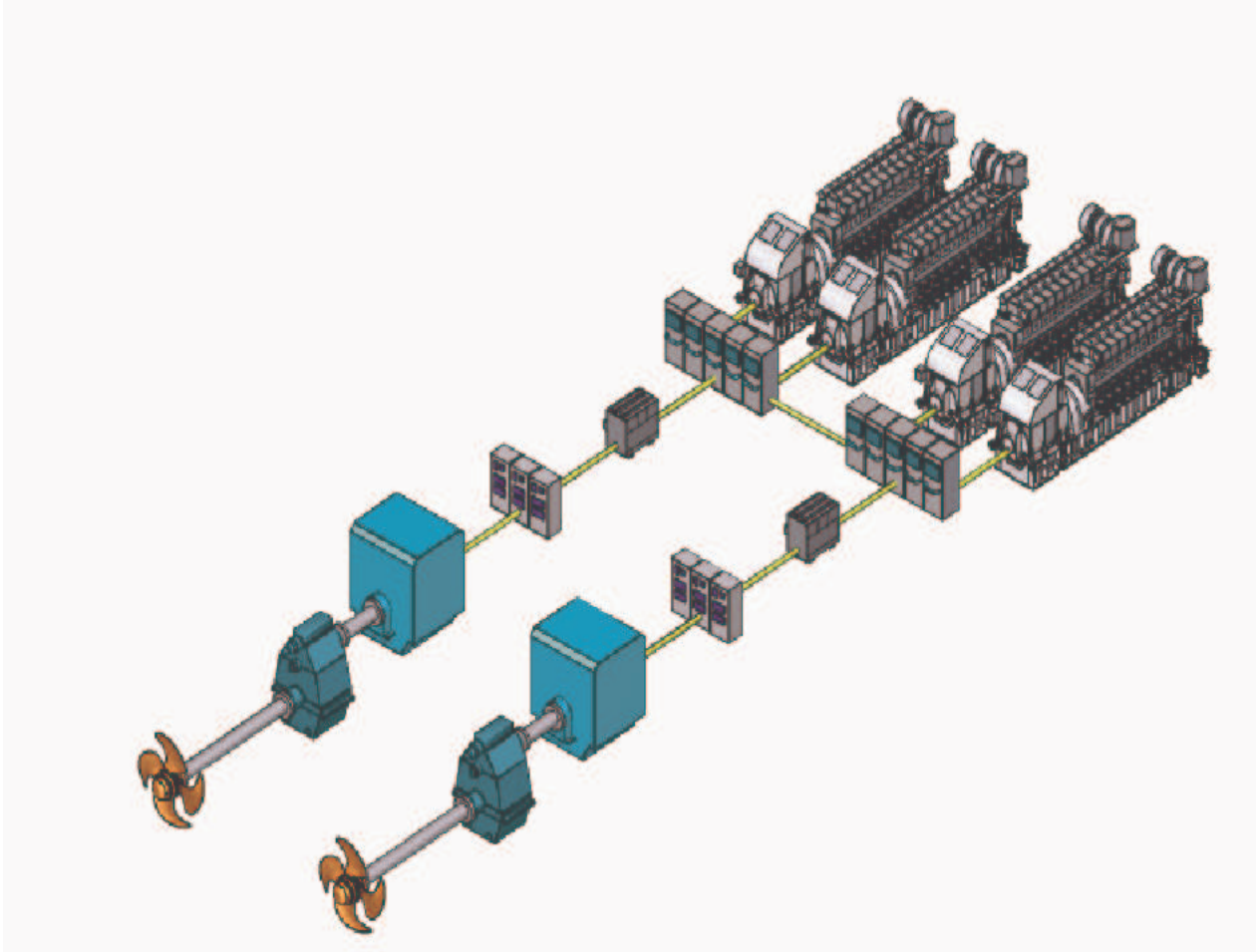


Diesel-electric Drives



Diesel-electric Propulsion Plants

A brief guideline how to design a diesel-electric propulsion plant



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Diesel-electric propulsion plants

1.1 Advantages of diesel-electric propulsion

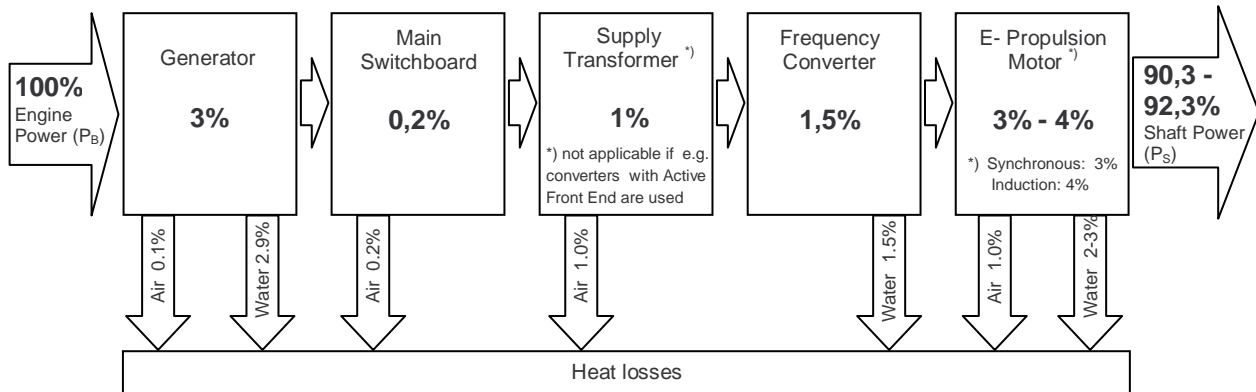
Due to different and individual types, purposes and operational profiles of diesel-electric driven vessels the design of a diesel-electric propulsion plant differs a lot and has to be evaluated case by case. All the following is for information purpose only and without obligation.

In general the advantages of diesel-electric propulsion can be summarized as follows:

