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Optimization of the Emissions Profile of a Marine Propulsion System using a Shaft Generator with a MMPT Based Control System and the use of EEDI and EEOI

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ESCUELA NAVAL ALMIRANTE PADILLA

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Outline

1. Introduction
2. Background
3. PTO/PTI Control Scheme
4. Simulation Results
5. Conclusions

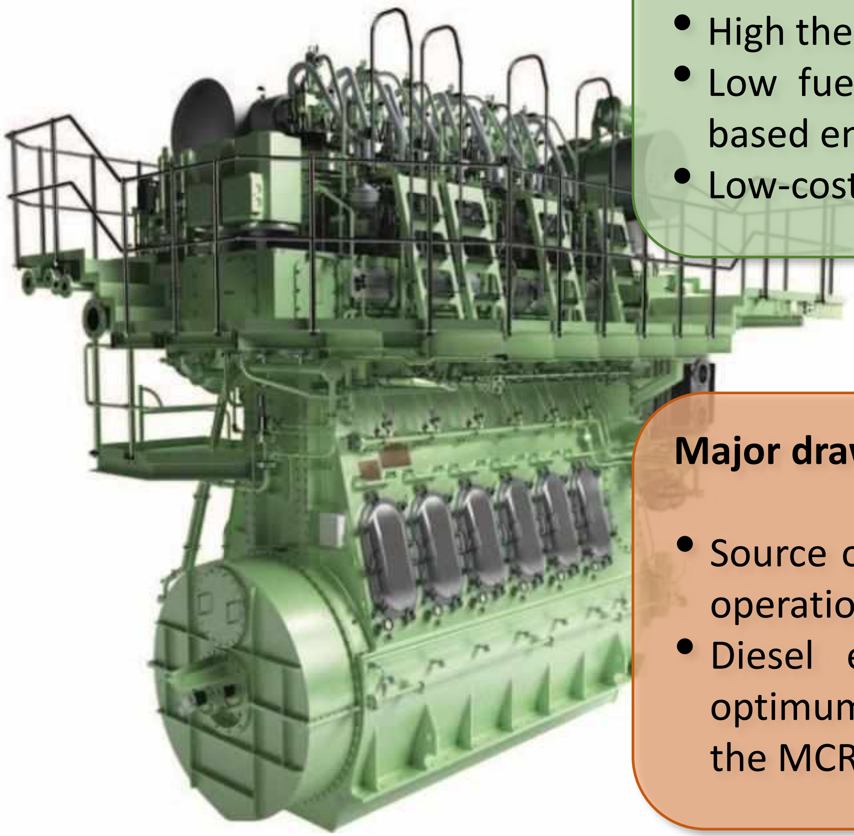
Introduction

- Marine propulsion systems have been in constant development since the 18th century, when the first thermal based engines were introduced.

- Nowadays the most common system used on board large carriers i.e. container ships and tankers, is a system considering a diesel engine as the prime mover.

- Most of these engines operate on the two-stroke cycle at low speed turbocharged and directly coupled to a single fixed-pitch propeller.

- Power installed vary from 10 MW and up to 80 MW.



Advantages of Diesel engines for marine applications:

- High thermal efficiency.
- Low fuel oil consumption, compared to other thermal based engines.
- Low-cost residual fuels.

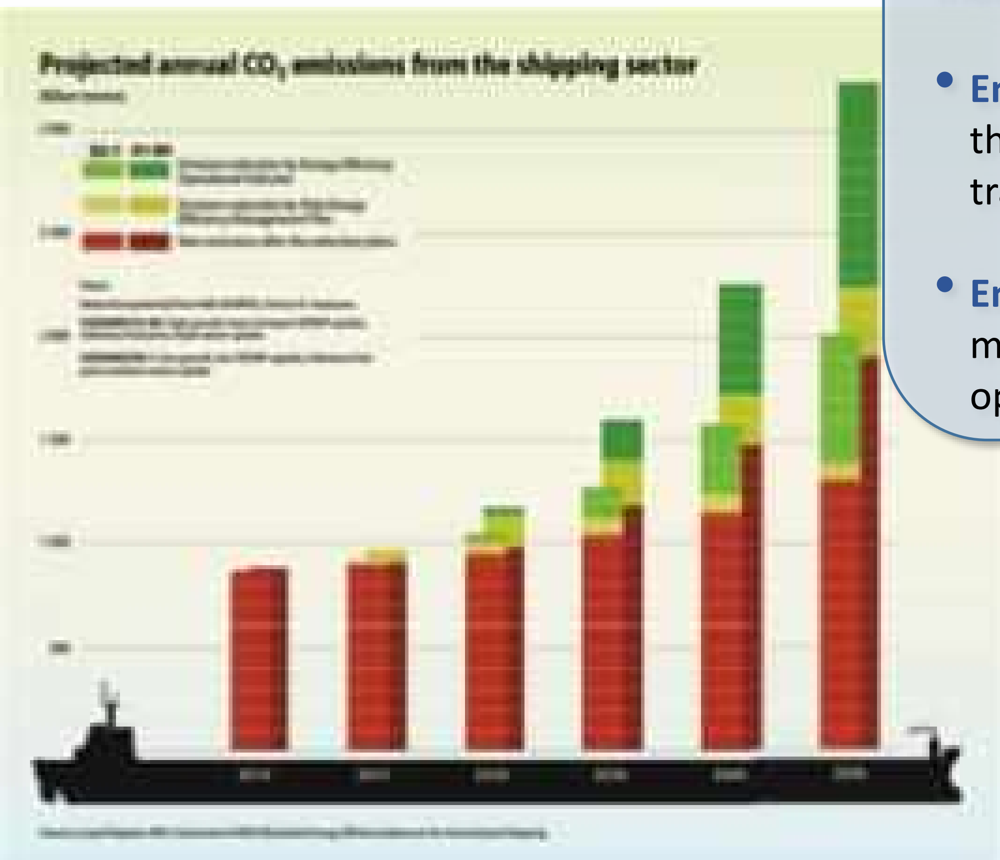
Major drawbacks of Diesel engines:

- Source of CO_2, SOx, NOx emissions, related to the ship´s operational condition.
- Diesel engines, as the one described, found their optimum fuel oil consumption point around 75% - 80% of the MCR.

IMO regulations establish control of CO_2 emissions, by introducing several operational efficiency indicators.

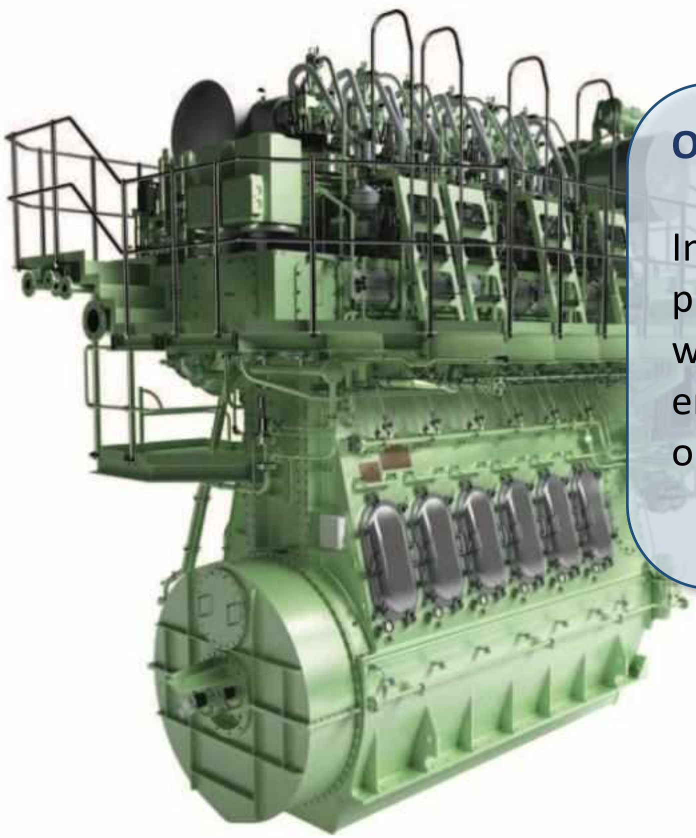
- **Energy Efficiency Design Index (EEDI)** estimates the CO_2 emissions, per ton-mile of goods transported.

- **Energy Efficiency Operational Indicator (EEOI)** measures the fuel efficiency of a ship in operation.



