Progress in Marine Hybrid Propulsion Drive Systems

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***Abstract*—The paper provides an overview of current marine hybrid propulsion drive solutions, focusing on a particular device for engaging and disengaging the electric motor or diesel engine on the same propeller shaft line. The coupling system is controlled by an overrunning clutch (freewheel type) with ball bearings, allowing a fast change in diesel or electric propulsion mode during sailing. Moreover, it does not require any electronics, limiting maintenance to occasional oil changes. In the examined case study the freewheel working principle is applied to the hybrid propulsion of a pleasure craft, achieving a more compact and lower cost powertrain.**

Keywords—marine hybrid propulsion, drive systems, freewheel, electric motor, shaft generator, diesel engine

I. Introduction

Ever more restrictive international regulations about pollutant emissions from ships are stimulating the continuous search for new "green" technical solutions in marine power generation and propulsion systems. Especially CO_2 emissions can be reduced by using alternative less polluting fuels, some of them more traditional as methane [1-3] and other more innovative in the maritime transport (e.g.: ammonia, methanol or hydrogen). There is growing interest in the role for synthetic e-fuels produced using green hydrogen, and among them, e-methanol would appear to be the most market ready marine e-fuel [4]. It could become increasingly competitive by the mid-2030s, on the contrary considerable barriers still need to be overcome for e-ammonia as a shipping fuel [5]. E-fuels can be used by internal combustion engines although still with some limitations and criticalities in marine applications, while Fuel Cell (FC) already represents a valid power generation device to use e-fuels [5-9]. Unfortunately, FC systems, as well as on-board batteries, do not yet allow to supply great powers with reduced weights and dimensions.

In this framework, diesel oil is still the most widely used marine fuel and will continue to do so in the coming years. Therefore, new technologies in ship diesel propulsion will have to be considered and developed. To this end, the efficiency of marine diesel engine can be increased by adopting Waste Heat Recovery (WHR) from the exhaust gas to produce electric energy [10-13], including innovative turbocharging solutions [14, 15].

As for small ship applications, diesel and electric power are used in the so-called hybrid propulsion configuration to reduce the low efficiency operation of combustion engines [16-21]. In detail, a motor-generator (i.e. a single machine working as either a shaft motor or a shaft generator) and a diesel engine can drive the shaft independently or together. Therefore, an auxiliary diesel generator meets the requirements of hotel and the electric motor power demand, while the adoption of electrical storage (batteries) provides a zero emissions/quiet mode option [22, 23].

Innovative hybrid propulsion projects are experiencing new solutions both in energy sources (e.g. hydrogen feeding a fuel cell) and in the shaft power train. With reference to this last aspect, the paper deals with particular drive systems involving overrunning clutches, responsible for the engagement or disengagement of the diesel engine and the electric motor. These devices are becoming increasingly popular in the off-highway and heavy-duty sectors of the vehicle construction. Currently, they are used in mobile cranes and heavy-duty transporters as well as in many earthmoving, road construction and construction site vehicles. These hybrid systems usually combine diesel engines with powerful (asynchronous) electric motors so that the wheels of the mobile machines can be driven in a single way or altogether. Obviously, the user has to rely on this work-sharing interaction between the thermal engine and the e-drive working reliably and efficiently over a long period. Therefore,

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many designers of hybrid drives use overrunning clutches based on the freewheel principle [24].

In comparison with other types of mechanical dynamic coupling, overrunning clutch is much easier to achieve process of coupling and can take advantage of a simple structure, low design cost and small shock.

II. Hybrid Drive Systems: State of the Art

The concept of hybrid propulsion on board large ships has been well known and applied for decades. In the first applications, the real need was to produce electric energy on board in a more efficient way using a shaft generator driven by the Main Engine (ME, characterized by a low specific fuel consumption in comparison with traditional marine gensets). Then, they started installing generators also working as electric motors by disconnecting the prime mover. Therefore, currently two operating modes exist for the electric machine:

- Power Take Off (PTO): the shaft generator covers the ship electric power demand alone or in parallel with gensets.
- Power Take In (PTI): the ME is declutched from the propeller shaft and the propulsion mechanical is provided by the electric machine working as electric motor. PTI mode is often associated to a ship propulsion emergency solution (e.g. failure of the prime mover).

However, the PTI mode can be associated also to the booster mode: gensets work in parallel with the prime mover by using the shaft generator as a motor. Therefore, gensets produce enough power to cover the hotel load and provide power to the propeller.

