Shaft generators for low speed main engines

MAN Energy Solutions
Future in the making

Future in the making

Contents

With the ever-tightening IMO Energy Efficiency Design Index (EEDI) phases, it has never been more important to improve the overall efficiency of the merchant fleet. The combination of a shaft generator and the MAN B&W two-stroke marine engine gives a powerful tool for complying with the EEDI.

The shaft generator can minimise the overall operating costs of the vessel when shifting the hotel load from the auxiliary generators to the main engine (ME). The advantages are the superior fuel economy of the ME and the reduction of auxiliary generator running hours.

This paper provides detailed descriptions of the shaft generator solutions available for MAN B&W low speed two-stroke engines. PTO guidelines with examples describing how to apply the guidelines for an MR tanker and an LPG carrier are also given.

Introduction

Because of the ever-tightening EEDI phases aiming at reducing the emission of greenhouse gasses (GHG), the installed propulsion power for new vessels is decreasing. A shaft generator reduces the EEDI, and helps reaching EEDI compliance. Compared to other means of increasing the efficiency of the total machinery plant on board, a shaft generator is often the most reliable and cheapest solution.

There are several benefits of installing a shaft generator on board a vessel. The shaft generator enables production of electric power by the ME that has a low specific fuel consumption. In addition, the lower number of running hours of the gensets reduces maintenance and expenses for spare parts.

In the early 2000s, shaft generators were most prevalent among larger container vessels. This was mainly due to a combination of low oil prices and high costs associated with power electronics for the generators. These vessels sailed mainly on fixed routes with a fixed speed, and thus kept a more or less constant engine speed along the propeller curve of the fixed pitch propeller (FPP). This meant that the shaft generator frequency stayed within the range of the nominal frequency, and power electronics such as frequency converters, which at the time were very costly, could be omitted. The reduced use of power electronics minimised the purchase costs but limited the generator application to vessels sailing at more or less fixed speeds.

Vessels equipped with a controllable pitch propeller (CPP) can vary the pitch. This has traditionally been applied to maintain a constant speed of the ME, and hereby the frequency of the shaft generator, which means the frequency converter is not required. However, the efficiency of the propeller drops at the lower propeller pitch required to maintain rpm high at low loads.

In recent years, the price of frequency converters has dropped significantly. Utilisation of a frequency converter extends the engine speed range in which a PTO is available for fixed pitch propeller plants. A frequency converter will also permit operation along a combinator curve for a CPP plant, increasing the number of vessel types and operating patterns that may benefit from a PTO installation.

This paper gives an overview of the shaft generator technology and its use with the two-stroke marine engine. The PTO layout guideline of MAN Energy Solutions (MAN ES) will be described along with examples evaluating shaft generator rpm stability, fuel savings and EEDI for a 50,000 dwt MR product tanker and a 38,000 m^3 LPG carrier.

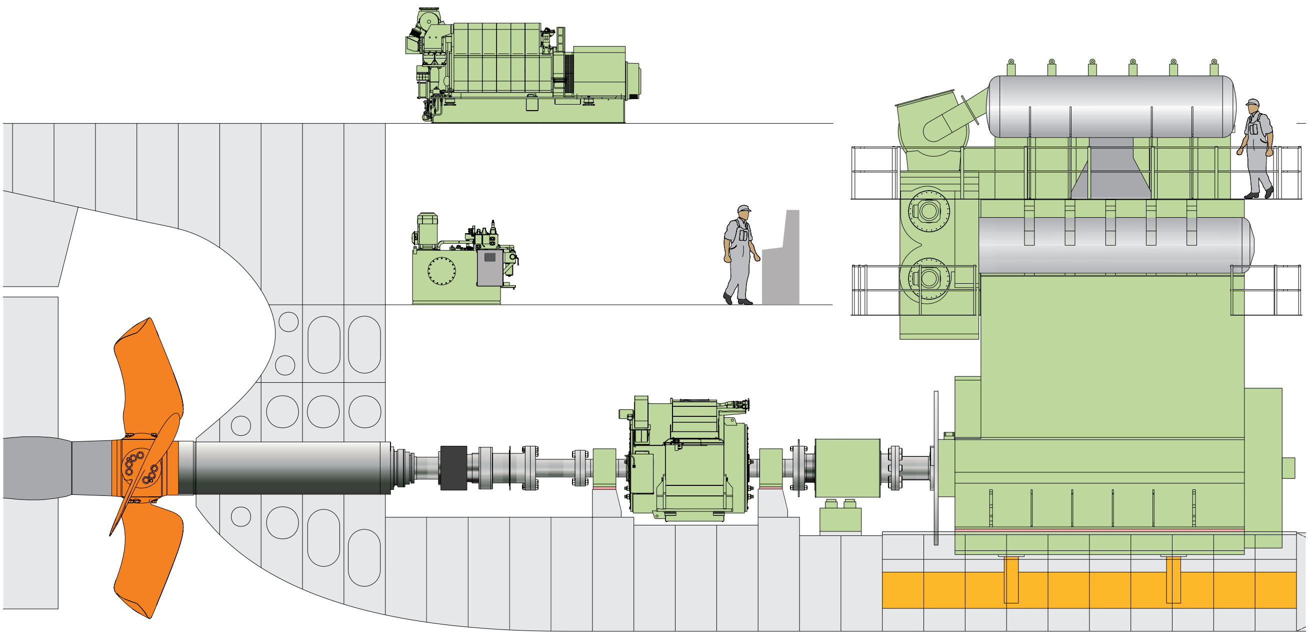


Fig. 1: Cross-section of a vessel equipped with an MAN B&W two-stroke engine connected to a shaft generator and a controllable pitch propeller

Shaft generator designations and operating modes

Numerous designs exist for shaft generator systems, which MAN ES categorises in two subgroups: engine-to-generator and generator-to-grid.

The engine-to-generator subgroup is related to the position of the shaft generator and the connection between the engine and the shaft generator system. The generator-to-grid subgroup is related to the power fed to the grid and the system between the shaft generator and the grid.

The shaft generator system can be placed either on the aft-end (towards the propeller) or on the front end of the engine. The front-end mounted generator can be mounted on the engine or on the tank top. The aft-end mounted generator can be mounted on the shaft or through a tunnel gear. An elastic coupling is required when using a gear to transfer the shaft power to the generator.

Table 1 shows current combinations of position, seating and connection for a shaft generator and an MAN B&W two-stroke marine engine. The table provides abbreviations explaining the different combinations. These abbreviations describe the shaft generator system considered.

When placing an engine order at one of MAN ES' licensees, it is important to provide information about the selected type of PTO to facilitate the selection of the correct interface to the engine control system (ECS).

Shaft generator operating modes

A shaft generator can have a multi-purpose-function on board a vessel and it can be applied in different modes depending on the situation. The following sections describe the three modes: power take-off, boost / power take-in, and power take-home.

Transit mode – power take-off (PTO)

In the typical application, the shaft generator generates electricity. In this mode, the shaft generator covers the need for electric power alone or in parallel with gensets if a frequency converter is installed. This mode can offer a significant fuel reduction because of the superior fuel economy of the ME compared to the gensets.

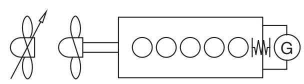
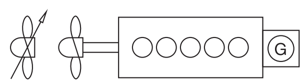
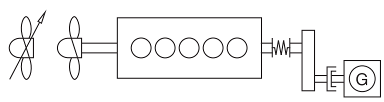
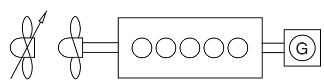
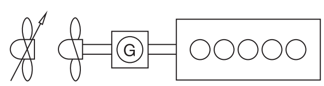
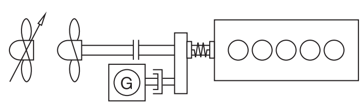
Position	Seating	Connection	Layout of shaft generator	Abbreviation
Front-end	On-engine	Geared (with elastic coupling)		FEG
Front-end	On-engine	Direct (no gear)		FED
Front-end	On tank top	Geared (with elastic coupling)		FTG
Front-end	On tank top	Direct (no gear)		FTD
Aft-end	Shaft mounted	Direct (no gear)		ASM
Aft-end	Shaft mounted	Geared (with elastic coupling)		ATG

Table 1: The different types and layouts of shaft generators available for an MAN B&W two-stroke engine

Fig. 2 shows a schematic overview of the transit mode.

When a vessel manoeuvres at low rpm, for example in port, the PTO feature is not engaged, instead a genset covers the hotel load. When the vessel has left the port and gained speed at open sea, the power delivered by the genset is provided by the PTO and the genset is stopped. At lower rpm, there is a smaller margin to the torque limiter. This margin narrows when using the PTO, which means a reduction of the acceleration power of the vessel. The consequence is that the passing time of the barred speed range increases, which is undesirable due to torsional vibrations in the ME shaft.

The vast majority of vessels with PTO are not equipped with a propeller shaft clutch (PSC), which is only installed if power taker home (PTH) is desired, see the section on page 8; "Diesel-electric mode – power take-home (PTH)".

Whether the electric power output of the shaft generator must be dimensioned to cover the total electric load while sailing, or the electric load for 80% of the operating time, for example, or operate in parallel with the gensets during peak load, is an optimisation exercise that largely depends on the vessel type and intended trade.

When evaluating the benefits of a shaft generator, the increased SFOC resulting from the increased load on the ME must be considered. The ME comparison (MECO) by MAN ES can indicate the influence of a PTO on the operational expenditure (opex), see the example with an MR tanker on page 19. An MECO can be obtained by contacting the MAN ES Marine Project Engineering department at: MarineProjectEngineering2S@man-es.com

Boost mode – power take-in (PTI)

In boost mode, the genset works in parallel with the ME. By utilising the shaft generator as a motor, the genset produces enough power to cover the hotel load and provide power to the shaft line and, thereby, propulsion power to the vessel. Naturally, the boost mode increases the total specific fuel consumption because the four-stroke genset has a lower fuel efficiency than the two-stroke ME. The boost mode is often used when a power peak is anticipated, for example, when a container vessel must catch up a delay, or when a vessel needs to achieve a higher ice-class without increasing the engine power. Fig. 3 shows the concept of the boost mode.

