise ships (> 200 m)	7 500 kW	11 000 kW	9 500 kW
Cruise ships (total)	5 800 kW	11 000 kW	7 300 kW

Table C3 Summary of System Voltage

	380 V	400 V	440 V	450 V	460 V	6.6 kV	10 kV	11 kV
Container vessels (< 140 m)	42 %	16 %	42 %	-	-	-	-	-
Container vessels (> 140 m)	6 %	79 %	-	3 %	-	12 %	-	-
Container vessels (total)	19 %	6 %	64 %	2 %		9 %		
Ro/Ro- and Vehicle vessels	-	30 %	20 %	43 %	7 %	-	-	-
Oil- and Product tankers	13 %	-	40 %	47 %	-	-	-	-
Cruise ships (< 200 m)	14 %	18 %	59 %	9 %	-	-	-	-
Cruise ships (> 200 m)	-	-	12 %	-	-	48 %	4 %	36 %
Cruise ships (total)	6 %	9 %	34 %	4 %	-	26 %	2 %	19 %

Table C4 Summary of System Frequency

	50 Hz	60 Hz
Container vessels (< 140 m)	63 %	37 %
Container vessels (> 140 m)	6 %	94 %
Container vessels (total)	26 %	74 %
Ro/Ro- and Vehicle vessels	30 %	70 %
Oil- and Product tankers	20 %	80 %
Cruise ships (< 200 m)	36 %	64 %
Cruise ships (> 200 m)	-	100 %
Cruise ships (total)	17 %	83 %

C2.7 Total power demand for a typical terminal

As an end of this chapter the data above will be used to give a picture of what energy demand two typical terminals will have. Port of Göteborg has been chosen as a first reference port, where the Ro/Ro terminals, Arendal and Älvsborg, have been studied for a complete shore-side connection of all berths at these areas. By examining arrival data for the terminals, where the information regarding vessel name, arrival time and departure time, has been used to calculate the power demand for each vessel, using the data above discussed in the chapter. To give a clear picture of the coverage degree, two months of the year at two different seasons of the year has been chosen; November 2007 and May 2008. The result of the study is shown in *Figure C27* and *Figure C28.* As illustrated, the two terminals together bring a maximal power demand of 14 MW, which occurs only during a couple of hours. 12 MW occurs at several occasions.

Port of Tallinn has been chosen as a second reference port. Here, the cruiser terminal has been observed. Arrival data has been collected for the period June, July and August 2008. The same procedure has been used, and the result of the study is illustrated in *Figure C29* to *Figure C31*. Worst case is an energy demand of 45 MW and takes place 23rd of July 2008, when five cruiser vessels superpose each other, see *Figure C32.* A common value of the energy demand in Port of Tallinn is 30 MW and happens several times during the cruiser season.

As seen from the study, huge demands are set on the electric grid of the port, and to be able to satisfy the energy demands, an upgrade of the electrical-infrastructure will be needed in most of the berths if a total shore-side power supply at a terminal is going to be possible.

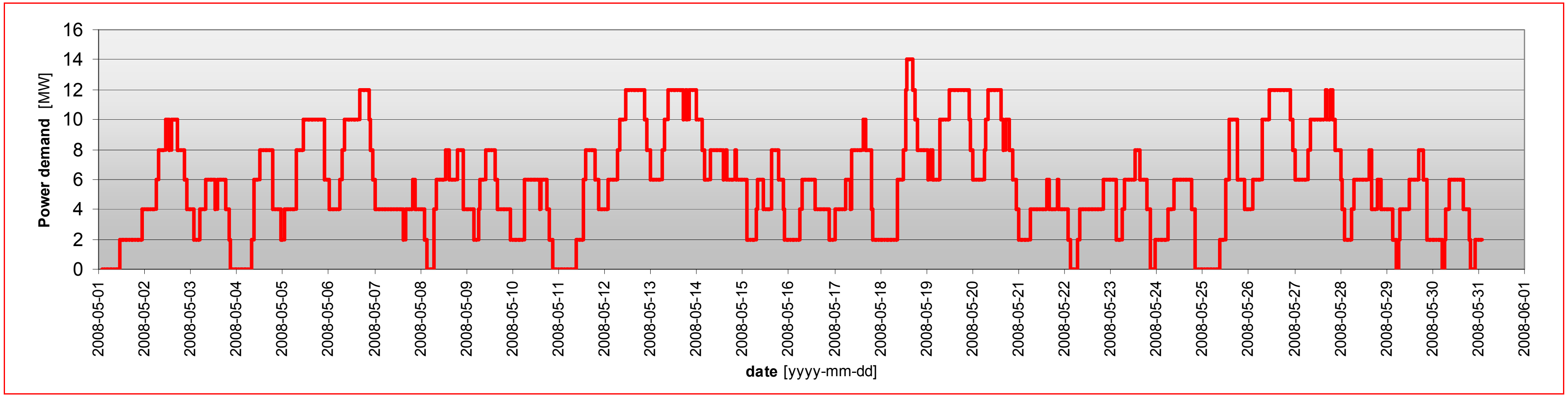


Figure C27 Case study: Ro/Ro vessel power demand during hostelling in Port of Göteborg – Terminal: Älvsborg and Arendal
May 2008

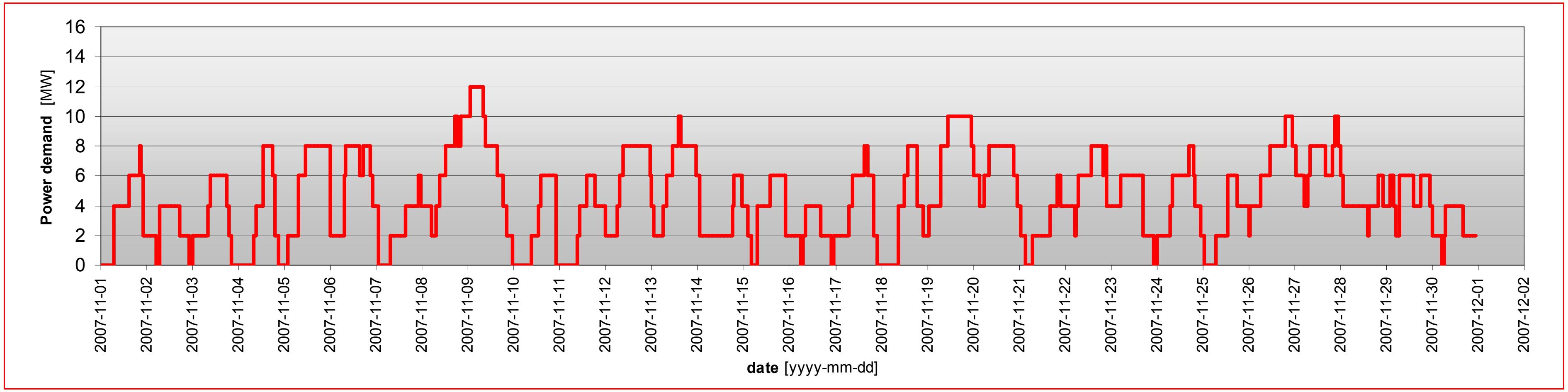


Figure C28 Case study: Ro/Ro vessel power demand during hostelling in Port of Göteborg – Terminal: Älvsborg and Arendal
November 2007

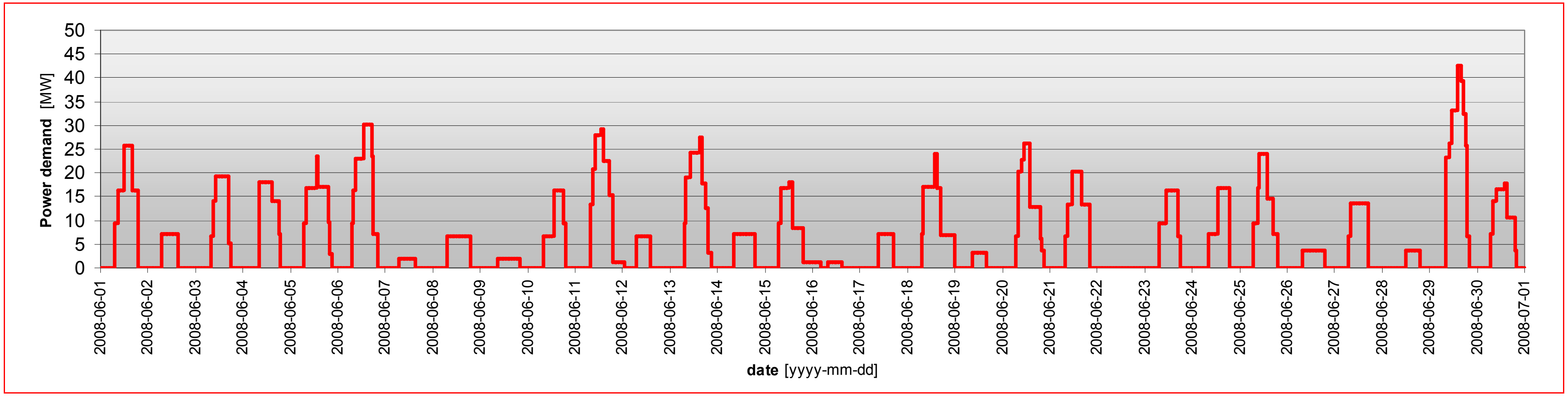


Figure C29 Case study: Cruise ship power demand during hotelling in Port of Tallinn
June 2008

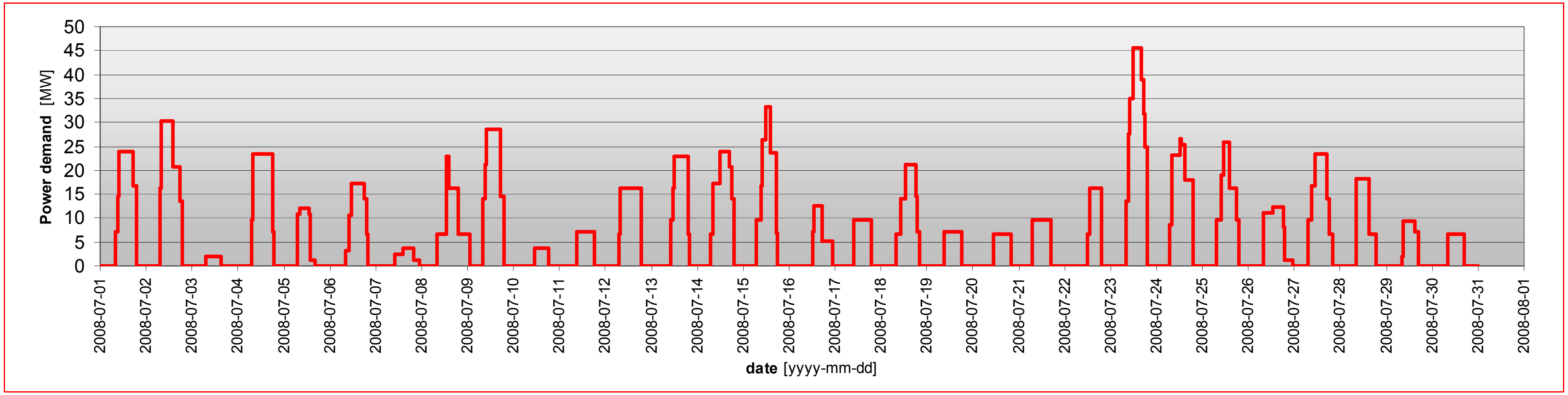


Figure C30 Case study: Cruise ship power demand during hotelling in Port of Tallinn
July 2008

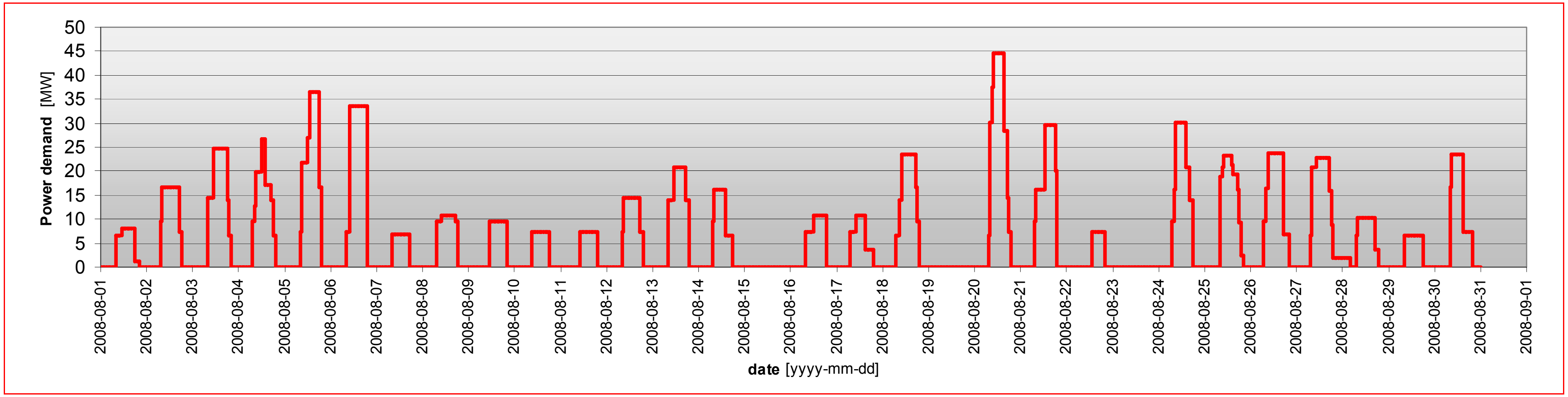


Figure C31 Case study: Cruise ship power demand during hotelling in Port of Tallinn August 2008

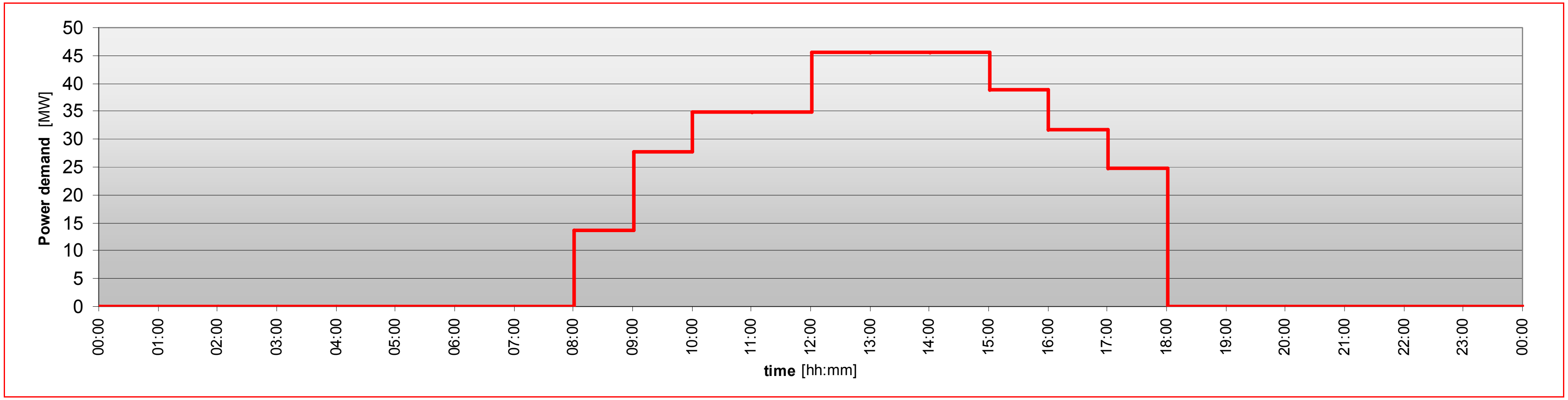


Figure C32 Case study: Cruise ship power demand during hotelling in Port of Tallinn "Worst case" July 23

C3 Docking patterns in port

Depending on the type of vessel that calls at the port, the docking arrangement looks different for different types of terminals. For example at Ro/Ro terminals the unloading and loading of the vehicles is executed with help of ramps, while container terminals are equipped with cranes to load and unload containers. To be able to shore-side connect the different types of vessels, the docking pattern should be considered when the vessels dock at berth, and how loading and unloading of the cargo is executed, so that cables and other connection equipment do not interfere with, e.g. cranes. This puts special requirements for how the connection points should be set for the different types of vessels.

The docking arrangement can be categorized into two groups of vessels - vessels that do not use cranes and vessels that do, see *Table C15*. For the purpose of practicality and applicability for vessels, the categorization of these groups can determine the ease of how the vessels can be connected with shore-side power supply. It is also important to know whether the vessels always dock at the same position while at berth and if the vessels need cranes to unload the load.

Table C5 Ship types and docking patterns

Category	Type of vessel
No cranes (32 % of vessel calls to EU Ports)	- Ro/Ro vessels - Tankers - Cruise and ferry vessels
Use cranes (68 % of vessel calls to EU ports)	- Container vessels - Dry bulk vessels

C3.2 Docking patterns for vessels that use cranes

Container and dry bulk vessels are often in a need of cranes for loading and unloading operations. The cranes often run the full length of the berth. While the cranes might work in one area of the berth for an extended time period, the cranes operate on fixed rails and require the full range of the quay. The cranes create a great restriction of the flexibility for the electrical connection to the ship, and no fixed electrical infrastructure can be installed that restrain the availability for the crane. The free space between the crane's outer rail and the side of the quay is approximately 1 meter, see *Figure C33* and *Figure C34*. Additionally, container and dry bulk vessels have an aptitude to dock at different positions at the same berth. This requires that more connection points are needed along the quay to make it possible for connection where long power cables are avoided, that otherwise can get in the way of the crane.

Figure C33 The free space between the crane and the quay-side is limited, approximately 1 meter.

Figure C34 Cranes operate on fixed rails and require the full range of the quay.

C3.3 Docking patterns for vessels which don't use cranes

The vessels that commonly dock at the same position and do not use cranes are tankers, cruisers and Ro/Ro- vessels. Tankers may discharge from either port or starboard. Ro/Ro vessels unload vehicles from the stern with either their port or starboard side against the wharf. Since Ro/Ro vessels use ramps for loading and unloading operations, see *Figure C35* and *Figure C36*, the stationing of these vessels are often at the same position of the berth, which makes shore-side connection operation easier. There is no need of the same amount of connection points next to the berth such as in the container terminal, where the vessels dock at different positions at the same berth, as presented above. The connection cables used in the Ro/Ro terminal are not risking getting in the way in the same manner as for container terminals and can therefore be allowed to be longer. The area at the quay is not restricted by rails, which makes the space at the quay less limited.

Figure C35 Ro/Ro ramp used for unloading and loading vehicles onboard.

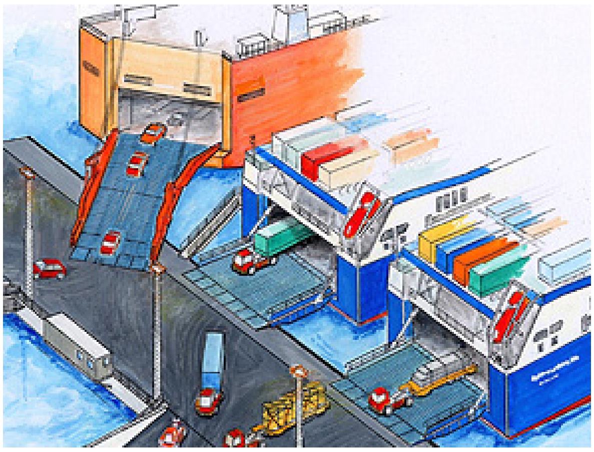


Figure C36 Unloading and loading activity at a Ro/Ro terminal.

C4 Norms and standards

As shore-side power supplies have grown in interest, three standard groups; *ISO, IEC* and *IEEE*, have been assigned to complete a full standard for shore-side power supply or cold ironing. The three standardization committees have different influences in different parts of the world. The main goal with the standards is to have the same purpose and not to conflict with each other. They are adapted to avoid language differences. The ISO and IEC standards have the biggest influence in the European countries, while the IEEE standard has the biggest impact in the US. The ISO standard is mainly covering the mechanical aspects, while the IEC and IEEE standards cover the electrical aspects of the connection. It is clear that the three groups cooperate so that there will be a world standard. There are currently no finished standard regarding shore-side power supply applications. The standard is still under development and it is expected to be released in mid 2009.

According to the members of the standardization groups, preliminary drafts of the standard are released, but not official. Contacts have been established with the standardisation groups and the corresponding members, and the members have stated that the standard will look in the following way:

Ro/Ro- and Container vessels are going to be high voltage connected with 6.6 kV, 7.5 MVA. The cable is going to be supplied by the vessels, for these types of vessels. An obligatory transformer for galvanic isolation between the shore and the ship should be adapted on the berth, only allowing one ship to be connected to each transformer. The connection frequency is set to 60 Hz, so a frequency converter is needed in European ports. Cruiser vessels are going to be high voltage connect with 6.6 kV or 11 kV, depending on the power demand of the vessel. As it looks today, both of these voltages shall be supplied at the berths. Furthermore, the standard requires a main circuit-breaker to be applied before the shore-side transformer and a secondary circuit-breaker to be applied before to the shore connection box, at each berth.

A big issue for the standard has been the question regarding safety. The members haven't really fully agreed on the safety question, but a suggestion of a key interlock has been recommended as protection for operators that connect the cable into the connection facility. Corresponding safety solutions that give the same or greater protection are acceptable. Additionally it is said that the outlet should be rated and withstand the minimum fault current of 16 kA. An optocable should be supplied for communication between the shore and the ship.

The standard groups and the corresponding standards are presented in *Table C6.*

Table C6 Standard groups and the corresponding standard

Standard Group	Name
ISO Standard	ISO/WD 29501 – On shore power supply, “Cold Ironing”
IEC Standard	IEC 60092-5XX - Electrical installations in ships, Special features – High-voltage shore connection system
IEEE Standard	IEEE P1713 – Electrical shore-to-ship connections

Part D - Technical design

D1 Evaluation of different design configurations

When the master thesis started in June, limited amount of information was supplied. Information such as power demand and the electrical infrastructure onboard the vessel had to be investigated. A technical study was made to receive the knowledge regarding the vessels in order to form a technical design. The result of this study has been illustrated in the previous chapters.

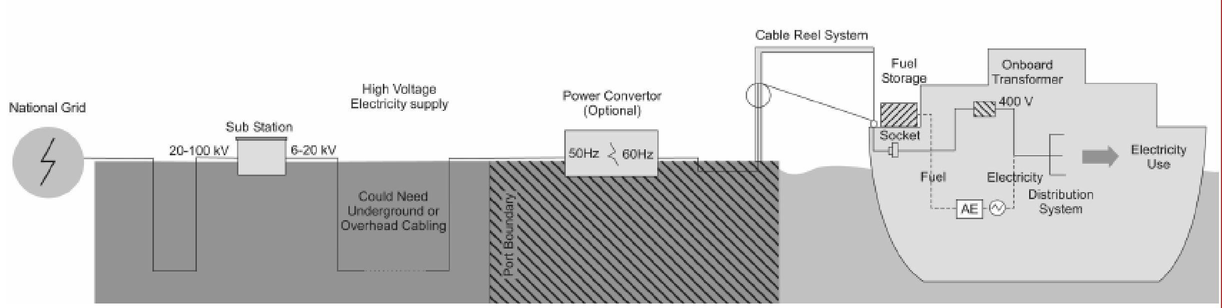
It has been shown from the technical survey and according to the standard, that there will be an insistence of frequency converters in European harbours, to be able to supply vessels with 50 Hz or 60 Hz to each berth. High-voltage cable is a requirement according to the standard and will be utilized due to the easiness of shore-side connection to vessels. The price to pay when desiring a smooth and quick shore-side connection is to equip the vessels with onboard transformers to adapt the voltage onboard to the voltage on shore. This is something that needs to be done on the majority of the vessels, since most of the vessels have low-voltage electric systems, according to the technical survey.

To construct a new infrastructure in a harbour to supply vessels with shore-side power can be done in several ways. The topologies can be designed either in a centrally placed system for frequency conversion, or where the frequency conversion takes place in the vicinity of the berth.

Three different main topologies have been considered and evaluated during the journey, in the basis of an evaluation of which topology is most suitable to utilize. The different topologies are presented in this chapter. The configuration which the European Union proposes in the recommendation to their member states regarding shore-side power supply is presented and evaluated as an introduction of this chapter. This chapter will end with a comparison summary of the different topologies.

D1.1 Typical configuration according to the EU recommendation

The European Union have presented, from their point of view, a typical shore-side power supply configuration in the recommendation *2006/339/EC*, which was presented previously in *Chapter B1.1*. The configuration is illustrated in *Figure D1* and described more in detail in *Table D1*. Other shore-side power supply configurations are possible depending on the type of vessel that is to be connected to the shore.



Position:	1	2	3	4	5	6	7	8	

Figure D1 Overview of Shore-side electricity connection according to EU recommendation 2006/339/EC

Table D1 Description of the shore-side electricity connection according to EU recommendation 2006/339/EC [35]

Position	Description
1	A connection to the national grid carrying 20-100 kV electricity from a local substation, where it is transformed to 6-20 kV.
2	Cables to deliver the 6-20 kV power from the sub-station to the port terminal.
3	Power conversion, where necessary. (Electricity supply in the Community generally has a frequency of 50 Hz. A ship designed for 60 Hz electricity might be able to use 50 Hz electricity for some equipment, such as domestic lighting and heating, but not for motor driven equipment such as pumps, winches and cranes. Therefore, a ship using 60 Hz electricity would require 50 Hz electricity to be converted to 60 Hz).
4	Cables to distribute electricity to the terminal. These might be installed underground within existing or new conduits.
5	A cable reel system, to avoid handling of high voltage cables. This might be built on the berth supporting a cable reel, davit and frame. The davit and frame could be used to raise and lower the cables to the vessel. The cable reel and frame could be electro-mechanically powered and controlled.
6	A socket onboard the vessel for the connecting cable.
7	A transformer on board the vessel to transform the high voltage electricity to 400 V.
8	The electricity is distributed around the ship, and the auxiliary engines switched off.

