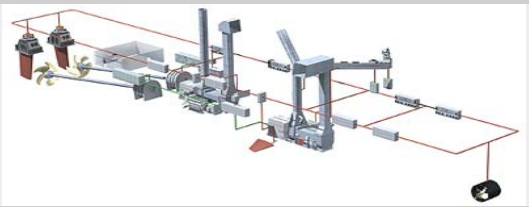




Diesel-electric propulsion concepts

How to match environmental and economical challenges ?

F. Oberhokamp, Research and Development
Hamburg, 09.10.2007

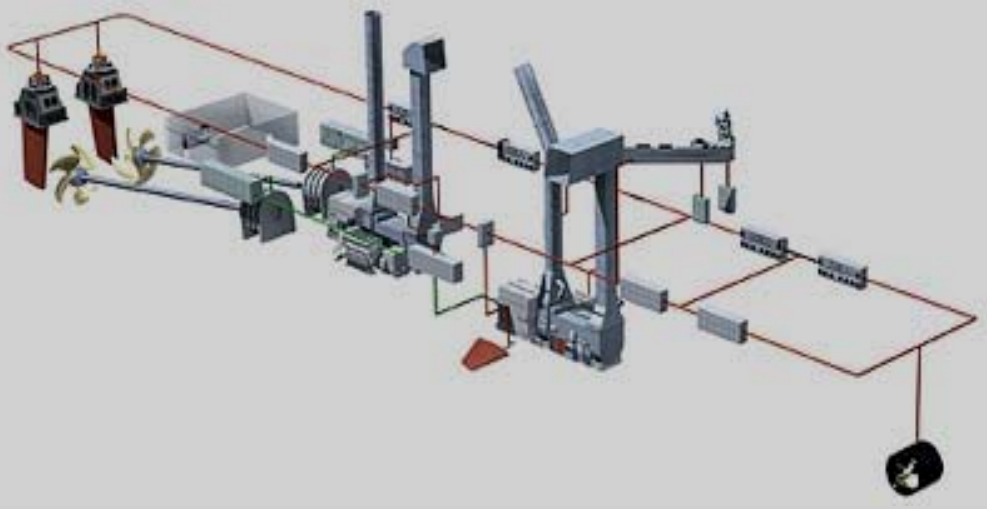
A company of
ThyssenKrupp
Technologies

ThyssenKrupp Marine Systems
Surface Vessel Division

ThyssenKrupp

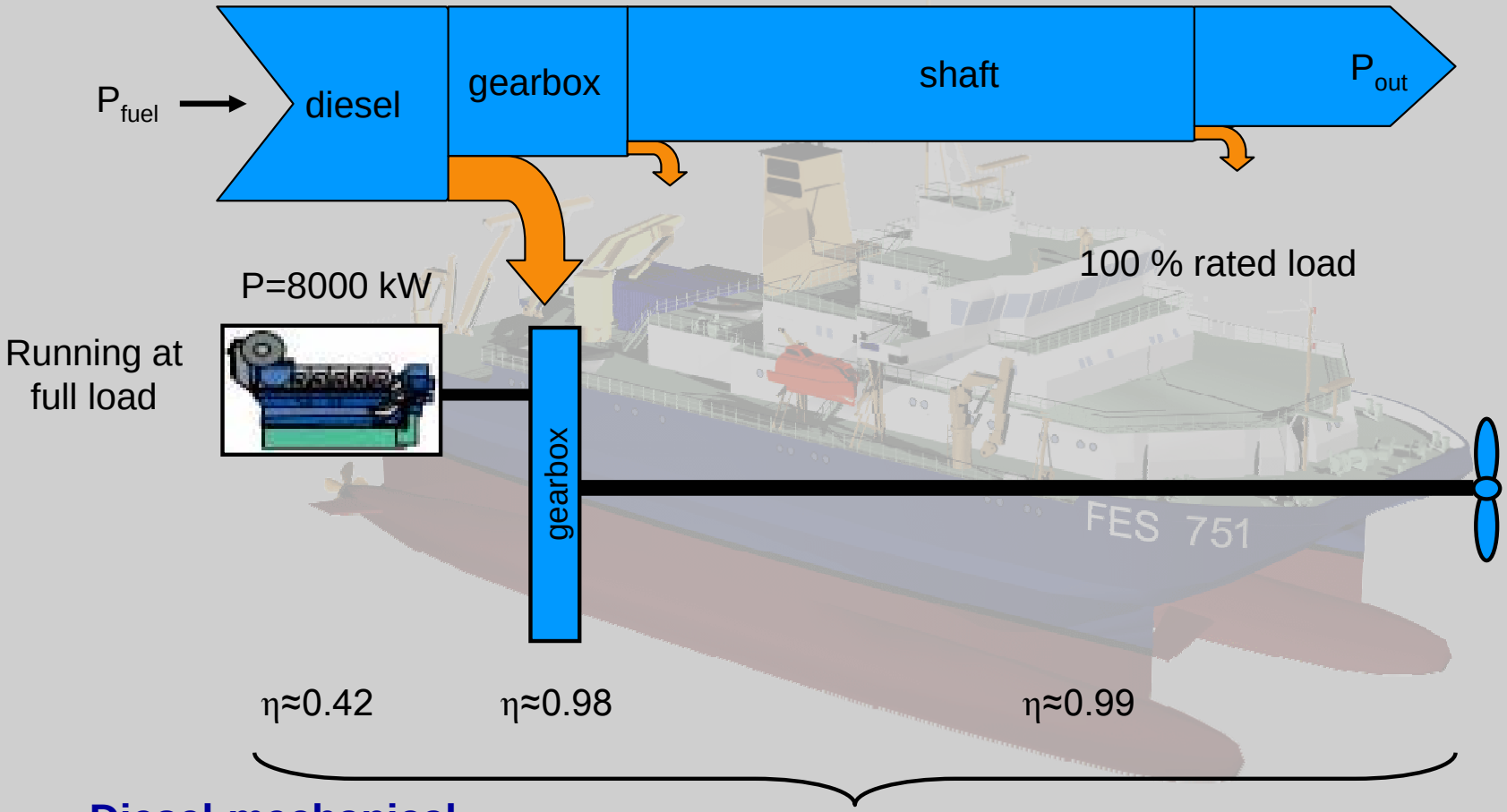
Topics

- **Diesel electric propulsion concepts vs. diesel mechanical configuration**
- **Efficiency for different load ranges incl. economical advantages**
- **Engine room area, weight aspects, spares and maintenance**