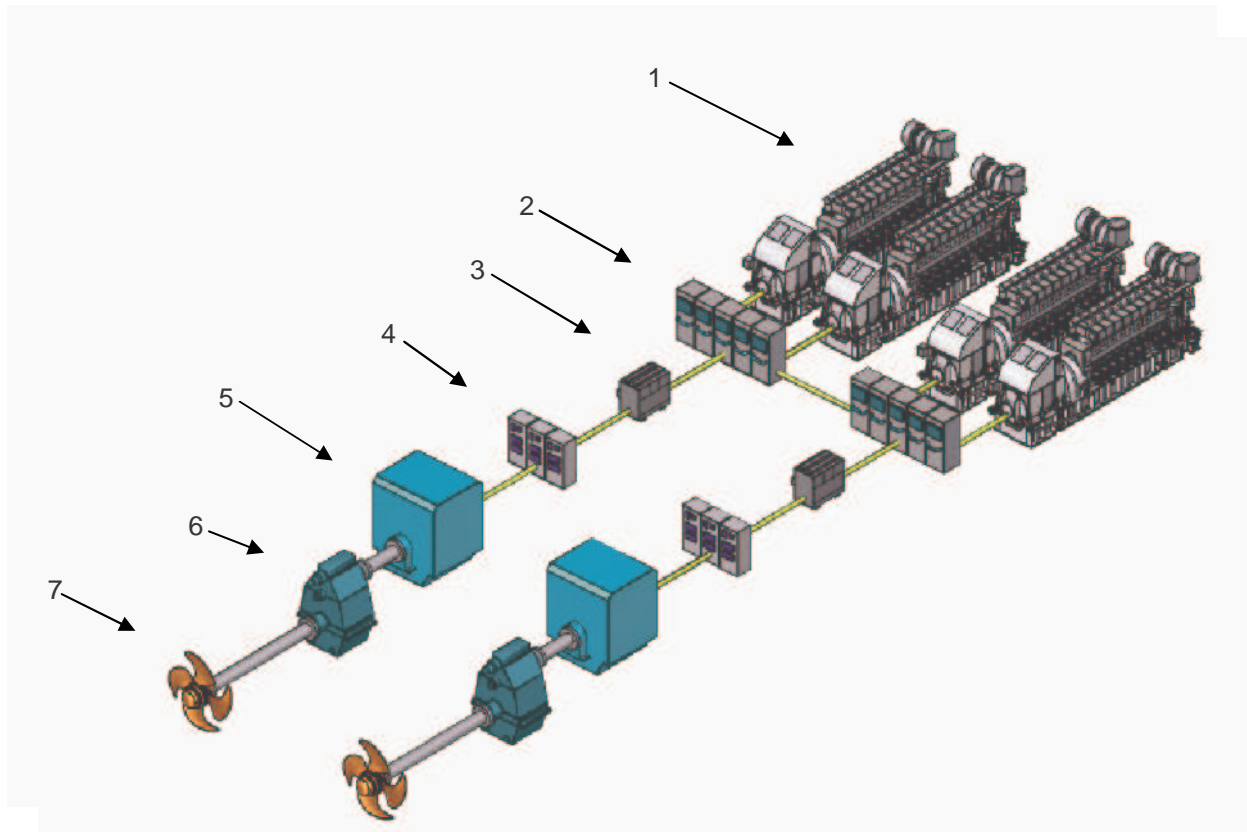
- Lower fuel consumption and emissions due to the possibility to optimize the loading of diesel engines / gensets. The gensets in operation can run on high loads with high efficiency. This applies especially to vessels which have a large variation in load demand, for example for an offshore supply vessel, which divides its time between transit and station-keeping (DP) operation.
- High reliability, due to multiple engine redundancy. Even if an engine / genset malfunctions, there will be sufficient power to operate the vessel safely. Reduced vulnerability to single point of failure providing the basis to fulfill high redundancy requirements.
- Reduced life cycle cost, resulting from lower operational and maintenance costs.
- Improved manoeuvrability and station-keeping ability, by deploying special propulsors such as azimuth thrusters or pods. Precise control of the electrical propulsion motors controlled by frequency converters.
- Increased payload, as diesel-electric propulsion plants take less space.
- More flexibility in location of diesel engine / gensets and propulsors. The propulsors are supplied with electric power through cables. They do not need to be adjacent to the diesel engines / gensets.
- Low propulsion noise and reduced vibrations. For example a slow speed E-motors allows to avoid gearboxes and propulsors like pods keep most of the structure bore noise outside of the hull.
- Efficient performance and high motor torques, as the system can provide maximum torque also at slow speeds, which gives advantages for example in icy conditions.

1.2 Efficiencies in diesel-electric plants

A diesel-electric propulsion plant consists of standard electrical components. The following efficiencies are typical:



1.3 Components of a diesel-electric propulsion plant



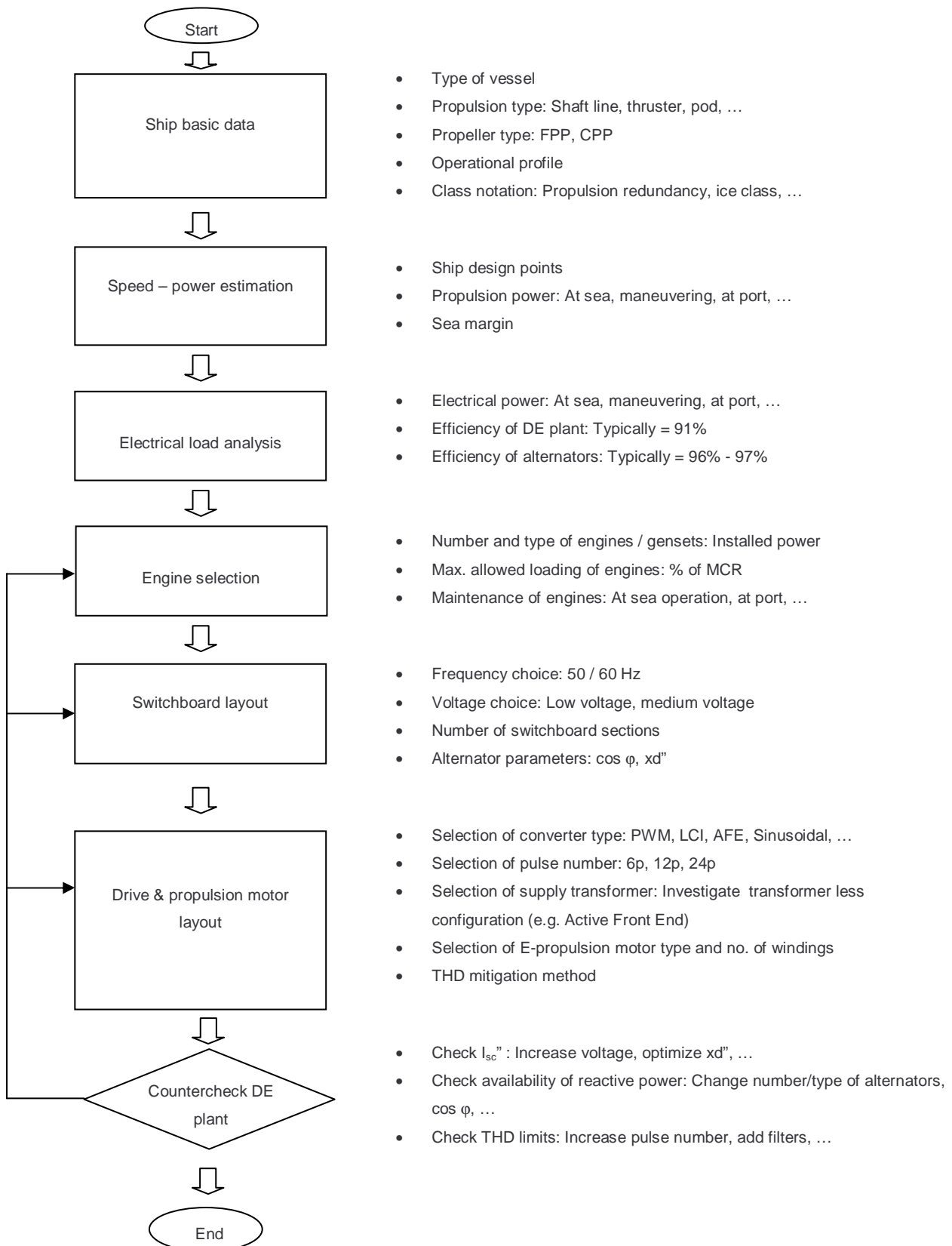
Example: Diesel-electric propulsion plant

Legend

1	Gensets: Diesel engines + alternators
2	Main switchboards
3	Supply transformers (optional): Dependent on the type of the converter. Not needed in case of the use of frequency converters with 6 pulses, an Active Front End or a Sinusoidal Drive
4	Frequency converters / drives
5	Electric propulsion motors
6	Gearboxes (optional): Dependent on the speed of the E-propulsion motor
7	Propellers / propulsors

1.4 Diesel-electric plant design

Generic workflow how to design a diesel-electric propulsion plant:





The requirements of a project will be considered in an application specific design, taking into account the technical and economical feasibility and later operation of the vessel. In order to provide you with appropriate data, please fill the form *Questionnaire* in the appendix.