The configuration expressed in the European recommendation is a form of a decentralised topology where the frequency converter is placed beside the berth. This configuration can be discussed whether this is a good solution or not. When supplying a frequency converter to each and every vessel that calls at the port, the dimensioning of the frequency converter has to be considered and adapted to the vessel that has the highest power demand while at berth. Therefore, this configuration will not be able to make use of the over capacity of the frequency converter when a vessel with lower power demand calls at the berth.

Furthermore, the configuration recommended by the European Union lacks a satisfying galvanic protection between the harbours and the vessels electric system. In those cases where the vessel is equipped with a transformer onboard, a galvanic protection is achieved in some degree. The connection cable and other connection equipment onboard the vessel is not galvanically separated from the electric system on land. The vessels that have the same voltage onboard as on land are missing the transformer, and therefore will these vessels totally lack the galvanic protection with the electric system on land.

An additional issue to mention is the connection arrangement at berth. The connection arrangement described in *Table D1* above, can be used for some types of vessels, but will not be functional for those vessels that use cranes for loading and unloading operations. There is a chance that the cable reel system is going to hinder the accessibility and form a type of safety concern. A solution where this is avoided is further desirable.

D1.2 Possible technical configurations

During the thesis work, several different suggestions on possible topologies have been assessed. These topologies have been cut down to three main topologies which are going to be the basis for evaluation if practicable for application in a harbour. Something that all topologies have in common is that each one of them has a transformer localised at each berth-side. There are several reasons for this. With the help of a transformer as the last link between the electric grid at shore and the electric system on the vessel, a galvanic separation between the grids is achieved. There are also possibilities to reduce the fault current, and a potential fault onboard a vessel will not have the same effect on a nearby connected vessel and therefore prevents a potential propagation of the fault, which can be fatal. Transformers at berth facilities even a higher voltage in the distribution grid to the berths, and thus reducing cable losses. This transformer is also a requirement according to the standard described in *Chapter C4*. According to the standard, cruiser vessels are expected to be connected with either 6.6 kV or 11 kV. This is achieved by changeover on the transformer at berth. There are thus several instances to have a transformer localised at each berth.

Another thing that the topologies have in common is that the output sockets are connected via an earth switch to satisfy the safety demands that are expected in the upcoming standard. The connection of the cable between the vessels shall be dead via an earth switch coupled to earth. Even before the cable is removed after connection with the vessel, the earth switch shall be coupled to earth. This is to prevent capacitive charging of the cable, which could lead to personal injuries to the cable operator. All output sockets that are not connected to any vessel shall be coupled to earth. This means that in those cases where there are several output sockets at the same berth, there is a demand that each one of the output sockets are coupled via a separate earth switch to allow those outlets that are not connected to the vessels to be disconnected and coupled to earth. More details regarding this is described in *Chapter D2.7.*

The main topology configurations are presented below in *Figure D2*, *Figure D3* and *Figure D4*, and each configuration is described in the following sections.

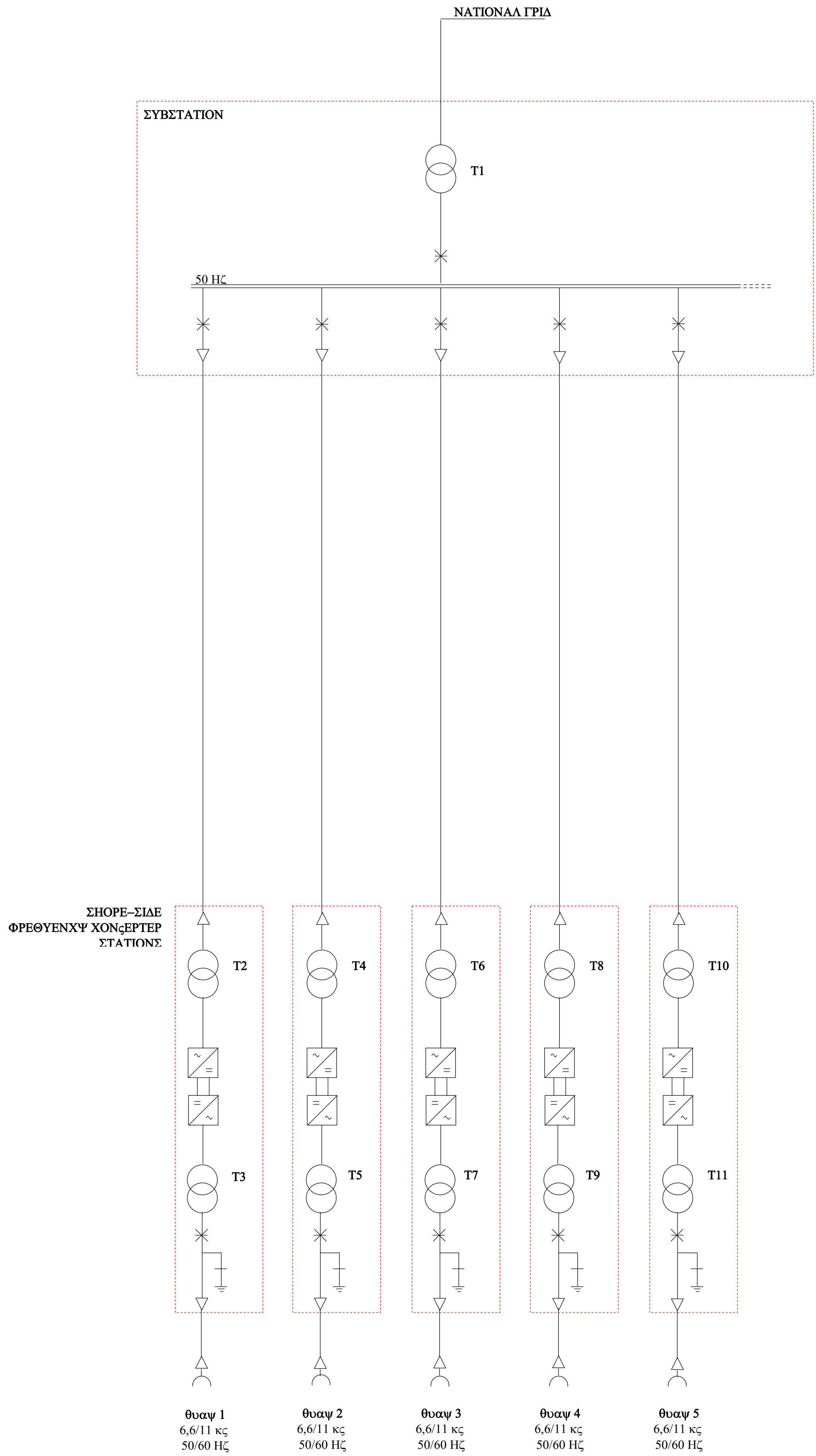


Figure D2 *Configuration 1*

Frequency converter located at berth

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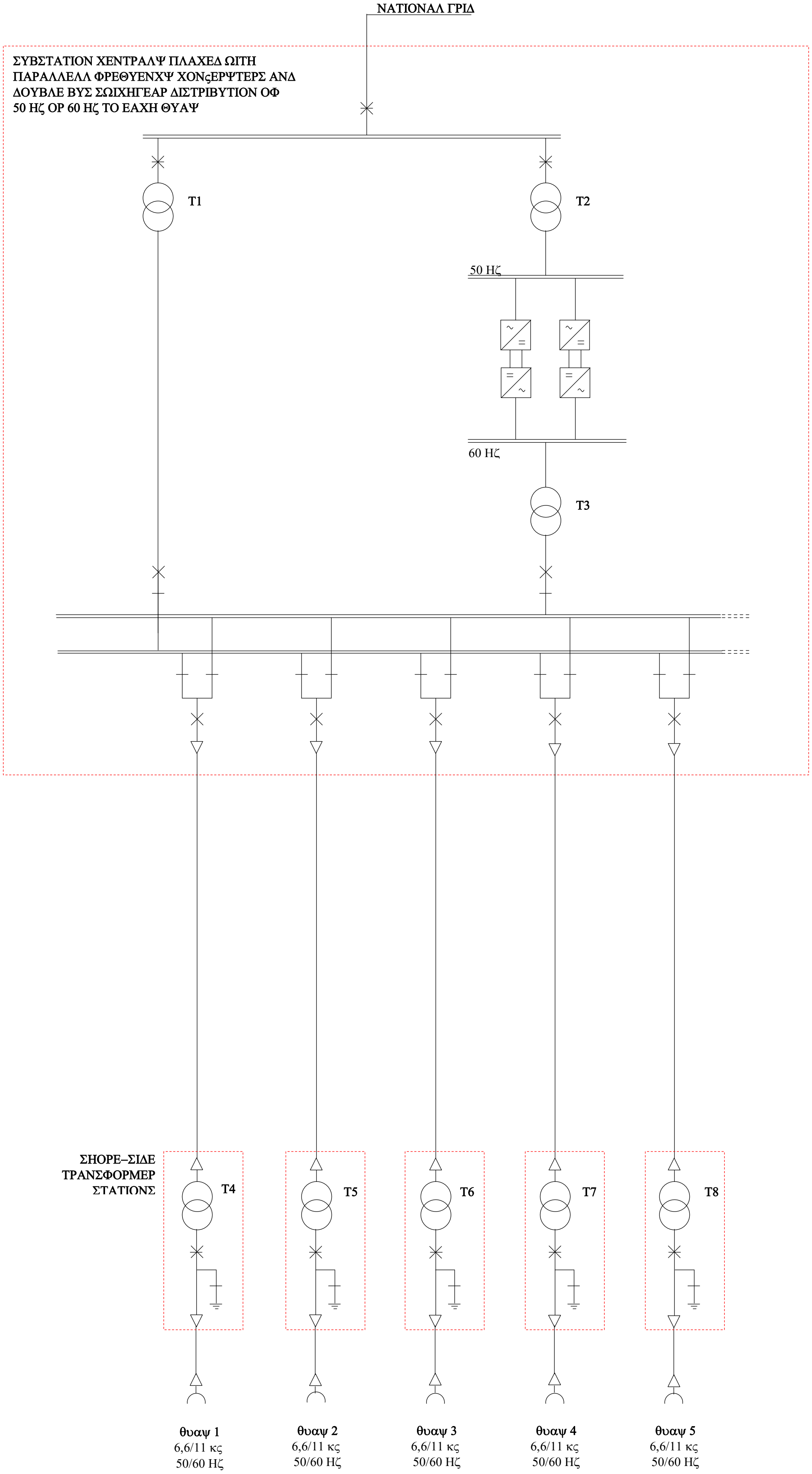

Figure D3 *Configuration 2*

Centrally placed converter(s)

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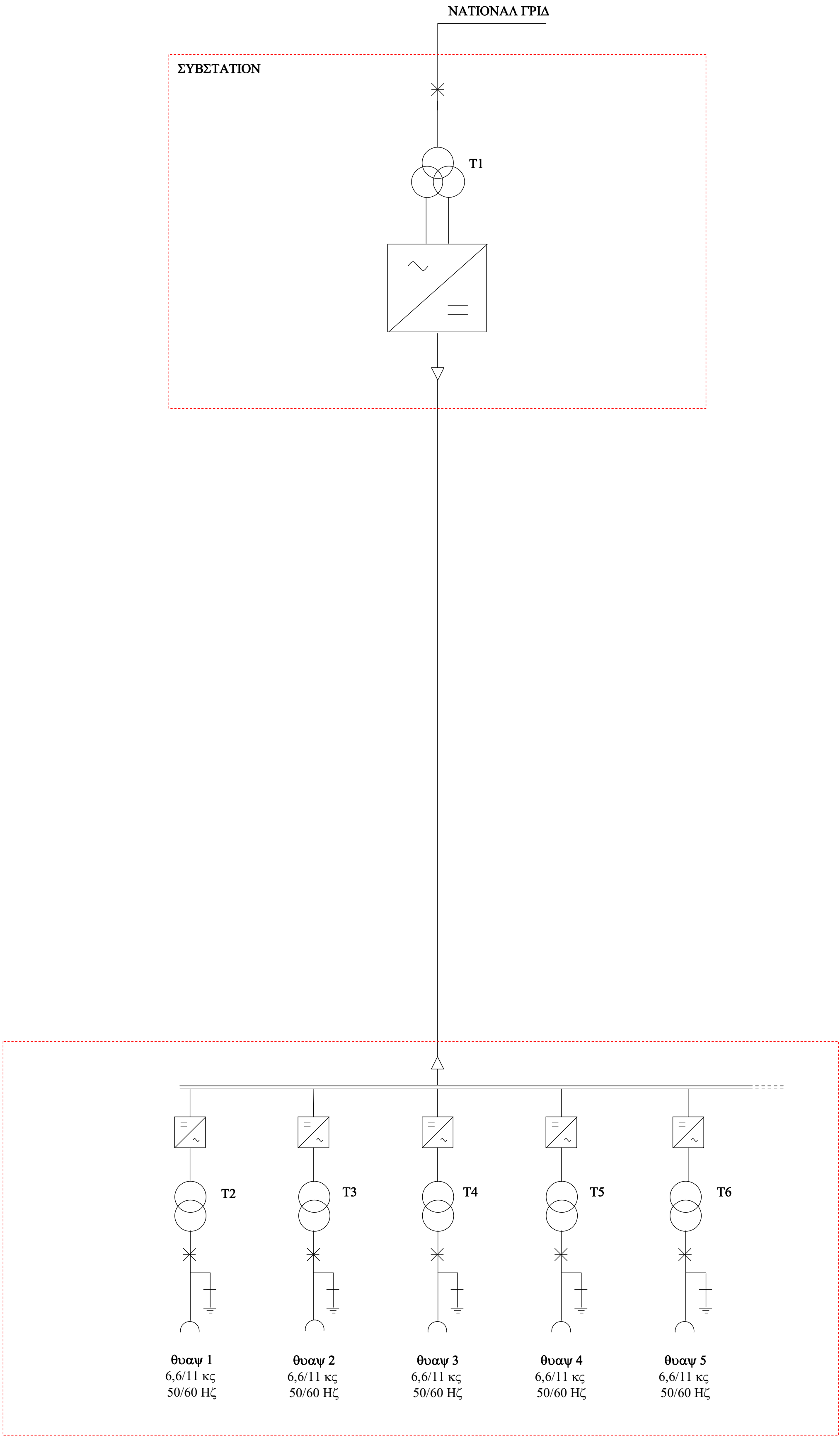


Figure D4 *Configuration 3*

DC distribution

ABB	SEPAERI1/SEISFAZ	Rev 2	2008-11-04

D1.2.2 Configuration 1 – Frequency converter located at berth

The first configuration is illustrated in *Figure D2*. This configuration is similar to the configuration recommended by the European Union, mentioned above. It is a decentralised system where a separate frequency converter is placed on each berth. These are radially feed from a common substation. The transformer at berth serves an additional function in this configuration. It serves together with the frequency convert as a curve shaper, to form the sinusoidal curve shape. To adapt the feeding voltage to the frequency converter an additional transformer is required. There are few frequency converters obtainable and which are suitable for this purpose, which require a voltage between 1 - 5 kV. This voltage in the feeding network and in the substation will result in very high currents at power ranges in this context. A step-down transformer is therefore necessary to be able to allow higher voltages in the feeding network, and in that way reduce the current and thereby reduce the cable losses. The dimensioning of the frequency converter has to be done by means of the highest power demand at the present berth, and has to have the same rated power output as the transformers at berth, this to avoid being a bottleneck in the total system.

This configuration has a free-standing system at each berth, which can be seen as an advantage if a fault occurs at the facility. If a fault takes place in one of the frequency converters then this berth can be disconnected without any influence on the other berths. Even regular service work is facilitated when having a separate system according to this configuration.

A disadvantage with this configuration is that it takes big amount of space at each berth, something which can be very critical for example in a container terminal, where both cranes and industrial trucks need accessibility, and where space for piling up containers already is limited. The space needed for the frequency converter, two transformers and switchgears with earth switch equipment and a disconnector, is approximately 190 m^2.

An additional disadvantage with this configuration is that the frequency converter is used for both frequencies. When a vessel with a 50 Hz electric system is connected, the frequency converter is feeding the vessel with 50 Hz, which can be considered as excessive, since the network grid is already feeding the system with 50 Hz. This is not a big problem, considering that today's frequency converters have a high efficiency, 98 – 99 %, but it is although noticeable at high power ranges and should be considered as a disadvantage.

D1.2.3 Configuration 2 – Centrally placed frequency converter(s)

The second configuration is shown in *Figure D3.* This configuration is based on a centrally placed installation for frequency conversion with matching switchgears with double busbars. A frequency converter, or several parallel connected frequency converters - depending on the power demand at the specific harbour, is coupled to one of the busbars via a step-down and a step-up transformer. To enable connection of simultaneously 50 Hz as well as 60 Hz vessels at the different berths, an additional busbar is integrated, which is directly connected to the national grid via a transformer. In that case, there is a busbar providing 50 Hz and the second busbar providing 60 Hz. Each berth that is connected from the centrally placed facility is fed via a breaker and a change-over switch. The change-over switch makes it possible to choose which busbar shall be connected to the berth at that specific occasion.

An advantage with this configuration is that the frequency converter is only used for what it is needed for - converting 50 Hz to 60 Hz. It is not burdened by the 50 Hz vessels, so a higher efficiency can be achieved in this facility. As mentioned earlier, the capacity of the totally installed frequency converter power can be exploited at a centrally placed frequency converter, rather than a separate frequency converter at each berth, where it is impossible to take advantage of the overcapacity of the frequency converter when a vessel with less amount of power demand is connected. According to the standard, mentioned in *Chapter C4*, the power output to each berth will be 7.5 MVA for container and Ro/Ro vessels. The study made in this report indicates a lower power demand for these types of vessels

(<4MW), see *Chapter C2.6*. With a centrally placed frequency converter, it is possible to dimension the frequency converter to the actual power demand at the terminal, according to a similar study made in *Chapter C2.7*. The transformer and other connection equipments at each berth can be dimensioned according to the stated power in the standard (7.5 MVA). The equipment itself at each berth will not cause a bottleneck, so it makes it possible to parallel connect additionally frequency converters as the power demand increases with new and bigger vessels. To dimension the frequency converters in *Configuration 1* according to the standard will be very costly, since the study above shows that the actual power demand is less then 7.5 MVA. In this configuration, only the transformers and other connection equipment at berth are in a need of dimensioning of the higher power, which is considerably less expensive.

An additional advantage with this configuration is that it takes the smallest possible space at each berth. The majority of the equipment is centrally placed, and can be placed far away from the terminals, where there is more space available.

A disadvantage with this configuration is that it is more vulnerable. For example, if a fault occurs at the frequency converters, there is a risk that the majority of the berths will not be able to serve 60 Hz to the vessels. Nevertheless, the 50 Hz busbar can still be used.

An additional disadvantage with the configuration is that there will be a higher price on the switchgear equipment, since a double busbar system is used with breakers and disconnectors to allow distribution of both frequencies.

D1.2.4 Configuration 3 - DC-distribution with alternators

The third configuration is illustrated in *Figure D4*. This configuration is completely different compared with the two previous configurations. This configuration consists of a centrally placed rectifier that converts the AC-voltage to DC-voltage. The DC-voltage is then distributed to the different berths in a form of DC-busbar where rectifiers can be coupled to the different berths. From the busbar it is possible to choose the frequency, depending on what type of vessel that is going to be connected. It is possible to create a complete module based system with this configuration. The advantage with DC-distribution is that it is possible to additionally reduce the cable losses. This configuration is similar to a down-scaled HVDC-light facility, but with the purpose to transfer power only in one direction.

The space this configuration will claim at each berth is somewhat larger compared to configuration 2, since a rectifier is added, but is smaller that in configuration 1. The centrally placed facility can even be smaller than the centrally placed facility in configuration 2.

There are at present no finished products available to be applied for this application in these power ranges. The reason of why this configuration is discussed in this report is that it is interesting for future shore-side power supply solutions. Information that have come by in the end of the thesis work has shown that this solution can be more cost-efficient compared with the other configurations, but more work is needed to be able to adapt the technology available today in order to use this configuration.

D1.3 Comparison summary of the different configurations

A complete summary of the different topologies is presented in *Table D2*. Additional component comparison for the different configurations is illustrated in *Table D3.*

Table D2 Summary of advantages and disadvantages for the different configurations

	Advantages	**Disadvantages**
Configuration 1 Frequency converter located at berth	+ Free-standing system at each berth - fault in one frequency converter and service maintains will not influence other berths.	- Big footprint needed at every single berth. - The frequency converter must be dimensioned by the means of the highest power demand on the present berth. - The frequency converter is in use even if a 50 Hz vessel is connected. - Large amount of transformers required, due to the need of a step-down and a step-up transformer for each frequency converter.
Configuration 2 Centrally placed frequency converter(s)	+ Small footprint need at every single berth. + Frequency converter is only used for converting 50 Hz to 60 Hz, so the converter is not burdened by the 50 Hz vessels, resulting in higher efficiency and the frequency converter can be dimensioned after the total power demand of the harbour, for 60 Hz vessels.	- More vulnerable. If a fault occurs in a frequency converter all connected berth will not be able to serve 60 Hz to the vessels. - The use of double-busbar switchgears instead of standard switchgears will increase the price.
Configuration 3 DC-distribution with alternators	+ Small footprint needed both at berth and for the centrally placed + Easier to build a modular based system + Low transmission losses	- No products available today to be applied for this power range. More R&D needed. - If a fault occurs in the centrally placed rectifier building or in the DC-link, no berth will be able to serve their vessels with on-shore power supply.

Table D3 Component comparison for the different configurations

	Configuration 1	Configuration 2	Configuration 3
Footprint needed at berth-side	Large (~190 m^2)	Small (~20 m^2)	Small (~30 m^2)
Footprint needed for centrally placed substation	Small (~60 m^2)	Large (~270 m^2)	Medium (~150 m^2)
Cable length	Same cable length for booth *Configuration 1* and *2*		Minimal
Number of transformers at berth-side	2	1	1
Number of centrally placed transformers	1	3	1
Total number of transformers on-shore for connecting:			
2 vessels	5	5	3
3 vessels	7	6	4
4 vessels	8	7	5
:	:	:	:
10 vessels	21	13	11

D2 Recommended design configuration

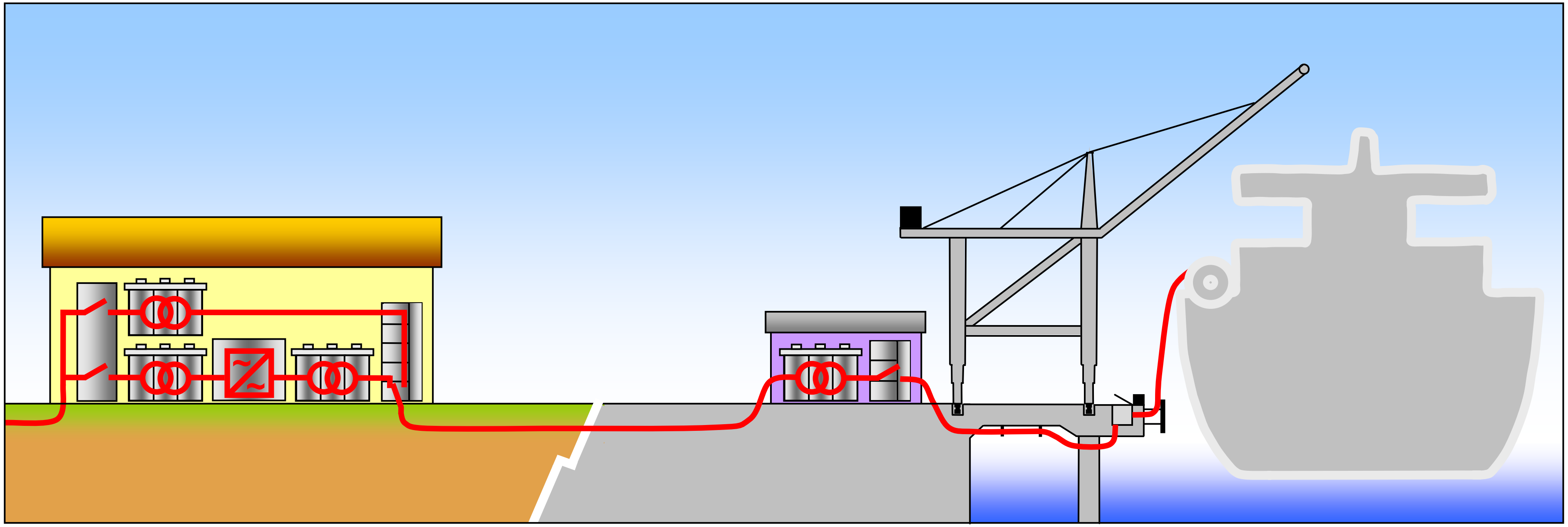
In the previous chapter, three different main topologies were considered and evaluated. The advantages and disadvantages were listed in *Table D2* and component comparison for the different configurations was presented in *Table D3*. With this information in mind, the most suitable topology has been chosen.

The first topology that was sketched on paper when the thesis work went into the design phase was the one that is called *Configuration 2*. It has been shown during the journey that this configuration seemed to be the most suitable configuration that could be implemented in a harbour where 50 Hz and 60 Hz is to be supplied to the vessels. Requirements that had impact on this evaluation were partly the space demand on quay that this configuration claims at each berth. The space demand in this configuration is considerably smaller than in *Configuration 1*, which would be difficult to implement for example in a container terminal, where each berth at the terminal would need an adjacent building for the frequency converter locally placed. With the centrally placed facility, a minimal space is taken at the quays, and thus there is no need to claim already occupied aria. Obviously, it is not the space demand that has the greatest impact on the evaluation. As a matter of fact, everything has a price. This configuration is seen as the most cost-efficient compared to the alternatives which today are possible to carry out, partly since the frequency converters are used for their main purpose – to feed the vessels that are in need of 60 Hz, and in that way the frequency converters should be dimensioned after the power need of these vessels, but this configuration also needs fewer transformers than *Configuration 1*. *Configuration 2* needs switchgear with double busbars, which becomes less expensive than all the extra transformers which are needed in *Configuration 1*.

