

**HYBRID PROPULSION SYSTEM FOR NEW GENERATION OF SHIPS****Sirus Silatan<sup>1</sup>, Pedram Edalat<sup>2</sup>, Mohammad Rahimi<sup>3</sup>**<sup>1</sup>Sirus Silatan, Faculty of Marine Science, Petroleum University of Technology; ssilatan69@yahoo.com<sup>2</sup>Pedram Edalat, Faculty of Marine Science, Petroleum University of Technology; Edalat@put.ac.ir<sup>3</sup>Mohammad Rahimi, Faculty of Marine Engineering, Amirkabir University of Technology; M\_rahimi@aut.ac.ir**Abstract**

Because of reduced fuel consumption, increasing of the fuel costs and growing of the environmental concerns, reduced environmental pollution and increase in life of a vessel's propulsion system, led energy consumption to become one of the most important subjects of the modern and developed countries and Hybrid system has been applied on vessels. Use of two or more energy sources is the main property of a hybrid system. Different combinations of Internal Combustion Engines (ICE), Steam Turbine (ST), Gas Turbine (GT), fuel piles with Electric Motor (EM) can be used for different transportation vehicles. A hybrid vessel system can be either combination of DE and EM or GT and EM. So each one of CODLOD/ CODLAD/ CODLOG/ or CODLAG systems can be called a hybrid system. A frigate (as a vessel) needs different speeds in different positions, cases and situations. Every situation needs different modes for a vessel. So the typical hybrid operation modes (PTI booster mode, Generator mode (or PTO-mode), Electrical mode and Electrical cross-connection mode (Electric Shaft) will be introduced.

**Keywords:** Hybrid system, CODLOD, CODLAD, CODLOG, CODLAG**Introduction**

Increasing of the fuel costs and growing of the environmental concerns, led energy consumption to become one of the most important subjects of the modern and developed countries. Land transportation systems are the most common target of most researchers while over 90% of the world's freight is transported on ships. As an example over 3.6 billion barrels of fuel are being transported by ships each year [1].

Increased trade tendency to use marine transportation which caused a sharp increase in fuel consumption, energy crisis in future and increased ship environmental concerns led designers and ship building companies to design new propulsion systems. New ship propulsion systems are designed to decrease the fuel consumption. There are different designs and each one has its advantages and disadvantages which will be discussed in this paper.

Early hybrid propulsion systems were installed on US Navy fleets and aircraft carriers and were used during the Second World War (1910-1920).

**Types of Ship propulsion systems**

Common ship propulsion systems which are discussed in this chapter may be listed as below: (a) Direct Drive (2 Engines), (b) CODOD (Father-Son) (c) CODAD, (e) CODOG, (f) CODAG, (g) COGOG, (h) COGAG, (i) COSAG (j) HYBRID (include: 1-CODLOD, 2-CODLAD, 3-CODLOG and 4-CODLAG), (k) CODLADAD, (l) CODLADOG and (m) FULL ELECTRIC PROPULSION SYSTEM

Most of these systems are capable of sailing in three main operational modes: high speed mode, cruise mode and silent speed operational mode.

**Ship Hybrid Systems**

Because of reduced fuel consumption, fuel cost, reduced environmental pollution and increase in life of a vessel's propulsion system, Hybrid system has been applied on vessels. Number of fuel bunkering is important for a frigate so that it can operate far from the base. Time is critical in a battle. Bunkering of a frigate causes loss of time and added costs. A frigate propulsion system should have lowest fuel consumption and highest efficiency. A Hybrid system has all of these properties. Hybrid vessel propulsion system has many differences with hybrid cars or trains. Use of two or more energy sources is the main property of a hybrid system. Different combinations of Internal Combustion Engines (ICE), Steam Turbine (ST), Gas Turbine (GT), fuel piles with Electric Motor (EM) can be used for different transportation vehicles. A hybrid vessel system can be either combination of DE and EM or GT and EM. So each one of CODLOD/ CODLAD/ CODLOG/ or CODLAG systems can be called a hybrid system. Hereinafter means of hybrid system is just vessel's hybrid system. In hybrid systems, required electricity for Electric Motor or others is being produced by Generators. These generators can be either Diesel Generator or Gas turbine generator or combination of them. Use of these types of