1.5 Engine selection

The engines for a diesel-electric propulsion plant have to be selected accordingly to the maximum power demand at the design point. For a concept evaluation the rating, the capability and the loading of engines can be calculated like this:

Example: Offshore Construction Vessel (at design point)

- Propulsion power demand (at E-motor shaft) 7200 kW (incl. sea margin)
- Max. electrical consumer load 1800 kW

No	Item	unit	
1.1	Shaft power on propulsion motors	P_s [kW]	7200
	Electrical transmission efficiency		0,91
1.2	Engine power for propulsion	P_{B1} [kW]	7912
2.1	Electric power for ship (E-Load)	[kW]	1800
	Alternator efficiency		0,96
2.2	Engine power for electric consumers	P_{B2} [kW]	1875
2.3	Total engine power demand (= 1.2 + 2.2)	[kW]	9787
3.1	Diesel engine selection	type	9L27/38
3.2	Rated power (MCR)	[kW]	2970
3.3	Number of engines		4
3.4	Total engine power installed	P_B [kW]	11880
4.1	Loading of engines (= 2.3 / 3.4)		82,4%
5.1	Check: Max. allowed loading of engines	% of MCR	90,0%

For the detailed selection of the type and number of engines furthermore the operational profile of the vessel, the maintenance strategy of the engines and the boundary conditions given by the general arrangement have to be considered. For the optimal cylinder configuration of the engines often the power conditions in port are decisive.

1.6 E-plant, switchboard and alternator design

The configuration and layout of an electrical propulsion plant, the main switchboard and the alternators follows some basic design principles. For a concept evaluation the following items should be considered:

- A main switchboard which is divided in symmetrical sections is reliable and redundancy requirements are easy to be met
- An even number of gensets / alternators ensures the symmetrical loading of the bus bar sections
- Electrical consumers should be arranged symmetrically on the bus bar sections
- The switchboard design is mainly determined by the level of the short circuit currents which have to be withstand and by the breaking capacity of the circuit breakers (CB)
- The voltage choice for the main switchboard depends on several factors. On board of a vessel it is usually handier to use low voltage. As a rule of thumb the following table can be used:

Total installed alternator power [MWe]	Voltage [V]	Breaking capacity of CB [kA]
< 10 – 12 (and: Single propulsion motor < 3,5 MW)	440	100
< 13 – 15 (and: Single propulsion motor < 4,5 MW)	690	100
< 48	6600	30
< 130	11000	50

- The design of the alternators and the electric plant always has to be balanced between voltage choice, availability of reactive power, short circuit level and allowed total harmonic distortion (THD)
- On the one hand side a small x_d'' of the alternators increases the short circuit current I_{sc} , which also increase the forces the switchboard has to withstand ($F \sim I_{sc}^2$). This may lead to the need of a higher voltage. On the other side a small x_d'' gives a lower THD. As a rule of thumb a $x_d''=16\%$ is a good figure for low voltage alternators and a $x_d''=14\%$ is good for medium voltage alternators.
- For a rough estimation of the short circuit currents the following formulas can be used:

	Short circuit level [kA] (rough)	Legend
Alternators	$n * P_r / (\sqrt{3} * U_r * x_d'' * \cos \varphi_{Grid})$	n: No. of alternators connected P _r : Power of alternator [kWe] U _r : Rated voltage [V] x _d '': Subtransient reactance [%] cos φ: Power factor of the network (typically = 0.9)
Motors	$n * 6 * P_r / (\sqrt{3} * U_r * x_d'' * \cos \varphi_{Motor})$	N : No. of motors (directly) connected P _r : Power of motor [kWe] U _r : Rated voltage [V] x _d '': Subtransient reactance [%] cos φ: Power factor of the motor (typically = 0.85 ... 0.90 for an induction motor)

Converters	Frequency converters do not contribute to the I_{sc} "	
------------	--	--

- The dimensioning of the panels in the main switchboard is usually done accordingly to the rated current for each incoming and outgoing panel. For a concept evaluation the following formulas can be used:

Type of switchboard panel	Rated current [kA]	Legend
Alternator incoming	$P_r / (\sqrt{3} * U_r * \cos \varphi_{Grid})$	P_r : Power of alternator [kWe] U_r : Rated voltage [V] $\cos \varphi$: Power factor of the network (typically = 0.9)
Transformer outgoing	$S_r / (\sqrt{3} * U_r)$	S_r : Apparent power of transformer [kVA] U_r : Rated voltage [V]
Motor outgoing (Induction motor controlled by a PWM-converter)	$P_r / (\sqrt{3} * U_r * \cos \varphi_{Converter} * \eta_{Motor} * \eta_{Converter})$	P_r : Power of motor [kWe] U_r : Rated voltage [V] $\cos \varphi$: Power factor converter (typically = 0.95) η_{Motor} : typically = 0.96 $\eta_{Converter}$: typically = 0.97
Motor outgoing (Induction motor started: DoL, Y/ Δ , Soft-Starter)	$P_r / (\sqrt{3} * U_r * \cos \varphi_{Motor} * \eta_{Motor})$	P_r : Power of motor [kWe] U_r : Rated voltage [V] $\cos \varphi$: Power factor motor (typically = 0.85...0.90) η_{Motor} : typically = 0.96

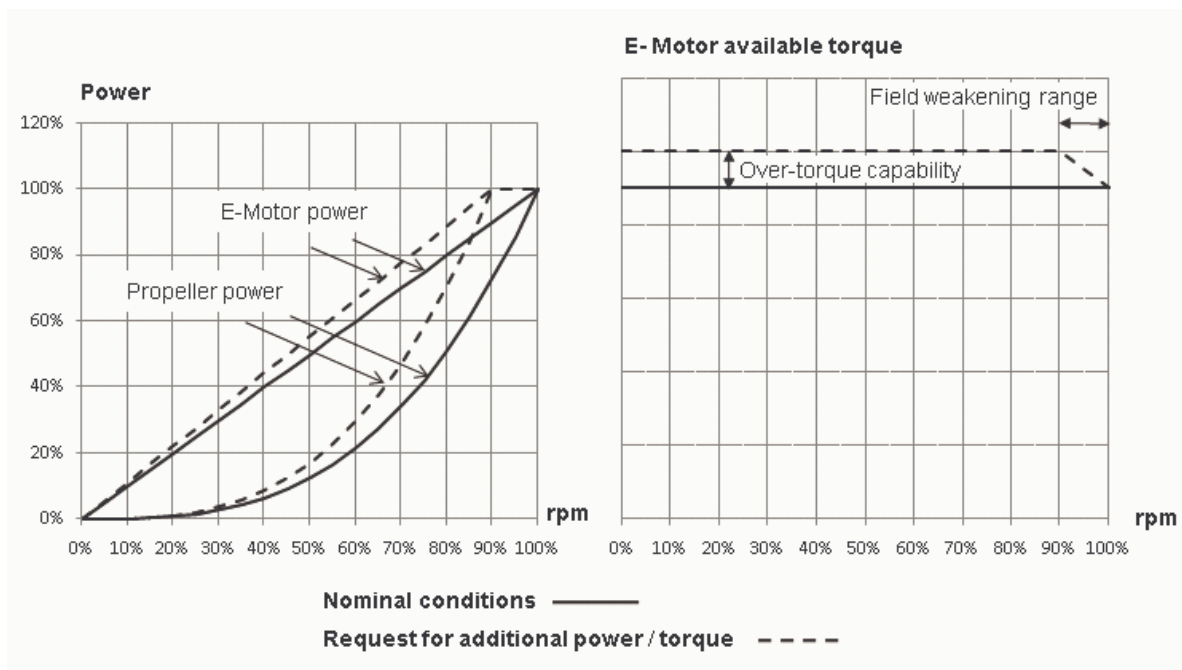
- The choice of the type of the E-motor depends on the application. Usually induction motors are used up to a power of 7 MW (η_{Motor} : typically = 0.96). If it comes to power applications above 7 MW per E-motor often synchronous machines are used. Also in applications with slow speed E-motors (without a reduction gearbox), for ice going or pod-driven vessels often synchronous E- motors (η_{Motor} : typically = 0.97) are used.
- In plants with frequency converters based on VSI-technology (PWM type) the converter themselves can deliver reactive power to the E-motor. So often a power factor $\cos \varphi = 0.9$ is a good figure to design the alternator rating. Nevertheless there has to be sufficient reactive power for the ship consumers, so that a lack in reactive power does not lead to unnecessary starts of (standby) alternators.
- The harmonics can be improved (if necessary) by using supply transformers for the frequency converters with a 30° phase shift between the two secondary windings, which cancel the dominant 5th and 7th harmonic currents. Also an increase in the pulse number leads to lower THD. Using a 12-pulse configuration with a PWM type of converter the resulting harmonic distortion will normally be below the limits defined by the classification societies. When using a transformer less solution with a converter with an Active Front End (Sinusoidal input rectifier) or in a 6-pulse configuration usually THD-filters are necessary to mitigate the THD on the sub-distributions.