Diesel-electric propulsion concepts vs. diesel mechanical configuration

Power flow and power efficiency - A simplified consideration

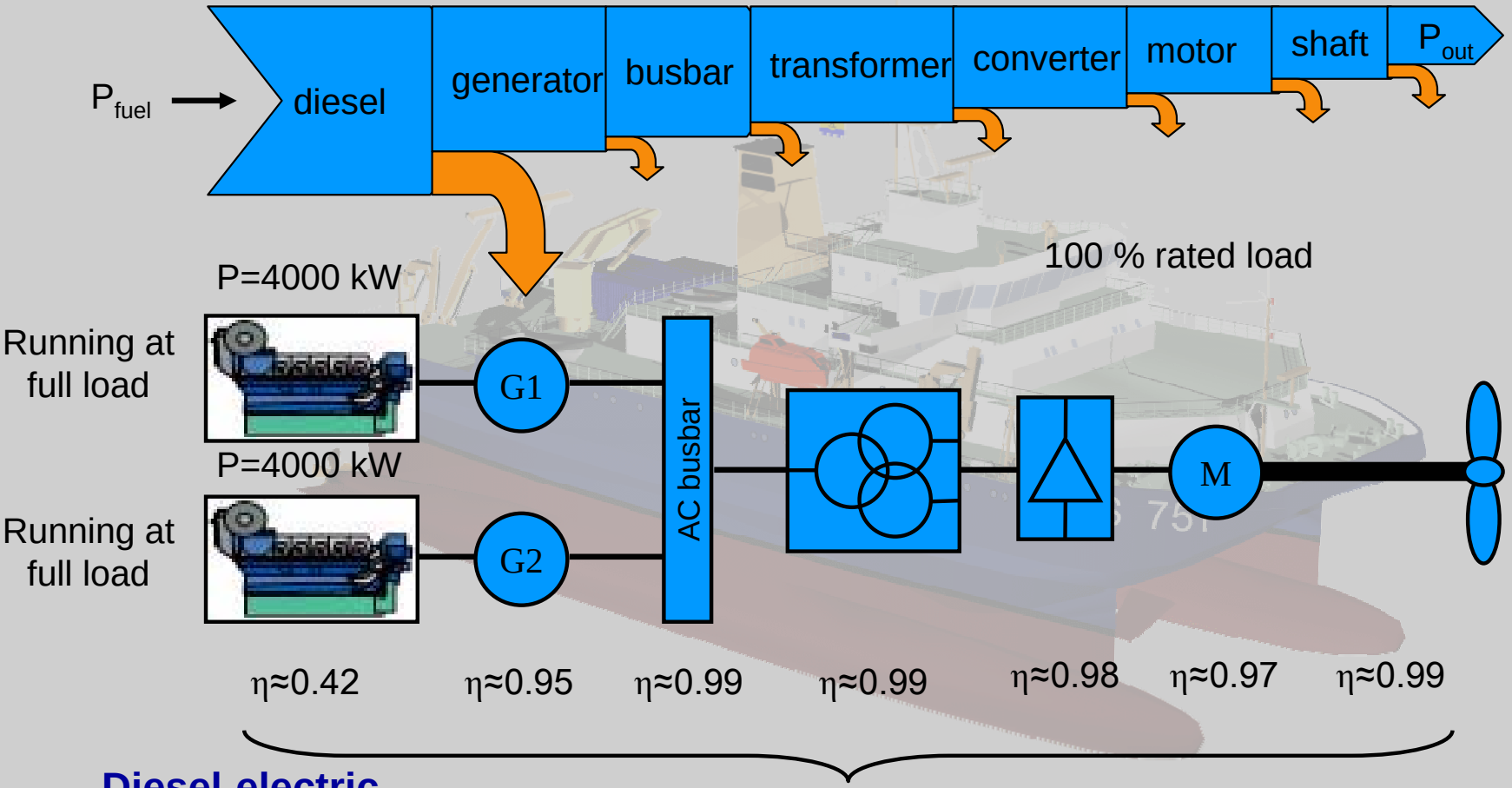


Diesel-mechanical configuration at full load

$$P_{out} = \eta \cdot P_{fuel} = 0.40 \cdot P_{fuel}$$

Diesel-electric propulsion concepts vs. diesel mechanical configuration

Power flow and power efficiency - A simplified consideration

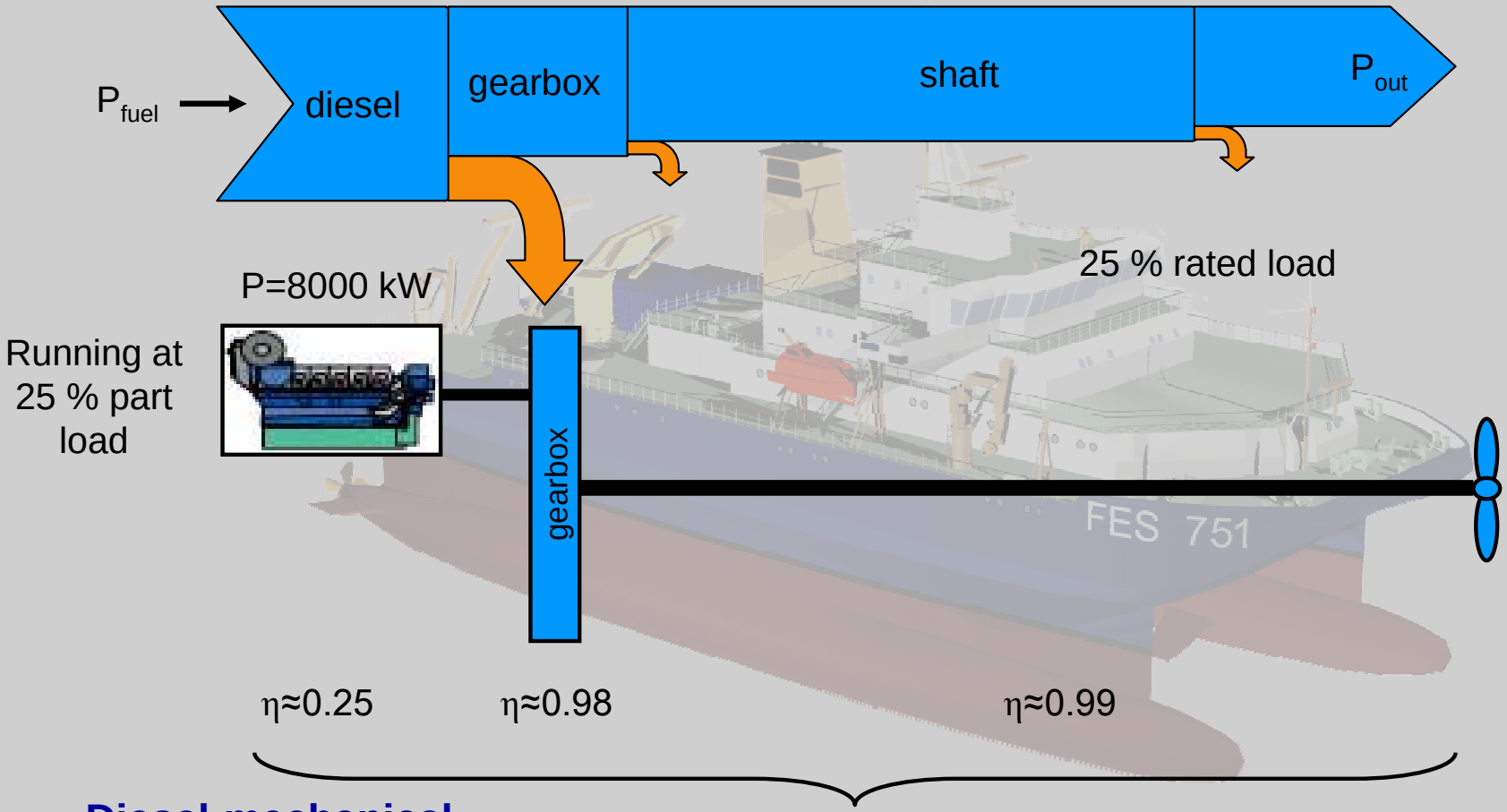


Diesel-electric configuration at full load

$$P_{out} = \eta \cdot P_{fuel} = 0.36 \cdot P_{fuel}$$

Diesel-electric propulsion concepts vs. diesel mechanical configuration

Power flow and power efficiency - A simplified consideration

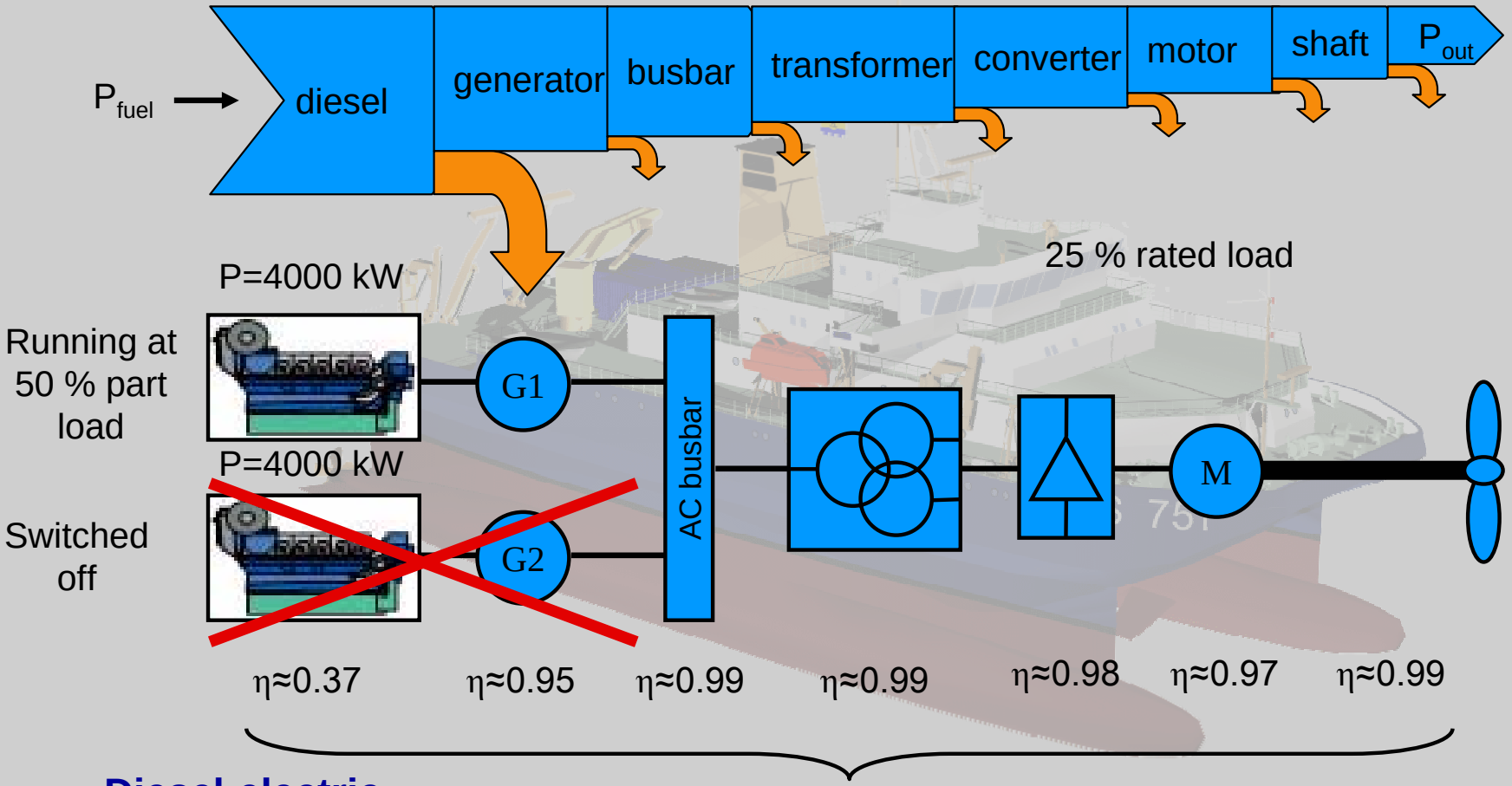


Diesel-mechanical configuration at part load

$$P_{out} = \eta \cdot P_{fuel} = 0.24 \cdot P_{fuel}$$

Diesel-electric propulsion concepts vs. diesel mechanical configuration

Power flow and power efficiency - A simplified consideration

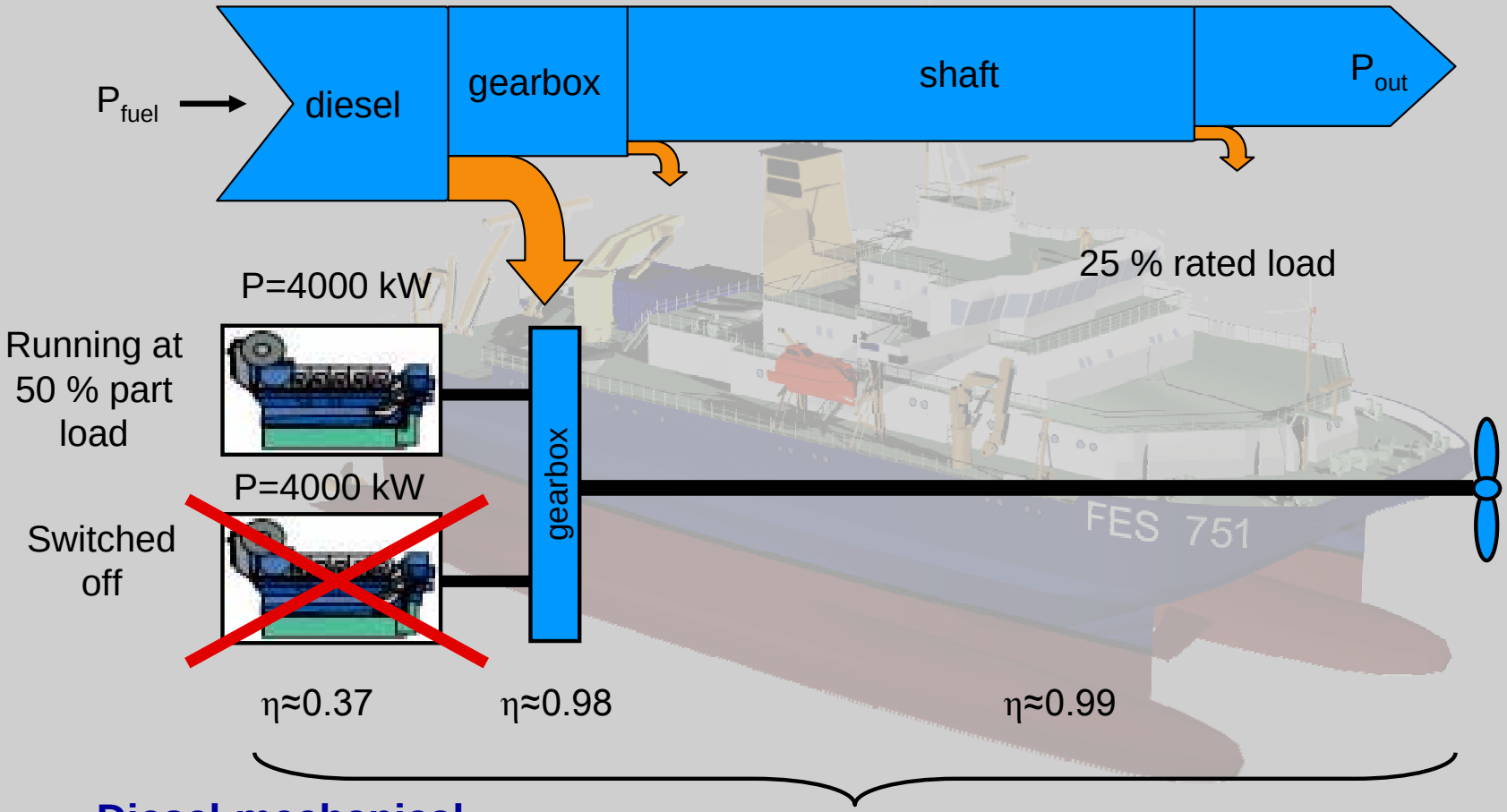


Diesel-electric configuration at part load

$$P_{out} = \eta \cdot P_{fuel} = 0.31 \cdot P_{fuel}$$

Diesel-electric propulsion concepts vs. diesel mechanical configuration

Power flow and power efficiency - A simplified consideration



Diesel-mechanical configuration at part load

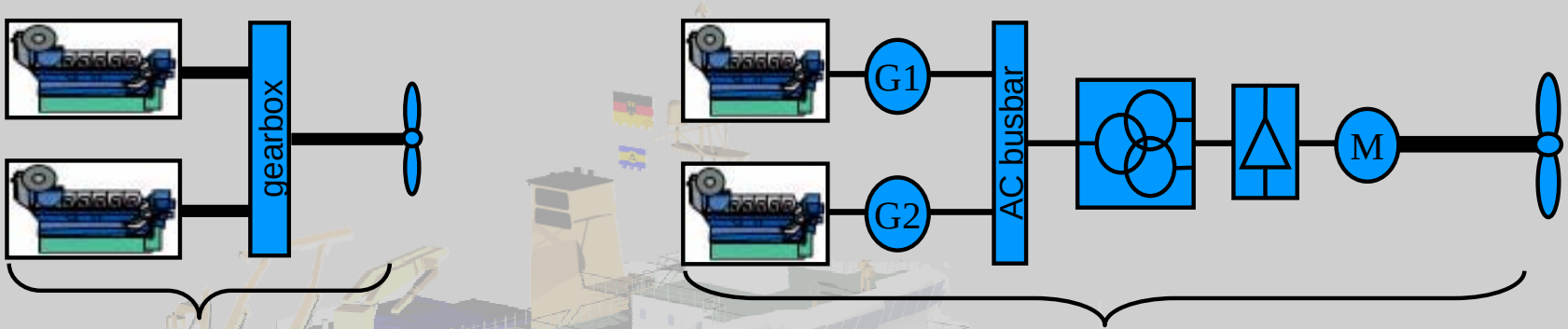
$$P_{out} = \eta \cdot P_{fuel} = 0.35 \cdot P_{fuel}$$

Power efficiency - A short summary

Diesel-mechanical configuration

Diesel-electric configuration

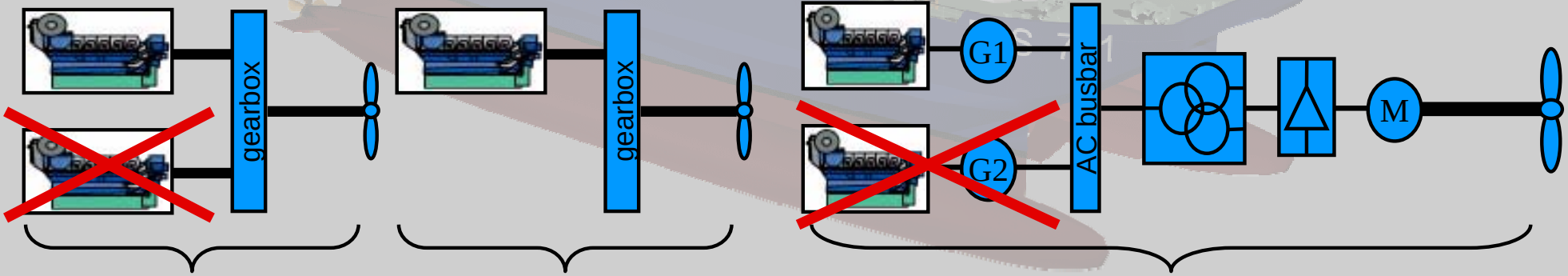
at 100 % full load conditions



$\eta = 0.40$

$\eta = 0.36$

at 25 % part load conditions



$\eta = 0.35$

$\eta = 0.24$

$\eta = 0.31$

Questions

At this restricted consideration the diesel-electric propulsion system has a smaller efficiency than the diesel mechanical configuration

Is it right to look only on the power train system ?

What about the consideration of the electric power generation ?

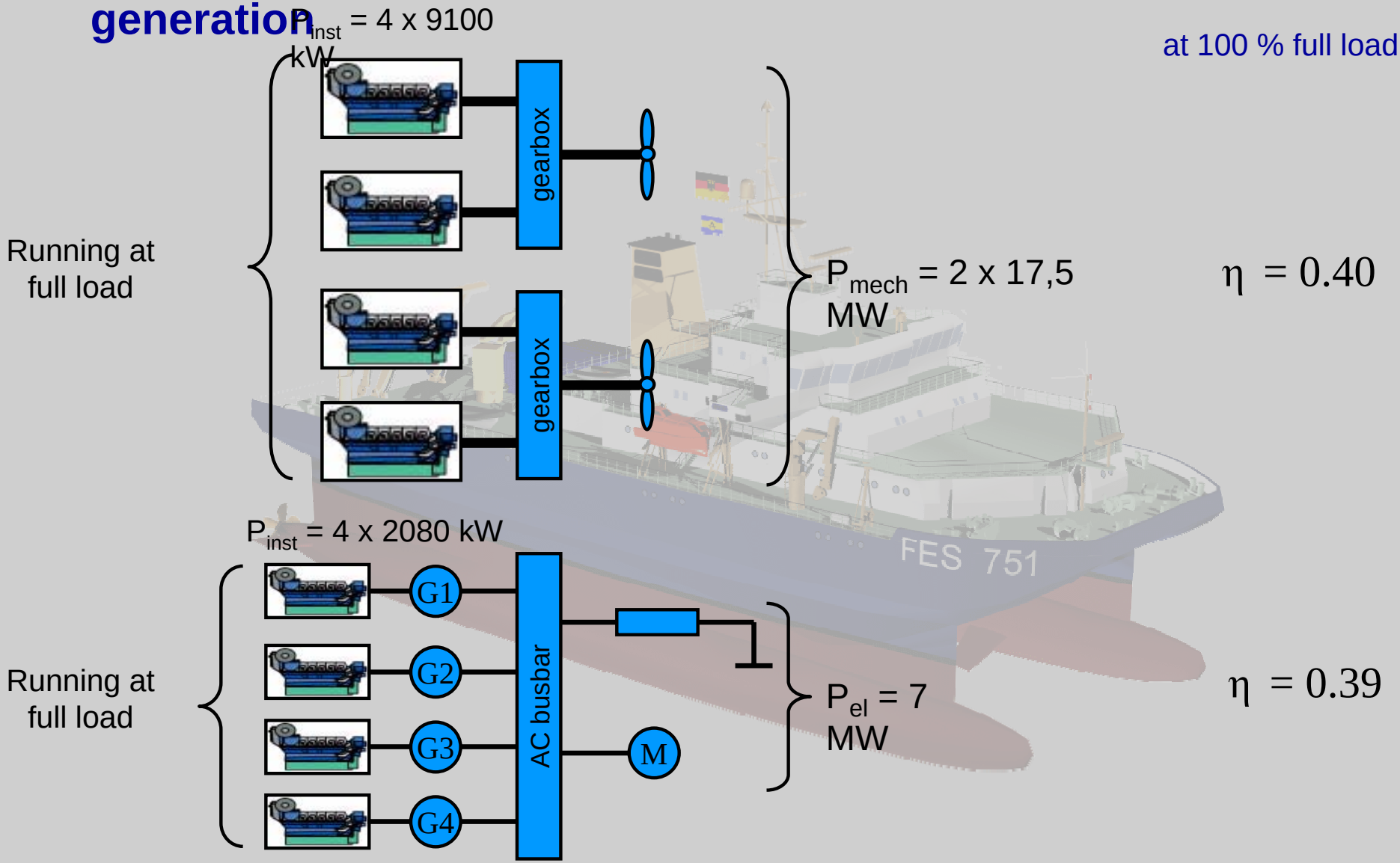
Obviously it's also important to consider the load distribution of prime movers !

New approach

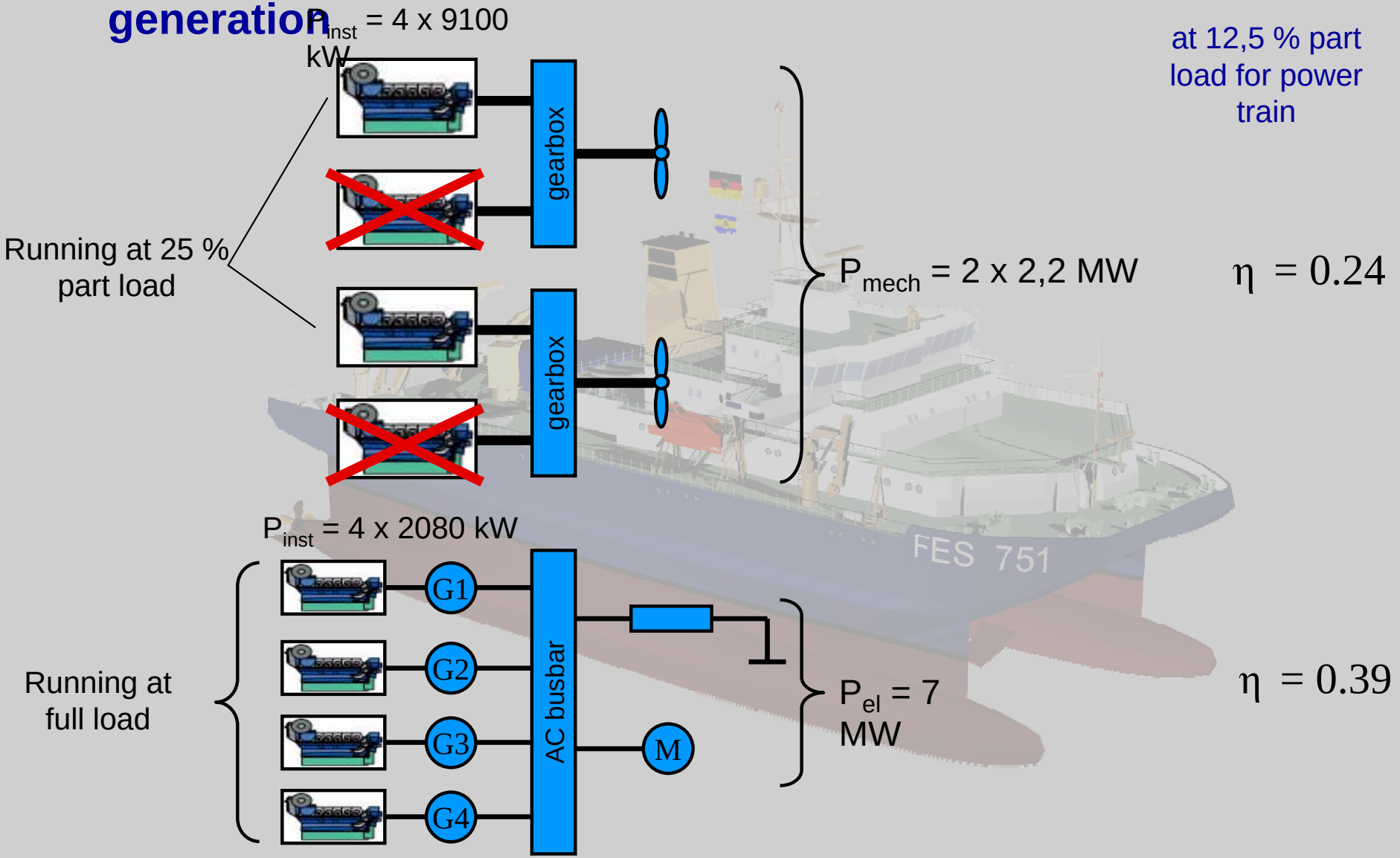
Consideration of the total system behavior

Total system consideration - power train and electric power generation

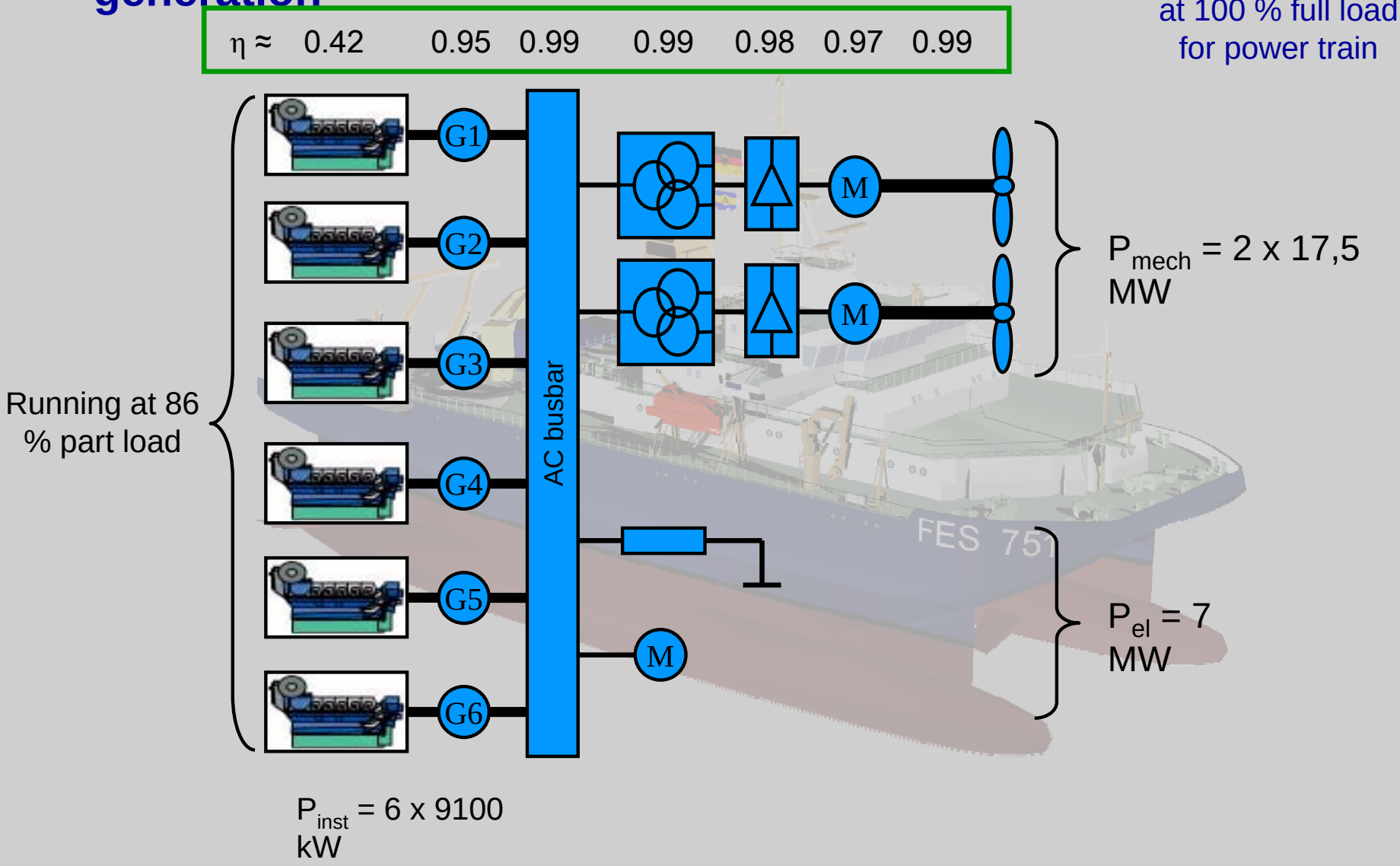
at 100 % full load



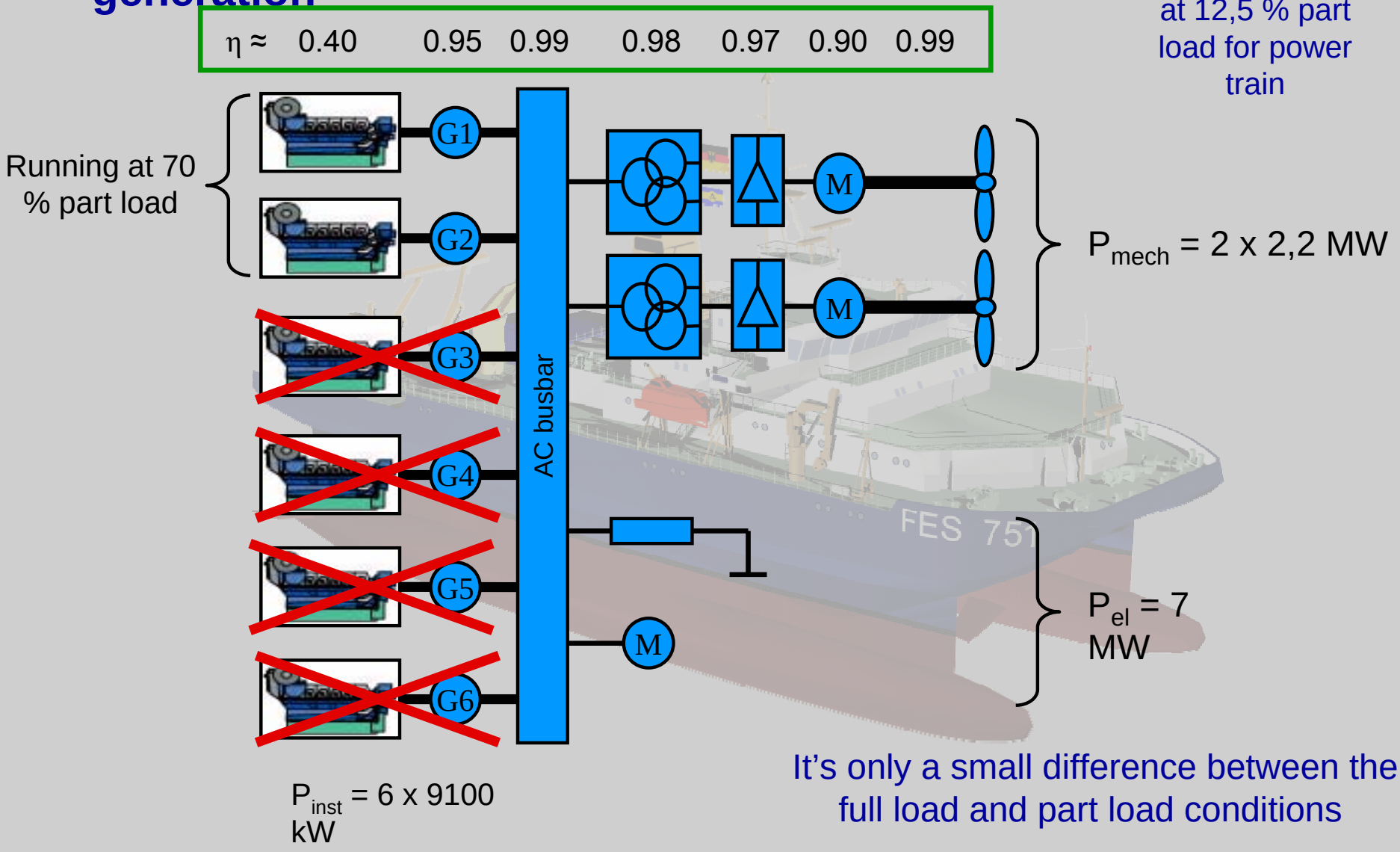
Total system consideration - power train and electric power generation