The disadvantage one should be aware of with this configuration is that it is more vulnerable if a fault occurs in one of the frequency converter utilities. In those cases where there are no parallel coupled frequency converters, there is no redundancy to be able to deliver 60 Hz to the vessels.

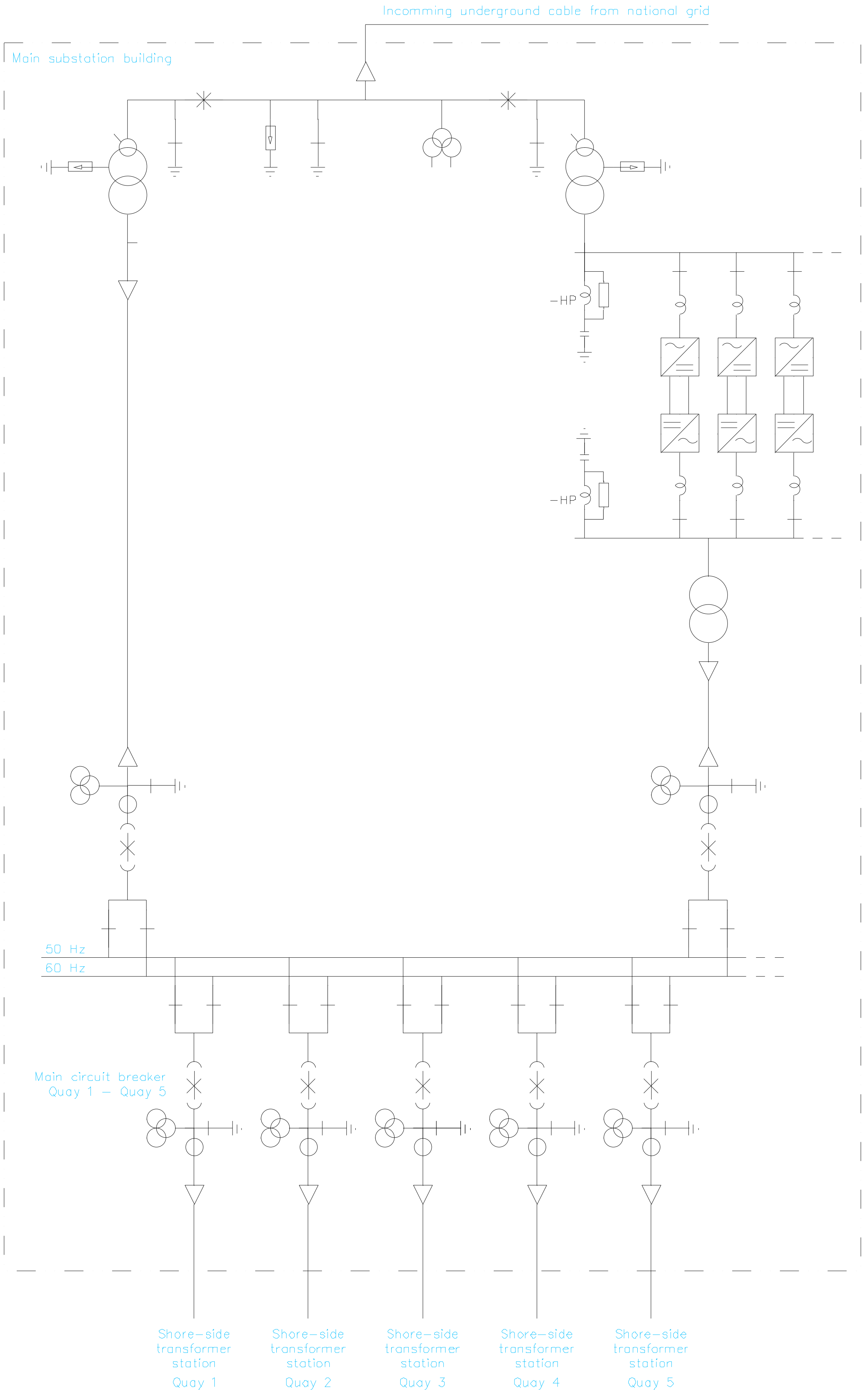
If there was a fully developed product for *Configuration 3*, then this had been a very interesting option with the same advantages as *Configuration 2*, and therefore further product development is recommended here to be able to enable such a configuration in the future.

Configuration 2 is the design configuration that is recommended for a shore-side connection according to this report. This configuration will be presented in this chapter in more detail to be able to be implemented in a harbour. In *Figure D5* an illustration is presented of the configuration. *Figure D6* and *Figure D7* represent the same configuration in form of a single line drawing.



Position:	1	2	3	4	5

Figure D5 Overview illustration of the recommended design configuration for shore-side power supply.



Title Shore-side power supply
Main substatin building
Figure D6

Prepared Patrik Ericsson
Approved
Project
Based on

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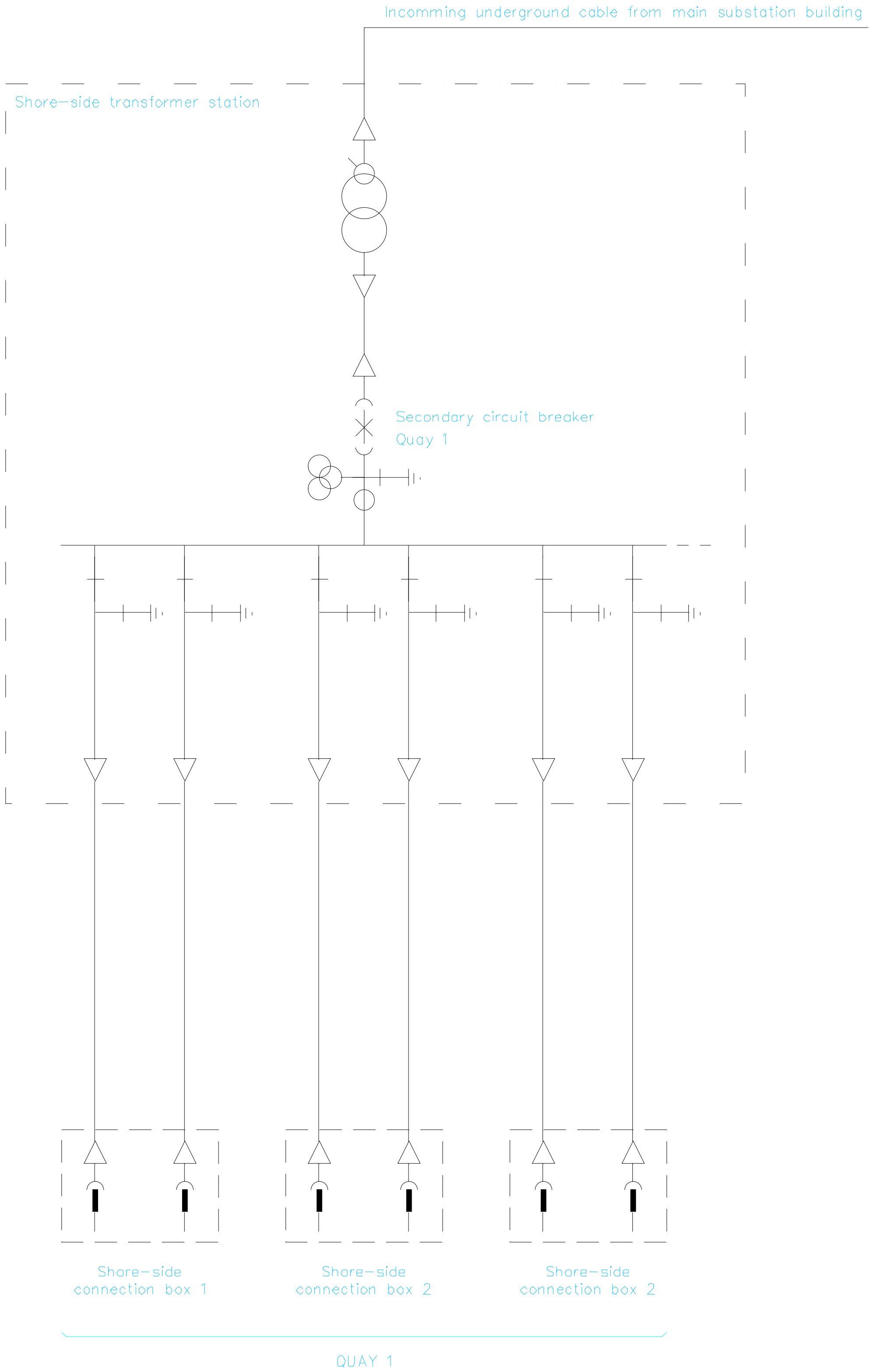

Title Shore-side power supply
Shore-side transformer station
Figure D7

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Prepared Patrik Ericsson
Approved
Project

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The overview illustration of the recommended design configuration in *Figure D5* is divided into five parts (*Position 1* to *Position 5*), see explanation in *Table D4*. The different parts will be presented from left to right in the sections below.

Table D4

Position	Description	Cross reference
Position 1	Main substation building	*Section D2.2*
Position 2	Cable arrangement	*Section D2.3*
Position 3	Shore-side transformer station and connection arrangement	*Section D2.4*
Position 4	Shore-side connection arrangement	*Section D2.5*
Position 5	Vessel connection requirements.	*Section D2.6*

D2.2 Main substation building

The main substation building (Position 1) represents the heart of the system and makes the centrally placed unity in the establishment. This facility contains coupling equipment such as, breakers, disconnectors, surge arrester and transformers to couple the shore-side connection infrastructure to the national grid. This connection interface has to be dimensioned and designed according to the existing grid in the port.

The main components that belong to the shore-side power supply infrastructure are located inside the building. Frequency converter with matching transformer and double busbar switchgear with shifting device and measuring transformers, are all gathered in the building and will be presented in this section. Relay protection and comprehensive control system are also localised here.

Figure D8 illustrates how the main substation building might look like. The size of the building will vary depending on how many berths are to be supplied with shore-side power and what power demand they have. To get an understanding of the size, calculations have been made to shore-side connect a terminal with seven berths. In that case where one frequency converter is needed, the measure of the building would be 18 x 15 m (270 m^2). A corresponding building with two frequency converters that are parallel coupled would be 28 x 15 m (420 m^2).

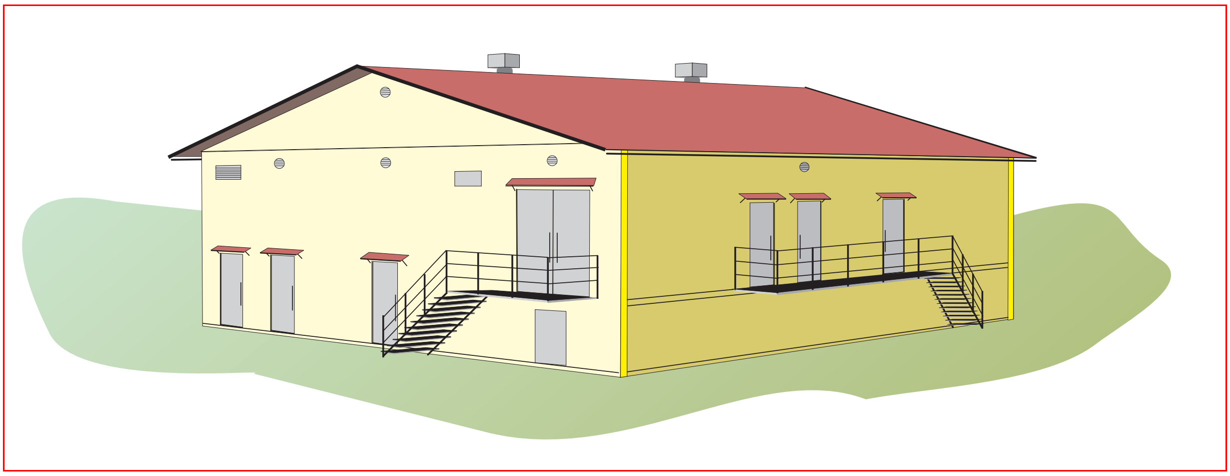


Figure D8 Main substation building, including 50/60 Hz converter.

D2.2.2 Frequency converter

The choice of frequency converter has been a laborious work to find a frequency converter that suite this application and with the possibility to build a module based concept where several frequency converters can be parallel coupled depending on what power demand needed. Frequency converters with these power ranges are normally not standard products which are in stock, but are instead custom-made for the supposed application. This of course influences the price tag negatively, since the production volume of these frequency converters are relatively small. The choice of frequency converter fell on ABB PCS 6000, as with adaption to this application with hardware and drives is called ABB PCS 6000 Harbour.

The ABB PCS 6000 uses a 6-pulse three-level IGCT converter on both sides, available in the power range between 6 – 11 MVA, with a variable input and output voltage up to 3.7 kV. To adapt the voltage to 3.7 kV, standard 6-pulse step-up and step-down transformers are used. In order to be able to build systems with higher power demands, the ABB PCS frequency converters can be parallel coupled, and thereby more power can be distributed to the berths. There are possibilities to use water cooling equipment, since the frequency converter is going to be located on the harbour area, where sea-water is available. If using sea-water as cooling aid, a heat exchanger is needed. Additional features such as reactive power control and voltage control on medium voltage distribution buses is integrated in the ABB PCS 6000.

The PCS 6000 uses advanced IGCT technology (Integrated Gate Commutated Thyristor) that has been developed by ABB, see *Figure D9*. An IGCT is a special type of thyristor similar to a GTO (Gate Turn-Off thyristor). The structure of an IGCT thyristor is very similar to a GTO thyristor. The advantage of an IGCT is that it can be turned on and off by a gate signal, and has lower on-state losses as compared to the GTO thyristor. An additional advantage with the IGCT, is that it can withstand higher rates of voltage rise (dv/dt), resulting in that no snubber is needed. Furthermore, the gate turn off current is greater than the anode current in an IGCT. This results in a complete elimination of minority carrier injection from the lower PN junction and faster turn off times, allowing the IGCT to operate at higher frequency. The disadvantage of the IGCT, is when it operates at high frequencies there are high switching-losses. The PCS 6000 converters are based upon the IGCT PEBB (Power Electronic Building Block) see *Figure D10*.

Figure D9 Single IGCT block unit.

Figure D10 IGCT PEBB – Power Electronic Building Block power stack (water cooled).

Today ABB PCS 6000 use a concept with containerized solutions, making the frequency converter, PCS 6000, independent from ambient conditions. There are two containers for the installation, see *Figure D12*. The size of the smaller container is 3 x 12.2 m and the size of the bigger container is 3 x 15 m. One container is equipped with the frequency converter and cooling equipment, see *Figure D11*, and the second container equipped with harmonic filters and protection relays for over current and over temperature. For implementation of the ABB PCS 6000 in the shore-side power supply configuration, all these equipments will be installed inside the main substation building.

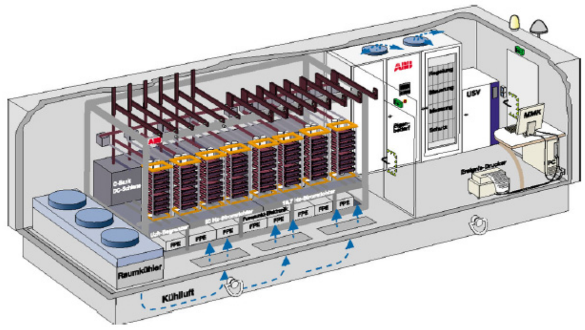


Figure D11 Container equipped with the frequency converter and cooling equipment

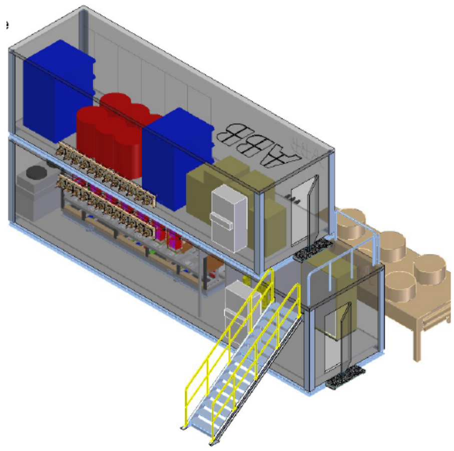


Figure D12 ABB PCS 6000 container solution

D2.2.3 Double busbar switchgear

To enable connection of simultaneously 50 Hz as well as 60 Hz vessels at the different berths, a switchgear with double busbars is needed to distribute the different frequencies to the different berths, depending on the power demand of the vessel at that time. UniGear double busbar system is one of the possible designs of UniGear type ZS1 switchgear, and the choice has fallen on this switchgear. It is three-phase, metal-enclosed compartmented, air-insulated switchgear type-tested and suitable for indoor applications up to 24 kV. The units are designed as withdrawable modules and are fitted with a double busbar system with two disconnectors. The line disconnector consists of a moveable copper tube included inside an epoxy insulator. Electrical contact is guaranteed by two connection springs. Additional protective insulating caps are mounted on both sides of the insulator, thus providing the device with a high level of reliability. Disconnectors are equipped with interlocking to prevent their incorrect operation. Operation of disconnector is only possible when circuit-breaker is in the open position. The line disconnectors can be manuvered by hand, but is also armed with motor manoeuvring, which allows full remote manoeuvring of the facility. Electrical data for the UniGear ZS1 double busbar system is shown in *Table D5*.

Table D5 Electrical data for UniGear ZS1 Double busbar system

Rated voltage	**kV**	**12**	**17.5**	**24**
Rated insulation voltage	kV	12	17.5	24
Test voltage (50-60 Hz)	kV 1 min	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Rated frequency	Hz	50/60	50/60	50/60
Rated short-time withstand current	kA 3 s	…31.5	…31.5	…25
Peak current	kA	…80	…80	…63
Internal arc withstand current	kA 1 s	…31.5	…31.5	…25
Main busbar rated current	A	4000	4000	2500

Each panel is made up of four independent power compartments, *see Figure D13*: busbar 1 (01), busbar 2 (02), apparatus (03), and feeder (04). There is a metallic segregation between all the compartments. In its front/top part the panel is fitted with a compartment to take the auxiliary instruments (05).

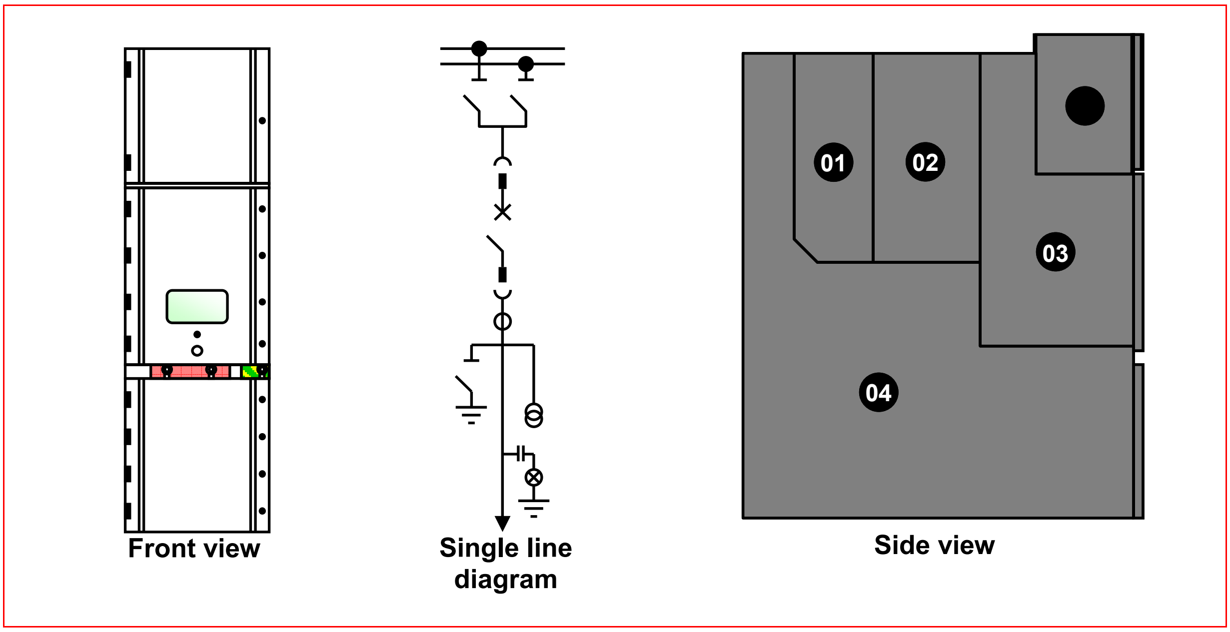


Figure D13 UniGear ZS1 Double busbar system.
Compartments: **01** Busbar 1, **02** Busbar 2, **03** Apparatus, **04** Feeder, **05** Auxiliary

Each unit is armed with earth switches and voltage and current transformers to allow power measurement for each separate berth and, as input to the protection relays to be able to trip the breaker if a fault occurs.

Each switchgear unit is also equipped with standard circuit-breakers. The choice of circuit-breaker to this application is ABB HD4 SF_6 circuit-breaker, see *Figure D14* and *Figure D15*. The SF_6 is used as insulation medium and to extinguish electric arc. SF_6 gas is an alternative to air as an interrupting medium. SF_6 is a colourless nontoxic gas, with good thermal conductivity and density approximately five times that of air. SF_6 is chemically inert up to temperature of 150 ˚C and will not react with metals, plastics, and other materials commonly used in the construction of high voltage circuit breakers. The breaking of current inside the SF_6 gas takes place without arc chopping and without generation of overvoltages. The dielectric property restoration that follows the interruption is extremely rapid, resulting in that there is no restrike after breaking.

The circuit-breaker is also fitted with a mechanically stored energy type operating mechanism. The tripping mechanism is free and allows for that reason opening and closing operation independent of the operator. The operating mechanism spring system can be equipped with a geared motor in order to allow full remote manoeuvring possibilities. Electrical data for the HD4 withdrawable circuit-breaker which is used in the medium voltage region is shown in *Table D6*.

Table D6 Electrical data for HD4 withdrawable circuit breaker

Rated voltage	**kV**	**12**	**17.5**	**24**
Rated insulation voltage	kV	12	17.5	24
Rated frequency	Hz	50/60	50/60	50/60
Withstand voltage	kV 1 min	28	38	50
Impulse withstand voltage	kV	75	95	125
Rated normal current	A	630…3150	630…2500	630…2500
Rated short-circuit breaking current (symm.)	kA	16…50	16…50	16…40
Rated short circuit making current	kA	40…125	40…125	40…100
Rated duration of short-circuit	s	3	3	3

Figure D14 HD4 withdrawable circuit breaker.

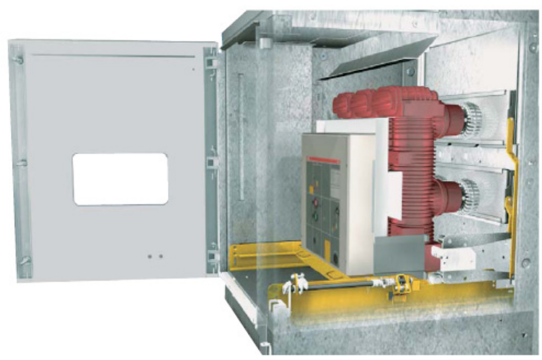


Figure D15 HD4 withdrawable circuit breaker inside the compartment.

In conclusion, the switchgear compartments will be armed and configured for incoming and outgoing supply, in the manner shown in the single line diagram which is illustrated in *Figure D16.* The two switchgear compartments to the left represent the incoming supply – the compartment far left supplies Busbar 1 with 50 Hz and the next compartment in the order supplies Busbar 2 with 60 Hz from the frequency converter. Thereafter comes the outgoing compartments that supply every single shore-side transformer station, that are localized at each quay which are going to have possibilities for shore-side connection. The switchgear compartments for incoming and outgoing supplies are constructed in the same way with two disconnectors, one for each bus, one earth-switch and one HD4 circuit-breaker. The disconnectors in the supplying compartments are interlocked to only use the disconnector that belongs to the bus it is supposed to feed. A possible manual change of the buses is possible in this configuration and might come in use if a fault would occur on one of the buses.

The manoeuvring procedure for disconnectors and breakers is explained in S*ection D2.7.*

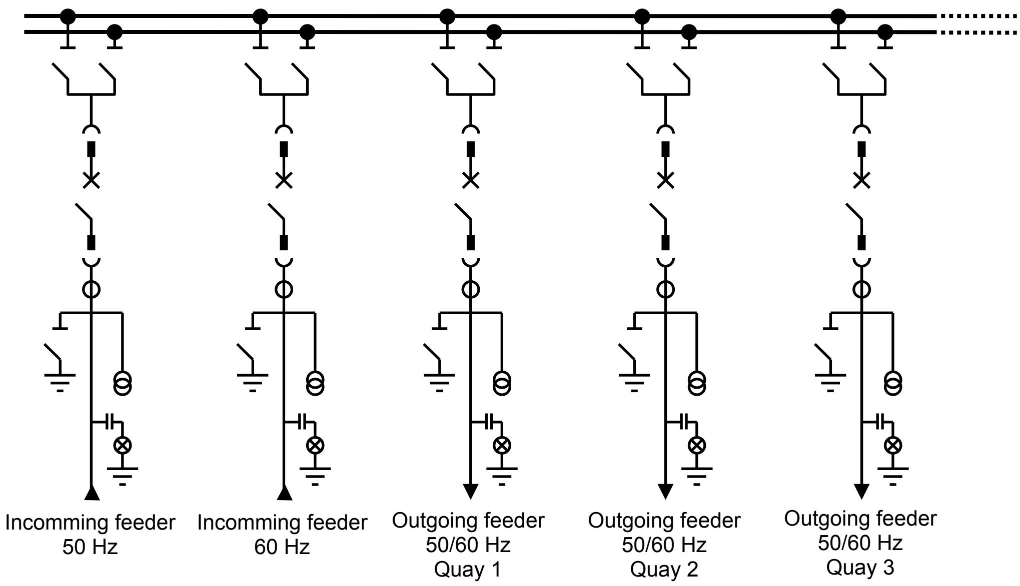


Figure D16 Single line diagram for switchgear configuration of incoming and outgoing feeders.