Problem identification

- Diesel engines as prime mover for naval applications major drawback referred to CO_2, SOx, NOx emissions
- International Maritime Organization (IMO), has implemented several regulations with big impact in the vessel's energy efficiency design and operation.
- Nowadays use of shaft generators has been justified only if the diesel engine prime mover is operating below 75% - 80% of it's rated power.
- Possibility to overload the prime mover, increasing the CO_2 emission.



Objective

In the present work a selective control scheme is being proposed, within a marine diesel engine propulsion system, with a direct driving shaft generator, to enable the diesel engine prime mover to operate on its minimum emissions operating point (MEOP).

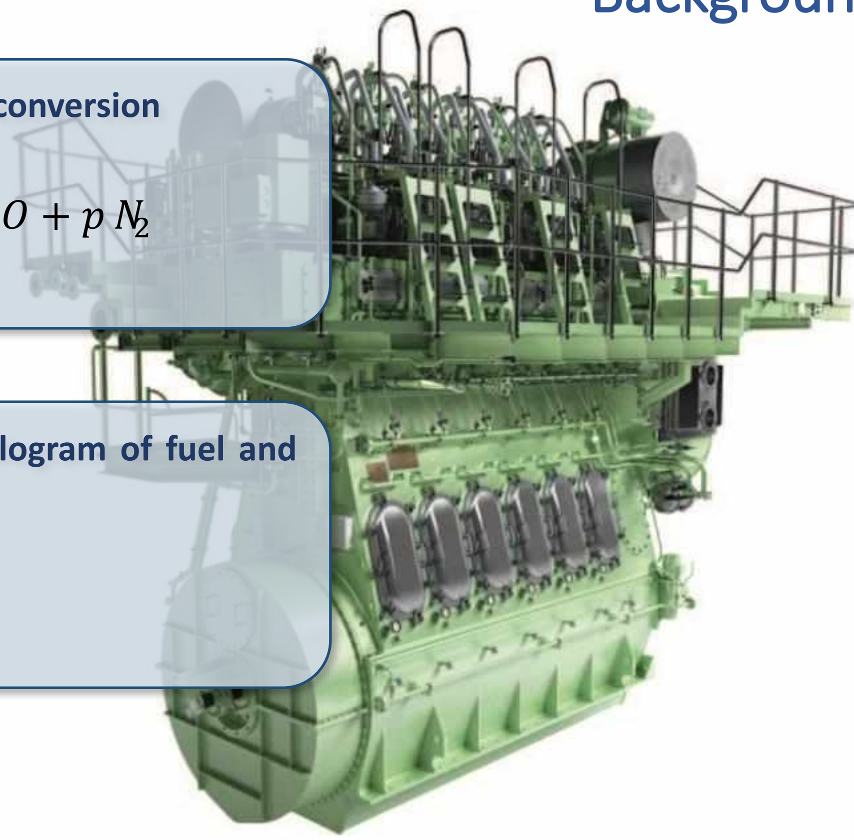
Background

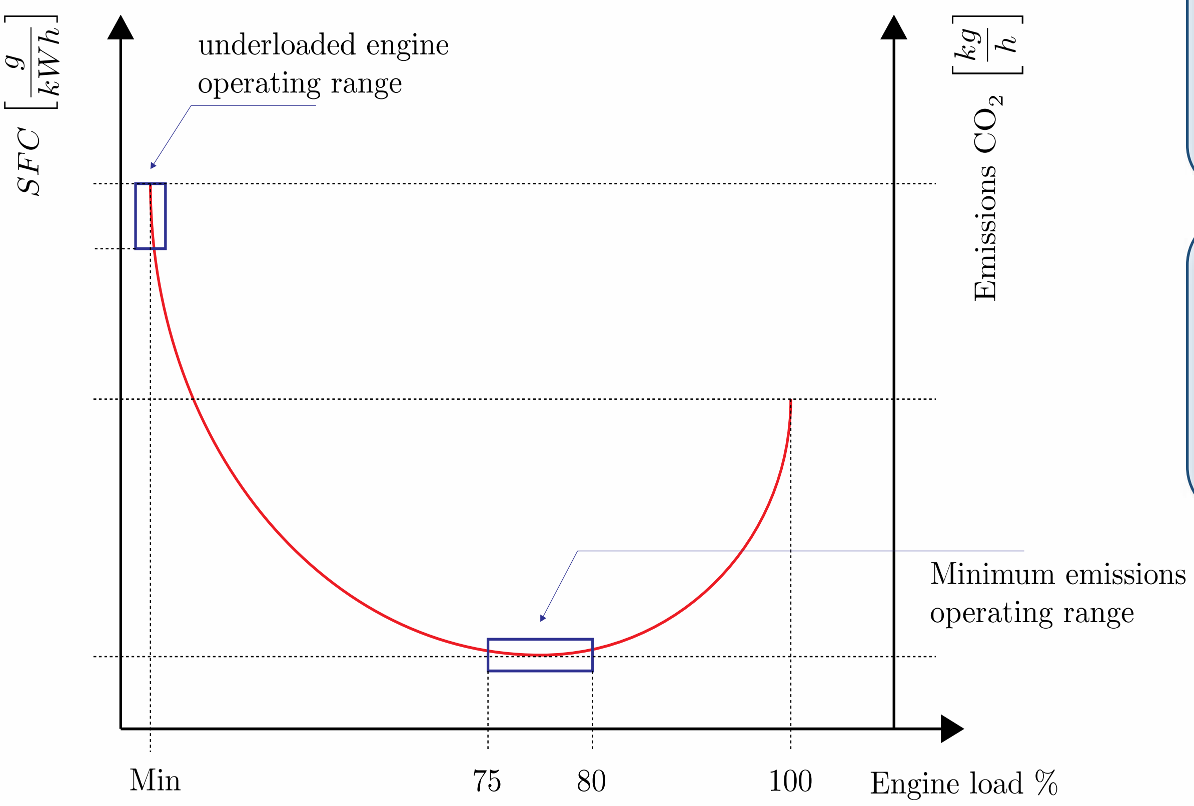
Emissions are generated during the process of energy conversion

$$C_mH_n + \left(m + \frac{n}{4}\right) O_2 + p\,N_2 \longrightarrow mCO_2 + \frac{n}{2} H_2O + p\,N_2$$

AFR_{St} minimum amount of air required to burn a kilogram of fuel and when compared to the actual air to fuel ratio (AFR)

$$\lambda = \frac{AFR}{AFR_{st}}$$





When operating at lower loads less fuel is available.

$\lambda < 1$

More fuel is to be provided to overcome the demand.

$\lambda > 1$ when above 75% - 80% rated load.

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME\,(i)} * C_{FME\,(i)} * SFC_{ME\,(i)}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE^*}\right) + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)}{f_i * f_C * Capacity * V_{ref} * f_w}$$

The EEDI is a measure of CO_2 emissions per ship´s capacity, per nautical mile applied to new ship designs.

$$EEDI = \frac{P_B * SFC * C_F}{DWT * V_S}$$

P_B corresponds to the 75% rated installed brake power in kW

C_F is the carbon factor in g CO_2/g fuel

DWT is the capacity of the ship in tonnes

V_s is the ship´s design speed in knots.

$$EEOI = \frac{\sum_j F_j * C_{Fj}}{m_{Cargo} * D}$$

The EEOI is the monitoring tool supporting the Ship Energy Efficiency Management Plan, SEEMP, applied to new and existing ships to measure the amount, in grams, of CO_2 per tonne cargo transported per nautical mile for a single voyage.

$$EEOI = \frac{SFC * C_F}{m_C * D}$$

m_c factor accounts for the mass of cargo transported in tonnes.

D distance, in nautical miles, of the cargo transported.

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE^*}\right) + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)}{f_i * f_C * Capacity * V_{ref} * f_w}$$

The shaft generator is considered a technological and operational improvement.

Its influence into of ship´s efficiency is presented introducing the Emissions Factor into the EEDI equation.