generators is related to vessels property such as engine room dimensions, generators power, propulsion system and etc. In HS system, Electric motor is an electric machine. This electric machine is rotating a propeller usually but in some cases it can be operated as a generator. Electricity produced by electric machine in generator mode can be used in accommodating other parts of vessel. Power produced by DG, EM or GT can be transmitted to Gear Box by clutches and cause the propeller to rotate. In response to circumstance and need of vessel for power, each clutch can be engaged or disengaged. RPM is reduced to suitable value by Gear box. Different types of hybrid system and their parts are shown in Fig 1.

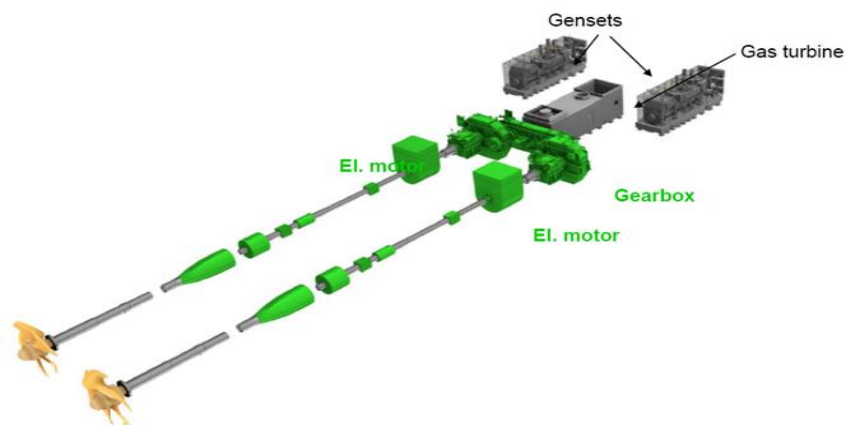


Fig1. A hybrid propulsion system (CODLAG) [2]

Before introducing different types of hybrid system, an introduction to vessel speeds.

Vessel speed order is shown in Tab 1. Log of operating time in every speed along life time of vessel and its needful power per total power are shown in Table 1.

According to Table 1, usage of electric motor in high efficiency for low speeds that is most time of operating speed of vessel and one or more DE or GT for high speeds is reasonable. All of above reasons justify applying hybrid system on vessels.

Table 1. Ship speed[2]

Task	Speed	Time	Power
Transit, Interception, SAR	15 - 20 knots	5 %	30 - 100 % of MCR*
Patrolling in operational zone	12 - 15 knots	20 %	15 - 30 % of MCR*
Loitering in operational zone	0 - 12 knots	75 %	<15 % of MCR*

\*MCR - Maximum Continuous Rating

### Different Ship Hybrid Systems

Hybrid systems can be divided to 4 types: (i) CODLOD, (ii) CODLAD, (iii) CODLOG and (iv) CODLAG.

The two first systems are combination of diesel engine and electrical motor but the second two systems are combination of electric motor and gas turbine.

#### i) CODLOD (Combined Of Diesel-Electric Or Diesel engine)

This system is a combination of electrical motor and diesel engine. Power transmission to propeller is either diesel engine power or electrical motor power. Electrical motors are used for low speed and diesel engines are used for high speed. This system is shown in Fig 2.

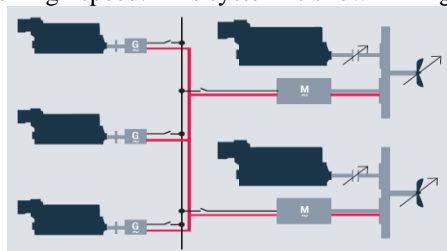


Fig 2. Schematic CODLOD propulsion system.