D2.3 Cable arrangement

The cable arrangement (Position 2) from the main substation building out to all shore-side transformer stations will be underground cables preferably on 24 kV in order to reduce the current in the conductors as much as possible which simultaneously gives lower transfer losses. Example of the cable arrangement can be seen in *Figure D17*.

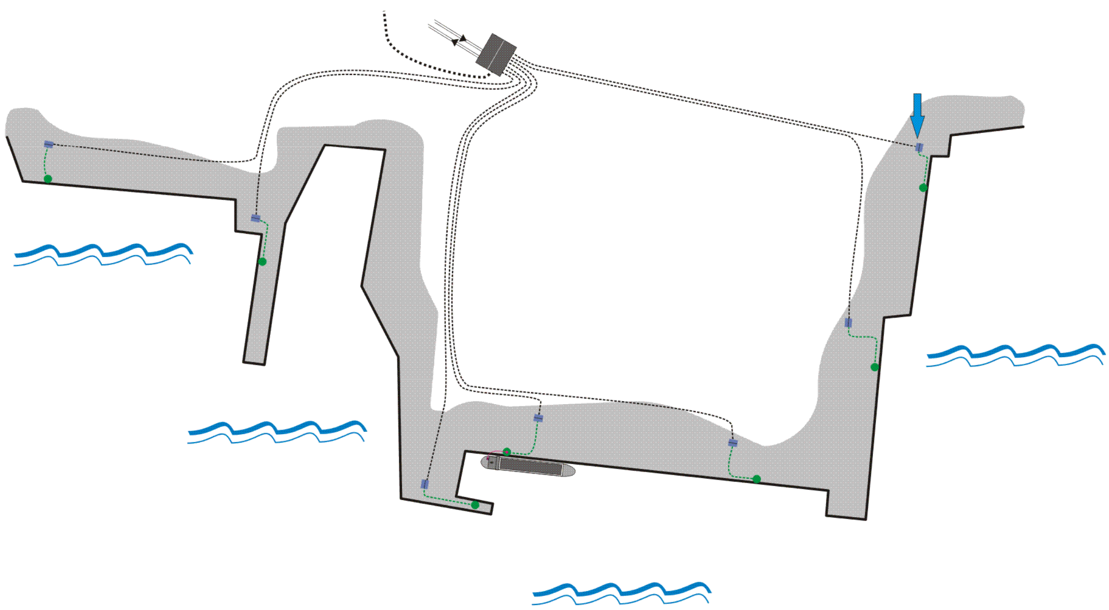


Figure D17 Possible cable arrangement in a typical harbour.

D2.4 Shore-side transformer station

The shore-side transformer station and connection arrangement (Position 3) is illustrated in *Figure D18.* Every single berth that will be shore-side power supplied will be equipped with a shore-side transformer station as close to the berth as possible. The transformer station contains the transformer, which is the last link between the electric grid at shore and the electric system on the vessel. The transformer station also includes a smaller switchgear with a secondary circuit-breaker together with disconnection and earth-switch equipment of the outgoing cables to satisfy the safety demands that are expected in the upcoming standard. The last part of the shore-side power supply is the connection point where the vessels actual connection is made. This is the operator's point of view the only point where the user comes in contact with. All other equipment are designed so that these can be manuvered and monitored with an overall control system.

This section describes the main components for the shore-side transformer station and connection arrangement.

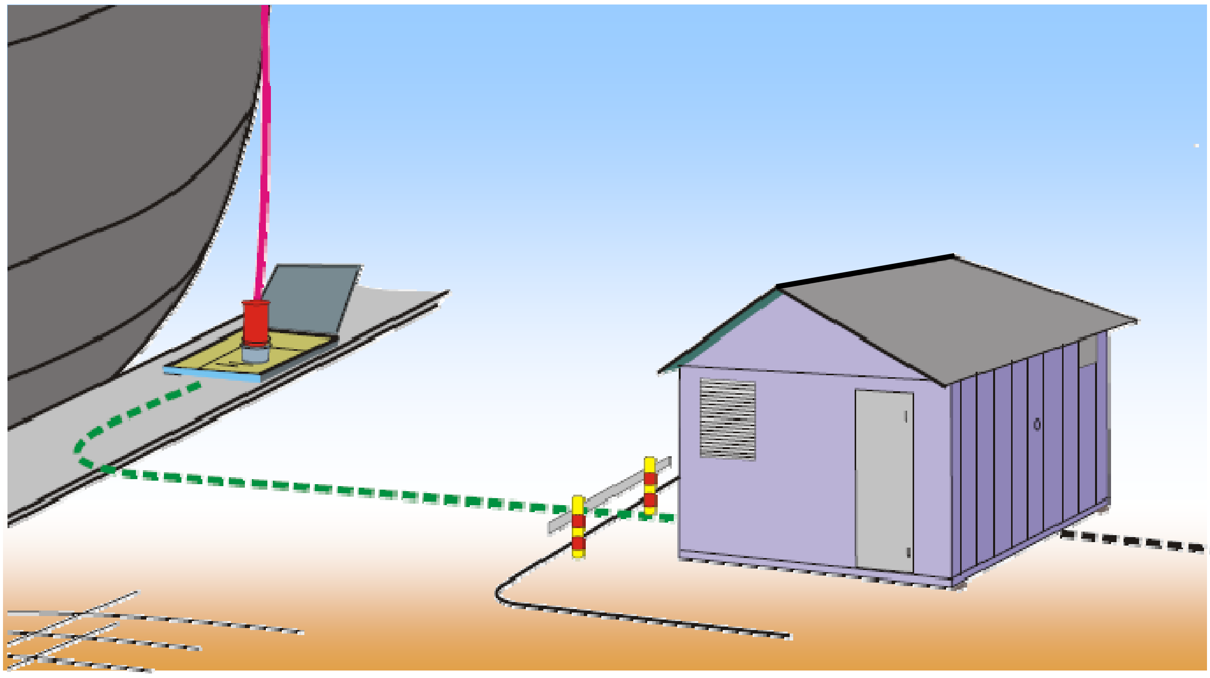


Figure D18 Shore-side transformer station and connection arrangement.

D2.4.2 The transformer

The reason for having a transformer at each berth has been mentioned several times earlier in this report, but it is worth repeating. With the help of a transformer as the last link between the electric grid at shore and the electric system on the vessel, a galvanic separation between the grids is achieved. There are also possibilities to reduce the fault current, and a potential fault onboard a vessel will not have the same effect on a nearby connected vessel and therefore prevents a potential propagation of the fault, which can be fatal. Transformers at berth facilities even a higher voltage in the distribution grid to the berths, and thus reducing cable losses.

This transformer is also a requirement according to the standard described in *Chapter C4*. According to the standard, cruiser vessels are expected to be connected with either 6.6 kV or 11 kV. This is achieved by a changeover on the transformer.

Since the vessels are going to be connected with either 50 Hz or 60 Hz, the same transformer is coupled to 50 Hz at one moment, and in the other moment to 60 Hz. If the frequency applied to a transformer is increased, the inductive reactance of the windings is increased, causing a greater voltage drop across the windings and a lower voltage drop across the load. However, an increase in the frequency applied to a transformer should not damage it. But, if the frequency applied to the transformer is decreased, the reactance of the windings is decreased and the current through the transformer winding is increased. If the decrease in frequency is enough, the resulting increase in current will damage the transformer. For this reason a transformer may be used at frequencies above its normal operating frequency, but not below that frequency. The conclusion is therefore that the transformer should be designed for the 50 Hz case so it doesn’t get damaged when connection of 60 Hz occurs.

The rating of the transformer has to be adjusted in that case when it is connected to 60 Hz. The scaling is done according to *Table D7.*

Table D7 Transformer rating scaling for a 50 Hz transformer used at 60 Hz.

Rating	Scaling
Power	~ 97 %
No-load losses	80-85 %
Load losses	~ 105 %
Impedance	115-120 %

The transformer in question will be of the Dyn-type with high resistance grounding. There are many reasons for this. High-resistance grounding solves the problem of transient over-voltages, thereby reducing equipment damage. Overvoltages caused by intermittent arcing faults, can be held to phase-to-phase voltage by grounding the system neutral through a resistance which limits the ground current to a value equal to or greater than the capacitive charging current of the system. Thus the fault current can be limited, in order to prevent equipment damage. So a resistance limits the fault current during a single-phase fault, but causes overvoltages in the non-faulted phases. In addition, limiting fault currents to predetermined maximum values permits the designer to selectively coordinate the operation of protective devices, which minimizes system disruption and allows for quick location of the fault. The resistance is chosen so that the single line to ground fault will be limited to 10-15 A, see *Figure D19,* allowing an over-current relay to detect the fault and trip the breakers.

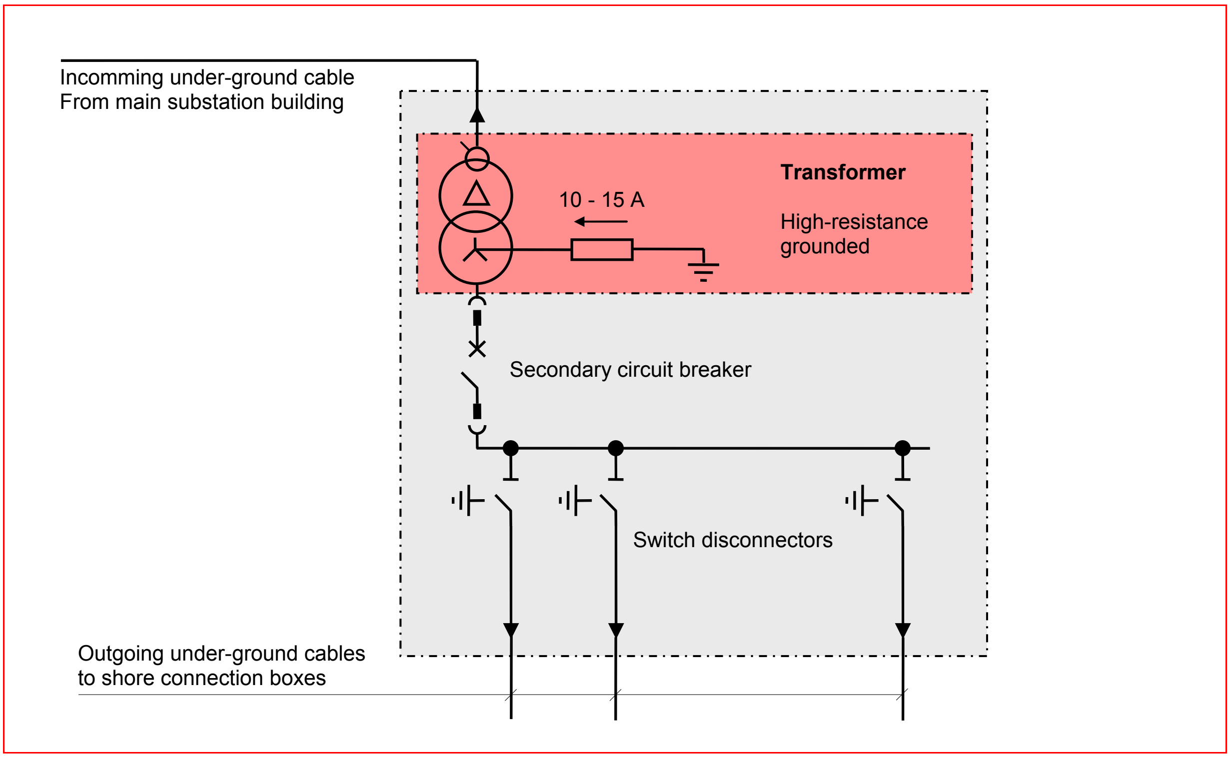


Figure D19 Single line diagram for shore side transformer station. High-resistance grounded transformer. The resistance is chosen so that the single line to ground fault will be limited to 10-15 A

The transformer in question has been chosen to Resibloc dry-type transformer, mainly due to its size properties. The space taken by a transformer on the berth is an important factor, due to the limited amount of space available at the berth. The Resibloc transformer can be minimized in size if it is equipped with air cooling fans. These fans increase the rated power output of the transformer, by up to 25 % and have low noise levels, resulting in that the transformer can be minimized in size. Additionally, the transformer can be equipped with water cooling systems, increasing the rated power output further more.

The Resibloc transformers are also characterised as environment and personnel safe transformers due to its non-explosive and extremely fire resistant properties, since less than 5% of the materials used can burn if the transformer is drawn into a normal fire. Additionally, the transformer is manufactured to withstand exposure to extreme conditions, such as chemicals and moisture. Moreover, the Resibloc transformers require minimal maintenance, and are capable of withstanding heavy load cycles.

The core design is an important factor the quality of any transformer. The core materials in the Resibloc transformers are geometrically arranged giving the best space factor and highest dimensional accuracy, resulting in low core losses and noise values.

Rating data for the shore-side transformer suitable for this application can be found in *Table D8*. Illustration of Resibloc 3-phase Dry-Type transformer with water cooling configuration is shown in *Figure D20*.

Table D8 Rating data for Resibloc Dry Type transformers suitable for this application

Rated power (with cooling)	kVA	4000	7500	12 500
Primary voltage	V	24 000	24 000	24 000
Secondary voltage	V	6 600	6 600	11 000
Primary tappings		+/-2x2,5 %	+/-2x2,5 %	+/-2x2,5 %
Primary insulation level	kV	U_m 24 / U_{AC} 50 / U_{LI} 125	U_m 24 / U_{AC} 50 / U_{LI} 125	U_m 24 / U_{AC} 50 / U_{LI} 125
Secondary insulation level	kV	U_m 7.2 / U_{AC} 20 / U_{LI} 40	U_m 7.2 / U_{AC} 20 / U_{LI} 40	U_m 12 / U_{AC} 28 / U_{LI} 75
Frecuency	Hz	50	50	50
Vector group		Dyn11	Dyn11	Dyn11
Impedance	%	7	8	8
No load losses	W	6 500	13 000	50 000
Load losses at 75 ^{o}C	W	24 000	18 000	72 000
Cooloig		AN/AF	AF/WF	AF/WF
Dimensions L x W x H	mm	2500 x 1500 x 2360	4270 x 2580 x 2800	4630x2680x3100

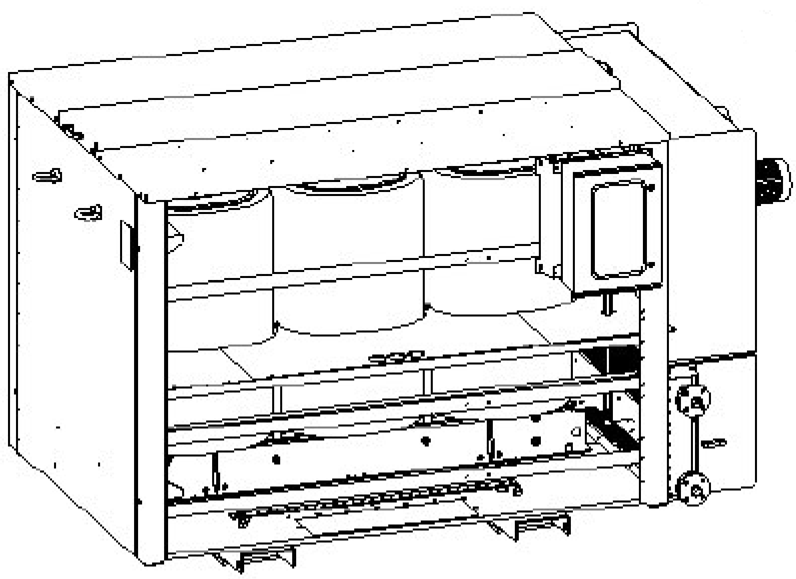


Figure D20 Resibloc 3-phase Dry-Type transformer Standard IEC 600076-11 Dyn11. Water cooling configuration.

D2.4.3 Shore-side switchgear

The shore-side transformer station will contain a smaller switchgear on the secondary side of the transformer. The switchgear is supplied with a compartment with a withdrawable circuit-breaker of the type HD4, which is described in *Section D2.2.3*. The switchgear in this case has been chosen to Uniswitch, which is somewhat smaller switchgear than UniGear ZS1, which is used in the main substation building. Outgoing cables are fed through switch disconnector departments, consisting of one 3-position switch disconnector that can be in one of three positions: closed, open or earthed, to prevent incorrect operation. Access to the cable compartment is possible in earthed position. Inspection of cable connections and fault indicators, when used, is easily carried out through the front-door window. Both the feeding circuit-breaker and all disconnectors to outgoing cables will be equipped with motor operation devices, allowing full remote controlling. Uniswitch switchgear front view and single line diagram for withdrawable circuit breaker compartment and switch disconnector compartment is illustrated in *Figure D21*. Rating date for the Uniswitch switchgear is presented in *Table D9.*

The reason why each one of the outgoing cables to the shore-side connection boxes are connected via switch disconnector departments is further explained in the end of *Section 2.5.2.*

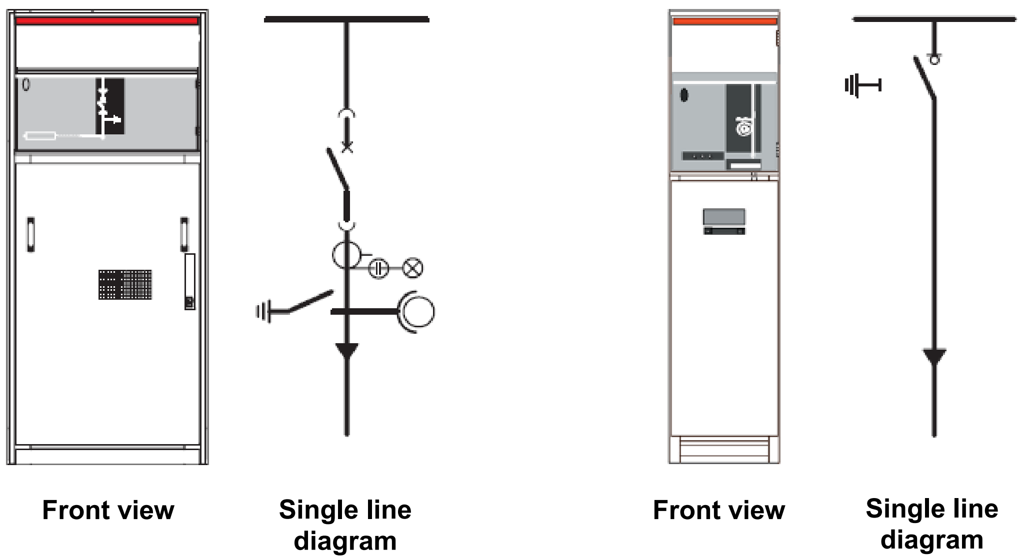


Figure D21 Uniswitch switchgear front view and single line diagram for withdrawable circuit breaker compartment and switch disconnector compartment.

Table D9 Electrical data for Uniswitch switchgear

		Withdrawable circuit breaker	Switch disconnector
Rated voltage	kV	12	12
Rated current, busbars	A	1250	800
Rated short time withstand current	kA	25	25
Max rated duration of short circuit	s	1	1

D2.5 Shore-side connection arrangement

The last part of the shore-side power supply infrastructure is the connection point where the vessels actual connection is made (Position 4). This is the operator's point of view the only point where the user comes in contact with. In *Chapter C3* – Docking patterns in port - the different docking patterns and loading and unloading procedures for the different vessels were explained. It was pointed that the shore-side connection should limit the accessibility as little as possible, for example, for cranes and industry trucks that operate in connection with the vessels. At Ro/Ro and cruiser terminals there are no problems with accessibility for cranes, since there is no crane activity here. On the other hand, the berths for cruiser vessels are mostly localized as centrally as possible in urban areas, and provide mostly shore-side room for both shopping and restaurants. Having a big cable gantry at each berth makes it difficult to fit in such environment, which was made in several previous installations mentioned in *Chapter B2*. Not at least, such an installation takes big space in claim, even when no vessels are connected. Having a connection point that is as minimal as possible is therefore desirable in all cases, and not only where cranes might come in the way. A uniform solution, where a connection box is hidden below ground, has been chosen. This solution will fit into a container terminal, between rail and quay, as well as at the berth for the biggest cruiser vessels in the urban areas, see *Figure D22*.

This section describes the shore-side connection arrangement.

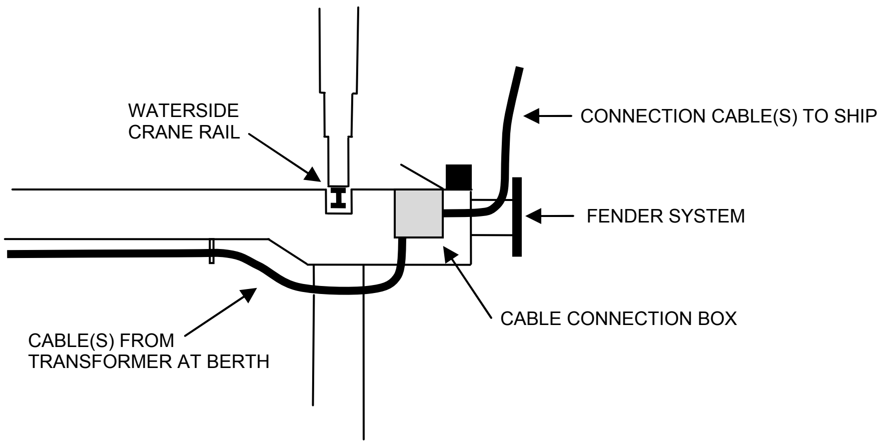


Figure D22 Shore-side connection arrangement fitted into a container terminal between rail and quay.

D2.5.2 Connection box

Cavotec has been delivering connectors for shore-side power supply in nearly two decades and its design has in principle become a standard in these contexts and is expected to be included in the upcoming standard mentioned in *Chapter C4*. The connection box mentioned above is one of the products that Cavotec supplies, and is used among others in Port of Los Angeles. As seen in *Figure D22*, the connection box claims space between the waterside crane rail and the berth-side, a distance which is less than one meter. With this solution it is possible to place the connection boxes at regular interval distances along the berth, to allow connection without too long connection cables, which might otherwise be the case since the connection point onboard the vessels might vary. The distance between the connection boxes, in Port of Long Beach's own standard for the harbour, has been defined to approximately 70 meters, which would signify three or four connection boxes per quay [46]. The stationing of the vessels in the Ro/Ro terminal, mentioned in *Chapter C3*, is often at the same position of the berth and therefore there is no need of the same amount of connection point next to the berth, and can consequently be limited to one or two connection boxes.

The connection boxes are available in two designs, one for connection of one connection cable from the vessel, and one for connection of double connection cables, see *Figure D23* and *Figure D24*.

Figure D23 Connection box for one connection cable

Figure D24 Connection box for double connection cables

The connection box does not only constitute to the vessels power connector cables, but also contains the connection point for communication between the vessel and shore-side power supply infrastructure. A fibre-optic connector is integrated in the shore connection box. Communication cables shall generally be fibre-optic according to the upcoming standard. The fibre-optic cable will be embedded inside the power cable, which is supplied to the vessel. The fibre-optic plug is external to the power cable plug, such that a replaceable fibre-optic jumper cable can be employed between the engaged power plug and the fibre-optic cable receptacle in the shore-side connection box.

A detailed drawing over Cavotec's shore-side connection box is illustrated in *Figure D25*. The rating data for the connection box is found in *Table D10*.

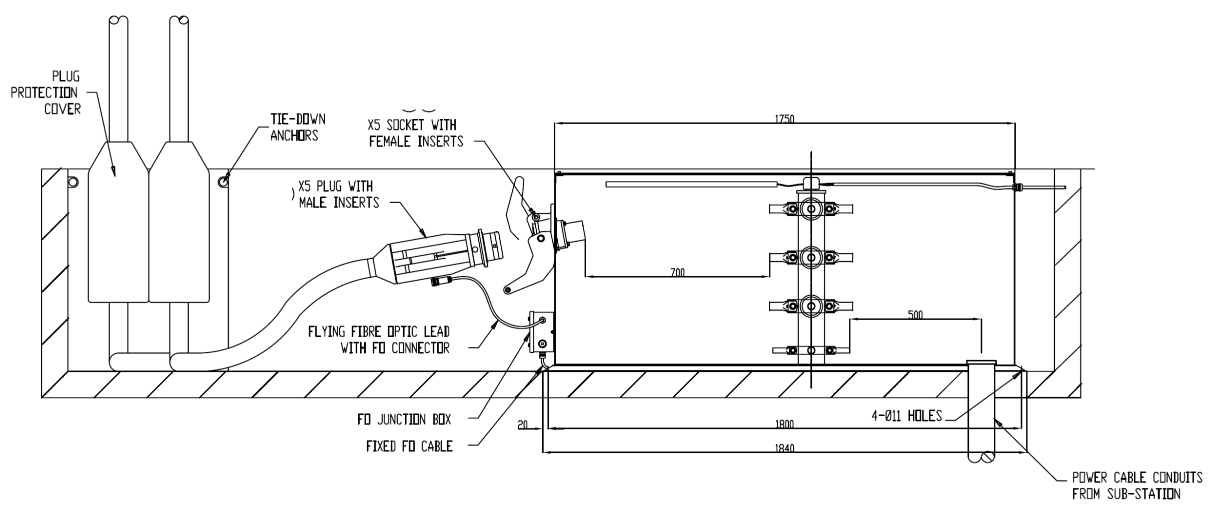


Figure D25 Cavotec shore-side connection box.