The final layout of the electrical plant and the components has always to be based on a detailed analysis and a calculation of the short circuit levels, the load flows and the THD levels as well as on an economical evaluation.

1.7 Over-torque capability

In diesel-electric propulsion plants, which are running with a fix pitch propeller, the dimensioning of the electric propulsion motor has to be done accurately, in order to have sufficient propulsion power available. As an electric motor produces torque, which directly defines the cost (amount of copper), weight and space of the motor, it has to be investigated what amount of over-torque is required to operate the vessel with sufficient power also in situations, where additional power is needed (for example because of heavy weather or icy conditions).

Usually a constant power range of 5-10% is applied on the propulsion (Field weakening range), where constant E-motor power is available.



Example: Over-torque E capability of a E-propulsion train for a FPP-driven vessel

1.8 Protection of the electric plant

In an electric propulsion plant protection devices and relays are used to protect human life from injury from faults in the electric system and to avoid / reduce damage of the electric equipment. The protection system and its parameters always depend on the plant configuration and the operational requirements. During the detailed engineering phase calculations like a short circuit and an earth fault calculation and a selectivity and protection device coordination study have to be made, in order to get the correct parameter settings and to decide, which event / fault should alarm only or trip the circuit breaker.

A typical protection scheme may include the following functions (Example):

Main switchboard:

- Over- and under-voltage
- Earth fault

Alternator:

- Short circuit
- Over-current
- Stator earth fault
- Reverse power
- Phase unbalance, Negative phase sequence
- Differential protection
- Over- and under-frequency
- Over- and under-voltage
- Alternator windings and bearings over-temperature
- Alternator cooling air/water temperature
- Synchronizing check
- Over- and under-excitation (Loss of excitation)

Bus tie feeder:

- Short circuit
- Earth fault
- Synchronizing check
- Differential protection (in ring networks)

Transformer feeder:

- Short circuit
- Over-current
- Earth fault
- Thermal overload/image
- Under-voltage
- Differential protection (for large transformers)



Motor feeder:

- Short circuit
- Over-current
- Earth fault
- Under-voltage
- Thermal overload/image
- Motor start: Stalling I_{2t}, number of starts
- Motor windings and bearings over-temperature
- Motor cooling air/water temperature

1.9 Drive control

The drive control system is a computer controlled system for the speed converters / drives, providing network stability in case of sudden / dynamical load changes. It ensures safe operation of the converters with constant and stable power supply to the E-propulsion motors and avoids the loss of power under all operational conditions. Usually the propulsion is speed controlled. So the system keeps the reference speed constant as far as possible within the speed and torque limitations and dynamic capability.

The drive control system normally interfaces with the propulsion control system, the power management system, the dynamic position system and several other ship control and automation systems. The functionality of the drive control system depends on the plant configuration and the operational requirements.

The main tasks of the drive control system can be summarized as follows:

- Control of the converters / drives, including the speed reference calculation
- Control of drive / propeller speed according to the alternator capability, including anti-overload prevention
- Control of power and torque. It takes care of the limits
- Control of the converter cooling

For some applications (e.g. for ice going vessels, for rough sea conditions, etc, where load torque varies much and fast) often a power control mode is applied, which reduces the disturbances on the network and smoothens the load application on the diesel engines.

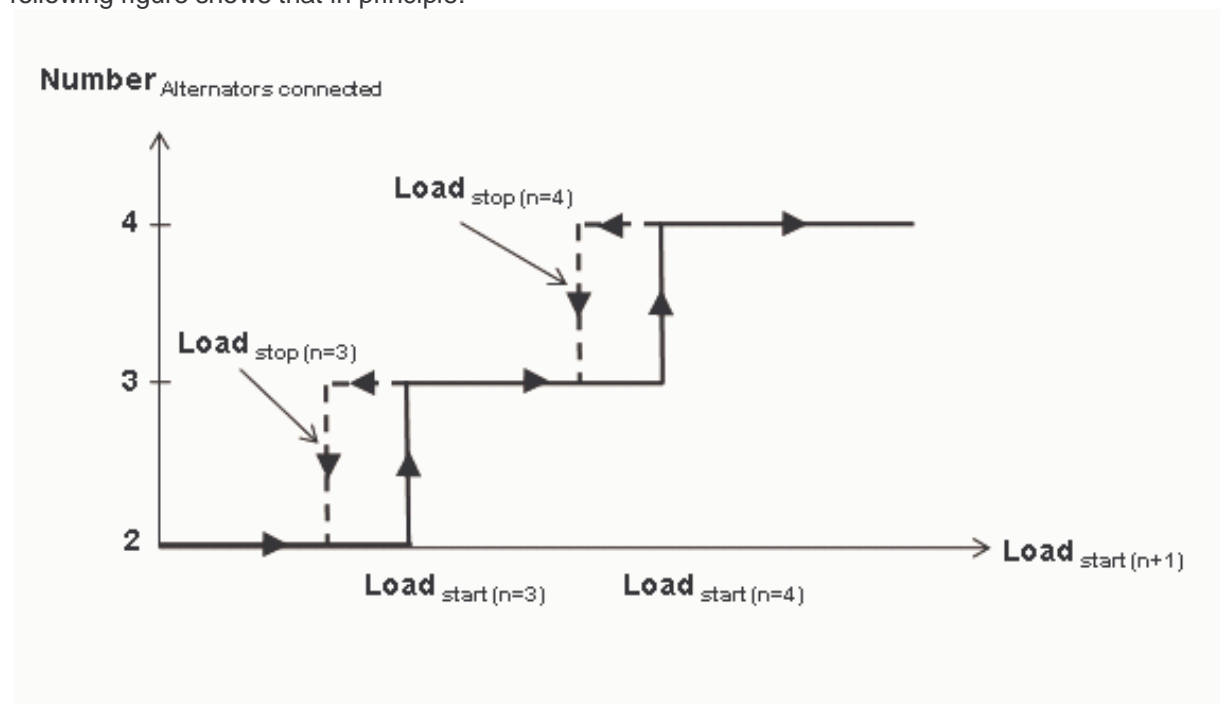
1.10 Power management

Power reservation

The main function of a power management system is to start and stop gensets / alternators according to the current network load and the online alternator capacity. The power management system takes care that the next alternator will be started, if the available power (= Installed power of all connected alternators – current load) becomes lower than a preset limit. This triggers a timer and if the available power stays below the limit for a certain time period the next genset / alternator in sequence is started. It also blocks heavy consumers to be started or sheds (unnecessary) consumers, if there is not enough power available, in order to avoid unstable situations.

