# Maritime Electrical Installations
# And
# Diesel Electric Propulsion

by

Alf Kåre Ådnanes

ABB AS

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# Preface

This tutorial report is written in order to give an overview of application and solutions, as well as an introduction to components used in vessels with electric propulsion.

The note is aimed to be a reference for those needing an update on recent solutions, and as a tutorial for new personnel in this exiting and fast developing area.

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Oslo,

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Alf Kåre Ådnanes
Technology Manager

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# 1. Introduction

## 1.1. Scope and Objectives

Electrical installations are present in any ship, from powering of communication and navigation equipment, alarm and monitoring system, running of motors for pumps, fans or winches, to high power installation for electric propulsion.

Electric propulsion is an emerging area where various competence areas meet. Successful solutions for vessels with electric propulsion are found in environments where naval architects, hydrodynamic and propulsion engineers, and electrical engineering expertise cooperate under constructional, operational, and economical considerations. Optimized design and compromises can only be achieved with a common concept language and mutual understanding of the different subjects.

The objective of this section is to give an introduction to electro-technology in general, and put special emphasis on installations for electric propulsion. It is the aim to give engineers with marine competence and background the necessary understanding of the most important electro-technical subjects used in design and configuration of ships with electric propulsion.

After an introductory review of the history of electric propulsion (chapter 1) and application areas of electric propulsion (chapter 2), an overview of the electric power system (chapter 3) and its associated control systems (chapter 4) follows. Than, the main characteristics of the electric propulsion drives are presented (chapter 5). Important design and engineering considerations are discussed (chapters 6 and 7) before ending by showing typical arrangements – by use of single line drawings of the electrical installations in some important applications (chapter 8). The reference list should not only serve as a link to the information presented in this section, but the publications are also recommended as a source for further studies of this topic.

## 1.2. Motivations for Electric Propulsion

The concept of electric propulsion is not new, the idea originated more than 100 years ago. However, with the possibility to control electrical motors with variable speed in a large power range with compact, reliable and cost-competitive solutions, the use of electrical propulsion has emerged in new application areas during the 80's and 90's.

Electric propulsion with gas turbine or diesel engine driven power generation is used in hundreds of ships of various types and in a large variety of configurations. Installed electric propulsion power in merchant marine vessels was in 2002 in the range of 6-7 GW (Gigawatt), in addition to a substantial installation in both submarine and surface war ship applications.

By introduction of azimuthing thrusters and podded thrust units, propulsion configurations for transit, maneuvering and station keeping have in several types of vessels merged in order to utilize installed thrust units optimally for transit, maneuvering and dynamically positioning (dynamic positioning - DP).

At present, electric propulsion is applied mainly in following type of ships: Cruise vessels, ferries, DP drilling vessels, thruster assisted moored floating production facilities, shuttle tankers, cable layers, pipe layers, icebreakers and other ice going vessels, supply vessels, and war ships. There is also a significant on-going research and evaluation of using electric propulsion in new vessel designs for existing and new application areas.

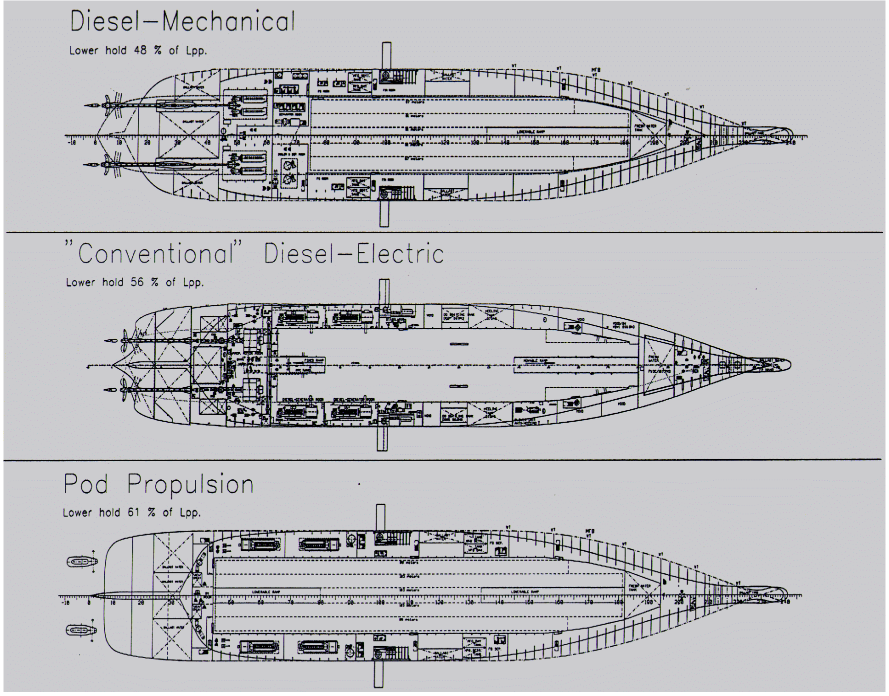


*Fig. 1.1. Three comparative concepts of a Ropax vessel showing how space can be better utilized with electric propulsion and podded propulsion.*

The following characteristics summarize the main advantages of electric propulsion in these types of vessels:

- Improved life cycle cost by reduced fuel consumption and maintenance, especially where there is a large variation in load demand. E.g. for many DP vessels a typically operational profile is equally divided between transit and station keeping/maneuvering operations.
- Reduced vulnerability to single failure in the system and possibility to optimize loading of prime movers (diesel engine or gas turbine).
- Light high/medium speed diesel engines.
- Less space consuming and more flexible utilization of the on-board space increase the payload of the vessel, see Fig. 1.1.
- Flexibility in location of thruster devices because the thruster is supplied with electric power through cables, and can be located very independent on the location of the prime mover.
- Improved maneuverability by utilizing azimuthing thrusters or podded propulsion.
- Less propulsion noise and vibrations since rotating shaft lines are shorter, prime movers are running on fixed speed, and using pulling type propellers gives less cavitation due to more uniform water flow.

These advantages should be weighted up against the present penalties, such as:

- Increased investment costs. However, this is continuously subject for revisions, as the cost tends to decrease with increasing number of units manufactured.
- Additional components (electrical equipment – generators, transformers, drives and motors/machines) between prime mover and propeller increase the transmission losses at full load.
- For newcomers a higher number and new type of equipment requires different operation, manning, and maintenance strategy.

High availability of power, propulsion and thruster installations, as well as safety and automation systems, are the key factors in obtaining maximum operation time for the vessel. The safety and automation system required to monitor, protect, and control the power plant, propulsion and thruster system, becomes of increasing importance for a reliable and optimum use of the installation (Blokland and van der Ploeg [18]).

## 1.3. Power Flow and Power Efficiency

In any isolated power system, the amount of generated power must be equal to the consumed power including losses. For an electric system consisting of an electric power generation plant, a distribution system, including distribution transformers and a variable speed drive, the power flow can be illustrated in Fig. 1.2.

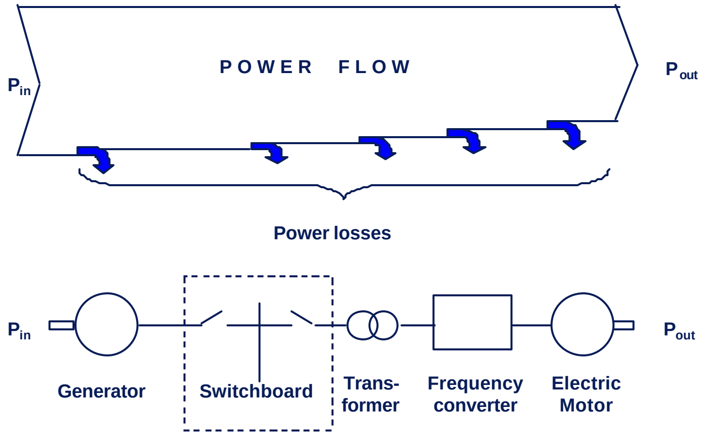


*Fig. 1.2: Power flow in a simplified electric power system.*

The prime movers, e.g. diesel engines or gas turbines, supply a power to the electric generator shaft. The electric motor, which could be the propulsion motor, is loaded by a power from its connected load. The power lost in the components between the shaft of the diesel engine and the shaft of the electric motor is mechanical and electrical losses which gives heat and temperature increase in equipment and ambient.

The electrical efficiency of the system in Fig. 1.2 is: $h = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}}$

For each of the components, the electrical efficiency can be calculated, and typical values at full (rated) power are for; generator: $\eta = 0.95\text{-}0.97$, switchboard: $\eta = 0.999$, transformer: $\eta = 0.99\text{-}0.995$, frequency converter: $\eta = 0.98\text{-}0.99$, and electric motor: $\eta = 0.95\text{-}0.97$.

Hence, the efficiency of a diesel electric system, from diesel engine shaft, to electric propulsion motor shaft, is normally between 0.88 and 0.92 at full load. The efficiency depends on the loading of the system.

Since the additional components between the prime mover and the propeller shaft in a diesel electric propulsion system contributes to a total of approximately 10% losses, the fuel savings potential is not due to the electrical component. One must regard the hydrodynamic efficiency of a speed controlled propeller compared to a fixed speed controllable pitch propeller (CPP), and the fuel efficiency of the prime mover when installed in a diesel electric system with constant speed and high loading, compared to in a mechanical propulsion system with strongly varying load. The differences may be significant, especially on low thrust operations as DP and maneuvering.

Fig. 1.3 shows the fuel efficiency of a typical medium speed diesel engine, and a power vs. thrust comparison of a variable speed and a controllable pitch propeller (CPP).

The hydrodynamic losses will vary significantly dependent on the operational condition for a CPP used in direct driven diesel solutions compared to variable speed fixed pitch propellers (FPP), which normally are used in electrical propulsion. In low load condition it is a rule of thumb that the zero-load hydrodynamic losses for a CPP is about 15%, while it is close to 0 for a speed controlled FPP, see Fig. 1.3(b). Notice that in most CPP configurations the propeller speed has to be kept constant on quite high rotations per minute (RPM) even though the thrust demand is zero. For FPP the variable speed drive will allow zero RPM at zero thrust demand. The advantage with CPP is that the propeller pitch ratio will be hydro-dynamically optimized for a wider speed range.

A propeller designed for high transit speed, will have reduced efficiency at low speed and vice versa. Hence, the operational profile is of major importance while designing the propulsion system.

The fuel efficiency characteristics of the diesel engine, with maximum fuel efficiency in the load range of 60 to 100% load, strongly contribute to the difference in power consumption for a traditional mechanical propulsion system, and a diesel electric propulsion system. In a power plant for diesel electric propulsion, the power generation will consist of multiple smaller diesel engines, where the number of running aggregates can be selected to have an optimum loading of each engine. The rating of the engines can also be adapted to fit the intended operational profile of the vessel, ensuring that it is possible to find an optimal configuration for most of the operational modes and time.

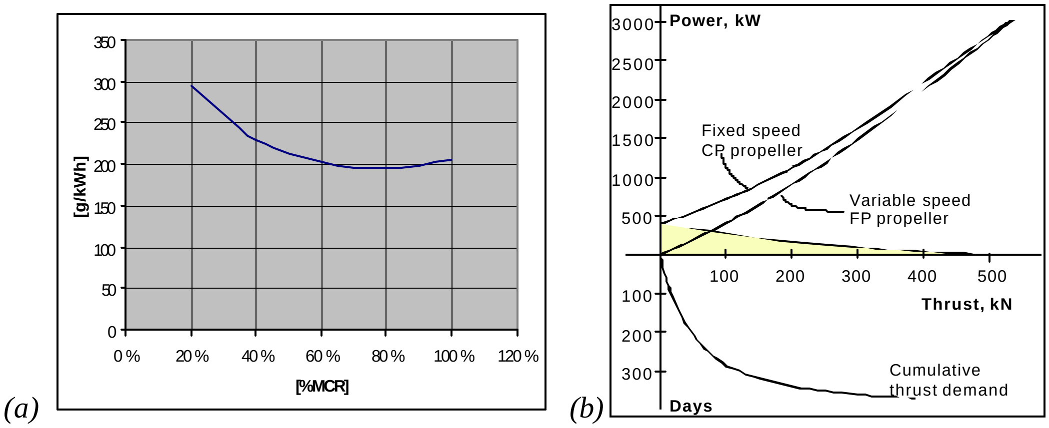


*Fig. 1.3: (a): Diesel engine specific fuel consumption (typical), Marintek [63] and (b): Propeller bollard pull characteristics (example), Ådnanes et.al. [57].*

For a field support vessel, with operational profile as shown in Fig 1.4, it was found that the fuel savings by using diesel electric propulsion was in the range of 700 tons of diesel per year. With a price of approx 40 cents per liter, this gives annual savings of in the order of 280 thousand USD. As shown, the savings will strongly be dependent on the operational profile, as shown in Fig 1.4(b). Here, the operational profile is split in DP/maneuvering and in Transit, showing how an increase portion of DP operations will increase savings, and vice versa.

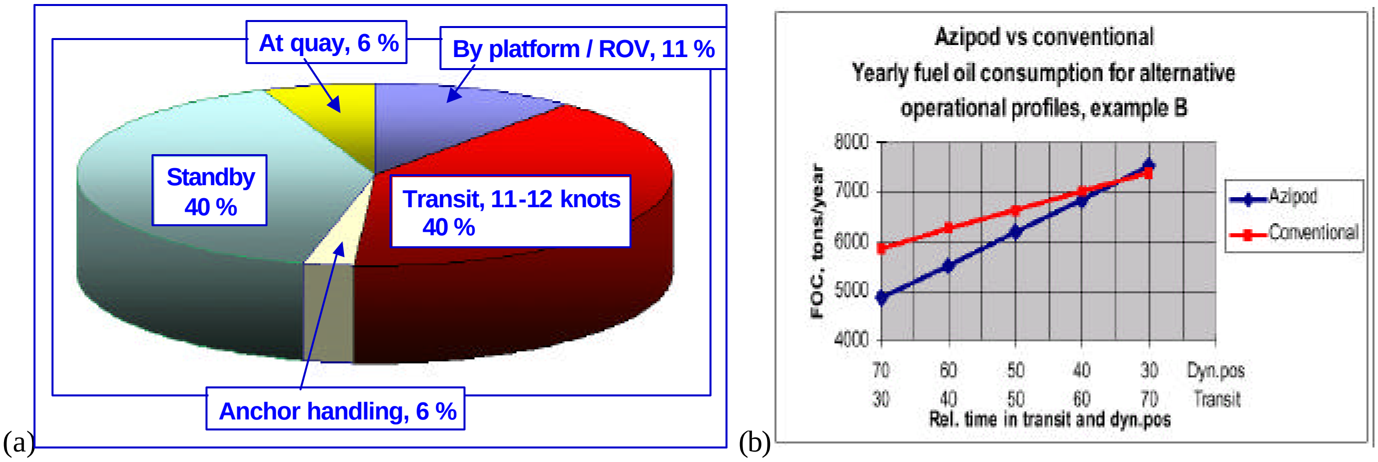


*Fig. 1.4: (a): Operational profile for a field support vessel. (b): Fuel consumption, compared for electric propulsion (Azipod) and conventional mechanical propulsion.*

## 1.4. Historical Overview of Electric Propulsion

After the rather experimental applications of battery driven electric propulsion at the end of the 19th century took place in Russia and Germany, the first generation electric propulsion was taken into use in the 1920's as a result of the strong competence of reducing transatlantic crossing times for passenger liners. At that time, the high propulsion power demand could only be achieved by turbo-electric machinery. "S/S Normandie" was one of the most renowned. Steam turbine generators provided electric power that was used to drive the 29MW synchronous electrical motors on each of the four screw shafts. The rotational speed was given by the electrical frequency of the generators. The generators would normally run one propulsion motor each, but there were also possibility for feeding two propulsion motors from each generator for cruising at lower speeds.

With the introduction of high efficient and economically favorable diesel engines in the middle of the 20th century, steam turbine technology and electric propulsion more or less disappeared from merchant marine vessels until the 1980's.

The development of variable speed electric drives, first by the AC/DC rectifier (Silicon Controlled Rectifier – SCR) in the 1970's and the AC/AC converters in the early 1980's enabled the power plant based electric propulsion system, which is typical for the second generation electric propulsion. A fixed voltage and frequency power plant consisting of a number of generator-sets feeding to the same network was supplying the propulsion as well as the hotel and auxiliary power. The propulsion control was done by speed control of the fixed pitch propellers (FPP). These solutions were firstly used in special vessels like survey ships and icebreakers, but also in cruise vessels. "S/S Queen Elizabeth II" was converted to electric propulsion in the mid 1980's, and later followed the Fantasy and Princess class cruise vessels, several DP vessels, and shuttle tankers. Notice that in direct driven diesel propulsion the thrust is normally controlled by a hydraulic system varying the propeller pitch angle. This is denoted as controllable pitch propellers (CPP).

Podded propulsion was introduced in early 1990's where the electric motor is installed directly on the fixed pitch propeller shaft in a submerged, rotateable pod. While this concept was originally developed to enhance the performance of icebreakers, it was early found to have additional benefits on hydrodynamic efficiency and maneuverability. After the fist application in a cruise liner, "M/S Elation", the advantages were so convincing that podded propulsion almost over night became a standard on new cruise liners, Fig. 1.5.

*Fig. 1.5: Cruise vessel "M/S Elation" (lower right) equipped with Azipod propulsion frees up space compared to sisterships (upper left) that can be utilized for other purposes, e.g. grey water treatement.*

# 2. Applications

## 2.1. Passenger Vessels – Cruise Ships and Ferries

Passenger vessels, cruise ships, and ferries have very high requirement for on-board comfort regarding noise and vibration. In addition, the reliability and availability is very critical for the safety of the passengers and the vessel. Consequentially, electric propulsion was early evaluated to be beneficial and taken into use.

The list of cruise vessels with electric propulsion is today long and increasing. As the podded propulsion is shown to give significant improvements in maneuverability and fuel costs, with an increase in propulsion efficiency of up to 10% (Kurimo [27]), a large and increasing portion of new-buildings are specified with electrical podded propulsion.

As the environmental concern is increasing, the requirements of reduced emission, spill, and damages on coral reefs by anchoring of the cruise vessels are increasing. Hence, the vessel must maintain its position solely by thrusters controlled by a DP system. This will increase the need for electrical propulsion and podded propulsion in the cruise market even more.

The same restrictions and tax penalties for gas emissions (COx, Nox and Sox) have resulted in that several recent new buildings of ferryboats for fjord and strait crossing have been equipped with electric propulsion. With frequent crossing schedules and quay docking, the improved maneuverability by podded propulsion has significantly reduced the fuel consumption. The propulsion power varies with the size of the vessel, from some few MW for smaller ferries up to 30-40 MW for large cruise liners. The hotel load can be a significant part of the total power installation, for a large cruise liner typically in order of 10-15 MW.

Fig. 2.1 shows a schematic overview of the main electrical and automation components in a typical cruise vessel with diesel-electric podded propulsion.

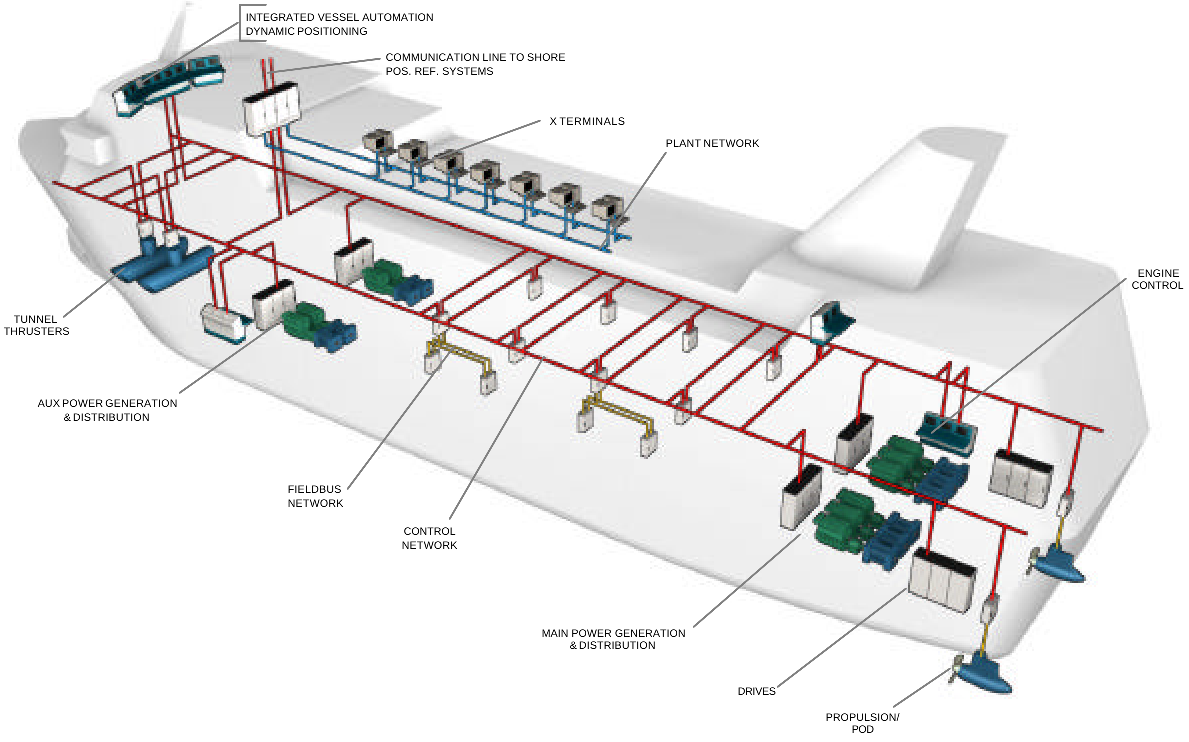


*Fig. 2.: Example of propulsion and control system layout for a cruise vessel.*

## 2.2. Oil and Gas Exploitation and Exploration: Drilling Units, Production Vessels and Tankers

Still a few years ago extensive oil and gas resources were accessible in shallow waters and could be exploited by fixed drilling and production units. In the North Sea, Gulf of Mexico (GoM), and Brazil as in several other areas, those new resources that remain are found in smaller and/or less available fields in deeper waters. These fields require new cost-effective methods to obtain acceptable economy and profit. Deep-water drilling and floating production have become possible with dynamic positioning or thruster-assisted position mooring. Thruster assisted positioning is applied in the North Sea, Canada, and areas with harsh environment. In Brazil, West Africa, and the planned USGOM (US Gulf of Mexico) installations, the trend has been to rely on mooring without thruster assistance for oil production and dynamic positioning for deepwater drilling.

The thrusters used for station keeping (DP operation) typically also constitutes the main propulsion in transit and maneuvering of the vessel, either all or selected units only.

Typical of these vessels is their large installed thruster power, typically 20-50 MW. Together with the production, drilling, utilities, and hotel loads, the installed power is typically 25-55 MW. The typical installation has a common power plant for all these loads, enabling flexibility to operation with high energy-efficiency and high availability. Fig. 2.2 shows a schematic overview of a semi-submersible drilling rig. See Farmer [10] and Ådnanes et.al. [57] and [59].

Shuttle tankers are used for transport of oil from an offshore facility (platforms, buoys, towers or FPSOs) to a processing or storage terminal onshore. There are numerous of different offloading methods in use. For most of them the shuttle tankers need to maintain a fixed position (station keeping) with high accuracy subject to varying environmental conditions. Therefore, there most of the shuttle tankers are equipped with a DP system. Most of the ships have installed electrical tunnel or azimuthing thrusters, whereof some are also having diesel-electrical systems for main propulsion, Hansa-Schiffart [14].

For many applications there is a high degree of redundancy in the propulsion for transit and station keeping. The solutions have normally a redundant power generation and distribution system, with redundant propulsion converters, and a tandem or redundant propulsion motor.

The introduction of podded propulsion may influence the design of the diesel-electric shuttle tankers, since it may be a more cost efficient solution to obtain redundant propulsion with to pod units than with two conventional shaft lines.

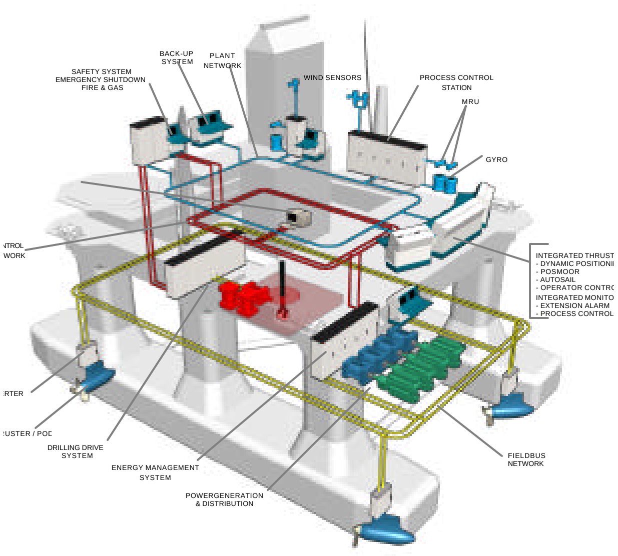


*Fig. 2.2: Example of electrical system layout for a semi-submersible drilling unit.*

## 2.3. Field Support Vessels and Offshore Construction Vessels

For vessels with dynamic positioning (DP) as the main operating mode, such as diving support vessels, crane ships, and pipe layers, electric propulsion was early taken into use, first with fixed speed CP propellers and later with variable speed thrusters.

The reduction in fuel consumption and environmental emission from diesel electric propulsion compared to conventional mechanical propulsion is significant for vessels with a diversified operational profile. Savings of 30-40% in fuel consumption annually has been reported from ship owners, and with the increased focus on operation costs and environmental impact from the oil industry, has given a large growth in number of field support vessels, first in the North Sea, and later in other geographical areas.

With the rapidly increasing need for high-speed communication system and a global fiber optic cable network, there has been established a large fleet of cable laying vessels with electric propulsion and dynamic positioning.

These vessels will be configured as DP vessels, class 2 or 3 (DnV [60], Lloyds [61] and ABS [62]), and most will have electric propulsion with a total power demand of 8-30 MW, depending on size and drilling/lifting capability.

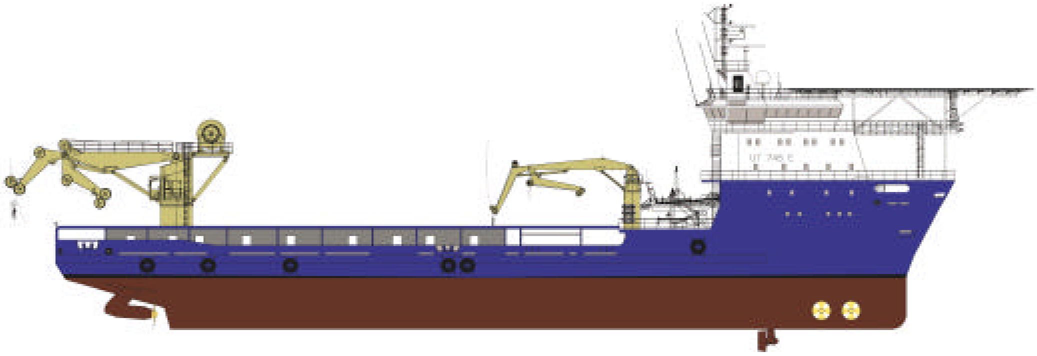


*Fig.2.3: Offshore supply vessel with electric propulsion.*

*Fig. 2.4: Some Offshore and Construction Vessels*

### 2.4. Dredgers and Construction Vessels

Diesel electric propulsion and station keeping facilities are also used in vessels for operations in more shallow waters, such as dredgers and construction vessels, wind mill installation vessels, etc.

Accurate maneuverability with improved fuel economy, in combination with a need to move working place frequently are typical performance criteria that are beneficial for electric propulsion in these applications. In ships with a large ship service electrical installation, the power plant can also be utilized better by combining the plants for ship service and propulsion power generation and achieve better redundancy and utilization of installed power capacity.

### 2.5. Yachts and Leisure Boats

A small and niche application area for electric propulsion is the yachting market. Comfort and environmental friendliness are essential design criteria for these ships, and electric propulsion with high requirements to low vibration and noise with high efficiency is now becoming more common.

The installed propulsion power is typically in the range of 500kW to 2000kW, and for larger ships even higher.

### 2.6. Icebreakers and Ice Going Vessels

The dynamic requirements for the frequency converters in propulsion application are low, compared to many other industrial applications. But in ice-going vessels and icebreakers, the load variations may be significant and rapid, and this implies that the propulsion system must have high dynamic performance in order to avoid overloading of components and undesired tripping. Electric propulsion has been used in a majority of new-buildings since the 80's. The basic configuration can be similar as for service vessels, with a redundant power generation and distribution system, although there will normally not be any DP requirement for the icebreakers.

As oil exploitation in arctic regions emerges, there is also an increasing demand for icebreaking and ice going field support, escort, and shuttle tankers.

The installed propulsion power may be in the range of 5-55MW, depending on ice breaking capability.

*Fig. 2.5: "M/S Botnica", Icebreaker which serves as a supply vessel in summer season, equipped with Azipod propulsion.*

### 2.7. War Ships

Despite the great interest in the application of electric propulsion to warships, there are quite few conventional surface warships with pure electric propulsion, but more are being projected. For sub-marines, electric propulsion with diesel engine generation and battery storage, fuel cell or nuclear power plant is applied.

Electric propulsion for war ships does not conceptually differ much from the merchandise vessels, but the solutions may differ since the requirements to availability and redundancy are normally stricter. Also, the ability to withstand shock and provide low noise signatures are prerequisites for electric drive when applied to a warship.

Fig. 2.6 shows the K/V Svalbard, a coast guard vessel in service since 2002 for the Norwegian Navy, equipped with dual Azipod propulsion system, and partially fulfilling military requirements.

*Fig. 2.6: "K/V Svalbard", Ice breaking coast guard vessel with podded propulsion for the Norwegian Navy.*

## 2.8. Research Vessels

Geo technical research vessels, oceanographic vessels, and fishing research vessels have in common very strict underwater noise requirements, typically several decades dB below normal levels for other applications.

This has traditionally been achieved by use of direct propulsion with DC motors, special considerations for filtering and reduction of vibrations and torque variations.

By use of modern frequency converters and filtering techniques, AC motors have become feasible for such high demanding applications as well, and are now taken into use in recent ship designs.

## 2.9. Trends and New Applications

Electric propulsion is continuously being investigated and evaluated for new applications. LNG and chemical tankers, Ro-Ro vessels, container vessels, fishing vessels are typical examples of large volume markets where electric propulsion yet is not taken into use because of the increased investment costs.

However, only small changes in operation and design criteria, such as increased fuel or emission costs, regulatory restrictions, and equipment cost reduction, may give a tremendous shift in technology application for several of new areas.

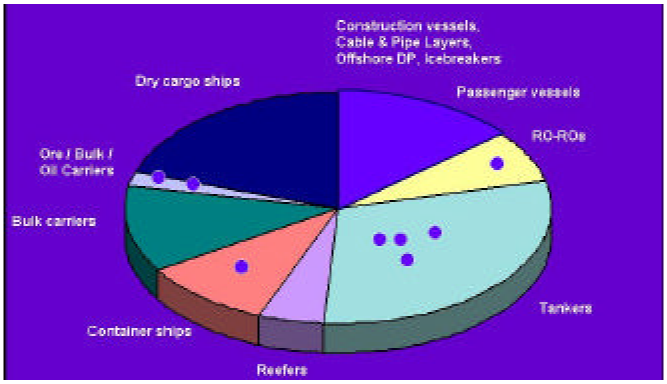


*Fig. 2.7: The world new build market of ships. Electric propulsion dominates in the sectors of construction, cable and pipe layers, offshore, icebreakers, and passenger vessels. In other segments, electric propulsion is less in use although there is a significant increase in interest for conceptual studies and designs.*

# 3. Overview of Electric Power System

## 3.1. Introduction

The main difference between the marine and a land-based electrical power system is the fact that the marine power system is an isolated system with short distances from the generated power to the consumers, in contrast to what is normal in land-based systems where there can be hundreds of kilometers between the power generation and the load, with long transmission lines and several voltage transformations between them. The amount of installed power in vessels may be high and this gives special challenges for the engineering of such systems. High short circuit levels and forces must be dealt with in a safe manner. The control system in a land-based electrical power system is divided in several separated sub-systems, while in a vessel; there are possibilities for much tighter integration and coordination.

The design of power, propulsion and control systems for a vessel have undergone significant changes and advances over a relatively recent period of time. Because of the rapidly expanding capabilities of computers, microprocessors and communications networks, the integration of systems which were traditionally separate, stand alone systems is now not only feasible, but fast becoming industry standards. The increasing demand for redundant propulsion and DP class 2 and class 3 vessels, requires system redundancy with physical separation. The interconnections of the diverse systems on a vessel have become increasingly complex, making the design, engineering and building of a vessel a more integrated effort.

Fig. 3.1 shows the schematics of the main power installations in a vessel with electric propulsion in a *Single Line Diagram (SLD).* This chapter describes the main components as they are applied in a marine electric installation:

- Electric Power Generation
- Electric Power Distribution
- Variable Speed Drives
- Propulsion / Thruster units

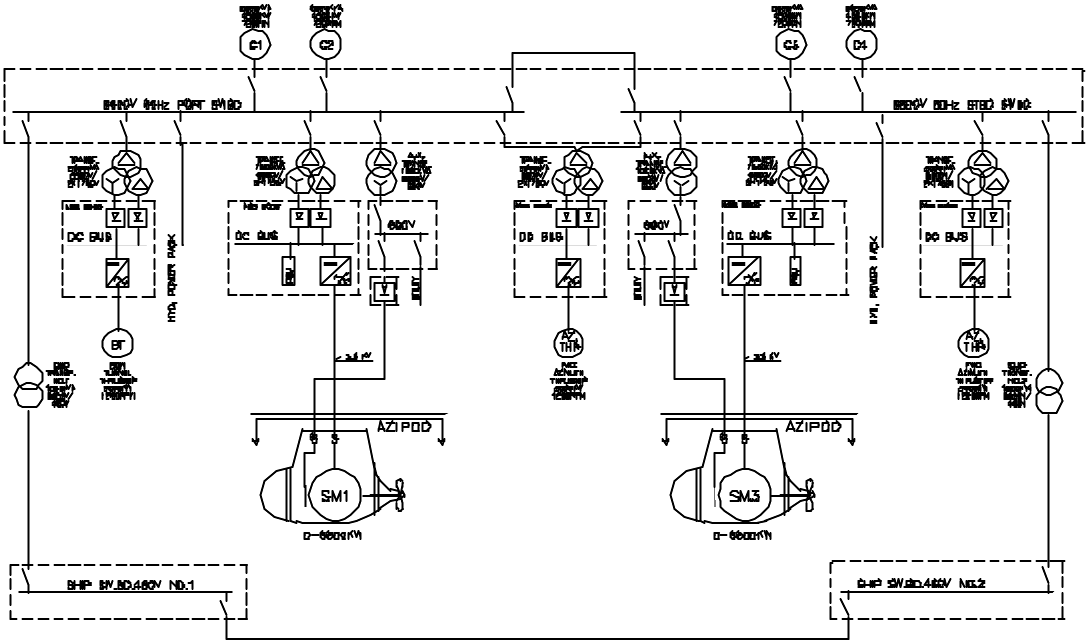


*Fig. 3.1: Single line diagram for a ship with podded electric propulsion;*
*G1-G4: Generators, SWBD: Switchboard, TRANSF: Transformer, BT: Bow Thruster,*
*AZ THR: Azimuthing thruster, AZIPOD$^{®}$: Podded propulsion.*

## 3.2. Electric Power Generation

### 3.2.1. Prime Mover

The source for power is most often a generator set driven by a combustion engine which is fueled with diesel or heavy fuel oil. Occasionally one can find gas engines [64], and also gas turbines, steam turbines or combined cycle turbines, especially for higher power levels, in light high-speed vessels, or where gas is a cheap alternative (e.g. waste product in oil production, boil-off in LNG carriers, etc.).

