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COMMON RAIL DIESEL-ELECTRIC PROPULSION FOR SMALL BOATS AND YACHTS

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ABSTRACT

The marine propulsion system is the heart of the ship. Its reliability will directly affect the safe navigation and operating costs of ship and its overall safety. The individuation of the best propulsive solution is one of the key technologies in marine field. Focusing on the study of comprehensive reliability, this study analyses operation environments of the marine propulsion system firstly, and then evaluate the comprehensive reliability of the chosen marine propulsion system. According to the fault tree of the marine propulsion system, a CRDID (Common Rail Direct Injection Diesel) electric hybrid marine engine system is taken as an example The result shows that a new engine CRDID-hybrid system can be reliably installed on small boats and yachts. It is believed that the knowledge gained in this study will provide a theoretical reference for research on comprehensive reliability of hybrid marine propulsion systems.

Keywords: diesel electric marine propulsion system, reliability, fault tree analysis, failure probability.

INTRODUCTION

The propulsion system reliability directly determines the safe navigation and operating costs of ship. The economy, space requirement, efficiency of propulsion and reliability are the most important parameters to the marine propulsion system. Generally a marine propulsion system includes following main parts: main engine, speed reducer, transmission shaft and propeller. The transmission shaft plays an important role in transferring the energy to the propeller. Its length and position is a large constraint in the maritime vehicle design. The faults of the marine propulsion system increase seriously, such as shaft system fracture, over worn of stern bearing, crankshaft failure of main engine (generally torsional vibration related), piston ring fracture (generally lubrication related), seal failure. A famous shipping insurance company in Switzerland has made an investigation to the fault accident claims of the ships from 1998 to 2004 [1]. The compensation rate is shown in Table-1 [2]:

Table-1. The statistical result of the marine fault accident claims of the ships which had taken service from 1998 to 2004 [2].

Compensation reason	**Failure frequency**	**Cost** (USD)	**Average cost** (USD)
Main engine	232 (41.6%)	69774.597 (46%)	300.623
Manipulate gear	66 (12%)	15636.563(10.3%)	236.918
Auxiliary diesel engine	120(21.5%)	27257.436(18%)	227.145
Boiler	65(11.6%)	18128.065(12%)	279.047
Propulsion shaft	63 (11.3%)	17798.483(12%)	282.275
Others	12(0.02%)	2559.295(0.01%)	213.275
Total	558	1551154	270.850

As it can be seen from Table-1, transmission related failure amount to 41.6%+12%+11.3%=65% for a cost of 46%+10.3%+12%=68.3%. The transformation from a mechanical system to an electric one seems to be convenient, at least for small vessels, where the generator, battery, conversion and driver technology is widely available. The average marine gasoline engine runs for about 1,500 hours before needing a major overhaul (TBO). The average marine diesel engine will have a TBO of 5000 hours under the same conditions. However, the number of hours that a marine engine runs is extremely dependent on the usage, the amount and quality of maintenance over the years. If frequently used and maintained the typical gasoline marine engine will run fine for the first 1, 000 hours. It is at this point that the engine starts to exhibit small problems. If these small problems aren't addressed properly, they can turn into major problems which may end engine life prematurely. Interestingly, an automobile engine usually runs almost twice as long (3, 000 hours) as your marine gasoline engine. The reason is that marine engines normally work under worse conditions than automobile ones. However, many gasoline engines that operate under the most atrocious conditions of salt air, damp bilges, intermittent operation, and long non-operating periods will certainly die early. This is the normal case for small boats, summer yachts and launches, where intermitted, and “short run" use is the rule. Diesel engines are built to finer tolerances than are gasoline engines. They will accept much more abuse and often have a TBO of 10, 000 hours. This fact means that, theoretically, a well-maintained diesel may last the life of the boat. In fact the average recreational boater logs an average of 250 hours per year: the 10, 000 hour diesel would last 40 years. From these considerations and from Table-1 it can be clearly seen that for small boats the well maintained diesel engine is not truly important for reliability calculations. On the contrary the transmission is. This fact is confirmed by the choice made by the Italian and German Navy for their newest traditional submarines that have single diesel propulsion.

Although diesels can add considerable cost to a boat, they should be seriously considered because of their durability, economy of operation and safety concerns. Diesel fuel has a much higher flash point than gasoline and does not present the same threat of explosion that gasoline fumes carry.