Class rules require from gensets / alternators 45 seconds for starting, synchronizing and beginning of sharing load. So it is always a challenge for the power management system to anticipate the situation in advance and to start gensets / alternators before consumers draw the network and overload the engines. Overloading an engine will soon decrease the speed / frequency with the danger of motoring the engine, as the flow of power will be altered from network to alternator (Reverse power). The electric protection system must disconnect such alternator from the network. An overload situation is always a critical situation for the vessel and a blackout has to be avoided.

The detailed power management functionality always depends on the plant configuration, the operational requirements but also on general philosophy and preferred solution of the owner. The parameters when to start or to stop a genset / alternator have always to be evaluated individually. The following figure shows that in principle:



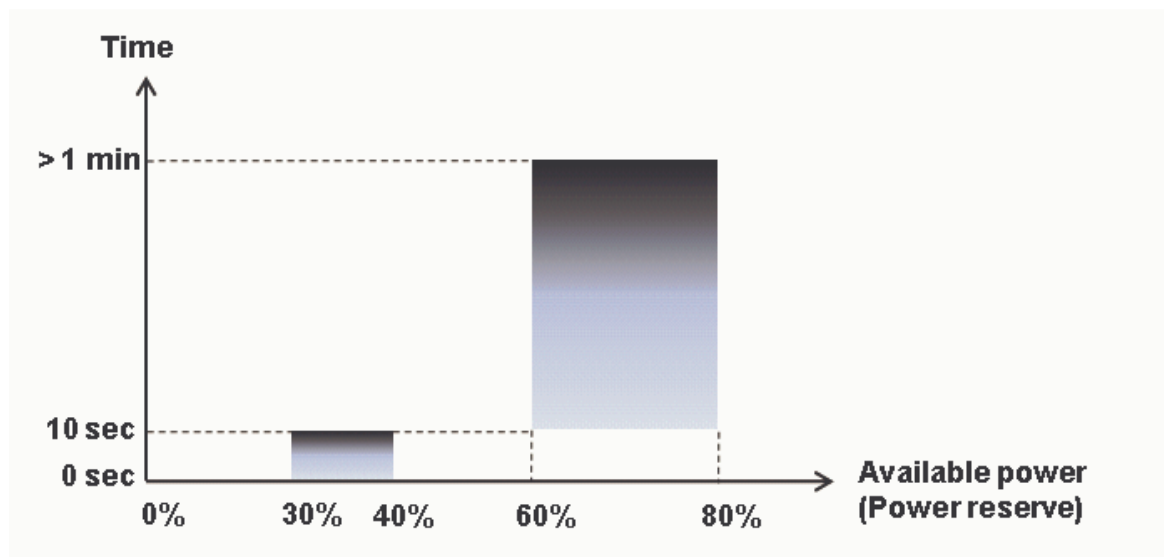
For example the load depending start / stop of gensets / alternators is shown in the next table. It can be seen that the available power depends on the status of the gensets / alternators when they get their starting command. As an example a plant with 4 gensets / alternators is shown:

No. of alternators connected	Alternator load	Available power (Power reserve) via load pick-up by the running gensets	Time to accept load
2	85%	$2 \times 15\% = 30\%$	0...10 sec
3	87%	$3 \times 13\% = 39\%$	0...10 sec
4	90%	$4 \times 10\% = 40\%$	0...10 sec

No. of alternators connected	Alternator load	Available power (Power reserve) by starting a standby ^{*)} genset	Time to accept load
2	70%	$2 \times 30\% = 60\%$	< 1 min
3	75%	$3 \times 25\% = 75\%$	< 1 min
4	80%	$4 \times 20\% = 80\%$	< 1 min

*) preheated, prelubricated, etc. Starting conditions see belonging MAN Diesel & Turbo Engine Project Guide

The available power for this example could look like this:





Power management system

Derived from the above mentioned main tasks of a power management system the following functions are typical:

- Automatic load dependent start / stop of gensets / alternators
- Manual starting / stopping of gensets / alternators
- Fault dependent start /stop of standby gensets / alternators in cases of under-frequency and/or under-voltage.
- Start of gensets / alternators in case of a blackout (Black-start capability)
- Determining and selection of the starting / stopping sequence of gensets / alternators
- Start and supervise the automatic synchronization of alternators and bus tie breakers
- Balanced and unbalanced load application and sharing between gensets / alternators. Often an emergency program for quickest possible load acceptance is necessary.
- Regulation of the network frequency (with static droop or constant frequency)
- Distribution of active load between alternators
- Distribution of reactive load between alternators
- Handling and blocking of heavy consumers
- Automatic load shedding
- Tripping of non-essential consumers
- Bus tie and breaker monitoring and control

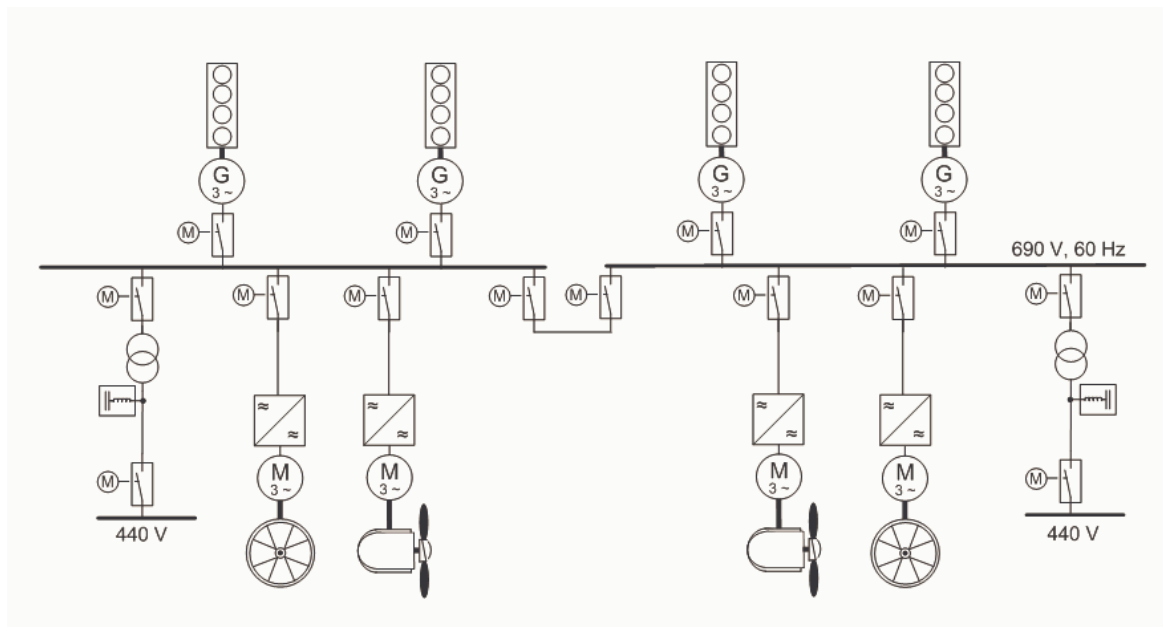
All questions regarding the functionality of the power management system have to be clarified with MAN Diesel & Turbo at an early project stage.