Table D10 Electrical data for Cavotec shore-power connection box

Rated voltage	kV	7.2
Rated breakdown insulation level (BIL)	kV	60
Test voltage	kV 1 min	20
Peak current (value refer to the peak current for a single socket)	kA	34.7
Rated short-time withstand current (value refer to the short-time withstand current for a single socket)	kA 1 s	16

The connection box is electrically interlocked by a pilot contact embedded in the socket and plug as illustrated in *Figure D26*. The pilot-pins are loop connected and the female pilot contacts are connected in series with the operating mechanism of the secondary circuit-breaker to ensure that the circuit-breaker trips if someone attempts to remove the cable when it is in use. For safety reasons, the pilots are last to be connected and first to be disconnected. This ensures that no disconnection under load can take place.

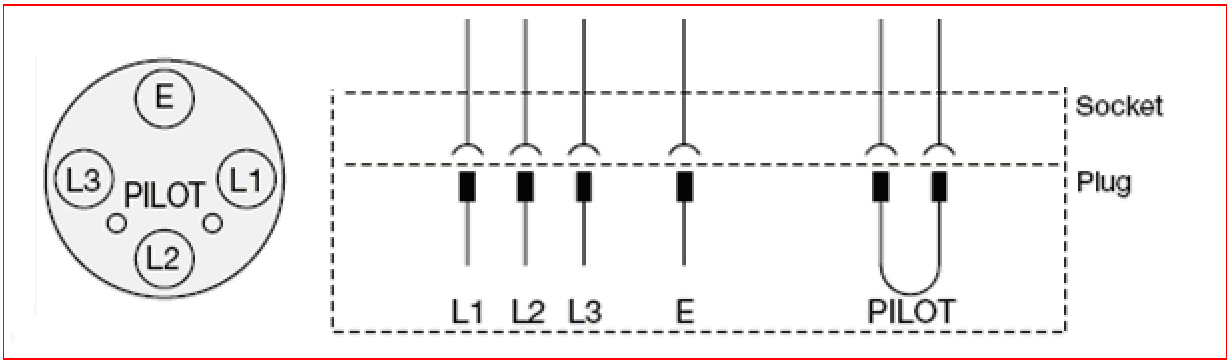


Figure D26 Pilot contact embedded in the socket and plug. The pilot-pins are loop connected and the female pilot contacts are connected in series with the operating mechanism of the secondary circuit-breaker.

Each socket in the shore-side connection box is supplied separately with a cable to the shore-side transformer station switchgear, where the cable is connected to a switch disconnector compartment, presented in *Section D2.4.3*. *Figure D27* illustrates a single line diagram for the connection arrangement of the shore-side connection box, for either single or parallel cable arrangement. All output sockets that aren't connected to any vessel will be coupled to earth. This means that in those cases where there are several output sockets at the same berth, there is a demand that each one of the output sockets are coupled via separate disconnector compartments, to allow those outlets that aren't connected to the vessels to be disconnected and coupled to earth before the main circuit-breaker is switched on. The control system will take care of this to secure that no outlets that aren't connected, are able to become energized.

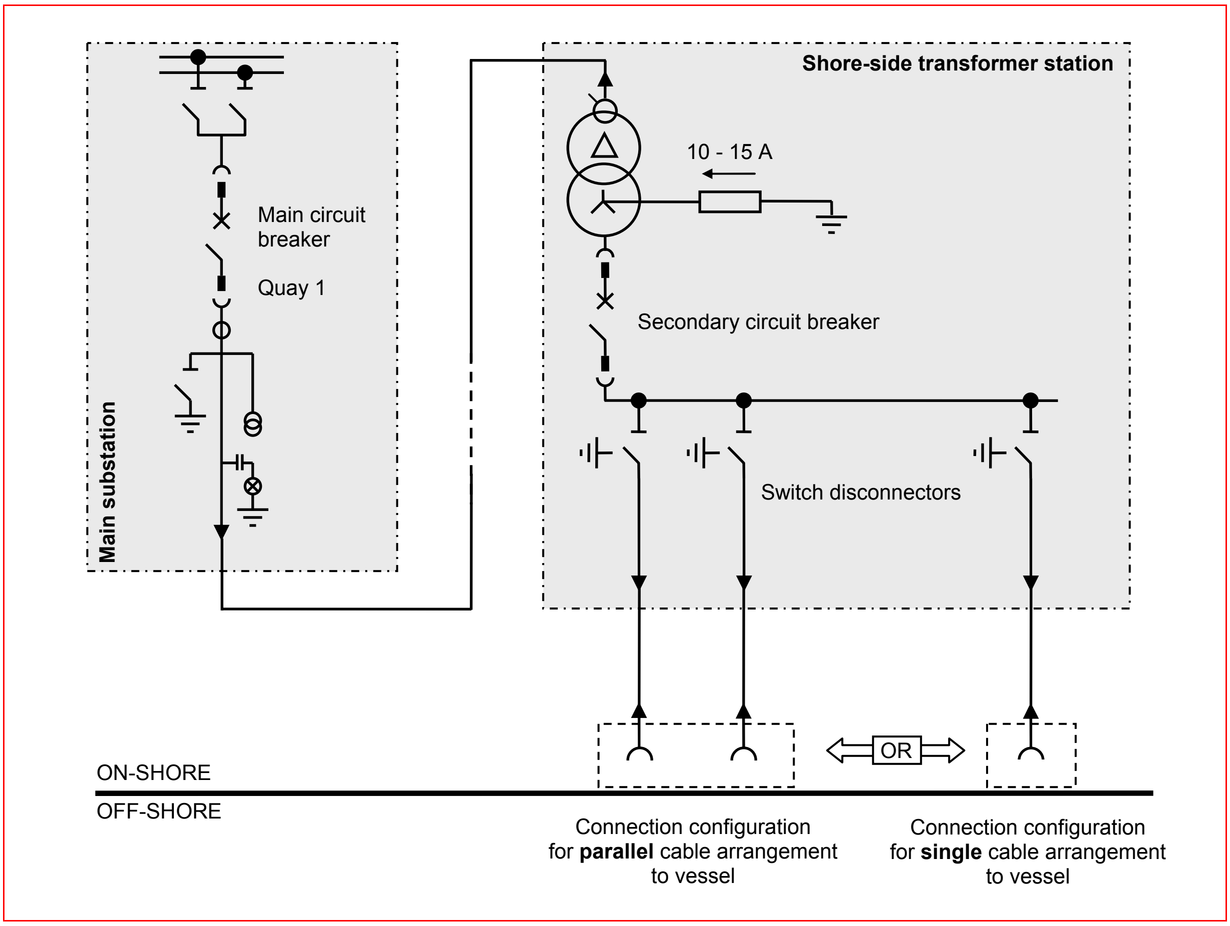


Figure D27 Single line diagram for shore side transformer station and example of configuration for either parallel or single cable arrangement to vessel at one berth. All output sockets that are not connected to any vessel is coupled to earth. This means that in those cases where there are several output sockets at the same berth, there is a demand that each one of the output sockets are coupled via a separate earth switch to allow those outlets that are not connected to the vessels to be disconnected and coupled to earth before the main circuit breaker is switched on.

D2.5.3 Shore-side connection cable

The connection cable shall in great extend as possible be provided by each vessel and beneficially be arranged with the help of a cable reel system, like the ones in *Figure B32* and *Figure B33*, to be hoisted with ease down to the shore-side connection box. The rated data for the connection cable that will meet the demands in the upcoming standard is shown in *Table D11*. A cross-section of the cable is illustrated in *Figure D28*. The cable includes, as mentioned before, an opto-cable to utilize the communication between the vessel and the shore-side power supply facility.

The cables available for shore-side power connection have a maximum continuous current on roughly 350 A, which makes that 4 MVA can be transferred per cable at 6.6 kV respectively 6.7 MVA at 11 kV. Two parallel connected cables give a maximum transmission power of 8 MVA respectively 13.4 MVA.

For those vessels that aren't able provide their own cable to the connection box, Cavotec has developed a mobile cable management system, see *Figure D29*. The cable management system is located on the berth, and due its mobile properties, the cable management system can easily be moved between berths in order to bring shore-side power supply to the moored vessels without restrict other port operations.

Table D11 Electrical data for Cavotec connection cable

Rated voltage $U_0/U/U_M$	kV	6/10(12)
Test voltage	kV	17
Rated current I_r (for continious operation at 45 °C ambient temperature (85 °C wire temperature) and reeled in 1 layer)	A	369
Rated short-time withstand current	kA 1 s	23.8
Phase cores	mm²	185
Earth cores	mm²	95
Pilot cores	mm²	4 x 2.5
Optical vable		6FO (62.5/125)
Operating electrical resistance	Ω/km	0.134
Reactance	Ω/km	0.081

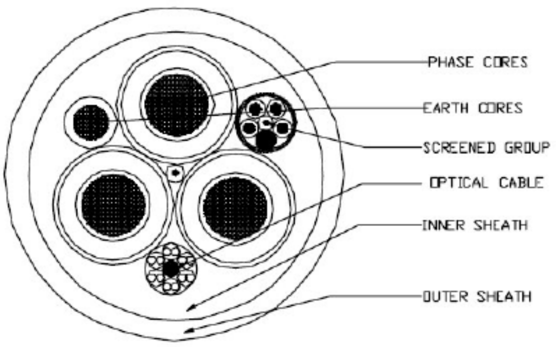


Figure D28 A cross-section overview of the cable

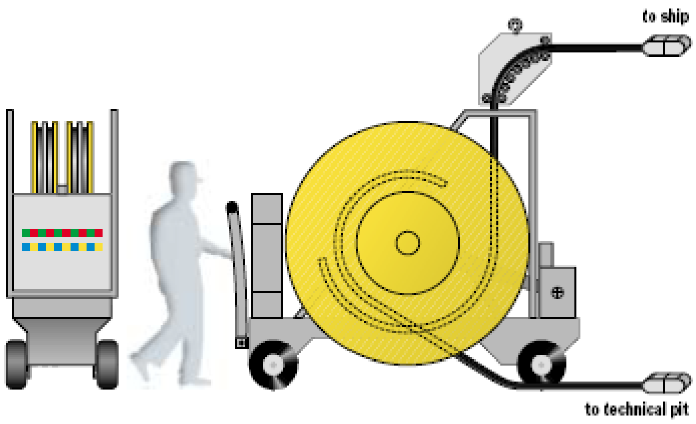


Figure D29 The mobile cable management system developed by Cavotec, features a new and innovative unit called the Cavotec Caddy.

D2.6 Vessel connection requirements

The vessel will be utilized with equipment to allow connection to the electric grid on shore (Position 5). As mentioned in the previous section, the connection cable shall be supplied by the vessel in great extend as possible. Onboard most of the vessels a transformer will be required, which was showed in the technical survey that was summarized in *Chapter C2.6*. This is something which is needed in order to allow a fast and effective connection, which is obtained with high-voltage arrangement. The report will not consider how a reconstruction shall be made onboard the vessel in order to adapt to the shore-side power supply, only concentrating on-shore. The equipment that the vessel is going to need except a connection cable and transformer to adapt the voltage from on-shore to the voltage onboard, is an upgrade of the existing synchronisation equipment and a circuit-breaker that is set when the vessel is synchronized and ready to be coordinated to the shore-side power supply. More information how the connection and synchronization procedure will be carried out is described in the section below.

D2.7 Shore-side power supply control and connection procedure

As presented in the previous sections, all circuit-breakers and disconnectors in the connection equipment that affect every single berth, have been equipped with remote control possibility to allow an overall control system that can be used and as much as possible be integrated in both the harbours and the vessels existing control system. This report doesn't treat questions such as communication protocol, and the reason for this is that there were no possibilities to obtain information regarding what protocol is going to be valid in the upcoming standard, and is therefore left for future work, until this information is available. The supervise control system for this system will be a SCADA system. SCADA stands for Supervisory Control And Data Acquisition. The main purpose of the SCADA system is to supervise, control, optimize and handle power generating – and power distributing systems. The SCADA system makes it possible to collect, store and analyse data from a great amount of measuring points in the grid, perform network modelling, simulate the use of electric power, determine fault and prevent blackouts.

The SCADA control system will serve as the users interface against the facility and the only manual intervention which shall be necessary for a normal connection of the vessel is the actual connection of the cable. All interlocking of circuit-breakers is taken care of by the control system and no manual lock or breaking will be necessary.

A flowchart over the SCADA control system connection procedure for an incoming vessel is shown in *Figure D30*. *Figure D31* shows the disconnection procedure of a vessel.

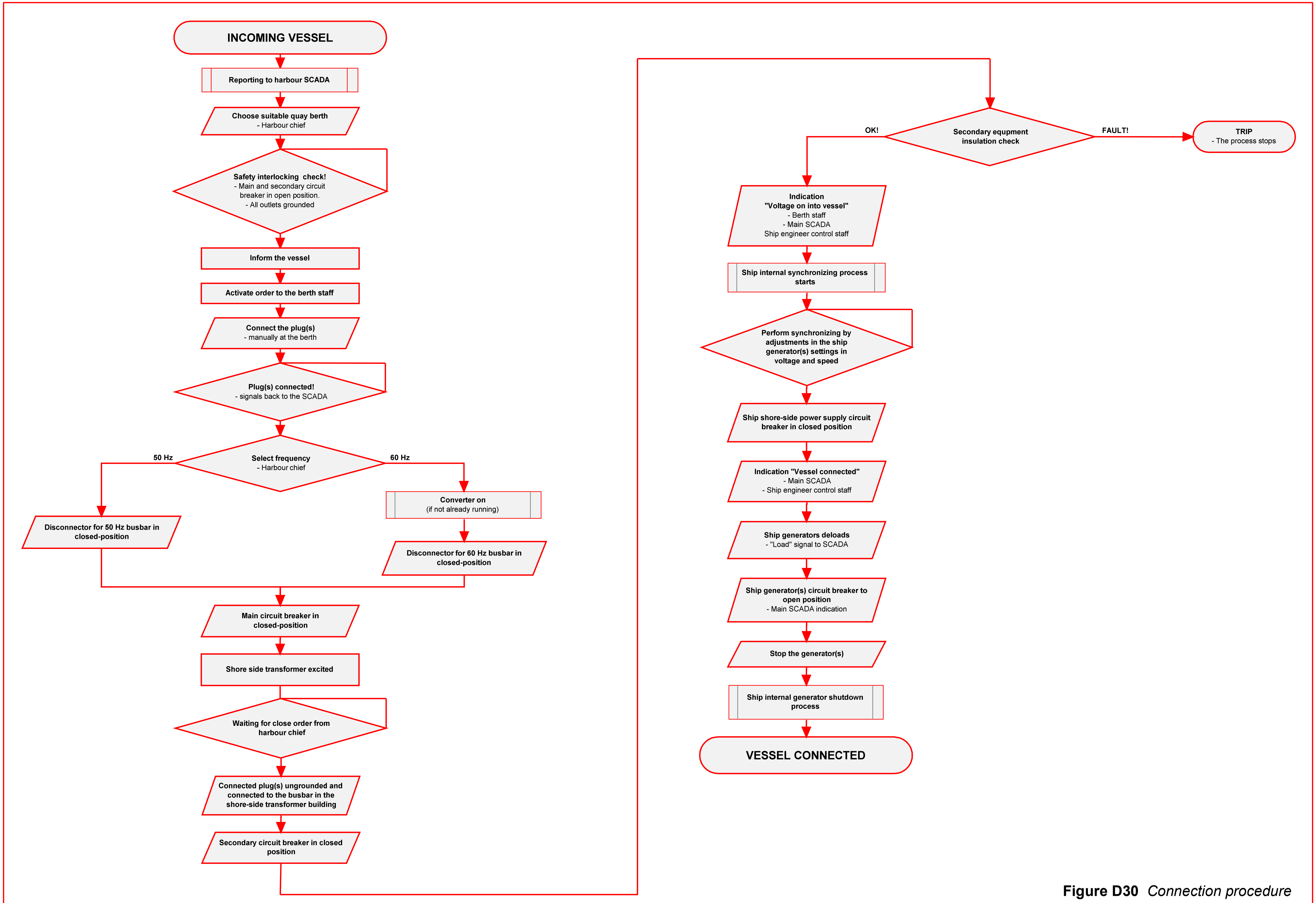


Figure D30 *Connection procedure*

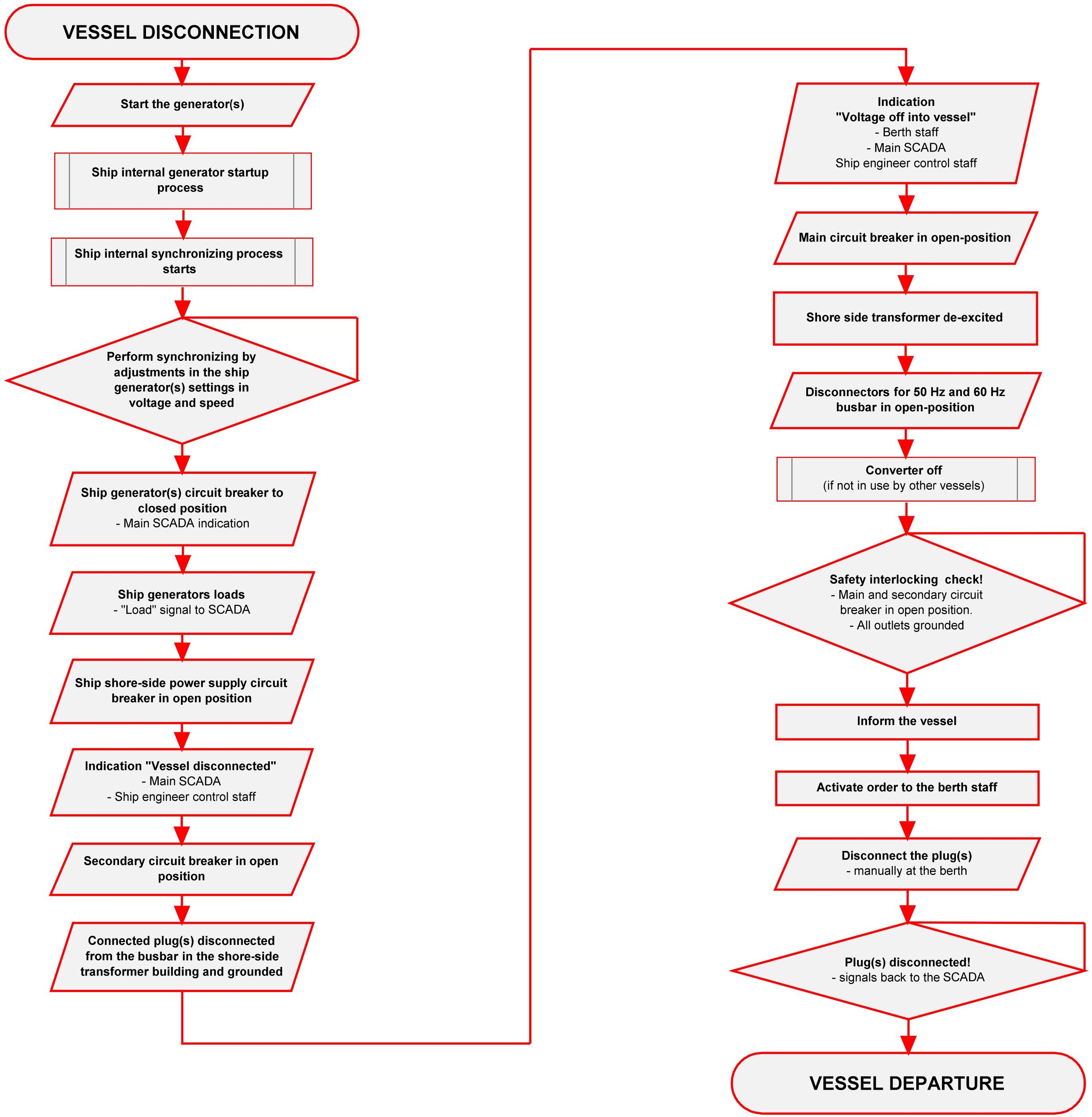


Figure D31 *Disconnection procedure*

D3 Design implementation in a typical harbour

This chapter will use the knowledge from the technical survey as basis for the implementation of the recommended configuration, which was presented in the previous chapter, in a typical harbour. The implementation will also be the basis for cost estimation and for upcoming calculations and simulations. A container terminal with five berths, which are all to be supplied with shore-side power supply, is chosen. It should be noted that the terminal in question is fictive, so that no sensitive information is presented.

Implementation design criteria:

- Five berths, 300 m each, shall have possibilities to connect with shore-side power supply in accordance with the emerging standard (6.6 kV, 7.5 MVA).
- Each berth shall have three connection points, each separated 70 m apart from each other, to allow shore-side power supply to vessels with different lengths and docking patterns, without having to use unnecessarily long connection cables.
- Every connection point shall be equipped with two outlets to allow parallel connection cables to the vessel, which is required to transfer the large amount of power.
- Moreover, the connection will be carried out according to the recommended configuration presented in *Chapter D2*.

In the beginning of this chapter the main ratings of the shore-side power supply is presented in this implementation. Even drawings of the facility are illustrated and in the end of this chapter a cost estimation of the system is presented.

D3.1 Installation equipment ratings

Container vessel's power demand while at berth was previously presented in *Chapter C2*. A summary of the power demand and system frequency according to the result from *Chapter C2.6* is shown in *Table D12*. The peak power demand for 95% of the vessels was 4 000 kW and the dimensioning of the facility has been made to cover 95% of the vessels that were in the previous study. The vessels that are to be connected have a power factor of 0.8 to 0.85. With recognition of this, an apparent power of 4 000 / 0.8 = 5 000 kVA is obtained for each vessel. Five berths provides thus a total power demand of 5 x 5 000 kVA = 25 MVA. Of all container vessels that were enrolled in the study, 26 % of the vessels had a system frequency of 50 Hz, while 74 % of the vessels had a system frequency of 60 Hz onboard. One can therefore expect that four out of five berths that are to be supplied with shore-side power supply, are going to be connected to 60 Hz vessels and therefore should the frequency converter be designed for this.

Table D12 Summary of power demand and system frequency for container vessels according to the result from *Chapter C2.6*

	Peak power demand for 95 % of the vessels	System frequency	
		50 Hz	60 Hz
Container vessels (total)	4 000 kW	26 %	74 %

Four vessels connected simultaneously to the frequency converter makes that the frequency converter shall be dimensioned for 4 x 5000 kVA = 20 MVA. Two parallel frequency converters, each on 10 MVA, are therefore required. The step up and step down transformers are going to be dimensioned for 20 MVA in order to adapt the voltage for the frequency converters.

To dimension only one berth for 50 Hz distribution is not reasonable, not at least due to that most of the feeder vessels that traffic European ports have a system frequency of 50 Hz, and many of these vessels that call at the port simultaneously is likely. Therefore should the 50 Hz distribution be dimensioned to handle several 50 Hz vessels that call the port. The only component in the facility which constitutes to a restriction on how many vessels that is to be connected simultaneously to the 50 Hz grid, is the transformer in the main substation building that feeds the 50 Hz bus in the Unigear ZS1 switchgear from the national grid. The cost for dimensioning this transformer for several berths is relatively small and has therefore been chosen to 15 MVA in order to allow that three vessels have the possibility to be connected simultaneously.

The total installed power in the port is thus 15 MVA for 50 Hz distribution and 20 MVA for distribution of 60 Hz vessels.