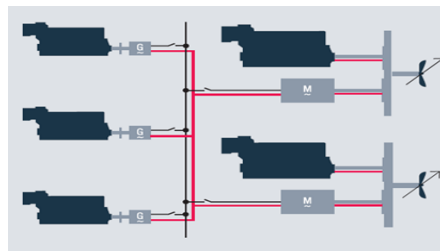


Fig 3. CODLAD propulsion system[3].

**ii) CODLAD (Combined Diesel-Electric And Diesel engine)**

In this system power of diesel engine or electrical motor can be transmitted to propeller in parallel. It means that engine and motor powers can be used at the same time. So gear box in this system is more complex than CODLOG system. CODLAD system is shown in Fig 3.

**iii) CODLOG (Combined Diesel-Electric Or Gas turbine)**

This system is combination of EM and GT. EM is used in low speed and GT is used in high speed. This system is very suitable and prevalent for most frigates (such as FREMM Frigate). A CODLOG system is shown in Fig 4.

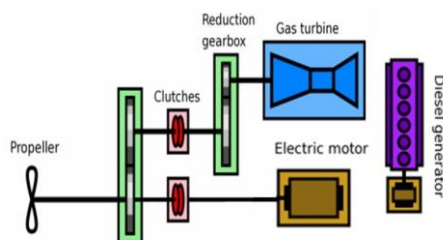


Fig 4. CODLOG propulsion system

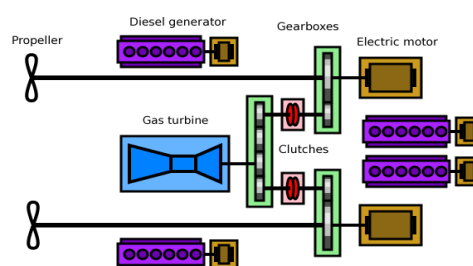


Fig 5. CODLAG propulsion system[4]

**iv) CODLAG (Combined Diesel-Electric and Gas Turbine)**

This system is combination of EM and GT. EM is used in low speed and GT is used in high speed and both of them are used for reaching maximum speed. This system can be designed by one or two GTs. Because of usage of GT and EM powers at the same time, Gear box is more complex in this system than CODLOG system (It is used in German navy F125. see Fig 5).

So hybrid system can have different combinations.

**Typical Hybrid ship operation modes**

A frigate needs different speeds in different positions, cases and situations. Every situation needs different modes for a vessel. In continuation, the typical hybrid operation modes will be introduced.

**1- PTI booster mode**

The PTI booster mode is selected for maximum speed. Together with the main engine, the electric machine works as an auxiliary motor, which delivers power support the propeller. The Gen.sets deliver the electric power, both for propulsion and the vessel's consumption. The PTI booster mode mainly increases the flexibility of the propulsion system for peak loads (Fig 6).

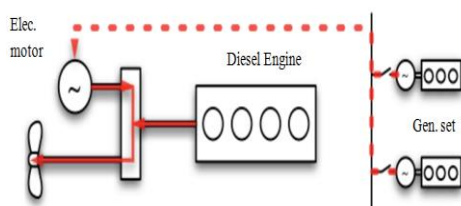


Fig 6. PTI booster mode

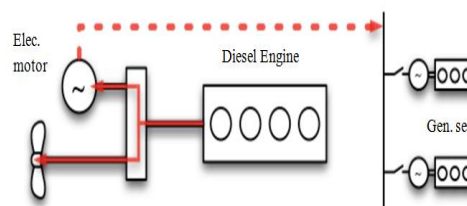


Fig 7. Generator mode (PTO-mode)

**2- Generator mode (PTO-mode)**

Not only does the main engine provide the power for ship propulsion, it also supplies the power needed for the ship's consumption. This mode is selected for transit sailing. It allows high loading of the main engine, running with low specific fuel consumption and therefore with minimal emissions. This also prolongs the maintenance period of the Gen.sets and gives an additional redundancy for the electric power generation (Fig 7).