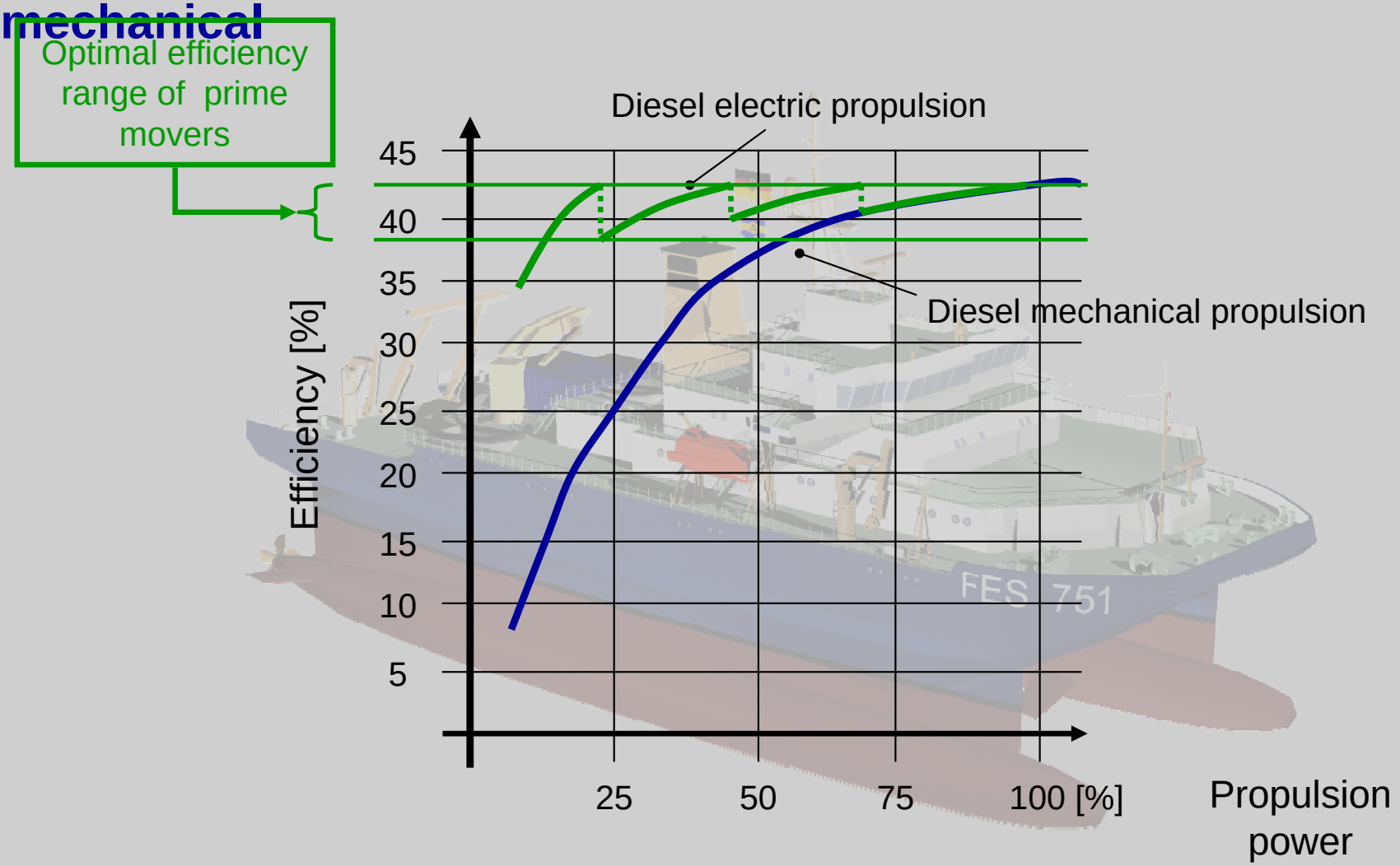
Total system consideration - power train and electric power generation



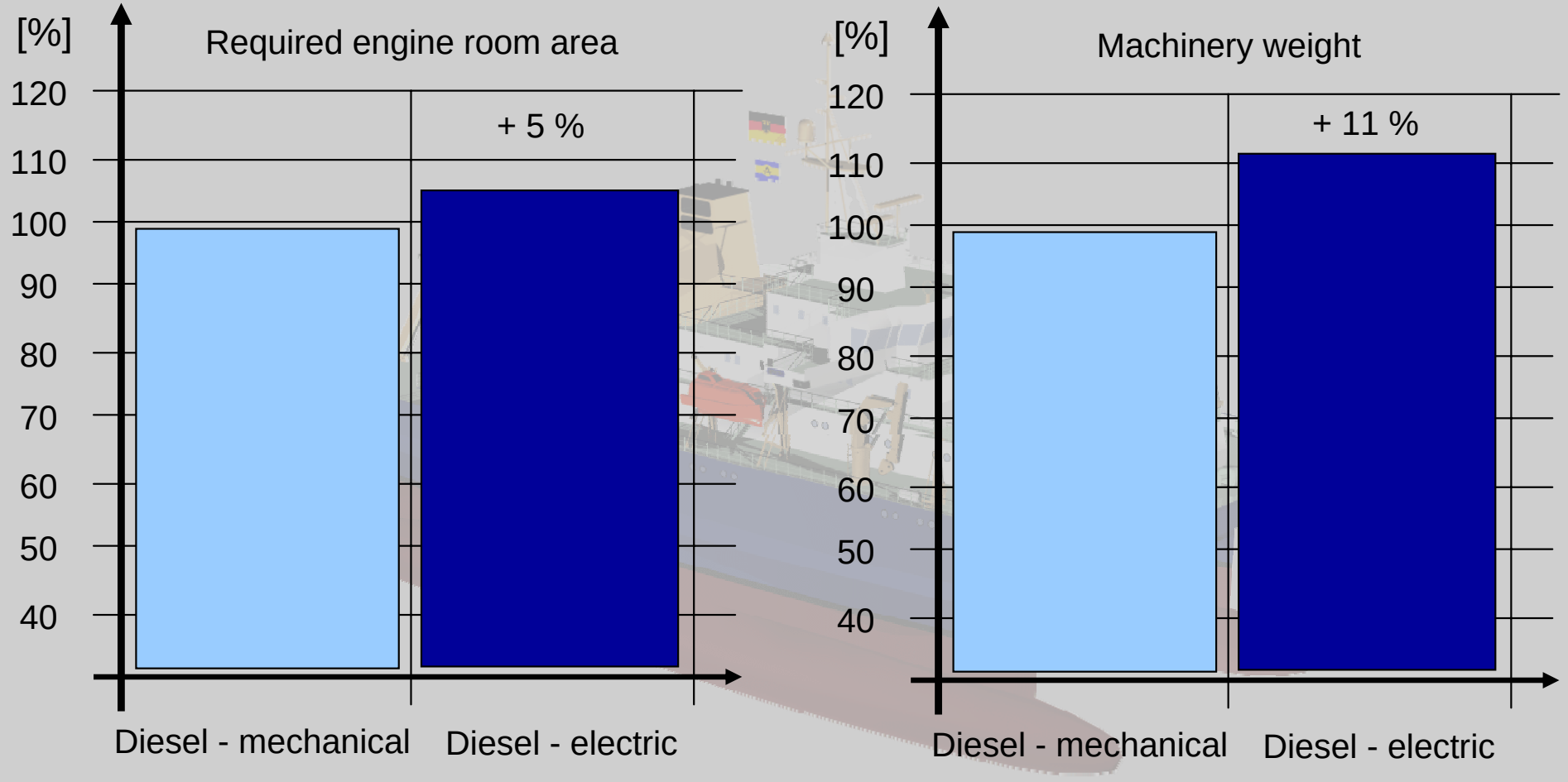
Total system consideration - power train and electric power generation



Efficiency of prime movers – diesel electric compared to diesel mechanical

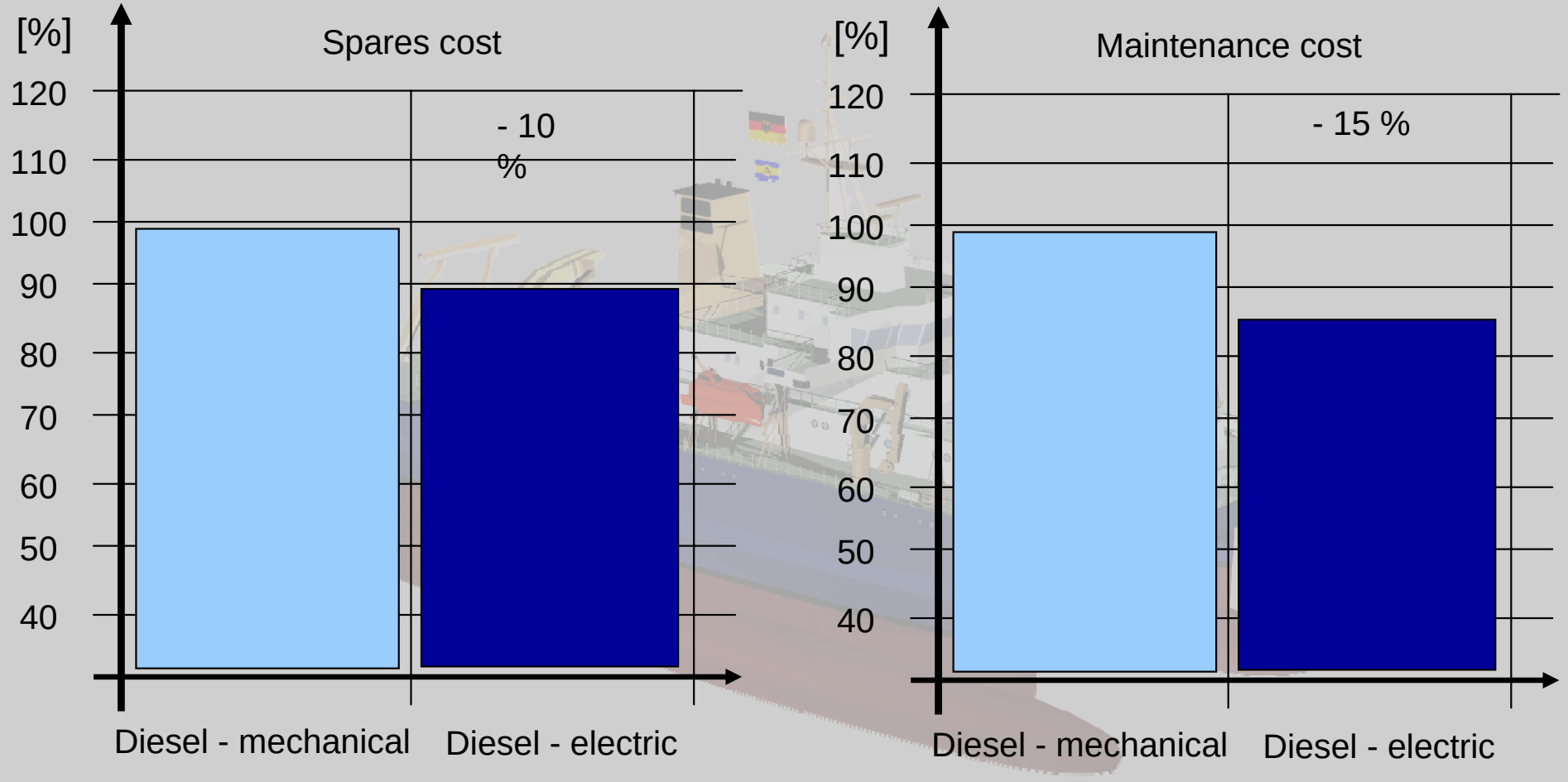


Engine room area, weight aspects, spare and maintenance cost by comparison



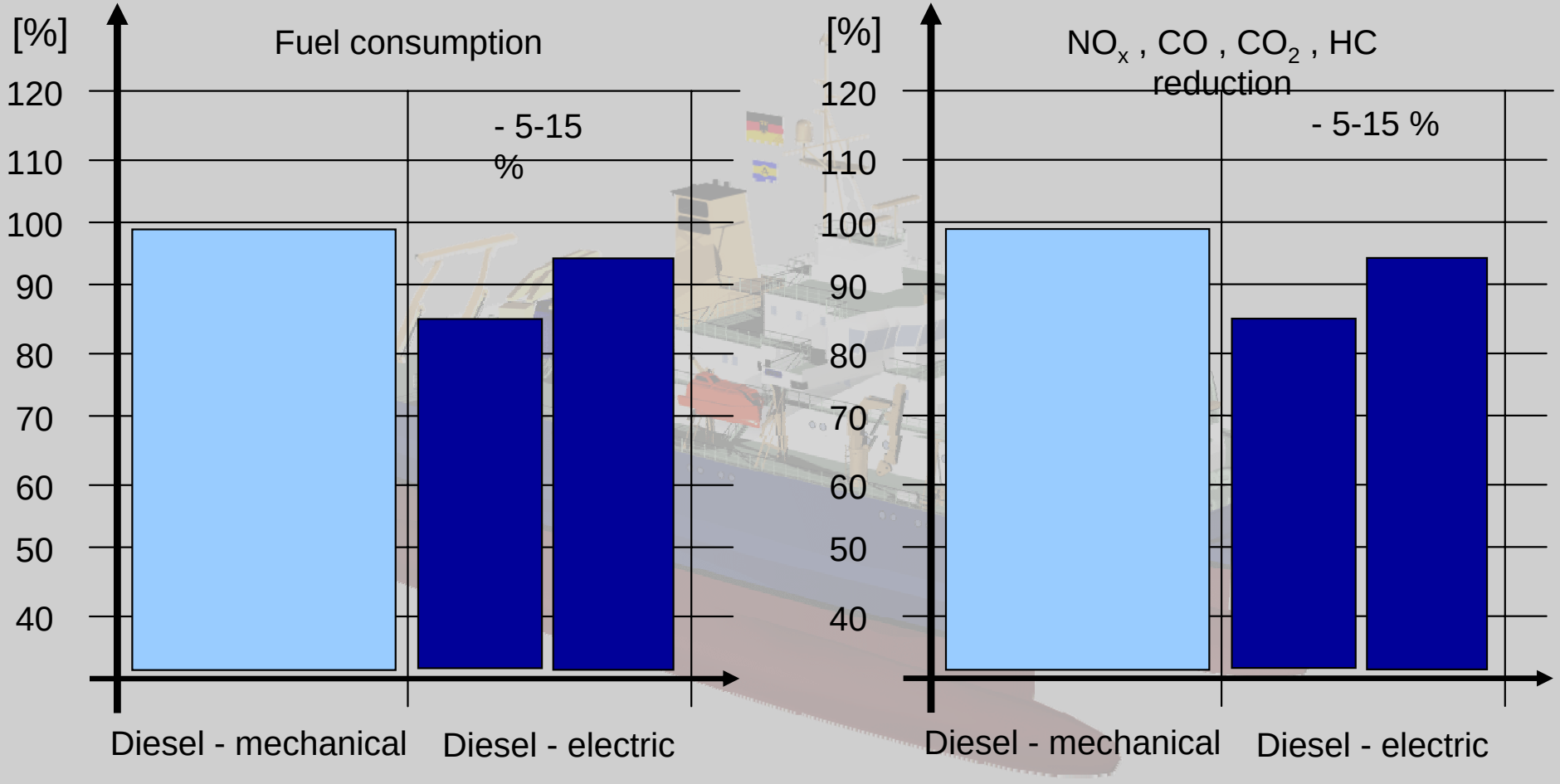
Values for orientation based on investigation results

Engine room area, weight aspects, spare and maintenance cost by comparison



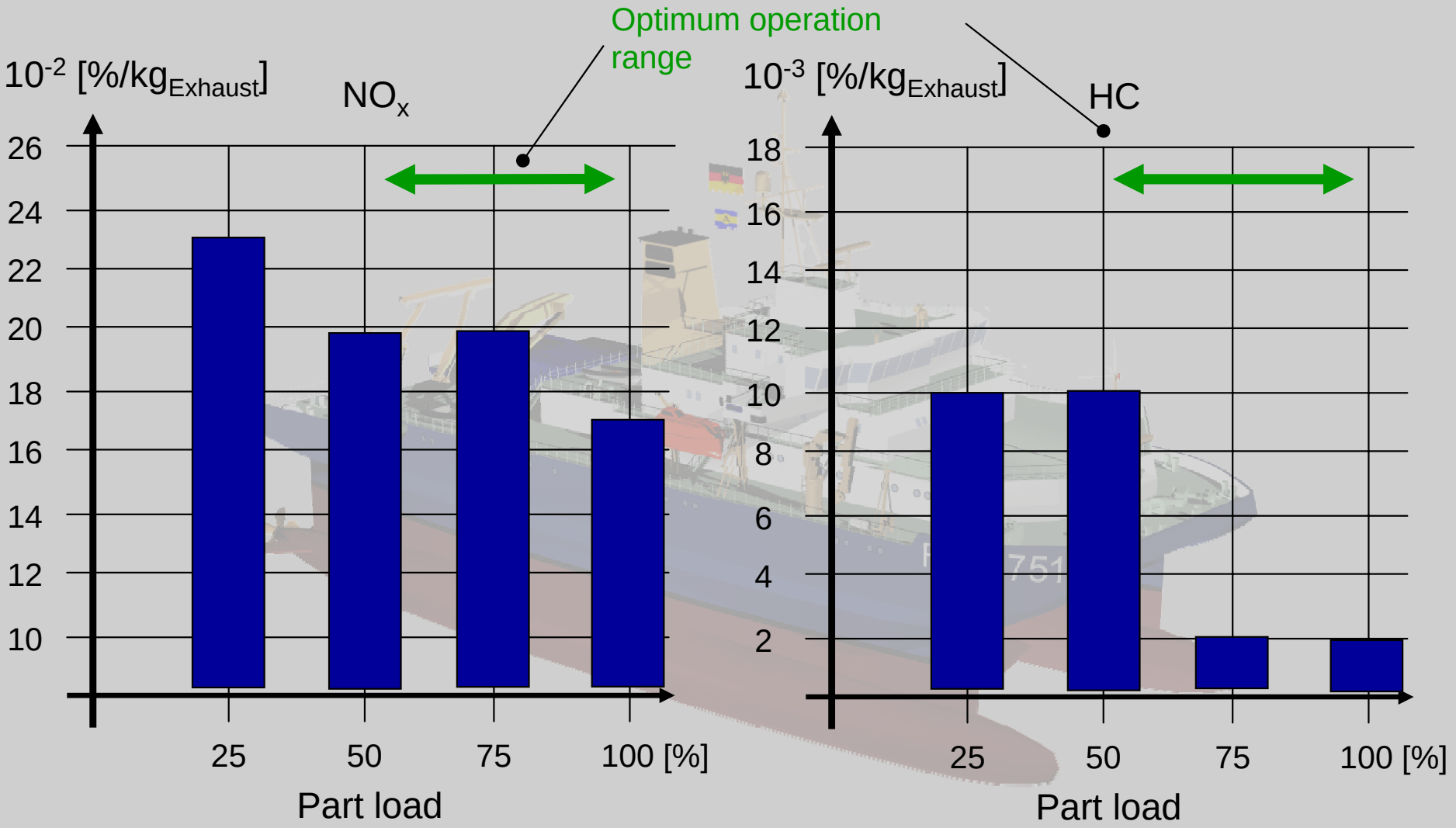
Values for orientation based on investigation results