The main substation building will be connected to the national grid through a 40 kV underground cable. The voltage level in the distribution grid to the shore-side power supply transformer station is set to 24 kV in order to reduce the cable losses and decrease the fault currents in the facility. A drawing of the shore-side power supply facility is shown in *Figure D32*. A single line drawing of the main substation building is presented in *Figure D33*. All five shore-side transformer stations are equally equipped and a single line drawing for this facility is illustrated in *Figure D34.*

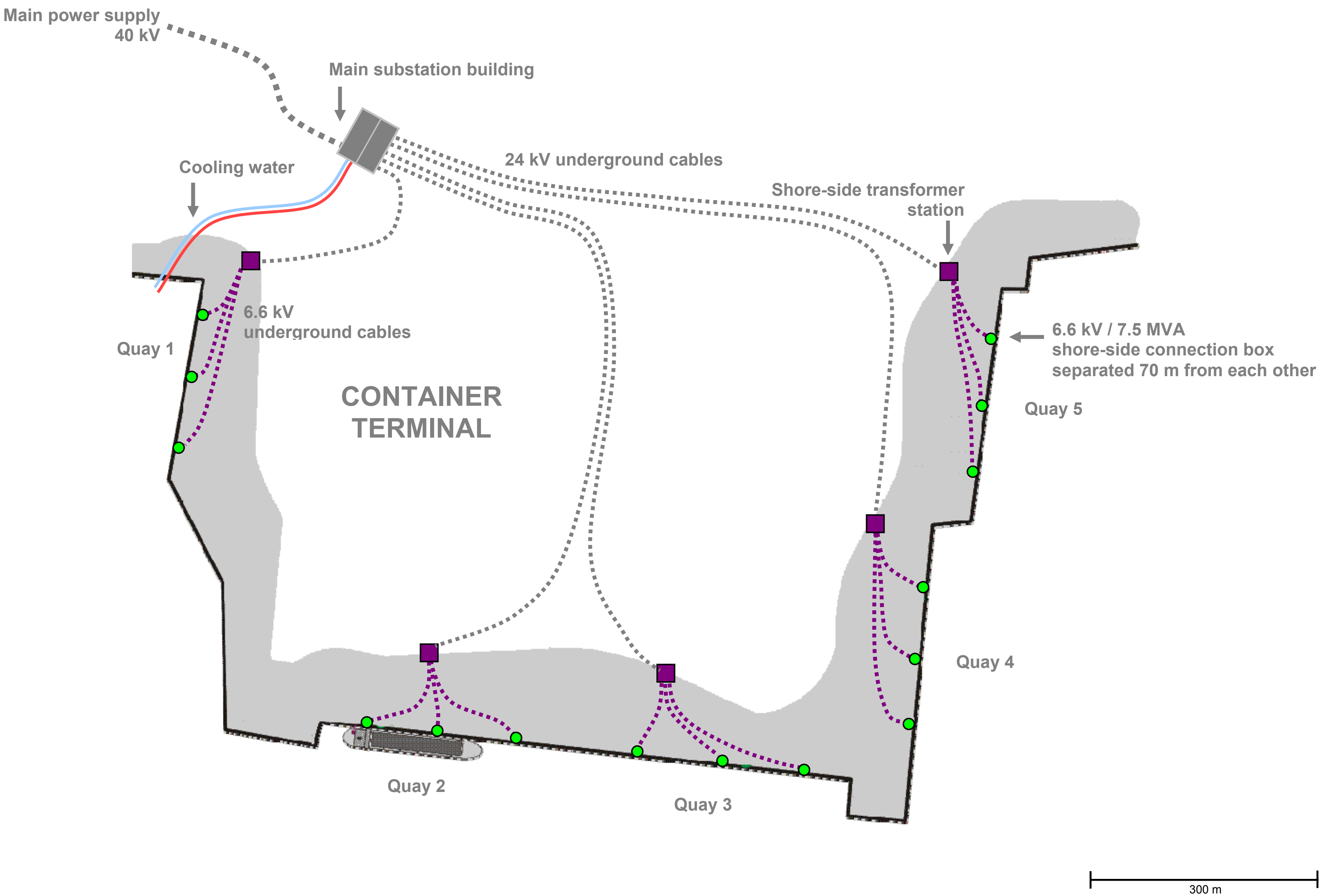
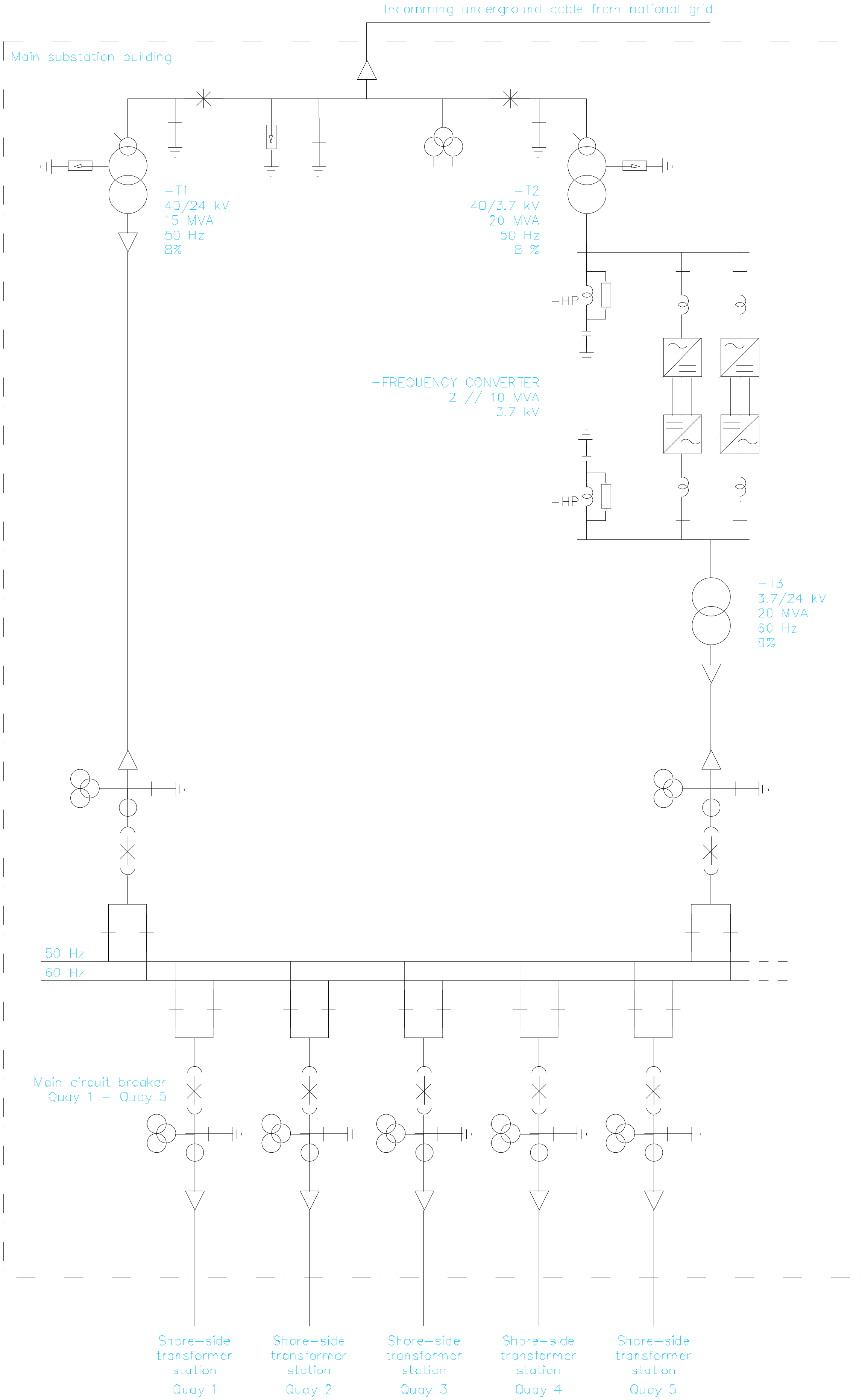


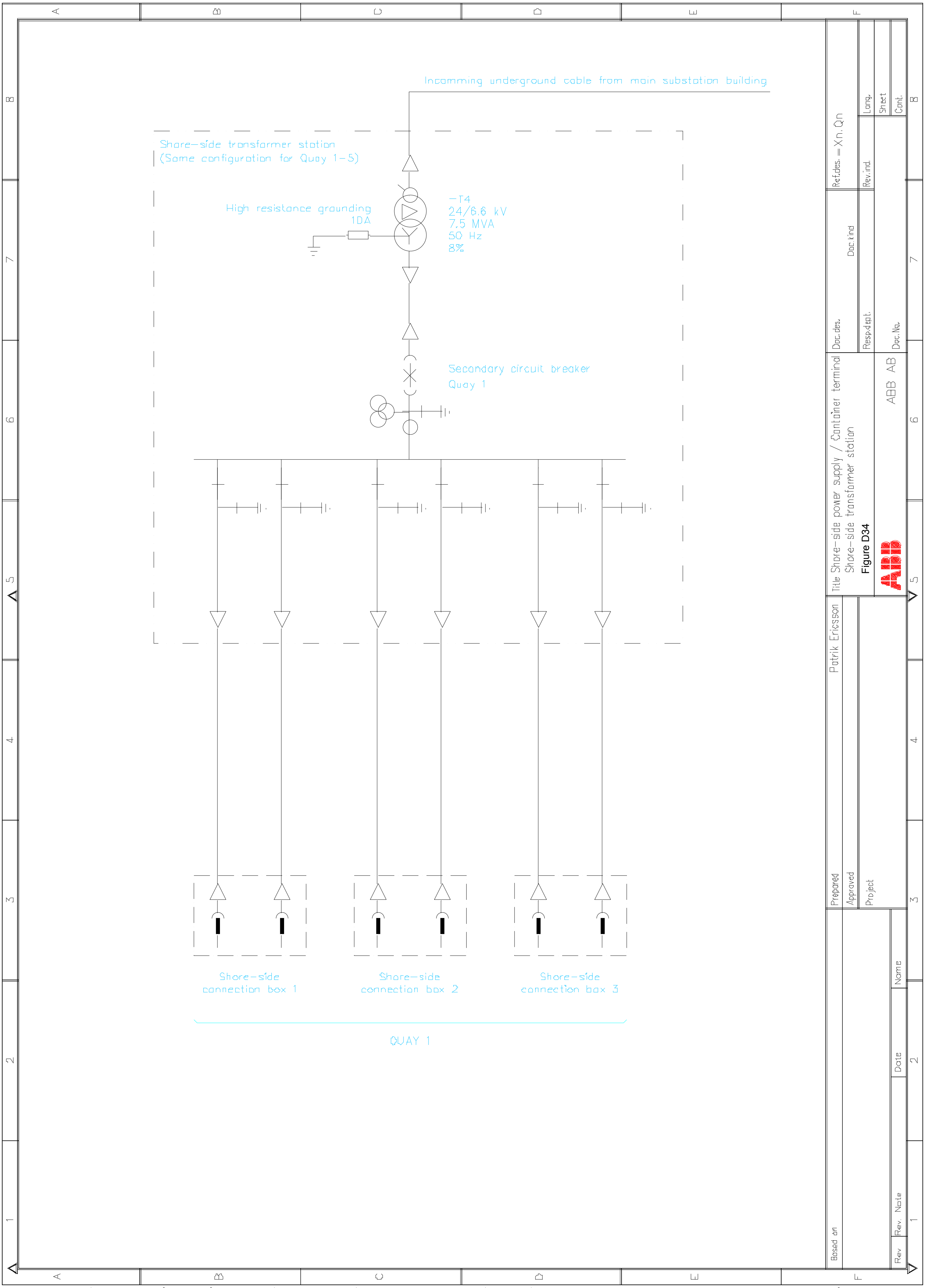
Figure D32 Shore-side power supply configuration in a container terminal



Title Shore-side power supply / Container terminal
Main substatin building
Figure D33

Ref.des. = Xn.Qn
Patrik Ericsson
ABB AB

Prepared | Approved | Project | Based on | Doc.des. | Doc.kind | Resp.dept. | Rev.ind. | Lang. | Sheet | Cont. | Doc.No. | Rev | Rev. Note | Date | Name


Incomming underground cable from main substation building
Shore-side transformer station
(Same configuration for Quay 1-5)
High resistance grounding
10A
-T4
24/6.6 kV
7.5 MVA
50 Hz
8%
Secondary circuit breaker
Quay 1
Shore-side
connection box 1
Shore-side
connection box 2
Shore-side
connection box 3
QUAY 1
Title Shore-side power supply / Container terminal
Shore-side transformer station
Patrik Ericsson
ABB AB
Prepared
Approved
Project
Based on
Ref.des. =Xn.Qn
Doc.des.
Doc.kind
Resp.dept.
Rev.ind.
Doc.No.
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Name

Figure D34

D3.2 Cost estimation

Table D13 contains a cost estimation for all the equipment needed for this installation. Observe that only the equipment costs and no installation, engineering and construction costs are included in the cost estimation. The total cost for the equipment is set to 1.0 p.u corresponding to 100% of the total price for the equipment. As seen the frequency converters stands for half of the total cost. In order to allow a competitive solution the costs need to be reduced. Having centrally placed frequency converter is currently the best way to reduce the installation and equipment costs, since the frequency converter can be dimensioned by the harbours actual power demand and not to be dimensioned by the standard.

Table D13 Cost estimation of equipment

Main substation building	**p.u**
- Frequency converters (2 x 10 MVA)	0.49
- Switchgear and breakers	0.03
- Transformers (1 x 15 MVA + 2 x 20 MVA)	0.14
- Control and protection relays	0.06
Sum	**0.72**

Shore-side transformer station and connection arrangement	**p.u**
- Switchgear and breaker	0.01
- Transformer (7.5 MVA)	0.03
- 3 connection boxes	0.01
Sum	**0.05**
Sum x 5 (Quay 1 – Quay 5)	**0.25**

Cables	**p.u**
- Underground cables 24 kV (7 km)	0.05
- Underground cables 6.6 kV (6 km)	0.01
Sum	**0.03**

	p.u
TOTAL	**1.0**

Part E - Simulations and calculations

E1 Simulations

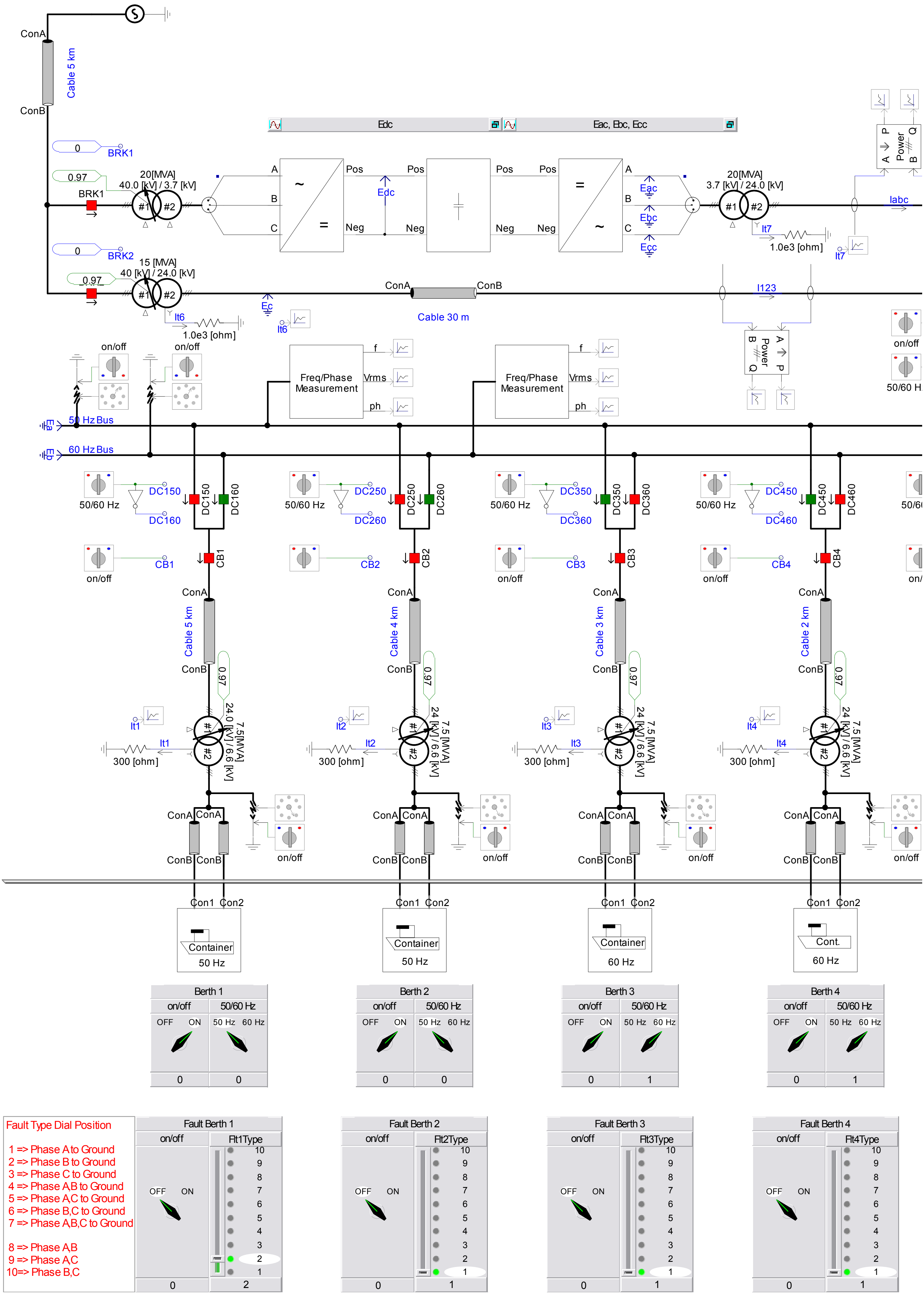
This chapter illustrates the simulation of the implemented configuration that was described in *Chapter D3*. The entire system is build up with help of PSCAD® - Power Systems Computer Aided Design. PSCAD® is a powerful electromagnetic time domain transient environment and powerful study tool.

With help of the program, the simulation of the entire system has been made in order to simulate a realistic system as possible where choice of frequency which is to be supplied to the different vessels, can be made with help of a control. The purpose of the simulation is to investigate how the system behaves at various faults and in that way retrieve answers such as, how a vessel is affected by a fault that occurs on a nearby vessel. Simulations have been made for both symmetrical three-phase to ground faults and single-phase to ground faults.

The simulation model consists of a simplified model of the frequency converter which was chosen in the recommended configuration. Further, all transformers and cables in the system are represented as close to reality as possible.

Those simulations that have been done have been verified with own calculations, and therefore will the simulation results be presented together with the calculations in the following chapter.

The simulations model is illustrated in *Figure E1*.


ConA
Cable 5 km
ConB
Edc
Eac, Ebc, Ecc
0
BRK1
0.97
20[MVA]
40.0 [kV] / 3.7 [kV]
BRK1
#1
#2
A
B
C
Pos
Neg
Edc
Pos
Neg
Pos
Neg
Pos
Neg
A
B
C
Eac
Ebc
Ecc
20[MVA]
3.7 [kV] / 24.0 [kV]
Iabc
It7
1.0e3 [ohm]
It7
Power
P
Q
A
B
0
BRK2
15 [MVA]
40 [kV] / 24.0 [kV]
0.97
It6
1.0e3 [ohm]
Ec
It6
ConA
ConB
Cable 30 m
I123
on/off
50/60 Hz
on/off
on/off
Freq/Phase Measurement
f
Vrms
ph
Freq/Phase Measurement
f
Vrms
ph
50 Hz Bus
60 Hz Bus
50/60 Hz
DC150
DC160
DC150
DC160
50/60 Hz
DC250
DC260
DC250
DC260
50/60 Hz
DC350
DC360
DC350
DC360
50/60 Hz
DC450
DC460
DC450
DC460
CB1
CB2
CB3
CB4
on/off
Cable 5 km
Cable 4 km
Cable 3 km
Cable 2 km
0.97
24.0 [kV] / 6.6 [kV]
7.5 [MVA]
24 [kV] / 6.6 [kV]
It1
It2
It3
It4
300 [ohm]
ConA
ConB
Con1
Con2
Container
50 Hz
60 Hz
Cont.
Berth 1
Berth 2
Berth 3
Berth 4
on/off
50/60 Hz
OFF
ON
50 Hz
60 Hz
0
1
Fault Type Dial Position
1 => Phase A to Ground
2 => Phase B to Ground
3 => Phase C to Ground
4 => Phase A,B to Ground
5 => Phase A,C to Ground
6 => Phase B,C to Ground
7 => Phase A,B,C to Ground
8 => Phase A,B
9 => Phase A,C
10=> Phase B,C
Fault Berth 1
Fault Berth 2
Fault Berth 3
Fault Berth 4
Flt1Type
Flt2Type
Flt3Type
Flt4Type
10
9
8
7
6
5
4
3
2
1

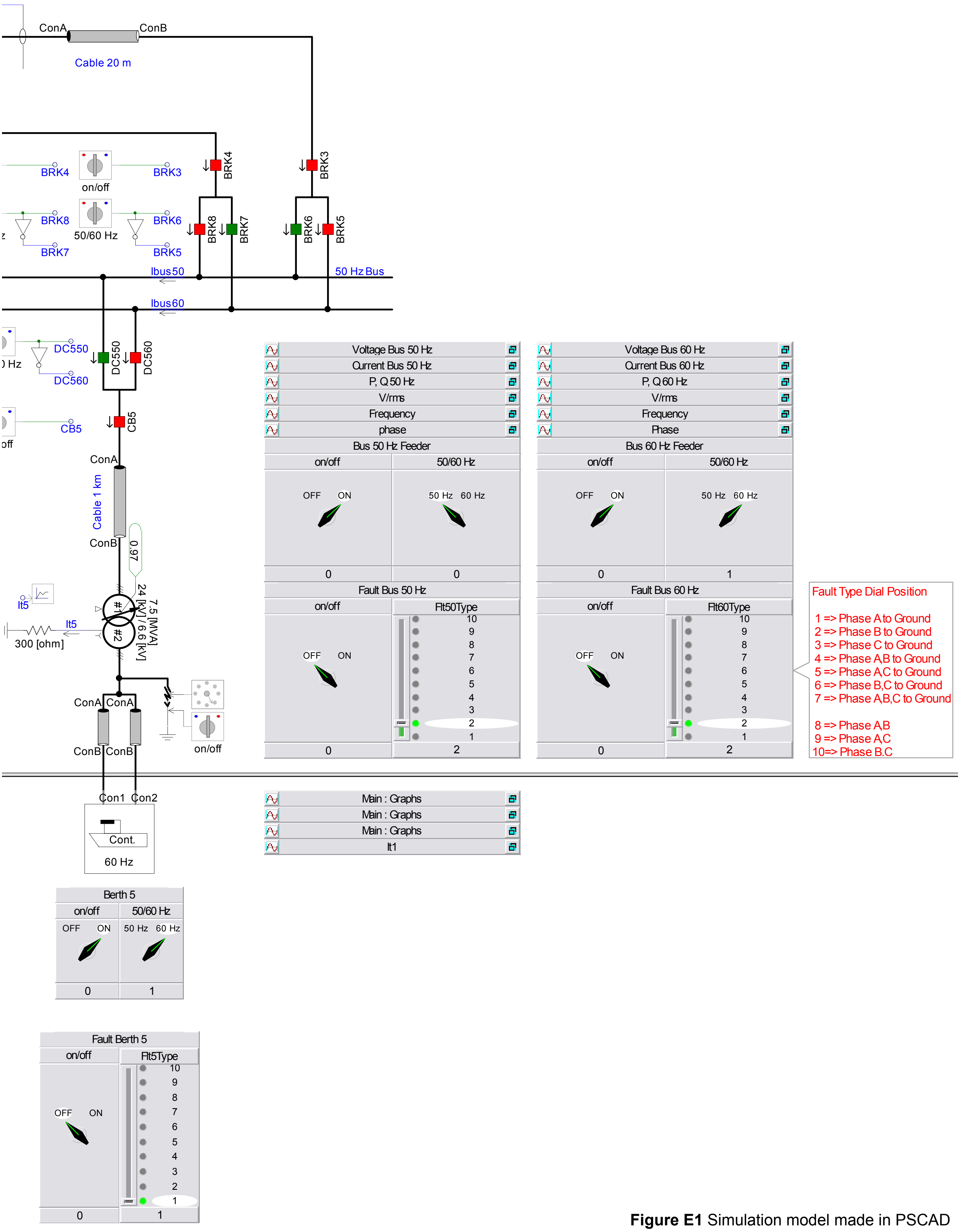


Figure E1 Simulation model made in PSCAD

E2 Calculations

This chapter contains all calculations represented of the system that was described in *Chapter D3,* where implementation of the recommended configuration took place in a container terminal. The chapter differs from the others in the sense that this chapter presumes that the reader has some base knowledge in electric power engineering in order to understand models and methods for the different calculations. The chapter begins with an impedance representation of the total system and is followed by calculations for system grounding, where models for sequence networks are used. Subsequently, calculations for balanced three-phase fault currents in the facility are made. Even voltage drop in the facility during a fault of a vessel is presented. The calculations are connected with the simulations that were described in *Chapter E1*.

All handmade calculations in this chapter concern the 50 Hz distribution and calculations for the 60 Hz distribution are made analogous. The frequency converter in itself is a current limiter, and therefore will all fault currents be limited in this case. The maximum current from the frequency converter is approximately two times the rated current, which in this configuration would imply a maximum current of 3.1 kA from the frequency converter, which will reduce all fault current in the facility in comparison with direct feeding from the grid. Two parallel connected frequency converters in the model will contribute to a maximum current of 6.2 kA.

E2.1 Impedance representation of the network

The entire grid can be described with an equivalent impedance diagram, see *Figure E1*. The impedances that are included in the system are presented in *Table E1*. Cable impedance data has been collected from datasheets and the impedances for the transformers can be calculated according to *Equation 1* and *Equation 2*, where data for the transformers are collected from *Figure D33* and *Figure D34*, presented earlier in the report.

$$Z_{T1} = x \cdot \frac{U^2}{S_{T1}} = j0.08 \cdot \frac{24^2}{15} = \underline{\underline{j3.0720 \ \Omega}} \quad (1)$$

$$Z_{ST1} = x \cdot \frac{U^2}{S_{ST1}} = j0.08 \cdot \frac{6.6^2}{7.5} = \underline{\underline{j0.46464 \ \Omega}} \quad (2)$$

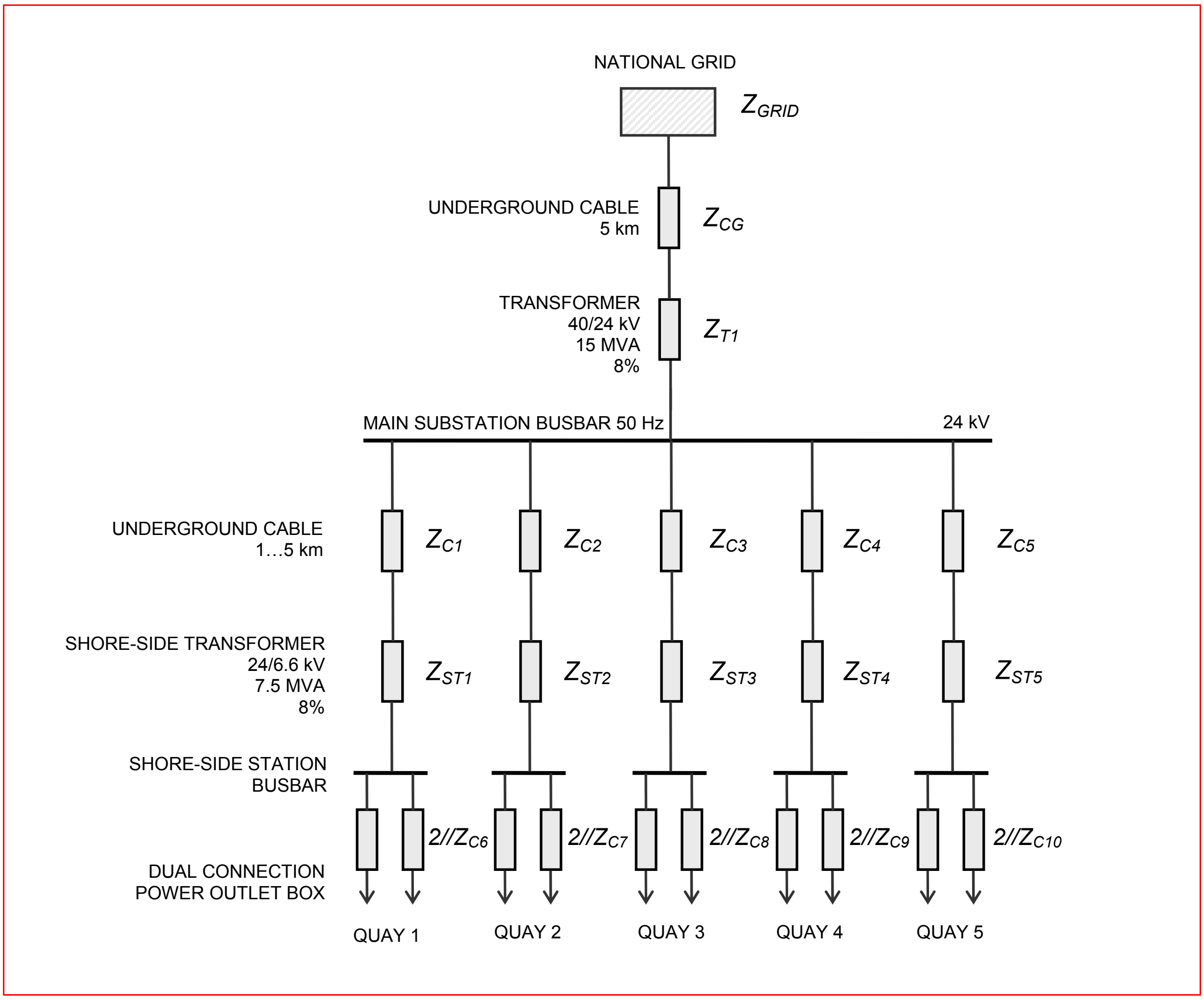


Figure E1 Equivalent impedance diagram of the system.