**3- Electrical mode**

The electric propulsion motor is mainly used at low speeds. It uses the power produced by the Gen.sets and runs the propeller via a gearbox. Usually the main engine is disconnected. An advantage of this mode is the efficient loading of the auxiliary Gen.sets. When using variable-speed E-motors the propeller can be operated on the combinator curve with higher propulsion efficiency, lower noise and lower vibrations emissions. In addition, less maintenance of the main engine is a benefit of this operation mode. In case of a main engine failure a “take-me-home (PTH)” functionality can easily be achieved as well (Fig 8).

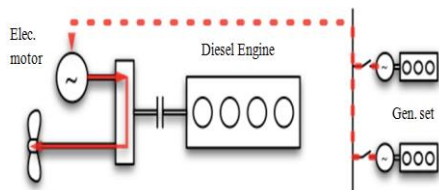


Fig 8. Electrical mode

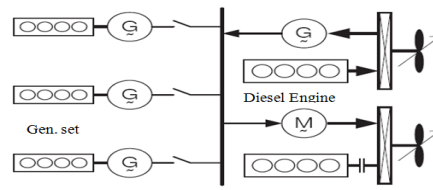


Fig 9. Electrical cross-connection mode

#### 4- Electrical cross-connection mode (Electric Shaft)

In the case of a twin propeller application there is a possibility of driving both propellers with the power of one main engine supplying one shaft machine (PTO) and the other shaft machine run as a “take-in device (PTI)”. This mode ensures extra redundancy and flexibility to the complete propulsion system.[5] For other hybrid system types may occur same modes with a little difference. For example in CODLOG or CODLAG systems GT can be play as diesel engine as above (Fig 9).

#### For better understanding, power per speed diagram of AUSTAL MRV 80 will be studied.

Figure 10 shows that at low speeds (point 1) the propulsion power required is not high. Providing the power by the main diesel engine gives a low and in-efficient main engine loading. A small electric motor is also able to deliver the power to sail the vessel, which can now be supplied by the auxiliary Gen.sets. They are usually smaller than the main engine and can therefore be operated with a higher specific loading. If, for example, both the main engine and the auxiliary Gen.sets are of medium speed types, a better overall plant efficiency is achieved.

At normal operation (point 2) the main engine operates in a range where it is optimized for fuel consumption. Usually a shaft alternator is also connected to the gearbox (PTO) as this is the most economic way to supply power to the propeller and to the vessel’s consumers. At high speeds (point 3) the shaft machine can be used as an electric motor for boosting, which gives extra power to the propeller.

Above diagram and its explanations can be told for CODLOG or CODLAG system but with a difference that GT should be run as a diesel engine.

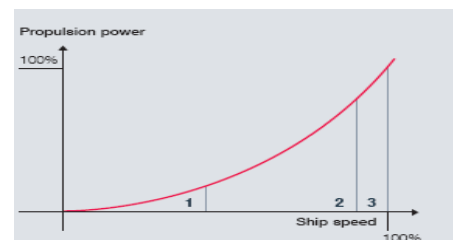


Fig 10. Power per speed of AUSTAL MRV 80[2]

### Comparison of Hybrid Systems

#### a) Compare of Hybrid System and another systems

Fully electrical and fully mechanical systems are the most used systems in transportation. in this part hybrid system is compared with both of the mentioned systems.

##### a-1 comparison of hybrid system and fully electrical system

Using of recyclable energy sources is the first way to reduce emissions. Full electrically powered vehicles are seen to be the best way of reducing emissions. But recharging of these vehicles in long distances is the main trouble. for example suppose that an electrically powered car should travel a long distance, limitation in numbers of batteries which can be carried and their charging capacity are the serious problems. but because of using two or more energy sources, a hybrid system can resolve above problems and it can also operate with higher efficiency in comparison with a fully electrical system. lower speed and higher cost of a fully electrical system, are the other problems in front of a hybrid system.