In a diesel-electric propulsion system, the diesel engines are normally medium to high-speed engines, with lower weight and costs than similar rated low speed engines that are used for direct mechanical propulsion. Availability to the power plant is of high concern, and in a diesel electric system with a number of diesel engines in a redundant network; this means high reliability but also sophisticated diagnostics and short repair times.

The combustion engines are continuously being developed for higher efficiency and reduced emissions, and at present, a medium speed diesel engine has a fuel consumption of less than 200g per produced kWh at the optimum operation point as seen in Fig. 3.2a). Even though this is regarded to be a high utilization factor of fuel, it represents only about 40% of the energy in the fuel, the rest of the energy being removed by the exhaust or heat dissipation.

Moreover, the efficiency drops fast as the load becomes lower than 50% of MCR (Max Continuous Rating). At this working condition, the combustion is inefficient, with high NOx and SOx content, and with a high degree of soothing which increases the need for maintenance. In a diesel electric system with several diesel engines it is hence an aim to keep the diesel engines loaded at their optimum operating conditions by starting and stopping generator sets dependent on the load, as seen in Fig 3.2b), with an aim to keep the average loading of each running diesel engine closest possible to its optimum load point.

For detailed description of design and functionality of diesel combustion engines, see Mahon [66].

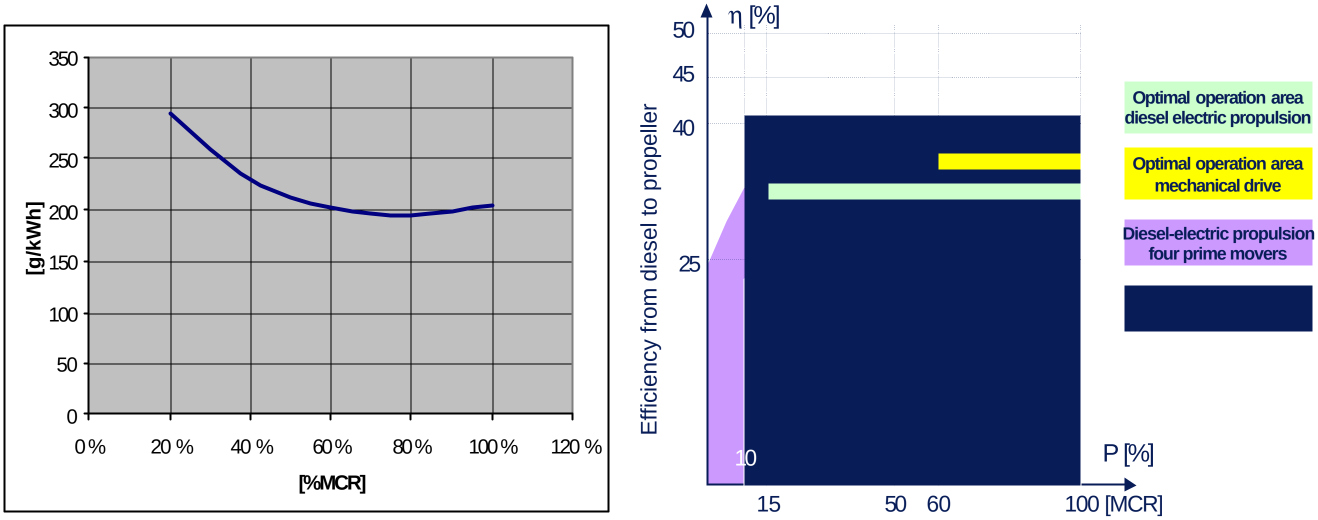


*Fig 3.2: a) Example fuel consumption for a medium speed diesel engine.*
*b) Total efficiency from engine to propeller shaft, in a single machine direct mechanical propulsion system and a four machine diesel electric propulsion system.*

### 3.2.2. Generators

The majority of new buildings and all commercial vessels have an AC power generation plant with AC distribution. The generators are synchronous machines, with a magnetizing winding on the rotor carrying a DC current, and a three-phase stator winding where the magnetic field from the rotor current induces a three-phase sinusoidal voltage when the rotor is rotated by the prime mover. The frequency $f$ [Hz] of the induced voltages is proportional to the rotational speed $n$ [RPM] and the pole number $p$ in the synchronous machine:

$$f = \frac{p}{2} \cdot \frac{n}{60}$$

A two-pole generator will give 60Hz at 3600RPM, a four-pole at 1800RPM, and a six-pole at 1200RPM, etc. 50Hz is obtained at 3000RPM, 1500RPM, and 1000RPM for two-, four-, and six-pole machines. A large medium speed engine will normally work at 720RPM for 60Hz network (10 pole generator) or 750RPM for 50Hz networks (8 pole generator).

The DC current was earlier transferred to the magnetizing windings on the rotor by brushes and slip rings. Modern generators are equipped with brushless excitation for reduced maintenance and downtime, Fig 3.3. The brush-less excitation machine is an inverse synchronous machine with DC magnetization of the stator and rotating three-phase windings and a rotating diode rectifier. The rectified current is then feeding the magnetization windings.

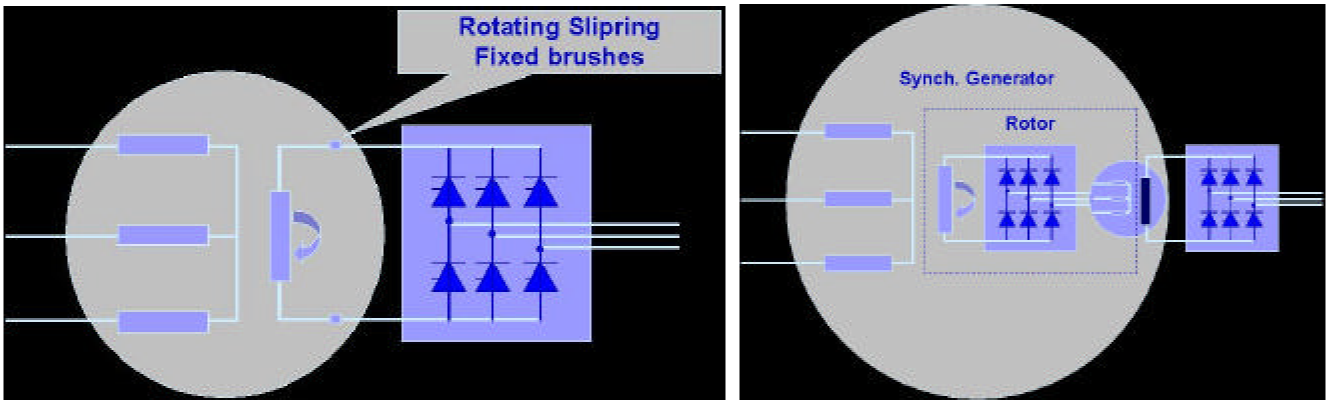


*Fig 3.3: Magnetization of the rotor winding, left: brushed; right: brush-less magnetization.*

The excitation is controlled by an automatic voltage regulator (AVR), which senses the terminal voltage of the generator and compares it with a reference value. Simplified, the controller has PID characteristics, with stationary limited integration effect that gives a voltage drop depending on the load of the generator. The voltage drop ensures equal distribution of reactive power in parallel-connected generators. According to most applicable regulations, the stationary voltage variation on the generator terminals shall not exceed ±2.5% of nominal voltage. Also, the largest transient load variation shall not give voltage variation exceeding -15% or +20% of the nominal voltage unless other has been specified and accounted for in the overall system design. In order to obtain this transient requirement, the AVR is normally also equipped with a feed-forward control function based on measuring the stator current.

In addition to the magnetizing winding, the rotor is also equipped with a damper winding which consists of axial copper bars threaded through the outer periphery of the rotor poles, and short circuited by a copper ring in both ends. The main purpose of this winding is to introduce an electromagnetic damping to the stator and rotor dynamics. A synchronous machine without damper winding is inherently without damping and would give large oscillations in frequency and load sharing for any variation in the load.

The stationary, transient and sub-transient models are known from the theory of synchronous machines. Simplified one could say that the flux linkages in the damper winding, which are “trapped” and resist changes due to being short-circuited, characterize the sub-transient interval. This is observed as an apparent lower inductance in the generator, which gives a stiffer electric performance during quick load variations, and helps to reduce transient voltage variations and the voltage variations due to harmonic distortion in load currents. This effect is only contributing for dynamic variations faster than characterized by the sub-transient time constant such as the first period of motor start transients and transformer inrush, and for harmonic distorted load currents.

Often, the generators are connected to a propulsion engine’s shaft, i.e. a shaft generator. The shaft generators are in some applications made for two-directional power flow, which means that it can be run as motor. This principle may be called a PTI-PTO concept (Power take-in – Power take out). Shaft generators have the disadvantage of forcing the main propeller to work at fixed speed if the generator output shall have constant frequency. This will reduce the efficiency of the propeller in low load applications. Static converters may be installed to keep fixed frequency for variable speed.

## 3.3. Electric Power Distribution

### 3.3.1. Switchboards

The main (or generator) switchboards are usually distributed or split in two, three, or four sections, in order to obtain the redundancy requirements of the vessel. According to rules and regulations for electric propulsion, one shall tolerate the consequences of one section failing, e.g. due to a short circuit. For strictest redundancy requirements, one shall also tolerate failure due to fire or flooding, meaning that water and fireproof dividers must be used to segregate the sections.

In a two-split configuration, with equally shared generator capacity and load on both sides, the maximum single failure scenario will hence be to loose 50% of generator capacity and loads. In order to avoid a high installation costs, the system will often be split in three of four, which reduces the required additional installations. Also, change-over switches which ensures that a generator or a load can be connected to two switchboard sections will have similar cost reducing effects, e.g. for azimuth thruster in Fig. 3.1.

In propulsion mode, the switchboards are normally connected together, which gives the best flexibility in configuration of the power generation plant. The load transients are distributed on a large number of diesel-generators, and the most optimal number of units can be connected to the network.

Another possibility is to sail with independent switchboard parts supplying two or more independent networks. In this case the ship is often assumed to be virtually blackout proof, which could be attractive in congested waters. In this operating mode one network including it’s connected propulsion units is lost if one switchboard section fails, the other, however, remaining operable. I practice, there are also other considerations to be made in order to obtain such independence, especially all auxiliaries, such as lubrication, cooling, and ventilation must be made independent. Also, loss of propulsion or station keeping power on one part of the system, will through control systems also have impact on the remaining parts, as the total power or thrust tends to be kept the same, e.g. for dynamic positioning.

The normal operation in DP vessels, in particular for class 3 operations, is to split the network in order to be tolerant to failure of one section. However, rules and regulations now allows for operation with closed tie breakers, if the protection circuits are designed to detect and isolate faulty parts without tripping the healthy parts. The NMD rules (Norwegian Maritime Directorate) has one of the more stricter practicing of these rules and will normally not accept connected networks in class 3 operations.

As the installed power increases, the normal load currents and the short circuit currents will increase. With the physical limitations on handling the thermal and mechanical stresses in bus bars and the switching capacity of the switchgear, it will be advantageous or necessary to increase the system voltage and hence reduce the current levels. Medium voltage has become a necessity to handle the increasing power demand in many applications.

Using the IEC voltage levels the following alternatives are most common selected for the main distribution system, with application guidelines from NORSOK [64]:

- 11kV: Medium voltage generation and distribution. Should be used when total installed generator capacity exceeds 20MW. Should be used for motors from 400kW and above.
- 6.6kV: Medium voltage generation and distribution. Should be used when total installed generator capacity is between 4-20MW. Should be used for motors from 300kW and above.
- 690V: Low voltage generation and distribution. Should be used when total installed generator capacity is below 4MW. Should be used for consumers below 400kW and as primary voltage for converters for drilling motors.
- For utility distribution lower voltage is used, e.g. 400/230V.

A few comments to these guidelines are necessary;

- Where a major part of the load consists of variable speed drives with no contribution to the short circuit level, there will normally not be any problems to utilize each voltage level to significantly higher generator capacities. For optimizing the installation, one should in each case calculate load and fault currents and select the right solution.
- In ships, low voltage (690V) motors are normally used for much higher power levels than 300kW. In each case, one must consider the load current, and starting characteristics for the drive, including alternative starting methods together with a comparison on overall costs.
- 440V distribution is quite common in ship installations. A lot of ship equipment is available only in 440V, which means that it might be difficult to avoid this voltage level in ship applications.

In US, or where the ANSI standard applies, several additional voltage levels are recognized, such as in [24]: 120V, 208V, 230V, 240V, 380V, 450V, 480V, 600V, 690V, 2400V, 3300V, 4160V, 6600V, 11000V, and 13800V. 3300V is also a commonly used system voltage in IEC applications, even though not recognized in [64].

Since the load current and fault current determine the limitation of the equipment, the actual power limits for each system voltage may deviate from these recommendations. This particularly applies to systems where a major part of the load is converter loads and does not contribute to short circuit power. Since these do not contribute to short circuit currents in the distribution system, it often allows increasing the power limits for the different voltage levels.

Safety is an issue of concern when yards and ship owners changes from low to higher voltages, often leading to a misunderstanding effort to keep voltages as low as possible. In the context of safety, it should be regarded that medium voltage switchboards is designed to prevent personnel to get contact with conductors, even in maintenance of the switchgears. The normal and fault currents are similarly smaller, giving less forces on the conductors and cables during e.g. short circuit. Although short circuits inside the switchboards are extremely rare, arc-proof design (IEC 60298-3) is available and will prevent person injury and limit the equipment damages if worst case should occur.

Circuit breakers are used for connecting and disconnecting generator or load units to the switchboards, or different parts of the switchboards together. Various circuit breaker technologies are applied. Air insulated units are the traditional solution, but today rarely applied except at low voltage levels. In the commonly used SF6 and vacuum breaker technologies, the current interruption takes place in an enclosed chamber, where the first one is filled with SF6 gas, which has higher insulation strength than air, and the vacuum breaker is evacuated by air. These designs give compact and long term reliable solutions for medium voltages. One should consider that vacuum breakers may chop the current and can cause overvoltage spikes when breaking an inductive loads with high di/dt that may require installation of overvoltage limiters.

For smaller powers, fused contactors are a cost and space beneficial alternative to the circuit breaker, and are available in air (low voltage), SF6 or vacuum insulated types. The problem with switching spikes is less with fused contactors since current interruption is softer (lower di/dt).

### 3.3.2. Transformers

The purpose of the transformer is to isolate the different parts of the electric power distribution system into several partitions, normally in order to obtain different voltage levels and sometimes also for phase shift. Phase shifting transformers can be used to feed frequency converters, e.g. for variable speed propulsion drives, in order to reduce the injection of distorted currents into the electric power network by canceling the most dominant harmonic currents. This reduces the voltage distortion for generators and other consumers. The transformers also have a damping effect of high frequency conductor emitted noise, especially if the transformer is equipped with a grounded copper shield between primary and secondary windings.

There are numerous different transformer designs in use, and the most common types are; air insulated dry type, resin insulated (cast or wound), or oil/fluid insulated. Regulations, ambient conditions, and user's, yard's, or supplier's preferences govern the selection of type, material, and design of the transformer.

Physically, the transformer is normally built as three-phase units, with three-phase primary coils and three-phase secondary coils around a common magnetic core. The magnetic iron core constitutes a closed path for magnetic flux, normally with three vertical legs and two horizontal yokes; one in bottom and one at top. The inner winding constitutes the low voltage or secondary windings, and the outer is the primary or high voltage winding. The ratio of primary to secondary windings gives the transformation ratio. The coils may be connected as a Y-connection or Δ-connection (also called D-connection). The connection may be different on primary and secondary sides, and in such transformers, not only the voltage amplitude will be converted, but there will also be introduced a phase shift between the primary and secondary voltages. The phase shift can also be adjusted by use of Z-connected windings, normally in the primary, where the phase shift angle can be accurately determined by the ratio of turns in the segments of the Z-windings. Three- or four winding transformers with multiple secondary windings are also in use, e.g. for multi-pulse drive applications.

A transformer with Δ-connected primary and Y-connected secondary is called a Dy type transformer. The first and capital letter describes the primary winding, and the second and small letter describe the secondary winding. The letter *n* is used to describe if the common point in a Y-connection is grounded, e.g. Dyn or Ynyn.

Transformers may be designed according to IEC standards. For converter transformers, it is essential that the design accounts for the additional thermal losses due to the high content of harmonic currents. IEC also gives design rules and guidelines for such applications.

## 3.4. Motor Drives for Propulsion and Thrusters

### 3.4.1. Introduction

The electrical motor is the most commonly used device for conversion from electrical to mechanical power and is used for electric propulsion, thrusters for propulsion or station keeping, and other on-board loads such as winches, pumps, fans, etc. Typically, 80-90 % of the loads in ship installations will be some electrical motors.

In this chapter, a brief overview of different motors and their applications in ship installations is given and for more detailed description of design, performance, and characteristics, references to other books are made.

The electrical motors in use are:

- DC motors.
  The DC motor must be fed from a DC supply, and since the power generation and distribution system normally is a three-phase system, this means that a DC motor must be fed from a thyristor rectifier. This gives also a speed control of the motor. For detailed description of the various construction of the DC motor, see Fitzgerald et.al. [68].

- Asynchronous (induction) motors.
  The asynchronous or induction motor is the workhorse of the industry. Its rugged and simple design ensures

in most cases a long lifetime with a minimum of breakdown and maintenance. The asynchronous motor is used in any applications, either as a constant speed motor directly connected to the network, or as a variable speed motor fed from a static frequency converter. Fitzgerald et.al. [68] gives a good explanation on design and operating performance of asynchronous motors.

- Synchronous motors.
  The synchronous machine is normally not used as a motor in ship applications, with exception of large propulsion drives, typically >5MW directly connected to propeller shaft, or >8-10MW with a gear connection. In power range smaller than this, the asynchronous motor is normally cost-competitive. The design of a synchronous motor is similar to that of an synchronous generator. It is normally not used without a frequency converter supply for variable speed control in ship applications. See [68] for design and operating performance.

- Permanent magnet synchronous motors.
  Permanent magnet synchronous motors are used in industrial drives for some few kW drives, also for direct on-line applications. In recent years, it has been introduced also for large power applications; in several MW propulsion drives, firstly in navy applications but now also in podded propulsion applications. The benefit of this design is high efficiency with compact design, making it especially interesting for podded propulsion where the dimensions should be as small as possible, and direct water cooling would eliminate the need for air cooling of the pod motor and simplify the construction and installation work. See [65] for description of design and performance.

- Other motors.
  A range of other motors is used in commercial or experimental applications. Few of them have gained a high market share, and especially not in marine applications. It might in future be seen some new concepts for variable speed drives, based on motor designs with higher efficiency, small dimensions, or specially designed for certain applications. They will most likely though be based on the principles described above or derivatives of these.

### 3.4.2. The constant speed, Direct-on-Line motor

An electric motor can be directly connected to the network, and such direct-on-line (DOL) motors are normally three-phase asynchronous, or induction motors. The asynchronous motor has a rugged and simple design, where the three-phase stator windings are similar to a generator stator winding. The rotor is cylindrical, with a laminated iron core and a short-circuited winding similar to the damper winding in a synchronous machine. At no-load, the voltages imposed to the stator winding will set up a magnetic field in the motor, which crosses the air gap and rotates with a speed given by the frequency of the imposed voltages, called synchronous frequency, $f_s$. The synchronous speed $n_s$ is hence:

$$n_s = \frac{f_s \cdot 60}{p/2} \text{ [RPM]}$$

As the shaft gets loaded, the rotor speed will decrease, and there will be induced currents in the rotor winding since they are rotating relatively to the synchronous rotating magnetic field from the stator windings. One defines the slip, $s$, as the relative lag of motor speed to the synchronous speed $n_s$:

$$s = \frac{n_s - n}{n_s}.$$

Hence the slip varies from 0 (no-load) to 1 (blocked rotor). The slip at rated load is normally below 0.05 (5%) for most motor designs, and even lower (2-3%) for large motors.

From the electrical model of the asynchronous motor, a mathematical formula can be developed for the rotor and stator current, shaft torque, and power as a function of slip. A complicating factor is that the parameters, especially the rotor parameters, are very dependent on the slip, i.e. frequency of the rotor currents, and these frequency dependencies must be regarded in order to obtain accurate results.

Fig. 3.4 shows the stator currents and shaft torque for an asynchronous motor, which is connected to a fixed frequency and stiff network, as function of rotor speed or slip. It also indicates the load curve for a typical CPP thruster application at zero pitch and full pitch. Start-up of a thruster motor should always be done with zero pitch in order to make sure that sufficient torque margin is available to secure start-up, and to minimize the starting time.

Under stationary conditions, the motor speed is close to synchronous speed, and the induced rotor currents are nearly proportional to the slip, and also the shaft torque. From the electrical model in Fig 3.16, one can then derive a simplified expression of the resulting rms stator current, $I_s$:

$$I_s = \sqrt{I_m^2 + I_r^2} = \sqrt{I_{mN}^2 + I_{rN}^2 \cdot \frac{T}{T_N}}$$

$I_m$ is the magnetizing current flowing through the magnetizing inductance $L_m$, neglecting magnetizing losses in $R_m$. $I_r$ is the rotor current referred to stator side, and $T$ is the torque. A subscript $N$ annotates quantities under nominal (rated) conditions, and simplified one may express, if neglecting effects of leakage inductance in rotor and stator:

$I_{mN} = I_{sN} \cdot \cos\phi_N$

$I_{rN} = I_{sN} \cdot \sin\phi_N$

When the slip approaches the peak torque and higher, the assumptions are not valid any longer, since the effects from neglecting leakage inductances becomes considerable, and the load stator current will typically follow a characteristics as shown in Fig. 3.4, typically with a quite flat current amplitude of approximately five times nominal current (locked rotor current).

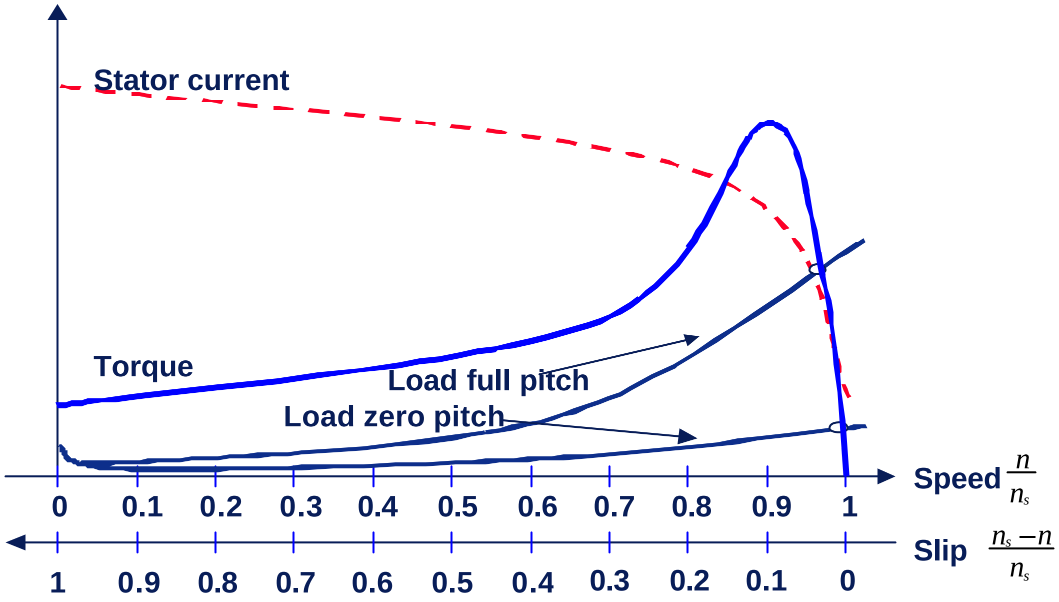
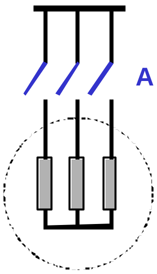


*Fig. 3.4: Load characteristics for a direct on line asynchronous motor with load curves for a CPP propeller.*

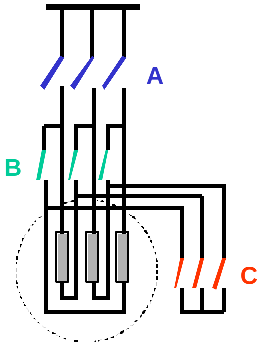
Due to the high starting current of asynchronous machines, it will often be necessary to install devices for soft starting. Soft starters typically reduce the locked rotor currents from 5 times to 2-3 times nominal current, and thereby also reduce the voltage drop. Soft starters must always be adapted to the load characteristics, as their principle is based on reducing the motor voltage at start-up, and hence reducing the torque capability of the motor. The most commonly used are:



**Direct On-Line (DOL):**

Start and running: A closed.

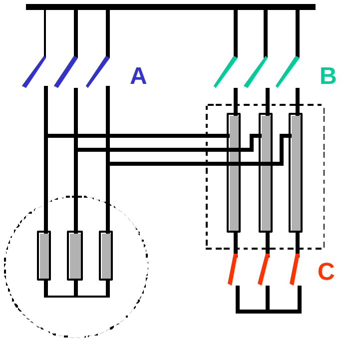
Used for motor ratings relatively low compared to running generator capacity, where electrical start-up transients are within acceptable limits and the load permits the starting torque transients.



**Star-Delta (Y-D) or Wye-Delta coupling:**

Start: A and C closed, B open
Running: A and B closed, C open

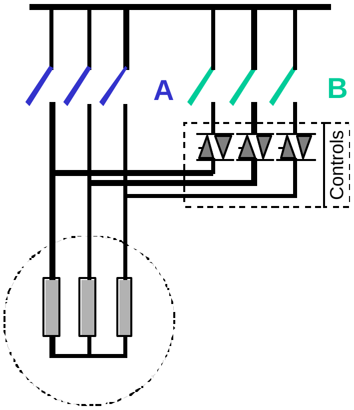
Reduces the starting current to about 1/3 of direct on line starting, but also reduces the starting torque similarly. The method can be used to reduce electrical start-up transients to acceptable values. The starting torque of the load must be low in order to ensure acceptable acceleration.



**Autotransformer start:**

Start: B and C closed, A open
Running: A closed, B and C open

Reduces the starting current, dependent on the ratio of the autotransformer. The network current is smaller than the motor current, given by the ratio of the transformer.
The starting torque is being reduced and must be checked to ensure acceptable acceleration of the load.



**Semiconductor (thyristor) soft-starters:**

Start: B closed, soft-starter used to control motor voltage.
Running: Normally a by-pass switch A to reduce losses.

Used to reduce the electrical starting transients in the network. The controls of the soft-starter can be utilized to program various acceleration ramps and adapt to possible constraints of the load. Since the starting torque is being reduced by the square of the motor voltage, the start characteristics must be carefully tuned in order to ensure acceptable acceleration.
During start-up, the soft starter generates 6-pulse harmonic distortion of the supply voltage.

### 3.4.3. Variable speed motor drives and control strategies

The direct on line motor will rotate with a speed directly determined by the network frequency. For propulsion, thrusters, pumps, winches, etc., there might be significant savings in power or fuel consumption by reducing the no-load dependent losses in operations. Also, controllability of the driven load will be greatly enhanced by controlling the speed of the motor. The penalty is primarily economically, by introducing additional investment costs, and also components that require maintenance. Reduced operating costs or increased earnings should pay back the additional investment if the investment shall be justified. With energy cost (including fuel, maintenance, taxes, etc.) of 1NOK per kWh for generated power onboard a vessel, one will save 8.76 million NOK (approx 1.1 million USD) annually for a 1MW average power reduction.

The most commonly used motor drives are:

- Voltage source inverter (VSI) type converters for AC motors, i.e. asynchronous, synchronous and permanent magnet synchronous motors.
- Current source inverter type (CSI) converters for AC motors, normally synchronous motors
- Cycloconverters (Cyclo) for AC motors, normally for synchronous motors
- DC converters, or SCR (Silicon Controlled Rectifier) for DC motors

In ships, the most used variable speed drives uses AC motors. Most drives, except the cyclo converter, will consist of a rectifier, which rectifies the line voltage, and an inverter, which generates the variable frequency and variable voltage source for the motor. More detailed description of these concepts will follow in a later section.

A motor controller contains the speed control, and the control of motor currents by controlling the switching elements of the rectifier and/or inverter. An interface to an overriding control system, vessel management system, maneuvering control, or dynamic position control is normally required. The motor controller acquires measurement signals and feedback signals from sensors in the drive, and motor. Typically motor currents, motor speed, and in some cases temperatures and voltages are measured.

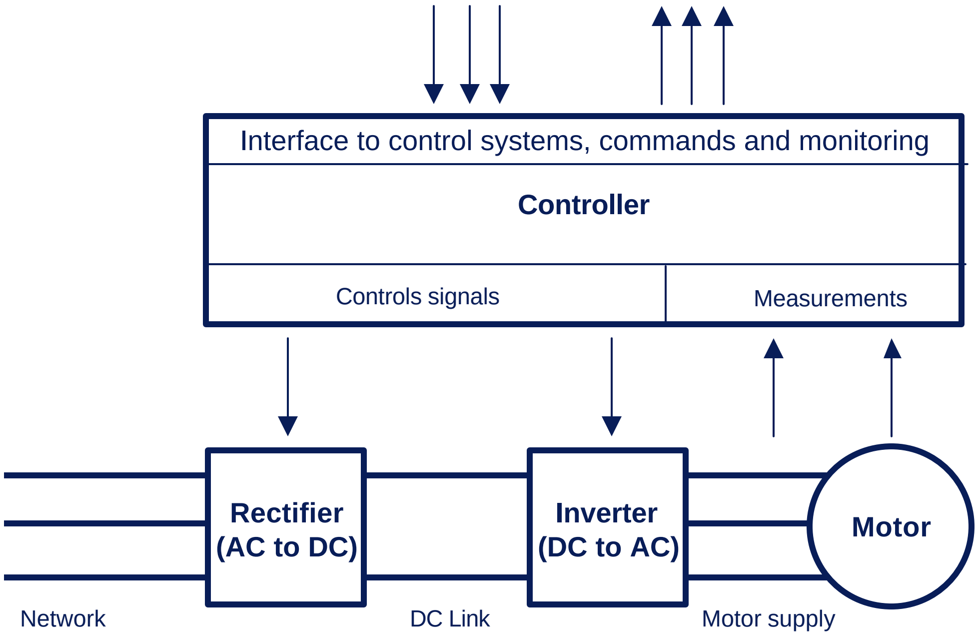
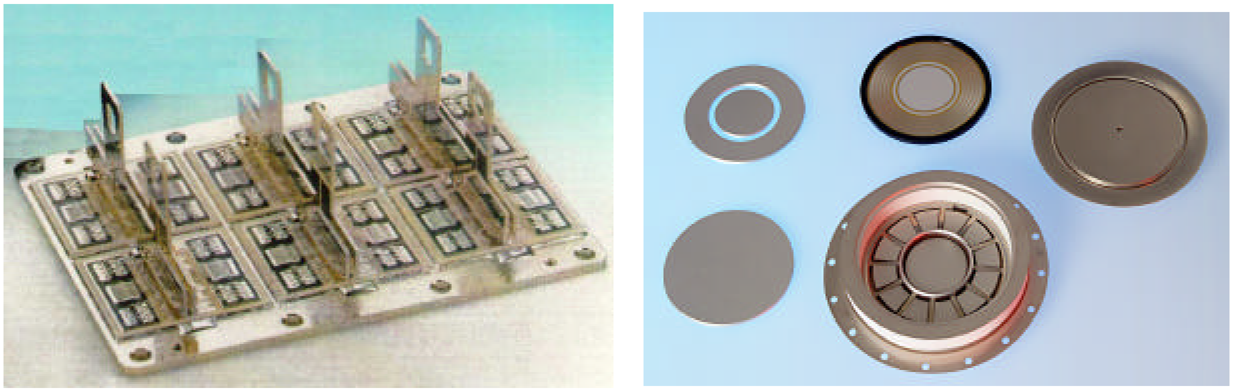


*Fig. 3.5: Schematics of a variable speed drive, showing a frequency converter with DC Link, typically for VSI and CSI type converters.*

The semiconductor components of the power electronic circuits are either uncontrollable (diodes) or controllable (thyristors, IGBTs, IGCTs). Fig 3.6 shows a low voltage IGBT module, containing all switching elements for a 690V inverter module, and a discrete medium voltage IGCT used in 3300V inverters.

Power electronics is regarded as a separate field of science, and for further studies, [67] and [69] can be recommended.



a) b)

*Fig 3.6:* *a) An IGBT with the encapsulation removed. This consists of several integrated components in one module.*
*b) An IGCT "hockey puck" opened, showing its building components. The silicon wafer is on top (middle).*

A motor can, if designed for it, run in both directions, with either a driving (motoring) or braking shaft torque. In order to categorize what conditions the motor drive is designed for, the *quadrant* terms are often applied. The quadrants refer the four quadrants of a speed-torque diagram, as shown in Fig 3.7. The motor is motoring, i.e. running the load with power input to the load shaft in quadrants I and III. Oppositely, the motor is braking, i.e. mechanical power is transferred from the load to the drive, when operating in quadrants II and IV.