Table E1 Impedance data of the system

Component		Impedance
Underground cable 40 kV 5 km	Z_{CG}	0.23+j0.12 Ω/km
Transformer 40/24 kV	Z_{T1}	j3.0720 Ω
Underground cable 24 kV 1…5 km	Z_{C1} - Z_{C5}	0.20+j0.10 Ω/km
Transformer 24/6.6 kV	Z_{ST1} – Z_{ST5}	j0.4646 Ω
Underground cable 6.6 kV 300 m	Z_{C6} - Z_{C10}	0.20+j0.10 Ω/km

E2.1.2 Per-unit representation of the impedances

The transmission system and several portions of the distribution system are operated at voltages in the kV range. This results in large amounts of power being transmitted in the range of kW to MW, and kVA to MVA. As a result, in analysis, it is useful to scale, or normalize quantities with large physical values. The calculation of system performance conveniently uses a per-unit representation of voltage, current, impedance, power, reactive power, and apparent power. The numerical per-unit value of any quantity is its ratio to the chosen base quantity of the same dimensions. Thus a per-unit quantity is a normalized quantity with respect to a chosen base value.

The conversion has several advantages:

- In the per-unit system of representation, device parameters tend to fall in a relatively fixed range.
- Ideal transformers are eliminated as circuit elements. This results in a large saving in component representation.
- The voltage magnitude throughout a given power system is relatively close to unity in the per-unit system for a power system operating normally. This characteristic provides a useful check on the calculations.

In power system calculations the nominal voltage of lines and equipment is almost always known, so the apparent power is a suitable base value to choose. In equipment, this quantity is usually known and makes a convenient base. The choice of the base quantity will automatically fix the base of current, impedance, and admittance. In a system study, the apparent power base can be selected to be any convenient value, such as 100 MVA.

The classical per-unit calculation is to begin by converting all impedances to per-unit (p.u) values. Per unit base values and formulae are used as follows:

$$Z_{p.u} = \frac{Z_{actual(\Omega)}}{Z_{base}} \qquad (3)$$

$$Z_{base} = \frac{U^2}{S_{base}} \qquad (4)$$

Inserting *Equation 3* in *Equation 4* results in:

$$Z_{p.u} = \frac{Z_{actual(\Omega)}}{\frac{U^2}{S_{base}}} \qquad (5)$$

Using *Equation 5* all impedances presented in *Table E1* are converted to per-unit values, and these conversions are presented below. A summary of the calculated per-unit impedances are shown in *Table E2* and all these impedances will be used in the following sections.

$$Z_{GRID(PU)} = \frac{S_B}{S_{GRID}} = \frac{100}{\infty} = \underline{\underline{j0 \quad p.u}}$$

$$Z_{CG(PU)} = \frac{Z_{CG} \cdot l}{\frac{U^2}{S_B}} = \frac{(0.23 + j0.12) \cdot 5}{\frac{40^2}{100}} = \underline{\underline{0.07188 + j0.03750 \quad p.u}}$$

$$Z_{C1(PU)} = \frac{Z_{C1} \cdot l}{\frac{U^2}{S_B}} = \frac{(0.20 + j0.10) \cdot 1}{\frac{24^2}{100}} = \underline{\underline{0.03576 + j0.01736 \quad p.u}}$$

$$Z_{C5(PU)} = \frac{Z_{C5} \cdot l}{\frac{U^2}{S_B}} = \frac{(0.20 + j0.1) \cdot 5}{\frac{24^2}{100}} = \underline{\underline{0.17882 + j0,08680 \quad p.u}}$$

$$Z_{T1(PU)} ... Z_{T5(PU)} = \frac{Z_{T1}}{\frac{U^2}{S_B}} = \frac{j3.072}{\frac{24^2}{100}} = \underline{\underline{j0.53333 \quad p.u}}$$

$$Z_{ST1(PU)} ... Z_{ST5(PU)} = \frac{Z_{ST1}}{\frac{U^2}{S_B}} = \frac{j0.4646}{\frac{6.6^2}{100}} = \underline{\underline{j1.06666 \quad p.u}}$$

$$Z_{C6(PU)} = \frac{Z_{C6} \cdot l}{\frac{U^2}{S_B}} = \frac{(0.20 + j0.1) \cdot 0.300}{\frac{6.6^2}{100}} = \underline{\underline{0.13774 + j0.06887 \quad p.u}}$$

Table E2 Impedance data of the network with per-unit representation

Component		**Impedance [pu]**
Underground cable 40 kV 5 km	$Z_{CG(PU)}$	0.07188+j0.03750
Transformer 40/24 kV	$Z_{T1(PU)}$	j0.53333
Underground cable 6.6 kV 1 km	$Z_{C1(PU)}$	0.03576+j0.01736
Underground cable 6.6 kV 5 km	$Z_{C5(PU)}$	0.17882+j0.08680
Transformer 24/6.6 kV	$Z_{ST1(PU)} – Z_{ST5(PU)}$	j1.06666
Underground cable 6.6 kV 300 m	2 // $Z_{C6(PU)}$ - $Z_{C10(PU)}$	0.13774+j0.06887

E2.2 System grounding

As mentioned *Chapter 2.4.2*, the choice of transformer in question is a Dyn- type with high-resistance grounding. The reason why high-resistance grounding is chosen is due to that high-resistance grounding solves the problem of transient over-voltages, thereby reducing equipment damage. Overvoltages caused by intermittent arcing faults, can be held to phase-to-phase voltage by grounding the system neutral through a resistance which limits the ground current to a value equal to or greater than the capacitive charging current of the system. Thus the fault current can be limited, in order to prevent equipment damage. So a resistance limits the fault current during a single-phase fault, but causes overvoltages in the non-faulted phases. In addition, limiting fault currents to predetermined maximum values permits the designer to selectively coordinate the operation of protective devices, which minimizes system disruption and allows for quick location of the fault. The resistance is chosen so the single line to ground fault will be limited to *12 A*. *Figure E2* represents the system during a single line fault, giving *Equation 6,* where $I_{fault,max}$ represents the single line to ground fault current. *Equations 6 – 12* present the approach of calculating the resistance.

$$I_{fault,\max} = 3 \cdot I_0 = \frac{3 \cdot U_f}{Z_+ + Z_- + Z_0} \quad (6)$$

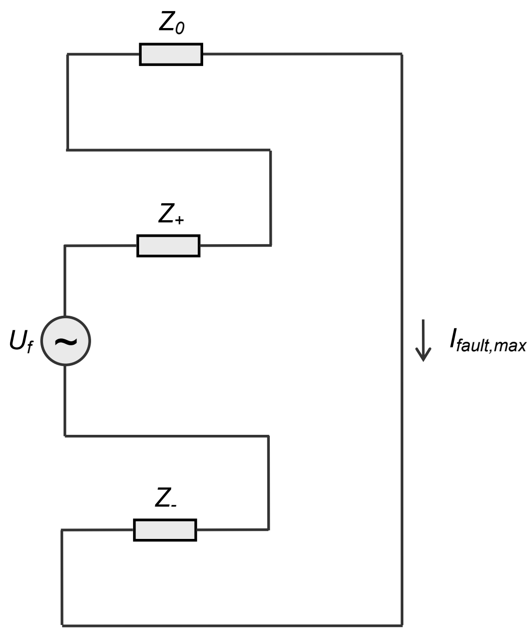


Figure E2 Sequence network during single line fault

Where Z_+, positive sequence network, and Z_-, negative sequence network, in *Equation 6* is presented in *Figure E3* and *Figure E4*. Z_0, zero sequence network, is illustrated in *Figure E5*.

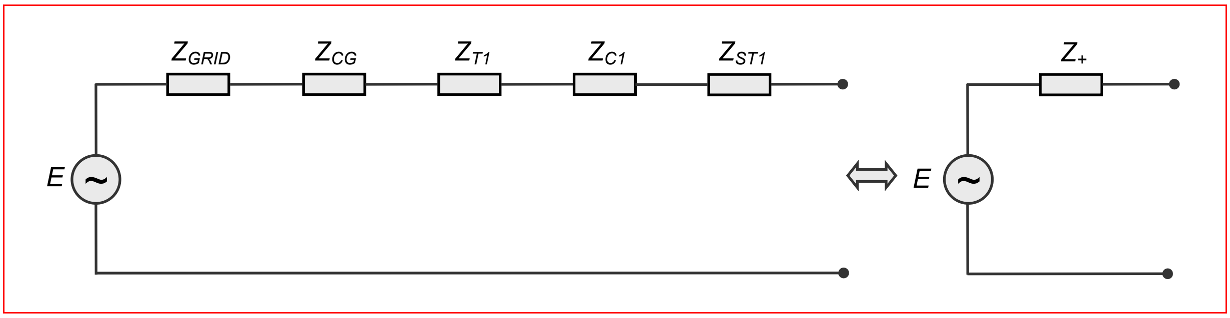


Figure E3 Positive sequence network representation

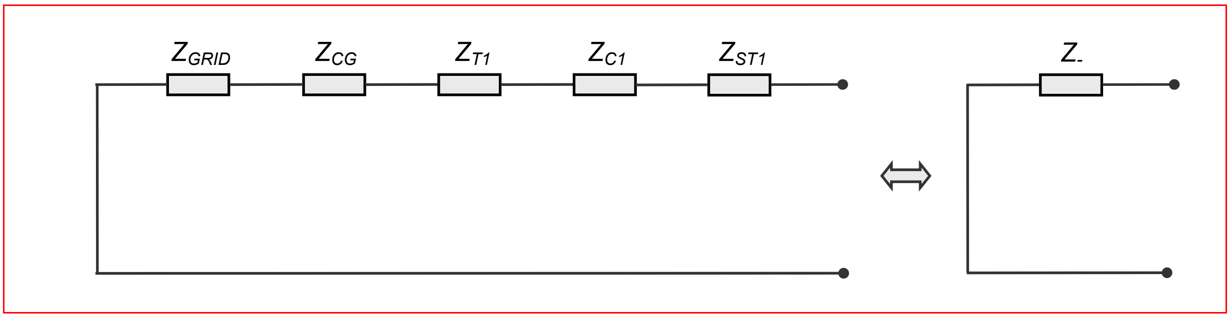


Figure E4 Negative sequence network representation

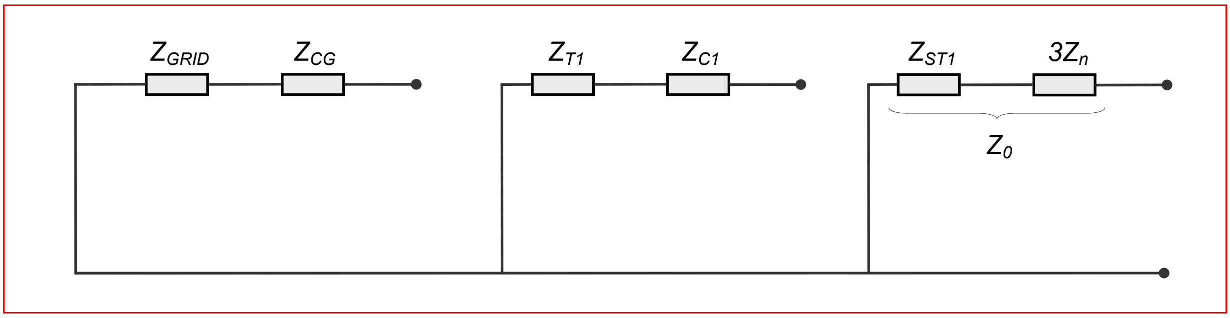


Figure E5 Zero sequence network representation

Since Z_- is equal to Z_+, as can be seen in *Figure E3* and *Figure E4*, *Equation 6* can be written as *Equation 7*.

$$I_{fault,\max} = \frac{3 \cdot U_f}{2Z_+ + Z_0} \quad (7)$$

Where $Z_0 = Z_{ST1} + 3Z_n$, see *Figure E5*. Z_n corresponds to the high-resistance, and Z_{ST1} corresponds to the impedance of the shore-side transformer. But since Z_0 is a high impedance resistance ($Z_0 >> Z_+$), it is assumed that Z_+ can be neglected, and therefore a simplification can be done, see *Equation 8*.

$$I_{fault,\max} = \frac{3 \cdot U_f}{Z_0} \Rightarrow Z_0 = \frac{3 \cdot U_f}{I_{fault,\max}} = \frac{3 \cdot \frac{6{,}6 \cdot 10^3}{\sqrt{3}}}{12} \approx \underline{\underline{952 \ \Omega}} \quad (8)$$

The searched resistance Z_n can be calculated according to *Equation 9*.

$$Z_0 = Z_{ST1} + 3Z_n \Rightarrow Z_n = \frac{Z_0 - Z_{ST1}}{3} \quad (9)$$

But, since $Z_0 >> Z_{ST1}$, further simplification can be made according to *Equation 10:*

$$Z_n = \frac{Z_0}{3} \approx 300 \ \Omega \qquad (10)$$

Using 300 Ω as grounding resistance Z_n, we will obtain a fault current of 12 A, see *Figure E6*.

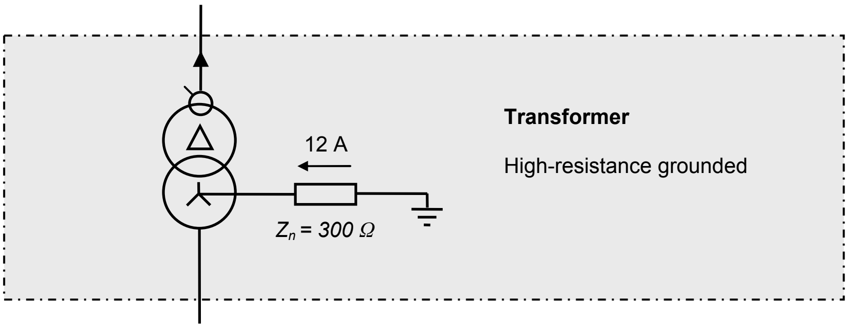


Figure E6 High-resistance grounded transformer. The resistance is chosen so that the single line to ground fault will be limited to 12 A, resulting in a resistance Z_n = *300 Ω*.

Figure E7 illustrates the simulated current during a single line to ground fault trough the ground resistance. As seen from the figure, the current corresponds to the calculated value.

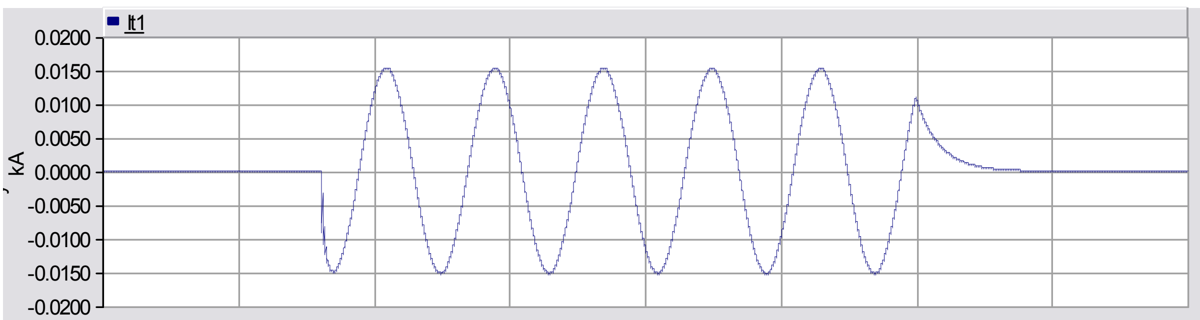


Figure E7 Single line to ground fault current through the transformer

As stated earlier in the text, when using high-resistance grounding the fault current is limited in order to prevent equipment damage, but causes overvoltages in the non-faulted phases, see *Figure E8*. The *Equation 11* and *Equation 12* presents the approach of the overvoltage in the non-faulted phases.

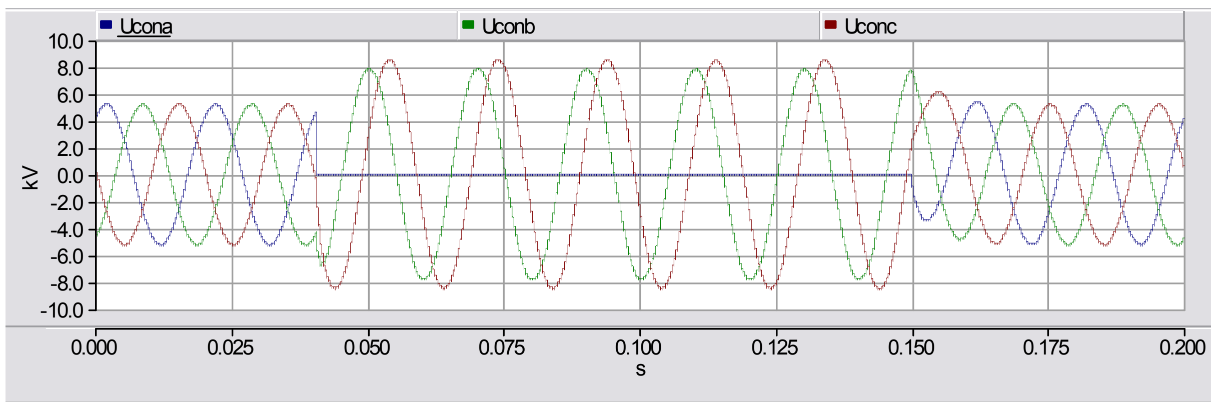


Figure E8 Overvoltage during a single line to ground fault.

$$
\begin{aligned}
U_b &= U_0 + a^2 U_1 + aU_2 = \\
&= -Z_0 I_0 + a^2 \cdot (1 - Z_1 I_0) + a \cdot (1 - Z_2 I_0) = \\
&= -(Z_0 + a^2 \cdot Z_1 + a \cdot Z_2) I_0 + a^2 + a, \quad \textit{where } a = e^{j120^\circ} = \cos(120^\circ) + j\sin(120^\circ)
\end{aligned} \tag{11}
$$

$$
\begin{aligned}
U_c &= U_0 + aU_1 + a^2 U_2 = \\
&= -Z_0 I_0 + a \cdot (1 - Z_1 I_0) + a^2 \cdot (1 - Z_2 I_0) = \\
&= -(Z_0 + a \cdot Z_1 + a^2 \cdot Z_2) I_0 + a^2 + a, \quad \textit{where } a = e^{j120^\circ} = \cos(120^\circ) + j\sin(120^\circ)
\end{aligned} \tag{12}
$$

As seen from Equation 6, the fault current $I_{fault,max}$ can be written as $3I_0$, $I_{fault,max} = 3I_0$. $I_{fault,max} = 12$ A corresponds to $I_{fault,max} = 0.001451$ p.u. Inserting numbers in *Equation 11* and *Equation 12*, resulting in U_b=U_c=1.63 p.u., corresponding to an overvoltage of approximately 10.8 kV. *Figure E8* illustrates the simulated overvoltage during a single line to ground fault. Observe that the figure shows phase-to-ground voltage.

E2.3 Calculation of balanced three-phase fault current

The fault current in a balanced system during a fault is dependent of the total system impedance. By adding up the impedances of each component of the grid, the total system impedance is calculated, and the fault current at a certain node in the system can be illustrated. The single line diagram of the configuration is illustrated in *Figure E9*. The figure shows those positions where balanced three-phase fault currents have been calculated, *Position A* to *Position H*. Observe that the calculations are based that only one fault occurs at the same time.

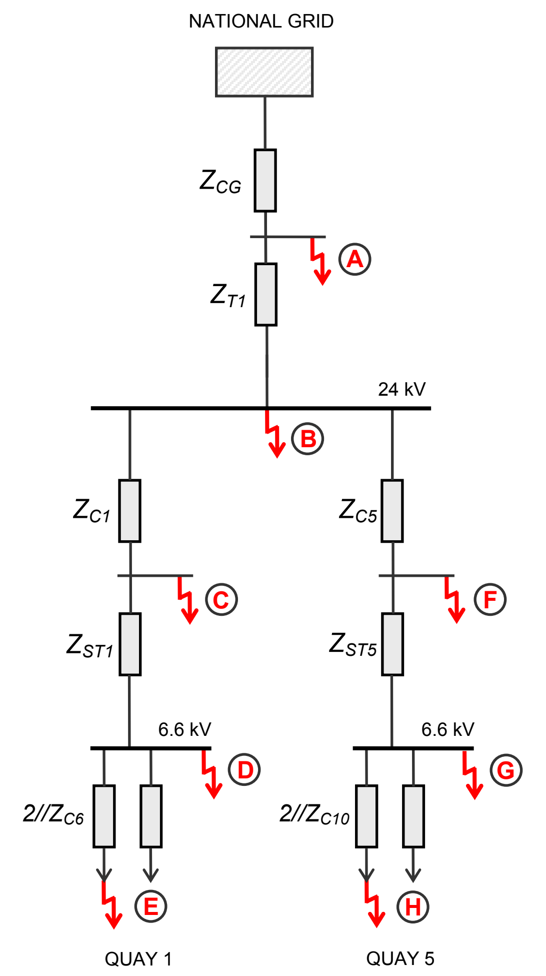


Figure E9 Fault current during three-phase fault for different fault positions

The use of per-unit conversion can considerably ease the calculations. *Equation 10* to *Equation 12*, present the method of fault current calculation of the configuration. The apparent power base was chosen to S_B=*100 MVA*. Z_{TOTAL} varies depending on where the fault occurs – *Position A* to *Position H*. *Table E3* illustrates how Z_{TOTAL} is changed for the different fault positions.

$$S_f = \frac{S_B}{Z_{TOTAL}} \quad (10)$$

$$S_f = \sqrt{3} \cdot U \cdot I_f^* \quad (11)$$

$$I_f = \left| I_f^* \right| = \left| \frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}} \right| \quad (12)$$

Table E3 Impedance data of the network with per-unit representation

Fault postion	Z_{TOTAL}	Z_{TOTAL}[pu]
Position A	Z_{CG}	0.07188+j0.03750
Position B	$Z_{CG}+Z_{T1}$	0.07188+j0.57080
Position C	$Z_{CG}+Z_{T1}+Z_{C1}$	0.10764+j0.58819
Position D	$Z_{CG}+Z_{T1}+Z_{C1}+Z_{ST1}$	0.10764+j1.65479
Position E	$Z_{CG}+Z_{T1}+Z_{C1}+Z_{ST1}+Z_{C6}$	0.24538+j1.72363
Position F	$Z_{CG}+Z_{T1}+Z_{C5}$	0.25070+j0.65760
Position G	$Z_{CG}+Z_{T1}+Z_{C5}+Z_{ST5}$	0.25070+j1.72426
Position H	$Z_{CG}+Z_{T1}+Z_{C5}+Z_{ST5}+Z_{C10}$	0.38844+j1.79313

Using *Equation 12* the fault currents for the different positions can be calculated. The results of the calculations are presented below:

Fault Position A

$$I_{fA} = \left| I_f^* \right| = \left| \frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}} \right| = \left| \frac{100 \cdot 10^6}{\sqrt{3} \cdot 40 \cdot 10^3 \cdot (0.07188 + j0.03750)} \right| \approx \underline{\underline{17.8 \ \ kA}}$$

Fault Position B

$$I_{fB} = \left| I_f^* \right| = \left| \frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}} \right| = \left| \frac{100 \cdot 10^6}{\sqrt{3} \cdot 24 \cdot 10^3 \cdot (0.07188 + j0.57080)} \right| \approx \underline{\underline{4.2 \ \ kA}}$$

Figure E10 illustrates the result of the simulation of fault Position B and corresponds to the calculated current during the fault.