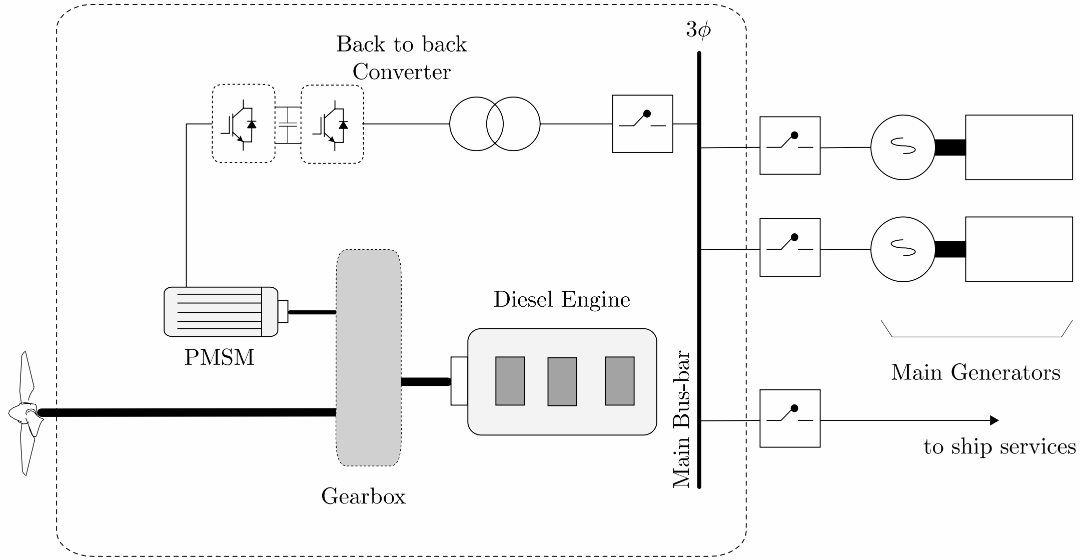
$$\left(f_i * P_{PTI} - f_{eff} * P_{AE}\right) C_{FAE} * SFC_{AE}$$

f_{eff} is the efficiency technology factor.

The reduction in power requirements that any technology generates is given by

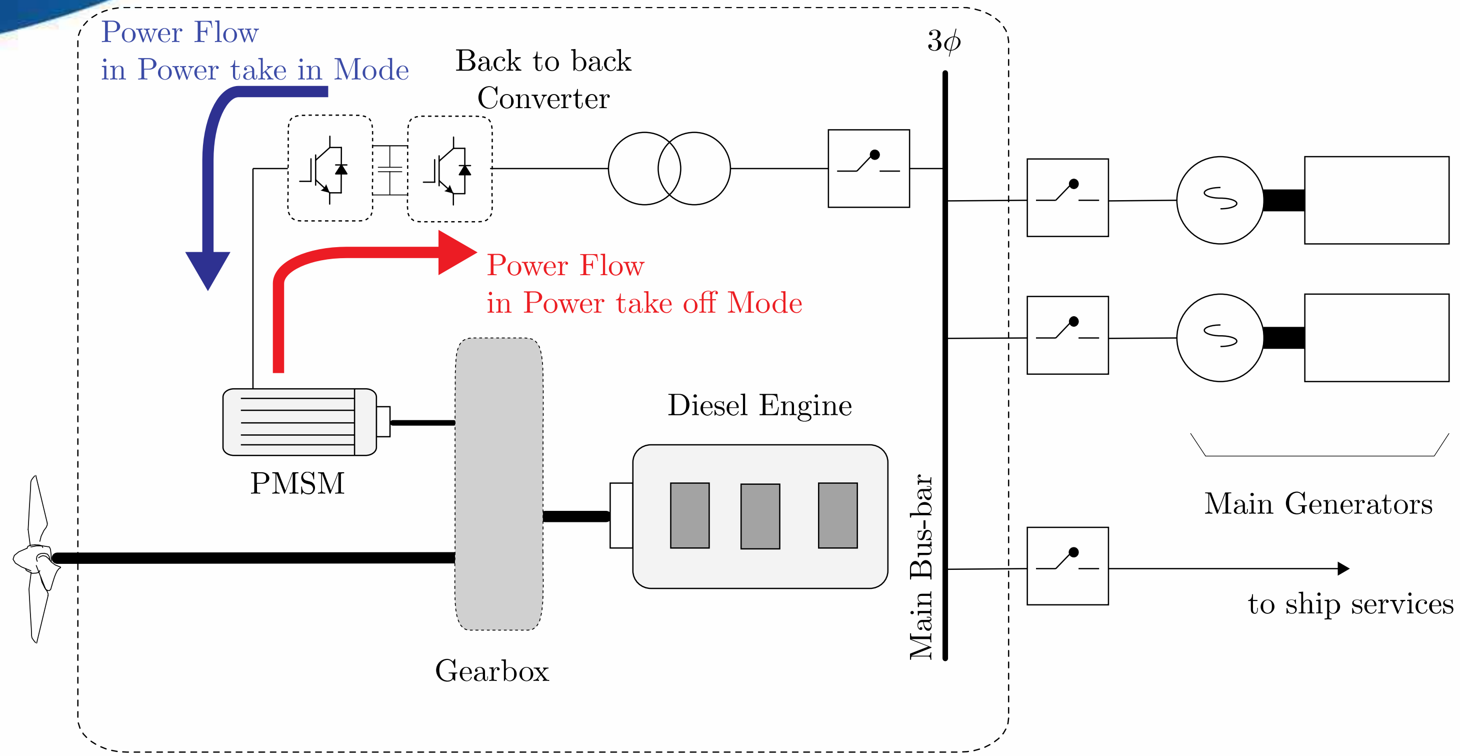
$$f_{eff} * P_{eff} * C_F * SFC$$

PTO / PTI Control Scheme



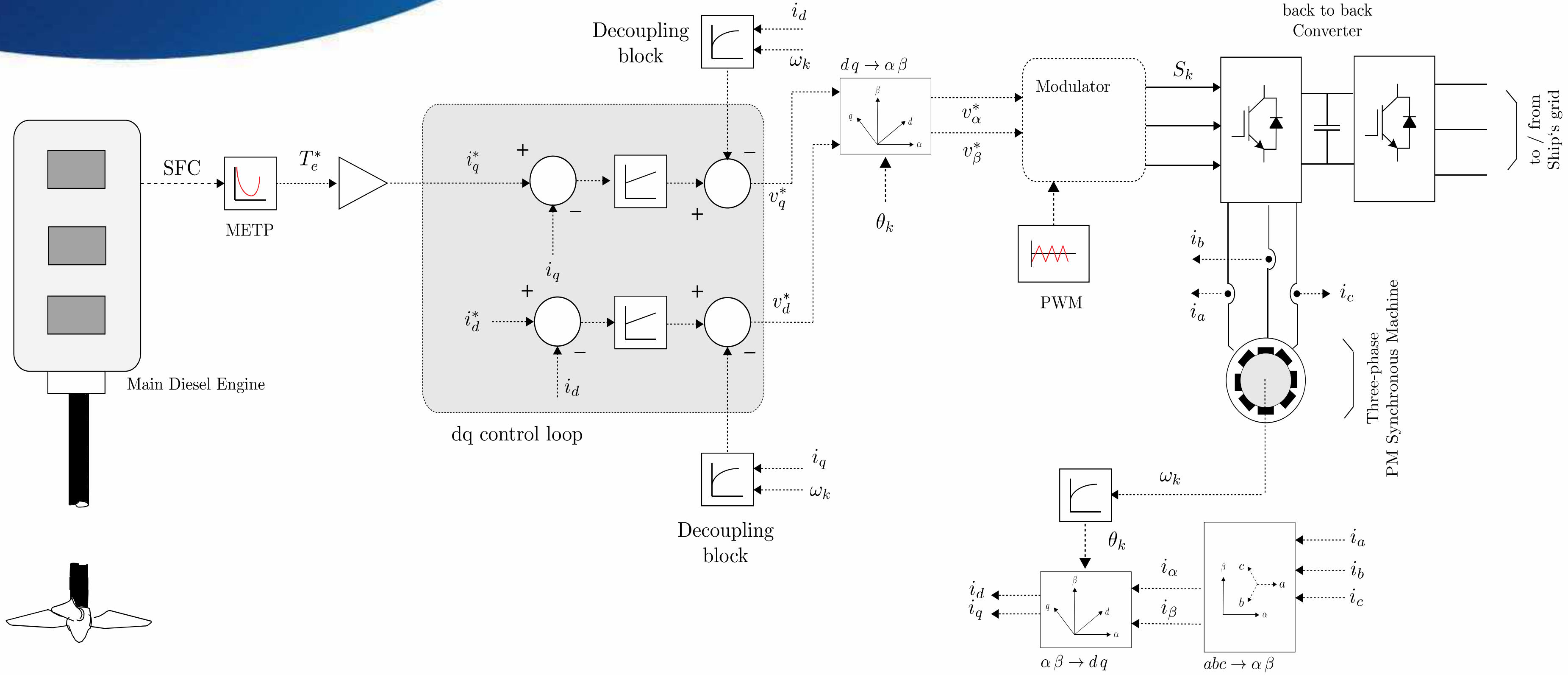
- Propulsion system consisting of a single shaft with PTO/PTI geared output.
- Low speed diesel engine prime mover.
- AC drive consisting of a permanent magnet synchronous machine (PMSM), coupled via a single-stage gearbox.