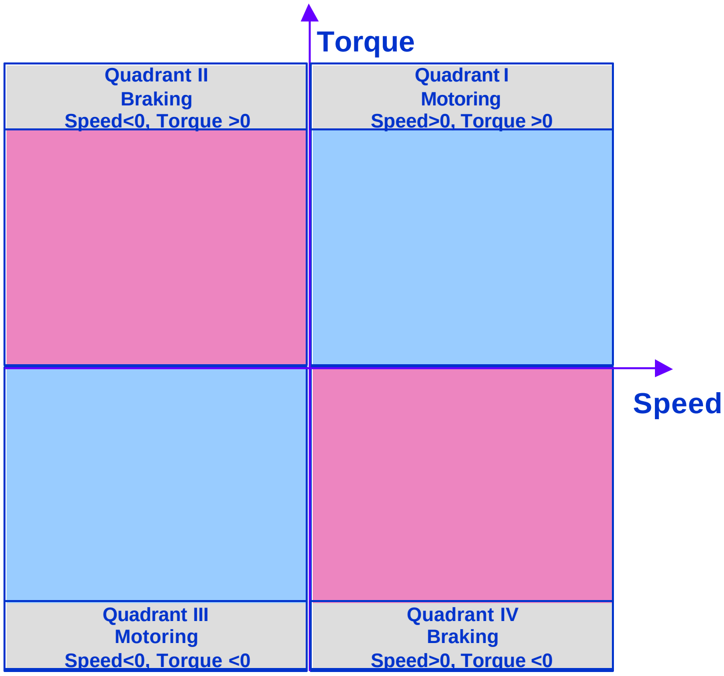


*Fig. 3.7:* *The motor drives are often categorized by which quadrant they are designed to operate in, e.g. whether they are designed to absorb regenerated power from its load. The quadrants refer to the torque-speed diagram.*

The motor drive normally comprises a speed control function, and the output from this control function can be interpreted as a torque command or reference, which is the input to the motor control algorithms. These algorithms use a more or less advanced motor model to control the motor currents and voltages by turning on or off the switching elements of the rectifier (if controllable) and the inverter.

In principle, the controllers will normally have a control block diagram as shown in Fig. 3.8. Torque control is achieved by removing the speed control loop, and give torque reference as a direct input to the motor drive as shown with dashed lines in Fig 3.8. Motor speed is normally measured, but new motor controllers are equipped with motor speed estimator, which eliminate the need for a dedicated speed sensor for most ship applications.

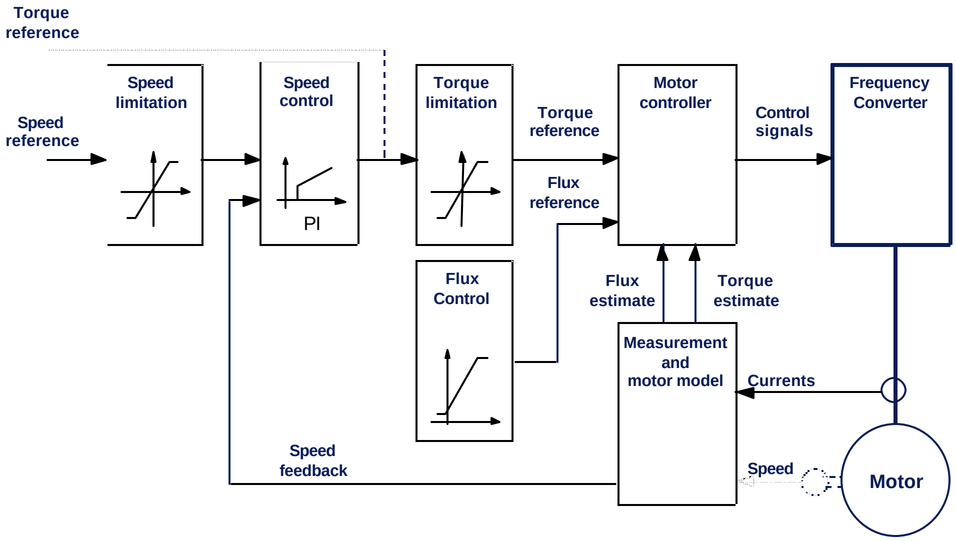


*Fig. 3.8: A generic and typical control block diagram for a motor drive controller.*

For most practical reasons, the speed control loop of a motor drive can be regarded as a PI (or PID) controlled closed loop with an inner closed torque control loop, which for control purposes be regarded as a first order time lag. For simulations and synthesis of overriding control loops, the simplified block diagram in Fig 3.9 should be applicable.

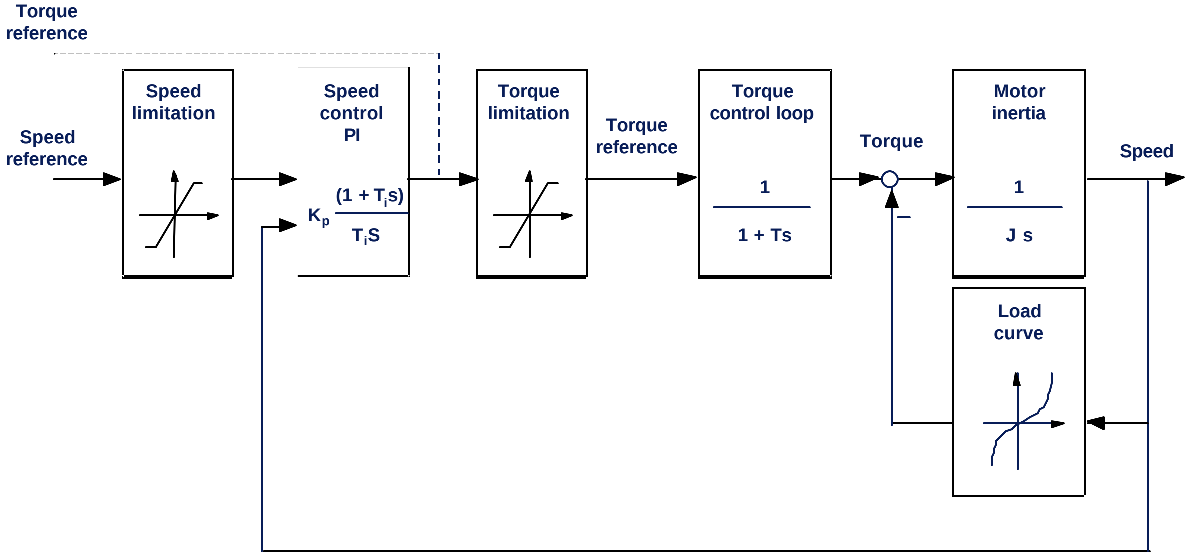


*Fig 3.9: Simplified block diagram for simulations and synthesis of overriding control loops.*

## 3.5. Propulsion Units

### 3.5.1. Introduction

This section presents the most commonly used principles of propulsion units in vessels with electric propulsion. The overview is not complete, since there are also other alternatives, e.g. water jets, also in use, however only for special and limited applications.

### 3.5.2. Shaft propulsion

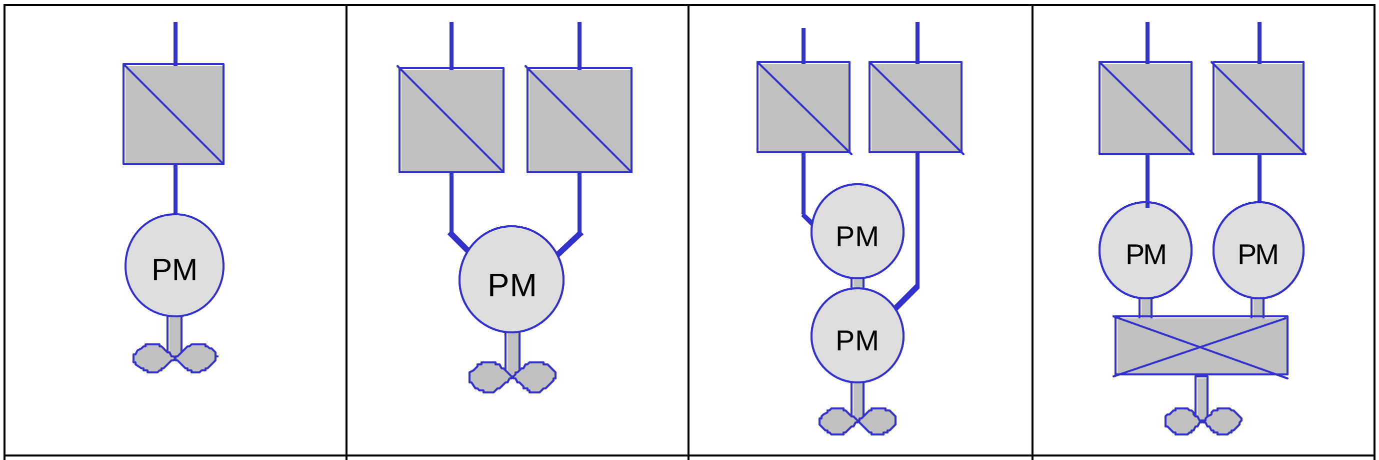
In a diesel-electric power and propulsion system wit shaft propeller, the propellers are normally driven by variable-speed electric motors. The horizontal motors may be directly connected to the shaft, which results in a simple and mechanically robust solution, or via a gear coupling, which allows for increased rotational speed of the motor and results in a much more compact motor. The disadvantage is increased mechanical complexity and increased mechanical power losses.

In diesel electric vessels, shaft lines are used in applications typically where the propulsion power is higher than available for azimuthing thrusters, or where the ability to produce transverse thrust, e.g. in station keeping and maneuvering is not needed – or can be produced cheaper by tunnel thrusters. Typically this applies for shuttle tankers, research vessels, larger anchor handler vessels, cable layers, etc.

The shaft line propulsion will always be combined with rudders, one rudder per propeller. By use of high-lift rudders, shaft propellers may also be used to provide a certain degree of transverse thrust. If additional transversal thrust is needed for maneuvering or station keeping, there will normally be required to install additional tunnel thrusters also in the aft of the vessel.

The propeller is normally speed controlled FPP (Fixed Pitch Propeller) type, which gives a simple and robust propeller design. In some applications, the propeller may be CPP (Controllable Pitch Propeller) type, even if it is speed controlled. To a certain degree, speed and pitch can be optimized for higher efficiency, and faster response than with only one control parameter. These benefits normally do not justify the additional investments in order to obtain combined speed and pitch control.

Fig 3.10 shows some typical drive configurations for shaft line propulsion system. These can be installed in single shaft propeller designs, or dual shaft designs.



Single motor drive

Two-winding motor with redundant converters

Tandem motor with redundant converters

Geared, dual shaft propulsion

*Fig 3.10: Some examples of shaft line drive configurations.*

### 3.5.3. Azimuth thrusters

Azimuth thrusters are thrusters that can be rotated in order to produce thrust in any direction. The thrust is controlled either by constant speed and CPP design, variable speed FPP design, or in rare cases with a combination of speed and pitch control. Variable-speed FPP designs has a significantly simpler mechanical underwater construction with reduced low-thrust losses compared to constant speed, CPP propellers.

In vessels with strict limitation of in-board height of the thruster room, the electric motor will normally be horizontal, and the azimuthing thruster will then consist of a Z-type gear transmission. Due to a simpler construction with less power transmission losses, vertically mounted motors and L-shaped gear transmission will normally be selected when the height in the thruster room allows for it.

A limitation of azimuth thrusters is their limited ability for producing thrust at negative pitch or RPM, because they are designed and optimized for unidirectional thrust. If they have a certain degree of negative thrust capability this should be utilized in order to maintain dynamic thrust capacity without performing continuous azimuth rotation.

The conventional azimuth thruster was earlier used for station keeping and maneuvering, but has recently also been taken in use as the main propulsion device in vessels with electric propulsion. In order to improve the hydrodynamics and steering capability that is required for propulsion, the shape of the thruster has been adapted, such as the “mechanical pod”. This is an azimuthing thruster, which is powered from an in-board, typically a horizontal motor, and the mechanical power is then transferred to the propeller with a Z-shaped gear. The underwater shape is optimized for low hydrodynamic resistance at higher ship velocity, for higher propulsion efficiency.

Some vendors can supply thruster devices with dual propeller, either on the same shaft, or with contra-rotating propellers. Contra rotating propeller increases the hydrodynamic efficiency by utilizing the rotational energy of the jet stream from one propeller, to create thrust from the other that rotates the opposite direction.

Conventional azimuth thrusters are at present (2002) in use with power ratings up to 6-7 MW.

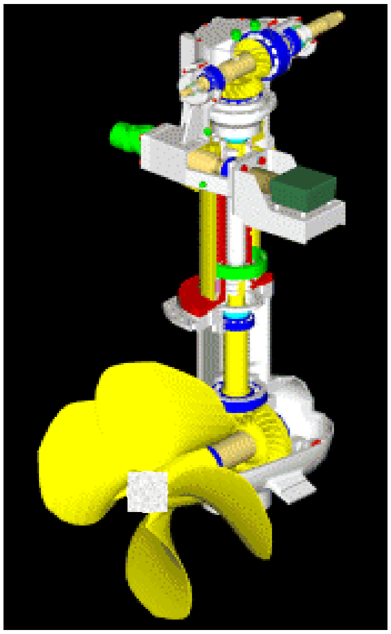


*Fig 3.10: Example of a Z-shaped azimuth thruster, showing main elements such as, propeller, shafts, shaft sealing, the two gears, and a minimum of six shaft bearings. The underwater house and gear houses are filled with lubricating oil.*

### 3.5.4. Podded Propulsion

Like the conventional azimuth thruster, the podded propulsion unit is freely rotate-able and may produce thrust any direction. The main difference is the integration of the electrical motor directly to the propeller shaft, inside a sealed pod unit that is submerged under the vessel hull.

The high power pod schematically drawn in Fig 3.11 shows the variable-speed electric motor, which is located in the sealed and compact pod. The fixed-pitch propeller is mounted directly on the motor shaft. Since a mechanical gear is avoided, the transmission efficiency is higher than in an azimuth thruster. The electrical power is transferred to the motor via flexible cabling or slip rings for 360-degree operation. Since the propeller pitch is fixed and there is no gear transmission, the mechanical construction has a lower mechanical complexity.

The pod can be designed for pushing or pulling operation. Especially the pulling type pod gives the propeller a near optimum and uniform wake field, which increases the hydrodynamic efficiency of the propeller and reduces the risk for cavitation, and hence give reduced noise and vibrations. A podded unit can rotate in both forward and aft directions if the thrust bearings are designed for it. The propeller is normally optimized for one main thrust direction, giving some reduced negative thrust capacity, but without the mechanical limitations of the mechanical thruster.

Podded propulsion units have been in operation in a decade in cruise vessels, icebreakers, service vessels and tankers. Recent new-built field support vessels, Fig 3.12, and semi-submersible drilling units are now also utilizing podded propulsion as station keeping/transit propulsion thrusters. The system is today available in power ranges from approximately 1 MW up to at least 25 MW. The larger units provide access into the pod for visual inspection.

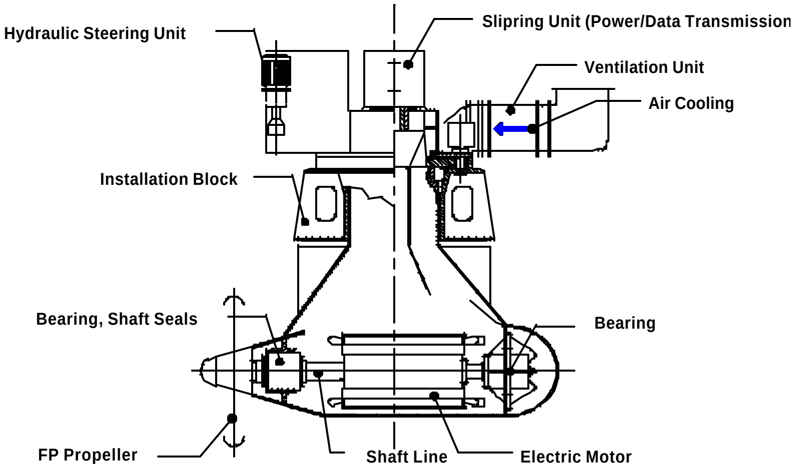


*Fig. 3.11: Podded propulsion.*

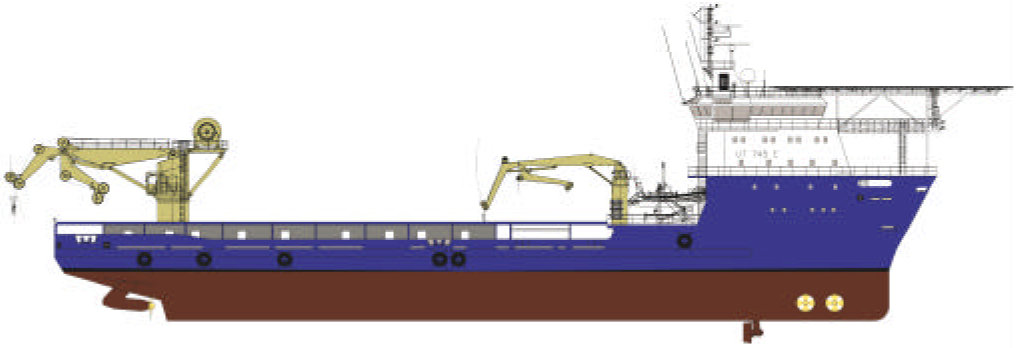


*Fig. 3.12: A Field Support Vessel with podded propulsion.*

## 3.6. Trends and New Concepts

### 3.6.1. Electric power generation

Electric power generation based on rotating prime movers and electric generators, is a mature technology, but there is continuously being evaluated alternatives to the traditional synchronous generator. The fuel cell technology is an area of great interest and research effort, mainly in the automotive industries.

A fuel cell is an electrochemical device that combines a fuel, e.g. hydrogen, and oxygen from the air to produce electricity, heat and water. Fuel cells operate without combustion, see Fig 3.13; hence, a hydrogen fuel cell is virtually pollution free. Since the fuel is converted directly to electricity, a fuel cell can operate at much higher efficiencies than internal combustion engines, extracting more electricity from the same amount of fuel. The fuel cell itself has no moving parts - making it a quiet and reliable source of power. The fuel cell is composed of an anode (a negative electrode that repels electrons), an electrolyte membrane in the center, and a cathode (a positive electrode that attracts electrons).

There is a range of various concepts under evaluation, such as; Phosphoric Acid, Proton Exchange Membrane or Solid Polymer, Molten Carbonate, Solid Oxide, Alkaline, Direct Methanol Fuel Cells, Zinc Air Fuel Cells, and Protonic Ceramic Fuel Cells.

Common for any of these alternatives is that the technology at present has a high production and maintenance cost – with high energy price. The dynamic capability should still be improved, and with the present low power density of the unit the use is in practice limited to smaller power ratings. There are reported some experimental vessel designs using fuel cell power generation, and is commonly assumed and expected that fuel cell will become commercially feasible within some time, but not in the very close future.

The fuel cell generates DC voltage and one could imagine two alternatives for distribution:

- DC distribution and DC load – most of the converter principles for propulsion drives are based on rectifying the AC supply before converting to variable frequency. The problem is mainly related to switching and protection of the distribution system, since interruption of high DC currents is difficult. The conversion to different voltage levels and supply of consumers that need AC supply will also become expensive. DC distribution has mainly been evaluated, and to some extent been used, in military applications.
- DC-AC conversion of the power. With this solution, the problems with voltage distribution and supply will be reduced, but for higher power levels, the solution is yet expensive.

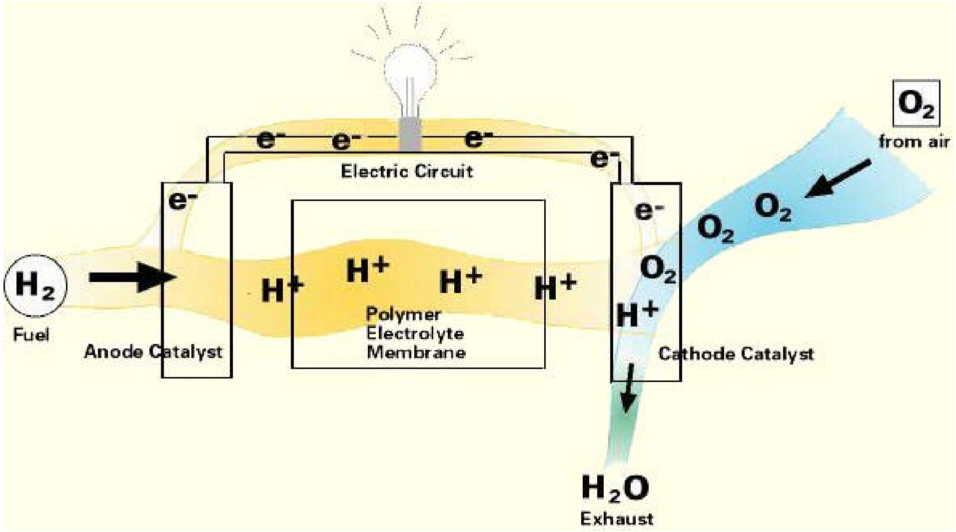


*Fig. 3.13: Principles of a Hydrogen fuel cell.*

DC distribution could also enable the use of compact and lightweight high-speed permanent magnet exited generators. As the power density of a rotating machine increase by its nominal rotational speed, there would be significant savings in weight and volume if speed could be increased from typically 500-900 RPM to 15000 RPM. The disadvantage will be a high frequency output with uncontrolled and varying voltage that would require large power conversion installations.

The fuel cell and power electronics developments open for large shifts in applied technology. The electric power generation, distribution, and propulsion technology, which has been applied until recently are lagging state-of-the-art industrial and automotive research and application, but these technologies will make progress step by step just similar to development of other new technologies.

### 3.6.2. Electric power distribution

It is not likely that there will be a dramatic shift in technology in electric power distribution for AC systems. A gradually introduction of new protection relays, programmable and with field-bus communication is already started and will continue. This means that as flexibility will increase, the total project costs will be reduced.

There is research and development of power-formers, static power converters that transforms voltages by use of power electronics. A high frequency transformer can give galvanic insulation, and the benefits will be reduced dimensions and weights, and elimination of transformer inrush problems. It is yet work to be done before power-formers will be applied in commercial vessels, but they will be essential components in order to enable future development of DC distribution systems.

### 3.6.3. Propulsion

The podded propulsion system is the largest step forward as propulsion unit in the recent years. The concept is not yet fully developed for all market and power applications, and there will be a continuous development to be seen. This may have significant impact on vessel design and allow for total new ship concepts for many areas.

In the CRP concept (Contra Rotating Pod), the podded propulsion is combined with a traditional shaft line driven propeller is shown in Fig. 3.14. The Pod is azimuthing and controlled with a variable speed electrical motor, and the shaft line propeller can be either speed controlled with electrical motor, or a conventional pitch controlled direct diesel driven propeller. The CRP concept has shown to give a large improvement in propulsion efficiency, as well as increased redundancy and propulsion power for a several ship types.

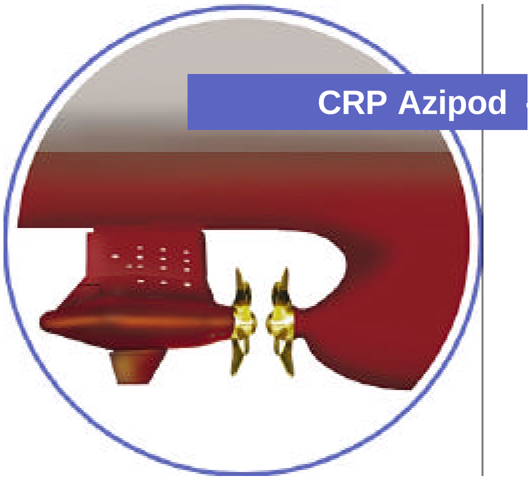


*Fig. 3.14: The Contra Rotating Pod (CRP) concept.*

# 4. Power and propulsion control

## 4.1. Introduction - Control Hierarchy

Fig. 4.1 may illustrate a modern, integrated control, monitoring, and protection system of a power and propulsion plant system, and the implemented functionality can be described in control hierarchy of Fig. 4.2.

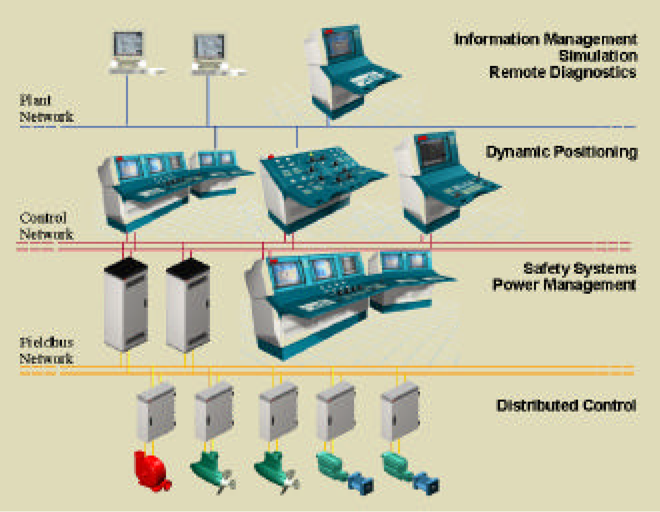


*Fig. 4.1: Integrated control system for a vessel, generic configuration.*

The user interface with presentation of status and measurements, input of operator commands, alarm handling, etc., is often implemented in operator stations, with a graphical user interface, push buttons etc. Operator stations are placed on bridge, engine control rooms, etc.

The system level controllers are implemented in control stations or PLCs. They can be centralized or distributed computers, depending on design philosophy for the vessel. In these one will find the energy management functions, such as power management, blackout prevention functions, start-up and reconfiguration sequence control.

Due to the need for separate testing, response time requirements, and vendor's responsibility, there will be a need for low-level fast-response control, monitoring, and protection of devices. Here are the fast control functions and most basic safety functions implemented. These are linked to the system control level by hard-wired or field-bus signal interface.

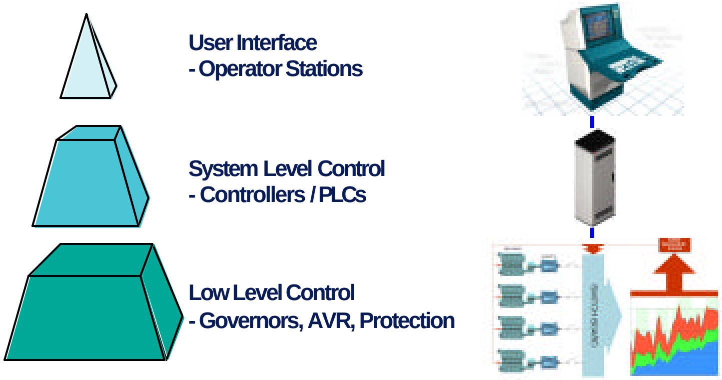


*Fig. 4.2: Control Hierarchy for a Power Plant*

## 4.2. User Interface

The user interface, represented by the bridge consoles and monitors, are the crew's contact for monitoring and control of the power and propulsion installations.

It has become more common to utilize GUI (Graphical User Interface) in ship applications, where light bulbs and push buttons were common few years ago. This allows for much more flexible and cost-efficient solutions, but also introduce a major challenge for vendors and users to specify and design a good user interface which combines safety issues with user friendliness, logical design and easy access to essential and desired information.

## 4.3. High level control functionality

### 4.3.1. Power management – Energy Management

In a system of electrical power installations, vessel and process automation system, and positioning system, the various parts of the automation system controls their parts of the power system, e.g. the dynamic positioning system controls the thruster drives, the off-loading control system use cargo pump drives, the process control system interacts with compressors and cooling/heating systems etc. The interconnecting point for all installed power equipment is the power distribution system. By starting and inrush transients, load variations, and network disturbances from harmonic effects the load and generators are interacting and influencing each other. Optimum operation and control of the power system is essential for safe operation with a minimum of fuel consumption. As it is the energy control system (energy, and power management system), which monitors and has the overall control functionality of the power system, it will be the integrating element in a totally integrated power, automation and positioning system.

The purpose of the Power Management System (PMS) is to ensure that there is sufficient available power for the actual operating condition. This is obtained by monitoring the load and status of the generator sets and the power system. If the available power becomes too small, either due to increased load or fault in a running generator set, the PMS will automatically start the next generator set in the start sequence. A power management system can also have extended functionality by monitoring and control of the energy flow in a way that utilizes the installed and running equipment with optimum fuel efficiency. Such systems can be called Energy Management System (EMS).

For PMS and EMS systems, the main functions can be grouped in:

- Power generation management:
  Overall control with frequency and voltage monitoring with active and passive load sharing monitoring and possibly control, and load dependent start and stop of generator sets. Since control logic and interlocking functions are a significant part of the power system switchboard design, the functionally of these systems must be coordinated.

- Load management:
  Load power monitoring and coordinator of power limitation functions in other systems, load shedding and start interlock of heavy consumers based on available power monitoring.

- Distribution management:
  Configuration and sequence control of reconfiguring the power distribution system. The distribution system should be configured to fit the requirements in the actual operational mode for the vessel.

The new generation production vessels and also drill ships/rigs have a complex power system configuration with advanced protection and relaying philosophies. There are close connections between the functional design and performance of the energy control system (power management system) and the power protection system functions. It is a challenge for involved parties to obtain an optimal and functional solution with several suppliers involved and a yard being responsible for all coordination.

Blackout of the power generating system is the most severe fault that can happen in an electric propulsion system. Various mechanisms to avoid blackout are linked to the power management system, such as the auto start/stop functions, reduction of propulsion and other loads, or shedding of non-critical loads. Figure4.3 illustrates the coordination diagram for a typical installation. Normally, the available power will be controlled within the boundaries for auto start/stop, but if a sudden increase in load, or tripping of a generator set should occur, the available power can be reduced. By monitoring load balance and/or network frequency, the load reduction and load shedding functions will then be activated to reduce the loading and safeguard the power generation until a new generator set is started and connected.

Should a blackout occur, and it does unfortunately happen from time to time, there will normally be required to have a system for sequence control of start-up and reconfiguration of the power system. This is implemented at the system control level, and includes sequences for starting and synchronizing generator sets and loads. There will normally also be a set of predefined operation modes, e.g. transit mode, station keeping mode, maneuvering mode, etc. with automatic sequence control for power system reconfiguration.

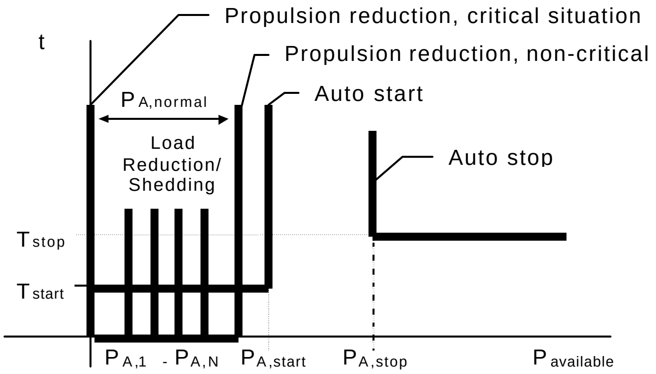


*Fig. 4.3: Example of a coordination diagram of black-out prevention functions.*

### 4.3.2. Vessel Management

In the Vessel Management term, it is common to include manual, automatic, and semi-automatic control of the vessels auxiliaries and helping systems, such as valves, HVAC (Heat, Ventilation, and Air Conditioning) system, ballast control, cargo control, etc. Also the alarm systems, watch call system, and safety systems, may be integrated in the Vessel Management system.

Most of the functions are normally monitored and possible to control from the bridge, or locally from control stations close to the system or engine control room.

### 4.3.3. Propulsion control and dynamic positioning

The propulsion control systems normally consist of

- Manual Thruster Control (MTC) system providing individual control of the thrusters and propellers.
- Autosail or auto pilot system performing automatic course keeping and course changing during transit operations, often in combination with tracking functionality.

And if the vessel is intended for use in station keeping operations, either

- Dynamic Positioning (Dynpos) System providing manually or automatically positioning by means of proper action of the thruster system, or
- Thruster assisted position mooring (Posmoor ATA) system providing manually (Posmoor TA) or automatically thruster assistance (Posmoor ATA) for position and heading control of anchored vessels.

It is not the intention of this system to describe these control systems in detail, for further studies, [71] can be recommended.

It should, however, be emphasized, that the propulsion and station keeping control functions are in most cases very critical for the safety of operations of the vessel. The need for careful consideration of their design is obvious, but one should never underestimate the need for matching and testing these control functions together with the power / energy management system, and low level controllers in switchboards, and propulsion drives.

## 4.4. Low Level control functionality

One may divide the low-level controllers in protection and control functions. The protection devices shall monitor the units for faults and from exceeding design constraints.

The low-level controllers are dedicated controllers for the purpose, often integrated with the equipment.

### 4.4.1. Engine protection and governor

The engine protection devices prevent and shut down the engine at over-speed, excessive temperatures, loss of lubrication, etc. The engine protection is usually delivered as an integral part of the engine, by the engine vendor, or partially integrated with vessel management system.

The governor controls the generated frequency by commanding fuel input to the prime mover, Fig. 4.4. It may be a so-called “speed droop” type, which implies that the steady-state frequency will drop proportionally with the active load (kW). The speed droop mode is a simple and robust method for obtaining load sharing between parallel-connected generators. However the load dependent frequency variations may cause difficulties in synchronizing generators or different bus sections. The frequency variation may also be undesired from the operation of loads. The isochronous governor contains a regulator with an integral effect and keeps the frequency equals to the set point. A signal, either hardwired or by high-speed bus-communication, between the governors, ensures a proper load sharing between the prime movers. Most governors applied in electric propulsion plants have both control modes available.