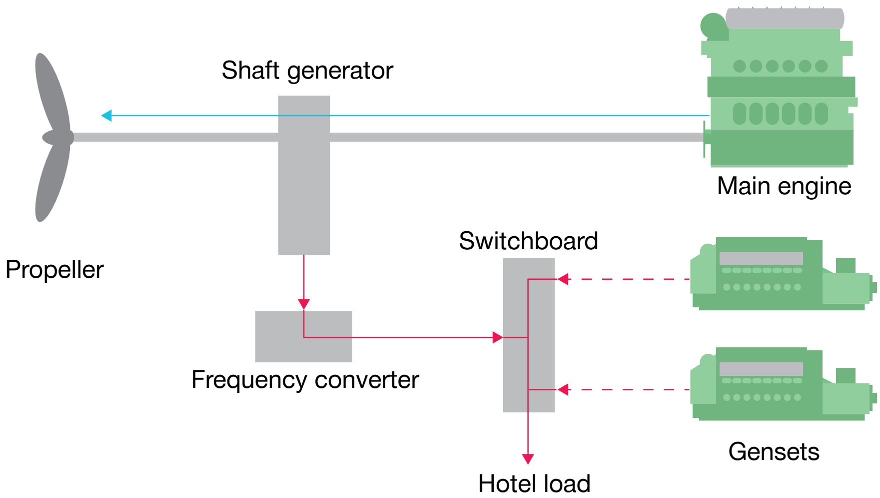


Fig. 2: Schematic view of the propulsion system with the shaft generator in PTO mode. The blue arrow represents the energy flow from the ME, and the red solid arrow represents the energy flow from the PTO. The dashed red arrows represent the energy flow from the gensets, when these operate in parallel, or when the vessel operates at low rpm without the PTO engaged.

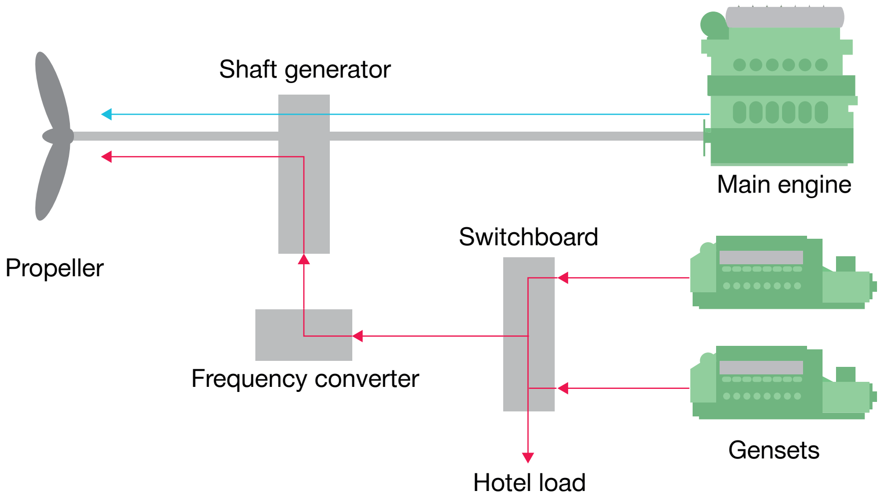


Fig. 3: Schematic view of the propulsion system with the shaft generator in PTI mode, and in parallel with the ME it will boost the propulsion power delivered to the propeller. The blue and red arrows are the energy flows from the ME and genset, respectively.

Diesel-electric mode – power take-home (PTH)

In diesel-electric mode, the ME is declutched from the propeller shaft line and does not supply propulsion power. Instead, the propulsion power comes from the genset alone as the only power source of the vessel. The power generated by the genset is supplied to the switchboard and then to the frequency converter before being transformed to mechanical power in the shaft motor. The diesel-electric mode increases the specific fuel consumption significantly as the power is produced by the less fuel-efficient genset. Fig. 4 shows the concept of the diesel-electric mode.

The diesel-electric mode is used if failures occur on the ME and at the same time a need for “power take-home” (PTH) occurs to safely reach a port. The PTH feature permits the vessel to depart with very short notice from a port in case of an emergency (a fire on the ship or on the port side) even if the ME is not operational.

Recently, discussions regarding underwater noise have been ongoing. By applying a battery pack to propel the vessel in PTH mode, it is possible to stop the genset and hereby mitigate the underwater sound radiation from energy production on the vessel. As an alternative, battery propulsion utilising electric energy from gensets suspended on elastic chocks to drive a shaft motor in PTH mode will also greatly reduce underwater noise emissions. Some ports reduce fees for vessels equipped with special underwater noise reduction devices.

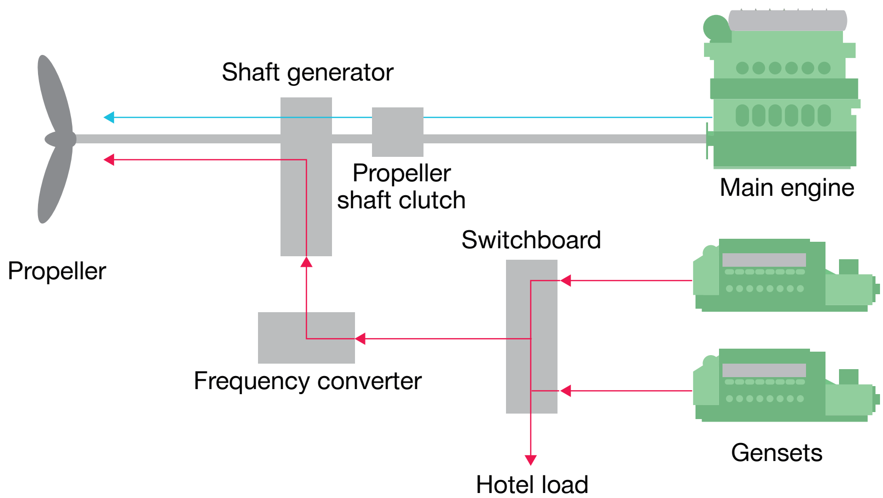


Fig. 4: Schematic view of the propulsion system where the shaft generator is working in PTH mode. The red arrows represent the energy flow from the gensets.

Advanced applications of PTO

At the quayside, gensets will normally cover the hotel load of the vessel. By using a declutchable propeller and a PTO, the ME can be declutched in order to produce electricity and in this way substitute one or more gensets while in port. If the propeller is to be declutched from the ME, while maintaining PTH as an option, two clutches, one on either side of the generator/motor, are required.

For some alternative fuels, gensets that are capable of operating on the alternative fuel used by the ME may not be available. In this case, a declutchable propeller may be especially attractive. However, when changing fuel from MDO to the alternative fuel, it is important to observe the limits imposed on minimum engine load as well as the requirements for stable operation on the alternative fuel.

Declutching the propeller from the ME reduces the inertia experienced by the engine, and special evaluations must be performed in cooperation with MAN ES to ensure that the engine will not overspeed in case of a tripping generator. Such evaluations may lead to a requirement for an enlarged turning wheel or pose limitations to the power permitted with the propeller declutched. Furthermore, the capability of the engine to maintain a stable rpm speed must be specifically considered when operating a generator with the propeller declutched.

The three considerations mentioned above may prove to be conflicting, and there may be other plant-specific requirements to consider. For any specialised utilisation of declutchable propellers, PTH and PTO, please contact the MAN ES Marine Project Engineering department at: MarineProjectEngineering2S@man-es.com

Dimensioning of power take-off

Dimensioning the optimum capacity of a PTO is a multi-disciplinary design exercise where not only the need for electric energy on board the vessel in various conditions must be considered. But also the possibilities for a PTO within the engine load diagram and for maintaining a stable speed while using the PTO must be considered as well. In the following chapter, the load limits of MAN B&W engines are introduced along with:

1. PTO layout limit, which sets the limit for the combined engine load for propulsion and PTO.
2. Design limits set to ensure rpm-stability.

The engine load diagram

The load diagram of an MAN B&W engine defines the power and speed limits relative to the specific maximum continuous rating (SMCR) point specified within the engine layout diagram. The position of the SMCR point within the layout diagram does not influence the appearance of the load diagram. Fig. 5 shows a load diagram.

Line 1: The engine layout curve, which passes to the 100% SMCR rpm and the 100% SMCR power point. The curve coincides with curve 2.

Line 2: The heavy propeller curve is the light propeller curve (line 6) shifted to the left by the propeller light running margin (LRM) of the propeller. The LRM is included to account for added resistance from wind, waves and hull fouling.

Line 3: Maximum continuous rpm. For engines with SMCR on the L1-L2 line in the layout diagram, up to 105% of L1-rpm can be utilised.

If the SMCR is sufficiently speed-derated, 110% of SMCR rpm, but no more than 105% of L1-rpm, can be utilised if permitted by the torsional vibration conditions, see also Chapter 3 of the MAN ES paper “Basic principles of ship propulsion”.

Line 4: This line represents the torque/speed limit for continuous operation of the engine, which is mainly defined by the thermal load of the engine components.

This limit can be extended temporarily with the AWC functionality described in the MAN ES paper: “Adverse Weather Condition functionality and minimum propulsion power”. The AWC functionality cannot be utilised for PTO operation and it is therefore not shown in Fig. 5.

Line 5: The line represents the maximum mean effective pressure (mep) acceptable for continuous operation.

Line 6: The light propeller curve for a clean hull and calm weather. This curve is often used for propeller layout.

Line 7: Maximum power for continuous operation. When increasing the rpm towards lines 3 and 9, the maximum power for continuous operation cannot exceed 100%.

Line 8: Normal overload operating limit of an engine without the AWC functionality.

Line 9: This is the maximum acceptable engine rpm at sea trial. 110% of SMCR-rpm, but no more than 107% of L1-rpm if permitted by torsional vibrations.

Line 10: This is the PTO layout limit explained in the following separate section.