- Back to back power converter for ship‘s grid interconnection, enabling bi-direction power flow.
- Ship‘s main busbar has been considered as an infinite busbar.
- Ship‘s power system is able to balance the active and reactive flow.



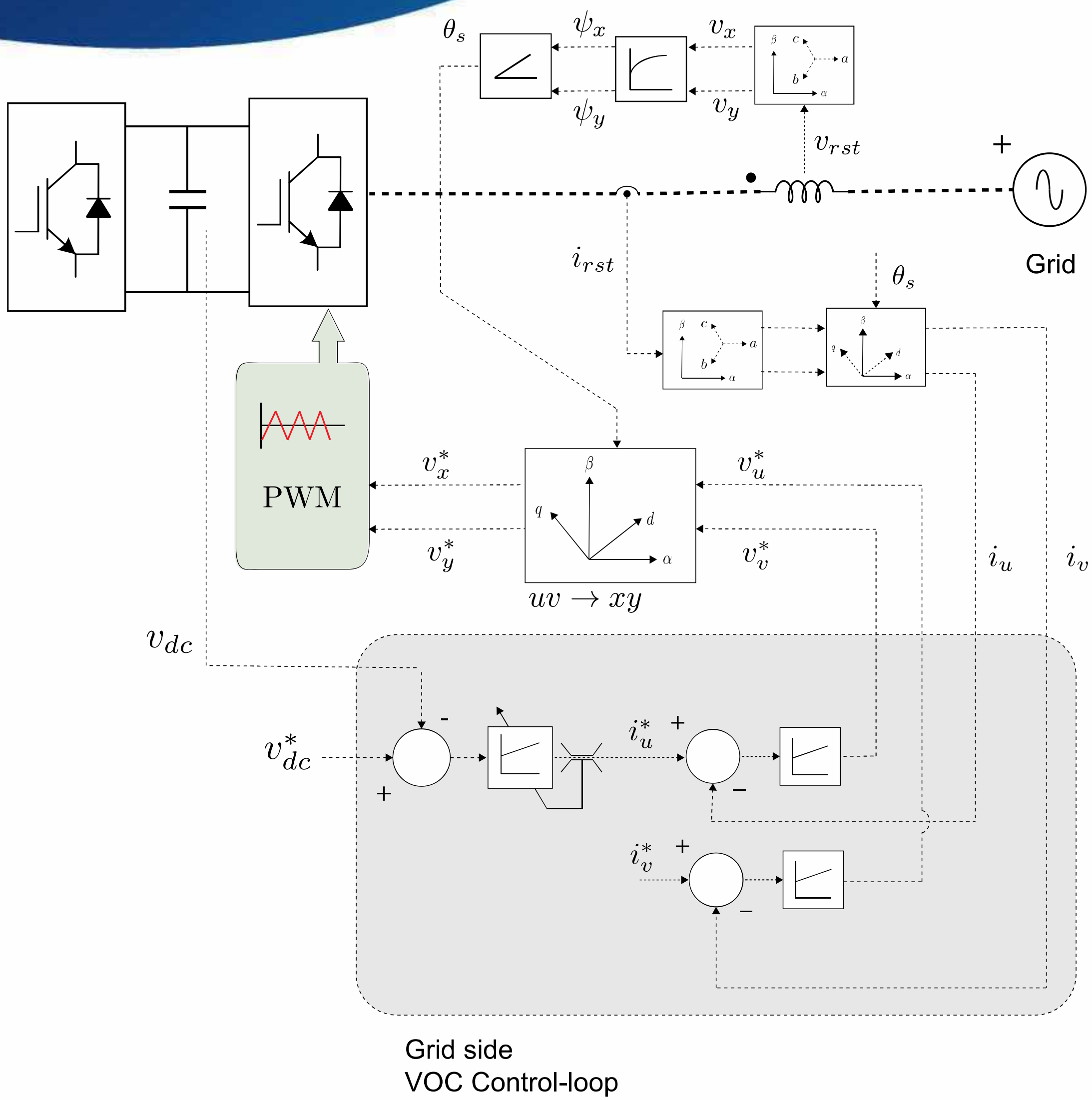
Control Goals:

- Ensure diesel engine minimum emissions operation point.
- Fulfil AC drive torque and current control in the dq synchronous reference frame (TFOC).
- Ensure grid side active / reactive power flow control.



Torque Field Oriented Control (TFOC) / Generator side control

- Decoupling of field and armature flux linkages.
- Maximizes the active power delivered / developed by the AC machine.
- Keeps the maximum field flux within its linear operation zone.



P – Q oriented control/Grid side control

- Decouples active and reactive power by rotating grid side currents into an arbitrary synchronous reference frame.
- Maximizes active power flow and power factor compensation.
- Enables dc-link voltage control.

Optimization Problem

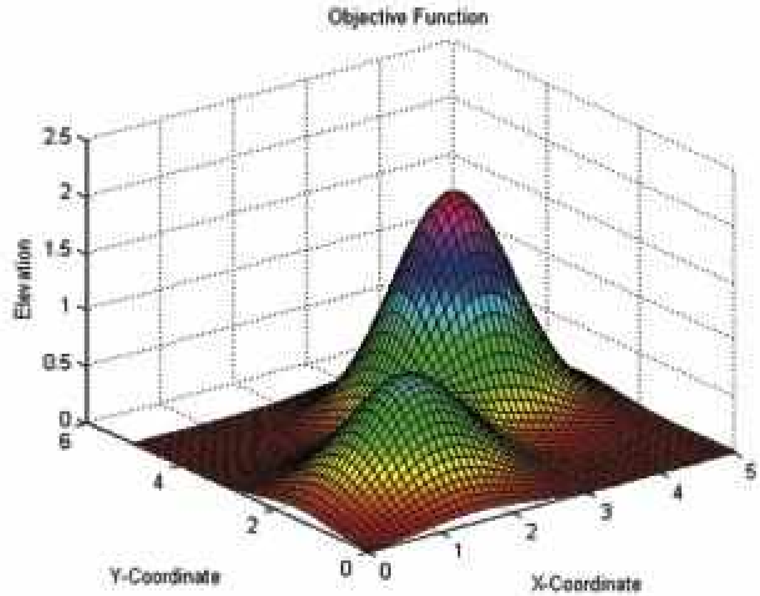
Let us define an optimization problem ϕ

$$\phi = \langle \mathbb{C}, \mathbb{S}, v, f(x) \rangle$$

$$\mathbb{C} = x \quad ; \quad x = \{x_0, x_1 \dots x_n\}$$

$$\mathbb{S} = x \pm \delta \quad ; \quad 0 < \delta < \epsilon$$

$$v = min\{f(x)|_{x \pm \delta}\} \quad : \quad x \in \mathbb{C}$$



$\mathbb{C}$ corresponds to the set of candidate solutions, $\mathbb{S}$ is the set of solutions with $\mathbb{S} \subseteq \mathbb{C}$; v is the optimization sense, thus v ={min, max} ; f(x) the objective function, f(x) : $\mathbb{S} \rightarrow \mathbb{R}$, and δ is the system state perturbation.