Fuel consumption and greenhouse gas emissions by comparison



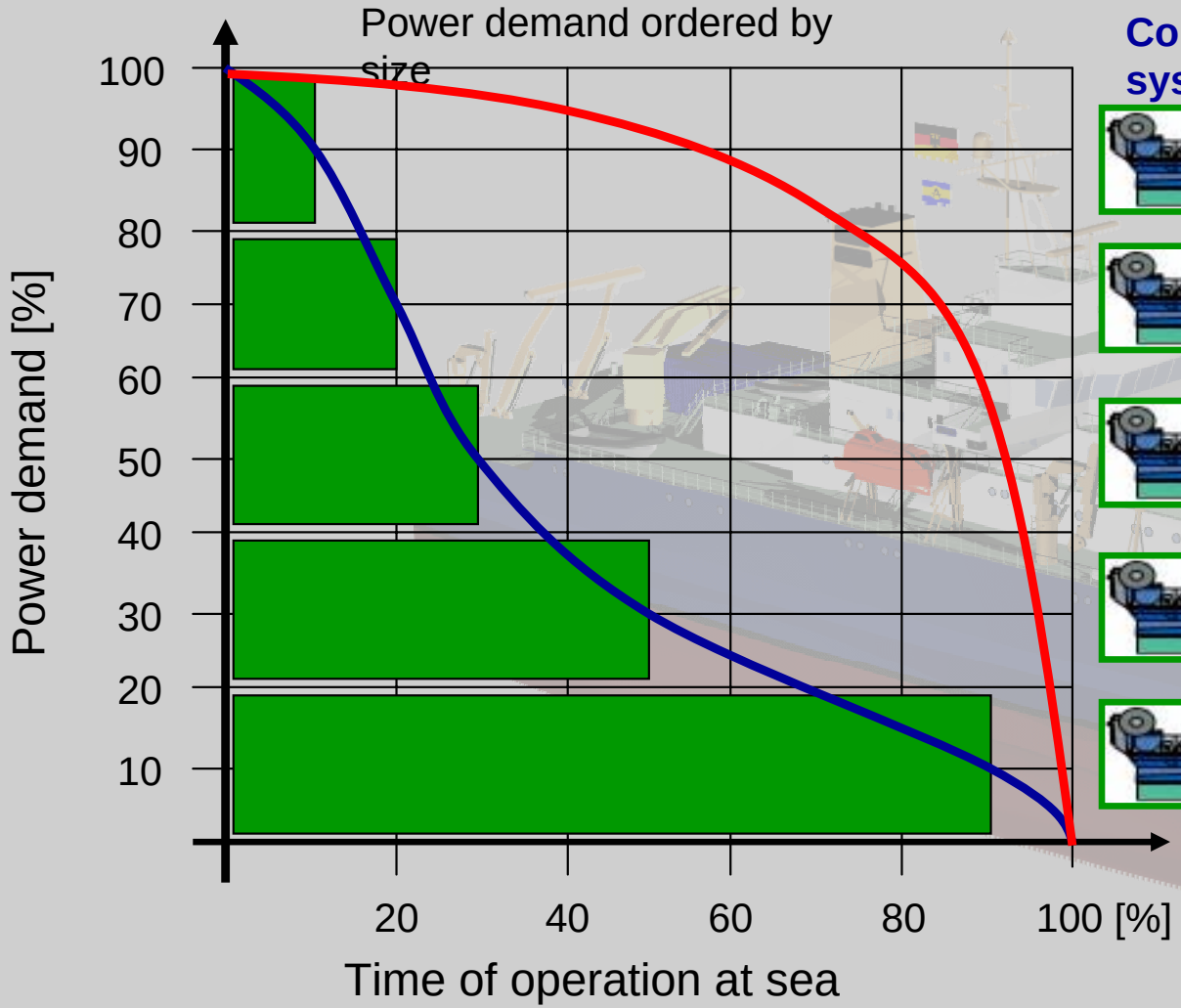
Values for orientation based on investigation results

Exhaust concentrations during part load conditions by comparison

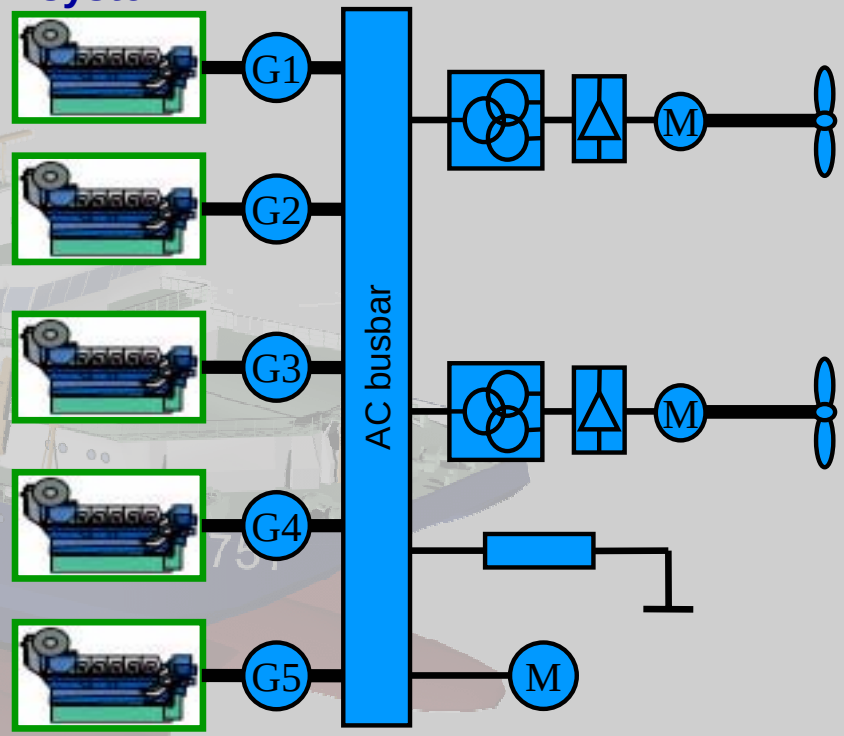


Values for orientation based on measurement results at a (MDO) diesel engine

Power demand characteristics of diesel electric propulsion systems

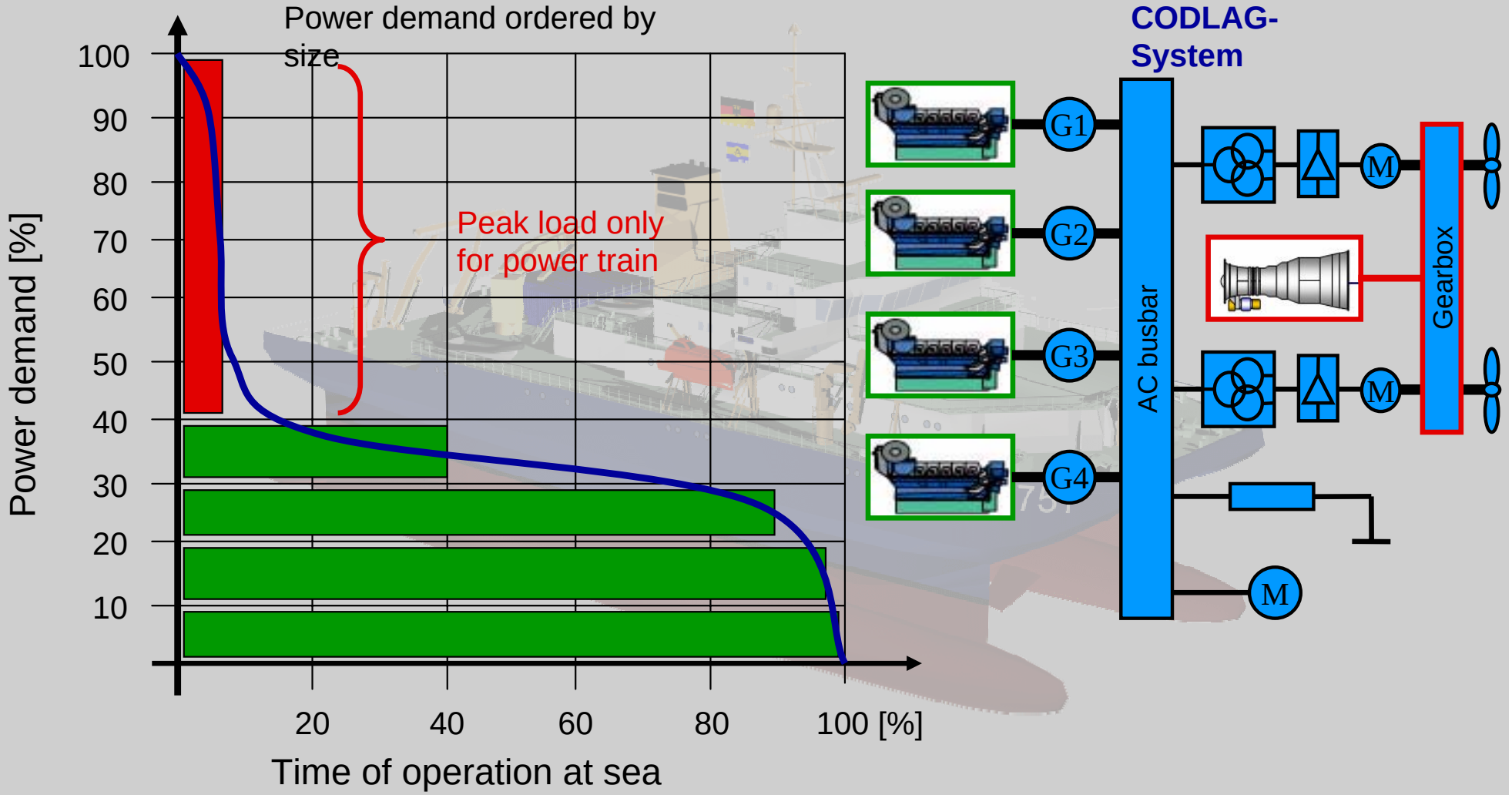


Common diesel electric propulsion system

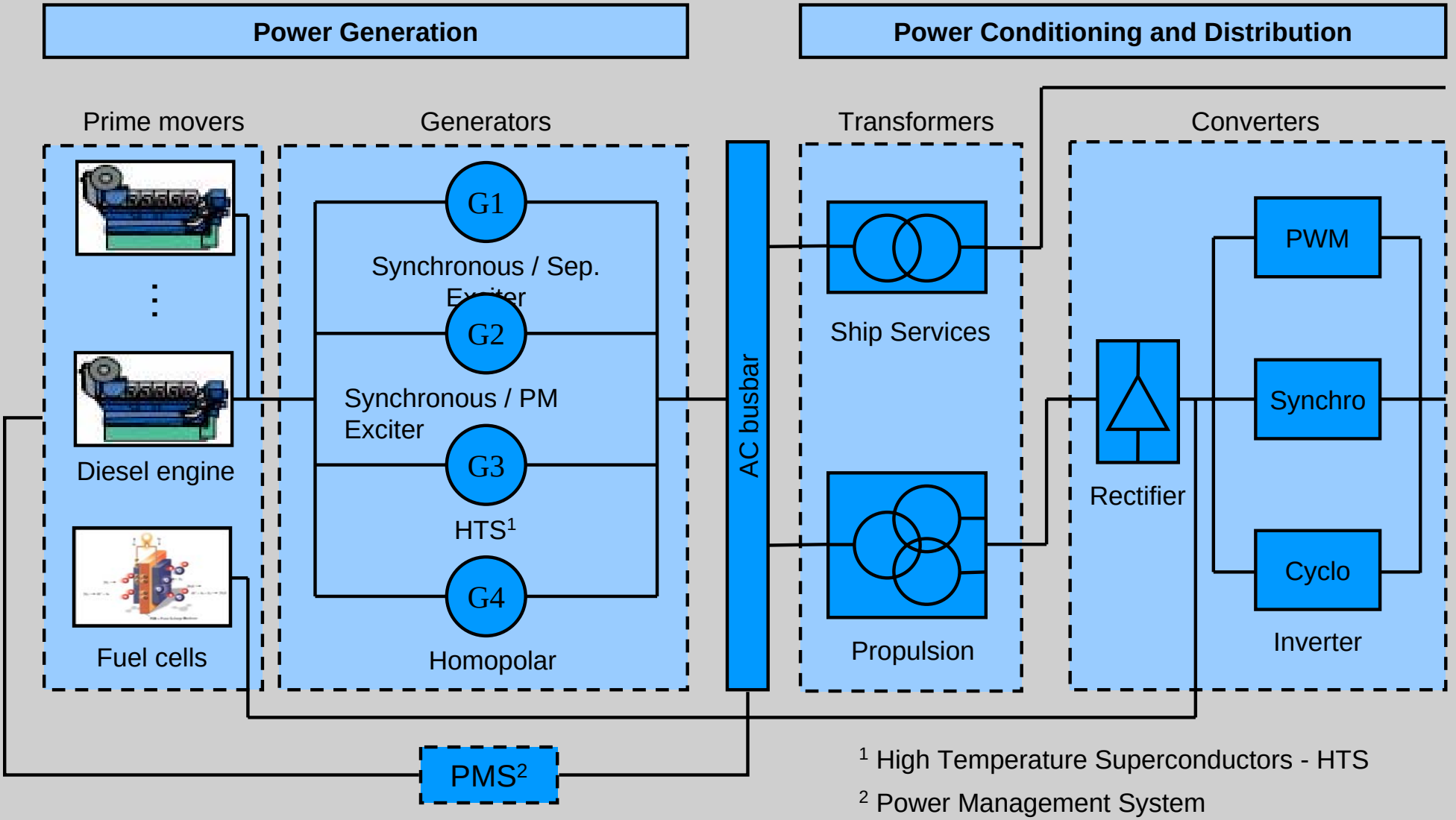


Diesel mechanical configuration has economical advantages for this load profile

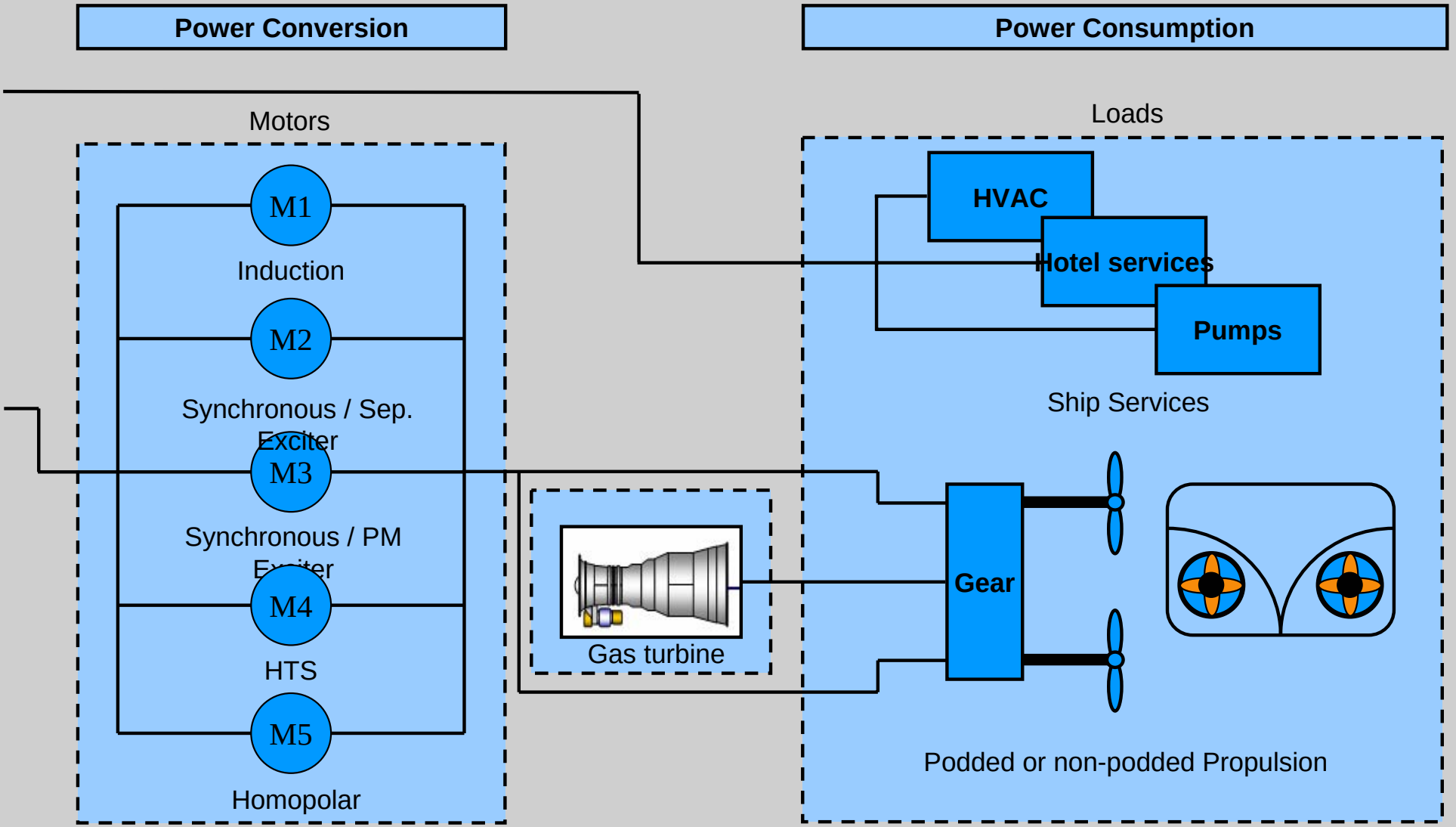
Power demand characteristics of diesel electric propulsion systems