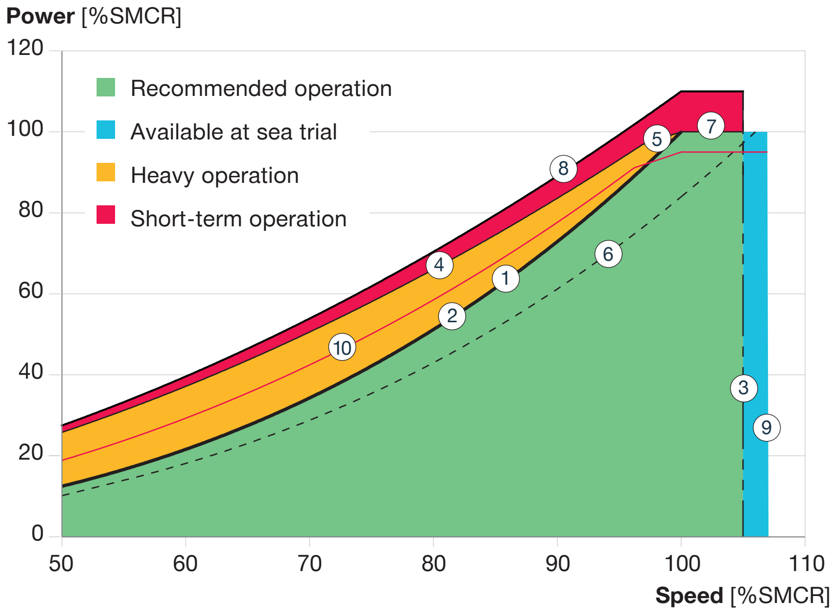


Fig. 5: Engine load diagram with the engine layout diagram applied. The numbers represent the different lines in the diagram. The load diagram is independent of the SMCR point. For further notes, see chapter 3 of the paper “Basic principles for ship propulsion”.

MAN ES PTO layout limit

In the following section, the MAN ES PTO layout limit guideline is described. When adding a PTO to the ME, the torque required for the PTO is added on top of the torque required for driving the propeller at the set speed. As a result, the operating point in the engine load diagram moves upward towards the torque limit of the engine.

When dimensioning a PTO, it is important to ensure stable PTO operation by considering the resulting increase of the torque required, and the resulting engine load. It is mainly done by balancing the thermal loads on the engine, and by ensuring an operating margin for torque variations resulting from, for example, added wave resistance. In order to balance these considerations in the dimensioning of the PTO design capacity, a PTO layout limit has been established. Table 2 gives the PTO mechanical power allowed under the PTO layout limit in relative figures.

The mechanical power of a PTO is the difference in power between the light propeller curve (line 6) and the PTO layout limit (line 10), see Equation (1).

Here P_{SMCR} and n_{SMCR} is the power and the engine speed at the SMCR point, n is the specific engine speed at which the mechanical PTO power is generated, and LRM is the light running margin. The magnitude of the propeller LRM influences the power available for PTO. Table 6 on page 24 shows the PTO power available as a function of engine speed, and propeller LRM relative to SMCR power.

It is important to underline that the difference between the light propeller curve (line 6) and the PTO layout limit (line 10) can be applied as mechanical load to the PTO. In the PTO, mechanical power is converted to electric power. The relation between electric and mechanical power is given by Equation (2).

Equation (2)

$$PTO_M = \frac{PTO_E}{\eta_{PTO}}$$

The efficiency η_{PTO} between mechanical and electric power is normally in the range of 90-95% at the design speed and load, decreasing slightly at lower speeds or loads.

For reasons of rpm stability, see the later separate section, the minimum speed permitted for PTO operation is 50% of the SMCR speed, whereas the maximum operating speed depends on the specific plant.

When determining the maximum speed for which to design the PTO, note that at 97% of the SMCR speed, a discontinuity in the PTO layout limit is encountered, because of the maximum 95% P_{SMCR} requirement. The PTO can work at a higher speed but it requires that the power management system (PMS) can reduce the load on the PTO to the level permitted by the PTO layout limit.

As an example: For a 23,000 teu ULCV with an MAN B&W 11G95ME-C10.5 engine (SMCR is 64,500 kW at 80 rpm) and a PTO with a mechanical power of 3,600 kW, the PTO speed can be extended to 102% of the SMCR speed before the light propeller curve and the added PTO power exceeds the PTO layout curve, see Fig. 6.

Table 2

RPM [% SMCR]	$PTO_{layout\ limit}$ [% SMCR]
60 – 96.2	100 × (rel. rpm [%] / 100%)$^{2.4}$
96.2 – 100	95 × (rel. rpm [%] / 100%)
>100	95

Table 2: SMCR dependent values for the mechanical power allowed under the PTO layout limit given in relative figures.

Equation (1)

$$PTO_M = P_{SMCR} \times \left[PTO_{layout,limit} - \left(\frac{n}{1 + LRM\% \times n_{SMCR}} \right)^3 \right]$$

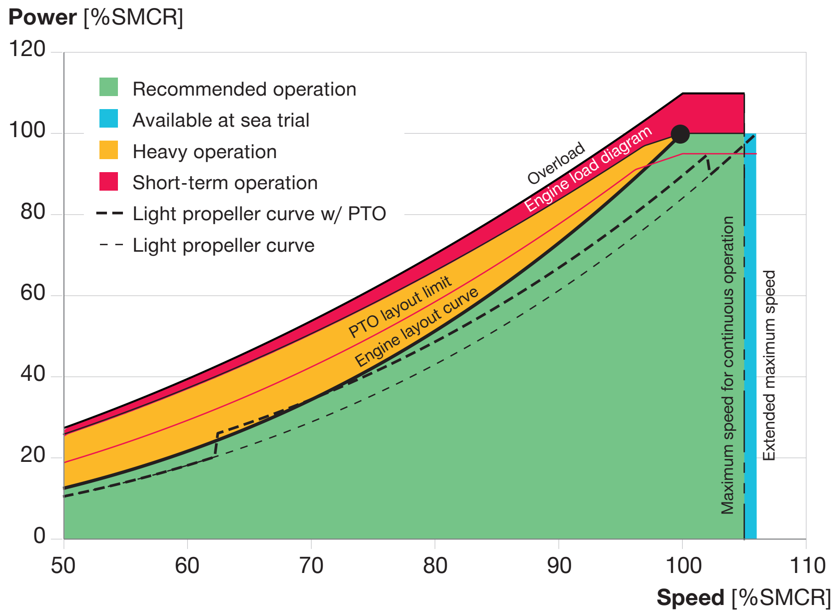


Fig. 6: Engine load diagram with a LRM of 6%. The light propeller curve with added PTO power works in the range of 63% to 102% of the SMCR speed.

PTO and rpm-stability design limits

Besides the constraints on PTO operation made by the load diagram, governed by the PTO layout limit, it is important to consider the impact of the PTO on the capability of the ME to maintain a stable rpm when operating the PTO.

If the generator is connected to the grid via a frequency converter, the mechanical torque from the generator is inversely proportional to the engine speed required to maintain constant electric power, i.e. if the engine speed is increased, the torque required to deliver the same power is reduced.

The inverse proportionality destabilises the engine speed: If the electric power output needs to increase, the torque required from the PTO increases. The engine must respond to this increase in torque and may reduce the speed slightly if the torque increase required is so big that the engine cannot increase the torque output instantaneously. This will result in a further increase of torque on the PTO in order to deliver the desired electric power, which may destabilise the rpm further.

The control of the engine speed of a two-stroke low speed marine engine is relatively slow by nature, because of the relatively low firing frequency. This can make it difficult for the ECS system to maintain a constant engine speed if the generator power is large compared to the power required for propulsion.

In order to ensure a stable engine speed, and to avoid rpm hunting while operating a PTO, there are a number of requirements to the power of a PTO relative to the NCMR of the engine. For example, that the maximum rpm of the layout diagram for the engine design must be established. Fig. 7 shows the different requirements to vessels with CPP and FPP.

MAN ES offers to provide an evaluation of the specific plant against a smaller fee if it meets any of the following criteria:

- If the mechanical PTO power output is higher than specified in Fig. 7 or if the PTO is used at below 40% NMCR speed.
- If the 1st node of the torsional vibration frequency in the shaft line, or across the coupling to a geared generator, is lower than 3Hz for FPP plants and 5Hz for CPP plants.
- If the PTO design includes a clutch for disconnecting the propeller.
- If the design deviates from a standard design.

The evaluation may lead to changes in:

1. Control equipment, which must include more signals from the plant.
2. Requirements to the mechanical PTO components driven by the engine.
3. Moreover, the evaluation may also lead to a change in the use of the PTO system.

In addition to considering operation down to 40% of the NMCR speed, the PTO must not operate below 50% of the SMCR speed as a general requirement. For very speed-derated engines with an SMCR in the left part of the layout diagram, the minimum PTO speed of 50% SMCR will in some cases be a stricter limit than the minimum speed of 40% of the NMCR.

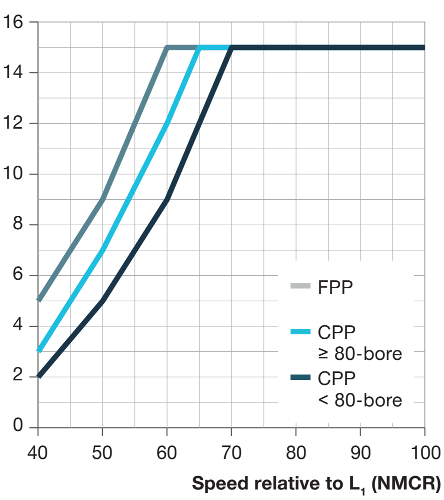


Fig. 7: Maximum mechanical PTO output relative to L1 to ensure acceptable governor performance and stability. It is an additional requirement that the PTO is not operated below 50% of the SMCR speed.

Methods to increase the PTO power

If the desired PTO cannot be accommodated within the PTO layout limit or the rpm-stability criteria, or a combination, various methods exist that can increase the power available for PTO.

If we consider first the PTO layout limit:

1. The propeller LRM can be increased to increase the margin between the light propeller curve and the PTO layout limit.

2. If it is undesirable to increase the LRM by reducing the propeller pitch to make the propeller lighter, and thereby run faster, the SMCR power of the ME can be increased while maintaining SMCR speed and propeller curve. This will also increase the margin between the light propeller curve and the PTO layout limit. Increasing the SMCR power to accommodate the PTO corresponds to the previous guideline for PTO layout from MAN ES. This guideline recommended adding the PTO power to the SMCR power required for propulsion and, to some extent, this may still be relevant for excessive PTO capacities.

3. A third option to increase the margin between the PTO layout limit and the light propeller curve is to decrease the SMCR speed, if it is possible within the layout diagram of the engine type considered. Torsional vibrations may be a concern to investigate and address adequately.

If the PTO for the specific propulsion plant does not fulfil the criteria for rpm stability, contact MAN ES for specific evaluations, which are performed against a fee.