##### a-2 Comparison of hybrid system and mechanical system

According to researches and the above description a hybrid system has many advantages in comparison with a fully mechanical system which some of them are mentioned in this part.

as it was mentioned before, one of the most important advantages of a hybrid system is its low Specific Fuel Consumption (SFC) if compared with a fully mechanical system. usage of different energy sources (electricity, fuel oil, gas or steam and etc) and different power source (EM, ICE, DE, GT and etc) at their highest efficiency causes a reduction in emission production. so it can be resulted that a hybrid system is more clear than a fully mechanical system. a hybrid system doesn't require an electricity connection for charging the batteries and this flexibility of a hybrid system is the cause of its popularity for being used in personal cars or in transportation vehicles around the world. a hybrid system is able to travel a longer distance and it can switch its power source after finishing the fuel oil or ICE (or Main Engine) being stopped, it can continue the way with lower speed using the energy from its batteries. So hybrid vehicles can travel more distances in comparison with fully mechanical vehicles by one time fuel charging (or bunkering). Moreover in a hybrid system batteries can be charged while the car is moving or stopped, so the batteries will never be fully discharged. So every system has its own advantages and disadvantages as is mentioned in Table 2.

Table 2. Comparison of electrical, mechanical and hybrid systems

	Fuel consumption	Pollution	speed	displacement	Ease of maintenance	Maintenance need	Maintenance cost	Complex equipment
Mechanical system	High	High	High	Mid	Easy	Low	Low	Low
Hybrid system	Mid	Mid	Mid	High	Normal	High	Mid	Mid
Electrical system	Low	Low	Low	Low	Hard	Mid	High	High

**b) Power**

Table 3 shows an overview of different propulsion system installations comparing hybrid mechanical and hybrid electric propulsion. Mechanical systems were continuously developed until approximately one decade ago from simple CODAD solutions to highly complex CODAG arrangements with a cross connect gear. In parallel, electric systems were increasingly accepted throughout the maritime world. Any of the listed configurations have their specific advantages and should be considered reflecting the vessel's needs. Driving factor for the selection of a certain configuration is not only low investment cost but also life cycle cost considering specific fuel consumption, maintenance intensity and overhaul periods as well as reliability and redundancy. The missions determine the platform, the platform determines the propulsion system and the propulsion system determines the reduction gear system. The potential prime movers in a propulsion system given their weights, dimensions and performance are individually selected.

Table 3. Propulsion system variants and existing applications for surface combatants [6]

Propulsion type	Description	Installed power range, MW	Typical application
CODELOD	Combined electric motor or diesel engine	DE 5 ... 10 EM 0.3 ... 0.6	- Netherlands Navy OPV - Korean Coast Guard OPV
CODELAD	Combined electric motor And diesel engine	DE 5 ... 10 EM 0.7 ... 1.5	
CODOG	Combined diesel engine Or Gas turbine	DE 2.5 ... 9 GT 15 ... 22	- German Navy F123 - ROKN FFX
CODAG	Combined diesel engine And Gas turbine	DE 5 ... 9 GT 20 ... 36	With cross connected gear: - German Navy f124 - U.S. Coast Guard NSC - U.S. Navy Without cross connector gear: - Lockheed Martin LCS - Austal LCS
CODELOG	Combined electric motor or Gas turbine	EM 2 ... 3 GT 20 ... 32	- Italian Navy FREMM
CODELAG	Combined electric motor And Gas turbine	EM 4 ... 6 GT 20 ... 25	- German Navy F125

**c) Fuel consumption**

Considering the specific fuel consumption of the prime movers for the four propulsion configurations, the fuel consumption per nautical mile vs. vessel speed is shown in Figure 11. Gear efficiency is considered for all fuel consumption figures; electrical conversion losses are taken account for with the CODELOD and CODELAG solutions. In a patrol of 5000 nm according to the mission profile listed in Table 1, the frigate would consume fuel (propulsion only) as listed in Table 4 for the different propulsion systems. The overall consumption is very close for all configurations.