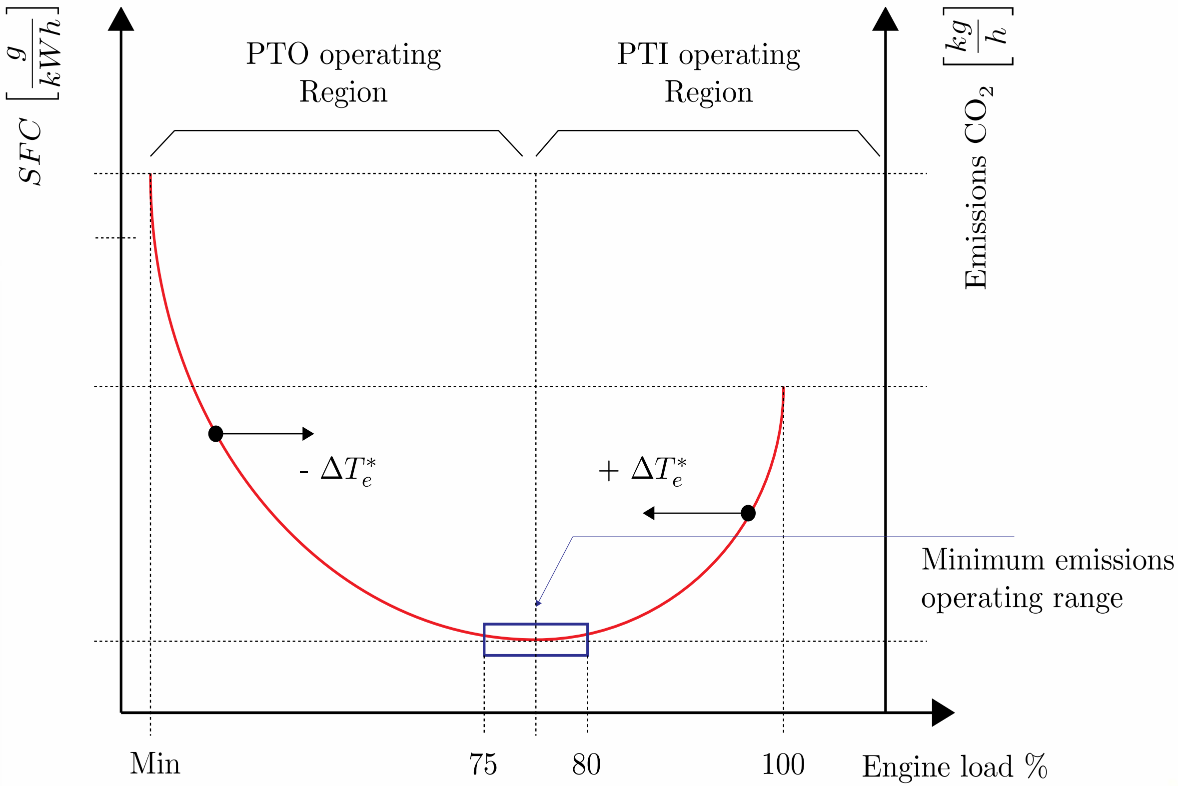
Optimization objective

The optimization objective is to minimize the CO_2 emission at any instant (k) by perturbations on the torque reference to the TFOC scheme.

$$SFC(k) = hc(\,QB(k) \pm \Delta Te^{\,*}\,)$$

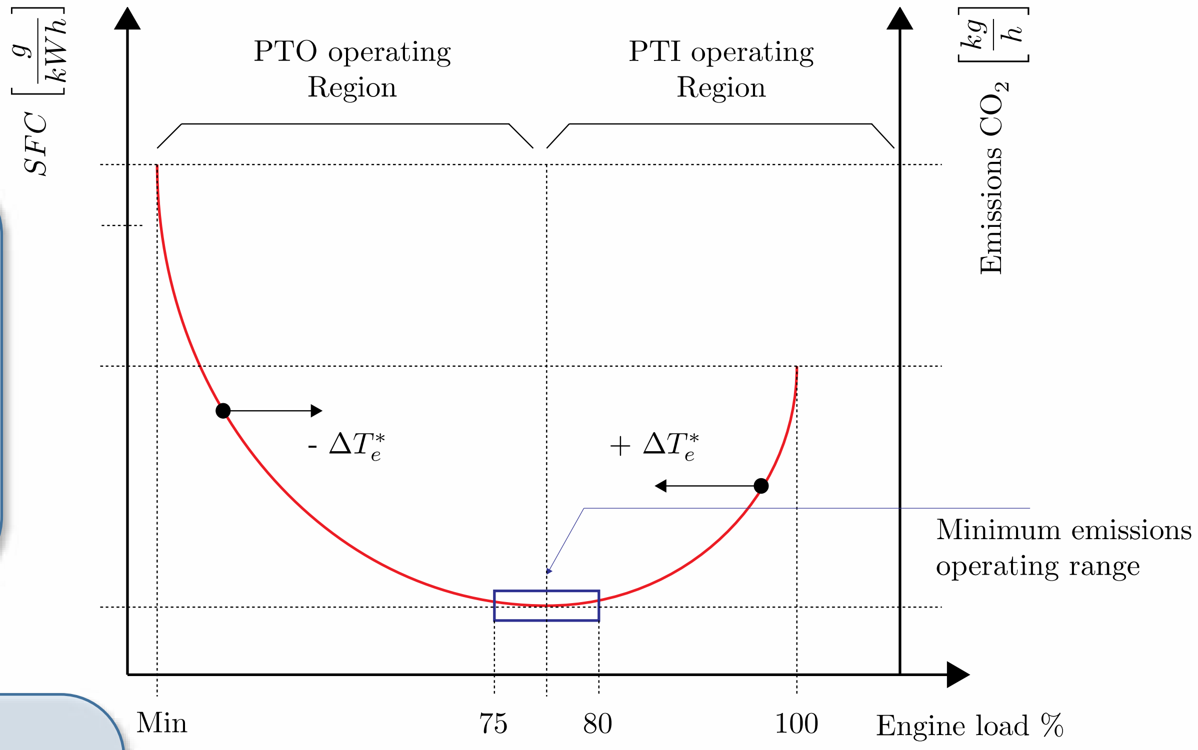
Q_B prime mover developed torque.

Te^* electrical torque reference.



The specific fuel consumption, SFC, denoted as g can be characterized as a non-linear discrete function depending on the engine load at a given instant $Q_B(k)$

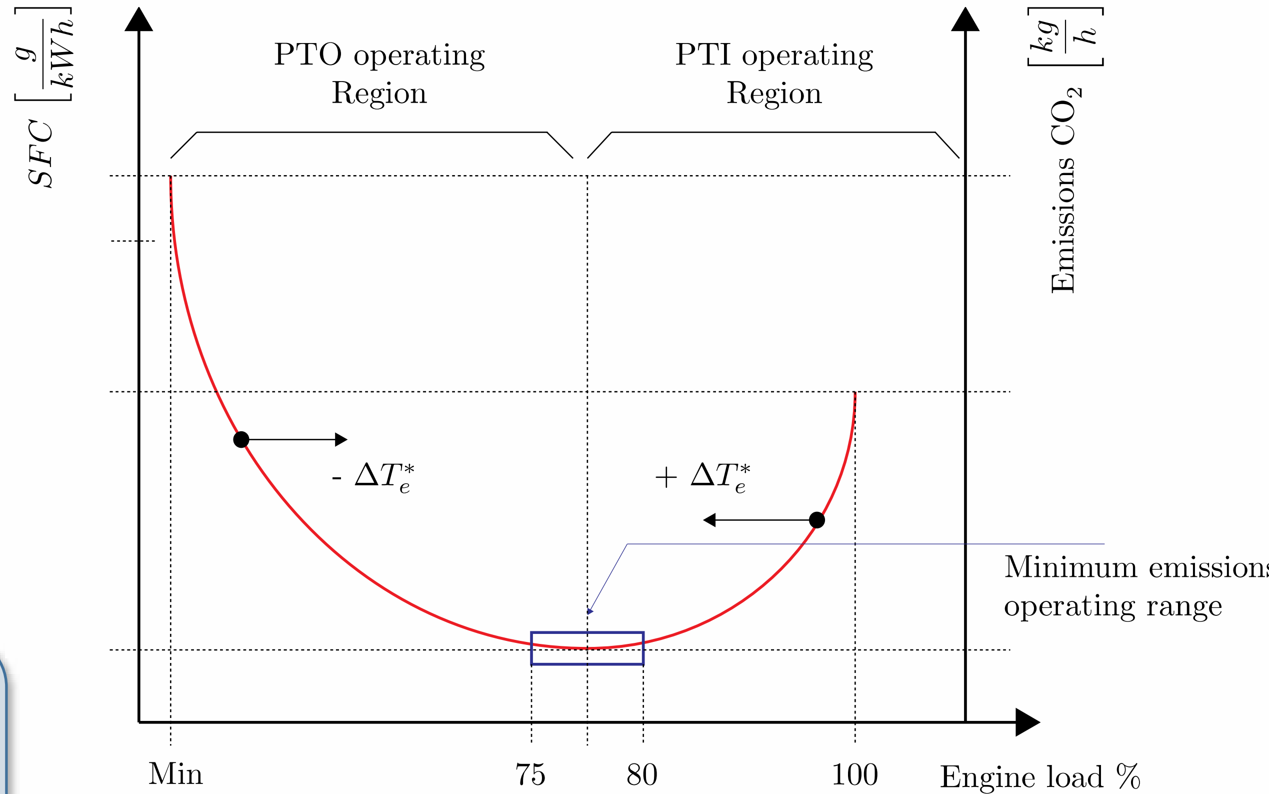
$$g(k)=h_d\,(\,Q_B(k)\,)$$



g(k) is the objective, thus g(k) =f (x(k))