An alternative to increasing the LRM by decreasing the propeller pitch, and thereby allowing the propeller to run faster, may be to reduce the number of propeller blades. There is a potential cost to this solution consisting of a decrease in propeller efficiency. By reducing the propeller blade number, the optimum rpm of the propeller is increased, which increases the LRM, i.e. the margin between the propeller curve and the engine load limits.

Reducing the propeller blade number requires careful evaluation of the propeller performance, and it must not be considered a standard tool for increasing the PTO power available, but it may be an option worth considering.

Operational design considerations

When the resistance on the vessel increases, e.g. from hull fouling or heavy weather, the propeller curve moves upward in the load diagram as more torque is required to maintain the same engine speed under the added resistance.

The power taken out via a shaft generator adds to the power required for driving the propeller. As resistance increases on the hull, e.g., when the sea state develops, there comes a point where load must be transferred from the shaft generator to the gensets to ensure a margin towards the torque limit.

If the torque limit has been reached, the speed of the engine will decrease, reducing the power available for PTO. If the PTO load is not decreased before the torque limit is met, a blackout of the vessel may ultimately occur. In order to avoid blackout, the electric load of the PTO must be transferred to the gensets and the full power of the ME made available for propulsion of the vessel. When the resistance of the vessel eases, the PTO can once again be engaged.

MAN ES is developing an enhanced interface for the integration of a PTO between the ECS system and the PMS. The enhanced interface offers a signal that describes the margin towards the load limits of the engine and a set point for when to initiate load sharing between the PTO and a genset.

Floating frequency systems and constant speed operation of CPPs

The load profile of a vessel changes according to the voyage, operation and weather. Therefore, the speed of the shaft is not fixed, but fluctuates. Normally, a frequency converter is used for FPP vessels or vessels with controllable pitch propellers operating along a combinator curve to prevent fluctuations of the electrical current.

For vessels like bulk carriers and tankers which may experience low speed variations, a floating frequency system can be utilised as an alternative to a system with a frequency converter. This system is often cheaper, but it requires that most of the electric components on board can tolerate a varying frequency, for example 50-60Hz. For systems which require a uniform frequency, a smaller frequency converter can be applied locally. However, the parallel working mode of PTO and auxiliary engines is, not an option as the frequency of the power delivered from the PTO may differ from the frequency of the gensets. Due to these limitations, and the lower cost of frequency converters, the popularity of floating frequency systems has dropped over the last decade.

If a CPP operating at constant rpm along a constant rpm-generator curve is considered, a synchronous converter can be used directly. This application results in a lower propeller efficiency at lower loads than by following a combinator curve. Therefore, this solution has also experienced reduced popularity as the cost of frequency converters, permitting operation along a combinator curve, has dropped.

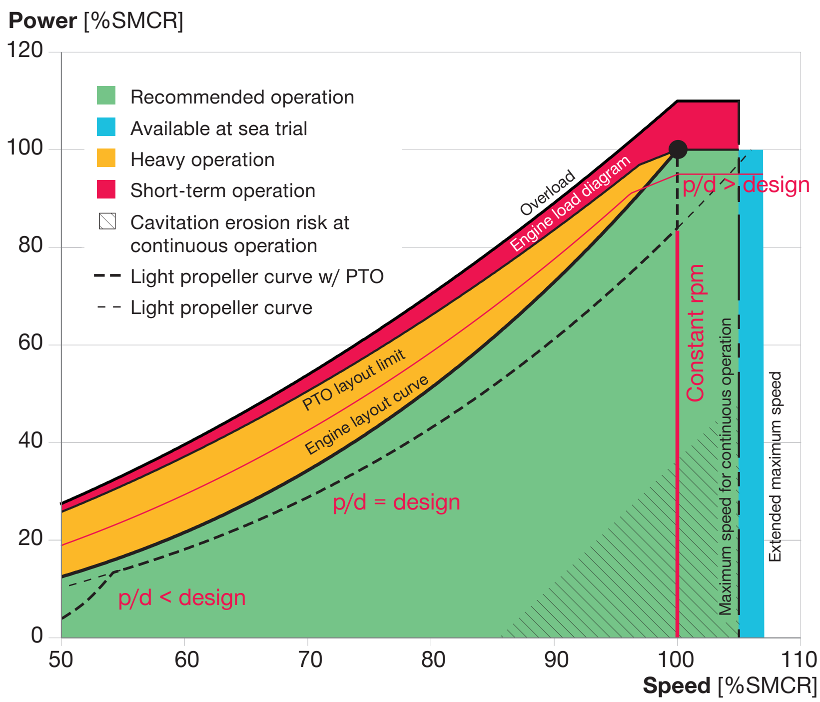


Fig. 8: From MAN ES paper “Basic principles of ship propulsion” on CPP curves

Existing generator solutions

With reference to Table 1, the following section presents some the shaft generators mentioned, their designations, and their operating modes. The generators are applicable for engines in the MAN ES two-stroke marine catalogue. As a common denominator, they enable fuel savings, reduce CO_2 emissions, and improve the EEDI attained.

The RENK MARHY® generator

The Maritime Hybrid Drive (MARHY) is a stand-alone aft-end tunnel geared generator (ATG). The system offers an electrical propulsion mode of PTO/PTI/PTH. The system is modular based and consists of a tunnel gear unit, a PSC, and an electrical package. The electrical package includes an electric motor, a frequency converter with a harmonic filter, and a digital control and monitoring system, see the system overview in Fig. 9.

The generator can be applied for any type of vessel with CPP or FPP with a maximum SMCR power of 60,000 kW. The electric power range of the generator is 500-10,000 kW.

The MARHY tunnel gear unit is mounted around the propeller shaft line, and it transmits torque from the shaft to the generator through a highly flexible coupling.

A conical PSC transmits the torque between the ME and the propeller shaft line. The PSC allows dis/engaging of the shaft and tunnel gearbox unit, which is required in PTH mode or during maintenance when the propeller must run freely. The PSC is fully automatically operated from the engine room.

To activate the PTH feature, the ME has to be disconnected from the propeller shaft line. At standstill, the PSC is opened. The reduced thrust to the propeller in PTH mode is then transmitted by the thrust bearings, which are integrated into the clutch. To switch back to the ME propulsion mode, the PSC must be engaged at standstill once again. The PSC is then moved into position and is closed hydraulically to eliminate any clearance.

The RENK MARHY tunnel gear system is also offered without a shaft clutch if PTO and PTH functionality is not required.

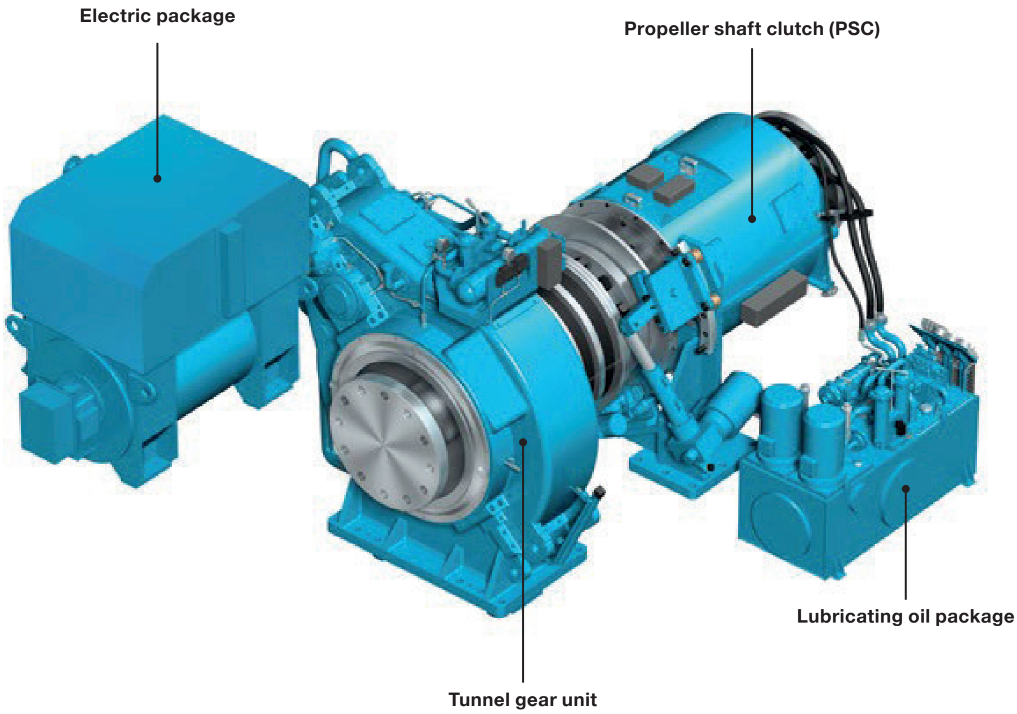


Fig. 9: The RENK MARHY® package with component description

The RENK/MAN ES IFPS generator

It is not always possible or practical to add a shaft generator between the ME and the propeller. The integrated front-end power system (IFPS) offers an alternative solution. The system is mounted directly on front-end of the engine, and therefore adds only limited length to the propulsion system.

The IFPS is of the front-end geared (FEG) generator type. The system offers a PTO mode and is modular based.

The system consists of a single stage gearbox with an integrated flexible coupling, one or multiple permanent magnet generators with associated frequency converters, and a transformer for connection to the vessel's grid. The gearbox is coupled to the crankshaft by a central intermediate shaft and an elastic coupling. An angle encoder can be added on the coupling.

The system can be used for vessels equipped with CPP or FPP. The system is module based with at least one and as much as four generators, each with a power output of 500 kW (2000 kW in total). The system can be used alone or in a parallel mode with another IFPS in a twin-screw propulsion plant or a genset.

Fig. 10 shows a system overview of the generator mounted on an MAN B&W two-stroke marine engine.

Since the generator is directly bolted to the front-end, no external loads are applied to the shaft line between the ME and the propeller. This eases the shaft alignment and reduces system installation costs significantly compared to stand-alone systems requiring shaft alignment.

For a specific vessel project, the decision of whether or not the IFPS solution is suitable must be based on a torsional vibration analysis, the selected propeller, and the capacity of the ME.