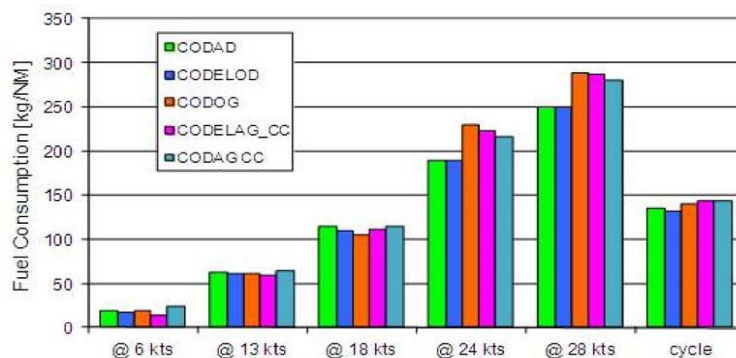


Figure 11. Specific fuel consumption [6]

Table 4. Total fuel consumption for a 5000 nm patrol in metric tons

	CODAD	CODELOD	CODAG	CODELAG w/CC	CODAG w/CC
5000 nm patrol (tons)	680	663	703	717	722

**d) Pollution**

As it has been told in above, hybrid system high efficiency leads to low fuel consumption and it causes reduction in environmental pollution due to low emission. International Maritime Organization (IMO) has very stringent rules for environmental pollution prevention. Annex vi MARPOL is related to AIR POLLUTON PREVENTION and it is obligatory that all oceanic vessels NO<sub>x</sub> should be less than 4.3 gr /kwh and SO<sub>x</sub> should be less than 1% in ECA (Emission Control Area). So the hybrid systems can be adapted by these rules and regulations simply.

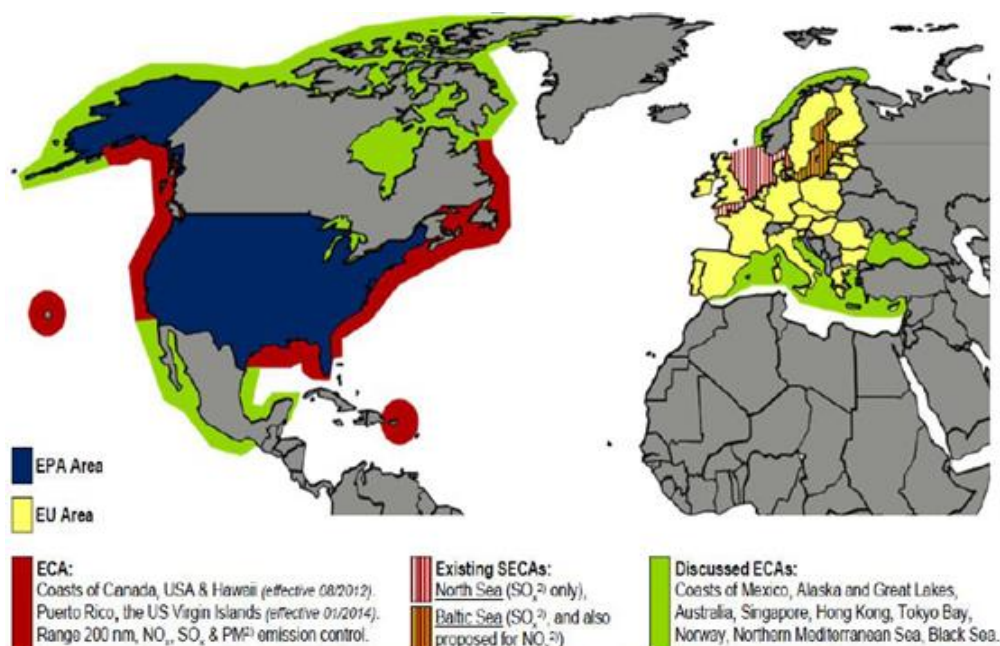


Fig 12. ECA (Emission Control Area)

**e) Power and Speed**

Five different propulsion system arrangements are investigated as potential solutions for the frigate's power plant. The features and performance of each arrangement are evaluated against pertinent parameters listed earlier. Table 5 shows an overview of the subject arrangements.