1.11 Example configurations of diesel-electric propulsion plants

Offshore Support Vessels

The term “Offshore Service & Supply Vessel” includes a large class of vessel types, such as Platform Supply Vessels (PSV), Anchor Handling/Tug/Supply (AHTS), Offshore Construction Vessel (OCV), Diving Support Vessel (DSV), Multipurpose Vessel, etc.

Electric propulsion is the norm in ships which frequently require dynamic positioning and station keeping capability. Initially these vessels mainly used variable speed motor drives and fixed pitch propellers. Now they mostly deploy variable speed thrusters and they are increasingly being equipped with hybrid diesel-mechanical and diesel-electric propulsion.



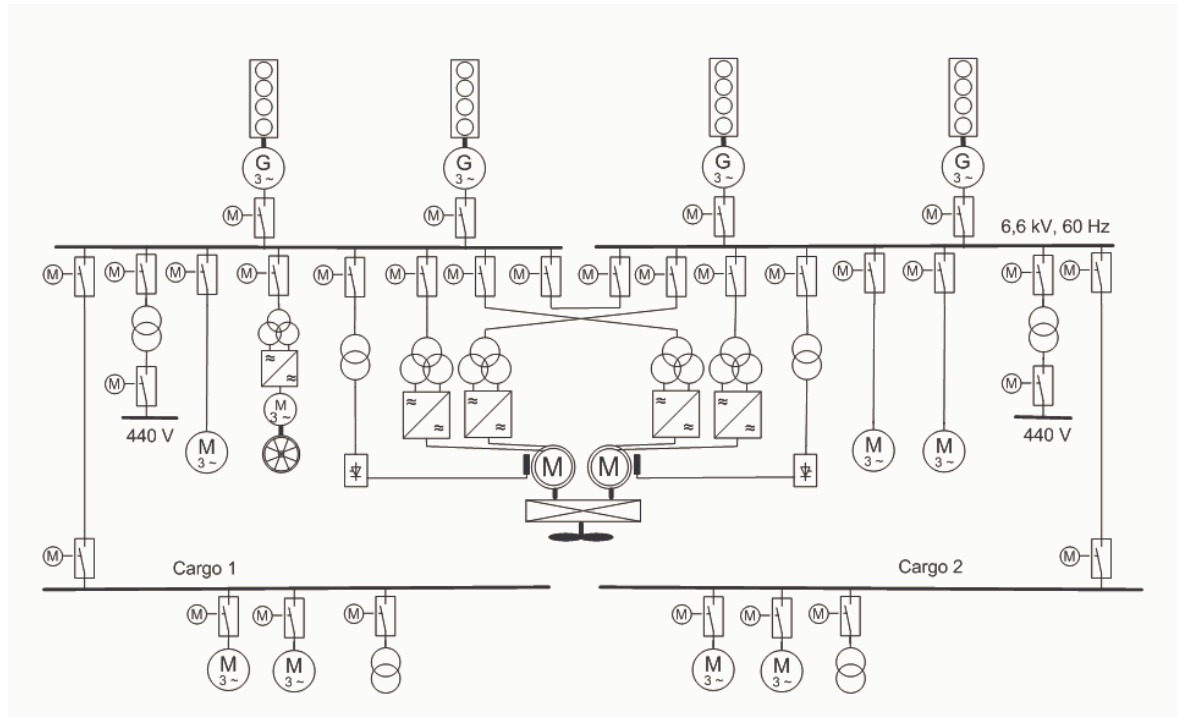
Example: DE-configuration of a PSV

In modern applications often frequency converters with a 6-pulse configuration or with an Active Front End are used, which give specific benefits in the space consumption of the electric plant, as it is possible to get rid of the heavy and bulky supply transformers.

Type of converter / drive	Supply transformer	Type of E-motor	Pros & cons
6-pulse Drive or Active Front End	-	Induction	+ Transformer less solution + Less space and weight - THD filter required

LNG Carriers

A propulsion configuration with two high speed E-motors (e.g. 600 RPM or 720 RPM) and a reduction gearbox (Twin-in-single-out) is a typical configuration, which is used at LNG carriers where the installed alternator power is in the range of about 40 MW. The electrical plant fulfils high redundancy requirements. Due to the high propulsion power which is required and higher efficiencies synchronous E-motors are used.



Example: DE-configuration (redundant) of a LNG carrier with geared transmission, single screw and FP propeller

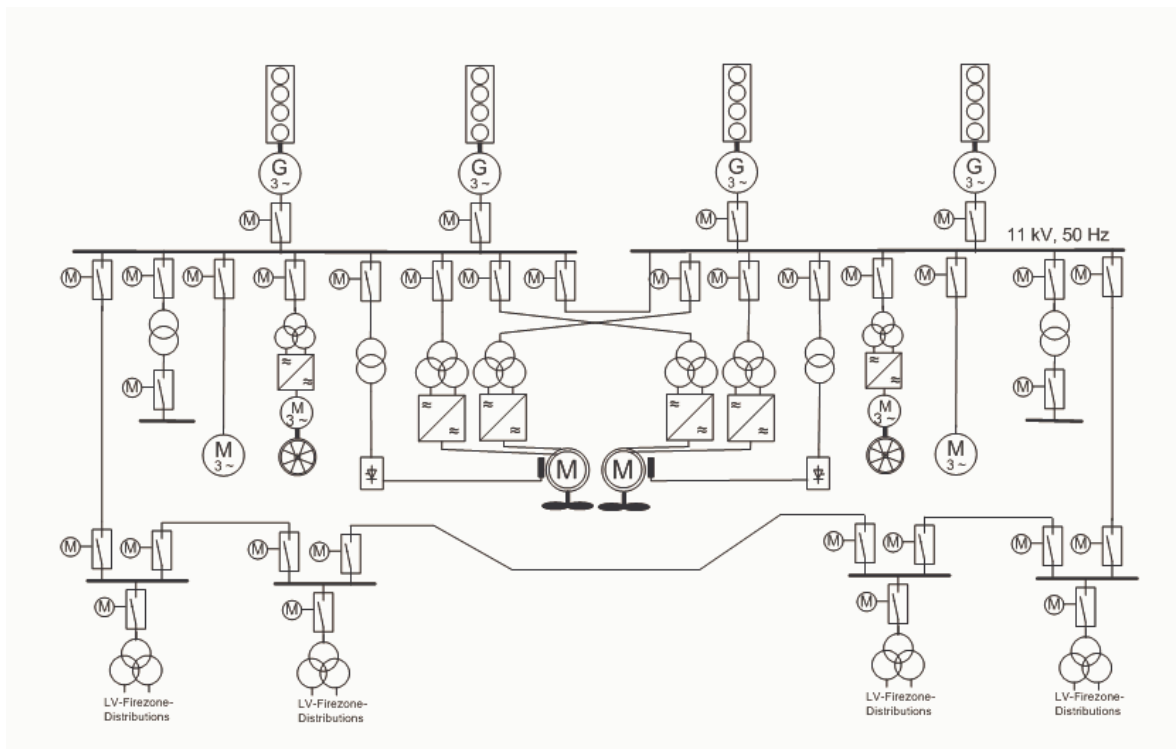
Type of converter / drive	Supply transformer	Type of E-motor	Pros & cons
VSI with PWM	24pulse	Synchronous	<ul style="list-style-type: none"> + High propulsion power + High drive & motor efficiency + Low harmonics - Heavy E-plant configuration

For ice going carriers and tankers also podded propulsion is a robust solution, which has been applied in several vessels.