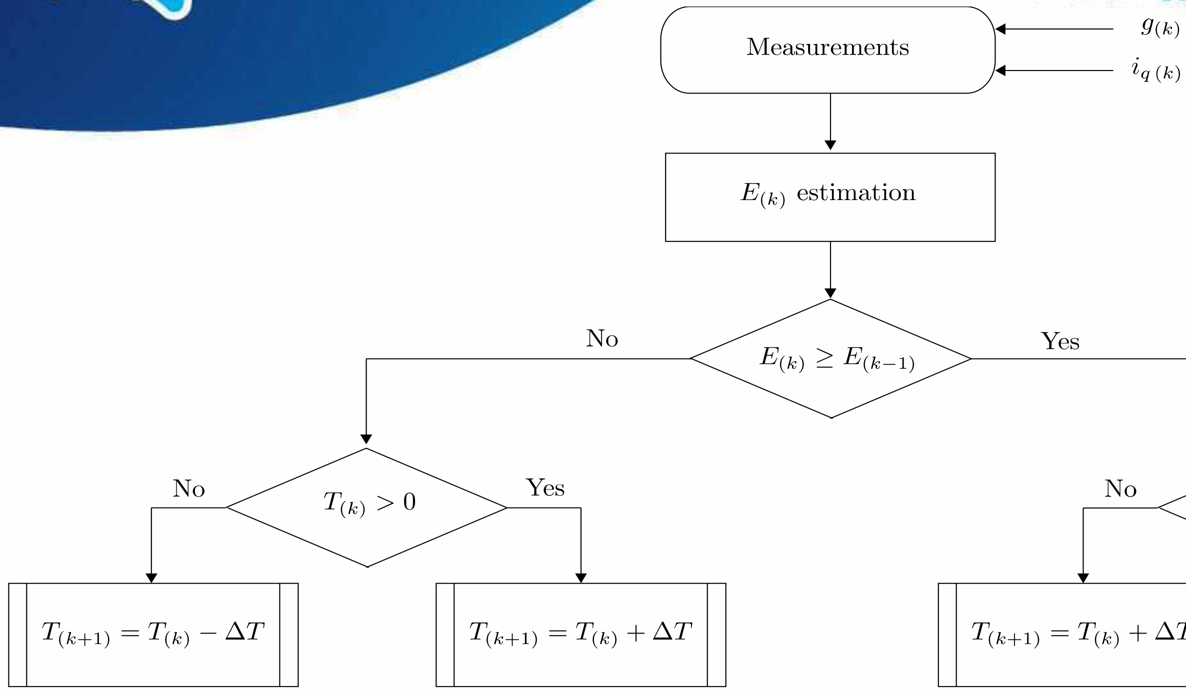
The system state is given by $x(k) = [\, x_0(k) \ldots x_n(k)\,]$

System state perturbation is introduced by variations on the torque reference $\delta = \Delta Te^*$;



The optimization solution can be expressed as

$$\mathbb{S} = \min\left\{ f\left(x_{(k)}\right) \Big|_{\, x_{(k)} \pm \delta} \right\}$$



g(k) objective function to be minimized.

P&O algorithm innitiating at an arbitrary state x

System perturbation in the electric torque reference ΔTe*

Moving direction of P&O given by: sign { iq (k) }

Set of solutions S restricted to PTI/PTO operation region S1 , S2 ; S1 ∪ S2 = S

O is achieved for δ = +Δ Te∗ for x ∈ S1 (PTI region)

O is achieved for δ = − Δ Te* for x ∈ S2 (PTO region)

Simulation Results

Type of Ship	Fuel Consumed	Capacity (dwt)	Speed (kn)	Cargo Transported (tonnes)	Installed Power (MW)
Very Large Crude Oil Carrier (VLCC)	Heavy Fuel Oil (HFO)	300.000 320.000	15 21	315.000 330.000	25 36

MAN G80ME-C9.2-TII diesel engine.

SMCR: 33 MW @72 rpms.

SFC: 187.1 g/kWh @low load - 166 g/kWh @high load.

NCR considered around 75% of the SMCR.

When consuming HFO, a carbon factor of 3.114 g CO_2/g Fuel was used to estimate the emissions.

Control Scheme Performance at PTO Operating Region

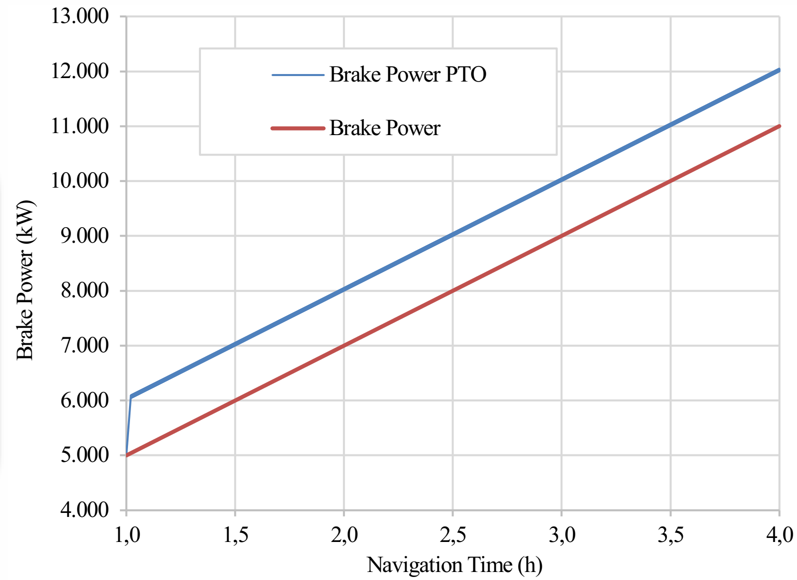
PTO operating region: simulating navigation time of 5 hours.

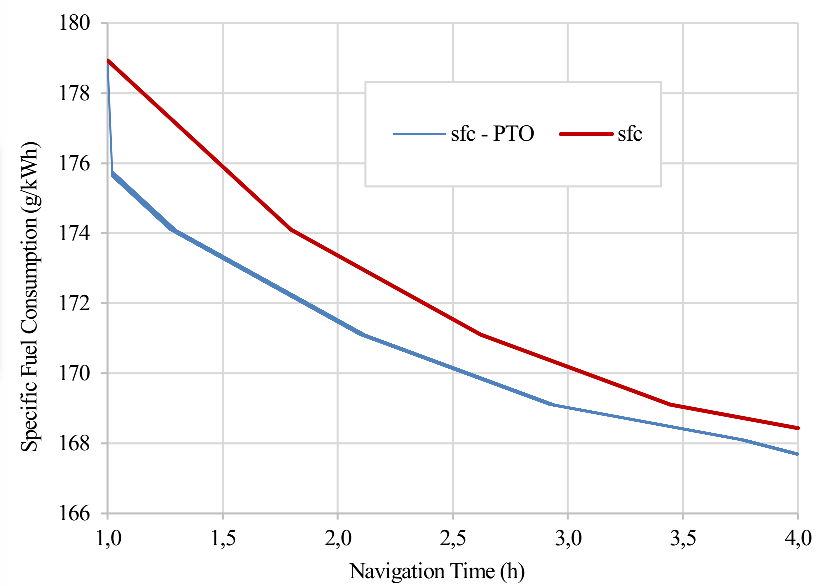
Linear increase of brake power from 5 MW to 12 MW.