Potential options for the power train of an diesel electric ship



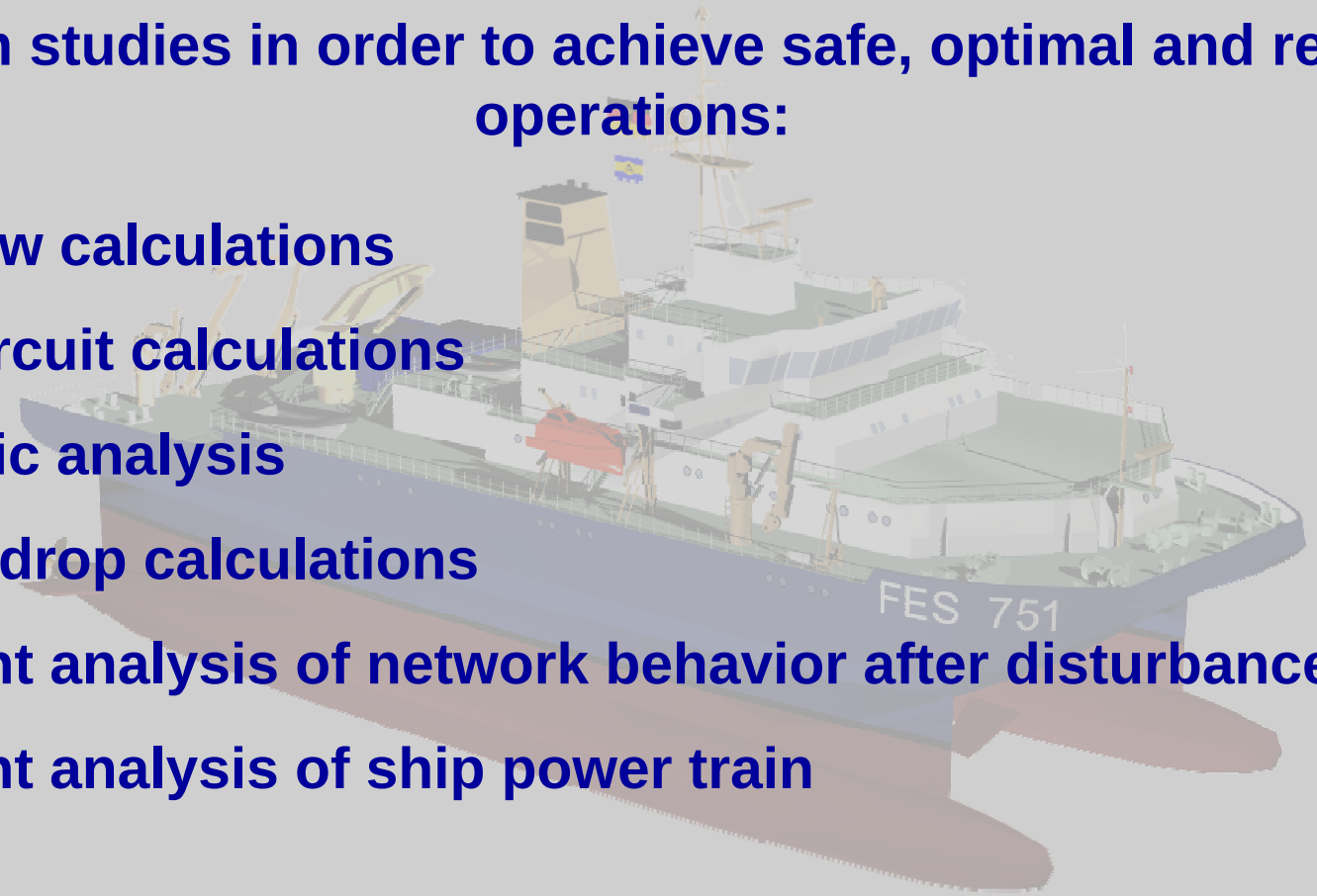
Potential options for the power train of an diesel electric ship



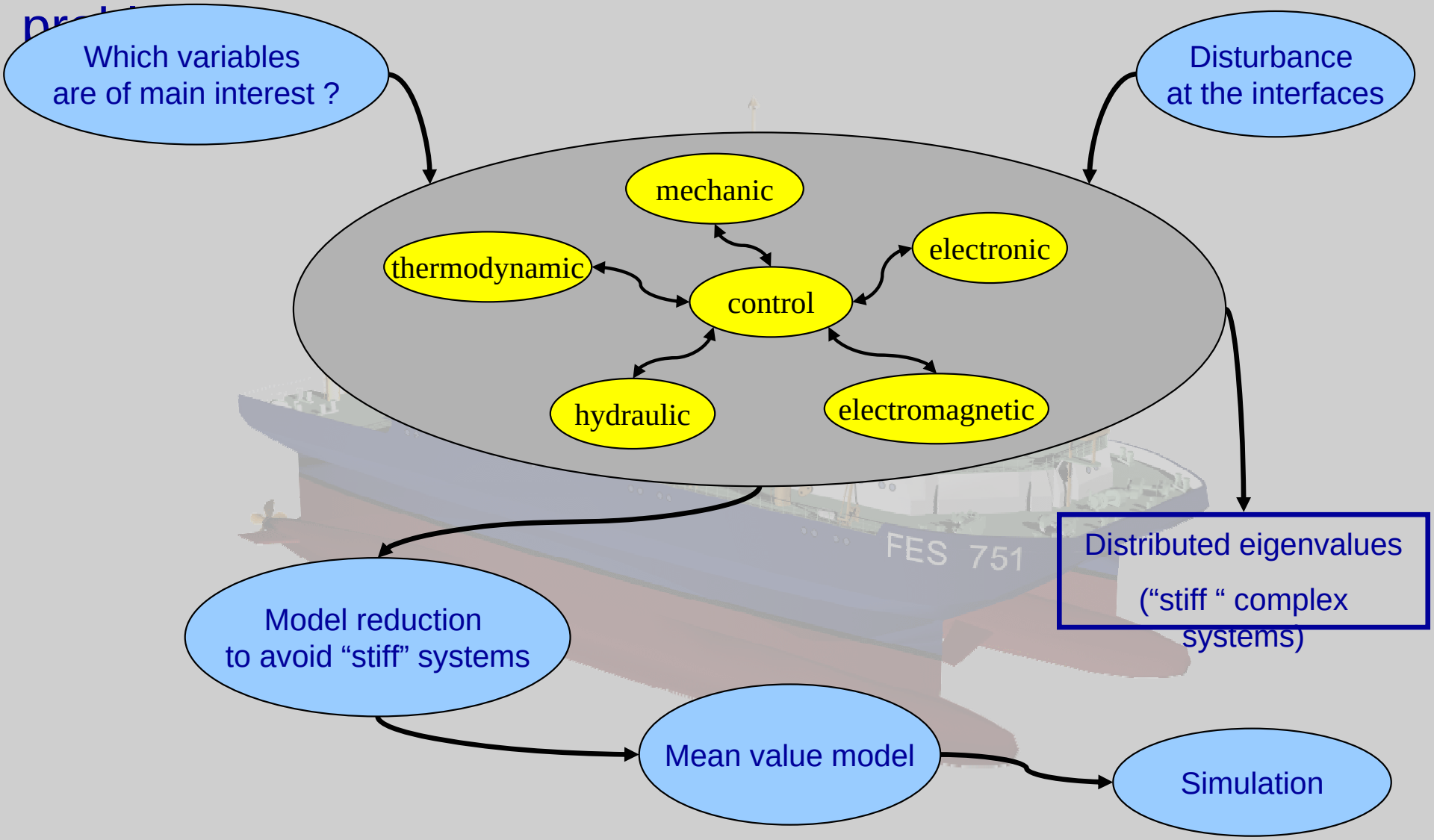
Application of simulation technology - use of model based design

System studies in order to achieve safe, optimal and reliable operations:

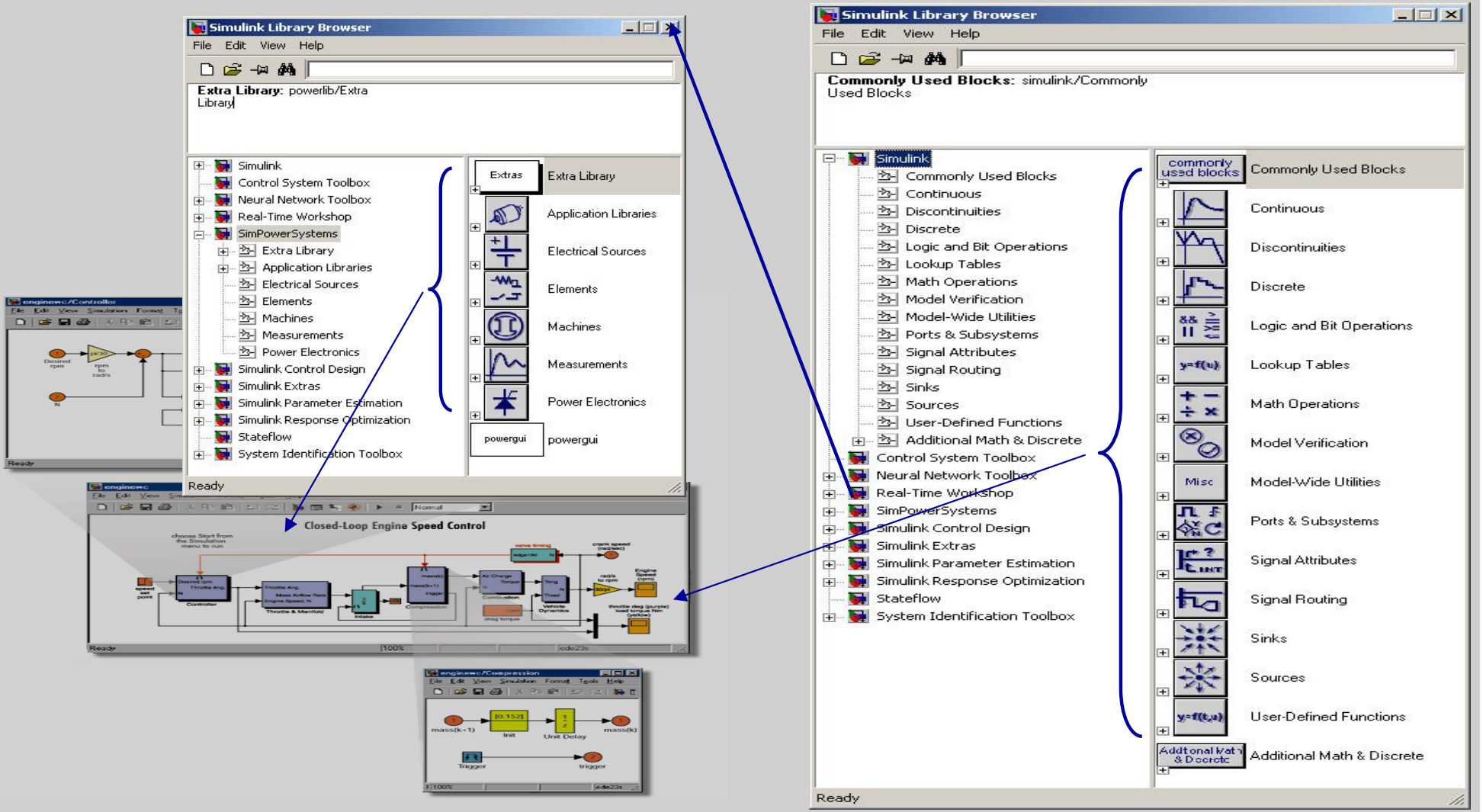
- **Load flow calculations**
- **Short circuit calculations**
- **Harmonic analysis**
- **Voltage drop calculations**
- **Transient analysis of network behavior after disturbance**
- **Transient analysis of ship power train**



Application of simulation technology – engineering



Application of simulation technology - Model based design approach with MATLAB / Simulink®

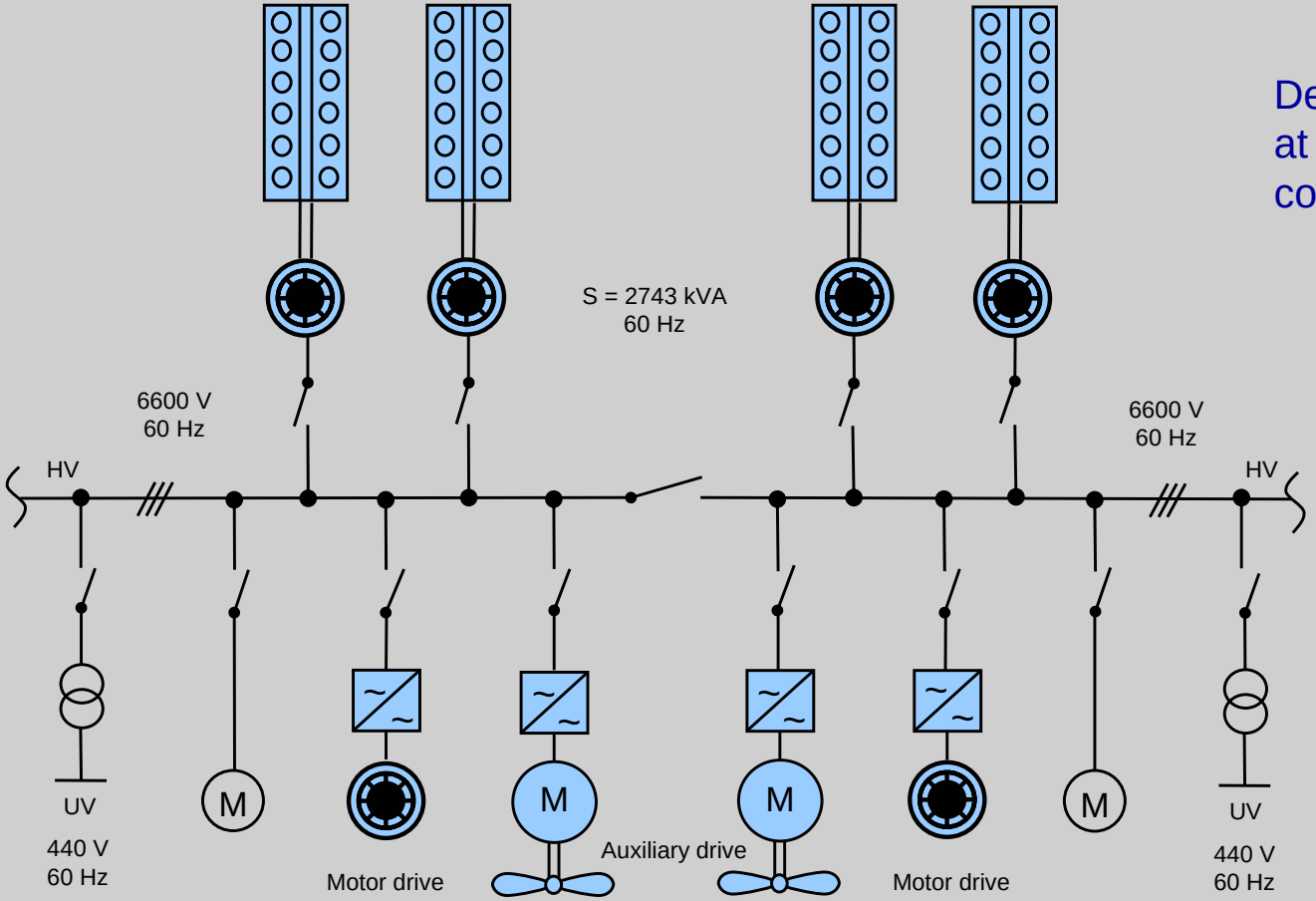


A company of ThyssenKrupp Technologies

ThyssenKrupp Marine Systems
Surface Vessel Division

ThyssenKrupp

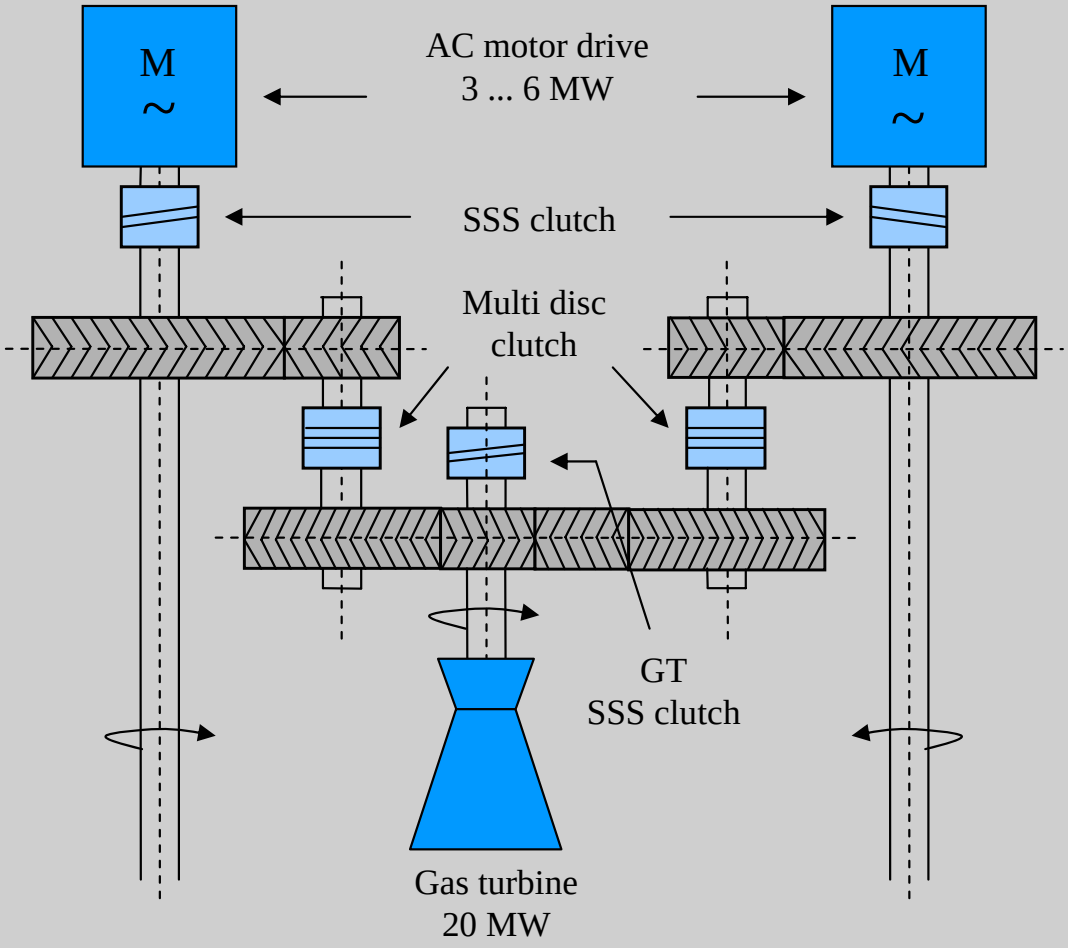
Application of simulation technology – selected examples



Developed component models at different levels of complexity:

- Diesel engine
- Generator
- AVR (exciter)
- Busbar
- Speed and torque control
- Motor drives
- Power Management
- Active / reactive load model

Application of simulation technology – selected examples



Developed component models at different levels of complexity:

- Two shaft gas turbine
- Gears
- Clutches
- Propeller shaft
- Propeller with pitch hydraulic
- Ship resistance
- Control
- Switch logic

Some mathematical equations in state space description

synchronous machine

$$\begin{pmatrix}\dot\psi_d\\ \dot\psi_q\\ \dot\psi_D\\ \dot\psi_Q\\ \dot\psi_e\end{pmatrix}=\begin{pmatrix}\omega_n r_s & 0 & 0 & 0 & 0\\ 0 & \omega_n r_s & 0 & 0 & 0\\ 0 & 0 & -1/T_D & 0 & 0\\ 0 & 0 & 0 & -1/T_Q & 0\\ 0 & 0 & 0 & 0 & -1/T_e\end{pmatrix}\begin{pmatrix}-\kappa_d & 0 & 1 & 0 & 1\\ 0 & \kappa_q & 0 & 1 & 0\\ -(1-\sigma_D)\kappa_d & 0 & 1 & 0 & \mu_D\\ 0 & -(1-\sigma_Q)\kappa_q & 0 & 1 & 0\\ -(1-\sigma_e)\kappa_d & 0 & \mu_e & 0 & 1\end{pmatrix}^{-1}\begin{pmatrix}\psi_d\\ \psi_q\\ \psi_D\\ \psi_Q\\ \psi_e\end{pmatrix}+\begin{pmatrix}\omega_n\dot\rho\psi_q\\ -\omega_n\dot\rho\psi_d\\ 0\\ 0\\ 0\end{pmatrix}+\begin{pmatrix}\omega_n & 0 & 0 & 0\\ 0 & \omega_n & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 1/T_e & 0\end{pmatrix}\begin{pmatrix}u_d\\ u_q\\ u_e\\ \dot\rho\end{pmatrix}$$

busbar

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix}_{ref}=\begin{bmatrix}r_{ges} & -x_{ges}\\ x_{ges} & r_{ges}\end{bmatrix}\cdot\begin{bmatrix}i_d\\ i_q\end{bmatrix}_{ges}$$