Cruise and ferries

Passenger vessels – cruise ships and ferries – are an important application field for diesel-electric propulsion. Safety and comfort are paramount. New regulations, as “Safe Return to Port”, require a high reliable and redundant electric propulsion plant and also onboard comfort is a high priority, allowing only low levels of noise and vibration from the ship’s machinery.

A typical electric propulsion plant is shown in the example below.



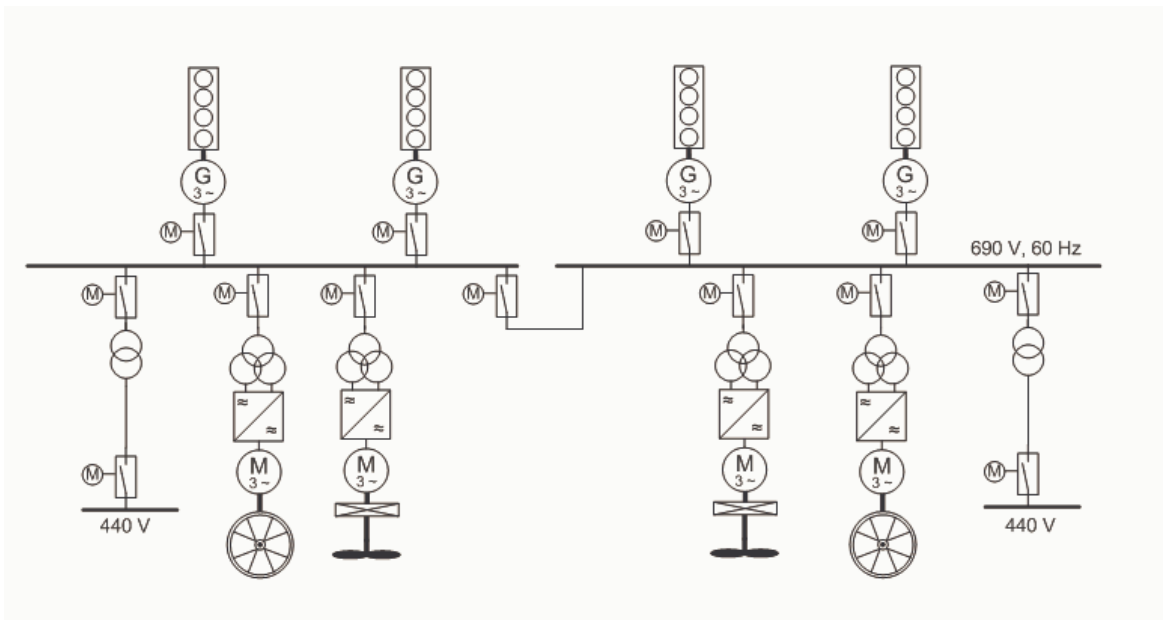
Example: DE-configuration (redundant) of a cruise liner, twin screw, gear less

Type of converter / drive	Supply transformer	Type of E-motor	Pros & cons
VSI with PWM	24pulse	Synchronous (slow speed 150 RPM)	+ Highly redundant & reliable + High drive & motor efficiency + Low noise & vibration - Complex E-plant configuration

For cruise liners often also geared transmission is applied as well as pods.

For a RoPax ferry almost the same requirements are valid as for a cruise liner.

The figure below shows an electric propulsion plant with a “classical” configuration, consisting of high speed E-motors (900 RPM or 1200 RPM), geared transmission, frequency converters and supply transformers.



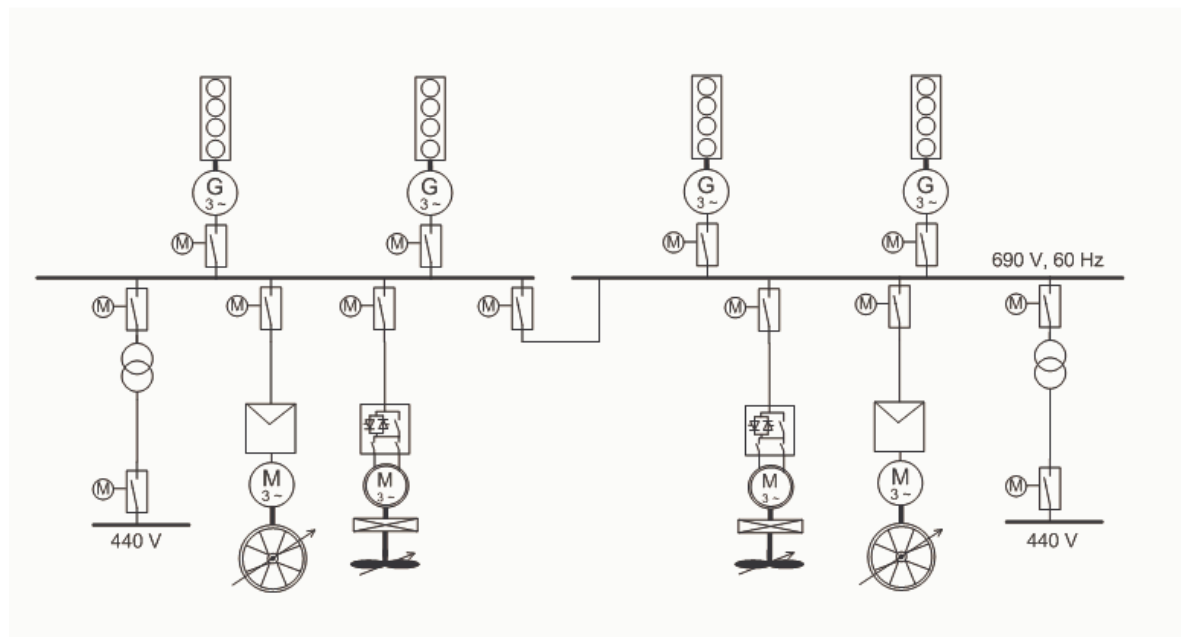
Example: DE-configuration (redundant) of a RoPax ferry, twin screw, geared transmission

Type of converter / drive	Supply transformer	Type of E-motor	Pros & cons
VSI-type (with PWM technology)	12 pulse, two secondary windings, 30° phase shift	Induction	+ Robust & reliable technology + No THD filters - More space & weight (compared to transformer less solution)

Advanced applications

As MAN Diesel & Turbo works together with different suppliers for diesel-electric propulsion plants an optimal matched solution can be designed for each application, using the most applicable components from the market (Freedom of choice). The following example shows a smart solution, patented by STADT AS (Norway).

In many cases a combination of an E-propulsion motor, running on two constants speeds (Medium, high) and a pitch controllable propeller (CPP) gives a high reliable and compact solution with low electrical plant losses.



Example: DE-configuration (redundant) of a RoRo, twin screw, geared transmission

Type of converter / drive	Supply transformer	Type of E-motor	Pros & cons
Sinusoidal drive (Patented by STADT AS)	-	Induction	<ul style="list-style-type: none"> + Highly reliable & compact + Low losses + Transformer less solution + Low THD (No THD filters needed) - Only applicable with a CP propeller



Questionnaire: Diesel-electric propulsion plants

In order to provide you with appropriate project material and to carry out proposals promptly and accurately, we would kindly request you to fill in as many of the following details as possible and return it with a complete set of arrangement drawings to your sales representative.