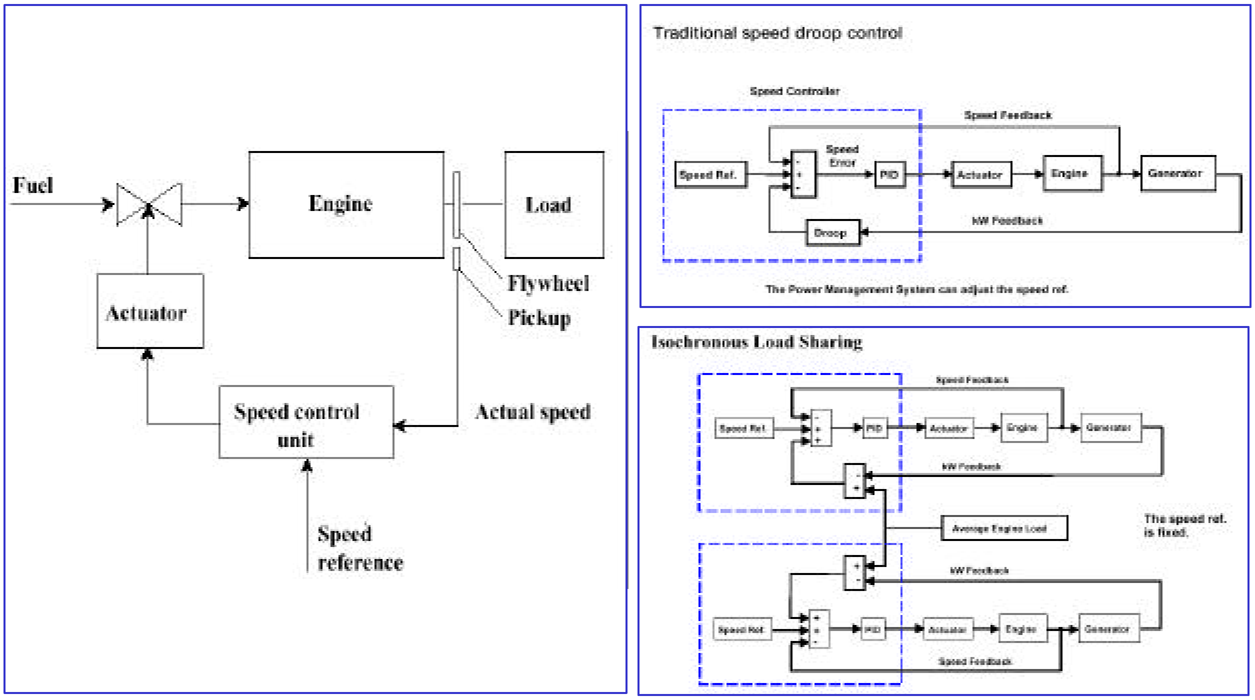


*Fig. 4.4: Governor for a diesel engine, schematics of speed droop and isochronous control modes.*

### 4.4.2. Automatic voltage regulator

The Automatic Voltage Regulator, AVR, controls the voltage by commanding magnetizing current to the field winding of the generator. As the governor, the voltage regulator can be controlled in droop mode, meaning that voltage varies a few percents (±2.5%) with the load. This gives a robust and simple sharing of reactive load (kVAr), which is a prerequisite for equal loading of the generators and the voltage variations normally gives no impact on synchronization and functionality.

In applications where the voltage variations by droop control are not accepted, there are alternative methods to reduce or avoid load dependent voltage droop:

- Voltage droop compensation: Adjusting the set point in order to partially or totally compensate the voltage droop. Should be used in combination with cross current compensation, which aim to obtain sharing of the reactive power by reducing the difference in generators' load currents.
- Integrating controller: One AVR or the power management system may contain an integrating controller that adjusts the voltage set points depending on the load, and avoid static voltage deviations.

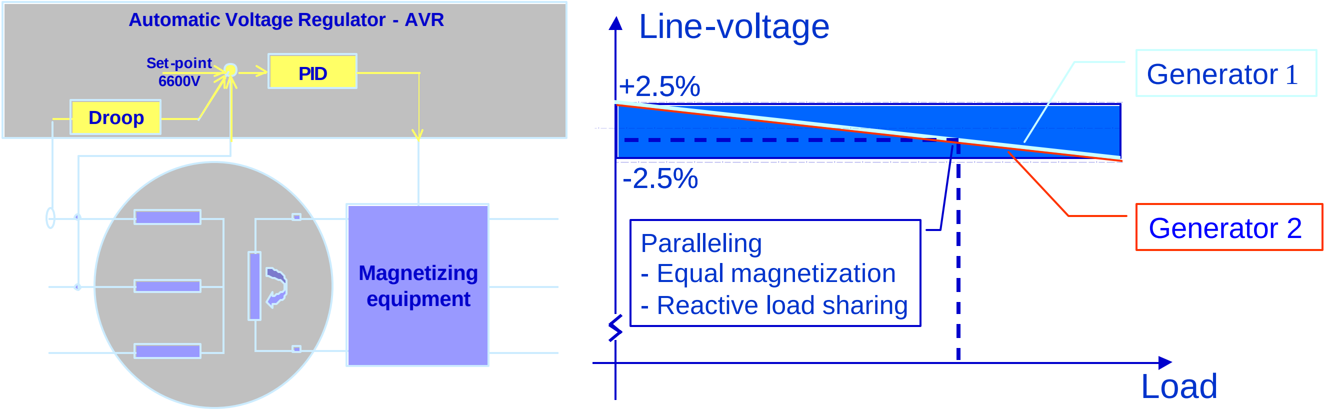


*Fig. 4.5: Paralleling of generators with droop control requires equal tuning of voltage regulators (AVR) in order to obtain reactive load sharing.*

### 4.4.3. Protection relays

In electrical power installations, protection devices and relays are used to protect human life or injury from faults in the electric system, and to avoid or at least reduce damage of equipment from operating outside specified limits or faults. The physical damage of equipment may be much reduced if the fault clearing time of e.g. short circuit can be shortened.

Protection relays are normally located in switchboard or sometimes in special control and protection panels. There is a range of types and functionalities, intended for dedicated applications. Today, the use of digital programmable protection relays is common. Digital relays may contain a range of protection functions that can be enabled and put together for the specific protection requirements for the desired application.

Based on measurements of currents, voltage, frequency, etc., the protection devices are programmed to disconnect parts or equipment of the system within preset times, which can be dependent on amplitude of measured values.

The protection functions and characteristics are defined by standards such as ANSI/IEEE and IEC, possibly with some adaptations. In ANSII C39.90, a list of protection devices or functions covers any normal needs for application engineering. This system may be used on connection diagrams, in instruction books and in specifications.

The protection scheme will vary depending on operational requirements and system configurations. A typical protection scheme may include the following functionalities:

Switchboards:

- Under- and overvoltage, typically alarm only
- Under- and overfrequency, typically alarm only
- Earth fault, trip or alarm depending on earthing philosophy
- Differential, or other fast short circuit protection

Generator:

- Overcurrent and short circuit
- Earth fault
- Reverse power
- Negative phase sequence
- Under- and overvoltage
- Overfrequency
- Under- and overmagnetization and/or capacitive reactive power
- Differential protection with transformer inrush blocking
- Synchronizing check with speed output to prime mover

Bus tie and transfer feeders

- Short circuit – may be included in generator protection
- Earth fault
- Synchronizing check
- Differential protection (in ring network configurations)

Transformer feeder:

- Over current
- Short circuit
- Thermal overload/image
- Earth fault
- Undervoltage
- Some times, especially for large transformers differential protection

Motor feeder:

- Overcurrent
- Short circuit
- Earth fault
- Thermal overload/image
- Negative phase sequence
- Motor start: stalling, I2t, number of starts
- Earth fault
- Undervoltage

The design and setting of an appropriate protection scheme is a trade-off between a general desire to disconnect faulty equipment with minimum time delay, and the need for disconnecting a minimum of the plant. The latter requirement is approached by selectivity or protective device coordination (PDC) studies. The purpose of these studies is to safeguard and document towards class and ship owner that selectivity has been designed into the power system.

Correct setting and verification of setting during commissioning and regular maintenance is essential for safe operations of a vessel. Faulty settings or deteriorated calibration may give unintended consequences and even blackout of the ship from relatively minor events. Since protection relays does not act under normal operations, it is also essential to safeguard their functionality and calibration by a regular test program.

As an example, the short circuit and over-current protection relay is considered. The characteristics and setting of such relays are normally presented in a logarithmic diagram as shown in Fig. 4.6.

At the current-axis, the normal load, overload, and short circuit current levels are indicated. Typically, the constant rating of the connected equipment defines the normal load range. Some equipment has an overload range also, where it is permitted to run with loads exceeding rated values in shorter intervals. In this diagram, an inverse current shape is shown for the overload region – indicating that the allowed time is reduced by the magnitude of overload currents. There are several types of inverse currents, to adapt the specific requirements. At high overload currents, the protection relays can either provide an instantaneous trip or time-delayed trip as shown. If there are no selectivity concerns for down-stream branches, e.g. for propulsion transformers, instantaneous trip can be applied for the short circuit currents. There is also plotted a point for start-up transients, which can be motor start currents or transformer inrush currents. This point must be on the inside (left side) of the setting curve to ensure that the equipment can be energized without tripping signal from the protection relay.

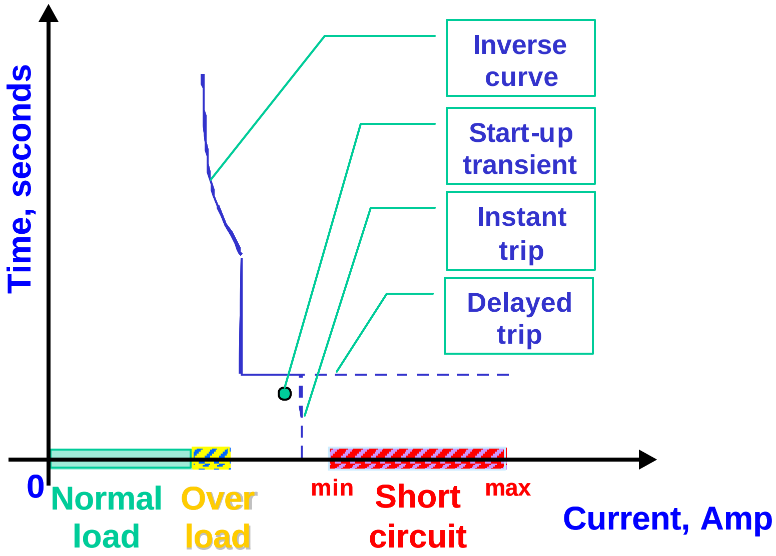


*Fig. 4.6: Simplified setting diagram for a short circuit / overload relay, showing amplitude and time settings.*

Figure 4.7 shows an example setting diagram for a ship system with two generators connected, one to each of two main switchboards, a bus tiebreaker, and a drive transformer. As seen, by adjusting the settings for time and current limits in the protection relays to the breakers for generators, bus-tie, and transformer, one may obtain selectivity in the system which in this case means that the protection relays trips the transformer breaker before tie breaker, which in terms acts before the generator protection upon short circuits in the system.

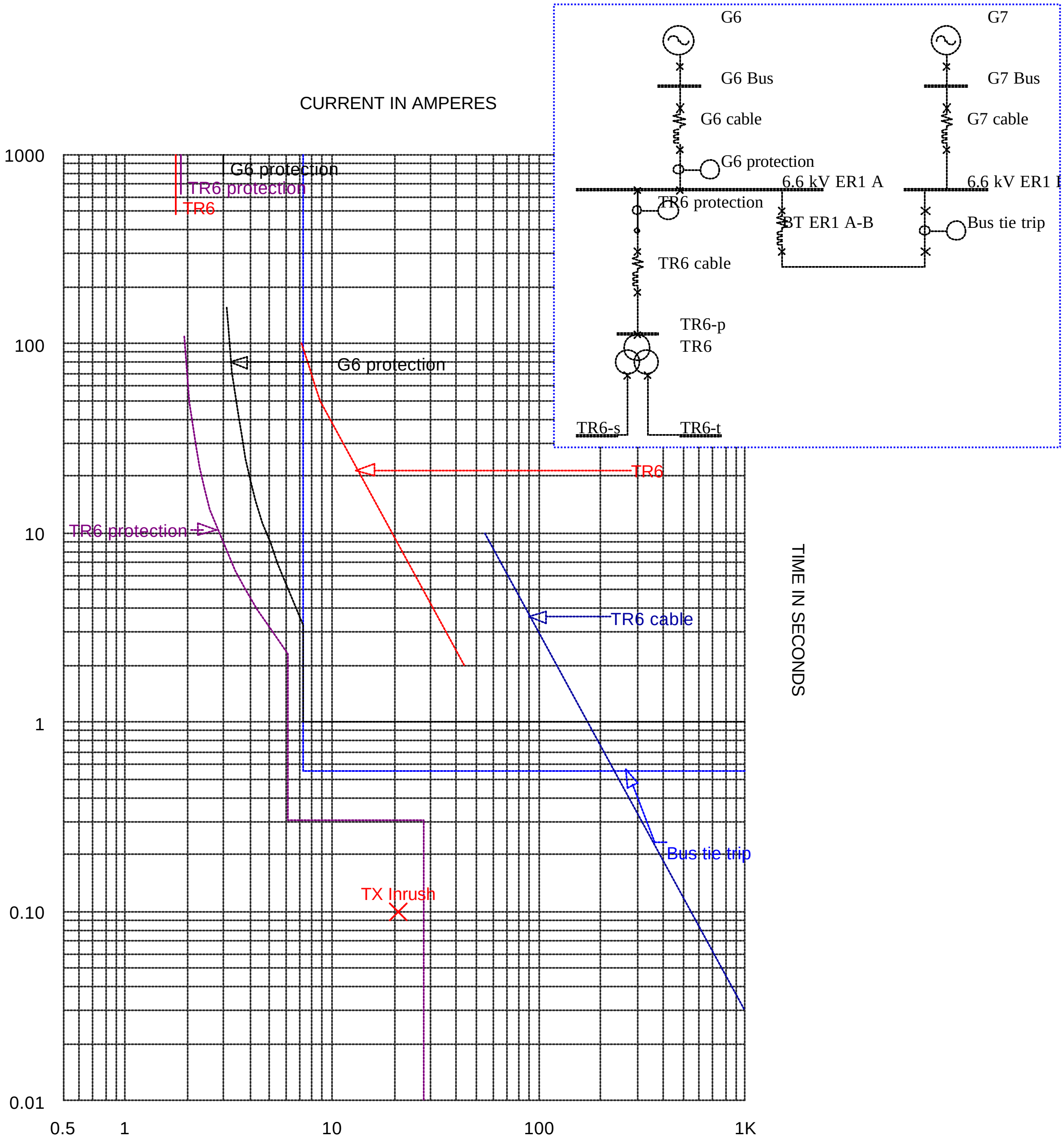


Chart 2 TR6 (2000kVA) protection.tcc    Ref. Voltage: 6600    Current Scale X 10^2

| SC levels: | <u>Comments:</u> |
|---|---|
| $I_{kmax}$: 7.8 kA | G6 protection = REM 545 over-current protection |
| $I_{kmin,}$: 1.4 kA | TR6 = Transformer withstand curve |
| | TR6 cable= Transformer cable (3x1x120 $mm^2$) |
| $I_{kmax\ 690V}$: 2.2 kA (ref 6.6 kV) | TR6 protection = Transformer over-current and short circuit protection curves |
| $I_{kmin,\ 690V}$: 0.9 kA (ref 6.6 kV) | |

*Figure 4.7: Example setting diagram for a two-split system with bus-tie, two generators and a three-winding drive transformer.*

### 4.4.4. Propulsion controller

As earlier explained, the propulsion is normally speed controlled. The propulsion controller will then keep the reference speed as far possible within the speed and torque limitations, and dynamic capability.

The propulsion controller will normally be interfaced with the thruster / propulsion system, the power generation and distribution system and/or power management system, and bridge control systems including remote control joystick, autosail systems, dynamic positioning, etc.

Since the propulsion power normally constitutes the major part of the total load for the power plant, it is also essential that the load reduction functions and blackout prevention functions are highly coordinated with the power plant design and power management functionality. Based on an overall blackout prevention philosophy, and prioritizing of the different consumers, a complete coordination program as shown in Fig. 4.3 can be made. Since response time is critical for blackout prevention, timing of load reduction is essential. Typically, the propulsion controller will contain three levels of load reduction in the blackout prevention philosophy:

- Maximum load limitation from available power calculation can be received from the power management system or by dedicated measurements. This gives a max kW loading for the motor drive, depending on the power allocation and priority used for the design of the power management system.
- A fast acting, event-trigged load reduction, typically a digital signal forcing the motor drive power to be reduced to a preset reduction ratio, or absolute value. The signal may come from the power management system or from the protection / control equipment within the switchboard.
- A fast acting, frequency trigged load reduction, only depending on a local frequency measurement at the drive’s line supply. Normally regarded as a last protection against under frequency trip due to generator overload in the blackout prevention philosophy.

Safety and monitoring functions of propulsion related equipment and auxiliaries are to some extent required by classification society. Depending on the overall system design, monitoring and shutdown functions may be included as part of the propulsion control system, or in the integrated automation system, or in a combination.

There has been shown that utilizing torque or power control for propulsion and thrusters [72] will have a stabilizing impact on performance and network disturbances in sailing and station keeping conditions. Figure 4.8 shows how the power drawn from the network will stabilize with a torque control approach compared to speed control, by reducing the effects from sea current and wave impact on the propeller’s thrust characteristics.

For ice going or icebreaking vessels, the load torque varies much and fast when the propeller hits the ice or blocks of ice. Power control has successfully been applied to reduce the load disturbances on the network.

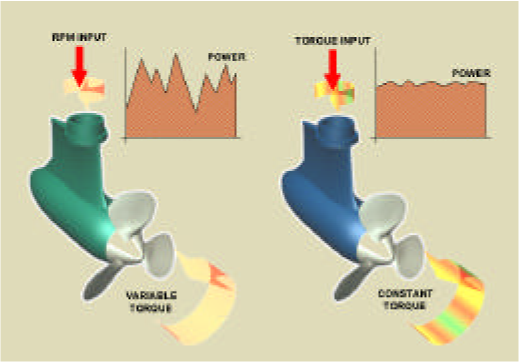


*Fig. 4.8: Torque, or power control of thrusters and main propulsion not only improve the dynamic performance of the positioning or sailing control functions, but also stabilizes the power taken from the network, and reduces the power disturbances compared to pure speed control and even more compared to pitch control-*

# 5. Electric Propulsion Drives

## 5.1. Introduction

Variable speed drives has been in industrial use since in many decades, but first at the end of the 1960’s by use of power semiconductors. At the beginning, DC motors where the most feasible alternative for propulsion control, but during the 1980’s, AC motor drives became industrially available, and commercially competitive. Since then, almost all new deliveries of electric propulsion are based on one of the AC drive topologies.

## 5.2. Variable Speed Motor Drives

The most commonly used converters for motor drives are, in the following order:

- Voltage source inverter (VSI) type converters for AC motors, normally asynchronous motors
- Cycloconverters (Cyclo) for AC motors, normally for synchronous motors
- Current source inverter type (CSI) converters for AC motors, normally synchronous motors
- DC converters, or SCR (Silicon Controlled Rectifier) for DC motors

The topic will be approached in opposite order, due to the fact that the DC converter is the simplest and easiest to understand, while the other ones have a more complex configuration, but building on much of the same building blocks as the DC converter,

### 5.2.1. Full-bridge thyristor rectifiers for DC motor drives (SCR)

The most commonly used DC motor is the shunt motor, which has separately supplied field winding and armature (rotor) winding. The armature current is transferred from the stationary terminals to the rotor by use of brushes connected to the rotating commutator. In practice, the armature current also flows through some additional stationary windings, which aids the commutation of current between the segments of the commutator, but this effect is not regarded here.

In a shunt DC motor the induced armature voltage is proportional to the magnetic field and rotational speed. The magnetic field is a function of the field current, and because of saturation effects, they are in practice not proportional. However, if neglecting the saturation, the armature voltage is:

$V_a = k \cdot \Phi(I_f) \cdot n \approx k \cdot K_\Phi \cdot I_f \cdot n = K_V \cdot I_f \cdot n$. $K_V$ is the induced voltage constant, $I_f$ the magnetization (field) current, $n$ is the rotational speed, $K_f$, and $K$ proportional constants, and $F$ is the motor flux.

The developed torque is proportional to armature current and magnetic field:

$T = k \cdot I_a \cdot \Phi(I_f) \approx k \cdot I_a \cdot K_\Phi \cdot I_f = K_T \cdot I_a \cdot I_f$. $K_T$ is the torque constant and $I_a$ the armature current.

Since the DC motor must be supplied from a DC source with limited voltage, field, and armature currents, the characteristic boundary of operations will be as shown in Fig. 5.1.

The operation is divided in a constant torque region, characterized with a constant field current, and a field weakening region where the field current is reduced to maintain the maximum armature voltage level as speed increases. Hence, the maximum torque boundary is in principle constant in the constant torque region, and inverse proportional to speed in the field-weakening region.

However, in the lower speed region, the armature current normally must be limited to avoid burning of the commutator, and in the higher speed region, it must be reduced to avoid flashing between the segments of the commutator. These limitations are indicated in the diagram.

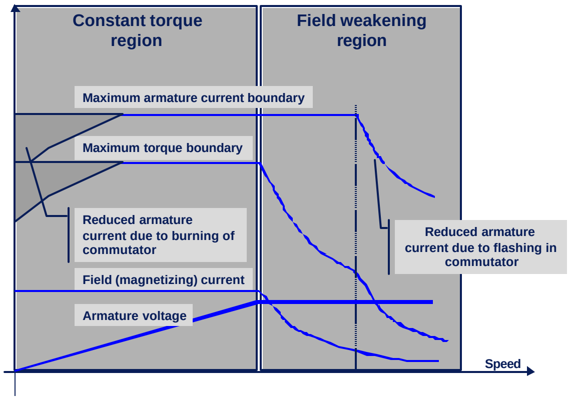


*Fig. 5.1: Characteristic maximum operating boundaries for a DC shunt (i.e. with separated magnetization) motor*

In the most common high-power applications, a full-bridge thyristor rectifier (Fig 5.2) feeds the DC motor with a controlled armature (rotor winding) current. Similarly, the field winding is excited with a regulated field current. The torque is controlled accurately and with low ripple if the armature inductance is high, but this, on the other hand, reduces the dynamic performance since the time constant of the armature increases. In this topology, the DC voltage on the motor armature windings is controlled by phase shifting the thyristors' conduction interval by the gate firing angle α. The gate firing angle can in principle be controlled from 0 to 180 degrees, and the voltage on the armature windings can hence be regulated from +1,35 to –1,35 times the line voltage. In practice, however, the gate firing angle will not be lower than 15degrees, in order to ensure controllability of the motor drive also with voltage drops in the network, and limited to 150 degrees to have a so-called commutation margin.

Since the armature current is controlled by use of the firing angle of the thyristor devices, the AC currents will be phase-shifted with respect to fundamental voltage. The phase angle of the current is almost equal to the gate-firing angle. Since the armature voltage is proportional to the rotating speed, one see that the phase angle, which is approximately equal to the gate firing angle, also will be approximately proportional to voltage and hence rotational speed. In a DC motor drive, where the speed is varying from 0 to 100%, the power factor will hence vary also from 0 to 0.96 (α=15degrees). A low power factor increases losses in the generation and distribution system and more generators may have to run than the active power of the load apparently would require.

Wear and tear on brushes and commutator is a source of failure and maintenance and also limits the standstill torque performance. When accounting for this and also for the fact that the practical limit for DC motor drives is 2-3 MW, the application of DC thruster drives is limited, with the exception of retrofits, in which existing installations are reused.

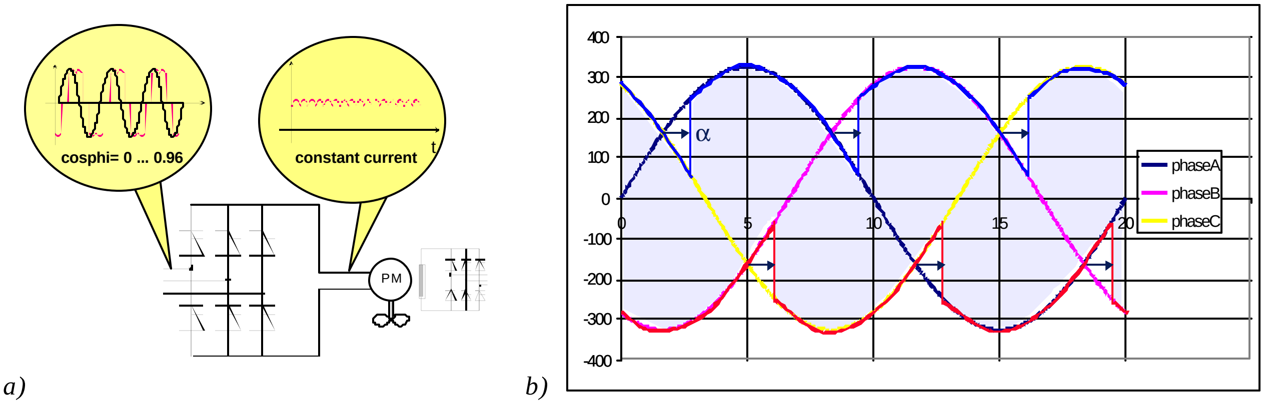


*Fig. 5.2: a) Full bridge thyristor DC drive (SCR). b) The (average) DC voltage to motor is controlled by delaying conduction of the thyristors with the gate firing angle **a** (here, **a** =30degrees). Average motor voltage is* $V_{dc} = 1.35 \cdot V_{ll} \cdot \cos a$ .

### 5.2.2. Current source converters

A DC current link fed by a thyristor-controlled rectifier and smoothed by an inductor characterizes the current source inverter (CSI), occasionally referred to as a load-commutated inverter (LCI) or Synchro. This converter is normally used together with a synchronous motor, but can also, with some modifications, be used to drive an asynchronous motor. The asynchronous motor variant was more common in the past, but is rarely seen in new installations.

The synchronous motor is similar to the synchronous generator, with rotating field (magnetizing) windings and three- or six-phase stator windings. Six-phase stator windings must be supplied from a double CSI inverter and is used to reduce the torque harmonics on the shaft. The synchronous motor must provide the commutation voltage for the inverter, which means that it must run with capacitive phase angle. The motor will thus be dimensioned for a higher current, and increase in size compared to a motor with a power factor of 1.

From the network side, the current source inverter is identical to a full bridge thyristor converter used for DC motor drives, and the characteristics towards the network can very much be considered to be the same. The inverter side, which feeds the motor, has the same topology as the rectifier, and uses the induced voltages from the motor instead of the network voltage.

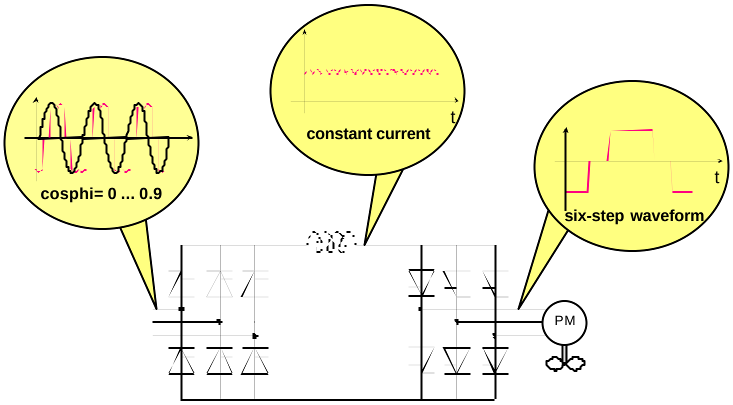
The thyristor rectifier results in a speed-dependent varying power factor, which is high (0.9) at nominal motor speed, and decreasing toward zero for low speeds. The supply current contains harmonics that must be regarded during the system design and should normally be reduced by use of a 12 pulse, 6-phase configuration.

The DC link current is directed through the motor phases by controlling the thyristors of the inverter stage. A 6-step current waveform is obtained, resulting in motor harmonics and torque ripples. The CSI requires a certain counter-induced voltage (EMF) from the motor to perform commutation. Hence, it is mainly used in synchronous motor drives in which the motor can be run with capacitive power factor.

At lower speeds, typically below 5-10% of rated speed, the EMF is too low to perform a natural commutation. In this speed range, the CSI is run in pulsed mode in which the current is controlled at zero level during commutation of the inverter output stage. Since the current and hence the torque are forced to zero level, the torque pulsation at the motor shaft is large in this operational area. The torque ripple and hence shaft vibrations should be carefully regarded in the propulsion system design to reduce vibrations and acoustic noise. These may have a detrimental effect on geared thrusters operating in DP mode.

The characteristic operating boundaries is shown in figure 5.4 for the topology in Fig. 5.3.

The CSI is used in large synchronous motor drives; the biggest one supplied is approximately 100 MW.



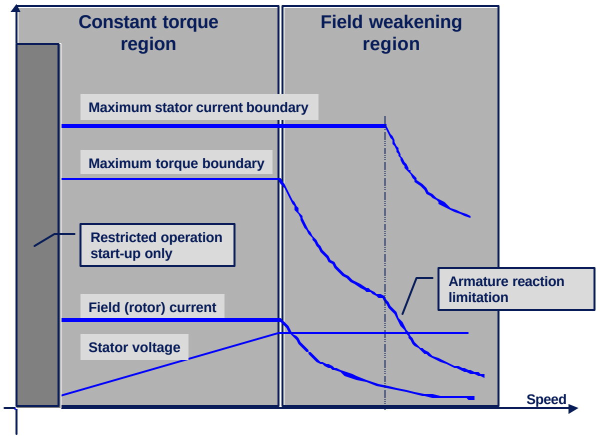


*Fig. 5.3: CSI (LCI) Drive with characteristic operating boundaries.*

### 5.2.3. Cycloconverters

The cycloconverter (Cyclo) is a direct converter without a DC link (see Fig. 5.4). The motor AC voltage is constructed by selecting phase segments of the supply voltage by controlling the anti-parallel thyristor bridge. A 12-pulse configuration with reduced line harmonic is drawn, but the cyclo can also be supplied in a 6-pulse configuration. In 6- pulse configuration, the feeding transformers can be substituted with reactors when the supply voltage matches the inverter voltage.

The motor voltage is controllable up to about one third of the supply frequency (about 20 Hz); thus it is most applicable in direct shaft drives without gear. It has been used for main propulsion systems, including podded propulsion.

The motor voltage contains a lower level of harmonics than the CSI, and the motor power factor may be kept high (unity in synchronous motor drives).

The supply power factor is motor voltage-dependent and is about 0.76 in the field weakening range. The content of line harmonics is speed-dependent and must be carefully regarded in system design when the motor drive is large compared with the installed power.

The operation boundaries are similar to those found in the CSI type of synchronous motor drives, except that the low speed limitations are not present, since the commutation takes place towards the network voltages and not the motor voltages. The cyclo converter has hence been preferred in applications where low speed operation and performance is essential, especially in ice breaking or ice going systems, but also in DP and passenger vessel applications where low speed / maneuvering performance is essential.

The Cyclo is available in a power range of 2-22 MW per drive motor.

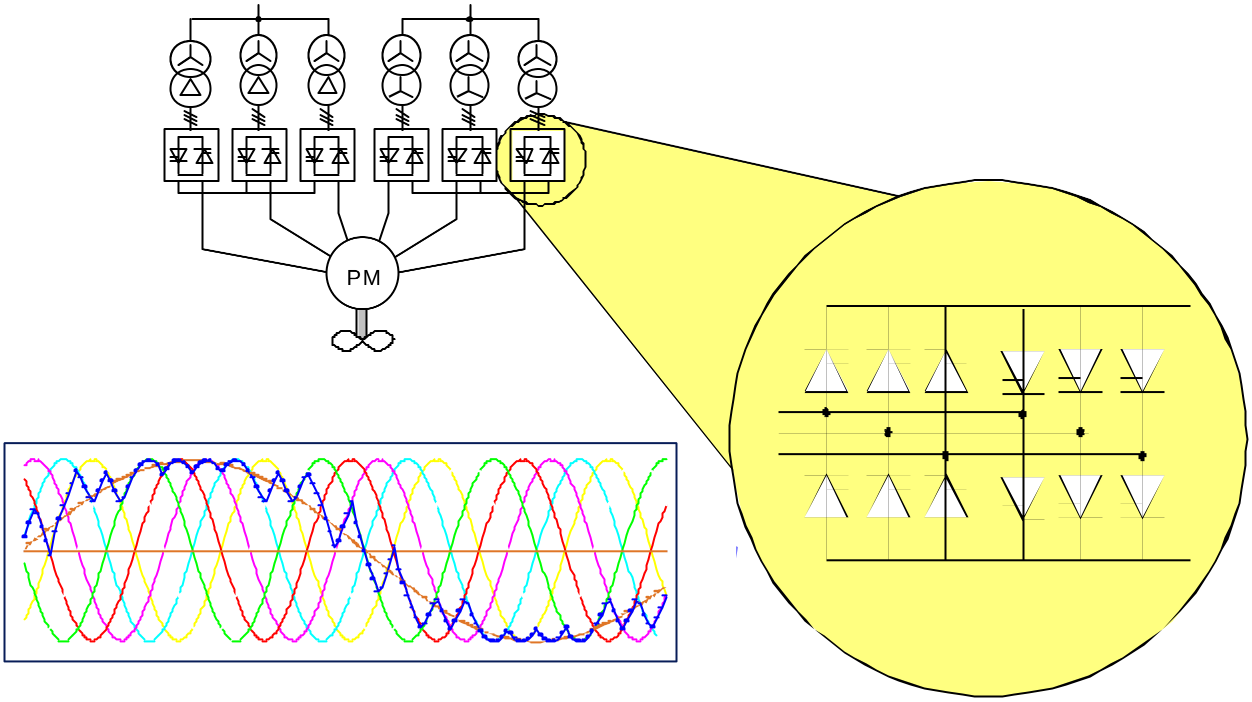


*Fig. 5.4: Cycloconverter drive with input and fundamental output waveforms. The output voltage is constructed by selecting phase segments of the supply voltage.*

### 5.2.4. Voltage source inverters

The VSI (Voltage Source Inverter) converter is by far the most used frequency converter in industrial applications. It gives the most flexible, accurate and high performance drive, and can be used with an asynchronous motor. It can also be used for synchronous and permanent magnet synchronous machines with much better performance than other alternatives. The main limitation of this drive topology has been the availability to high power components, and its competitiveness towards other drive topologies in the high power range. Until recently, the practical limit for these drives was around 8-10MW, but as new components become available, this limit has increased and today it can be applied in drives exceeding 30MW.

A rectifier, normally an uncontrolled diode rectifier connected to the network, characterizes the VSI. This rectifies the network voltage, which hence gives a relatively constant DC voltage, which is further smoothed by a capacitor bank in the DC link. The capacitor in the DC link also ensures that high frequency switching ripple from the inverter module does not enter the network. A six-pulse VSI converter fed induction motor drive is drawn in Fig 5.5.