In advanced PTO applications, in port the ME can be declutched to produce electricity and substituting one or more gensets. In this operating mode, two clutches, one on either side of the generator/motor, are necessary to maintain PTI mode too. For some alternative fuels, gensets burning the same fuel used by the ME may not be available. Therefore, especially in this case, a declutchable propeller may be a proper solution [25].

Several design solutions exist for hybrid drive systems, mainly different in each component position and number of clutches. In general, the PTO/PTI system can be placed either on the aft-end (towards the propeller) or on the front end of the ME [25]. In the case of the most traditional solution, the aft-end mounted generator can be directly installed on the propeller shaft or through a gearbox (connecting also the ME). In the latter configuration, an elastic coupling is required for the generator.

From all the previous considerations, it is clear that each configuration can have a different impact on the project in terms of weights and dimensions. Mainly for this reason, hybrid propulsion applications, based on PTO/PTI, spread much later in small craft than large ships, and they are still evolving to reduce weight and costs. In pleasure boats, there are the two following solutions for the PTO/PTI connection to the main diesel engine.

A. *Geared connection*

It is the solution traditionally used onboard large ships, scaled to smaller craft. A gearbox, equipped with an additional clutchable PTO/PTI, allows the diesel propulsion, electric propulsion and booster mode. These gearboxes are usually available on the market only from approximately 600 kW of input power. In the lower power range, the direct connection solution is suitable.

To compensate for the lack of PTO/PTI gearboxes at small power, it is possible to connect the electric motor to the shaftline through a pulley and a belt drive system (Fig. 3). When a standalone generation is needed, then a further clutch is required to disconnect the propeller shaft.

The pulley/belt drive provides a great flexibility. Drive ratio of the electric motor can be set independently from the gearbox. This allows matching of the motor to a wide range of engine models.

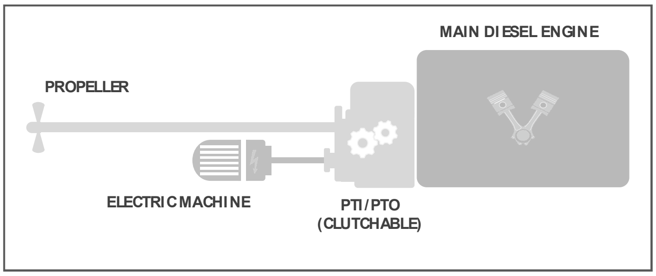

Fig. 1. Geared connection between electric motor and ME [26].

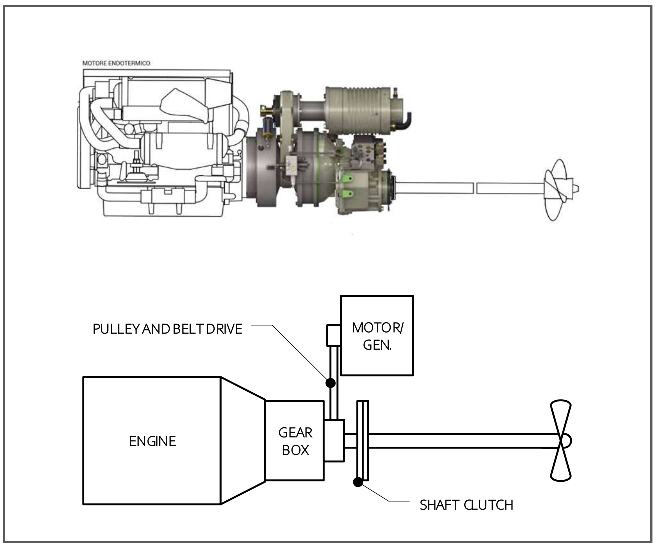

Fig. 2. Pulley and belt drive system [27], [28].

B. *In-line direct connection (integrated flywheel generator)*

The shaft generator is direct mounted on the flywheel housing of the main diesel engine. The shaft generator location reduces the width space, with only a small extension in engine length.

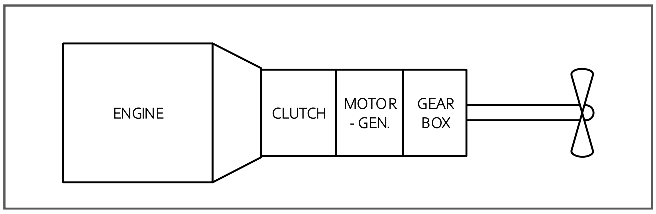

Fig. 3. Flywheel hybrid drive system.