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix}_1=\begin{bmatrix}\cos\Delta\delta_1 & -\sin\Delta\delta_1\\ \sin\Delta\delta_1 & \cos\Delta\delta_1\end{bmatrix}^T\cdot\begin{bmatrix}r_{ges} & -x_{ges}\\ x_{ges} & r_{ges}\end{bmatrix}\cdot\begin{bmatrix}i_d\\ i_q\end{bmatrix}_{ges}$$

$$\vdots$$

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix}_n=\begin{bmatrix}\cos\Delta\delta_n & -\sin\Delta\delta_n\\ \sin\Delta\delta_n & \cos\Delta\delta_n\end{bmatrix}^T\cdot\begin{bmatrix}r_{ges} & -x_{ges}\\ x_{ges} & r_{ges}\end{bmatrix}\cdot\begin{bmatrix}i_d\\ i_q\end{bmatrix}_{ges}$$

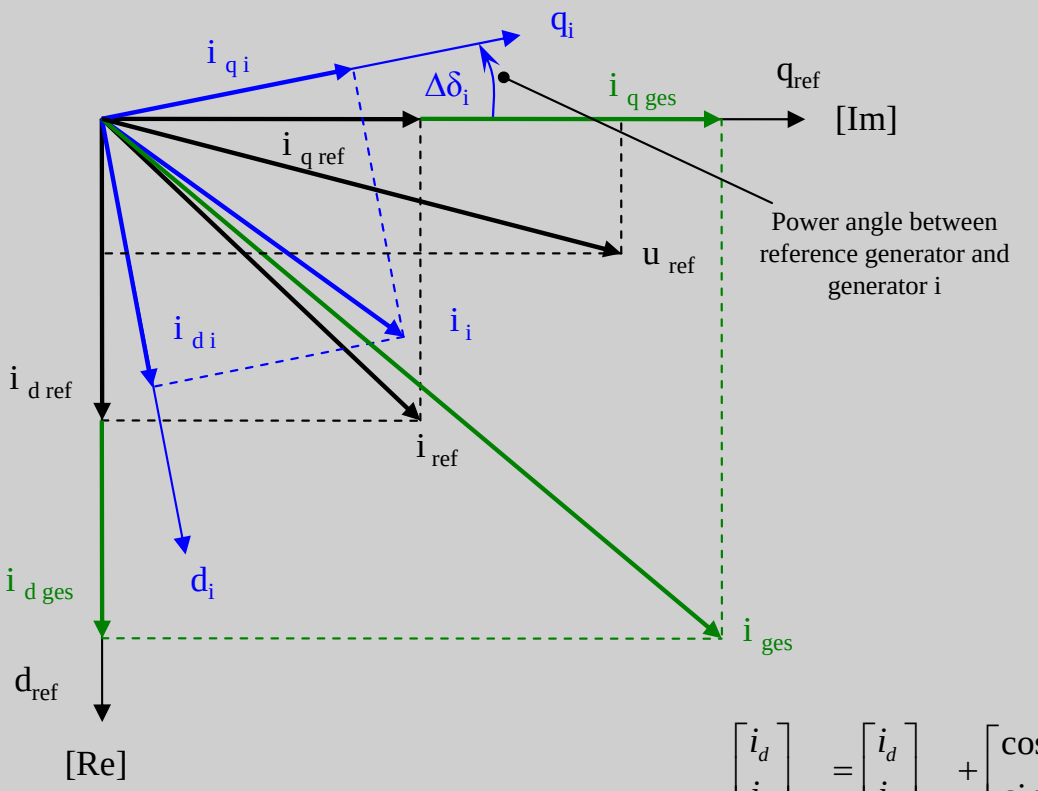
asynchronous machine

$$\begin{bmatrix}\dot\psi_{qs}\\ \dot\psi_{ds}\\ \dot\psi_{qr}\\ \dot\psi_{dr}\end{bmatrix}=\begin{bmatrix}-R_s & 0 & 0 & 0\\ 0 & -R_s & 0 & 0\\ 0 & 0 & -R_r & 0\\ 0 & 0 & 0 & -R_r\end{bmatrix}\cdot\begin{bmatrix}L_s & 0 & L_m & 0\\ 0 & L_s & 0 & L_m\\ L_m & 0 & L_r & 0\\ 0 & L_m & 0 & L_r\end{bmatrix}^{-1}\cdot\begin{bmatrix}\psi_{qs}\\ \psi_{ds}\\ \psi_{qr}\\ \psi_{dr}\end{bmatrix}$$
$$+\begin{bmatrix}0 & -\omega & 0 & 0\\ \omega & 0 & 0 & 0\\ 0 & 0 & 0 & -(\omega-\omega_r)\\ 0 & 0 & (\omega-\omega_r) & 0\end{bmatrix}\cdot\begin{bmatrix}\psi_{qs}\\ \psi_{ds}\\ \psi_{qr}\\ \psi_{dr}\end{bmatrix}+\begin{bmatrix}u_{qs}\\ u_{ds}\\ 0\\ 0\end{bmatrix},$$

permanent magnet synchronous machine

$$\begin{bmatrix}\dot i_d\\ \dot i_q\end{bmatrix}=\begin{bmatrix}-\frac{R}{L_d} & 0\\ 0 & -\frac{R}{L_q}\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\end{bmatrix}\begin{bmatrix}u_d\\ u_q\end{bmatrix}+\begin{bmatrix}\frac{L_q}{L_d}\cdot p\cdot\omega_r\cdot i_q\\ -\left(\frac{L_d}{L_q}\cdot p\cdot\omega_r\cdot i_d+\frac{\psi_{Pm}\cdot p\cdot\omega_r}{L_q}\right)\end{bmatrix}$$

Phasor diagram for a multi-machine system



busbar voltage

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix}_{ref} = \begin{bmatrix} r_{ges} & -x_{ges} \\ x_{ges} & r_{ges} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_{ges}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix}_1 = \begin{bmatrix} \cos\Delta\delta_1 & -\sin\Delta\delta_1 \\ \sin\Delta\delta_1 & \cos\Delta\delta_1 \end{bmatrix}^T \cdot \begin{bmatrix} r_{ges} & -x_{ges} \\ x_{ges} & r_{ges} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_{ges}$$

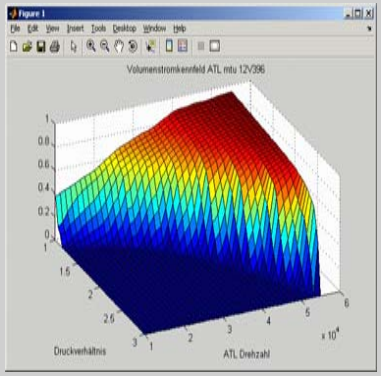
$$\vdots$$

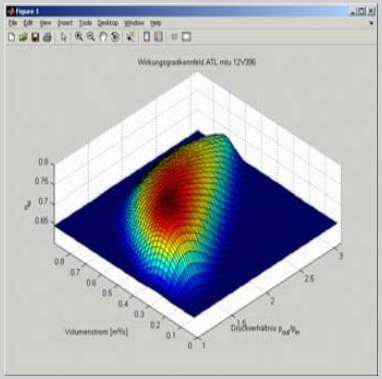
$$\begin{bmatrix} u_d \\ u_q \end{bmatrix}_n = \begin{bmatrix} \cos\Delta\delta_n & -\sin\Delta\delta_n \\ \sin\Delta\delta_n & \cos\Delta\delta_n \end{bmatrix}^T \cdot \begin{bmatrix} r_{ges} & -x_{ges} \\ x_{ges} & r_{ges} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_{ges}$$

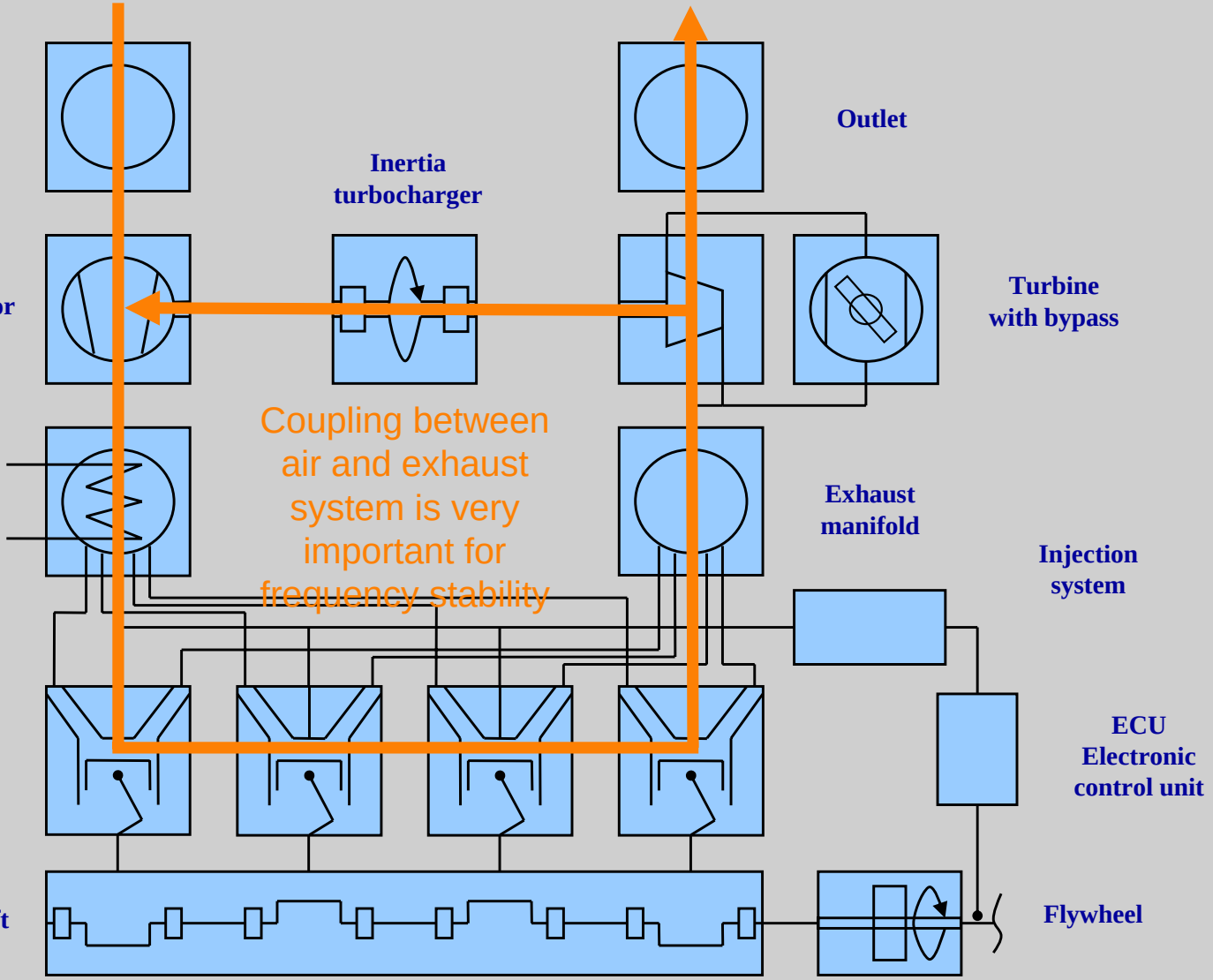
busbar current

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix}_{ges} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}_{ref} + \begin{bmatrix} \cos\Delta\delta_1 & -\sin\Delta\delta_1 \\ \sin\Delta\delta_1 & \cos\Delta\delta_1 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_1 + \begin{bmatrix} \cos\Delta\delta_2 & -\sin\Delta\delta_2 \\ \sin\Delta\delta_2 & \cos\Delta\delta_2 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_2 + \cdots + \begin{bmatrix} \cos\Delta\delta_n & -\sin\Delta\delta_n \\ \sin\Delta\delta_n & \cos\Delta\delta_n \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}_n$$

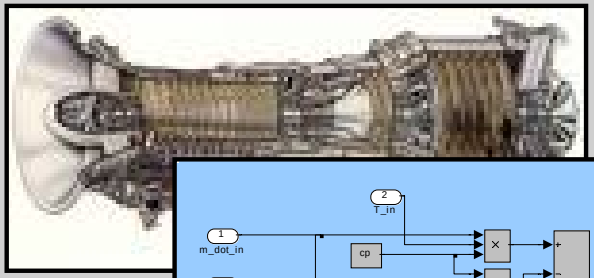
Diesel engine model for transient system behavior







Twin shaft gas turbine model



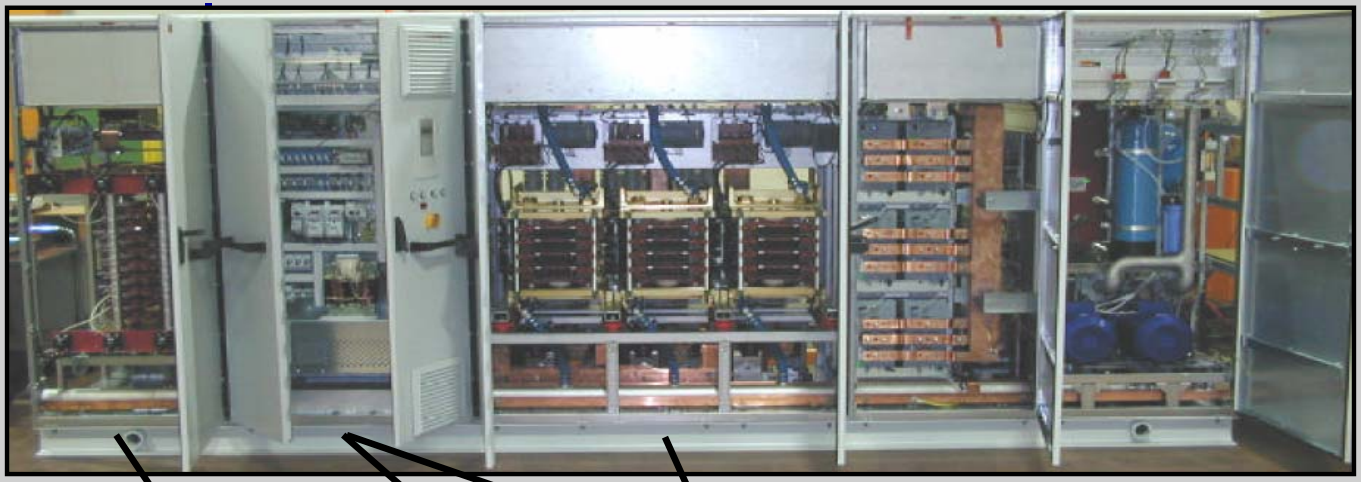
Third-level

Second-level

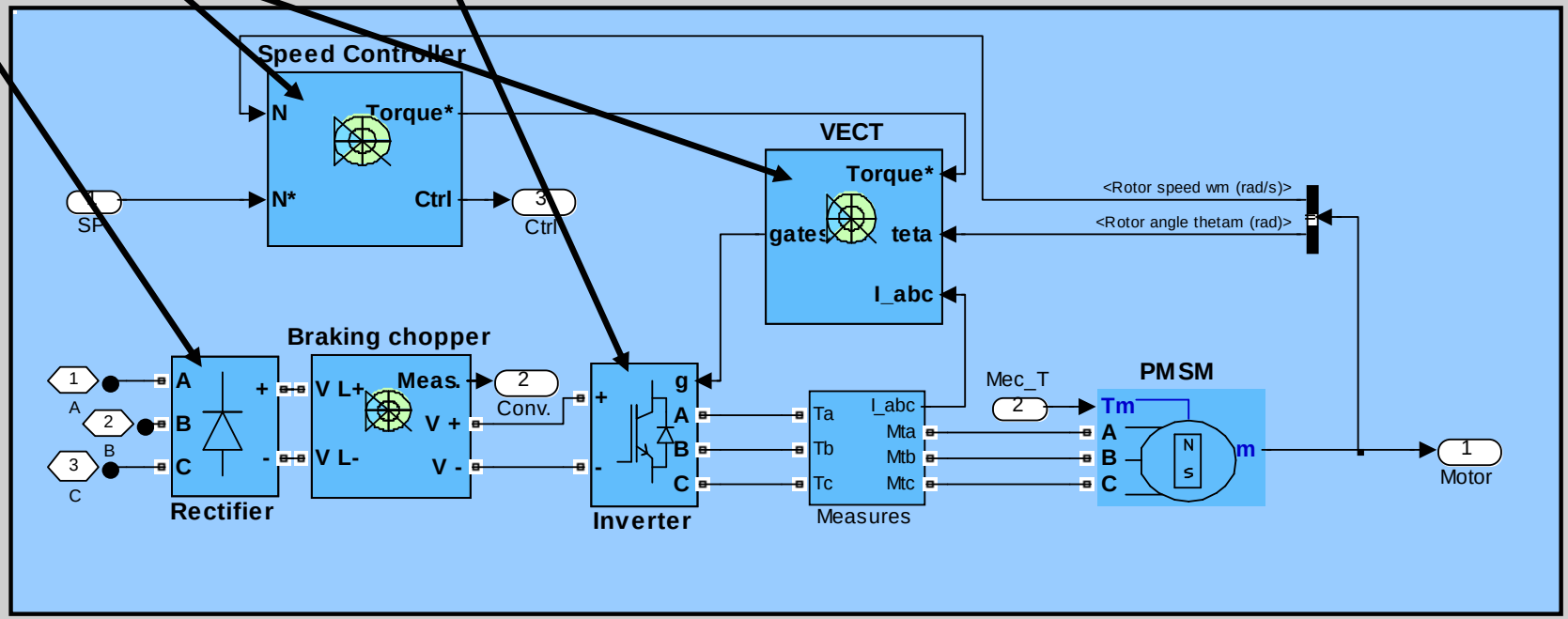
Top-level of simulation model

Input
Mechanical load
Output
Inertia HP-Turb
Inertia LP-Turb
HP Turbine
LP Turbine
Compressor
Combustion chamber
Receiver
Fuel-system
gas turbine control
Speed reference
-K-
Gain3
m_dot / theta
[m_dot_nd_turb]
n_turb/M_turb
p / theta
T_Abg
T_W
p_Abg