The HHI EMG - engine mounted generator

The engine mounted generator (EMG) is of the front-end direct-coupled (FED) generator type. The EMG is mounted directly on the front of the engine. Therefore, no changes are required to the intermediate propeller shaft line. The generator itself works as a flywheel, which means additional space is saved. The difference

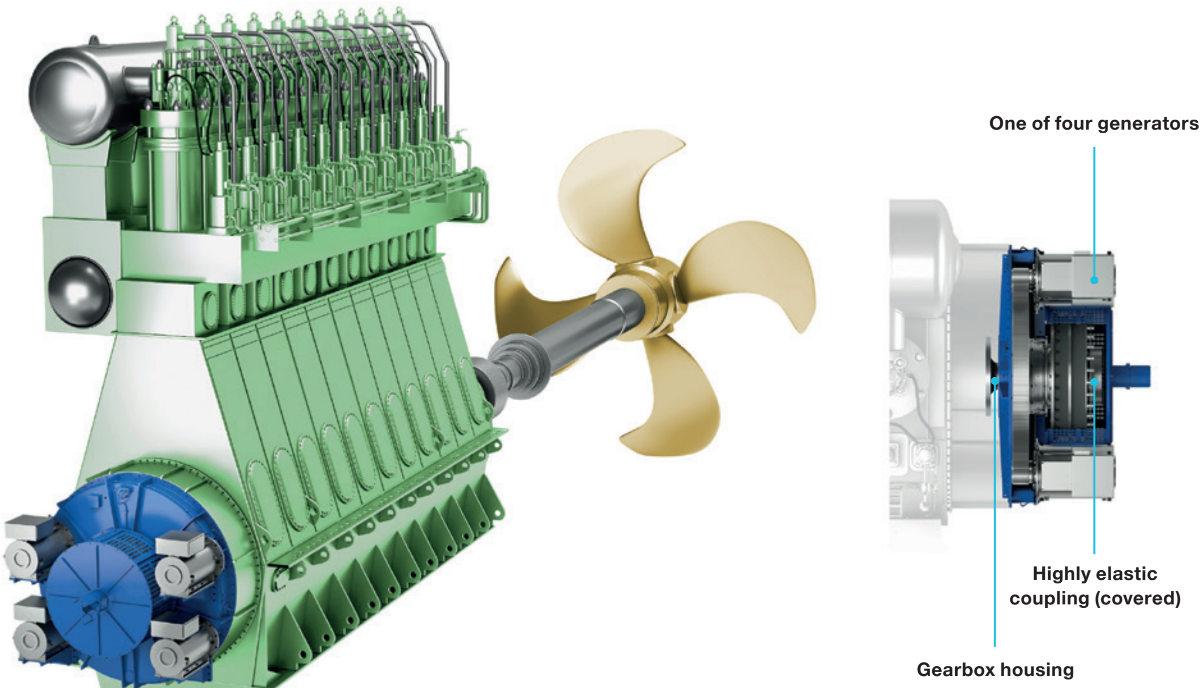


Fig. 10: Left: The RENK/MAN-ES IFPS generator mounted on the frontend of a MAN ES two-stroke marine engine. Right: a cross-section view of the IFPS showing generator, coupling and gearbox housing.

between the EMG and the IFPS is that the EMG does not have a gearing between the shaft crankshaft and the generator. This means that the generator operates at the same low speed as the ME, which results in a low current and a greater need for smaller generator wires and more windings compared to that of an IFPS.

Fig. 11 shows a schematic of the EMG design and a cross-section of the system.

The generator has approximately the same weight as the original ME turning wheel, which means the bearing loads of the ME are unchanged when the generator is applied.

Originally, the EMG was designed for an MAN B&W 7G80ME-C9 engine. It is the plan of HHI and HHI to offer the EMG solution to a larger scale of MAN B&W engines. As each propulsion train (engine – shafting – propeller) differs from vessel design to vessel design, each EMG solution must be evaluated and accepted by both HHI and MAN ES. This is a matter of mechanical, electrical, rpm-stability and torsional constraints.

The aft-end direct mounted shaft generator

The aft-end direct-mounted shaft generator is of the ASM generator type. The generator is integrated directly on the intermediate propeller shaft away from the engine structure and requires no gearbox or flexible coupling. The generator has no physical interface with the ME.

The intermediate propeller shaft is part of the generator as it constitutes the rotor part. The alternator maker mounts the intermediate propeller shaft. The stator housing is mounted on a separate foundation prepared by the shipyard; see Fig. 12 for an overview of the generator.

The generator offers propulsion modes PTO and PTI. The high electric capacity of such a PTO system has made it a popular choice for container vessels.

Before installation, the following preparations must be performed:
- Tank top foundation for the alternator
- Cooling water supply for water-cooling of the alternator
- Wiring between alternators
- Frequency converter system, switchboard and control system.

For the traditional thyristor converter solution, additional seating for the synchronous condenser unit and the static converter cubicles are necessary but can be avoided by using the shaft generator type with PWM technology.

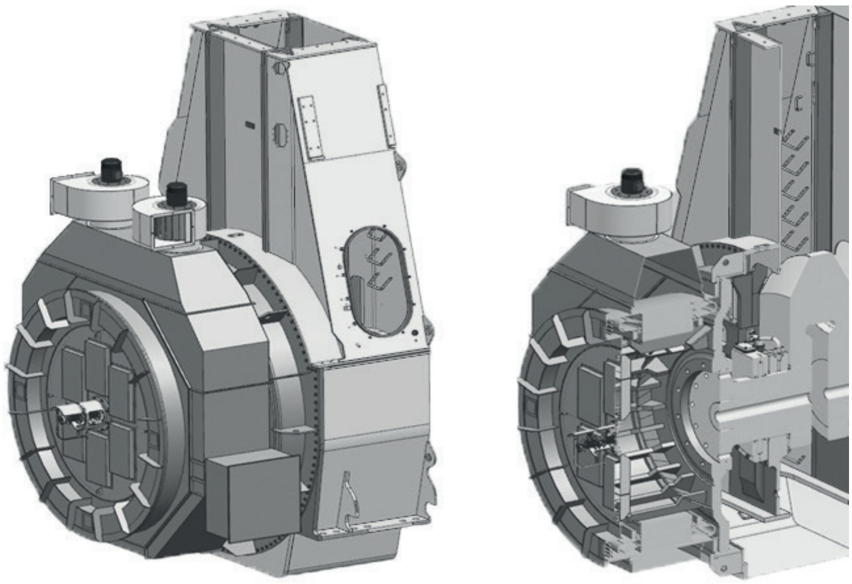


Fig. 11: The HHI EMG presented along a cross-section view of the system

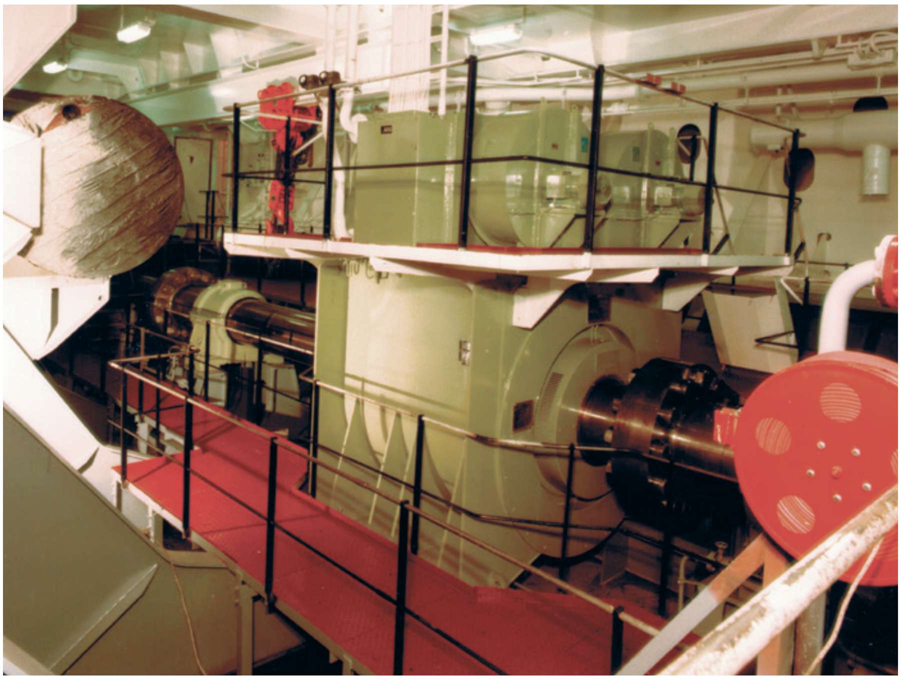


Fig. 12: Installation of the aft-end direct-mounted shaft generator 1300-60

PTO and the energy efficiency design index

The aim with the EEDI number is to enable comparison of GHG emissions from new ships, using a baseline calculated from existing ships built in the period 1999 to 2009. The EEDI number expresses the CO_2 emissions relative to the transport work performed.

The EEDI value is calculated by the simple form in Equation (3).

Equation (3)

$$EEDI = \frac{P_{ME} \times C_F \times SFC}{capacity \times V_{ref}}$$

- P_{ME} is the power of the ME at 75% MCR
- C_F is the non-dimensional carbon factor accounting for the amount of CO_2 (mass) emitted per mass of fuel burned
- SFC is the specific fuel consumption in g/kWh at 75% MCR
- Capacity is the engine deadweight tonnage
- V_{ref} is the vessel speed at 75% MCR.

The complete equation for calculating the index also considers the emission contribution from gensets/auxiliary engines, P_{AE} (genset), shaft generator/motor and efficiency technologies. Equation (4) represents the numerator of the EEDI equation.

In the EEDI equation, the variable fj..i refers to the availability of alternative energy systems installed on board, for example, cranes, ramps, etc. This contribution is not treated here.

By installing a shaft generator, it is possible to substitute SFC_{AE} by SFC_{ME} which reduces the EEDI index. Besides, P_{ME} can be reduced by the nameplate power of the PTO, $P_{PTO,\ NP}$ if P_{PTO}, NP/0.75 is sufficient to cover P_{AE}. Nothing more than P_{AE} may be subtracted from P_{ME} because of the P_{PTO}.

Equation (5)

$$\left(\left(P_{ME} - \frac{P_{PTO,NP}}{0.75}\right) \times 0.75 + P_{PTO,NP}\right)$$

As the reference speed V_{ref} must be consistent with P_{ME}, the reference speed will also be reduced by the PTO installation. However, as the power consumption of a typical merchant vessel is proportional to the speed by an exponent of 3 to 4, $P \propto V^{3\ to\ 4}$, the reduction of P_{ME} in the numerator by the PTO improves the attained EEDI to a greater extent than the speed reduction to V_{ref} in the denominator.