Table 5. Propulsion system variants [6]

`HRF2	MW	RPM	Fuel <sup>1)</sup> g/KWh	CODAD		CODELOD		CODOG		CODELAG with CC		CODAG with CC	
				NO	Power, MW	NO	Power, MW	NO	Power, MW	NO	Power, MW	NO	Power, MW
DE 20V	9.1	1150	195	4	36.4	4	36.4				0	2	18.2
DE 12V	5.4	1000	195					2	(10.8)				
GT1	21	3600	225					2	42		0	1	21
GT2	32	3300	225							1	32		
GEN-SET DE 12V	5.2	1000	225 <sup>2)</sup>			1	(5.2)						
Electric motor 1	2.4	1800	228 <sup>3)</sup>			2	(4.8)						
Electric motor 2	4.7	150	228 <sup>3)</sup>							2	9.4		
Total input shaft power					36.4		36.4		42		41.4		39.2
Max speed. kts					28.0		28.0		29.4		29.2		29.0

NOTES:

- 1) At nominal load.
- 2) Generator efficiency considered.
- 3) Generator, convertor, and electric motor efficiency considered.

## Conclusions

- By compare of different types of ship propulsion systems can find that Hybrid System has less Specific Fuel Consumption (SFC), lowest pollution, highest efficiency, good power output and varied arrangement capability in ship engine room than other systems. So can express that Hybrid System is a proper system with high efficiency.
- According to researches and the above description a hybrid system has many advantages in comparison with a fully mechanical and full electrical systems which some of them are mentioned in this paper.
- New ship propulsion systems are designed to decrease the fuel consumption and hybrid system (with different arrangement) is the best system to this purpose.
- Hybrid system has more latitude for arrangement of machinery in engine room of vessel.
- A vessel needs different speeds in different positions, cases and situations. Every situation needs different modes for a vessel.
- Due to different Hybrid System modes and speeds, it can be a proper propulsion system for frigates.

## List of Symbols

CODLAD	Combined Of Diesel-Electric And Diesel engine
CODLAG	Combined Of Diesel-Electric And Gas turbine
CODLOD	Combined Of Diesel-Electric Or Diesel engine
CODLOG	Combined Of Diesel-Electric Or Gas turbine
DE	Diesel Engine for propulsion
DG	Diesel-Generator set for electric power generation
EM	Electrical Machine for propulsion
GT	Gas Turbine for propulsion
GT-G	Gas Turbine-Generator set for electric power generation
ICE	Internal Combustion Engines
ST	Steam Turbine

## References:

- [1] Benjamin Houston Gully, " Hybrid Powertrain Performance Analysis for Naval and Commercial Ocean-Going Vessels ", Ph.D. Thesis, The University of Texas at Austin, August 2012
- [2] Hubert F. Ohmayer , " Propulsion System Choices for modern Naval Vessels " , MTU Company, Washington, November 2012
- [3] MAN Diesel & Turbo, " Hybrid Propulsion, Flexibility and maximum efficiency optimally combined " , MAN Company brochure, 2010
- [4] Sven De Breucker, Eefje Peeters and Johan Driesen, " Possible applications of Plug-in Hybrid Electric Ships ", Ph.D. Thesis, KULeuven, ESAT – Electa, Kasteelpark Arenberg 10 , B-3001 Heverlee, 2004
- [5] Bas Kwasiękyj, " Hybrid propulsion systems, efficiency analysis and design methodology of hybrid propulsion systems " , Master Thesis, Delft University of Technology, Conducted at MAN Diesel & Turbo SE, Augsburg, March 2013
- [6] B. Pinnekamp, F. Hoppe and, M. Heger and RENK AG, " Combined Marine Propulsion Systems: Optimization and Validation by Simulation " , American Gear Manufacturers Association, October 2012