Operational conditions and installation

Engines like to run long and steady. The shorter the running time between stops, the fewer the hours they will deliver before needing major repairs. The adverse operating conditions have a great deal to do with their longevity. Marine engine manufacturer recommend that engine compartments should be supplied with lots of dry, cool (15°C), clean air. As a rule of the thumb, the very minimum fresh air vent area (in square meters) for natural ventilation can be calculated by dividing engine horsepower by 5, 000. Automotive engines usually operate at a temperature of 90°C, for this reason they can resist to worse environmental condition than the maritime engine design. However, for corrosion resistance such high temperatures should be avoided. Air intake should be as cool as possible in order to obtain the best efficiency.

The hybrid CRDID installation example: actual situation. The boat under consideration is a racing sailboat fitted with two inboard diesel engines. An APU (Auxiliary Power Unit), powered by an engine (Volvo Penta D1 30) with a displacement 1, 130cc, a dry mass of 157 kg and a maximum output power of 27HP@2800rpm is installed for electric power generation. The main propulsion engine is a Volvo Penta D2 75 with a displacement of 2, 200cc, a dry mass of 264 kg and a maximum output power of 72HP@2700rpm. This engine can also work as an APU with its 1.4kW generator. The transmission to the propeller is of the stern drive (S-drive) type. A high capacity, maintenance free, lead battery complete the installation. Fuel consumption is 18 l/h for the main engine and 6.8 l/h for the APU. With the new proposal, as will be highlighted in the following, the reliability of the propulsion and power generation system will increase significantly, by an ambivalence of the tasks performed by the two engines.

Issues identified

The dry mass of 421 kg for the two engines appeared immediately noticeable. In fact, we find ourselves in front of a boat for extreme sport activity, where performance is required. Then a weight reduction is highly desirable. Also the fact that only one motor is intended for the propulsion does not guarantee a high reliability level. Even if the Volvo Penta D2-75 is an extremely reliable engine, accidental events during use are common and a failure of the unit may be caused by external factors. In this case the sailboat must rely to sail for docking. This practice may be not allowed in the desired port.

In addition, the current position of the two combustion engines is quite close to the stern of the boat, even if this is not a particularly convenient installation point. With the new more compact and lightweight CRDID, it will be possible to lower the center of gravity and to advance it of a few inches. This fact will improve the navigability and the performances.

New installation specifications

It is estimated a possible reduction of total mass down about 250 kg with simplified installation being the propeller(s) powered by electric motor(s). The reliability in the complex should increase because each of the two combustion engines will be able to generate and amount of electrical power sufficient to drive the electric motor. The new CRDID engines should also have and higher efficiency and reduced emissions. The reduction of fuel tank capacity will also contribute to a further reduction in weight.

CRDIDs available

Several CRDID conversions for the marine application are available on the market; however for this specific application a "direct conversion" was preferred. A few CRDID from the automotive market are known to the authors, their performances are summarized in Table-1. These engines have been originally converted to aircraft use. Of these conversions only the modifications on the engines and the new FADEC are kept, being in this case the direct transmission to the propeller unnecessary.

Table-2. CRDIDs from the automotive field.

Engine	**Automotive power** (HP)	**Naked mass** (kg)	**Ultimate power** (HP)	Crankcase	**BSFC gr/HPh** (Euro 0)
Audi V12tdi	500@4,000rpm	220	900@5,200rpm	CGI	148
AudiV8tdi	327@4,000rpm	195	600@5,200rpm	CGI	148
Fiat 2000jtd	190@4,500rpm	114	250@5,200rpm	Cast Iron	152
Peugeot 1600 HDI	115@3,800rpm	92	200@5,000rpm	All. alloy	151
Fiat 1300jtd	95@4,400rpm	105	200@6,000rpm	Cast Iron	154
SmartCDI	54@4,400	63	100@5,200rpm	All. alloy	160

As it can be seen only the SmartCDI derived power unit has an output power compatible with the dual engine requirement. The data of this engine in its aircraft conversion are summarized in Table-2. The architecture of this engine is the type three-cylinder-in-line, cylinder block and cylinder head are made of aluminum alloy (Table-3).

Table-3. Data of the engine chosen.

Description	Data	Unit
Bore	65.5	mm
Stroke	79	mm
Displacement	799	cc
Length	1188	mm
Width	450	mm
Height	450	mm
Dry mass with 70 HP generator	103	kg
Specific fuel consumption	150	gr/HPh

The CRDID can be easily used as an APU; in fact the FADEC can be programmed to be used at constant rpm up to the maximum output power.

The racing-derived fully programmable FADEC has an additional optional protection up to IP68 (immersion in water).

The cooling system

Marine engines generally use two types of cooling systems, direct circulation of seawater or indirect circulation. In this system the installation includes two circuits: the first uses sea water that is not in contact with the engine, while the second, with the cooling liquid exchange the heat with the sea water one through a liquid-to-liquid plate unit. It is perfectly possible to use the sea-water circuit electric pump as a bilge pump in case of emergency. The FADEC can also control the cooling system.