Nonetheless, using the power take-in function (PTI) to increase the service speed of the vessel will have the opposite effect on the EEDI due to the increased fuel consumption of the gensets.

Equation (4)

MAIN ENGINE EMISSIONS	AUXILIARY ENGINE EMISSIONS	SHAFT GENERATOR / MOTOR EMISSIONS	EFFICIENCY TECHNOLOGIES
$\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot SFC_{ME(i)} \cdot C_{FME(i)}\right)$ +	$(P_{AE} \cdot C_{FAE} \cdot SFC_{AE})$ +	$\left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEff(i)}\right) C_{FAE} \cdot SFC_{AE}\right)$ −	$\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)$

Shaft generator selection - examples

This section exemplifies the selection process when specifying a propulsion plant with a shaft generator. The section will consider the PTO layout limit, rpm-stability evaluations, and evaluate impacts on EEDI as well as fuel economy. The following section has two examples, one with an MR product tanker and one with an LPG carrier.

MR tanker

The first example considers a 50,000 dwt MR product tanker. The tanker is equipped with an MAN B&W 6S50ME-C9.7 engine with an SMCR equal to 7,800 kW at 93.5 rpm connected to an FPP. The design speed is 14.5 knots.

The hotel load of the tanker is assumed to be 350-400 kWe. In order to have sufficient PTO power margin, a PTO with an electric power output of 500 kWe is installed. The PTO has a mechanical efficiency of 92%, which means the mechanical PTO power is equal to 500 kWe/92% = 543 kWm.

Table 3 shows the particulars of the MR tanker.

Table 3

Particulars of the 50,000 dwt MR tanker		
Scantling draught	m	12.8
Length between perpendiculars	m	177.0
Waterline length	m	179.6
Breadth	m	32.2
Propeller diameter	m	6.8
Sea margin	%	15
Engine margin	%	10
LRM	%	6
Design speed	knots	14.5
Type of propeller	-	FPP
Block coefficient	-	0.82

MAN PTO guidance

Fig. 13 shows the load diagram of the MAN B&W 6S50ME-C9.7 engine. The SMCR point, the light propeller curve for 6% LRM, the engine layout curve, and the PTO layout limit are plotted in the figure. The figure shows how the mechanical PTO power is added to the power required along the light propeller curve in the range of 50-101% SMCR speed. As the combined load of the light propeller curve and PTO does not exceed the PTO layout limit, the intended PTO of 500 kWe can be applied.

RPM stability

When selecting a shaft generator, the PTO stability must also be considered when deciding whether the PTO is suitable or not for the engine.

The mechanical PTO power relative to the NMCR of the engine is 543 kWm/10,680 kW = 5.1%.

According to Fig. 7 in the section PTO and rpm-stability design limits", the relative power of 5.1% corresponds to approximately 40% of the NMCR speed with an engine bore size smaller than 80 cm for an FPP plant. Because 50% SMCR speed equals 40% NMCR speed in this case, it is not necessary to take further action towards rpm-stability. Therefore, the conclusion is that a PTO system with an electric output of 500 kWe can be applied to the system in the working domain of 50-98% SMCR speed without creating stability problems.

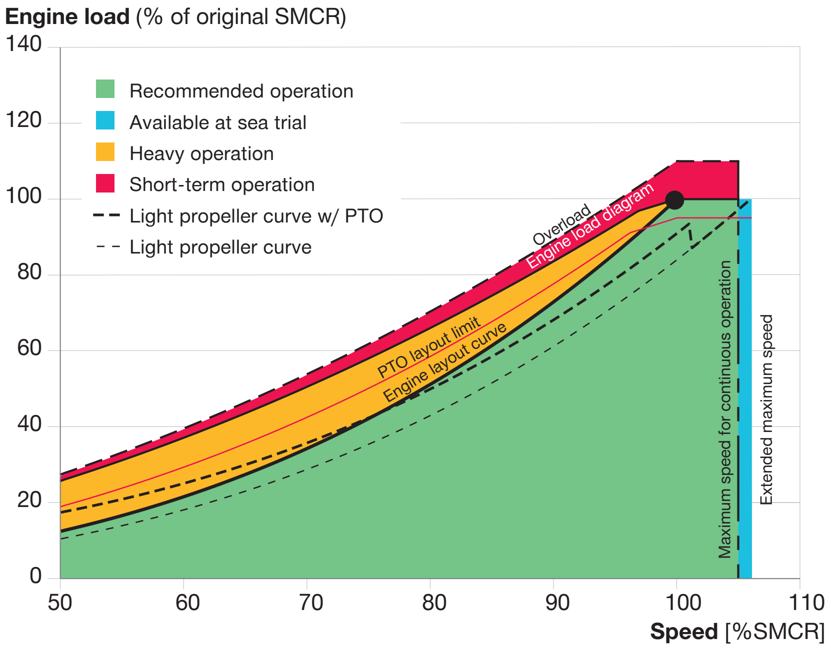


Fig. 13: The load diagram of the MAN B&W 6S50ME-C9.7 engine together with the SMCR point, the light propeller curve for 6% LRM, the engine layout curve, and the PTO layout limit.

EEDI calculation

The following section will first calculate the EEDI value without PTO applied and afterwards with PTO applied. The EEDI calculation is based on the formula presented in section “PTO and the energy efficiency design index” on page 16. For the calculation, the following assumptions have been made:

1. The vessel reference speed at 75% MCR has been estimated to 13.26 knots using the Holtrop Mennen method.
2. The $SFOC_{ME}$ at Tier II is estimated to 157.6 g/kWh through CEAS.
3. A margin of 6% is added to the $SFOC_{ME}$.
4. For a ME smaller than 10,000 kW, the auxiliary power P_{AE} is equal to 5% of 75% of the MCR, which is determined to 390 kW.
5. An $SFOC_{AE}$ of 200 g/kWh is assumed for the auxiliary engines, and a margin of 5% is added.

Equation (6)

The attained EEDI then becomes:

$$\text{Attained EEDI without PTO} = \frac{(P_{ME} \times 0.75 \times C_{F,ME} \times SFOC_{ME} + P_{AE} \times C_{F,AE} \times SFOC_{AE})}{dwt \times V_{ref}} =$$

$$\frac{7800 \times 0.75 \times 3.206 \times 167.1 + 390 \times 3.206 \times 210}{50{,}000 \times 13.26} = 5.11$$

Equation (7)

The EEDI relative to the reference line becomes:

$$\text{EEDI relative to reference line} = \frac{\text{Attained EEDI}}{1{,}218.8 \times 50{,}000^{-0.488}} =$$

$$5.11/(50{,}000 \times 1218.8^{-0.488}) = 82.5\%$$

Vessels built after 1 January 2020 must comply with the EEDI phase 2, which requires 20% reduction of the reference line. In the case, without the PTO, the attained EEDI lies 17.5% below the reference line, which is not sufficient to comply with the environmental legislation. The PTO output, $P_{AE,PTO}$, that may replace the auxiliary power is equal to $500 \times 0.75 \times 0.75 = 281$ kW.

Due to the $P_{AE,PTO}$ factor, the reference speed is reduced to 13.06 knots.

Equation (8)

The attained EEDI with PTO then becomes:

$$\text{Attained EEDI with PTO} =$$

$$\frac{\left(\left(P_{ME} - \frac{P_{AE,PTO}}{0.75}\right) \times 0.75 + P_{AE,PTO}\right) \times C_{F,ME} \times SFOC_{ME} + \left(P_{AE} - P_{AE,PTO}\right) \times SFOC_{AE} \times C_{F,AE}}{dwt \times V_{ref}} =$$

$$\frac{\left(\left(7800 - \frac{281}{0.75}\right) \times 0.75 + 281\right) \times 3.206 \times 167.1 + (390 - 281) \times 210 \times 3.206}{50{,}000 \times 13.06} = 4.84$$

Equation (9)

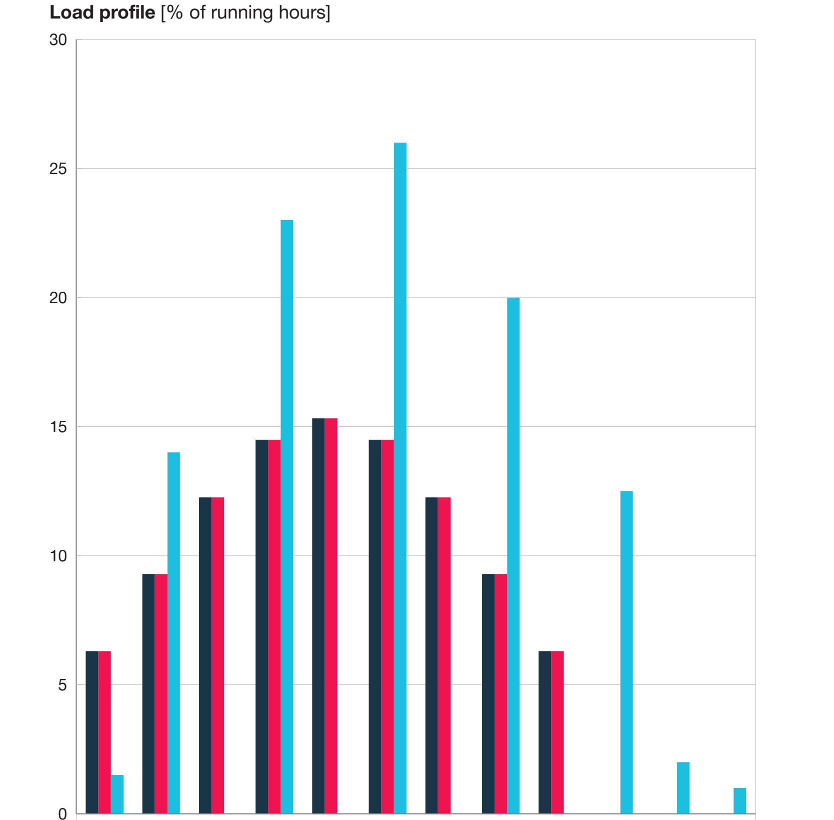
$$\text{EEDI Relative to reference line} = \frac{4.84}{1{,}218.8 \times 50{,}000^{-0.488}} = 79.1\%$$

Compared to the reference line, a 20.9% EEDI reduction can be achieved with a PTO. This is enough to ensure compliance with EEDI phase 2. For compliance with EEDI phase 3 in 2025, lowering the SMCR power could be considered, and alternative fuels with a lower carbon factor could be used.