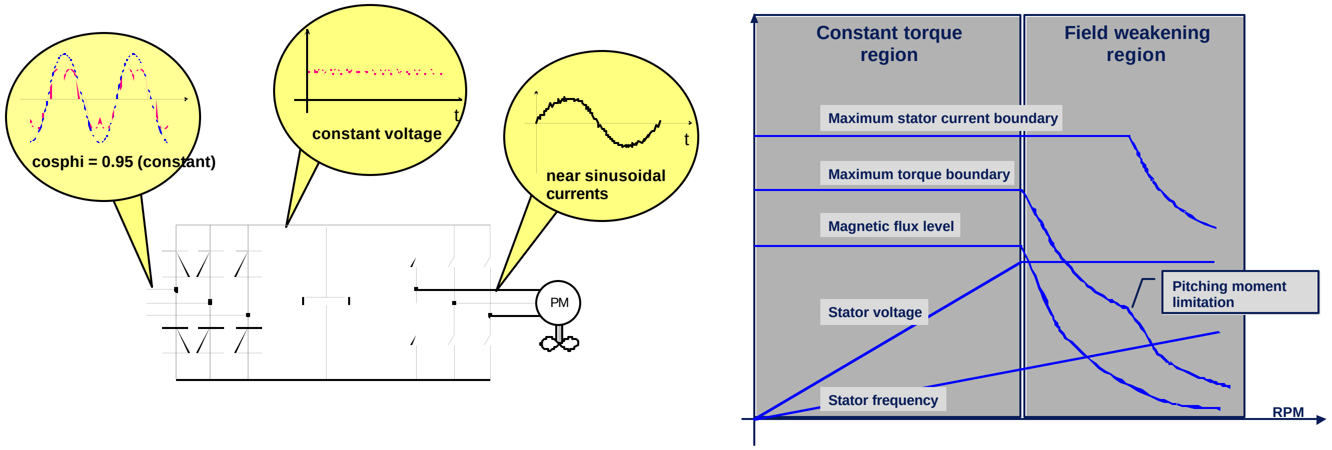
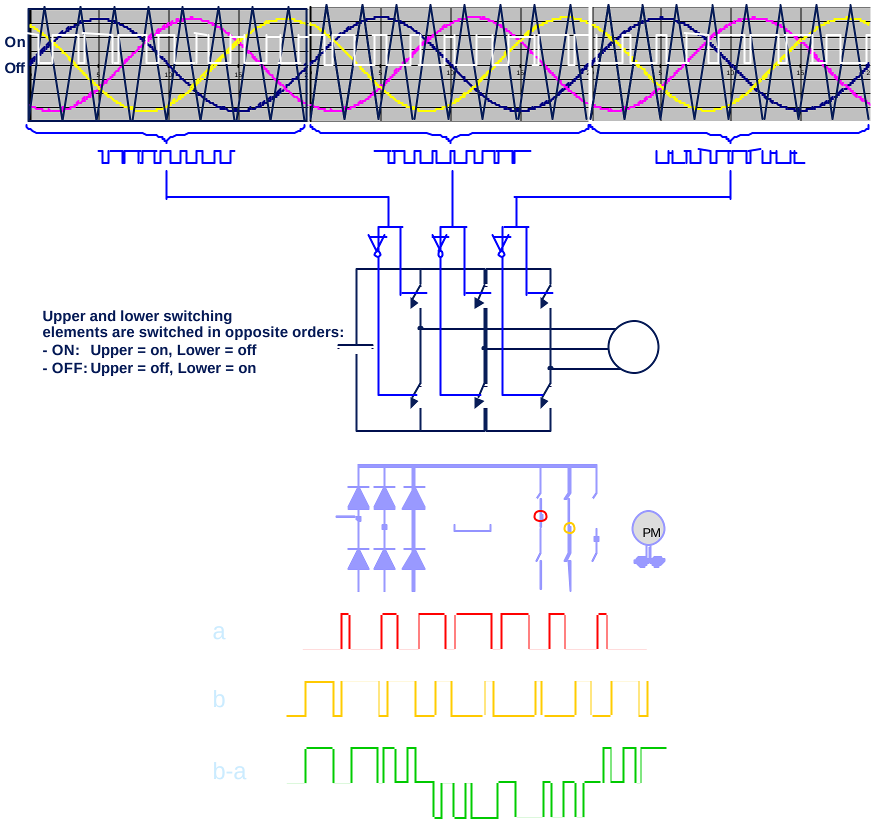


*Fig. 5.5: Two-level PWM drive and its inherent limitations.*

The rectifier in Fig. 5.5 represents a six-pulse configuration used where the converter is directly connected to the network. The dominant harmonic currents are of the 5th, 7th, 11th, and 13th harmonic order. The harmonic distortion can be further decreased when using 12-pulse configuration with a dual feeding via a three-coil transformer, hence canceling the 5th and 7th harmonics. Where a transformer is necessary for voltage adaptation, the 12-pulse configuration should normally be used. Using PWM drive and 12-pulse configurations, the resulting harmonic distortion will normally be close to the limits defined by rules and guidelines, but additional means may be required, e.g. filtering.

There are several ways to control the switching elements in order to obtain the desired voltage output to the motor. The most common methodology is to use the PWM (Pulse Width Modulation) in some variant. In its most basic version, a three phase PWM voltage is generated by comparing three sinusoidal reference values to a high frequency triangular signal, as shown in Fig 5.6. While the sinusoidal reference is higher than the triangular signal, the upper switching element in the inverter leg gets a firing signal; the lower is turned off, and opposite when the sinusoidal reference signal is lower than the triangular signal. The voltages from the inverter to the motor terminals follow the same pattern; with instantaneous values equal positive and negative voltage levels of the DC link for positive and negative gate control signal respectively. The line voltage, which is what influences the motor, is then the difference between two phase voltages as shown in Fig, 5.6.

As an alternative to such PWM methods, there are vector modulation techniques, and direct modulation techniques as in the direct torque control (DTC), where the gate firing signals are generated directly by calculating which of the 8 possible voltage vectors (including two zero vectors) to be applied to the stator windings.



Upper and lower switching elements are switched in opposite orders:
- ON: Upper = on, Lower = off
- OFF: Upper = off, Lower = on

*Fig. 5.6: Generation of switching pulses to the PWM modulated inverter, and resulting output voltages to the motor phase and between two lines.*

There are various methods to implement the motor controller, which attempts to create input to the motor which gives the desired torque:

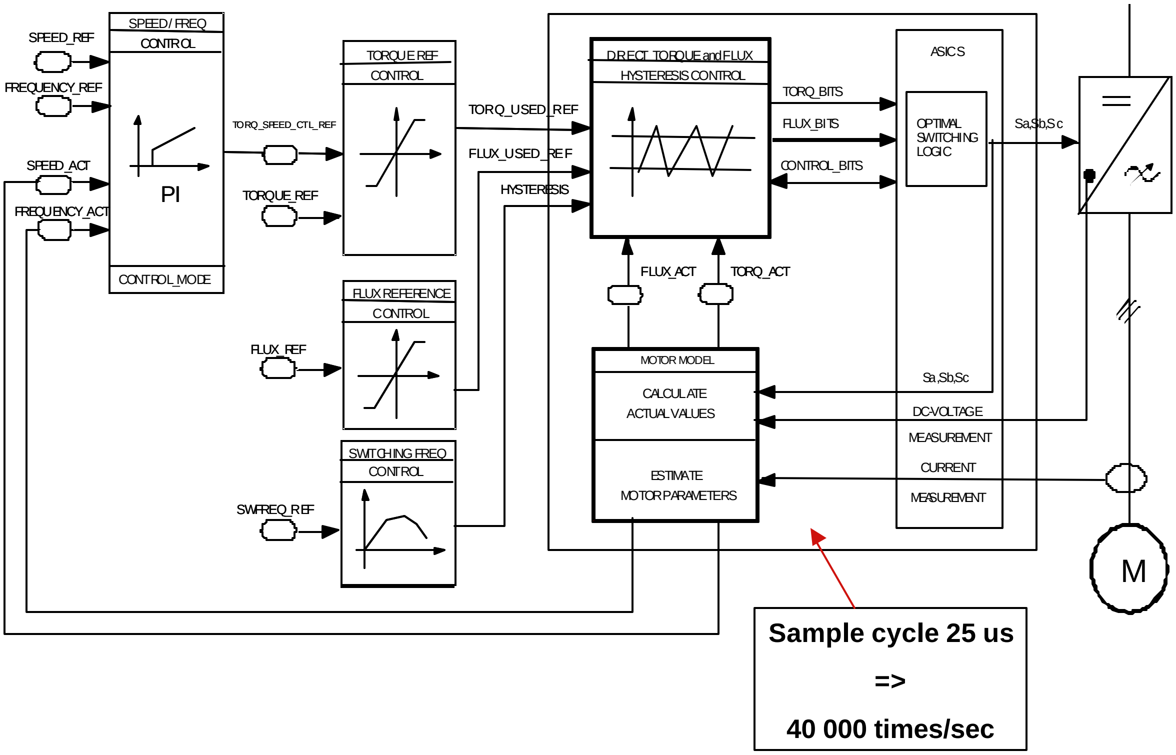
- Scalar control
  Scalar control is the simplest and first applied technology for control of asynchronous motors. It was possible to implement in analog electronics, which was the only feasible in the earlier days of motor control. The scalar control is based on the stationary model of the asynchronous motor, as described in Fig. 3.18, and from this the corresponding voltage and frequency was calculated which would give the desired torque or speed in the motor. The disadvantage is that the model is only valid in stationary condition, and that the model parameters are highly dependent on temperature, frequency, etc. Hence, the scalar methods have a poor dynamic performance, with a poor utilization of the motor capacity.

- Rotor flux vector control
  This methodology was developed in the late 60's by the German scientist Blaschke. The method is based on a model of the motor voltage, fluxes, and currents referred to vectors in a rotating coordinate system. With the coordinates oriented in synchronism with the rotating flux in the rotor winding, the current vector's components are de-coupled in a flux component and a torque component, similar to the DC motor's field current and armature current. The method requires computer capacity far above what was available when the control methodology was developed, and this method found its commercial application in the early to mid 80's. A disadvantage is still that the model required to do the vector transformation, contains parameters highly varying, especially the rotor resistance which depends on temperature. In order to obtain a good

dynamic performance, the rotor resistance should be adapted on-line or the temperature should be measured. Fig. 6.3 shows a schematic diagram for this control scheme.

- Advanced stator vector control
  The same de-coupling of flux and torque control can be achieved by using a model of stator fluxes and currents in a stator oriented coordinate system. This model can be made independent on the highly varying rotor parameters, but requires a much higher computer capacity of the controller. By simulation, this methodology was known as early as the late 80’s. Then in the mid 90’s the method, also known as direct torque control (DTC) was made commercially available. The mathematical model of the asynchronous motor must be solved with typically 40kHz sampling frequency for accurate control, and will then not be able to estimate the electrical quantities of the motor, but also the mechanical speed of the motor. This enables the use of tacho-less drives in most applications, which is regarded as a great enhancement of the reliability of the system.

Fig 5.8 shows the limitations of the VSI type asynchronous motor drive. The voltage limitation on stator voltage is given by the maximum output voltage from the inverter by the given, constant DC link voltage. The inverter unit or motor max current gives the limitations in stator current and torque. Normally, this means that the motor is limiting the current and torque in continuous load operations, and the inverter current at intermittent load. There is also another limitation; labeled with “pitching moment limitation” that is a characteristic of the induction motor itself. It normally occurs at 150 to 200% of nominal speed, which normally is outside of the operational speed range of a propulsion motor.



**Sample cycle 25 us**

**=>**

**40 000 times/sec**

*Fig. 5.7: Simplified block diagram for flux vector control scheme, also known as Direct Torque Control (DTC).*

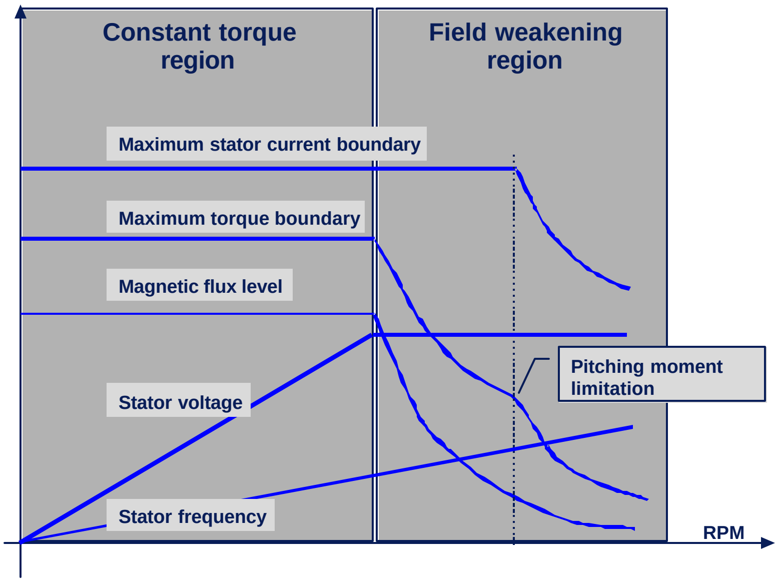


*Fig. 5.8: Characteristic maximum operating boundaries for a VSI asynchronous motor drive.*

The topology in Fig. 5.5 is capable of running the motor in both directions. Due to the diode rectified power supply, power can however only be taken from the network, not be fed back to the network during regenerative braking. The inverter part, feeding the motor, has the capability to also perform regenerative network. If this should happen in the topology shown, the DC link voltage would increase and the components might suffer from damages due to overvoltage. All converters have a built in overvoltage protection, that limits the braking power if the DC link voltage increases above a safety limit.

In order to be able to regenerate power, e.g. due to a crash-stop maneuver by reversing the propeller speed, as seen in Fig. 5.9, it is common to build in a transistor controlled resistor bank to the DC link, which is activated before the safety limit for DC link overvoltage. The regenerated power will then be dumped in this resistor. Alternatively, the rectifier can be equipped with a full bridge thyristor rectifier in anti-parallel with the diode rectifier (see next section) or an active front end (similar to the inverter module) can be applied as a rectifier unit in order to feed power into the network.

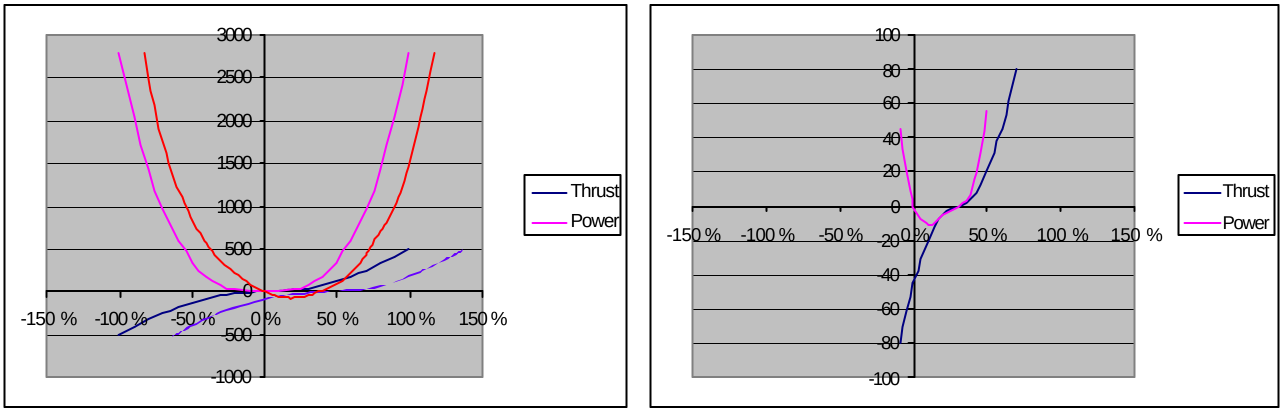


*Fig. 5.9: Braking capability (4-quadrant operation) is required for propulsion drives, where the crash stop maneuver is accomplished by speed reversal of the propeller.*

Under bollard pull condition the power flow will be positive, i.e. from network to motor, in stationary. Dynamically, there might be a dynamic braking moment to stop or reduce the speed of the propeller, if the speed reduction is so fast that one have to apply braking torque in addition to the hydrodynamic braking torque.

Fig. 5.10 illustrates the four quadrants of operation in a torque-speed diagram. The topology in Fig. 10 may only operate in quadrants I and III. With resistor braking or active front end, the VSI converter may operate in all four quadrants. This is typically needed for main propulsion, winches, elevators, etc., while thrusters normally use a two-quadrant converter.

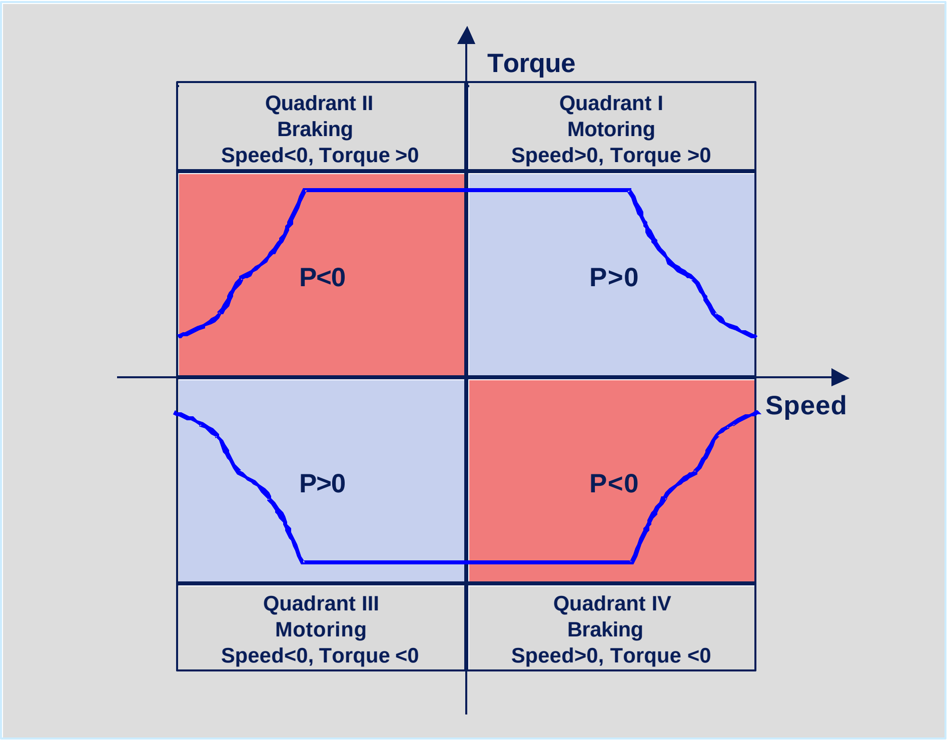


*Fig.5.10: The four quadrants of operations*

The six-pulse converter in Fig.5.5 does not draw a sinusoidal current from the network. In order to reduce the distortion, it is common to use a 12 pulse configuration as is shown in Fig 5.11. This is fed from a transformer with 30 degrees phase shifted secondaries (Ddy transformer) and with series or parallel connection of two six-pulse diode rectifiers, the resulting distortion of the primary currents will be significantly reduced. Similarly, one can also use 18-pulse (three diode rectifiers and four winding transformer) or 24-pulse (four diode rectifiers and a five-winding transformer) to further reduce the distortion. A 12-pulse configuration will normally be enough to bring the distortion down to an acceptable level. Harmonic distortion will be described more in detail in a later section.

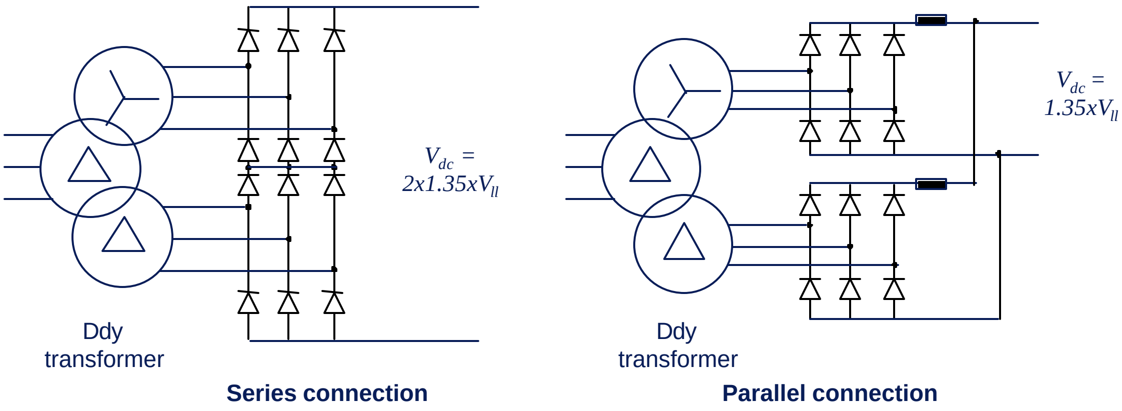


*Fig 5.11: 12 pulse diode rectifiers.*
*Series connection is often used in medium voltage converters, parallel in low voltage converters.*

Medium voltage converters are usually a modified version of the one shown in Fig. 5.5. Due to the increased voltages, the DC link voltage must be divided on more components in series in the inverter part, as shown in figure 17. This shows a three-level converter, since the output voltage now can be varied between three levels, +, 0, and -, while the two-level converter in Fig 6.1 can only be varied between + and -. The three-level converter will also give lower current distortion in the feeding currents to the motor for the same switching frequency as a two-level converter. This means that switching frequency can be kept lower, given lower losses in the component, with an acceptable current, and hence torque ripple, as shown in Fig 18.

A medium voltage, 12 pulse, three-level VSI drive for induction motor drives with water-cooling is shown in Fig. 5.14.

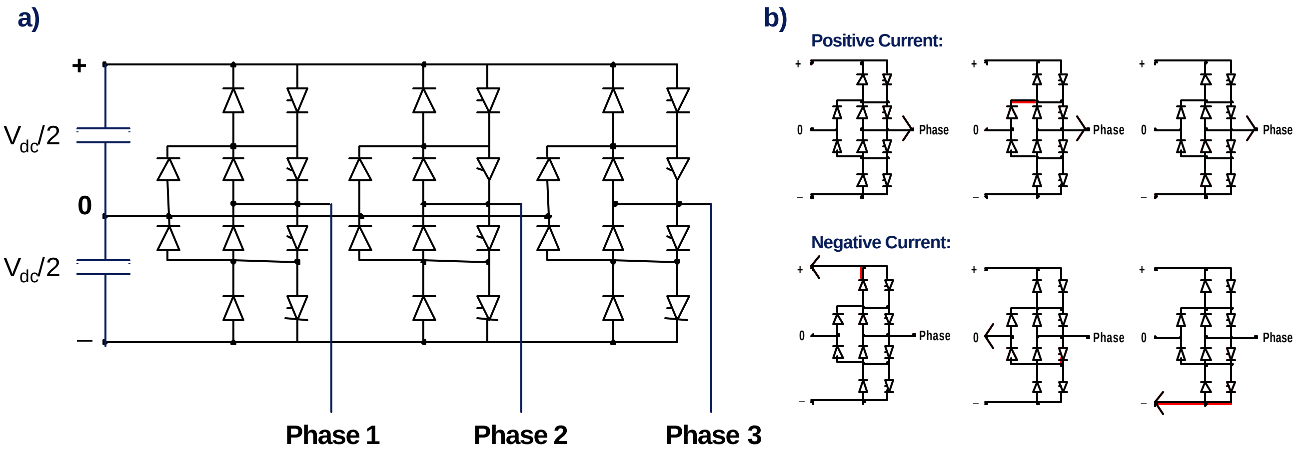


*Fig 5.12: a) Three-level inverters are often applied in medium voltage converters, since the voltage stress on each component will be lower and the harmonic distortion of the motor current will be lower at the same switching frequency, see Fig 5.13. b) Shows how current may flow to obtain, from left; + voltage, 0 voltage, and – voltage to the motor.*

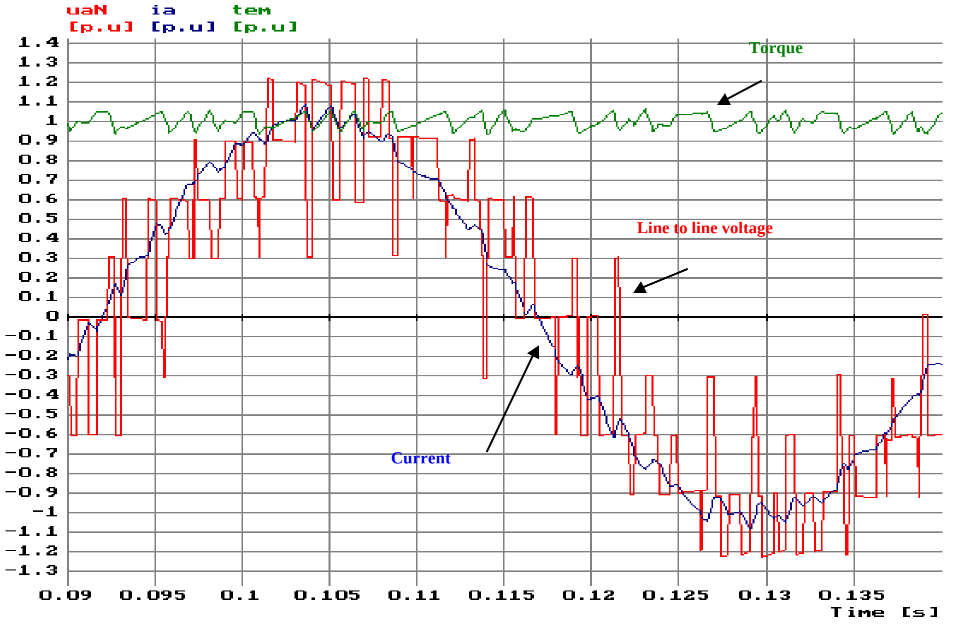


*Fig 5.13: Example of the line-line voltage output from a three-level inverter. The voltage steps will be lower compared to a two-level converter, and the current ripple will be similarly lower with the same switching frequency.*

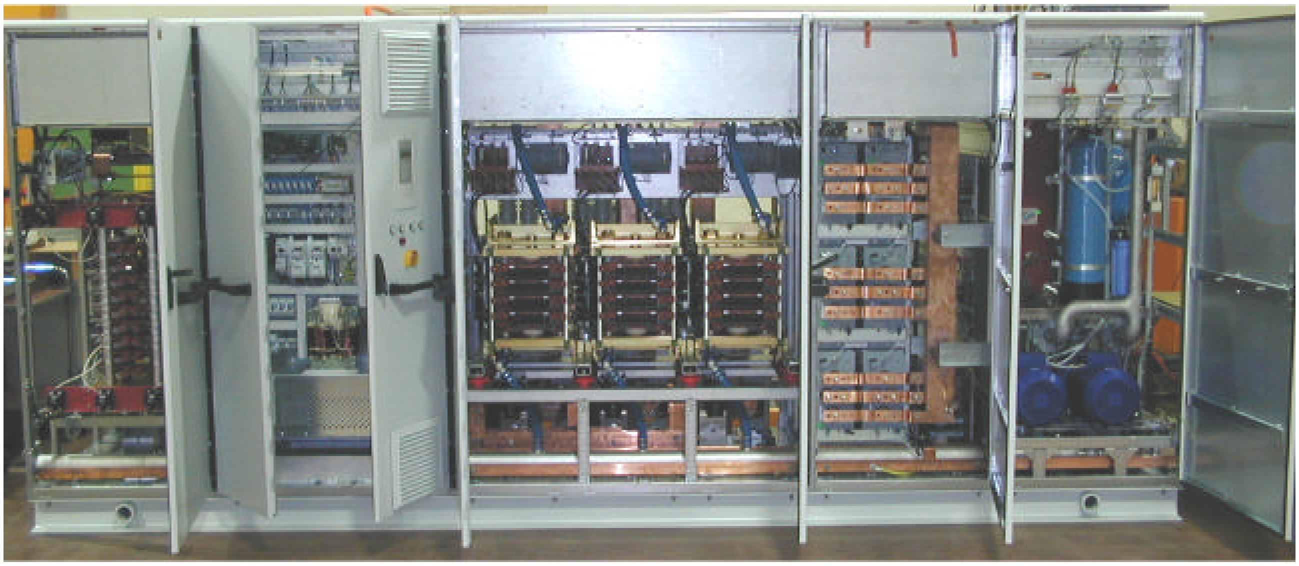


*Fig. 5.14: A medium voltage, 3300V IGCT VSI drive for induction motor drives (ABB ACS 6000).*
*Cabinets (from left):*
*1: Diode rectifers,*
*2: Terminal cabinet and control modules,*
*3: IGCT inverter module,*
*4: DC link capacitors,*
*5: Water-cooling unit with heat exchanger and circulation pumps.*
*The internal cooling water must be de-ionized (non-conducting) since the components are directly mounted without insulation to the water-cooled heat sinks. In low voltage drives, the power modules are normally isolated from the cooling heat sink, hence normal fresh water can be applied.*

### 5.2.5. Other converters

In addition to the most used topologies mentioned here, other variants are occasionally also seen. Examples are CSI with PWM current output, step-wave with multiple transformer output and extremely low motor voltage distortion, and VSI Pulse Amplitude Modulated (PAM) converters with a thyristor-controlled DC link voltage and a 6-pulse voltage output. The use of these technologies is limited and normally only seen in special applications.

### 5.2.6. Comparison of electric motor drive alternatives

The characteristics of a DOL-started fixed-speed CPP unit and a variable speed FPP unit are compared in Table 5.1. Because of a lower power factor and higher starting transients more diesel-generators should, in general, be connected to the power network with fixed-speed thrusters than with variable-speed thrusters, and hence with variable speed thruster and propulsion drives:

- Average loading will be higher with less running hours.
- Fuel costs, wear and tear, and maintenance will decrease.
- Smaller dimensioning of the power plant may be achieved.

A thruster drive has two prices: one before and one after installation. The equipment cost of the variable-speed drives will often be higher than that of the constant-speed controllable-pitch propeller. Maintenance cost and fuel consumption will on the other hand be reduced since in DP operation the thruster power is usually only partially utilized.

*Table 5.1. Comparisons of drive alternatives.*
*Low thrust equals low speed in variable speed drives and small pitch in fixed speed drive for CPP propeller.*

| | DOL asynchronous motor + CPP | SCR DC motor drive | Cyclo-[1] converter | CSI (LCI)[2] | VSI DTC[3] |
|---|---|---|---|---|---|
| Start-up amps | Typ. 5 x rated current | ≈ 0 (transformer inrush) | ≈ 0 (transformer inrush) | ≈ 0 (transformer inrush) | ≈ 0 (transformer inrush) |
| Start-up torque transients | Typ. 2-3 x rated torque | ≈ 0 | ≈ 0 | Up to 50% of rated torque | ≈ 0 |
| Power consumption, low thrust | ≈ 15% of nominal power | ≈ 0 | ≈ 0 | ≈ 0 | ≈ 0 |
| Amps at low thrust | 45-55% of nominal | F(torque) | F(torque) | F(torque) | ≈ 0 |
| Power Factor - full load | ≈ 0.85 | > 0.9 | > 0.76 | > 0.9 | > 0.95 |
| Power factor variation with load (cosϕ) | 0.15 .. 0.85 (non-linear) | 0 .. 0.9 (prop. speed) | 0 .. 0.76 (prop. speed) | 0 .. 0.9 (prop. speed) | > 0.95 (≅ constant) |
| Dynamic response (power, torque) | 3-5 sec (pitch control) | < 100 ms | < 100 ms | Slower | < 10 ms |
| Torque ripple | None | Smooth | Smooth | Pulsating | Smooth |
| Zero-thrust crossing | Smooth if negative thrust allowed | Discontinuous | Smooth | Pulsating | Smooth |
| Efficiency at full load | High | Lower | High | High | High |
| Harmonic distortion:<br>- at low speed /thrust<br>- at full speed /thrust | <br>None<br>None | <br>F(torque)<br>F(torque) | <br>F(torque)<br>F(torque) | <br>F(torque)<br>F(torque) | <br>≈ 0<br>F(power) |
| Short circuit contribution | Typ. 5 x nominal power | No | No | No | No |
| Motor matching required | - | Some | Some | Yes | No |
| Commutator | No | Yes | No | No | No |

[1] With synchronous motor
[2] With synchronous motor
[3] With cage induction motor

# 6. System Design

## 6.1. Introduction

One of the more experienced class surveyor has stated: “*Nobody should make the mistake of assuming that diesel electric propulsion is easy*”. On the other side, diesel-electric propulsion has proven to be reliable and robust when all aspects of design and engineering are sufficiently carefully examined.

The main difference between the marine power system and a land-based system is the fact that the marine power system is an isolated system with short distances from the generated power to the consumers. The amount of installed power gives special challenges for the engineering of such systems.

The design and engineering phase can simplified be illustrated by Fig. 1. Even before the vessel concept design starts, a market assessment based purpose and requirement specification for the vessel should be the made as the basis for the design work.

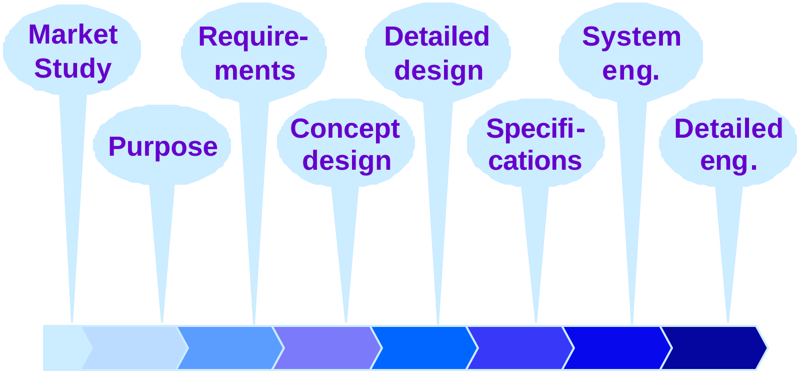


*Fig.6. 1: Stages in design and engineering work.*

The system design and engineering can be divided in two phases, however, the first phase is not fully independent on the possibilities and constraints of the second;

1. Design, conceptual and detailed:
   In these phases, the vessel capability must be specified and analyzed in order to define the amount of thrust required for sailing, maneuvering, and station keeping, as applicable for the intended operations.
   Based on the goals and objectives for the vessel operations, the type of propulsion and propulsion / thruster units, their rating and location on the vessel should be determined, as well as the most optimal configuration and splitting of the power generation and distribution system.

   The design phase will result in a set of technical specifications for the vessel, which is the basis for the further engineering work.

2. Engineering, system and detailed:
   During these engineering phases, several analytical and numerical calculations have to be performed in order to achieve safe and reliable operation, in common described as *standard* network analysis or electrical power system studies:

   - Load flow calculation
   - Short circuit calculations
   - Ground fault calculations
   - Relay coordination study
   - Harmonic analysis
   - Voltage drop calculation of inrush of transformers and starting of motors

Dependent on system configuration and vessel application the following *extended* analysis can also be required, or necessary:

- Transient analysis of network behavior after disturbance, e.g. short circuit
- Reliability or failure mode analysis

A thorough and precise work in this phase is essential for safe, reliable, and cost efficient operations, and flexibility for future upgrades and modifications of the system later during the lifetime of the vessel.
Such work has been made much more simple and accurate by use of computer aided engineering and design tools, and there is a whole range of such available and in daily use.

## 6.2. Life Cycle Cost Assessment of Conceptual Design

The starting point for the conceptual design of the electric power generation and propulsion system is based on the intended operation and operating profile of the vessel which is the results of the vessel and hull design work.

If the vessel has a relatively flat operating profile, meaning that propulsion power is close to constant for most of the life time, e.g. a VLCC tanker in fixed charters, electric propulsion will normally not be economically feasible unless there are other requirements which makes it beneficial. Such can be; large power requirements for other processes, high maneuverability, redundancy, low noise and vibration, etc.