Permanent-magnet synchronous motor drive with



A medium voltage control unit for motor drives

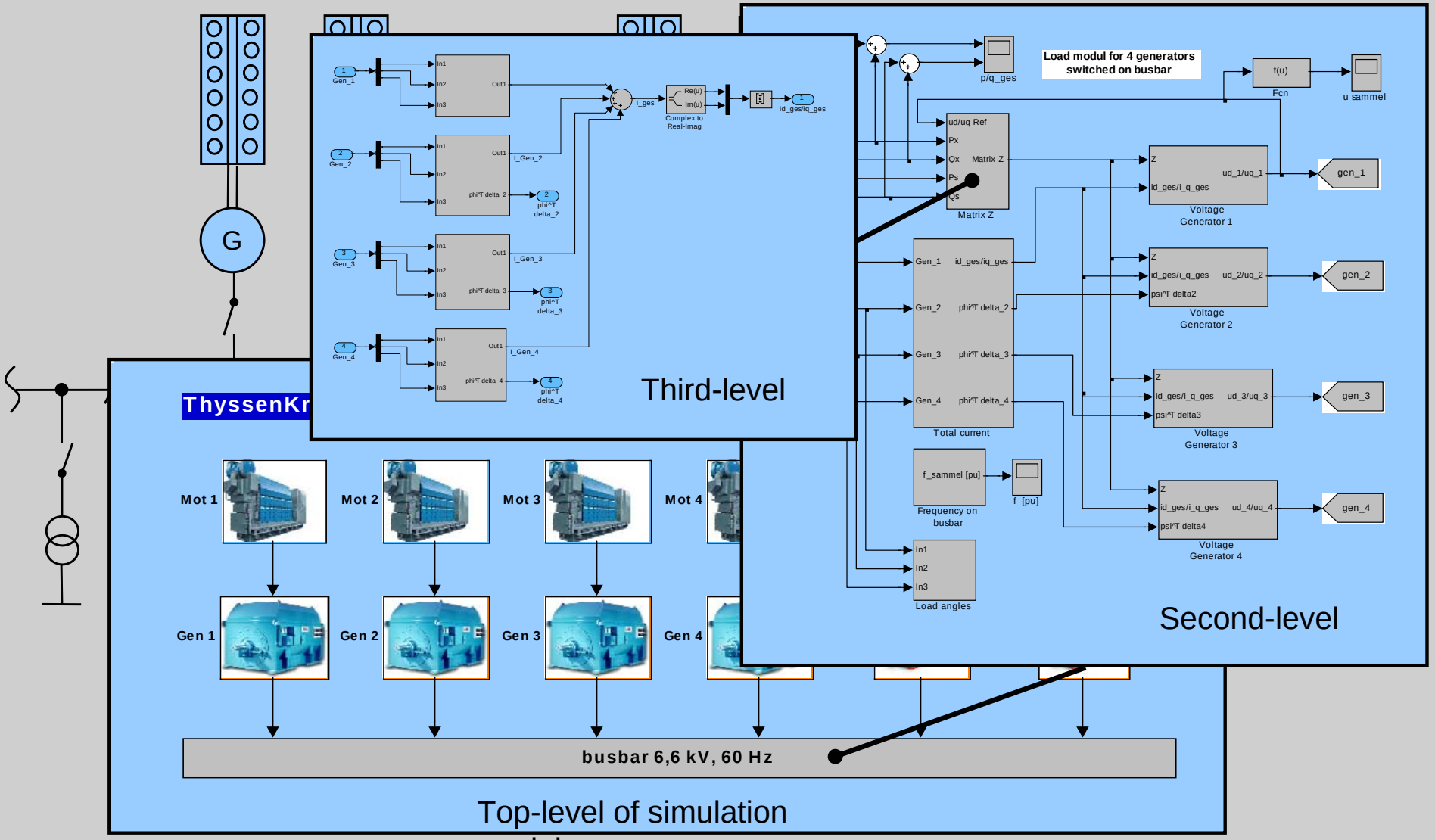


A company of ThyssenKrupp Technologies

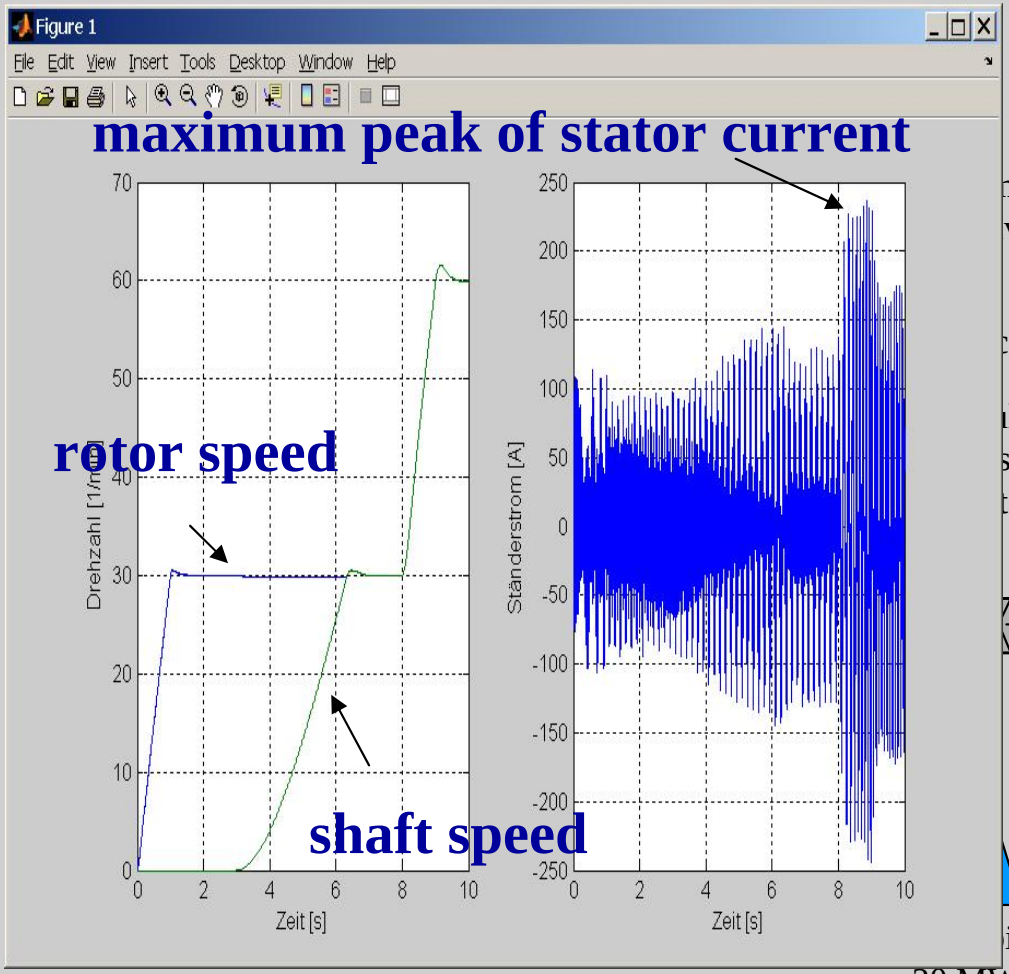
ThyssenKrupp Marine Systems
Surface Vessel Division

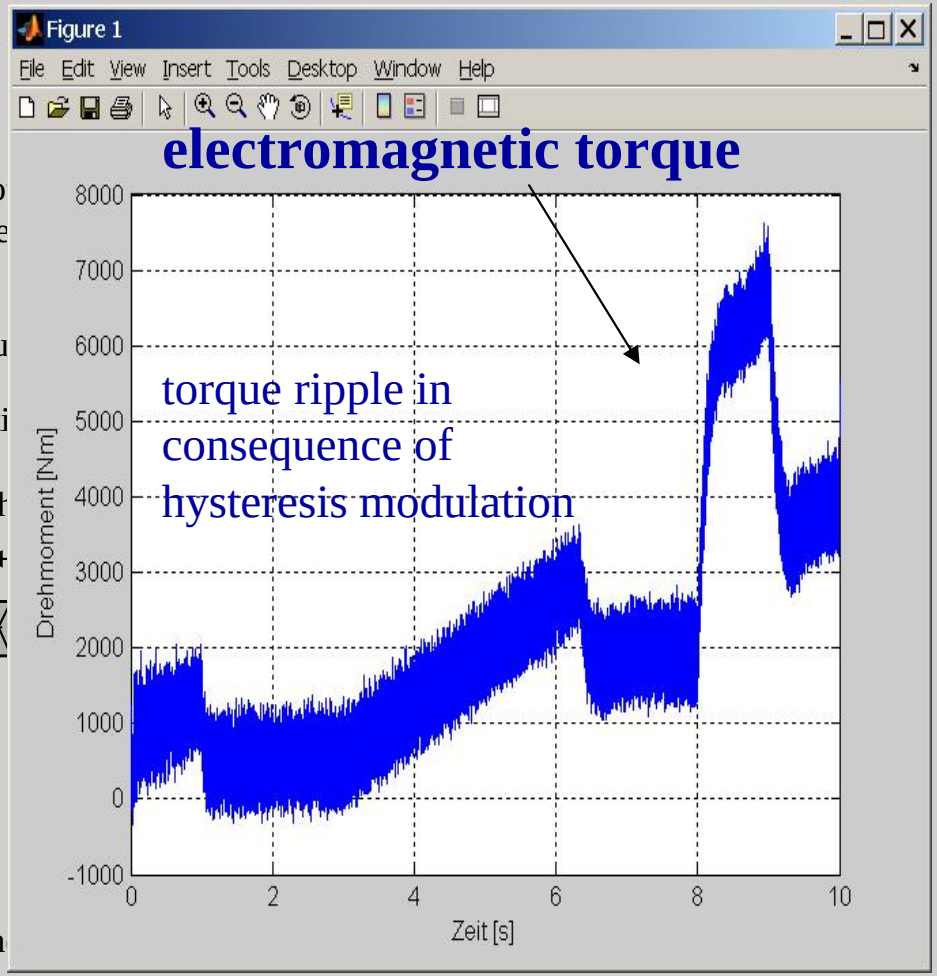
ThyssenKrupp

Busbar with diesel engines, generators and electrical loads



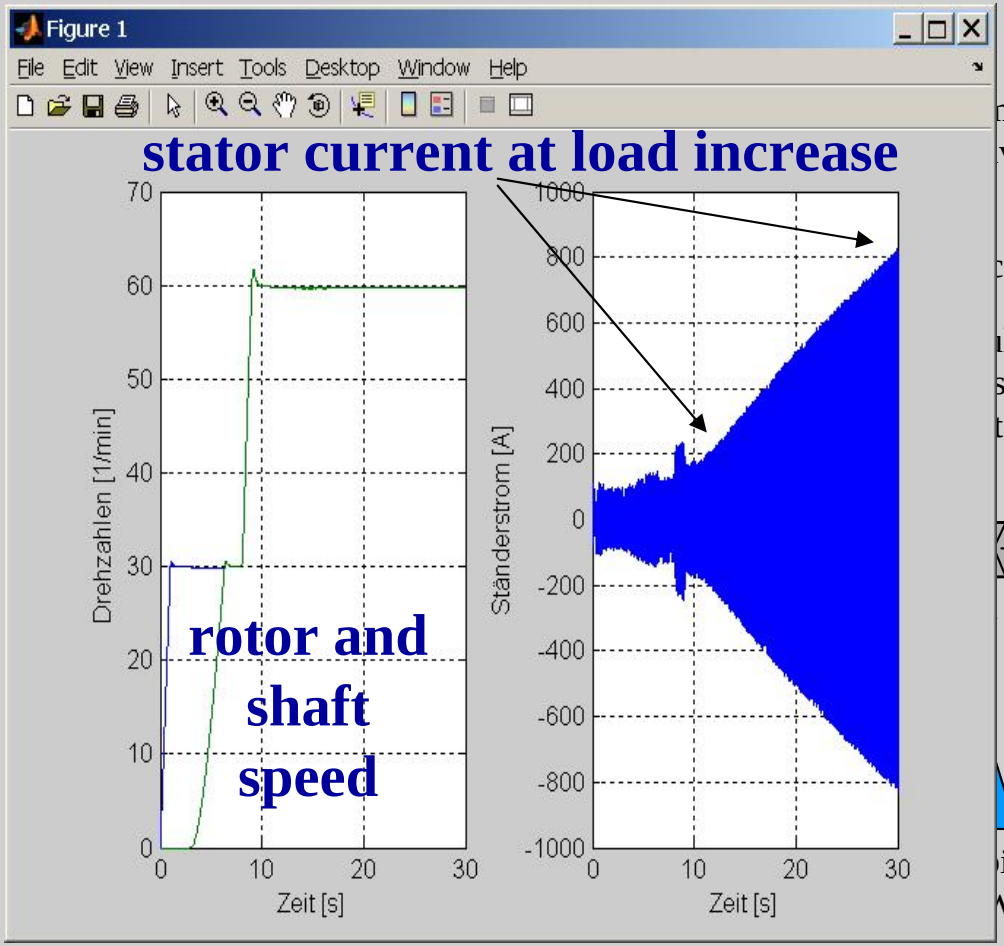
Clutch maneuver simulation of electric motor drive

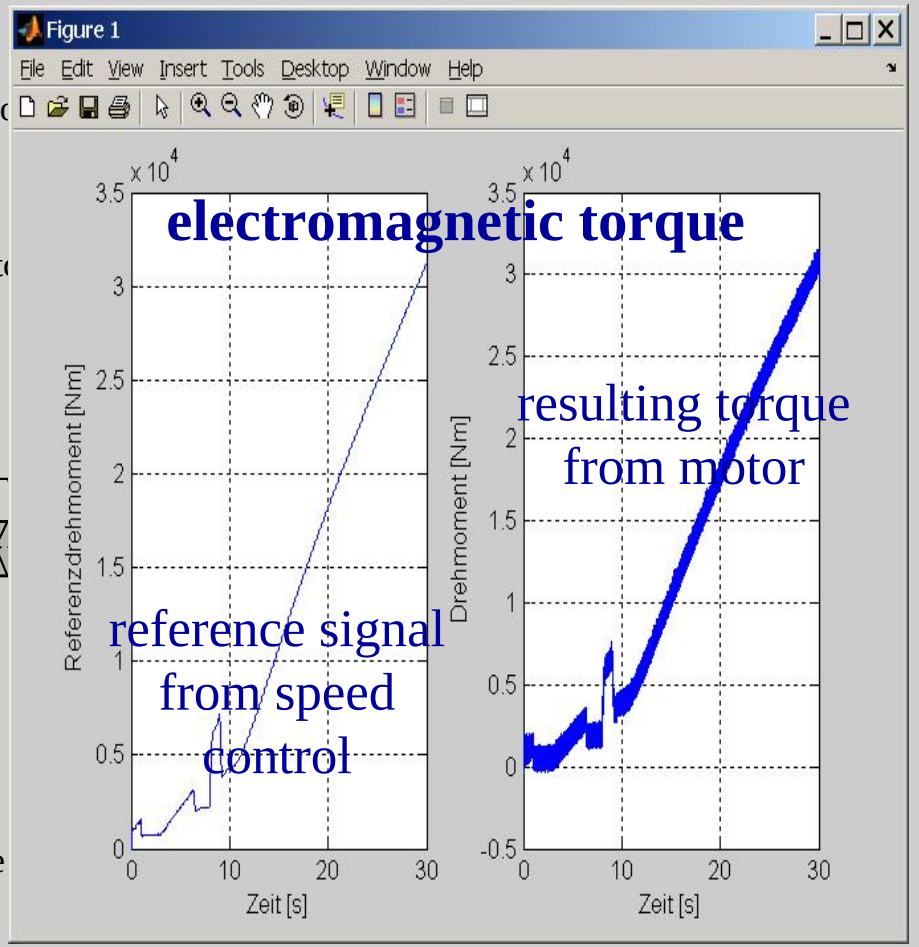




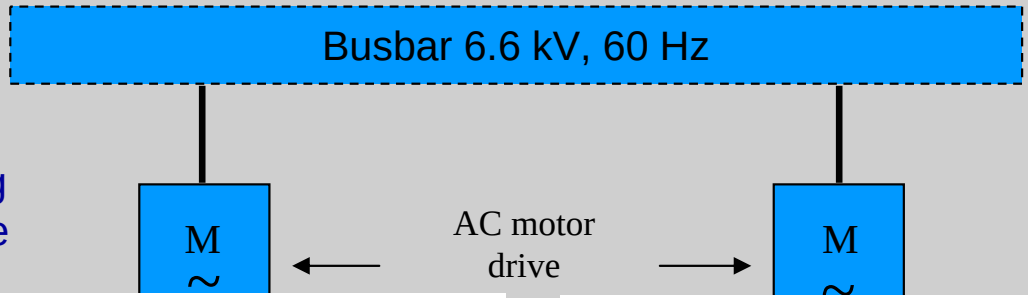
20 MW

Clutch maneuver simulation with propeller pitch adjustment

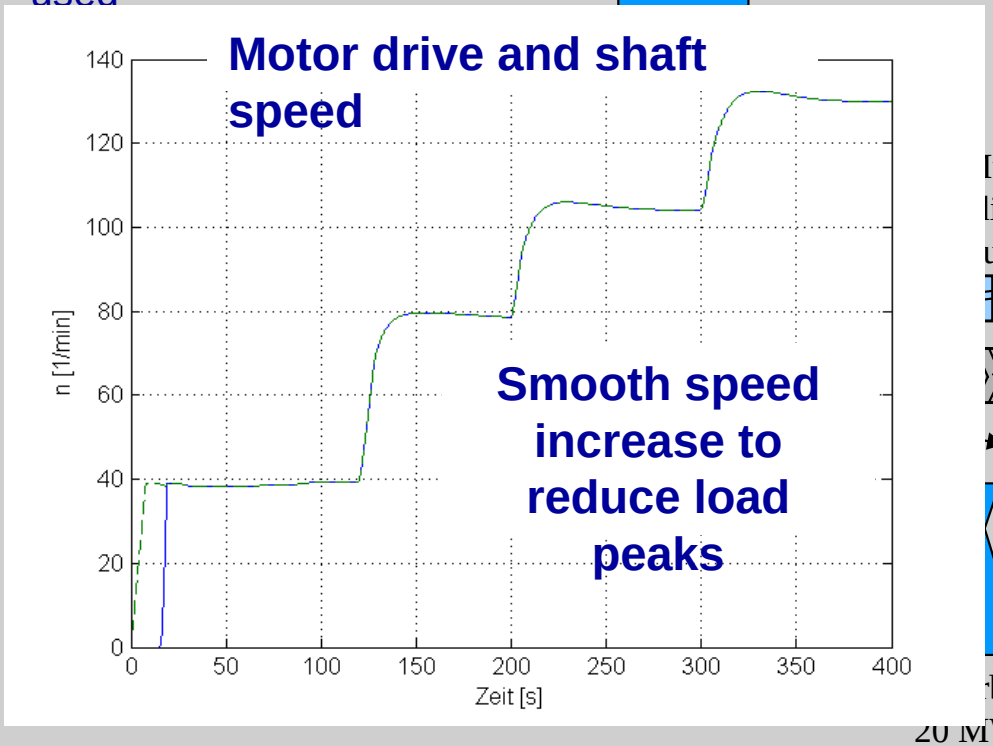


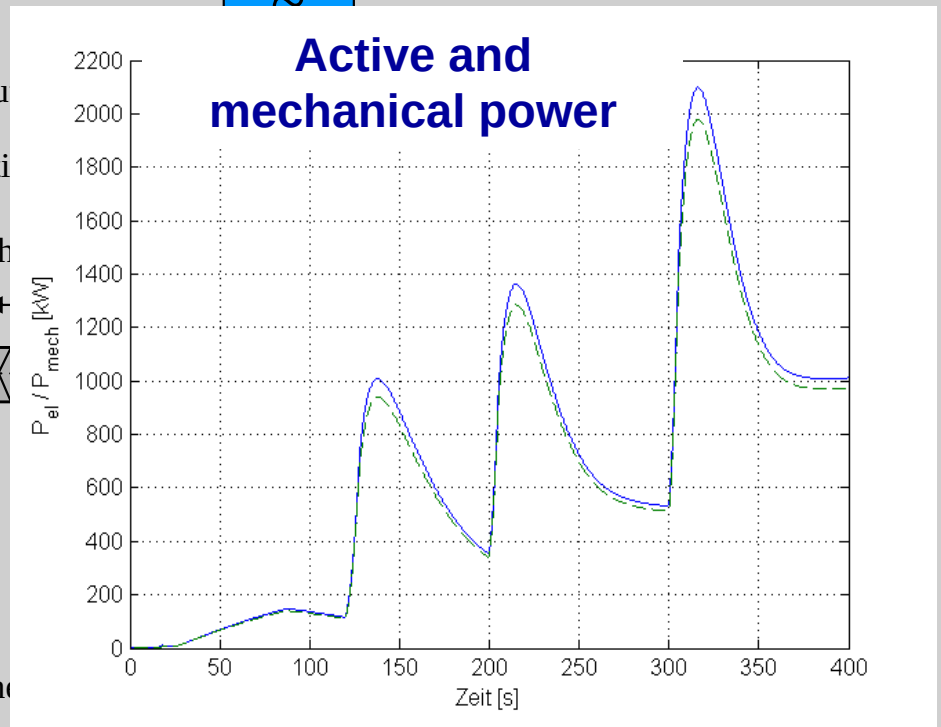


Electric motor drive acceleration and busbar load



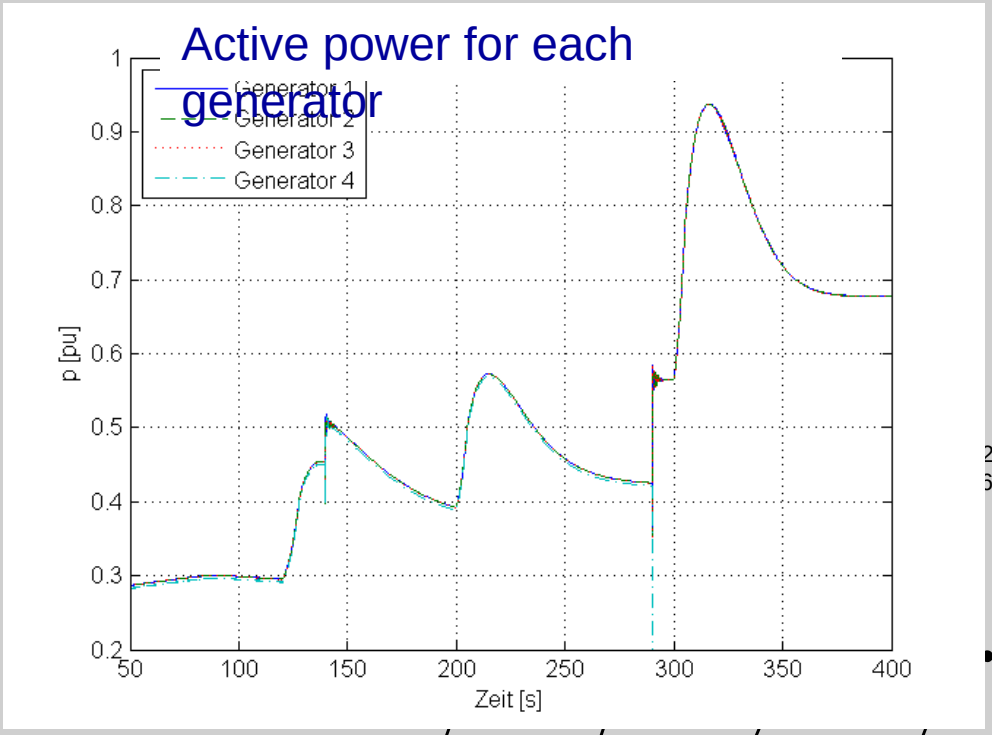
Reduced models for long time system behavior are used