Fuel consumption

The original power plant has an installed power of 99.3HP and a maximum fuel consumption of 24.8 l/h. With the same power output the CRDID hybrid will need only 18 l/h. Even including the electric efficiency of the generator and of the electric motor of $\eta_m = \eta_g = 0.95$, the power required will be (1) with a fuel consumption of 20.1 l/h:

$$P_r = \frac{P_{prop}}{\eta_m \eta_g} = 110.3 \left[HP \right] \quad (1)$$

Reliability of the individual components and systems

Single component reliability in 1,500h is summarized in Table-3. The failure probability concept can be explained with the following example. To evaluate the reliability of a lamp, it is theoretically sufficient to turn on 100 lamps at the same time. After 1, 000h the number of lamp burnt can be calculated. This number is the "failure probability", while the number of the lamps still working is the "reliability ".

Table-4. Failure probability of the main components.

Item	**Failure probability in 1, 000h** (%)
CRDID	10
Generator	3
Rectifier	10
Battery	0.0000001
Inverter	10
Electric motor	10
Wiring	0.0001

The electric motor probability Figure includes its driver. The CRDID reliability takes into account the fact that the engine is experimental.

Single battery-charger (rectifier) assembly

In this assembly, each of the two APU is able to charge the battery pack or to supply the electrical to the electric motor/propeller. So in case of failure a CRDID, the other would still be able to supply electric energy to the electric motor propeller. The remaining CRDID can also charge the battery. In alternative, at the reduce rate of the power required to charge the battery, it is able to power the battery that powers the motor/propeller (Figure-1).

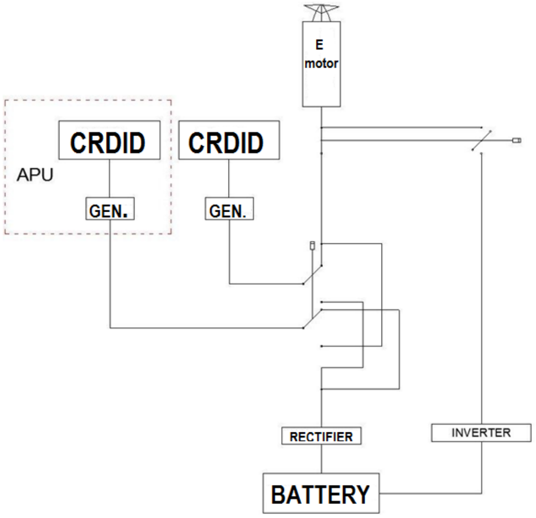

Figure-1. Single rectifier assembly.

In the assembly of Figure-1 it is possible to identify 3 branches.

The branch that goes from the CRDID to the electric motor (2):

$$P = (1-(1-P_{CRDID}P_{generator})^2)P_{E-motor}P_{wiring} = 0.88 \qquad (2)$$

The branch that recharges the battery (3)

$$P = (1-(1-P_{CRDID}P_{generator})^2)P_{rectifier}P_{battery}P_{wiring} = 0.88 \qquad (3)$$

The branch that moves the engine through the battery alone (reduced autonomy) (5):

$$P = P_{inverter}P_{battery}P_{wiring} = 0.81 \qquad (4)$$

The branch that moves the engine through the battery while it is recharged by the CRDID (limited output power) (5):

$$P = (1-(1-P_{CRDID}P_{generator})^2)P_{rectifier}P_{battery}P_{inverter}P_{wiring} = 0.71 \qquad (5)$$

The reliability of (3) is too low to be acceptable. So an assembly with two rectifiers is adopted (Figure-2).

Assembly with two rectifiers (Figure-2)

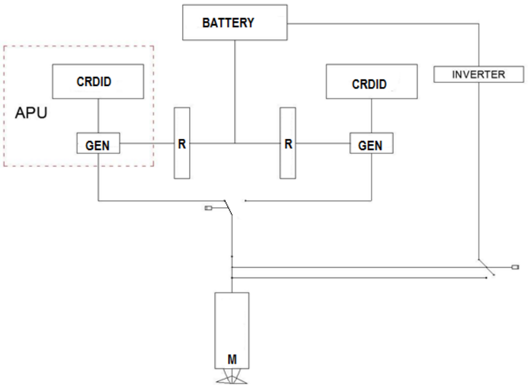

Figure-2. Two rectifiers (R) are introduced.