For vessels with more variable operation profile, as shown in Fig. 6.2, diesel electric propulsion may be profitable, by pure fuel and maintenance savings, or in combination with increased income.

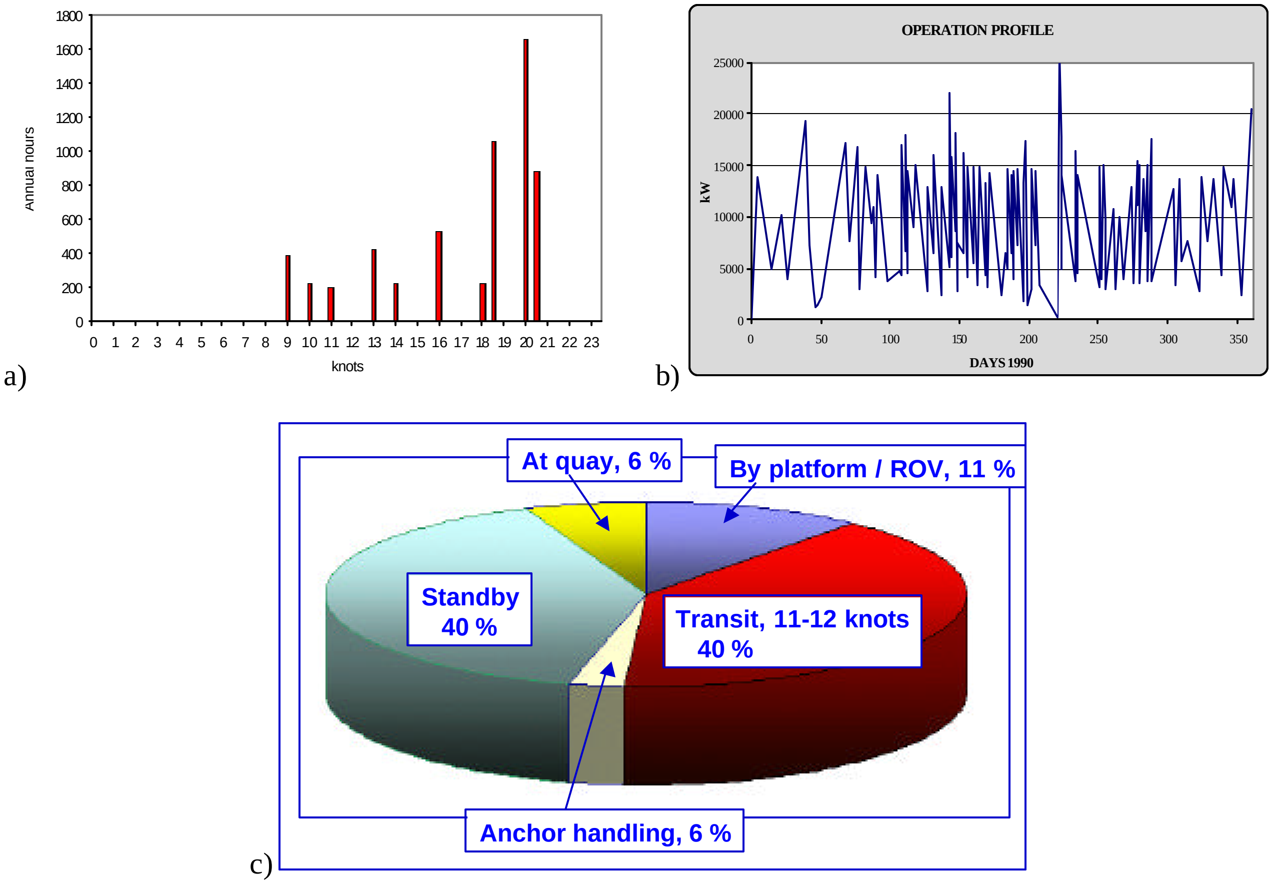
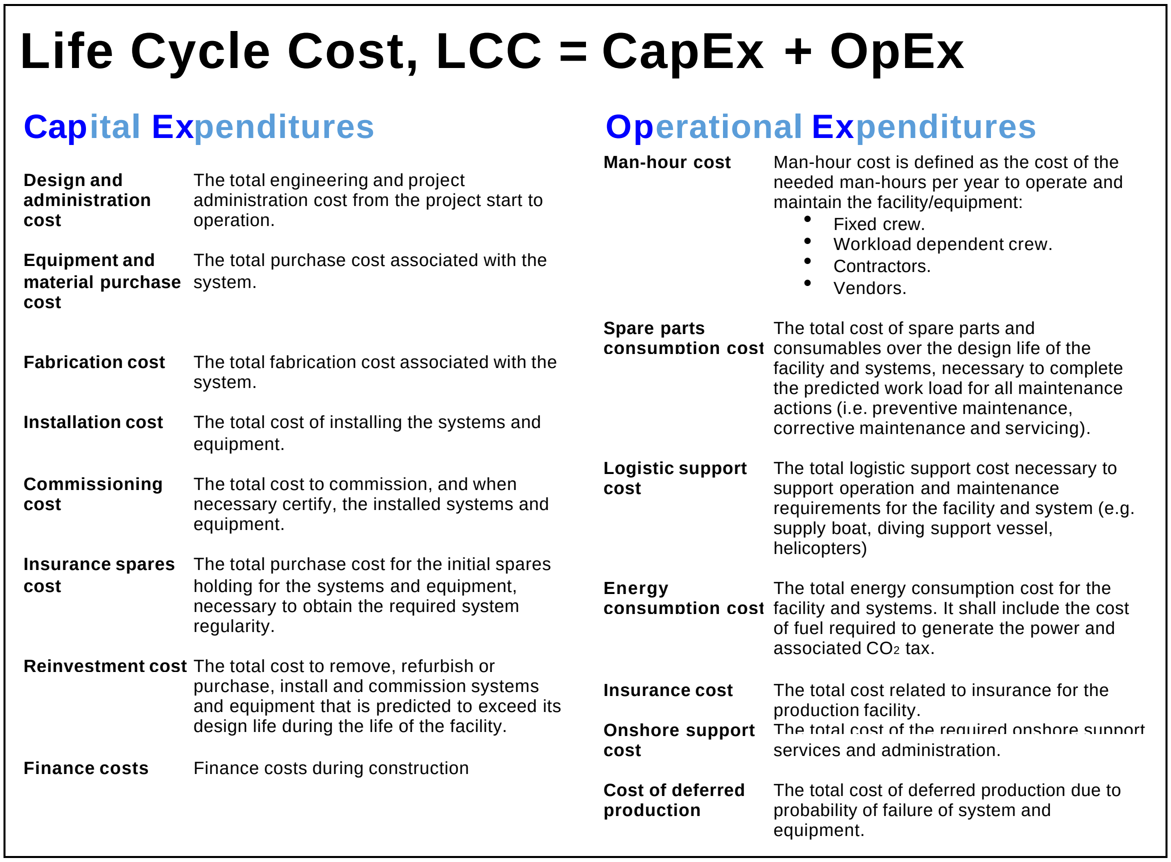


*Fig.6.2: a) Operating profile for a cruise vessel (hours per year) and*
*b) for a shuttle tanker in the spot market (per day over a year) and c) for a field support vessel*

An accurate comparison of different concepts should be accomplished by use of a Life Cycle Cost assessment (LCC). There are several ways to do this, and Norsok has suggested a method, intended for use in offshore industry, but it can also be applied for ships. The main elements of the LCC are divided in CAPEX (Capital Expenditures) and OPEX (Operation Expenditures), and are listed in Fig. 6.3

Although a life cycle cost of the complete vessel and its operations ought to be done for a fair and precise comparison of different concepts, this is too seldom done, mainly because of lack of competence, lack of reliable data or lack of time and resources at this stage, or a combination. It is likely to believe that conventional propulsion system is more often selected as a consequence of this, than opposite.



**Life Cycle Cost, LCC = CapEx + OpEx**

**Capital Expenditures**

| | |
|---|---|
| **Design and administration cost** | The total engineering and project administration cost from the project start to operation. |
| **Equipment and material purchase cost** | The total purchase cost associated with the system. |
| **Fabrication cost** | The total fabrication cost associated with the system. |
| **Installation cost** | The total cost of installing the systems and equipment. |
| **Commissioning cost** | The total cost to commission, and when necessary certify, the installed systems and equipment. |
| **Insurance spares cost** | The total purchase cost for the initial spares holding for the systems and equipment, necessary to obtain the required system regularity. |
| **Reinvestment cost** | The total cost to remove, refurbish or purchase, install and commission systems and equipment that is predicted to exceed its design life during the life of the facility. |
| **Finance costs** | Finance costs during construction |

**Operational Expenditures**

| | |
|---|---|
| **Man-hour cost** | Man-hour cost is defined as the cost of the needed man-hours per year to operate and maintain the facility/equipment:<br>• Fixed crew.<br>• Workload dependent crew.<br>• Contractors.<br>• Vendors. |
| **Spare parts consumption cost** | The total cost of spare parts and consumables over the design life of the facility and systems, necessary to complete the predicted work load for all maintenance actions (i.e. preventive maintenance, corrective maintenance and servicing). |
| **Logistic support cost** | The total logistic support cost necessary to support operation and maintenance requirements for the facility and system (e.g. supply boat, diving support vessel, helicopters) |
| **Energy consumption cost** | The total energy consumption cost for the facility and systems. It shall include the cost of fuel required to generate the power and associated $CO_2$ tax. |
| **Insurance cost** | The total cost related to insurance for the production facility. |
| **Onshore support cost** | The total cost of the required onshore support services and administration. |
| **Cost of deferred production** | The total cost of deferred production due to probability of failure of system and equipment. |

*Fig. 6.3: Elements in Norsok's Life Cycle Cost assessment.*

## 6.3. Standard Network Analysis and Electrical Power System Studies

### 6.3.1. Load flow calculations

The aim of the load flow and short circuit calculations is to determine whether the thermal and mechanical stresses on equipment, such as generators, cables, switchboards, and transformers, is below the maximum design values, under normal as well as contingency conditions.

It also gives information about the setting of transformer tappings and voltage regulators that ensures that the voltage levels on the different distribution buses and load terminals are within permitted stationary deviation limits.

Load flow calculations are performed to find stationary values of loads in the generation and distribution network, and since the network in ships normally are radial, it is a fairly straight-forward exercise. It is normally done prior to the short circuit calculations in order to obtain its starting values.

### 6.3.2. Short circuit calculations

Short circuit calculations are done to ensure that fault current in short circuits does not exceed breaker's and other equipment's maximum ratings. Under short circuit, the mechanical stresses on bus-bars and cabling becomes much higher than under normal operation, and class rules and standards defines certain limits that the equipment shall be designed for.

A typical short circuit current waveform for a generator is shown in Fig.6. 4. As seen, the initial current has a significant DC component, which together with the sub-transient short circuit current may give a high peak value typically in the order of 10 times nominal current for the generators. The short circuit currents are being reduced, as the DC component decays rapidly, typically with a time constant of 20-100 ms. After 300-500 ms, the transient short circuit current is typically reduced to 3-5 times nominal generator current, and dependent on the system design, this is normally the breaking current for a circuit breaker for a branch.

A sustained short circuit current will after a second or more, reach a stationary value, which according to rules and regulations shall be at least three times nominal current for a generator in order to detect faults reliably, for clearing faulty branches.

The short circuit current is found by numerical simulation or by analytical methods. IEC 61363 is normally applied for short circuit calculations in ships.

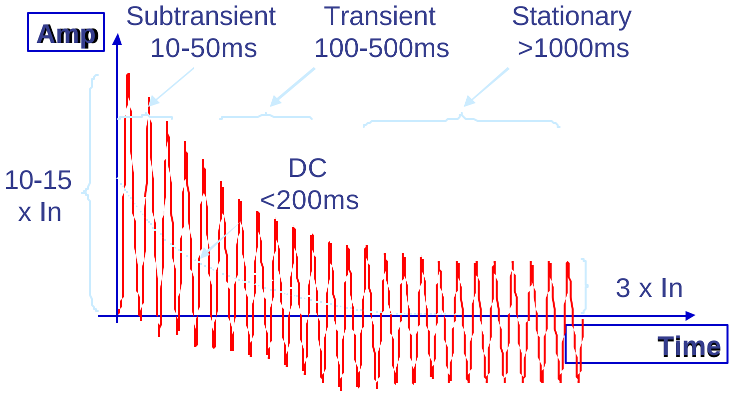


*Fig. 6.4: Typical short circuit current.*

### 6.3.3. Ground fault calculations

If one phase is short-circuited to ground, there will flow a ground fault current. Its magnitude depends heavily on the method of system grounding, which are:

- Ungrounded
  Ground fault currents will still flow due to capacitive coupling between healthy phases and ground, typically in the order of a few amps in a ship installation.
- Low resistance grounding
  Ground fault currents will flow through the ground fault, with a low resistance ground resistor limiting the fault current to not less than 100A.
- High resistance grounding
  Ground fault currents will flow through the ground fault, with a high resistance ground resistor, limiting the fault current typically less than 20A.
- Bolted ground
  Create a high ground fault current, in the order of a short circuit current.

- Coil grounding
  With a proper tuned coil grounding, the fault current is theoretically very low. Not commonly used in ships, mainly since the network configuration varies, and tuning of the coil is impractical.

System grounding in ships are normally either low or high resistance grounding of system neutral point or, or ungrounded. It might also be a combination of these in different parts of the distribution system.

Ground fault calculations are done to ensure that the fault current is low enough to reduce the risk of damaging equipment, and to determine the levels needed to adjust ground fault detection relays.

For some ships (especially tankers), there might be desired or required to operate with isolated neutral point in order to reduce fault currents to a minimum. Due to system capacitance, a fault current with a typical magnitude of some Ampere will still flow through the ground fault. The power system may be allowed to continue operation with such low fault currents until it is possible to disconnect and repair faulty parts without large disturbances in operations. The disadvantages with this grounding method is that one can experience high overvoltages due to resonance in the fault current circuits, and it might also be difficult to identify in which branch the fault current occurred.

A high impedance neutral point grounding limits the ground fault currents typically to less than 20A. Also with this fault current it might be allowed to continue operation with a fault for a limited period of time. The grounding resistor will reduce the risk of resonance oscillations and it is easier to detect and disconnect the faulty branch of the power system. High impedance neutral point grounding is normally the preferred method in medium voltage systems.

Low impedance neutral point grounding gives high ground fault currents and a ground fault must be cleared by disconnecting faulty parts immediately (typically <200ms). Compared to isolated and high impedance grounded neutral point, this method will reduce the voltage stress on the healthy phases during the fault.

### 6.3.4. Relay Coordination / Selectivity Study

Each feeder in and out from a switchboard is equipped with protection relays or fuses for detection and disconnection at short circuit, sustained overload conditions, and ground fault. Ground faults with low fault currents may be accepted for continuous operation.

An over-current / short circuit relay is typically adjustable by level of fault currents and time to disconnect. Fuses have correspondingly a certain current-time characteristic selected for the application. A normal load condition shall not initiate a disconnection. If the load current is higher than the defined normal condition, i.e. in overload, the relay starts a time counter, and disconnects after a certain, and preset time delay. If load current is even higher, the relay starts another time counter, that disconnects the branch after a shorter time period, defined by the selectivity study in a way that protection devices in lower parts of the system shall be activated first, and protection in higher parts later.

Adjusting these settings or selecting of fuses shall according to rules and regulations clear any fault selectively, by disconnecting a minimum of the distribution system limited to the parts that are directly affected by the fault. Deviations might be necessary, if the consequences are regarded not critical.

### 6.3.5. Harmonic Distortion

The harmonic distortion level may be significant in electric propulsion systems, as the main loads usually are variable speed propulsion/thruster drives with frequency converters. Harmonics and harmonic analysis is described in a separate section.

### 6.3.6. Voltage Drop Calculations

At start-up of heavy motor consumers or energizing large transformers, the start-up transient current may be several times larger than the nominal rated current. For a motor, typically 5-8 times higher, and for a transformer, up to 10-12 times higher.

A typical motor start transient with a direct on-line (DOL) started motor is shown in Fig. 6.5. The motor starting current, is similarly to a short circuit, a complex time varying curve containing a DC term, and transient as well as stationary terms during the acceleration time. The time for acceleration to full speed is determined by the motor rating and the load curve of the motor.

The associated voltage transient is shown as a nearly instantaneous maximum drop immediately after the motor is connected. Then, the AVR starts to increase magnetization to compensate for the increased load currents of the generators. When the motor reaches the pitching moment, the stator currents quickly reduce and since the generators now are over-magnetized for the new load, a certain voltage overshoot occur. High start-up currents may cause a significant voltage disturbance in the network, and class requirements set a limit for acceptable transient voltage variations. This limit is typically –15% and +20% (DnV).

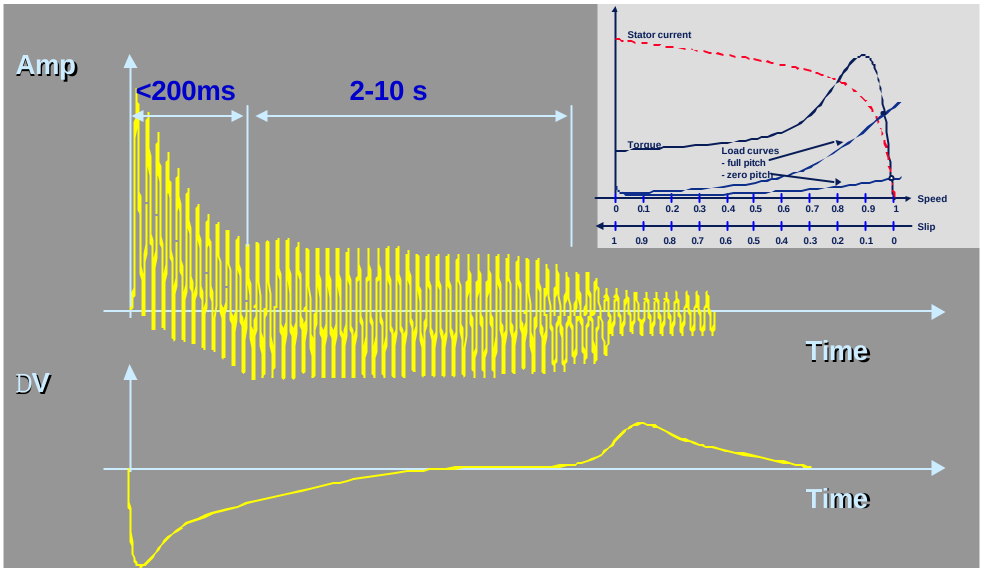


*Fig. 6.5: DOL (direct on-line) motor start current and voltage transient.*

There are analytical methods for calculating such voltage drops, though numerical simulations find the most accurate result.

In order to not exceed the required voltage variations, there might be a need to adjust the characteristics of the generator or the large consumers, or introduce means to reduce the start-up transients. For motors, such means could be soft-starting devices, star-delta starters, or autotransformer start. For transformers, pre-magnetizing could be evaluated. Generators with low transient reactance will also give a lower transient voltage drop.

## 6.4. Extended Analysis and Studies

### 6.4.1. Transient Analysis

In addition to the fault calculations and voltage drop calculations mentioned, there are occasionally a need for more thorough analysis of the transient behavior of the network during and after clearing a fault.

Typically, such analysis includes voltage and frequency stability (i.e. will voltage and frequency of the generators be re-established after the fault is cleared?) and re-acceleration of motor loads (will essential motors be able to accelerate without tripping after the fault is cleared?).

Such analysis are extensive and require accurate modeling of the network and regulators for voltage and frequency in order to be reliable. It is normally only done when regarded necessary, and in systems with large motors.

### 6.4.2. Reliability analysis and FMEA

Especially for ships where availability of the power system is essential and with redundancy requirements, there is normally a request for reliability analysis or Failure Mode and Effects Analysis (FMEA or FMECA – C for "Criticality"). These shall identify the consequences of faults in components or system, their criticality and assess the probability for such events. Its objective is to identify critical characteristics that can be improved in the design or specially considered for operations.

The reliability analysis is a quantitative approach to find the likelihood for certain fault scenarios, such as loss of parts of propulsion power, blackout, loss of positioning capability, etc. It is normally accomplished by use of a fault three analysis and calculation, known from statistics theories.

The FMEA/FMECA is a more qualitative approach, focusing on identifying the consequences of certain fault scenarios, with a qualified description of how such scenarios are detected, and avoided / compensated for.

Typical elements for each scenario are:

1. Description of initial conditions
2. Description of failure mode of components
3. Description of effects on system
4. Description of consequences (No, low, high, severe, catastrophic)
5. Description of occurrence (Rarely, seldom, normal, frequent)
6. Description of detection and corrective actions
7. Description of criticality (acceptable, not acceptable)

The result is normally input to an overall FMEA/FMECA analysis for the plant, documenting the need for design improvements, operational instructions, etc.

# 7. Harmonic Distortion

## 7.1. Introduction

When the connected load in a network is not linear, i.e. not draws sinusoidal currents, the load currents will distort the sinusoidal voltages. This deviation from a sinusoidal voltage or current wave form is called harmonic distortion.

Distortion of currents and supply voltage waveforms may lead to:

- Accelerated aging of insulation material.
  Increased power dissipation (losses) in equipment connected to the network, such as generators, motors, transformers, cables, etc., from the harmonic currents, may cause overheating and deterioration of the insulation, and reduced life time of the equipment.

- Overloading of electronic equipment:
  Increased load current of electronic equipment that has been designed for sinusoidal voltage supply, may cause overheating and malfunction of this equipment.

- Malfunction:
  The distorted waveform may cause electromagnetic interference or erroneous measurement signals if the equipment is not designed for the actual distortion. It is particularly necessary that measurement systems of monitoring and protection devices are made for true RMS measurements in order to function properly.

The harmonic distortion level may be significant in electric propulsion systems, as the main loads usually are variable speed propulsion/thruster drives with frequency converters.

Rules and regulations normally give guidelines or requirements that limit the harmonic distortion in a ship network. However, these limitations are not a guarantee for proper functionality. It is therefore necessary to be able to predict harmonic distortion, evaluate the effects, and perform the proper means to manage the voltage distortion, without functional faults over the life time of the installation.

## 7.2. Harmonics of VSI converters

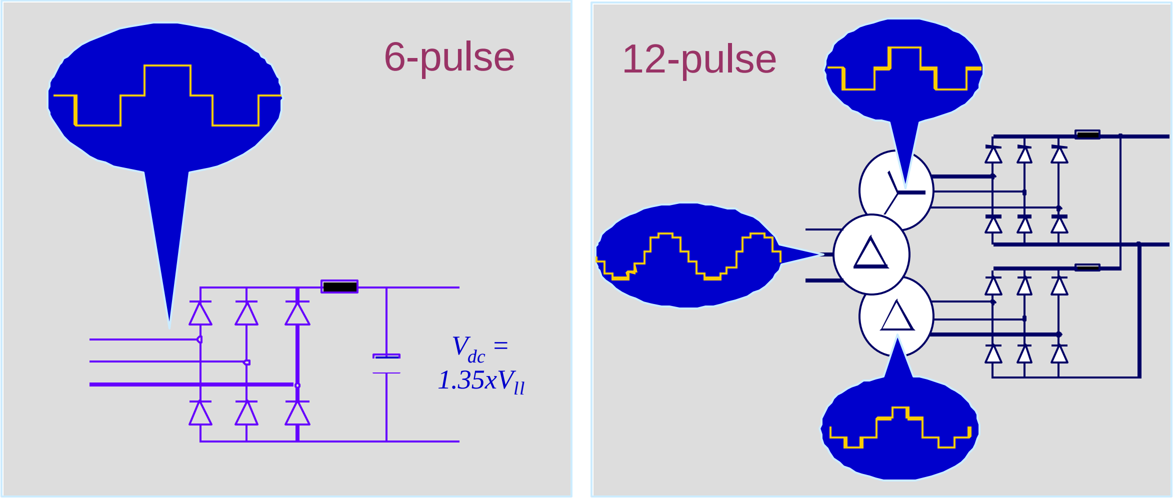
A Fourier series, i.e. the infinite series of sinusoidal components and a dc term, can in general express any periodic waveform:

$$u(t) = u_{dc} + u_1 \sin(\omega_1 t) + u_2 \sin(2\omega_1 t + \varphi_2) + u_3 \sin(3\omega_1 t + \varphi_3) + \ldots + u_h \sin(h\omega_1 t + \varphi_h) + \ldots$$

Some of the terms can be zero, such as the dc terms in most AC applications and the triple harmonics in symmetric three-phase systems which are isolated from ground.

The frequency converters are inherently non-linear and the currents to a motor drive are not sinusoidal but distorted by harmonic components of generally any order, but as we will see, most of the frequency components are zero under ideal conditions.

When analyzing the harmonic distortion of the network supply, one can normally, at least initially, disregard the motor side behavior, by assuming ideal de-coupling between the network and motor sides by the DC link. In Figure 1, a VSI converter with diode rectifier and smoothing DC inductor and capacitor has been shown, in a 6-pulse and a 12-pulse configuration. If the smoothing DC components are large, the current waveforms will approach the ideal shapes as shown in Fig. 7.1.



(a) (b)

*Fig. 7.1: Ideal waveforms in a 6- and 12-pulse VSI converter.*

By observation, one can see that the current into the 12 pulse rectifier is equal to the 6-pulse rectifier, but the phase shift of the Y-connected transformer secondary will shift all voltages and currents by 30 degrees, compared to the D-connected secondary. The current waveforms shown, are those of the transformer windings.

Assuming that converter and transformer are symmetrically designed and output stage of converter is assumed to be de-coupled from rectifier current, only the *characteristic* harmonic components is present in the input currents to the line supply of the frequency converter. For a 6-pulse converter these are:

$$h = 6\,xn \pm 1, n = 1,2,.. \Rightarrow h = 5,7,11,13,...$$

In a 12-pulse converter, multiples of sixth (+/- 1) harmonics, which are present in the secondary and tertiary windings of the feeding transformer, will due to the 30-degree shift be cancelled in the primary windings and thus the remaining harmonic current components will be of order:

$$h = 12xn \pm 1, n = 1,2,...$$
$$\Rightarrow h = 11,13,23,25,...$$

The Total Harmonic Distortion (*THD*) is a measure of the total content of harmonic components in a measured current, *THD(i)*, or voltage, *THD(u)*:

$$THD(i) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} i_{(h)}^{\;2}}}{i_{(1)}}, \textit{ and } \; THD(u) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} u_{(h)}^{\;2}}}{u_{(1)}}$$

where $u_{(1)}$, $i_{(1)}$ are the fundamental RMS value of the voltage and current, and $u_{(i)}$, $i_{(i)}$ are the RMS value of the $i^{th}$ harmonic of the voltage (or current). Normally, one will only regard harmonics up to and including the 50th harmonic order.

### 7.3. Harmonics of CSI converters

For a CSI converter, the characteristic harmonics will be similar to a VSI converter. However, the de-coupling between the line supply and the motor sides are not as ideal as for the VSI, and the harmonics of the line side currents are strongly influenced by the motor side harmonics. In addition to the pure harmonics, a CSI drive also generates non-integer harmonics to the power network. Non-integer harmonics are interfering components at frequencies that are not exact multiples of the system frequency.

In an CSI drive these non-integer harmonics are due to the DC pulsation frequencies caused by the machine converter and are therefore synchronous with the motor frequency according to the following formula:

$$f_i = h \cdot f_N \pm p \cdot f_M$$

where

| | |
|---|---|
| $f_i$ | Non-integer harmonic component |
| $h$ | Characteristic harmonic component from drives (1, 5, 7, 11, 13 etc) |
| $f_N$ | Network frequency |
| $p$ | Pulse-number of the drive |
| $f_M$ | Machine frequency |

The amplitude of the non-integer harmonic components are mainly determined by the size of the DC inductor, i.e. the larger inductor the lower amplitudes. Secondly, the amplitudes are in general much smaller than the integer harmonic components.

### 7.4. Harmonics of cyclo converters

For cycloconverters the harmonic component content of the input current will be a function of both input frequency and output frequency, for a 6-pulse cycloconverter:

$$f = (6 \times n \pm 1)\, f_i \pm (6 \times p)\, f_o\,,$$
$$n = 1,2,...,\ p = 0,1,......$$

where $f_i$ is input fundamental frequency and $f_o$ is output fundamental frequency.

As seen, also here there is a rich content of both harmonics and no-integer harmonics in the current, and thus voltage waveforms.

The amplitude of the non-integer harmonics are normally significantly high, and it is normally regarded difficult to establish an efficient tuning of a passive filter to reduce the harmonic level with cyclo converter loads.

### 7.5. Limitations by Classification Societies

The classification societies have quite recently started to define limitation on allowable THD for voltage waveforms on the switchboards. For example DnV says that for distribution systems the $THD_v$ shall normally not exceed 5 %, unless being stated from vendor or system responsible, e.g. by documentation that affected equipment is designed and tested to the actual conditions. It is not defined how documentation and testing shall be done.

A harmonic analysis study is usually required for documenting the harmonic distortion level and to find dimensioning criteria for generators, transformers, and if necessary, filters for reduction of harmonic distortion.

## 7.6. Harmonics of ideal 6- and 12-pulse current waveforms

For the idealized current waveforms in Fig. 1(a), one can establish the harmonic spectrum by the following relation (since the wave-form is an odd function with average zero):

$$i_h = \frac{2}{T}\int_{-T/2}^{T/2} i(t)\sin\left(\frac{2hp}{T}t\right)dt$$

Using this relation, one find the following spectrum, where $\hat{I}$ is the amplitude of the current:

$$i_1 = \hat{I}$$
$$i_2 = i_3 = i_4 = 0$$
$$i_5 = i_1/5$$
$$i_6 = 0$$
$$i_7 = i_1/7$$
$$i_8 = i_9 = i_{10} = 0$$
$$i_{11} = i_1/11$$
$$i_{12} = 0$$
$$i_{13} = i_1/13$$

...

$i.e.:$

$$i(t) = \hat{I}\sum_h \frac{1}{h}, h = n\cdot 6 \pm 1, n = 1,2,3,4,....$$

Fig. 7.2 shows the result of this series, where the terms up to 37th harmonics are included, showing how the resulting waveform converges towards the original six-pulse shape.

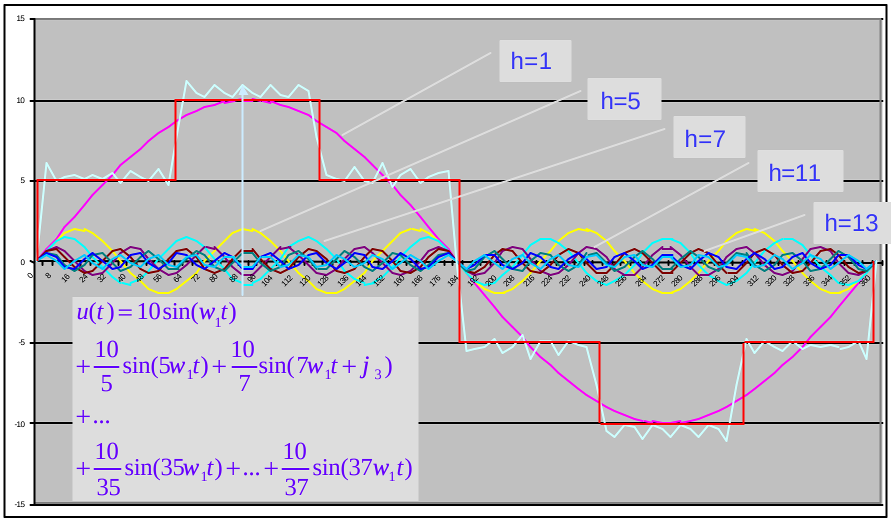
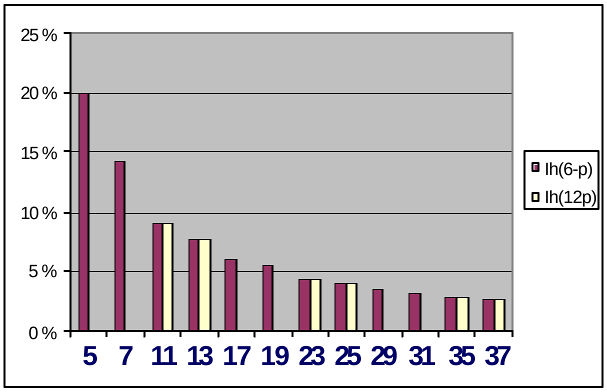


*Fig.7.2: Harmonics up to 37th of a six-pulse current waveform.*

6-Pulse

$$h = 6xn \pm 1, n = 1,2,..$$

$$\Rightarrow h = 5,7,11,13,...$$



12-Pulse

$$h = 12xn \pm 1, n = 1,2,...$$

$$\Rightarrow h = 11,13,23,25,...$$

*Fig.7.3: Characteristic harmonics of a six and 1twelve pulse current wave-form.*

In the 12 pulse current waveform, the harmonics of order 5, 7, 17, 19, etc., cancel due to the 30 degree phase shift of the three-winding transformer. These harmonics will flow in the transformer windings, but with opposite phase, in the secondary windings of the transformer, and by the summing, they will circulate inside the transformer only, and not flow into the network.

The total harmonic distortion of these current wave forms can be found by the relation,

$THD(i) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} i_{(h)}^{2}}}{i_{(1)}}$, which yields $THD_{(i)}$ about 30% for the 6-pulse current, and 15% for the 12-pulse current.

These are ideal current waveforms. In practice, impedance due to inductance, resistance, and capacitance alters the current shape. The corresponding harmonic spectrums that can be measured in a typical installation with VSI converters are shown in Fig. 7.4.

It is obvious that the characteristic harmonics are lower than could be expected from ideal curves, and that non-characteristic harmonics, here 5th, 7th, etc, occur due to non-ideal transformers and uneven load distribution of the parallel connected rectifiers in the 12 pulse converter.