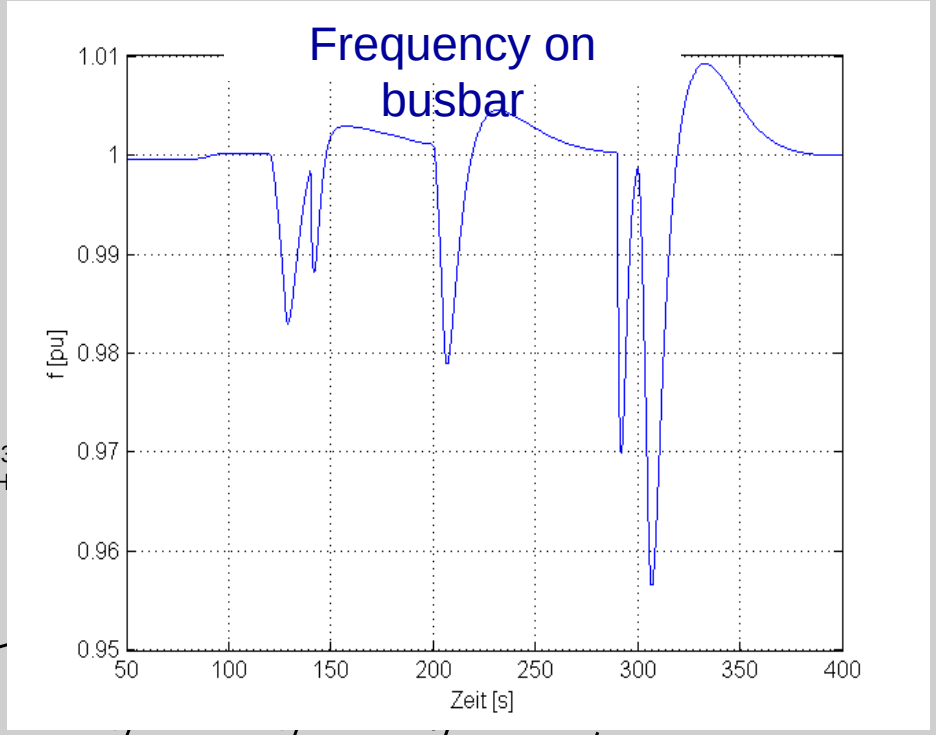


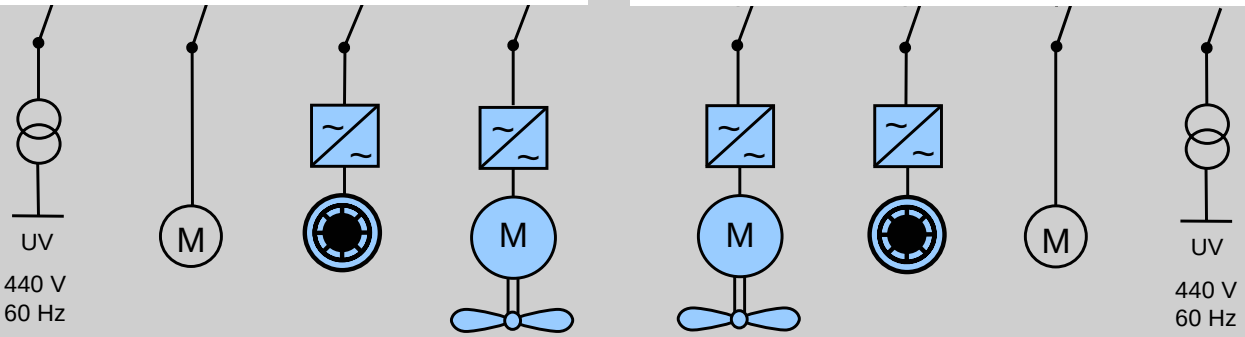


clu
lulti
lisc
utch
rbin
20 MW

Malfunction of one generator





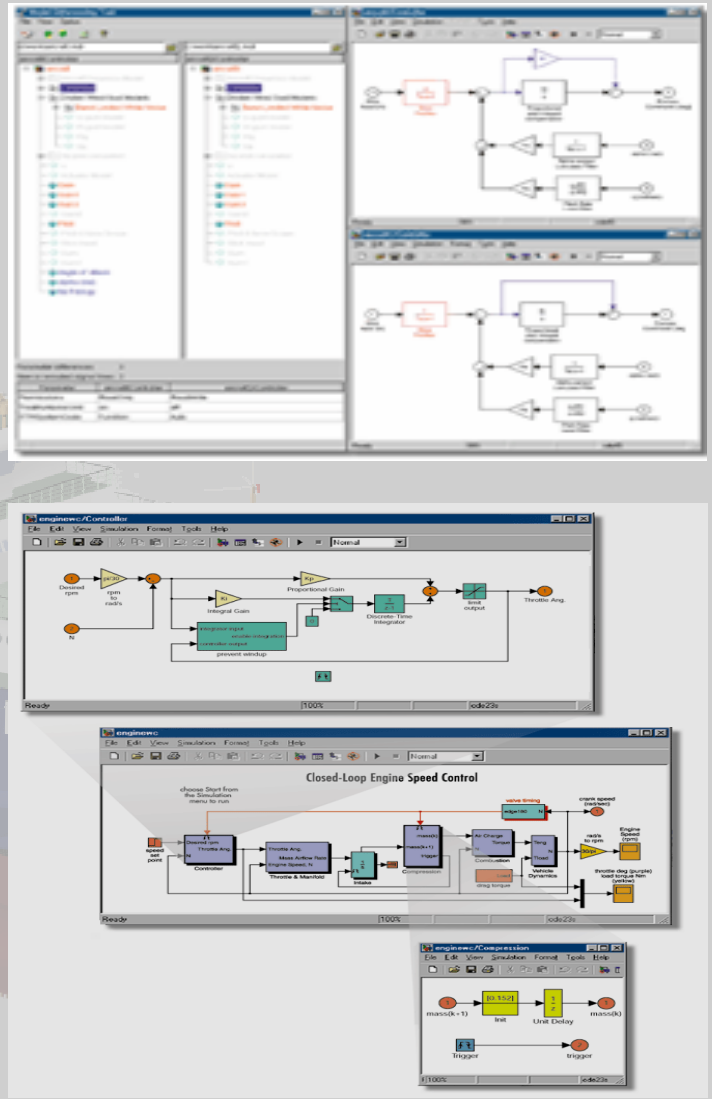


Suddenly disconnection under load of generator 4 at t = 280 s

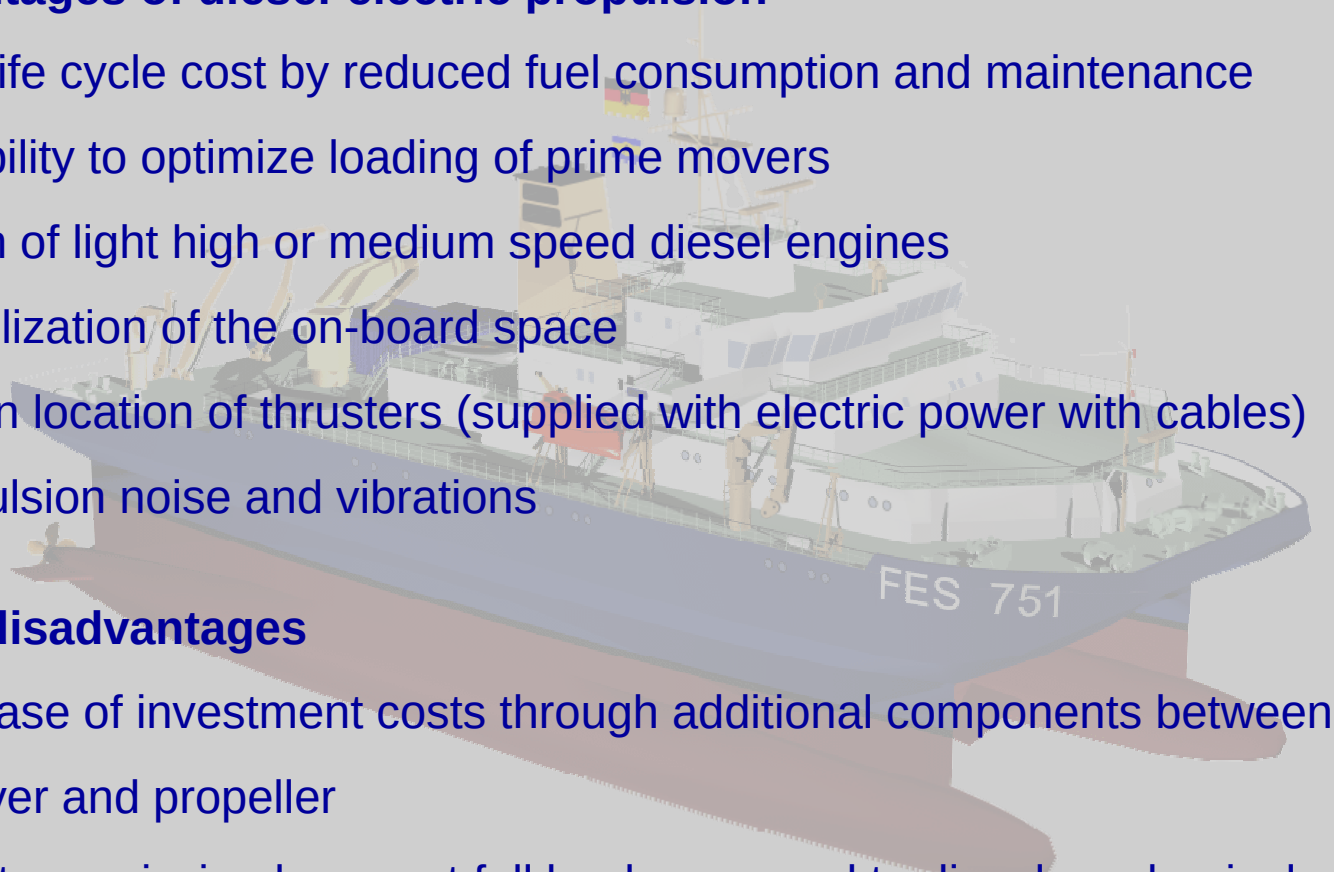
Why is simulation so important ?

Some applications:

- To understand and predict system dynamics
- Concept tradeoffs for marine propulsion systems
- Validate machinery selection
- Control algorithm synthesis and analysis
- Problem isolation and correction
- Sea trial support



Diesel-electric propulsion concepts vs. diesel mechanical configuration - a short summary



Main advantages of diesel-electric propulsion

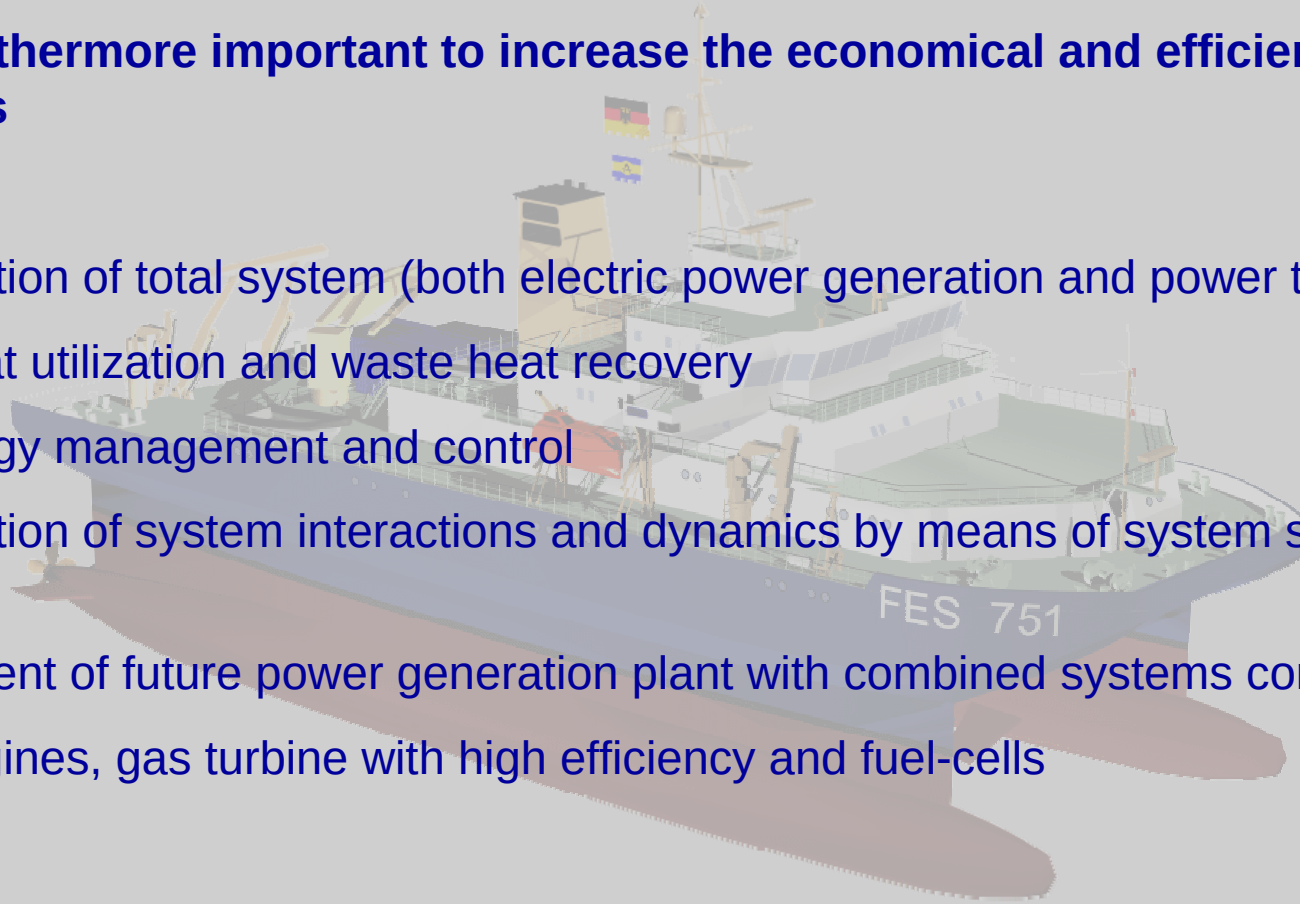
- Improved life cycle cost by reduced fuel consumption and maintenance
- The possibility to optimize loading of prime movers
- Application of light high or medium speed diesel engines
- Flexible utilization of the on-board space
- Flexibility in location of thrusters (supplied with electric power with cables)
- Less propulsion noise and vibrations

and some disadvantages

- Light increase of investment costs through additional components between prime mover and propeller
- Increased transmission losses at full load compared to diesel mechanical propulsion

Diesel-electric propulsion concepts vs. diesel mechanical configuration - a short summary

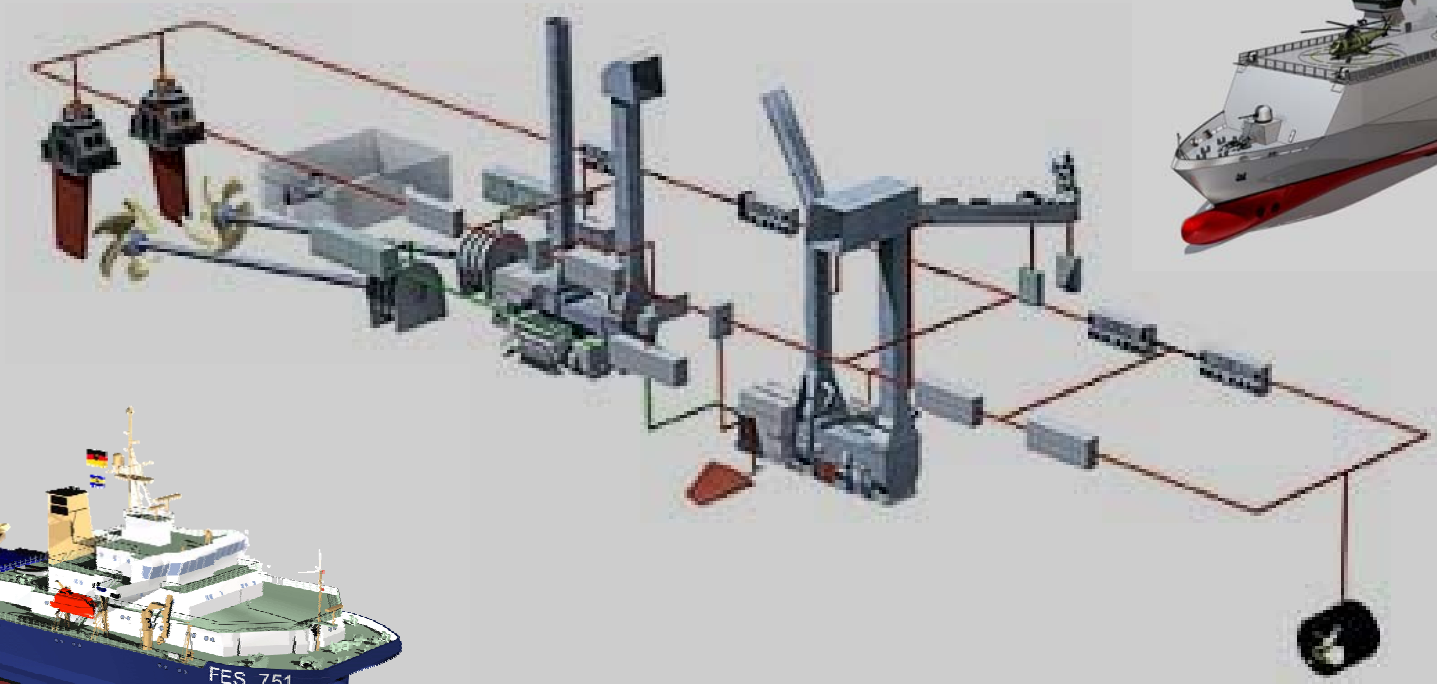
What is furthermore important to increase the economical and efficiency advantages



- Consideration of total system (both electric power generation and power train)
- Waste heat utilization and waste heat recovery
- Total energy management and control
- Consideration of system interactions and dynamics by means of system simulation tools
- Development of future power generation plant with combined systems consisting of diesel engines, gas turbine with high efficiency and fuel-cells

Diesel-electric propulsion concepts

How to match environment and economical challenges ?



Many thanks for your attention

A company of ThyssenKrupp Technologies

ThyssenKrupp Marine Systems
Surface Vessel Division

ThyssenKrupp