It should be noted that a greater EEDI discount could be obtained by increasing the $P_{AE,PTO}$ beyond 500 kWm to the value of P_{AE}, thereby achieving the full benefit on the EEDI of a PTO. This must be done with consideration to the MAN ES PTO layout limit, and the rpm stability requirements.

Relative savings in operation expenditure

By installing a PTO, the overall opex of the vessel decreases as the highly efficient ME can perform the electricity production. A vessel's opex depends on its load profile. An operating profile consisting of 250 days/year at sea, where 1,200 hours/year are in NECA/SECA, and 4,800 hours/year are in global waters is assumed for the calculation. See the load and operating profile in Fig. 14.



Load [%]	25	30	35	40	45	50	55	60	65	70	80	90
Global	1.5	14	0	23	0	26	0	20	0	12.5	2	1
SECA	6.3	9.29	12.26	14.49	15.32	14.49	12.26	9.29	6.3	0	0	0
NECA	6.3	9.29	12.26	14.49	15.32	14.49	12.26	9.29	6.3	0	0	0

Time [%]

Fig. 14: Load profile of the vessel showing the time spent in globally, NECAs and SECAs

In the calculation, a fuel price of 250 USD/tonne and a lubricating oil price of 2,000 USD/tonne is assumed.
The vessel utilizes the Tier III EGRBP technology and therefore a price of 200 USD/tonne is assumed for the NaOH (in a 50% solution, as well as a price for handling the discharged sludge of 100 USD/tonne.

The opex of the vessel without PTO is 1,789,689 USD/year and the opex with PTO is 1,722,670 USD/year. The numeric difference corresponds to an opex reduction of 3.74%. The saving indicates that it is a positive business case to include a PTO in the design, as can be seen in Fig. 15, where the NPV of a period of 15 years is calculated.
In addition to the fuel savings, the reduction of running hours on the gensets, and thereby reduced overhauling costs, may be reduced significantly. However, the genset overhauling costs are highly dependent on the operation of the vessel, which is

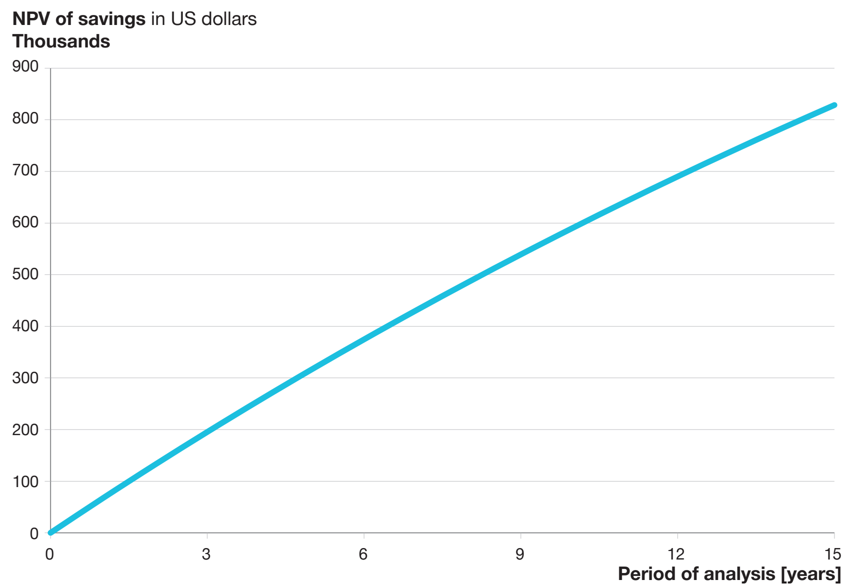


Fig. 15: NPV of savings in USD for a period of 15 years point, the light propeller curve for 6% LRM, the engine layout curve, and the PTO layout limit.

the reason for not including these in the specific example.

Similar ME comparisons (MECO) can be obtained by contacting the MAN ES Marine Project Engineering department at: MarineProjectEngineering2S@man-es.com

Medium gas carrier

The second example considers a 38,000 m³ LPG carrier. As an initial engine design, an MAN B&W 6S50ME-C9.7 engine with an SMCR of 7,800 kW at 93.5 rpm is chosen. The vessel is equipped with an FPP and the service speed is 16.2 knots, see Table 4 for vessel particulars.

The transported LPG is cooled by a refrigeration system, see Table 5 for electric cooling load for ballast, laden and cooling-down conditions. The electric output of the PTO is designed to cover 1,300 kWe at laden condition. The 1,700 kWe needed in cooling-down mode is covered by assistance from the genset. The mechanical efficiency of the PTO is 92%, which means the mechanical power transfer is 1,300 kWe/92% = 1,413 kWm.

Load diagram adjustment for PTO

Fig. 16 shows the load diagram of the MAN B&W 6S50ME-C9.7 engine with an LRM of 6%. The PTO is applied in the interval of 80-98% of the SMCR speed. Note that the combined power of the light propeller curve and the mechanical PTO power exceeds the PTO layout limit. As mentioned previously, it is the mechanical power of 1,413 kWm that is added to the light running curve in the load diagram. This indicates that the PTO output is too large for the initial design. By adjusting the LRM and SMCR power parameters, the 1,300 kWe PTO can be fitted to the engine.

Table 4: Particulars of the 38,000 m³ LPG carrier

Deadweight scantling	t	30,500
Draught scantling	m	9.69
Length between perpendiculars	m	183.0
Waterline length	m	185.8
Breadth	m	31.2
Propeller diameter	m	5.8
Sea margin	%	15
Engine margin	%	10
LRM	%	6
Design speed	knots	16.2
Type of propeller	-	FPP
Block coefficient	-	0.78

Table 5: Electric load table of the 38,000 m³ LPG carrier

		Ballast	Laden	Cool down
Total load	kWe	800	1,300	1,700

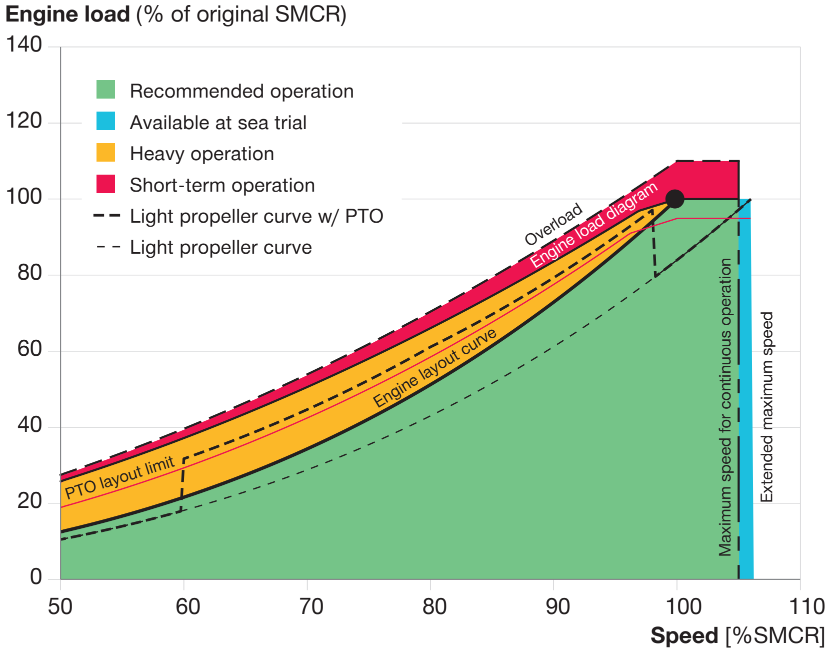


Fig. 16: Load profile of the LPG vessel, where a PTO of 1,413 kWm is added to the light propeller curve

By increasing the LRM to 8.2%, the light propeller curve with mechanical PTO power becomes compliant with the PTO layout curve at approximately 85% SMCR speed, see Fig. 17 for the load diagram containing the modified light propeller curve and the resulting PTO load.

As Fig. 18 shows, by increasing the SMCR power to 8,500 kW, the 1,300 kWe PTO becomes fully compliant with the PTO layout limit.

In the example, a maximum PTO rpm of 98% SMCR speed is utilised. The engine and PTO can be operated at higher speeds if the power taken out is reduced at higher engine speeds, respecting the PTO layout limit.

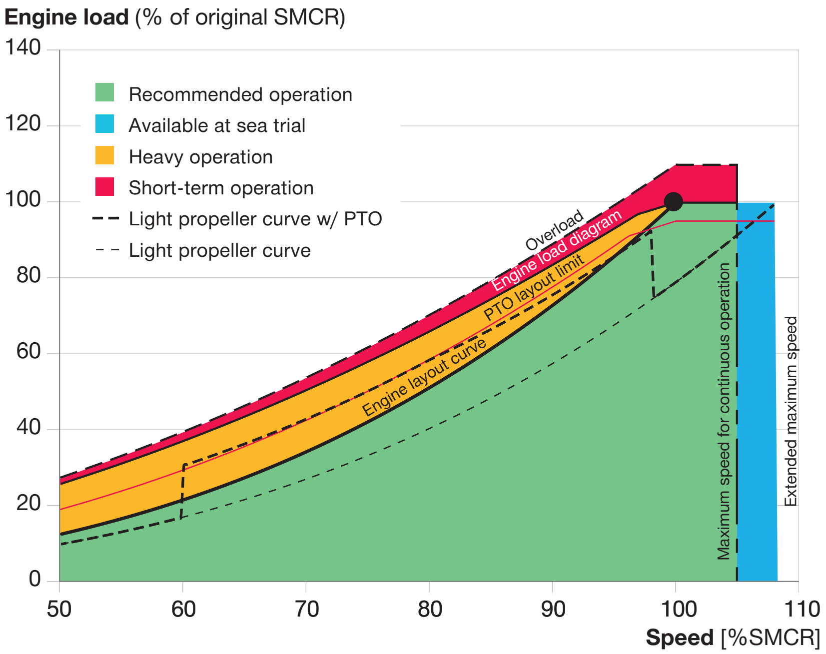


Fig. 17: Load profile of the LPG vessel, where a PTO of 1,413 kWm is added to the light propeller curve