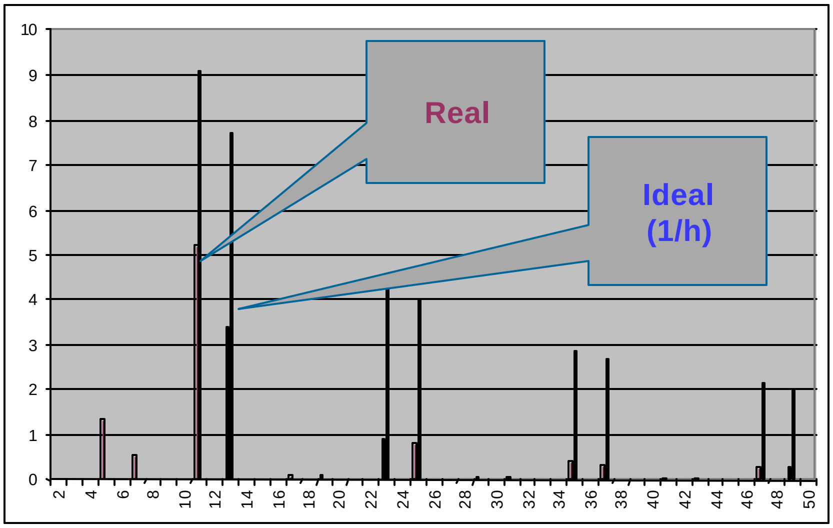


*Fig. 7.4: Characteristic harmonics of a 12 pulse current waveform, comparing the real values of a practical installation with the ideal amplitudes.*

## 7.7. Calculating harmonic distortion

### 7.7.1. Basics

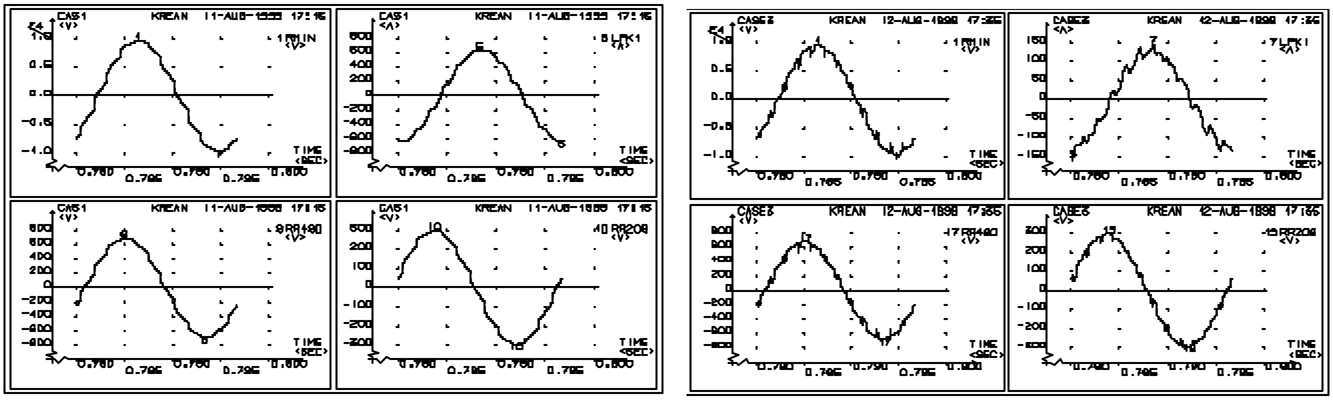
The harmonic currents drawn by a non-linear load from the network will be distributed in the network and flow through the other equipment in the power network. If regarded to be a current source of harmonic current components, it is obvious that the harmonic currents will flow through the paths with lowest impedance for the harmonics. These are normally the running generators, large motors, or large distribution transformers to other (higher or lower) voltage levels.

There are two types of simulation tools available: time domain simulation and the more commonly applied, which calculates in frequency domain. The benefit of the frequency domain calculation tools is that the time and work for modeling and calculation of large systems is much shorter than for a time domain simulation. However, the accuracy will normally be lower, since one has to decide the harmonic content of the load current, which in reality is dependent on the network configuration and can only be determined by time domain simulation or by equivalent figures from similar systems. Special considerations should be made for PWM type of controllers and use of passive filters, where time domain simulations are strongly recommended in order to obtain results that are necessary for correct design and dimensioning.

The simulation circuits can normally be assumed ideal, with symmetric supply and neglected impedance in switchboards and cables. In practice transformers and converters are not ideally symmetrical, nor is the network impedance. Further, there must be expected that non-characteristic current components are present. These effects will usually have a negligible effect unless resonance frequencies become excited.

Cable and load impedance's, especially capacitive components may increase the distortion on low voltage distributions. In network with high voltage distortion one should avoid the use of tube lighting with capacitive compensators.

An example of waveforms of switchboard voltage and currents to the thruster is calculated by the time domain analysis program KREAN and shown in the two figures below. Fig. 7.5a shows a simulation with only thruster drives with diode bridge converters. Figure 7.5b shows a simulation where thruster drives with diode bridge and drilling drives with thyristor bridge are running simultaneous.



(a) (b)

*Fig. 7.5: (a): Example of switchboard voltage waveforms for a system with converters with diode bridge rectifiers. $THD_V$ is approximately 7%.*
*(b): Example of switchboard voltage waveforms for a system with converters with both diode and thyristor bridge rectifiers. $THD_V$ is approximately 9%.*

### 7.7.2. Frequency domain – harmonic injection

In this method, the nonlinear load is represented by a harmonic current source, injecting harmonic currents to the network. The network in terms are modeled as a system where its various parts, generator, cable, transformer, motors, etc., are modeled with an appropriate impedance model, representing the impedance for the harmonic frequency currents injected by the harmonic current source.

An example of such models is shown in Fig.6., with a harmonic current source representing the frequency converter, and impedance models for generator, cable, transformers, and loads, e.g. motors.

By calculating the resulting voltages from the harmonic currents, the harmonic voltages are found in the branches or points of interest. Summing up these, the harmonic voltage distortion is finally found.

There are several calculation software programs assisting in building up and calculation of harmonic distortion in the frequency domain. Building up large networks is quite simple by library models, and calculation times are short.

The main challenge is to find a good harmonic representation of the converter, especially when using converter types where the harmonic spectrum is highly dependent on the network, such as with VSI converters. Library models are not always to be trusted.

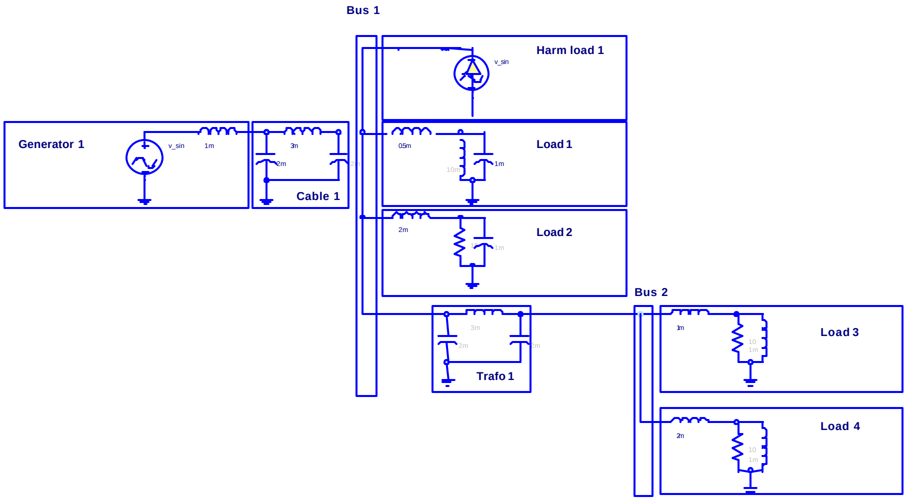


*Fig. 7.6: Impedance model of a network used in frequency domain calculation of harmonic distortion.*

### 7.7.3. Time domain – network simulation

By building up a circuit model of the network, with discrete impedance models, one can perform a time domain simulation of the system. Initial values of voltages and currents are chosen, and after some simulation time, the system has stabilized sufficiently to represent stationary conditions.

By taking one fundamental period of the voltage or current waveform of interest, one can then perform a Fourier transformation and find the harmonic spectrum at any point or branch of the system.

A simplified circuit model for the same system as in Fig. 7.6 is shown in Fig 7.7. It is quite obvious that a complex network is cumbersome to model and time consuming to simulate. Time step in the simulation must also be relatively short in order to give accurate results.

The great benefit is, that this model gives an accurate calculation of the voltages and currents, and also the harmonic spectrum of the nonlinear loads.

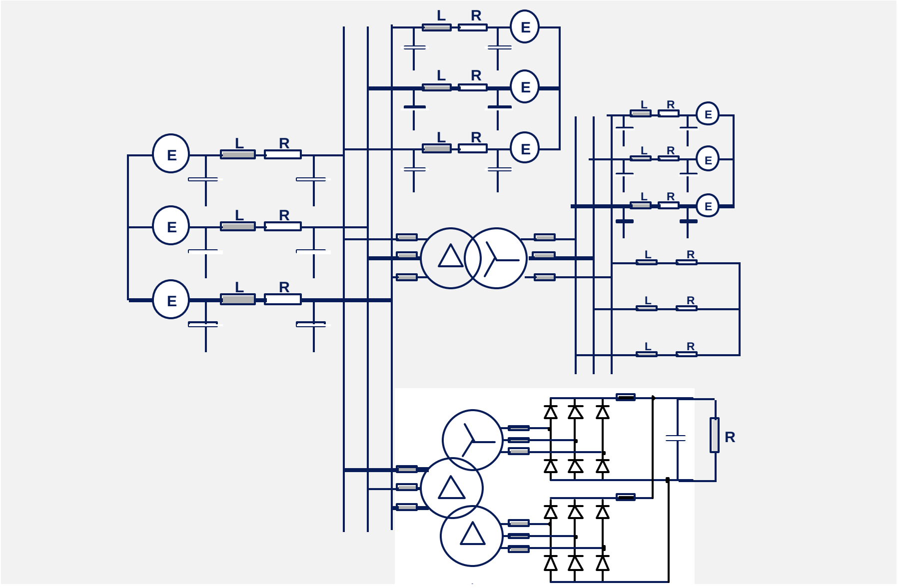


*Fig.7.7: Simplified circuit model of a network used in time domain simulation of harmonic distortion.*

### 7.7.4. Comparison of the frequency and time domain simulation

Frequency domain calculations are widely used because of the simple modeling and short calculation times. If the harmonic representation of the converter currents is accurate, the results are also accurate. It is not always straightforward to find the harmonic representation, which may strongly be influenced by the network characteristics. Then, a time domain simulation can be used, either for a complete calculation, or for a part of the system that is representative enough to give a good harmonic model of the converter, and feed this results into a frequency domain calculation for the complete system.

To illustrate the potential faults, if comparing the results of the time domain simulation with a corresponding frequency domain calculation of the same system with the ideal harmonic currents of a 12-pulse rectifier, the real voltage distortion gives THD=8%, while the frequency domain calculation with ideal current waveforms results in 20%. This difference is of course so large that the result from the latter calculation is use-less for any engineering aspect.

## 7.8. Managing harmonics

In a vessel with diesel electric propulsion, the frequency converters may constitute up to 80-90% of the actual load of the generators. Harmonic effects must be considered, and managed, in order to avoid deterioration and malfunction of equipment, and to meet the rules and regulations' requirement for harmonic distortion levels.

There are certain engineering aspects that may be used to obtain these objectives, discussed in the following.

### 7.8.1. Generator impedance

The harmonic currents injected to the power distribution system will mainly follow the lowest impedance routes, which normally are the generators.

For the frequencies of interest in the harmonic analysis, the generator sub-transient impedance is used. The d- and q-axis sub-transient inductance are normally different, especially in a generator with salient poles, and the average of these, $x_d$" and $x_q$" are normally used, alternatively the negative sequence impedance, $x_-$.

A generator with low sub-transient inductance is normally larger than one with larger sub-transients. Normally, the value is about 20%, while it is relatively achievable to reduce this to 15% or even lower.

Another effect of lowering the sub-transient inductance is that the short circuit current level increases. One must therefore always make a trade-off with what is desired from harmonic distortion point of view, the equipment rating for short circuit currents, and the associated overall costs.

### 7.8.2. Converter topology

The different converter topologies give different harmonic distortion. Normally the power rating and application determine the selection, but when possible, a converter with lower harmonic distortion should be selected to manage the overall distortion levels. Normally, a VSI type converter gives the lowest distortion in electric propulsion applications.

Increasing the rectifier's pulse numbers also give a lowering of the harmonic distortion, but must be trade-off by the associated costs of transformers and converter.

There are also converters with an active front end, constituted by switching elements instead of diodes. This kind of converters give a much more sinusoidal current shape towards the network, similar as to the motor. However, the costs of these products are much higher than with diode rectifiers.

### 7.8.3. Design of supply transformer

When a transformer feeds the converter, the transformer's short circuit impedance should be selected high to smoothen the load current and reduce the harmonic content. It must not be selected so high that the voltage drop over the transformer at full load reduces the power capability of the converter below the specified rating. Normally, the short circuit impedance will be selected between 5 and 8%. A typical distribution transformer will rarely exceed 4%.

Also, the transformer should be equipped with a conductive sheet between the primary and secondary windings, grounded with an efficient high-frequency ground strap. This will not influence the lower harmonic transfer from secondary to primary windings, since these are magnetically coupled. For the very high frequencies, typically above MHz range, the coupling is more capacitive, and the grounded sheet will act as a screen for capacitive currents, leading them to ground instead of to the primary. Such screens are normally required to fulfill EMC regulations (Electro-Magnetic Compatibility), and will also aid as a protection against flashover from a high voltage primary to the low voltage secondary if the insulation should fail.

### 7.8.4. Passive filters

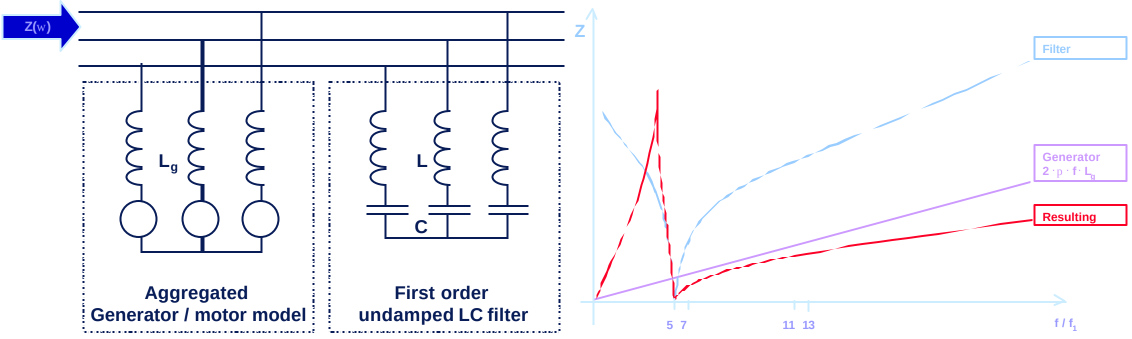
A passive filter consists of inductances and capacitances, and sometimes also a resistance.

Fig. 7.8 shows the circuit diagram for a first order LC filter. The impedance in one of these branches for a certain frequency *f* is, where $w=2p\cdot f$:

$$Z_{filter}(w) = jwL + \frac{1}{jwC} = jwL\left(1-\frac{1}{w^2LC}\right)$$

As seen, the impedance has a series resonance, i.e. a zero impedance frequency, for

$$w = \sqrt{\frac{1}{LC}}$$



(a) (b)

*Fig. 7.8: Passive filter in a network with a generator. Z(w) represents the resulting frequency between two lines, as experienced by a frequency converter connected to the network. (a) circuit diagram. (b) frequency response.*

For currents with this frequency the impedance through the passive filter approaches zero, and the filter will ideally draw all currents of this frequency from the network without distortion. When tuned to the most significant harmonic frequency, the voltage distortion will thereby be reduced.

If there are several harmonics with significant value, it might be used several parallel connected filters, each tuned for one harmonic frequency.

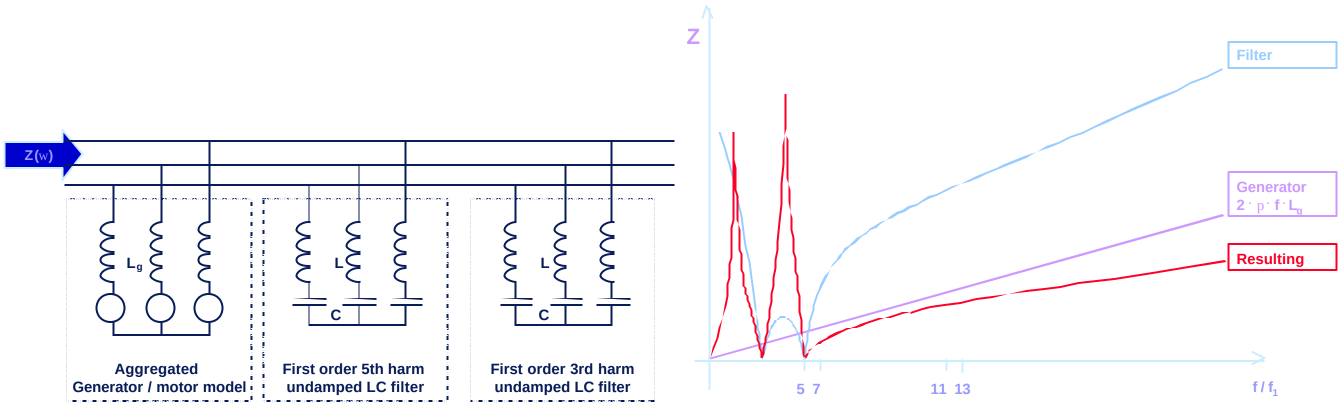
Connecting the filter to the network, its impedance will come in parallel to the generator impedance. The resulting network impedance will then be a paralleling of the generator impedance and filter impedance:

$$Z\ (w) = Z_{gen}(w) \big| \big| Z_{filter}(w) = \frac{jwL_g \cdot jwL\left(1 - \dfrac{1}{w^2 LC}\right)}{jwL_g + jwL\left(1 - \dfrac{1}{w^2 LC}\right)}$$

In addition to the series resonance with a zero impedance at $w = \sqrt{\dfrac{1}{LC}}$, this also have a parallel resonance with at $w = \sqrt{\dfrac{1}{\left(\dfrac{L_g}{L} + 1\right) LC}}$, meaning that the impedance of harmonics with this frequency approaches infinite high values. If this network is injected by harmonic currents of this particular frequency, the result can be excessive harmonic distortion and deterioration of equipment. Parallel resonance will always occur when passive filters are applied, the objective is to ensure that not any harmonic current will excite it.

In practice, both the series and the parallel resonance approach finite values due to damping effects from resistive components in the network impedance. Fig. 7.8(b) shows a typical impedance curve for a network with generators and a passive filter tuned to the 5th harmonic. As seen, the zero impedance coincides with the 5th harmonic, but also have some reducing effects on the 7th and higher harmonics due to its paralleling of the inductance with the generator.

Also, it is seen that a series resonance occurs at about 3rd harmonic. This may cause problems if one expects that the network is subject to third harmonic currents, e.g from transformer inrush. This resonance frequency can be shifted by adding a 3rd harmonic filter to the network in parallel to the 5th harmonic network as shown in Fig. 7.9, with resulting frequency as shown.



(a)

(b)

*Fig 7.9: Passive filter in a network with a generator. Z(w) represents the resulting frequency between two lines, as experienced by a frequency converter connected to the network. (a) circuit diagram. (b) frequency response.*

Passive filters may be an efficient way to reduce harmonic distortion. The design may be difficult, especially if the network is complicated, in the meaning of many possible configuration alternatives. Paralleling of filter units, min and max generator configurations, max capacitive loadings of the generators, etc. are important aspects in the design. Also, adding filters to the network will alter the load current waveforms of the converters, and the filter design will always be an iterative approach before finding the final design.

## 7.9. Active filters

An active filter is a power electronic unit connected to the power distribution with switching components, such as IGBTs, similar to the inverter stage of a motor drive. This feeds a capacitor bank, as shown in Fig. 7.10.

By use of the switching elements, one can define a shape of the currents which shall flow from the active filter towards the network. If measuring the load current of a nonlinear load, e.g. a motor drive, the active filter can then be used to compensate for the harmonics of the non-linear load, such that the resulting current of the non-linear load and the active filter becomes sinusoidal. Due to the switching of the power semiconductors, a high frequency filter is necessary to remove high frequent noise.

Active filtering is an efficient way of removing harmonic distortion. However, the rating of the filter is relatively high compared to the non-linear load it is supposed to filter, and the cost tend to be higher than many other alternatives.

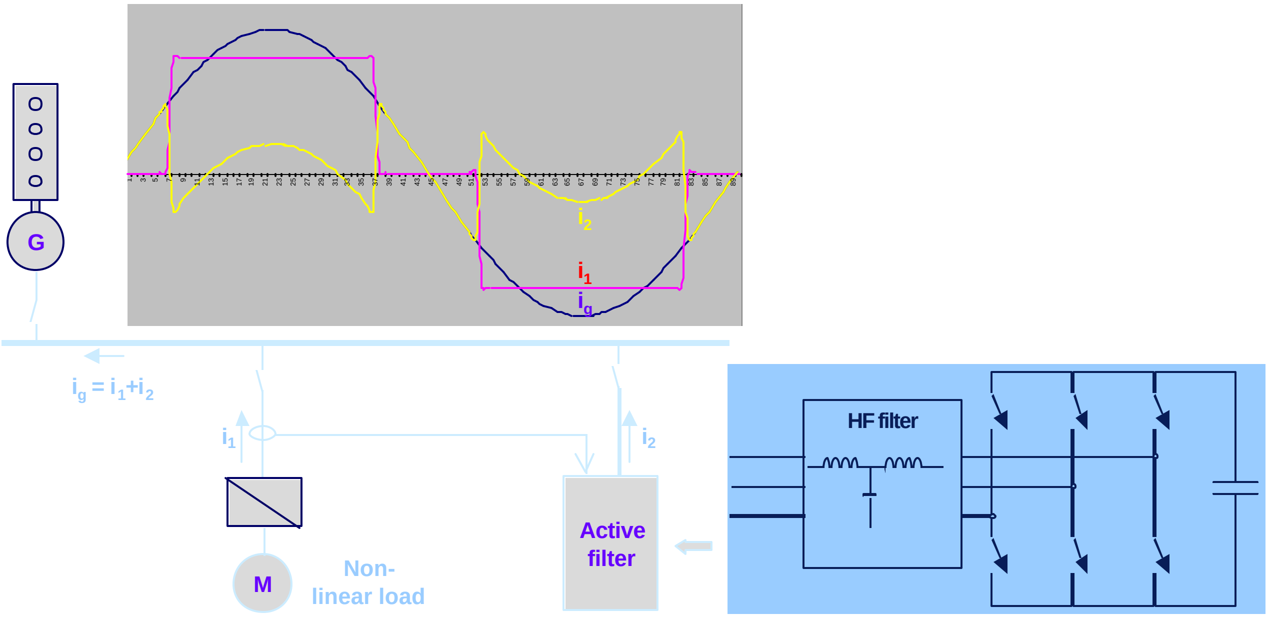


*Fig. 7.10: An active filter connected to a six-pulse converter, generating the harmonic currents that compensates for all harmonics of the non-linear converter load. The resulting current flowing to the network and generator ideally becomes sinusoidal.*

## 7.10. Clean power supplies

A more cost efficient way of supplying sensitive equipment with non-distorted voltages could be to create smaller or larger “islands” of clean power. This can be obtained by:

- Rotating converters, i.e. motor-generator sets, which completely de-couple the clean power, supply from the “dirty” network.

- Static converters, utilizing power electronics technology to convert the “dirty” network supply to a clean supply

- UPS (Uninterruptible Power Supply) which is a static voltage converter, with battery backup also for maintaining AC power supply to essential equipment during power blackout.

# 8. Example configurations

## 8.1. Field Support Vessels

The term “Field Support Vessel” includes a large class of vessel types and applications, such as Platform Supply Vessels (PSV), ROV support vessels, Multipurpose Vessels, Anchor Handlers (AHTS), etc. Their power requirements for station keeping, sailing, and vessel loads varies over a wide range.

Traditionally, Field Support Vessels were equipped with direct mechanical propulsion system, with medium speed diesel engines and geared power transmission.

Higher focus on safety, redundancy, fuel economy, and station keeping capability has given an increased demand for more modern design, utilizing electric propulsion with azimuthing or Azipod propulsion systems.

The following figures show some example configurations for smaller size, medium size, and large size propulsion power installations. In all these examples, the tunnel thrusters are shown with fixed speed, controllable pitch. Fuel economy and stricter noise requirements have made variable speed control more attractive for recent new buildings. Also, variable speed electric motor drives are more commonly used for winches, pumps, and other auxiliary drives.

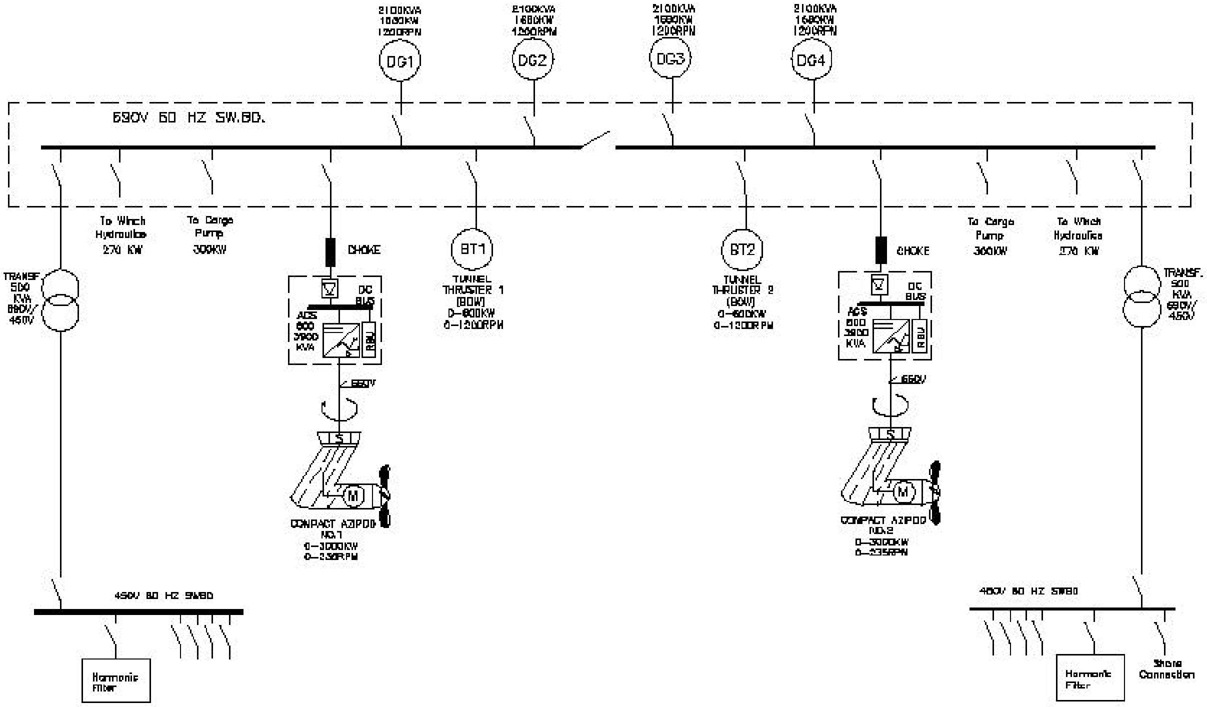


*Figure 8.1: Power plant for a large PSV, Multipurpose supply vessel, or small AHTS with Azipod propulsion system.*

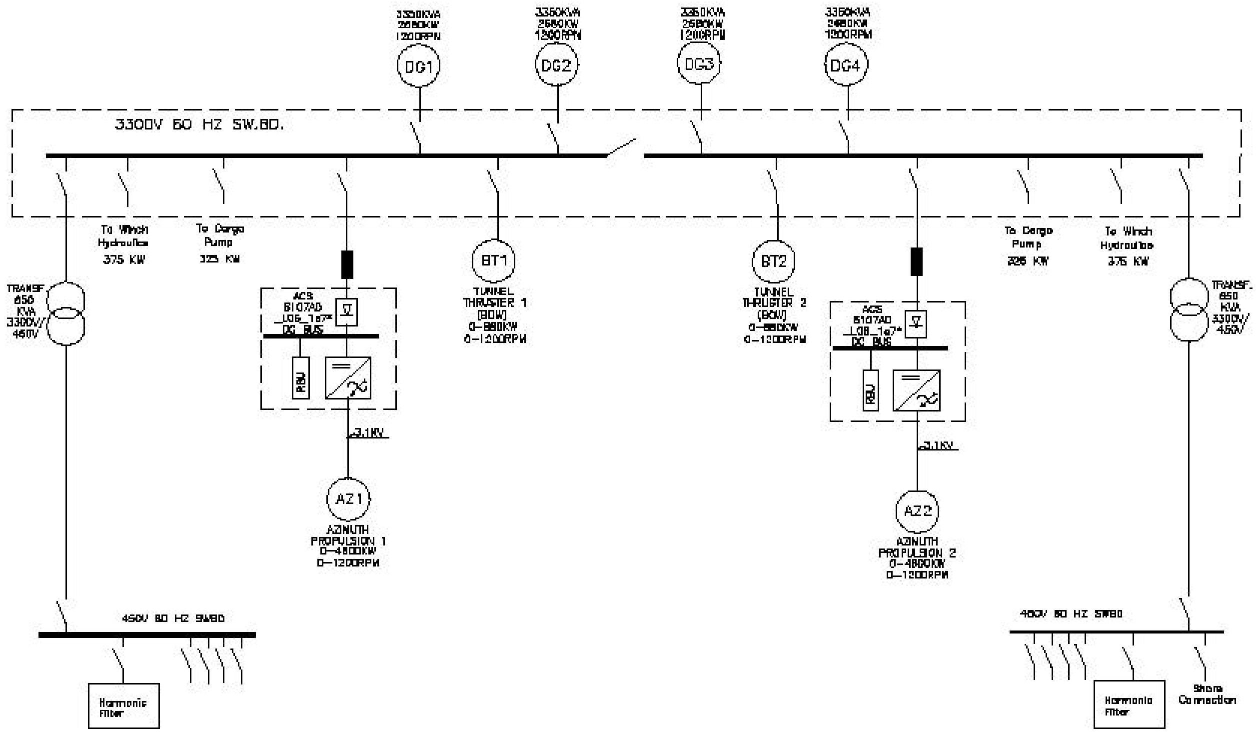


*Figure 8.2: Power plant for a medium size AHTS, with azimuth thruster propulsion system.*

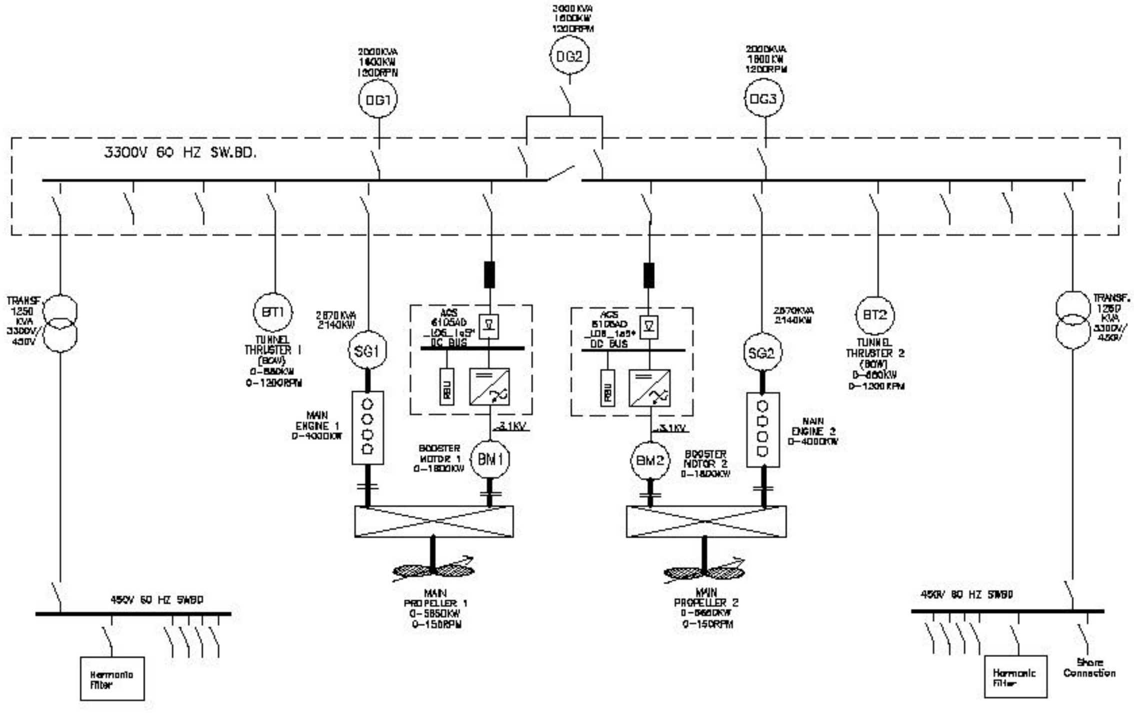


*Figure 8.2: Power plant for a larger AHTS, with hybrid electrical and mechanical propulsion system.*
*An AHTS may have a very high power demand to meet the bollard pull requirement, and it is often seen that a pure electric installation will not be cost competitive. The hybrid solution allows for efficient use of the diesel engines with the electrical drives as booster drives in bollard pull condition, while electric drives are used for transit and station keeping purposes.*

## 8.2. Cruise Vessels and Ferries

Within this market segment, there are also a variety of vessel sizes and dimensions, from smaller fjord-crossing passenger ferries, to the largest cruise vessels.

The main driving forces for these applications towards electric propulsion are: safety and comfort for passengers and crew, fuel economy, and utilization of space.