In Fig. 3, the electric machine is placed between the thermal engine and the gearbox. The clutch between the electric motor (PTI) and the ME allows to disengage the ME from the propulsion system in the electric propulsion mode.

III. Freewheel clutch for hybrid drive solutions

In the small pleasure craft field, arrangement and spaces are strictly design fact.

The traditional reduction gearboxes with two input shafts and their relative clutches require more space than is available on such types of vessels. In this context, it appears to be useful a different architecture for hybrid drivetrains. In the present paper a more compact solution is proposed; it consists of a freewheel fitted between the main engine and the electric motor, on the same shaft.

A freewheel is a sort of overrunning clutch device that allows power transmission from a driving shaft in a single direction of rotation. It consists of clamping elements arranged between an inner and outer ring, circumferentially distributed by a cage housing. The rings are connected to the driving and driven shafts respectively. The clamping elements are effective in one sense of rotation (driving mode), in opposite one the torque transmission is not allowed (freewheeling operating mode).

The driving operation is possible if the inner ring is at standstill or turning slower than the outer ring. The shafts are decoupled if the inner ring overcomes the speed of the outer driving shaft. The name of overrunning clutch is due to this behavior.

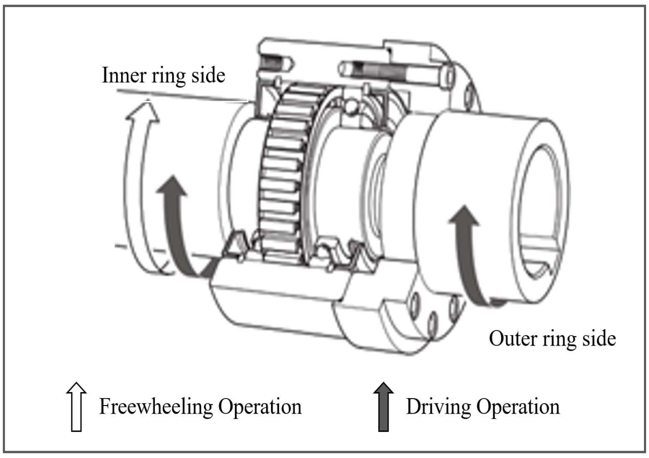

Fig. 4. Freewheel operating principle.

For the above-mentioned characteristics in a hybrid diesel electric application, it is possible to engage and disengage the different power source without any external control.

This arrangement allows a more compact drivetrain, particularly useful in small crafts and in retrofitting cases, where is important to minimize the impact on the existing plant.

IV. Case study

In this case study, the retrofit of the engine room of the existing boat of the serie Tornado, model 45 Express, owned by Sorrento Luxury S.r.l, is presented. This small commercial vessel is currently used for charter.

TABLE I. Main Boat characteristics

Length	13.45 m
Beam	3.80 m
Draft	0.98 m
Displacement	9750 kg
Max speed	36 knots
Diesel engines	2 x 257 kW@3800 rpm
E-motors	2 x 90 kW@4000 rpm
FC power	30 kW

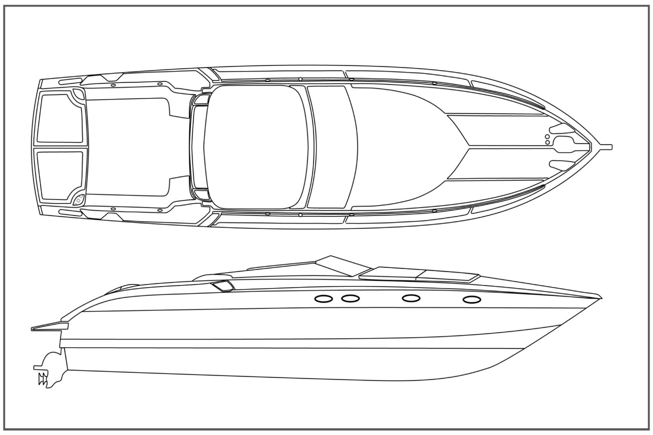

Fig. 5. General drawings of the Tornado 45 Express.

Tab. 1 shows the main technical characteristics of Tornado 45, while the general drawings are illustrated in Fig 5. The target of Tornado 45 retrofit is sailing without CO_2 emissions in the restricted area of Punta Campanella and around Capri Island, in Naples.

The proposed solution is a parallel hybrid configuration, where the two main engines and electric motors are both connected mechanically to the sterndrive propeller system, in order to provide propulsion power either simultaneously or individually. The whole powertrain is shown in Fig. 6.