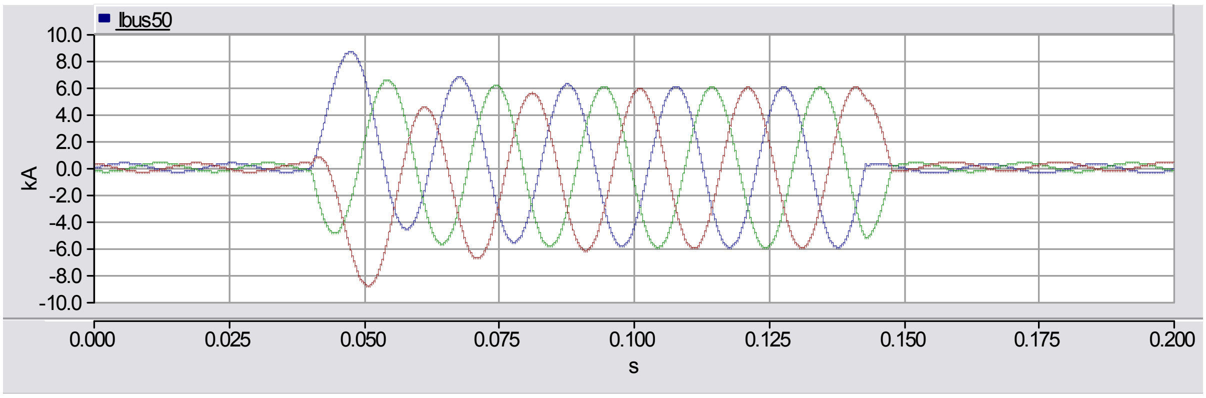


Figure E10 Fault current at Position B

Fault Position C

$$I_{fC} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 24 \cdot 10^3 \cdot (0.10764 + j0.58819)}\right| \approx \underline{\underline{4.0 \ \ kA}}$$

Fault Position D

$$I_{fD} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 6.6 \cdot 10^3 \cdot (0.10764 + j1.65479)}\right| \approx \underline{\underline{5.3 \ \ kA}}$$

Fault Position E

$$I_{fE} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 6.6 \cdot 10^3 \cdot (0.24538 + j1.72363)}\right| \approx \underline{\underline{5.0 \ \ kA}}$$

Fault Position F

$$I_{fF} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 24 \cdot 10^3 \cdot (0.25070 + j0.65760)}\right| \approx \underline{\underline{3.4 \ \ kA}}$$

Fault Position G

$$I_{fG} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 6.6 \cdot 10^3 \cdot (0.25070 + j1.72426)}\right| \approx \underline{\underline{5.0 \ \ kA}}$$

Fault Position H

$$I_{fH} = \left|I_f^*\right| = \left|\frac{S_B}{\sqrt{3} \cdot U \cdot Z_{TOTAL}}\right| = \left|\frac{100 \cdot 10^6}{\sqrt{3} \cdot 6.6 \cdot 10^3 \cdot (0.38844 + j1.79313)}\right| \approx \underline{\underline{4.8 \ \ kA}}$$

Figure E11 illustrates the result of the simulation of fault Position H and corresponds to the calculated current during the fault.

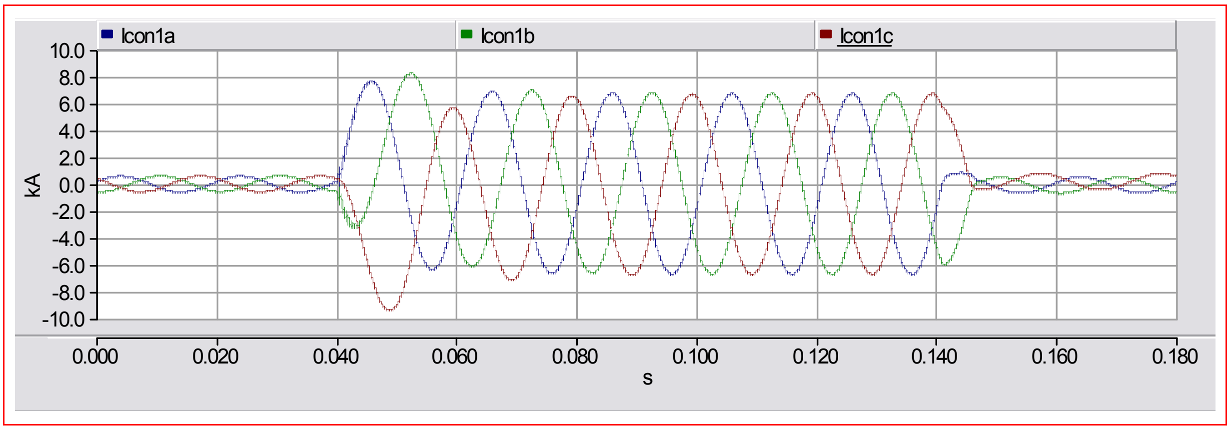


Figure E11 Fault current at Position H

A summary of the fault currents for the different positions is illustrated in *Figure E12*.

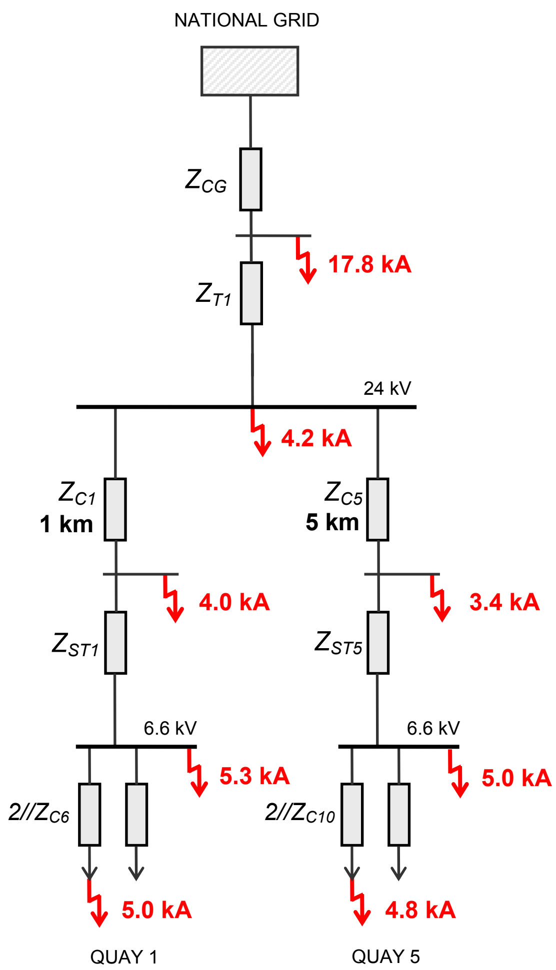


Figure E12 Calculated fault currents for the different positions

E2.4 Calculation of voltage drop on bus

The voltage dip magnitude during a fault is dependent on two impedances, the source impedance, and the impedance to the fault. With a simple model using voltage division, the voltage dip at a certain node in the system can be calculated, by using the *Equation 13*. The used model is shown in *Figure E13*.

$$U = E \cdot \frac{Z_{fault}}{Z_{fault} + Z_{source}} = E \cdot \frac{Z_{C1} + Z_{ST1} + Z_{C0}}{Z_{C1} + Z_{ST1} + Z_{C0} + Z_{CG} + Z_{T1}} = \\ = 1.0 \cdot \left| \frac{0.17350 + j1.15283}{0.24538 + j1.72363} \right| \approx 0.67 \quad p.u \tag{13}$$

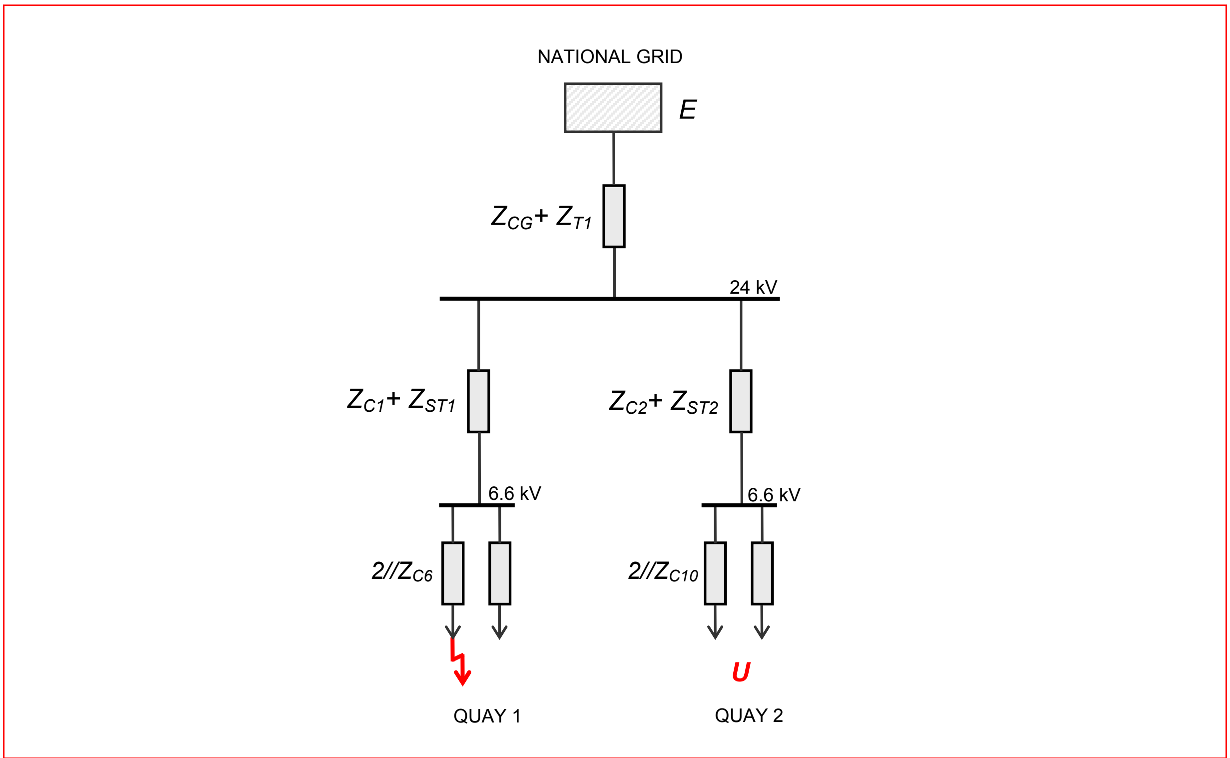


Figure E13 Single line diagram of the system

Inserting figures of the source impedance and the impedance to the fault in *Equation 13* gives a voltage drop of 33 %. This means if a fault occurs at on *Quay 1*, the nearby vessel will experience a voltage drop by 33 %, see *Figure E14*. As seen from the figure the voltage before a fault occurs is 5.5 kV and during the fault the voltage experienced at *Quay 2* is approximately 3.7 kV, corresponding to a voltage drop of 33%. During a single line to ground fault the nearby vessel is not affected in the same way by the fault as during a balanced three-phase fault, see *Figure E15*.

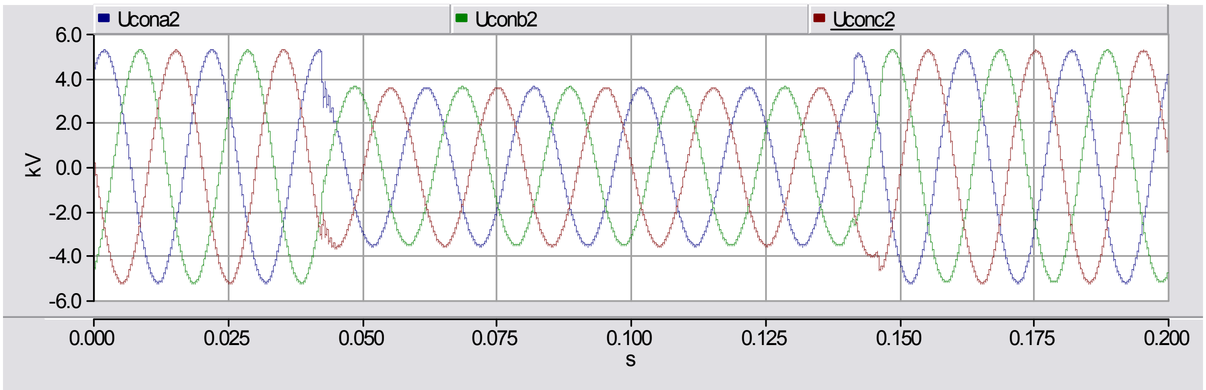


Figure E14 Voltage drop experienced by a nearby vessel during a balanced three-phase fault

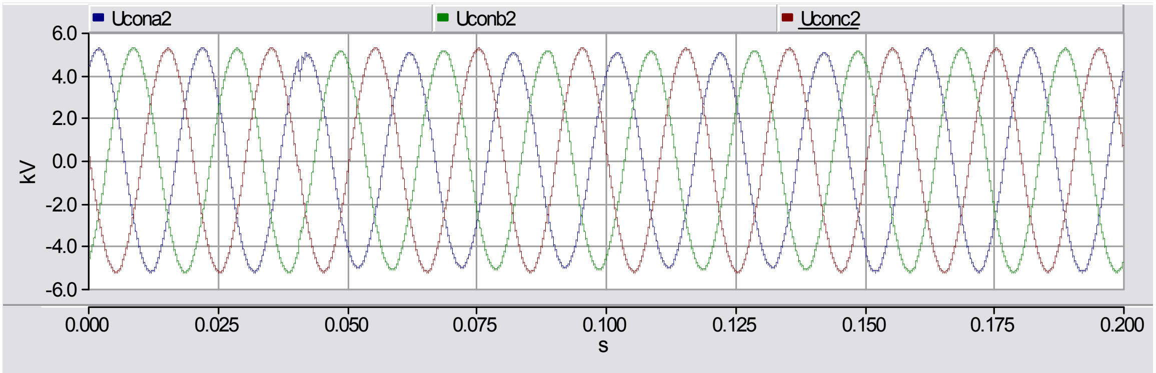


Figure E15 Voltage experienced by a nearby vessel during a single line to ground fault

Part F - Conclusions

F1 Conclusions

Ocean-going marine vessels represent one of the largest, most difficult to regulate, source of air pollution in the world and are also an essential component of the international trade and goods movement process. These marine vessels are similar to floating power plants in terms of electric power, and it has been indicated that the marine vessels are growing in length and will therefore be in need of higher power demand.

During the master thesis it has been shown trough communication with ports, shipping owners and shipbuilding yards that shore-side power supply is a really interesting topic, and that today's marine vessel emission regulation needs to be stricter. The first step to regulate the emission discharge from marine vessels has been introduced by the European Union. It has been decided to lower the sulphur limit from 4.5 % to 0.1 %, but it has been shown that it isn't enough, and therefore shore-side power supply is recommended and preferred.

Since most of the ports worldwide are investigating the possibilities to use shore-side power supply, shore-to-ship connections are definitively going to happen. Although, it depends on how fast implementation will take place and how much the ports and private investors are willing to pay for the technical solutions available today.

In the report it has been shown that the cost for the frequency converter is corresponding to at least 50 % of the total equipment cost, and in order to allow a competitive solution the costs need to be reduced. Having centrally placed frequency converter is currently the best way to reduce the installation and equipment costs, since the frequency converter can be dimensioned by the harbours actual power demand and not to be dimensioned by the standard.

Therefore is a module based frequency converter desirable, where the same module can be used as building blocks for different power needs and in that way increase the production volumes of the building blocks and reduce the costs of the frequency converters. In order to retrieve module based frequency converters, research and development of today's technology is needed.

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Appendix

APPENDIX I   List of oil- and product tankers included in the technical survey

Name	IMO	GT	Length m	V	Hz	Aux. gen. kW	Hotelling kW
Vitta Theresa	8918605	1892	98	380	50	160	107
Fryken	8819718	3987	100	440	60	1529	1024
Lady Stephanie	9014781	3393	100	440	60	960	643
Mistral	9009190	3494	100	440	60	528	354
Visten	8819732	3987	100	440	60	648	434
Amalia Theresa	9293640	3933	103	440	60	1440	965
Bro Genius	9263605	4107	115	440	60	1155	774
Emirates Swan	9333125	5776	118	450	60	1320	884
Bro Goliath	9297204	4745	119	440	50	2750	1843
Marinus	9232840	4808	119	380	50	2055	1377
Bro Jupiter	9163764	8848	120	450	50	2400	1608
Acavus	9308754	8351	127	450	60	950	637
Euro Swan	8810918	10420	139	440	60	3785	2536
Helene Knutsen	9005780	11737	142	440	60	2550	1709
Navigo	9013426	10543	145	440	60	2974	1993
Libelle	9186730	8067	146	380	50	2480	1662
Bregen	9035266	10012	150	440	60	1750	1173
Great Swan	8912508	14332	170	380	50	2800	1876
Abu Dhabi Star	9418119	29734	183	450	60	2700	1809
Baltic Champion	9260029	23240	183	450	60	2220	1487
Bow Summer	9215270	29965	183	450	60	3780	2533
Champion Pacific	8007999	21777	183	450	60	1800	1206
Apollon	9289532	30053	186	450	60	2220	1487
Artemis	9291640	3002	186	450	60	2220	1487
Aliakmon	9323962	35711	213	450	60	1680	1126
Aberdeen	9125736	47274	221	450	60	3040	2037
Amazon Explorer	9231511	43075	228	450	60	2250	1508
Gulf Progress	9198783	44067	229	450	60	3300	2211
Theresa Baltic	8308123	41766	229	450	60	4100	2747
Aktea	9291236	60007	248	440	60	2250	1508

APPENDIX II List of Ro/Ro vessels included in the technical survey

Name	IMO	GT	Length m	V	Hz	Aux. gen. kW	Hotelling kW
City of Amsterdam	9174751	9950	100	450	60	1 050	252
Birka Explorer	8820860	5409	122	440	60	1 256	377
Baltic Eager	7804065	14738	137	400	50	2 256	677
Miranda	9183790	10471	154	400	50	2 360	708
Mistral	9183788	10471	154	400	50	2 360	708
Birka Trader	9132014	12251	155	400	50	2 600	780
Global Carrier	7528647	13117	156	450	60	2 560	768
Global Freighter	7528568	13145	156	450	60	2 560	768
Antares	8500680	19963	158	400	50	3 260	978
Finnhawk	9207895	11530	163	400	50	2 500	750
Finnkraft	9207883	11530	163	400	50	2 500	750
Helena	8903155	22193	170	440	60	2 820	846
Aegean Leader	9054119	48319	180	450	60	2 520	605
Baltiysk	8318130	20126	187	440	60	3 904	1 171
Runner	8807416	20729	190	440	60	5 078	1 523
Vegaland	7718539	20871	190	450	60	3 040	912
Beachy Head	9234094	23235	193	460	60	6 112	1 834
Longstone	9234082	23235	193	460	60	6 112	1 834
Aida	9316139	60942	199	450	60	3 800	912
Asian Emperor	9176632	55729	200	450	60	3 540	850
Asian Sprit	8600208	53578	200	450	60	3 120	749
Delphinus Leader	9174282	57391	200	440	60	3 300	792
Hoegh Durban	9279331	59217	200	450	60	4 800	1 152
Tor Fressia	9274848	32289	200	400	50	6 520	1 956
Tor Primula	9259513	32289	200	400	50	6 520	1 956
Trica	9307284	28289	205	450	60	5 984	1 795
Kraftca	9307360	28289	205	450	60	5 984	1 795
Faust	9332925	71583	228	450	60	3 838	921
Fedora	9332949	71583	228	450	60	3 838	921
Saudi Diriyah	8121757	44171	249	440	60	4 880	1 464

APPENDIX III List of cruise ships included in the technical survey for voltages and frequencies

Name	IMO	GT	Length (m)	Passengers	V	Hz	Average time in port
NATIONAL GEOGRAPHIC ENDEAVOUR	6611863	3132	88	110	380 V	50	14:00
ISLAND SKY	8802894	4280	91	114	440 V	60	07:00
SEA CLOUD II	9171292	3849	117	96	380 V	50	28:40
VISTAMAR	8701193	7498	121	330	380 V	50	07:40
HANSEATIC	9000168	8378	123	184	440 V	60	02:15
OCEAN MAJESTY	6602898	10417	131	535	400 V	50	08:10
SEABOURN PRIDE	8707343	9975	134	204	440 V	60	20:00
SPIRIT OF ADVENTURE	7904889	9570	139	470	440 V	60	09:10
SILVER CLOUD	8903923	16927	156	296	440 V	60	09:40
SILVER WIND	8903935	16927	156	315	440 V	60	10:45
DELPHIN	7347536	16331	156	590	400 V	50	07:45
VAN GOGH	7359400	16331	156	650	400 V	50	06:00
OCEAN MONARCH	5282627	10545	162	503	400 V	50	05:00
ASTORIA	8000214	18591	164	500	440 V	60	07:45
DISCOVERY	7108514	20186	169	600	450 V	60	07:30
COSTA MARINA	6910544	25441	174	1025	440 V	60	09:10
BLACK WATCH	7108930	28668	178	758	440 V	60	09:00
BOUDICCA	7218395	28388	178	1022	440 V	60	08:00
SAGA ROSE	6416043	24474	189	789	440 V	60	08:10
SAGA RUBY	7214715	24116	191	500	440 V	60	07:50
AMADEA	8913162	28717	193	618	450 V	60	07:00
MAXIM GORKIY	6810627	24220	195	788	440 V	50	07:40
PRINSENDAM	8700280	37845	204	768	440 V	60	09:45
ALBATROS	7304314	28518	205	812	440 V	60	09:30
THOMSON CELEBRATION	8027298	33933	215	1214	440 V	60	08:45
ARTEMIS	8201480	44588	231	520	6.6 kV	60	08:15
AMSTEDAM	9188037	62735	238	1380	11 kV	60	08:10
ASUKA II	8806204	50142	241	960	6.6 kV	60	09:50
PACIFIC DAWN	8521232	70285	245	1900	6.6 kV	60	09:50

CENTURY	9072446	70606	249	1778	6.6 kV	60	07:55
ORIANA	9050137	69153	260	1975	6.6 kV	60	09:45
SUN PRINCESS	9000259	77441	261	2342	6.6 kV	60	07:00
DAWN PRINCESS	9103996	77441	261	2342	6.6 kV	60	10:25
SEA PRINCESS	9150913	77499	261	1950	6.6 kV	60	07:45
SPLENDOUR OF THE SEAS	9070632		264	2076	6.6 kV	60	08:50
CELEBRITY MERCURY	9106302	76522	264	1896	6.6 kV	60	10:00
RHAPSODY OF THE SEAS	9116864		279	2435	6.6 kV	60	15:45
VISION OF THE SEAS	9116876	78340	279	2416	6.6 kV	60	11:00
CROWN PRINCESS	9293399	113651	289	3599	11 kV	60	07:15
ARCADIA	9226906	82972	290	1968	11 kV	60	08:35
COSTA MEDITERRANEA	9237345	85619	293	2680	11 kV	60	08:40
COSTA ATLANTICA	9187796	85619	293	2680	11 kV	60	09:30
RADIANCE OF THE SEAS	9195195	90090	293	2100	11 kV	60	17:00
BRILLIANCE OF THE SEAS	9195200	90090	293	2501	11 kV	60	10:20
QUEEN ELISABETH 2	6725418	69053	294	1500	10 kV	60	10:30
CELEBRITY SUMMIT	9192387	90280	294	2499	11 kV	60	11:20
VOYAGER OF THE SEAS	9161716		311	3138	11 kV	60	10:20

APPENDIX IV List of cruise ships included in the technical survey for power demand

Name	IMO	GT	Length m	Passengers	Hotelling kW
NATIONAL GEOGRAPHIC ENDEAVOUR	6611863	3132	88	110	1280
ISLAND SKY	8802894	4280	91	114	3600
SEA CLOUD II	9171292	3849	117	96	1290
VISTAMAR	8701193	7498	121	330	2360
HANSEATIC	9000168	8378	123	184	4400
OCEAN MAJESTY	6602898	10417	131	535	4260
SEABOURN PRIDE	8707343	9975	134	204	3200
SPIRIT OF ADVENTURE	7904889	9570	139	470	2112
SILVER CLOUD	8903923	16927	156	296	6912
SILVER WIND	8903935	16927	156	315	6912
DELPHIN	7347536	16331	156	590	3816
VAN GOGH	7359400	16331	156	650	3816
OCEAN MONARCH	5282627	10545	162	503	5220
ASTORIA	8000214	18591	164	500	7240
DISCOVERY	7108514	20186	169	600	3636
COSTA MARINA	6910544	25441	174	1025	2265
BLACK WATCH	7108930	28668	178	758	6740
BOUDICCA	7218395	28388	178	1022	6740
SILVER SHADOW	9192167	28258	182	388	3000
MAXIM GORKIY	6810627	24220	195	650	3000
SEVEN SEAS MARINER	9210139	48075	216	769	7250
VOLENDAM	9156515	61214	238	1440	7250
AMSTEDAM	9188037	62735	238	1380	7250
ASUKA II	8806204	50142	241	960	6000
PACIFIC DAWN	8521232	70285	245	1900	6700
NORWEGIAN SUN	9218131	78309	258	2350	7250
NORWEGIAN SKY	9128532	77104	259	2450	7250
SUN PRINCESS	9000259	77441	261	2342	7250
DAWN PRINCESS	9103996	77441	261	2342	6800

CELEBRITY MERCURY	9106302	76522	264	1896	9500
NORWEGIAN SPIRIT	9141065	75338	269	3760	7250
VISION OF THE SEAS	9116876	78340	279	2416	7250
OOESTERDAM	9221281	81769	285	1968	7250
SAPHIRE PRINCESS	9228186	115875	290	3100	7250
DIAMOND PRINCESS	9228198	115875	290	2600	7250
RADIANCE OF THE SEAS	9195195	90090	293	2100	7250
CELEBRITY SUMMIT	9192387	90280	294	2499	7250
NORWEGIAN STAR	9195157	91740	294	2240	7250
CORAL PRINCESS	9229659	91627	294	3178	7250
INDEPENDENCE OF THE SEAS	9349681	154407	339	4375	11000