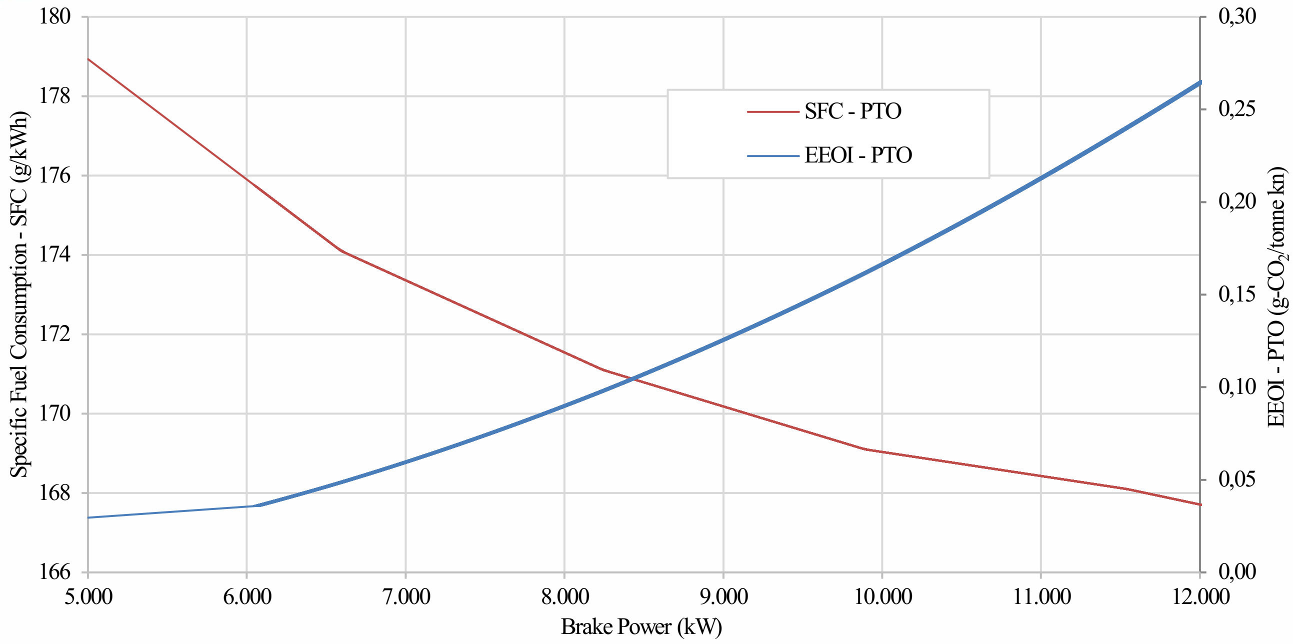
Decrease of the SFC from a maximum value at low engine load.

Increase in the brake power when using a shaft generator is around 5% of the SMCR.

Decrease in the SFC.





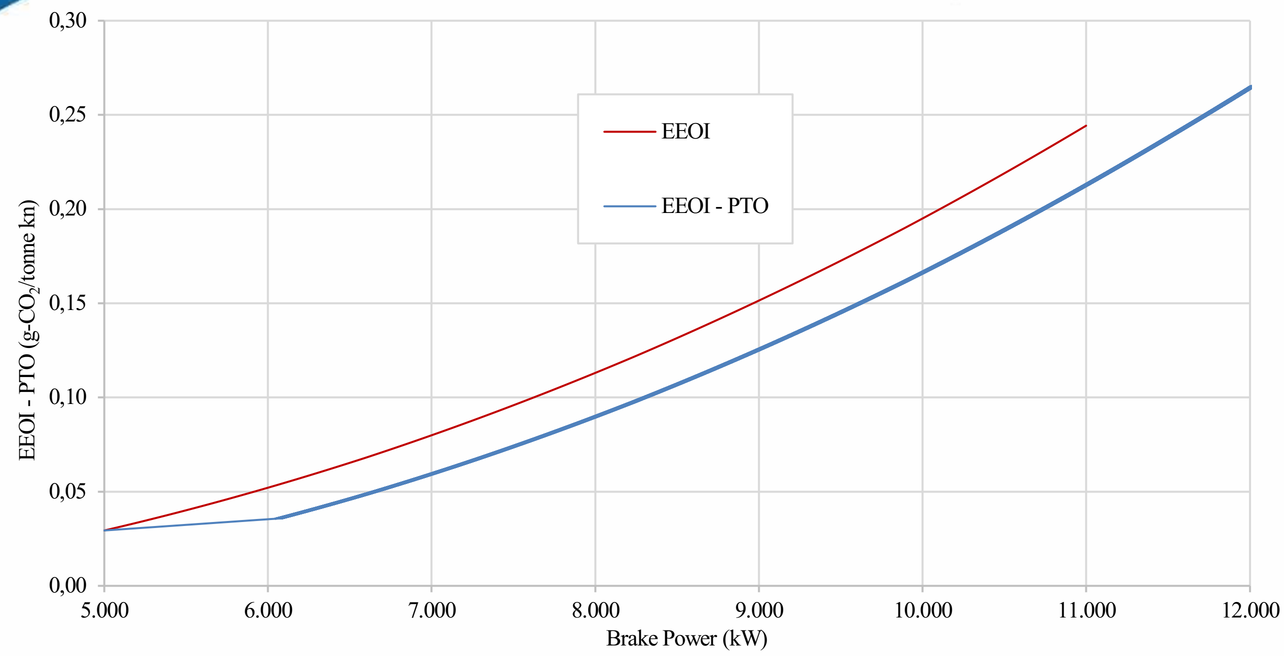


EEOI performance applying the shaft generator control scheme (PTO region)

The SFC decreases while the engine load increases, which gives a set of EEOI values in accordance with the amount of fuel consumed over the navigation period.

Increment of EEOI is considered low over the engine load and reflects the decrease of the SFC.

Although the decrease of the SFC is not quite significant allows for a decrease of the EEOI value, which leads to a reduction of the amount of operational CO_2 emissions.



EEOI performance with and without shaft generator control scheme (PTO region)

Control scheme applied makes the ship to reduce the amount of operational CO_2 emissions even though an extra amount of brake power is necessary to be generated providing great assertiveness of the methodology.

SFC is reduced over the period when operating at the PTO operating region.

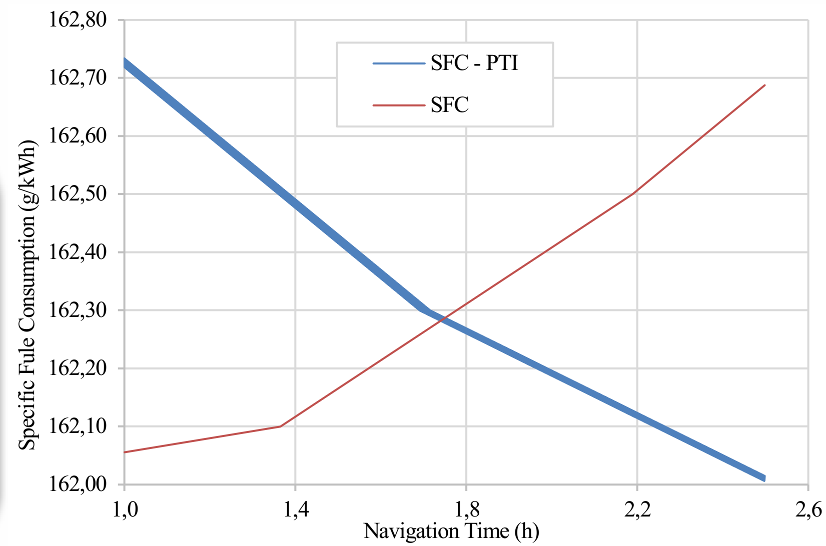
Control Scheme Performance at PTI Operating Region

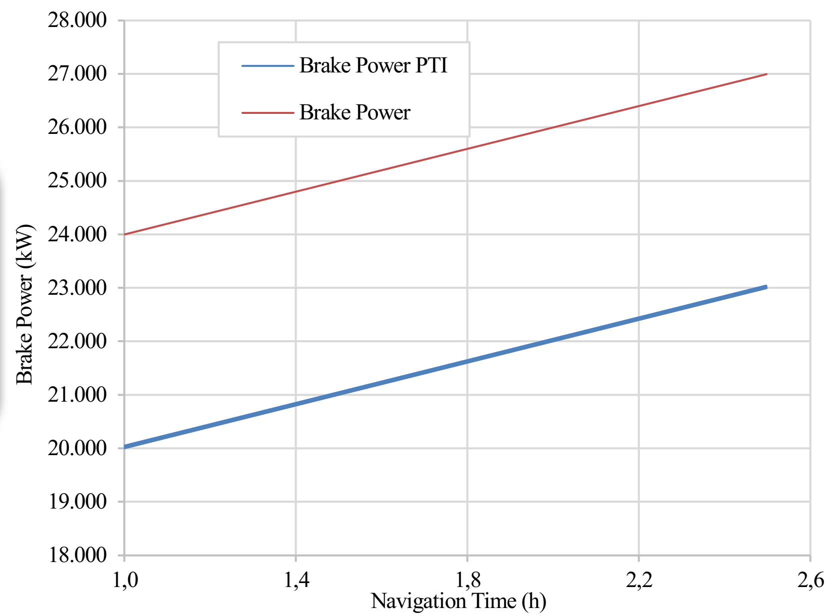
PTI operating region simulating a period of navigation time of 2,5 hours.