The overrunning clutch is fitted between the flywheel of the main engine and the electric PTO/PTI machine, allowing to engage/disengage the mechanical connection only by changing the engine throttle position and the electric motor speed, without any additional controller in comparison with a traditional clutch system [29].

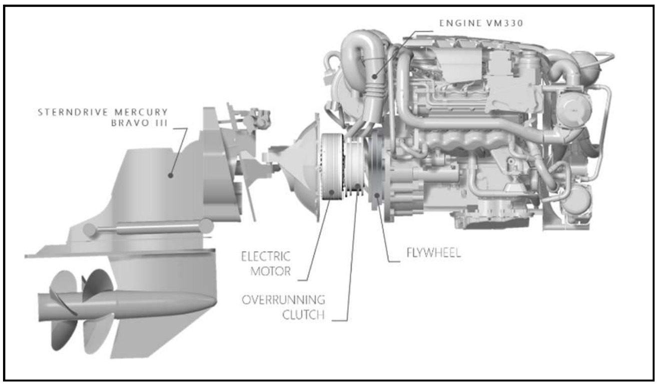

Fig. 6. Powertrain of each propulsive shaftline.

The assessment of Noise, Vibration and Harshness (NVH) problems for the innovative hybrid powertrain is particularly important for this case study, not only to ensure the level of comfort required onboard but also the reliability of the propulsion. Fig. 7 shows a schematic view of the complete powertrain section. The stator of the axial flux electric motor is connected to the diesel engine casing (dark grey), which is mounted on resilient supports. The outer ring of the freewheel is connected to engine freewheel (purple color) via an elastic coupling. In the driving mode this part engages the inner ring, and moves the rotor of the e-motor. In the electric mode the diesel engine flywheel is at rest so that the only power source is the electric motor. As usual, the drive shaft is connected to the pod through a cardan joint.

The system is subject to different torque pulsating sources, as the diesel engine, the propeller shaft and the e-motor with its electrical driver. Two elastic coupling are added to control torsional vibrations, after the flywheel and before the propeller shaft connection. The effect of torsional vibration on the freewheel during particular operating conditions could cause variations in the engagement force and state that, in order of seriousness, generate noise, chattering, wear and heat, perhaps even originating a more serious failure.

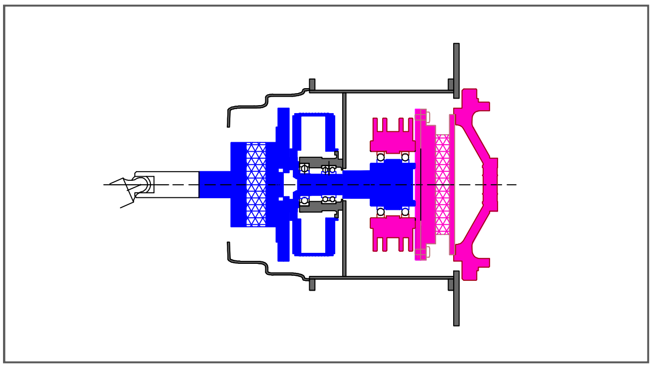

Fig. 7. Powertrain section.

Fig. 8 shows the considered power plant configuration. Two energy sources, battery pack (BP) and a fuel cell, are linked on the same high voltage DC link. These provide high voltage electric power to the drive systems, while auxiliary loads are managed via a converter to transform the high voltage DC power into low voltage DC power. An axial flux permanent magnet motor is considered, due to its high power/torque density. A controller that converts DC power into regulated AC power drives the electric motor. It is foreseen an onboard charger, which converts the AC power from the shore into regulated DC power for the battery charging purpose.

The hybrid power system allows the following operation modes:

- *Diesel mode*: the propulsive power comes only from the diesel engines, while the electric motors are off. The overrunning clutch is in driving operation, allowing torque transmission to the propeller (the outer and inner rings are engaged and rotate at same speed).
- *Electric propulsion mode*: propulsive power comes only from the electric motors, fed by the battery pack. The overrunning clutch is in freewheeling operation, allowing the mechanical disengagement because the inner ring is faster than the outer one. Structural limits impose that the speed difference between the two rings of the freewheel does not exceed 1600 rpm. Therefore, in this operating mode, the shaft electric motor cannot exceed 1600 rpm, limiting the maximum speed of the boat to 10 knots.
- *Booster mode*: the propulsive power comes from both the engines and electric motors, which are fed by the battery pack. The overrunning clutch is in driving operation, with torque transmission to the propeller. The electric motor is controlled to increase its speed that is limited by the diesel engine governor.
- *Battery Charging and propulsion mode*: the engines supply power to the propulsion and to the battery pack as well, through the shaft generator. This operating mode become effective when the
- *Fuel Cell for range extender*: the fuel cell supplies power for recharging the battery when the state of charge falls to a minimum threshold, while it stops recharging if the battery state of charge approaches the maximum allowed threshold.
- *Plug-in mode*: the vessel is at harbor and no power is available for propulsion. The onboard charger can recharge the battery pack from the shore power grid.