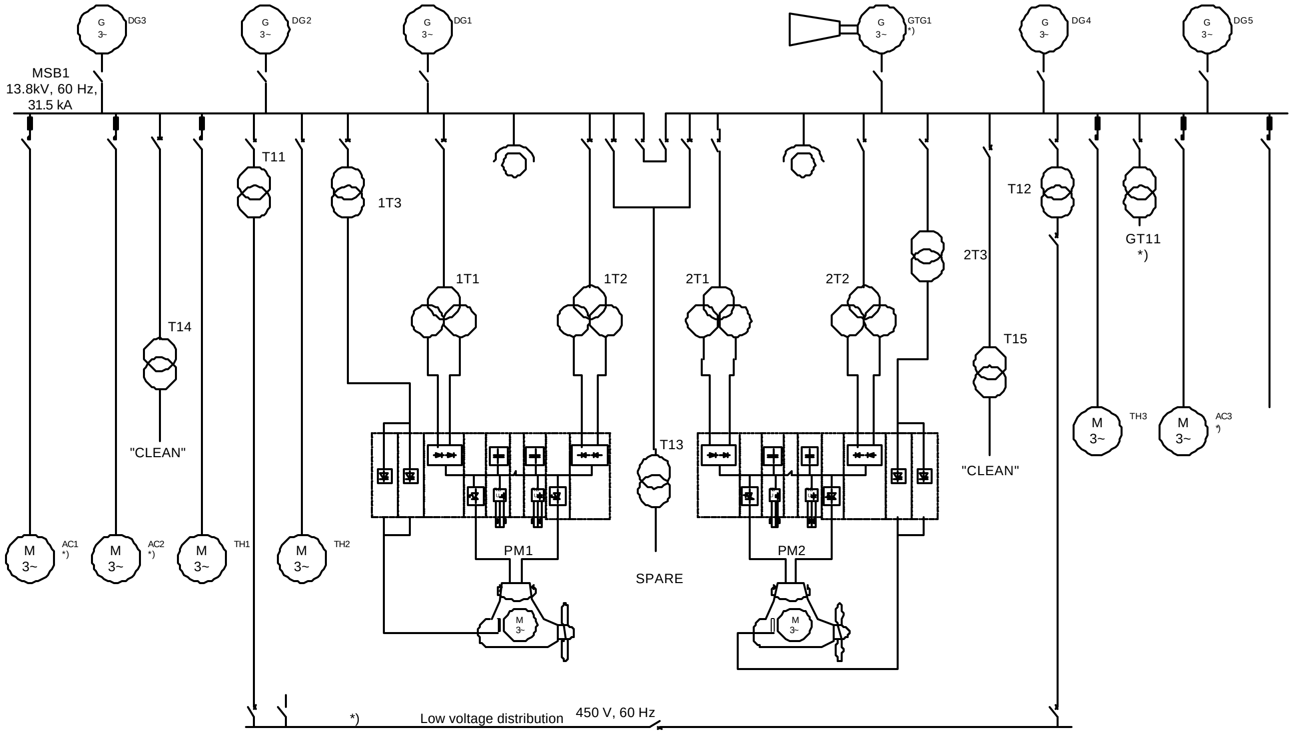


*Figure 8.3: Power plant for a Cruise Vessel with Azipod propulsion system.*

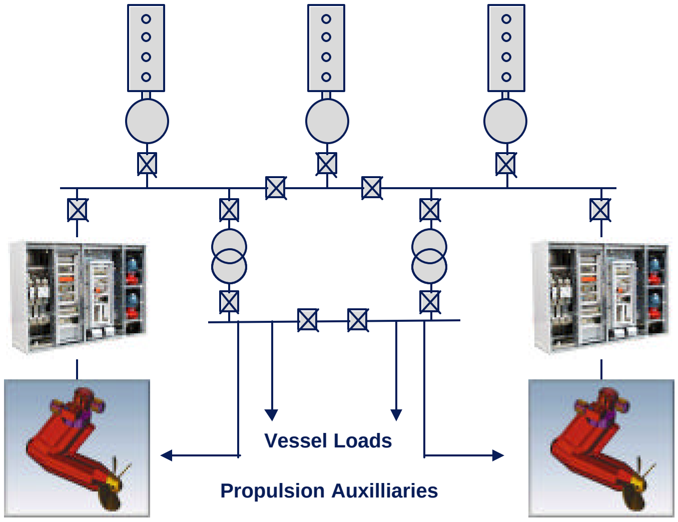


*Figure 8.3: Power plant for a passenger ferry with Azipod propulsion system.*

## 8.3. Oil tankers, LNG carriers

The configuration in Figure 8.4 has been installed on several shuttle tankers and multipurpose shuttle tankers operating in accordance to requirements of the North Sea, delivered in mid 90's. With the new type of VSI frequency converters, a similar design would be as shown in Figure 8.5.

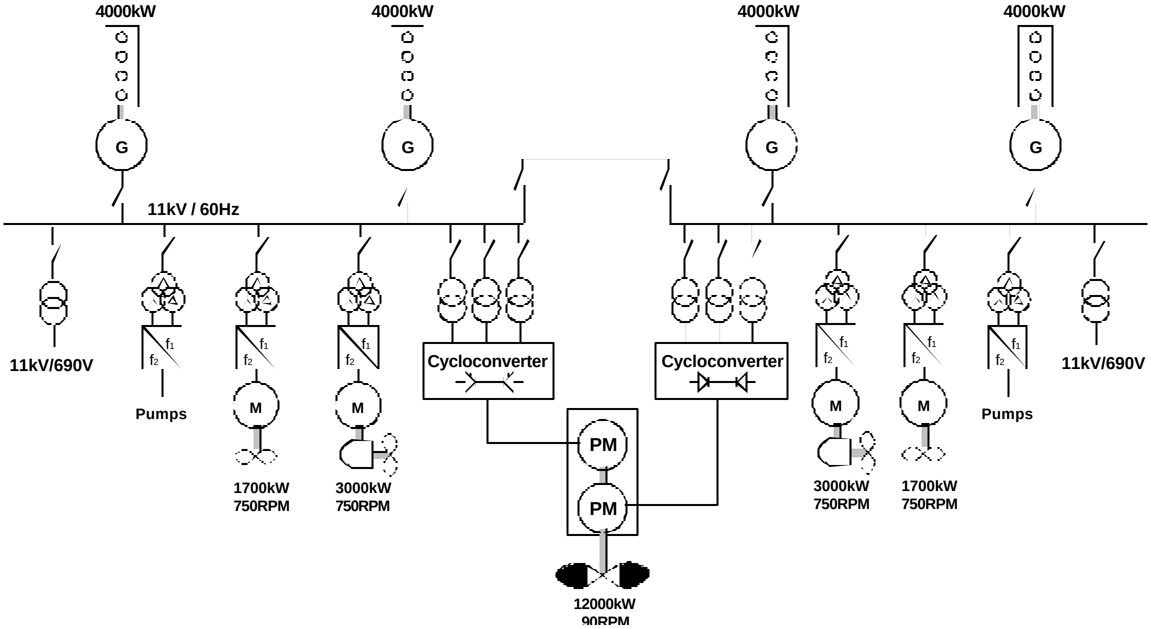


*Figure 8.4: Power and propulsion plant for a shuttle tanker with single screw propulsion and redundant electrical system as delivered for several vessels during the 90's, with cycloconverters.*

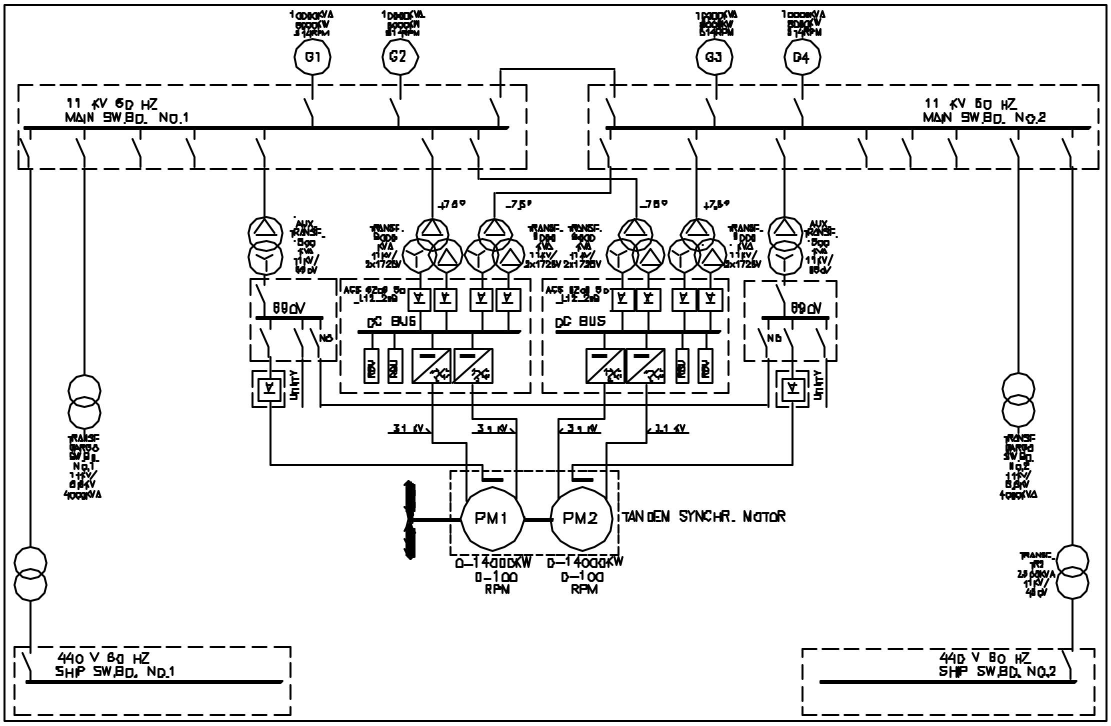


*Figure 8.5: Power and propulsion plant for a shuttle tanker with single screw propulsion and redundant electrical system, using state-of-the-art VSI frequency converters. With 24 pulse rectifiers, harmonic distortion will be low.*

With direct propulsion as shown in Figures 8.4 and 8.5, the propulsion motors will have the same RPM as the propeller, and hence, becomes relatively large. Where geared power transmission is accepted, one can reduce the overall space requirements and costs, by increasing the RPM of the motors by use of reduction gears, as shown in Figure 8.6.

The electrical system configuration, and the redundancy of the electrical system will be equal to the direct propulsion systems, and with one additional component in the mechanical system. One should note that one normally will not gain full redundancy credit by the classification societies by single shaft line, and relatively large azimuthing or similar thruster devices must supplement the propulsion system in order to get redundant propulsion or DP2/DP3 class notations.

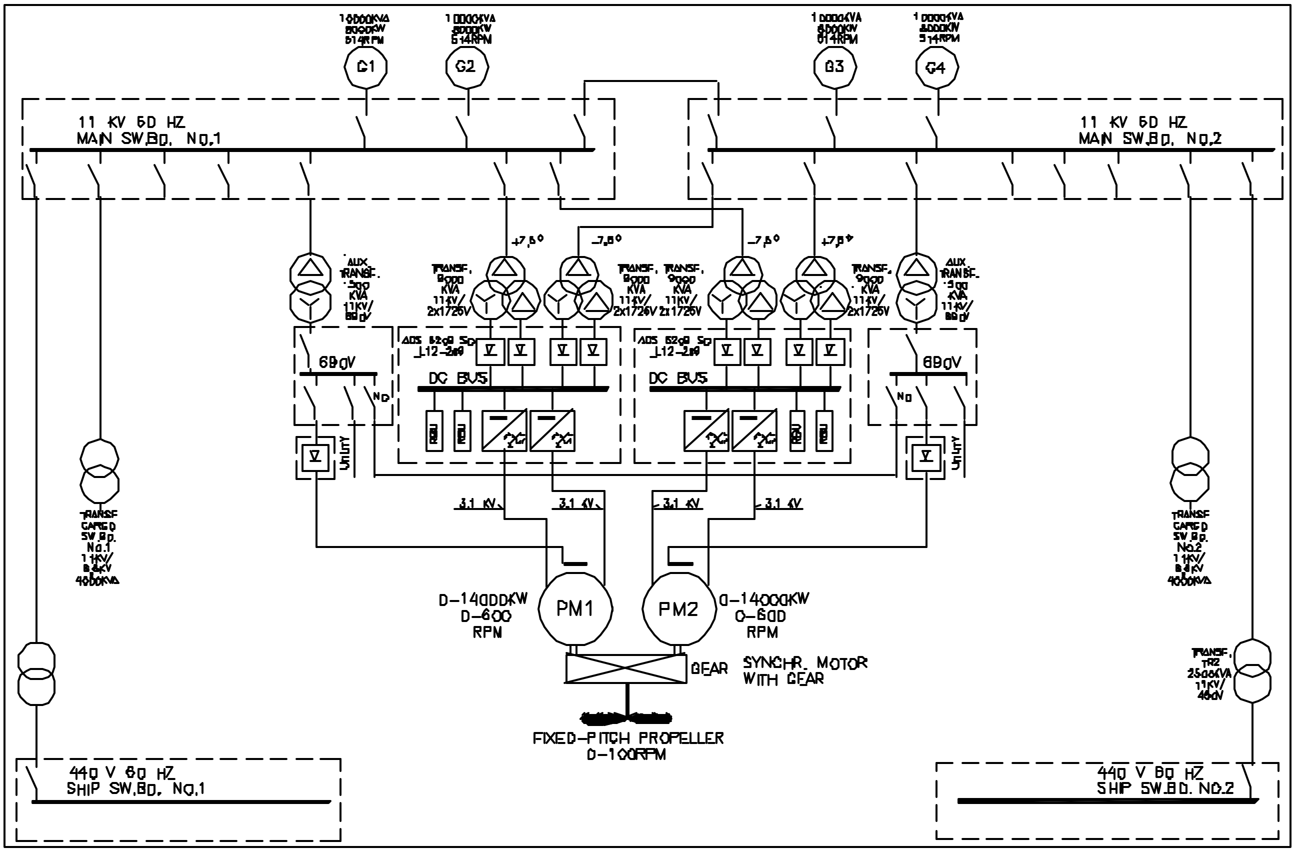


*Figure 8.6: Power and propulsion plant for a shuttle tanker with single screw propulsion and redundant electrical system, using state-of-the-art VSI frequency converters. Geared transmission is used to increase the RPM of the propulsion motors and reduce the overall space requirements and costs.*

For ice going tankers, the Azipod propulsion system is a robust solution, and has been utilized in several vessels. The configuration in Figure 8.7 with some variations has been used in several vessels, including the pilot installations of Azipod. During the more than 10 years of operations of these two vessels, it has proven to be very a robust and reliable propulsion system in ice conditions. The system in Figure 8.7 is delivered for an ice breaking tanker, where the most efficient ice breaking capability is obtained by going backwards into the ice.

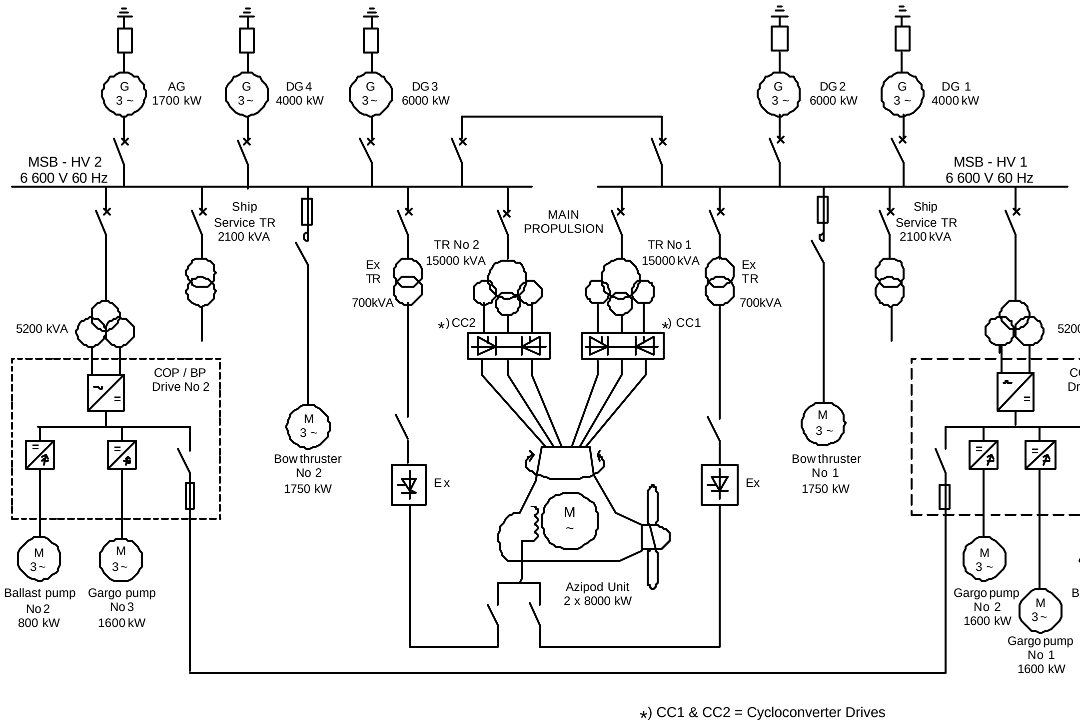


*Figure 8.7: Power and propulsion plant for an ice going / breaking shuttle tanker with single Azipod propulsion and redundant electrical system.*

Redundant propulsion or DP2/DP3 notations will normally lead to a dual propulsion system, e.g. a dual shaft solution as shown in Figure 8.8 or dual Azipod propulsion, Figure 8.9. Here, the electrical system, and the propulsion system may be totally independent, fulfilling the strictest integrity requirements by class societies.

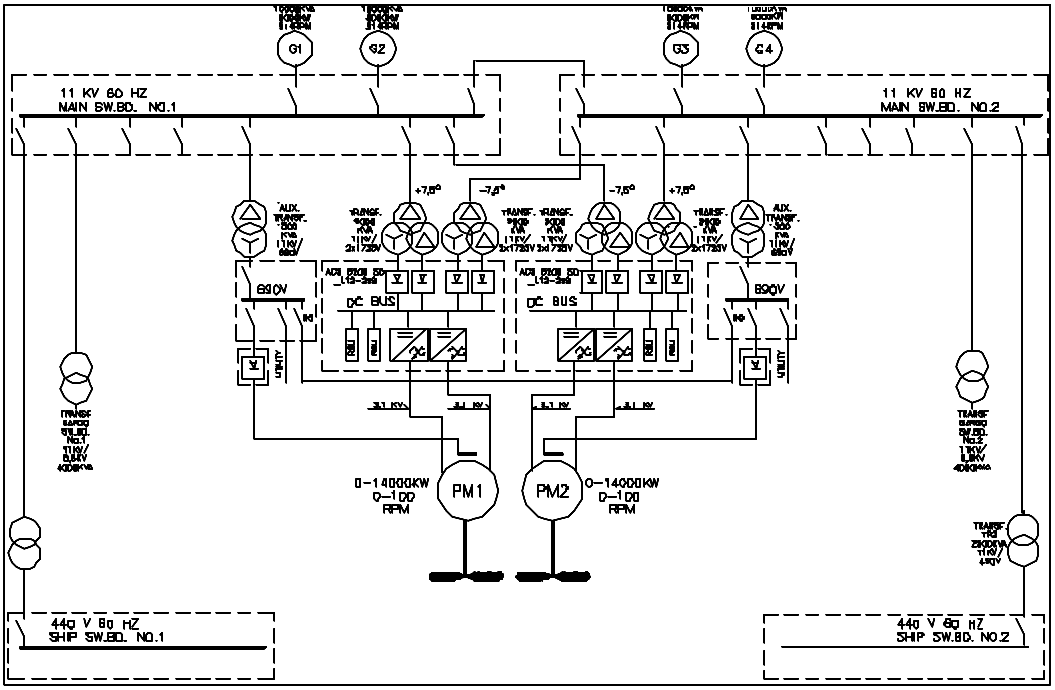


*Figure 8.8: Power and propulsion plant for a shuttle tanker with dual screw propulsion and redundant electrical system, using state-of-the-art VSI frequency converters. The configuration is typically to be used in ships with redundant propulsion and/or DP class notation.*

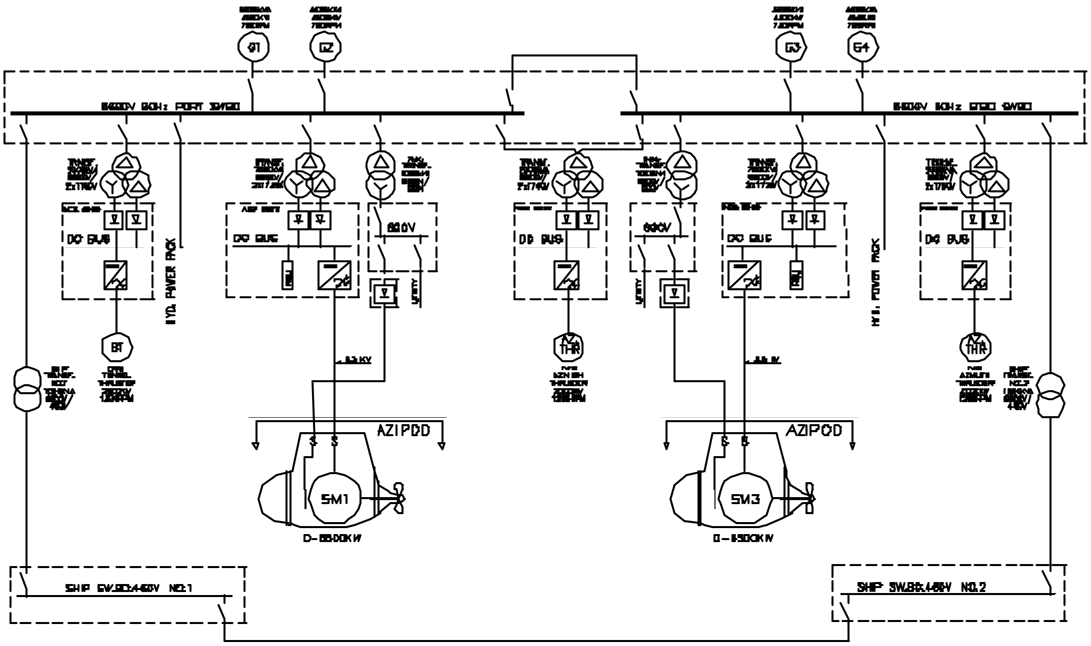


*Figure 8.9: Power and propulsion plant for a tanker with redundant Azipod propulsion system.*

Figure 8.10 shows a configuration where main propulsion drives are combined in a Multidrive topology with cargo pump inverters. Since cargo pumps and propulsion normally will not be used simultaneously, this topology fully utilizes installed switchboard, transformer, and rectifier components for overall cost optimization.

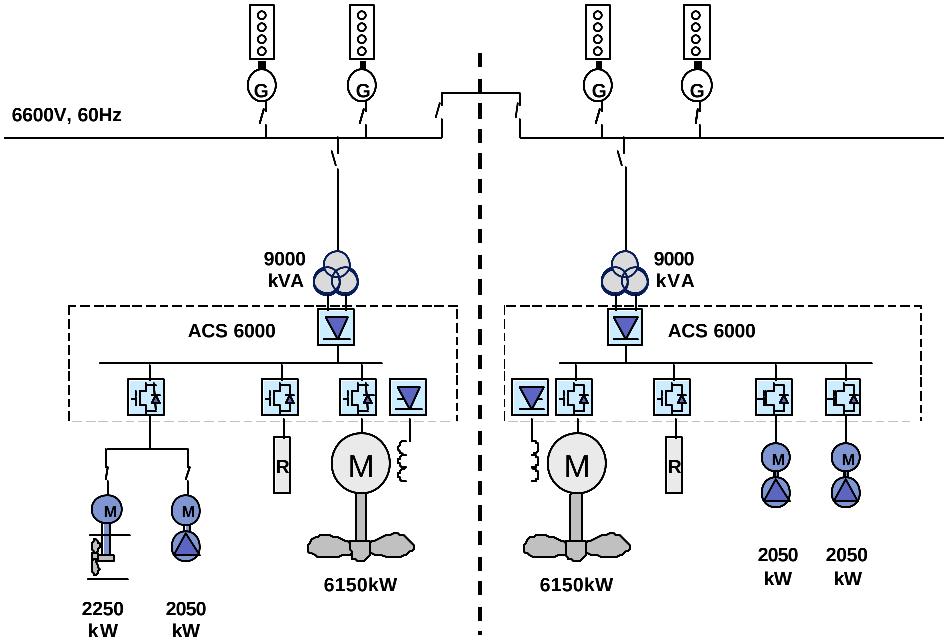


*Figure 8.10: Power and propulsion plant for a tanker with twin screw, redundant electrical propulsion system. Multidrive is utilized for optimizing overall costs and reducing the space.*

## 8.4. The concept of contra rotating Azipod propulsion (CRP)

The concept of contra rotating propulsion is known to increase the propulsion efficiency. By combining a shaft line propeller with an “active rudder” Azipod, and let the two propellers face each other and rotate in the opposite directions, the contra rotating effect will be obtained.

Figure 8.11 shows a solution with such CRP propulsion system, with full redundancy in the electrical system, and propulsion redundancy in the combination of shaft line propeller and the Azipod.

This CRP concept has been evaluated for various types of vessels, including passenger vessels, container vessels, tankers, and LNG carriers, and is now (2003) being delivered for a fast speed RoPax vessel.

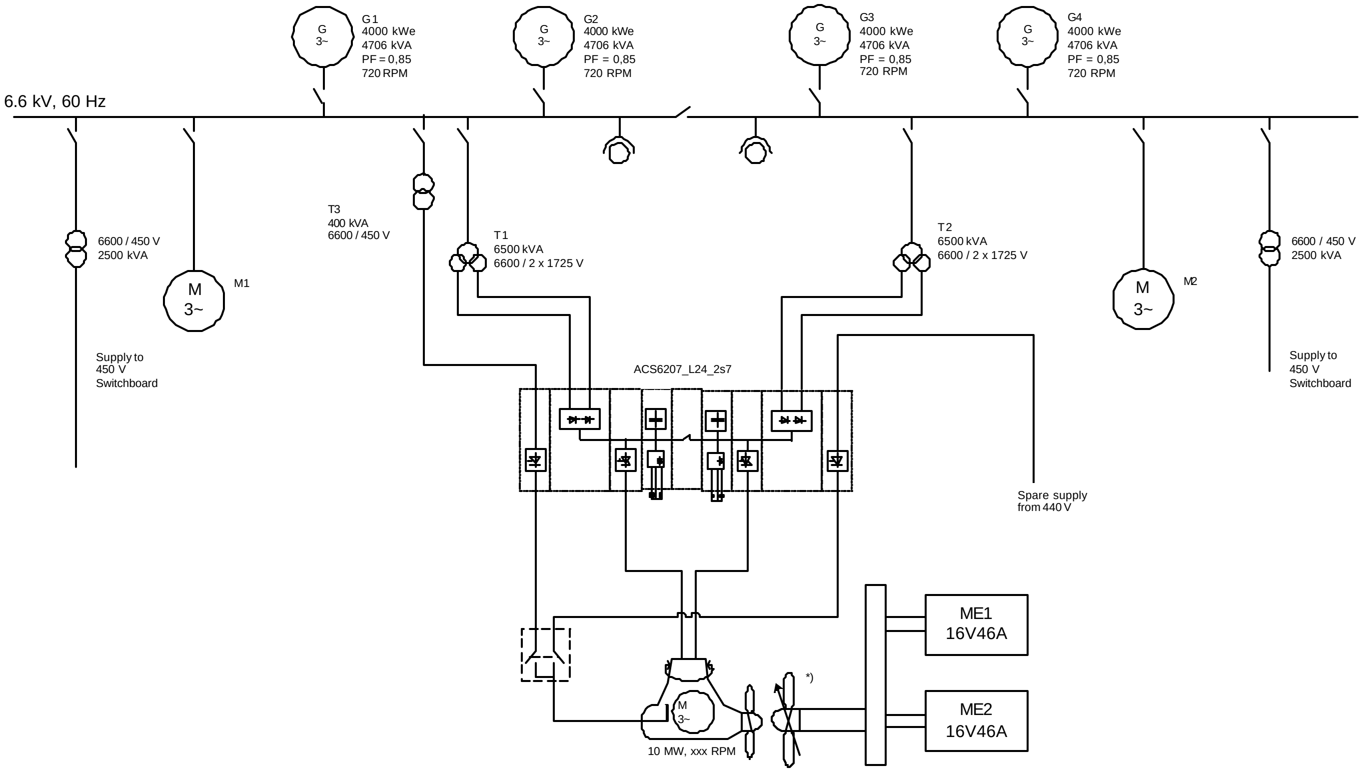


*Figure 8.11: Power and propulsion plan with redundant, contra rotating Azipod propulsion (CRP) system.*

## 8.5. Semi-submersible drilling rigs and drill ships

Drilling semi-submersible rigs and ships operates most of their lifetime in stationary positioning. DP rigs and ships utilize thruster devices for station keeping and for transit between locations.

Using fixed pitch, speed controlled propellers will significantly improve fuel savings and operation economy. The power system configuration depends much on the environmental requirements for the vessel. A two, three, or four-split power system is typical, e.g. the four-split system for a semi-submersible rig shown in Figure 8.12.

The drilling plant also requires a substantial power, typically to 5-10MW. Figure 8.12 shows a commonly used Multidrive configuration; with common DC link and line supply and with individual inverters for each of the drilling AC motors. Compared to stand-alone rectifiers and DC motor drives, this solution gives much less network distortion with higher efficiency, and enables the use of robust, reliable, and standard AC motors with far less maintenance than DC motors.

As an alternative to fixed pitch mechanical azimuthing thrusters, the podded thrusters have been introduced in several vessels. The driving forces are higher efficiency, reduced space requirements, and higher reliability due to the simpler and more robust mechanical construction.

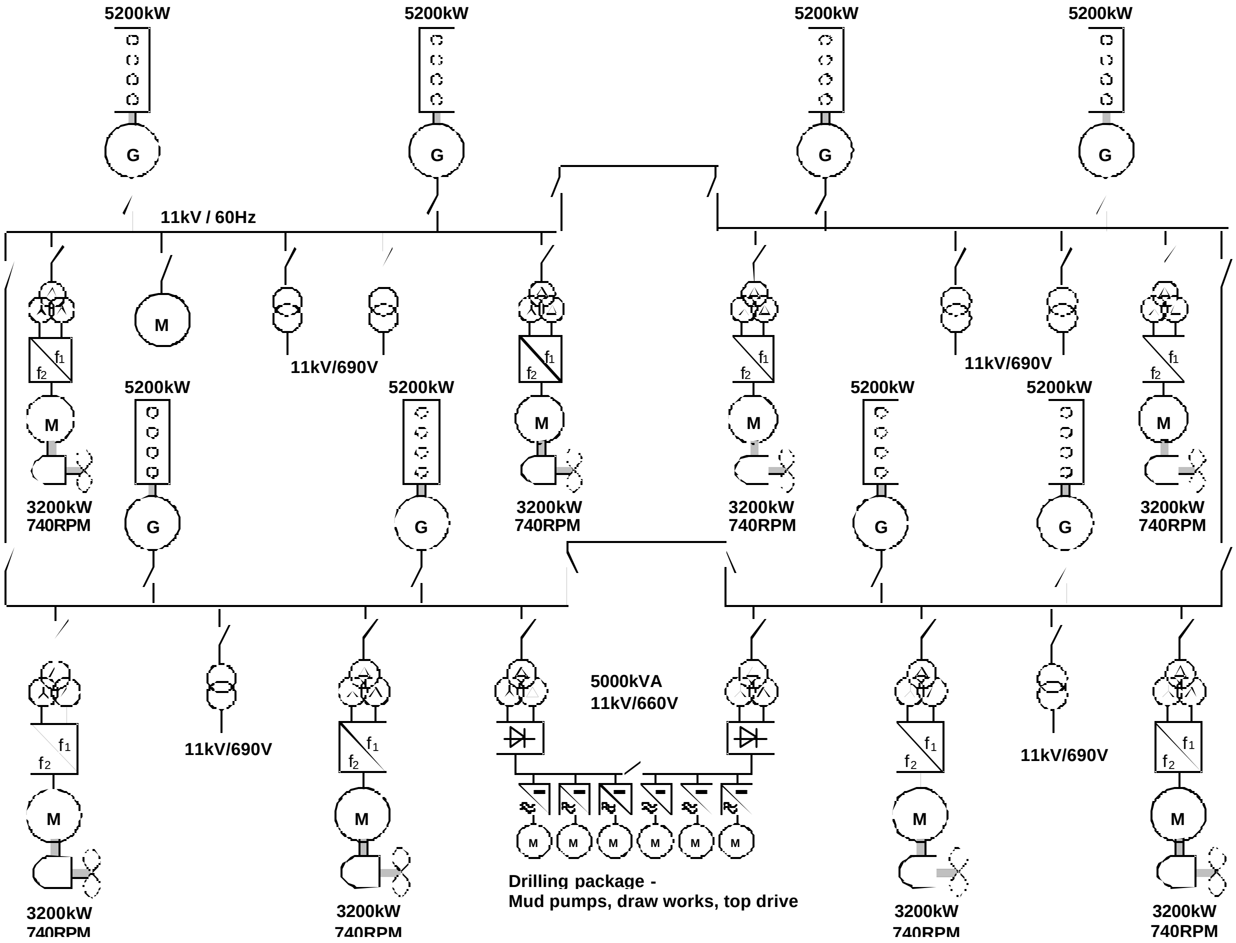


*Figure 8.12: A four-split power system with variable speed fixed pitch azimuth or Azipod thrusters.*

## 8.6. Floating Production Vessel

Nearly any floating production vessels are kept on location by using a mooring system. Some of them, especially in harsh environment, utilize azimuthing thrusters and/or shaft line propellers and tunnel thrusters to obtain heading control and reduce the strain of the mooring lines.

Figure 8.13 shows a configuration installed in a North Sea FPSO where it is important to control the heading towards the dominating environmental forces in order to avoid break of mooring lines. Similar configurations are used in other North Sea and Canadian FPSOs.

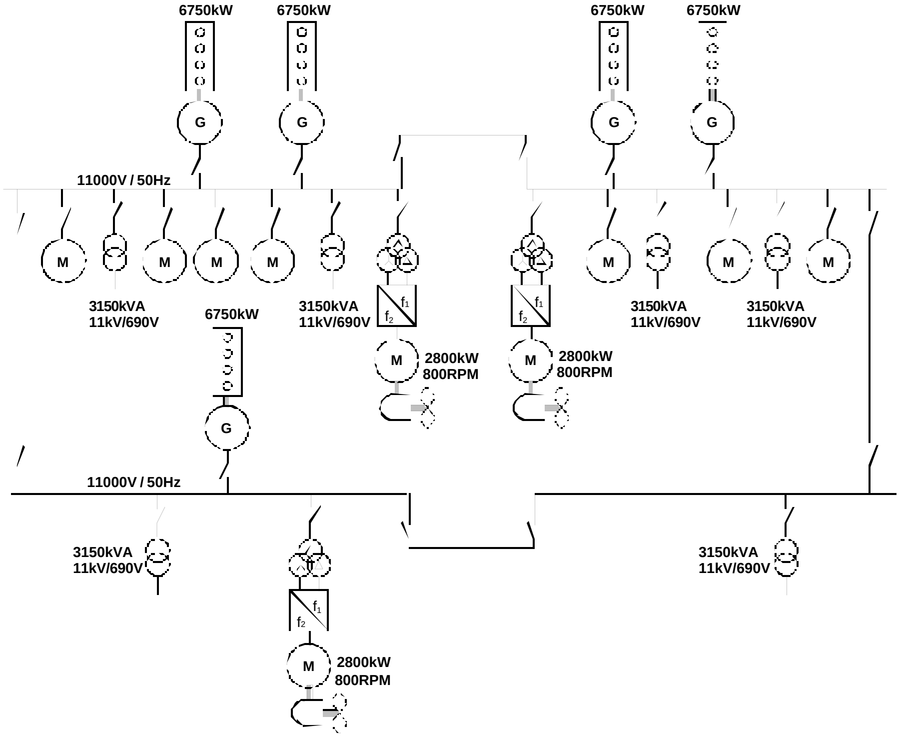


*Figure 8.13: Power configuration for an FPSO with thruster assisted mooring system. The thrusters are primarily installed to reduce the strain of the mooring lines, but can also be utilized for transit of the vessel.*

# Appendix 1

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