The solution proposed in Figure-2 has the peculiarity of having two rectifiers connected in parallel. This trick increases to an acceptable level the reliability of the branch (es) charging the battery (6).

$$P = (1-(1-P_{CRDID}P_{generator}P_{rectifier})^2)P_{battery}P_{wiring} = 0.99 \qquad (6)$$

The reliability level of the other branches is unchanged. However, has an advantage of the present: in case of failure of one of the two APU, unlike the previous case, with this solution it is possible to power the electric motor and charge the batteries at the same time?

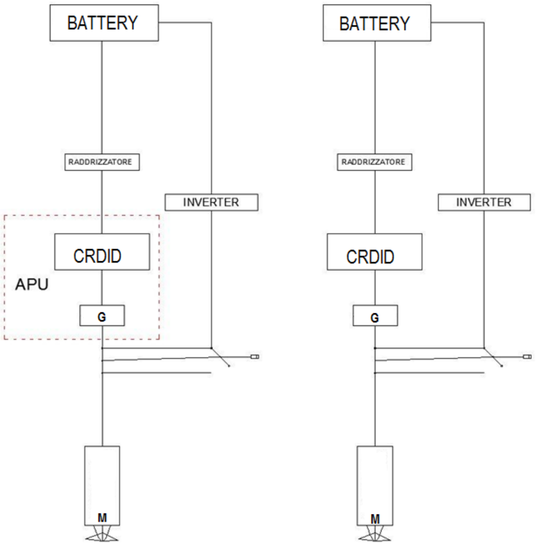

Figure-2. Fully redundant assembly

Assembly with two independent redundant systems

The assembly of Figure-3 offers higher reliability against higher costs. This assembly solution lends itself particularly well to the case of boat type "catamaran" as each of the two systems can be installed on a hull. The probability of the branch CRDID-electric motor is then (7):

$$P = (1-(1-P_{CRDID}P_{generator}P_{motor}P_{wiring})^2) = 0.95 \quad (7)$$

For the branch CRDID-Battery we have (8):

$$P = (1-(1-P_{CRDID}P_{generator}P_{rectifier}P_{battery}P_{wiring})^2) = 0.96 \quad (8)$$

The reliability of the branch battery-electric motor can be calculated with (9).

$$P = (1-(1-P_{motor}P_{inverter}P_{battery}P_{wiring})^2) = 0.95 \quad (9)$$

The reliability of the three solutions is summarized in Table-5.

Table-5. Reliability levels for assemblies of Figure 1, 2 and 3.

Action	Ass. 1	Ass. 2	Ass. 3
Power to propeller from CRDID	0.88	0.88	0.95
Battery charging	0.81	0.99	0.96
Power to propeller from battery	0.88	0.88	0.95

Cost analysis

The cost analysis is an integral part of the design work. An indicative cost of the main components is summarized in Table-6.

Table-6. Unitary cost of main components.

Item	Unitary cost (€)
APU	20,000
Rectifier	250
Electric motor driver	3,000
Inverter	1,000
Wiring (each cable)	30

Depending on the assembly chosen we have the different costs summarized in Table-7.

Table-6. Number of items and total cost.

# of items	Ass. 1	Ass. 2	Ass. 3
APU	2	2	2
Rectifier	1	2	2
Electric motor+driver	1	1	2
Inverter	1	1	2
Wiring (each cable)	9	12	12
Total cost (€)	44,500	44,860	48,860

As it can be seen the difference between the three solutions is not high. It is then convenient to adopt the assembly N. 3.

CONCLUSIONS

The marine propulsion system is the heart of the ship. Its reliability will directly affect the safe navigation and operating costs of ship and its overall safety. The individuation of the best propulsive solution is one of the key technologies in marine field. Focusing on the study of comprehensive reliability, this study analyses operation environments of the marine propulsion system firstly, and then evaluate the comprehensive reliability of the chosen marine propulsion system. According to the fault tree of the marine propulsion system, a CRDID (Common Rail Direct Injection Diesel) electric hybrid marine engine system is taken as an example The result shows that a new engine CRDID-hybrid system can be reliably installed on small boats and yachts. A fully redundant twin system (Figure-3) is the most cost-effective solution. Even with the extremely conservative reliability level assumed for the calculation the system has an acceptable reliability. The reliability value assumed are valid only for the first prototype, the serial reliability Figure will be far better.

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Symbols

Symbol	Description	Unit
P_r	CRDID(s) max output power	HP
P_{prop}	Power at the propeller	HP
η_m	Electric motor efficiency	-
η_g	Elecgric generator efficiency	-
P	Reliability	%
P_{CRDID}	Reliability of CRDID	%
$P_{generator}$	Reliability of the generator	%
$P_{rectifier}$	Reliability of the battery charger	%
$P_{battery}$	Reliability of the battery	%
P_{wiring}	Reliability of wiring and switches	%
$P_{inverter}$	Reliability of the inverter	%