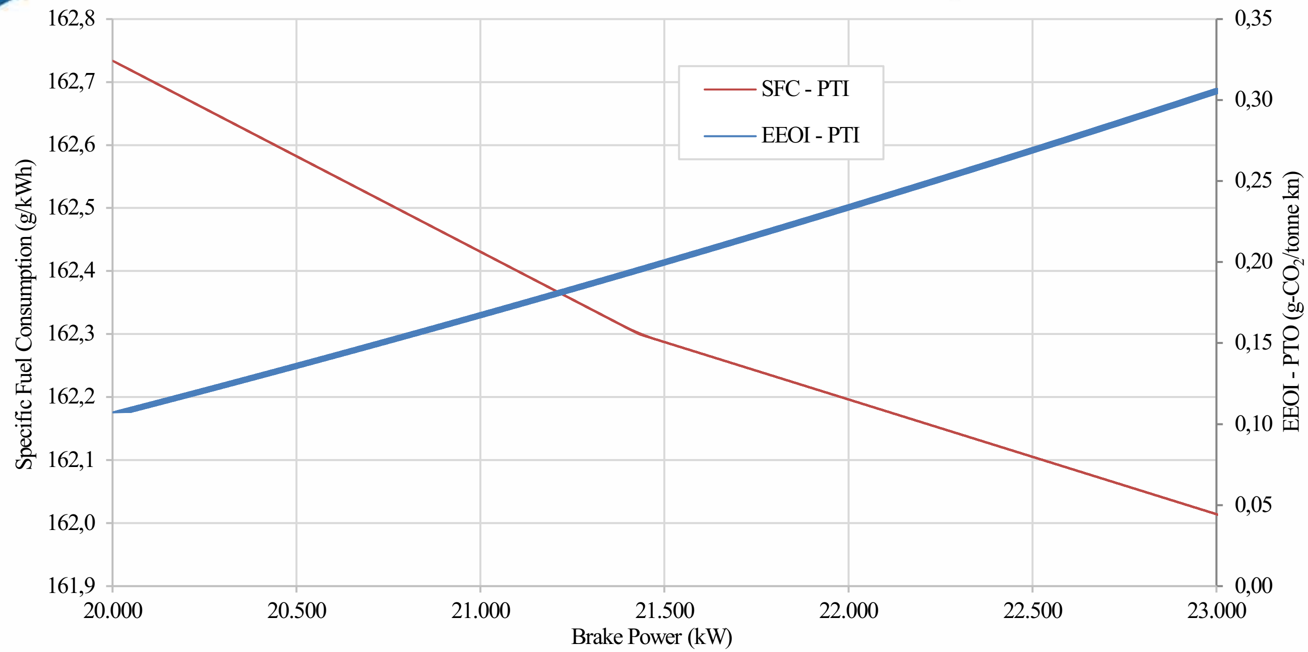
Brake power lineally increases from 24 MW to 27 MW when not having a shaft generator, which also means an increase in the SFC

When applying the control scheme in PTI mode, reduces the brake power around 5% of the SMCR.

Reduction in the SFC is reduced as consequence.





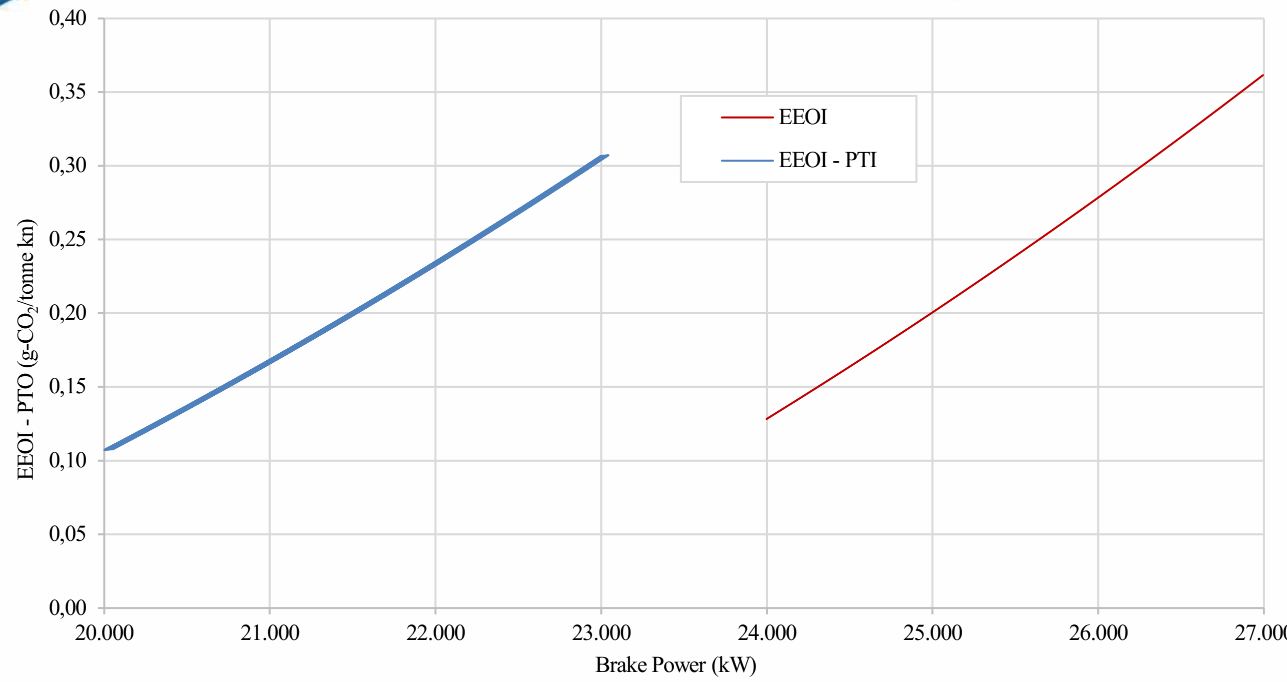


EEOI performance applying the shaft generator control scheme (PTI region)

SFC decreases while the engine load increases, which gives a set of EEOI values in accordance with the amount of fuel consumed over the navigation period and the navigated distance.

The lineal increment of the EEOI is considered low over the engine load and reflects the decrease of the SFC as a reflection of the application of the control scheme.

Operational emissions are reduced in accordance with the reduction of the SFC.



EEOI performance with and without shaft generator control scheme (PTI region)

Results are showing that the control scheme applied makes the ship to reduce the amount of operational CO_2 emissions because the engine to works closer to MEOP, providing great assertiveness of the methodology.

Conclusions

- Results presented, differentiating the performance of the control scheme of the shaft generator, are quite significant when compared to not having a shaft generator installed.
- Results of the fuel consumed by the engine when simulating the PTO and PTI conditions are not quite significant yet are helping to reduce EEOI values at both operating regions, which means less operational CO_2 emissions.
- The control scheme when simulating the engine performance at PTI operating region makes the engine to work closer to the MEOP, which leads to low SFC therefore, low operational emissions.
- The control scheme shows assertiveness and accuracy at both operating regions reducing the SFC.
- The perturb and observe optimization function presents an accurate performance to obtain a local search for the minimum emissions point, starting at a random state.
- The ship and engine data considered for the simulations is open source and provides great value to continue to be used in this research.

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