General data

Name: _____

Address: _____

Phone: _____

E-mail: _____

Project: _____

Type of vessel: _____

Propulsion principle:

Diesel-electric CODLAD CODLAG _____

Main particulars:

Length, overall [m]: _____

Length, pp [m]: _____

Breadth, moulded [m]: _____

Depth, moulded [m]: _____

Draught, design [m]: _____

Draught, scantling [m]: _____

DWT, at sct draught [t]: _____

Gross tonnage [GRT]: _____

Crew + Passengers: _____ + _____



Classification society: _____ Class notation: _____

Additional class notations: _____ Redundancy: _____

Ice class: _____

Ambient conditions:

Max. machinery room temperature [°C]: _____

Max. sea water temperature [°C]: _____

Max. fresh water temperature [°C]: _____

Speed and margins

Speed:

Ship design speed [kn] : _____ (at maximum propulsion shaft power)

Sea margin [%] : _____

Max. allowed load of engines [%] : _____ % MCR

Propulsion system and power demand

Main Propulsion:

- | | | |
|--|--|--|
| <input type="checkbox"/> Shaft propulsion: | <input type="checkbox"/> Single Screw: | <input type="checkbox"/> Single in – single out |
| | | <input type="checkbox"/> Tandem |
| | | <input type="checkbox"/> Twin in – single out |
| | <input type="checkbox"/> Twin Screw: | <input type="checkbox"/> Two shaft lines |
| | | <input type="checkbox"/> 2x Twin in – single out |

Steerable rudder propellers (= Azimuth thrusters)

Pods



Data for main propulsion:

FPP: Number: _____
Max. shaft power on propulsion E-motor (per propeller; including sea margin)
[kW]: _____
Propeller revolution [RPM]: _____
Input speed (= E-motor RPM): _____
Reduction gearbox: yes no

CPP: Number: _____
Max. shaft power on propulsion E-motor (per propeller; including sea margin)
[kW]: _____
Propeller revolution [RPM]: _____
Input speed (= E-motor RPM): _____
Reduction gearbox: yes no

Azi. thruster: Number: _____
Max. shaft power on propulsion E-motor (per thruster; including sea margin)
[kW]: _____
Input speed (= E-motor RPM): _____
Propeller type: FPP CPP

Pod: Number: _____
Max. shaft power on propulsion E-motor (per pod; including sea margin)
[kW]: _____
E-motor speed [RPM]: _____

_____ Number: _____
Max. shaft power on propulsion E-motor (each; including sea margin)
[kW]: _____
Propeller revolution [RPM]: _____
Input speed (= E-motor RPM): _____
Reduction gearbox: yes no



Data for manoeuvring propulsors:

Bow thruster: Number: _____
Max. shaft power on propulsion E-motor (each; including sea margin)
[kW]: _____
Input speed (= E-motor RPM): _____
Propeller type: FPP CPP

Stern thruster: Number: _____
Max. shaft power on propulsion E-motor (each; including sea margin)
[kW]: _____
Input speed (= E-motor RPM): _____
Propeller type: FPP CPP

_____ Number: _____
Max. shaft power on propulsion E-motor (each; including sea margin)
[kW]: _____
Input speed (= E-motor RPM): _____
Propeller revolution [RPM]: _____
Propeller type: FPP CPP

Electrical load balance

Max. total electrical power demand at sea:

for main propulsion [kW_{el}]: _____
for vessel's consumers [kW_{el}]: _____

Max. total electrical power demand at manoeuvring:

for main propulsion [kW_{el}]: _____
for manoeuvring propulsors [kW_{el}]: _____
for vessel's consumers [kW_{el}]: _____



Max. total electrical power demand at port:

for vessel's consumers [kW_{el}]: _____

The five biggest electrical consumers of the vessel
(apart from main propulsion and maneuvering propulsors):

Name: _____ ; kW_{el} : _____

Name: _____ ; kW_{el} : _____

Name: _____ ; kW_{el} : _____

Name: _____ ; kW_{el} : _____

Name: _____ ; kW_{el} : _____

Please provide us with a complete E-Load-Balance of the vessel.

Electrical system and motors

Number of generators: _____

Power per generator [kW_{el}]: _____

Power factor: _____

Revolution of generators [RPM]: _____

Frequency [Hz]: _____

Voltage level of generator and MSB [V]: _____

Voltage levels of sub-switchboards [V]: _____

System grounding of MSB: 3-phase, 3-wire, isolated from hull
 3-phase, 3-wire, isolated via high-resistive resistor

Main propulsion E-motors:

Number of winding systems: 1 2

Speed control: variable speed via frequency converter



Manoeuvring E-motors (i.e. bow thrusters):

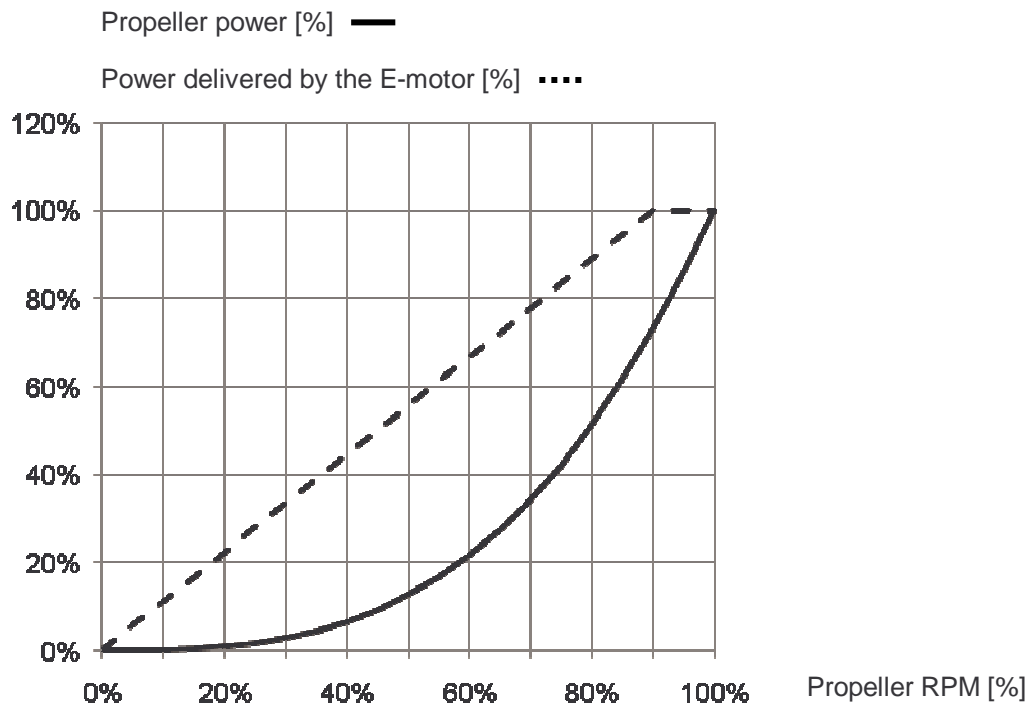
variable speed via frequency converter

constant speed (Start via Y/ Δ -unit)

constant speed (Start via Softstarter)

Dimensioning of frequency converter and propulsion E-motor

The design of the frequency converters and the torque capability of the propulsion E-motors is usually rated in between a constant power range of 90% ...100% of the propeller revolution (for a FPP-driven vessel).



Torque capability:

Constant power form _____ % to 100% of propeller RPM

Max. over-torque capability of the E-motor: _____ %

Single line diagram

Please provide us with a complete single line diagram of the vessel, if available.