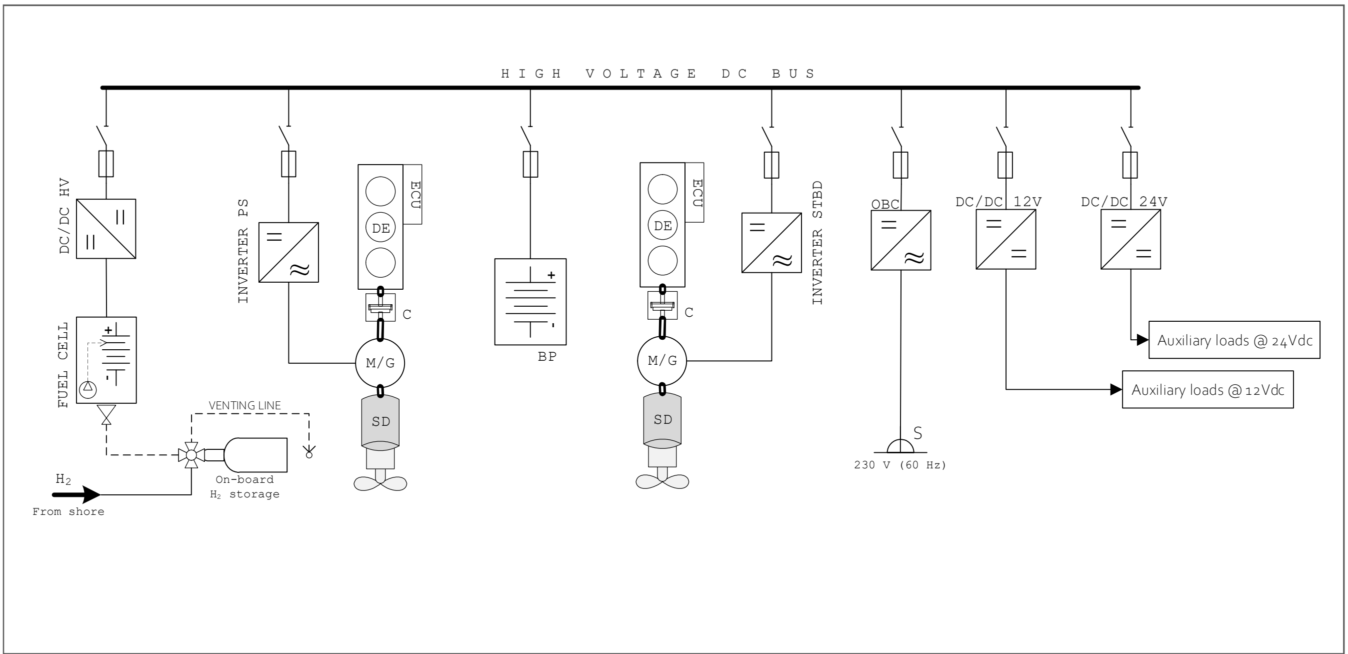

Fig. 8. Power plant configuration

V. CONCLUSION

The paper shows an innovative application, at least in the marine hybrid power plants, by outlining the main benefits compared to more traditional configurations for hybrid drive systems. The proposed power train is revised on the introduction of a freewheel (overrunning clutch) system to drive diesel engine and electric machine, and then to change operating mode. The main advantages are represented by a simpler and more compact structure, low vibrations and cost (especially maintenance cost, being limited to some occasional oil changes). In comparison with similar applications, the freewheel solution, designed for the hybrid propulsion of the boat Tornado 45, allows for a drive system (considering shaft electric motor and connection device) that is approximately 93% lighter and 37% shorter, with a 20% smaller radial footprint.

On the other hand, the limit in the speed difference between inner and outer ring of the freewheel affects the maximum speed of the vessel in the electric propulsion mode. Moreover, the specific solution requires an appropriate check of the torsional vibrations of the examined drive system, to avoid unwanted malfunctions.

Another innovative aspect is represented by the possible use of a fuel cell to recharge the onboard batteries, in addition to or better in place of the shaft generator.

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