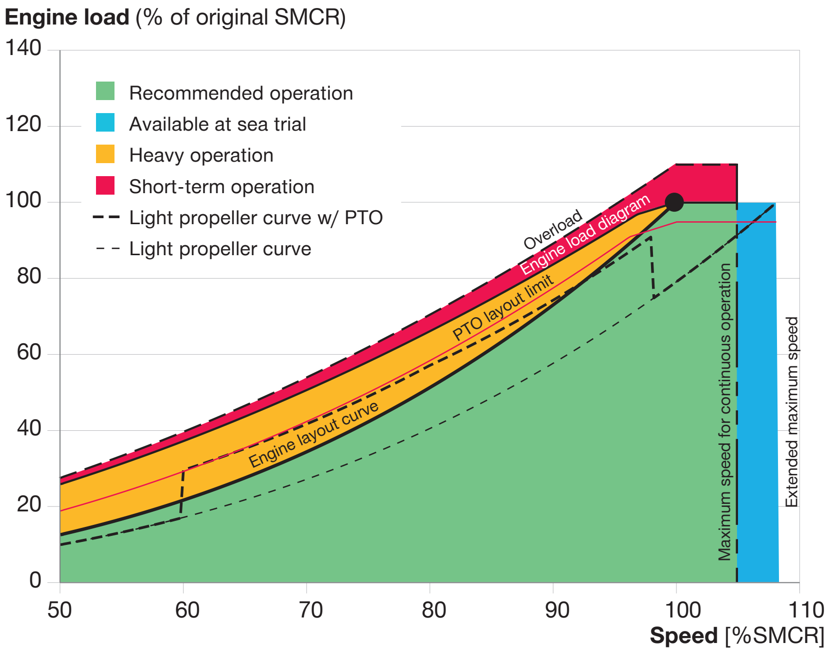


Fig. 18: An increase of the SMCR power to 8,500 kW enables the 1300 kWe PTO to become fully compliant with the PTO layout limit.

For the given example, the minimum PTO speed of 74.8 rpm is higher than 46.8 rpm, which corresponds to 40% NMCR, and the mechanical PTO power of 1,413 kWm constitutes only 13% of the NMCR of the MAN B&W 6S50ME-C9.7, which is 10,680 kW. However, the governor stability point in the lower range of maximum PTO, mechanical power, and speed is outside the FPP curve, see the solid red curve in Fig. 19. This indicates that the PTO mechanical power and speed should be adjusted in the lower range. When decreasing the mechanical power in the lower range by 5%, and increasing the speed in the lower range by 5%, the rpm-stability guidelines becomes fully compliant with the section "PTO and rpm-stability design limits", see page 11.

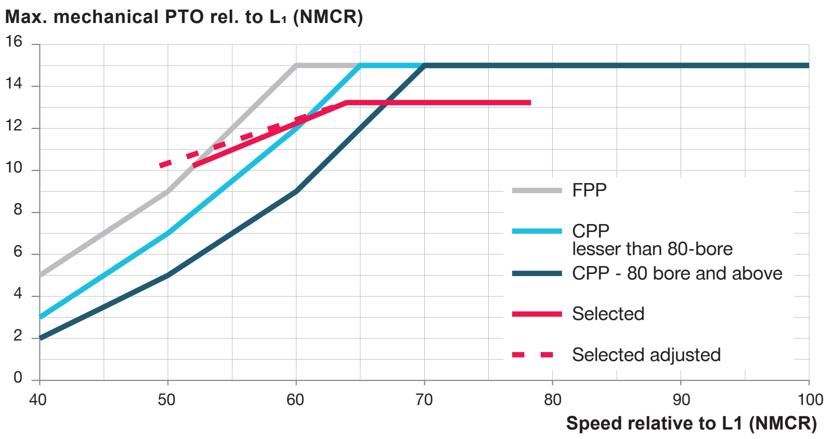


Fig. 19: Adjustment of the governor stability for the PTO. The solid red line indicates the unadjusted PTO and the dashed red line indicates the adjusted PTO, where the lower range mechanical power and speed has been corrugated.

Conclusion

By installing a shaft generator, the hotel load of the vessel can be covered by the shaft generator at sea instead of the gensets. As described in this paper, applying a PTO offers a number of advantages as it lowers the vessel's EEDI and reduces the total fuel consumption, because the specific fuel oil consumption of the ME is lower than for gensets. Moreover, as the genset running hours go down, so do the genset maintenance costs.

By applying a PTO, it will in some cases be possible to reduce the number of gensets installed on board, which will help cover the cost of the PTO.

The shaft generator can either be mounted aft-end or at the front-end of the engine. Three different modes exist: PTO, PTI, and PTH. The most applied mode for vessels with generators is PTO without PTI and PTH. Utilisation of PTI and PTH depends on the vessel segment and design.

The PTO solution benefits not only the owner by lowering the OPEX, but also the environment by reducing the ever-stricter EEDI value set by the IMO.

For guidance on how shaft generators influence the two-stroke engine, or on specific projects involving a shaft generator, the MAN ES Marine Project Engineering department can be contacted at: MarineProjectEngineering2S@man-es.com

Abbreviations

ECS	Engine control system
EEDI	Energy efficiency design index
GHG	Greenhouse gas
LRM	Light running margin
ME	Main engine
NMCR	Nominal maximum continuous rating
OPEX	Operational expenditure
PMS	Power management system
PTH	Power take-home
PTO	Power take-off
PTI	Power take-in
PSC	Propeller shaft clutch
SFC	Specific fuel consumption
SMCR	Specific maximum continuous rating

Appendix

Table 6: Maximum mechanical PTO power [% of SMCR power] as a function of engine speed and propeller LRM.

Table 6: MAN B&W two-stroke engines – PTO layout guidance

Engine speed [% of SMCR]	Propeller light running margin [%]						
	4%	5%	6%	7%	8%	9%	10%
50%	7.8	8.1	8.5	8.7	9.0	9.3	9.6
51%	8.1	8.4	8.7	9.0	9.3	9.6	9.9
52%	8.3	8.7	9.0	9.3	9.7	10.0	10.3
53%	8.6	8.9	9.3	9.6	10.0	10.3	10.6
54%	8.8	9.2	9.6	9.9	10.3	10.6	11.0
55%	9.0	9.4	9.8	10.2	10.6	11.0	11.3
56%	9.3	9.7	10.1	10.5	10.9	11.3	11.7
57%	9.5	10.0	10.4	10.8	11.2	11.6	12.0
58%	9.7	10.2	10.7	11.1	11.6	12.0	12.4
59%	9.9	10.4	10.9	11.4	11.9	12.3	12.8
60%	10.1	10.7	11.2	11.7	12.2	12.7	13.1
61%	10.4	10.9	11.5	12.0	12.5	13.0	13.5
62%	10.6	11.2	11.7	12.3	12.8	13.3	13.8
63%	10.8	11.4	12.0	12.6	13.1	13.7	14.2
64%	11.0	11.6	12.3	12.9	13.5	14.0	14.6
65%	11.1	11.8	12.5	13.1	13.8	14.4	14.9
66%	11.3	12.1	12.8	13.4	14.1	14.7	15.3
67%	11.5	12.3	13.0	13.7	14.4	15.0	15.6
68%	11.7	12.5	13.2	14.0	14.7	15.3	16.0
69%	11.8	12.7	13.5	14.2	15.0	15.7	16.4
70%	12.0	12.9	13.7	14.5	15.3	16.0	16.7
71%	12.1	13.0	13.9	14.7	15.5	16.3	17.1
72%	12.3	13.2	14.1	15.0	15.8	16.6	17.4
73%	12.4	13.4	14.3	15.2	16.1	16.9	17.8
74%	12.5	13.5	14.5	15.5	16.4	17.3	18.1
75%	12.6	13.7	14.7	15.7	16.6	17.6	18.4
76%	12.7	13.8	14.9	15.9	16.9	17.9	18.8
77%	12.8	14.0	15.1	16.1	17.2	18.2	19.1
78%	12.9	14.1	15.2	16.3	17.4	18.4	19.4
79%	13.0	14.2	15.4	16.5	17.7	18.7	19.8
80%	13.0	14.3	15.5	16.7	17.9	19.0	20.1
81%	13.1	14.4	15.7	16.9	18.1	19.3	20.4
82%	13.1	14.5	15.8	17.1	18.3	19.5	20.7
83%	13.1	14.5	15.9	17.3	18.6	19.8	21.0
84%	13.1	14.6	16.0	17.4	18.8	20.0	21.3
85%	13.1	14.7	16.1	17.6	19.0	20.3	21.6
86%	13.1	14.7	16.2	17.7	19.1	20.5	21.8
87%	13.0	14.7	16.3	17.8	19.3	20.7	22.1
88%	13.0	14.7	16.4	18.0	19.5	21.0	22.4
89%	12.9	14.7	16.4	18.1	19.6	21.2	22.6
90%	12.8	14.7	16.4	18.1	19.8	21.4	22.9
91%	12.8	14.6	16.5	18.2	19.9	21.6	23.1
92%	12.6	14.6	16.5	18.3	20.0	21.7	23.4
93%	12.5	14.5	16.5	18.4	20.2	21.9	23.6

Table 6: MAN B&W two-stroke engines – PTO layout guidance

Engine speed [% of SMCR]	Propeller light running margin [%]						
	4%	5%	6%	7%	8%	9%	10%
94%	12.4	14.5	16.5	18.4	20.3	22.1	23.8
95%	12.2	14.4	16.4	18.4	20.4	22.2	24.0
96%	12.0	14.2	16.4	18.4	20.4	22.3	24.2
97%	11.0	13.3	15.5	17.6	19.7	21.7	23.6
98%	9.4	11.8	14.1	16.3	18.4	20.4	22.4
99%	7.8	10.2	12.6	14.8	17.0	19.1	21.2
100%	6.1	8.6	11.0	13.4	15.6	17.8	19.9
101%	3.4	6.0	8.5	10.9	13.2	15.4	17.6
102%	0.7	3.3	5.9	8.4	10.8	13.1	15.3
103%	0.0	0.6	3.3	5.8	8.3	10.6	12.9
104%	0.0	0.0	0.6	3.2	5.7	8.1	10.5
105%	0.0	0.0	0.0	0.5	3.1	5.6	8.0
106%	0.0	0.0	0.0	0.0	0.5	3.0	5.5
107%	0.0	0.0	0.0	0.0	0.0	0.4	3.0
108%	0.0	0.0	0.0	0.0	0.0	0.0	0.4
109%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
110%	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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