The Study of the Application of Hybrid Propulsion System onOPV withControllable Pitch Propellers

Eddy Setyo Koenhardono[1], Amiadji[2], Rahmat Kristomi[3]

Abstract—as a patrol ship, the offshore patrol vessel (OPV) 80 m has an operational profile consist of several conditions: loitering (10 knots), patrol (18 knots), and interception (22 knots). Applying diesel mechanic propulsion system, load factor of each OPV 80 m's main engine during loitering (10 knots) and patrol (18 knots) conditions in sequence have the value of 7% and 49.54%. The load factor permitted by the engine maker ranges between (60% ~ 90%) MCR, However, By applying hybrid propulsion system, the load factor of the OPV 80 m's shaft motor during loitering condition has the value of 87.26% while the load factor of its main engine during patrol and interception conditions becomes 62.10% and 89.949%.In terms of economic aspects, for 30 years of operation period of OPV 80 m, total of present values of hybrid application is significantly much lower than the diesel mechanical application, with the difference between them is IDR579.205.295.632,-.

Keywords—operational profile, shaft motor,load factor, diesel mechanical propulsion.

I. INTRODUCTION

The offshore patrol vessel(OPV) 80 m is one of the patrol ship with the duty to watch over the exclusive economic zone (EEZ) over illegal activities, such as infiltration of foreign troops, smuggling, illegal fishing, piracy, and other similar activities [1]. A diesel mechanical propulsion (DMP) system applied to the OPV 80 m[2] operates during all conditions: including loitering (10 knots), patrol (18 knots), and interception (22 knots).

Based on the results of preliminary analysis, load factor (LF) of each main engine during loitering, patrol, and interception conditions in sequence is just about 6%, 45%, and 75%. Such very low LF during loitering and patrol causes the operation of the main engines beyond range of permitted operation condition set by the engine maker all the time. This results in increase of*specific fuel oil consumption* (SFOC) and in a long term decrease of the lifetime of engines' parts due to excessive vibration [3]. To overcome this situation, the propulsion system of the OPV 80 m needs to be re-engineered. The re-engineering process is carried out by changing the existing DMP system to hybrid propulsion system.

The hybrid propulsion system is a dynamic combination of DMP and diesel electric propulsion (DEP) systems **(Figure 1)**. This system has four propulsion modes: shaft motor, shaft generator, mechanical, and booster modes [4].These various propulsion modes could adapt to meet the requirement of the various OPV 80 m's operation condition. Such propulsion system is worth considering to be applied to the OPV 80 m due the operational flexibility it offers.

This paper presents a configuration layout and specification of the hybrid propulsion system applied as well as the comparison between the DMP and hybrid systems in terms of both technical and economic aspects.

A. *Shaft Motor/ Power Take Home (PTH)Mode*

Shaft motors are used as the only propulsion engineduring loitering condition, while the main enginesare not activated at all [5]. The Advantages gained by this mode are:

1. preventing low main engine's LF and lower its usage load for it is inactive at all, and
2. noise and vibration generated will be much lower so that the chances of a successful loitering condition are increasing [6].

Electrical power supply to shaft motors come from diesel generator sets (D/Gs) through main switchboards(MSB) and frequency converters(FC) **(Figure 2)**.On the existing DMP system configuration, 4 x 450 kWe of D/Gsare installed [7].On hybrid propulsion system configuration, compensating for additional electrical load due to the operation of 2 x shaft motors, the capacity of D/Gs is to be increased as much as 2 x the shaft motor rating plus starting load of each shaft motor. Each shaft motor will be started by thefrequency converter (F/C). By using the F/C starter, required starting current can be lowered to 1 ~ 1.5 full load current only [8].

B. *Shaft Generator / Power Take Off (PTO) Mode*

In this shaft generator mode,the main engines take role as the only propulsion engines [5]. To prevent low LF condition on the main engines, some amount of their brake power is used to rotate the rotors of the shaft motors at their rated speed x (1 + slip) **(Figure 3)** so that the shafts motor are converted to be shaft generators [9].

Eddy SetyoKoenhardhono, Department of Marine Engineering, SepuluhNopember Institute of Technology, Surabaya 60111, Indonesia. E-mail:eddy-koen@its.ac.id

Amiadji, Department of Marine Engineering, SepuluhNopember Institute of Technology, Surabaya 60111, Indonesia. E-mail: amiadji@its.ac.id

RahmatKristomi, Department of Marine Engineering, SepuluhNopember Institute of Technology, Surabaya 60111, Indonesia. E-mail: kristomirahmat@gmail.com

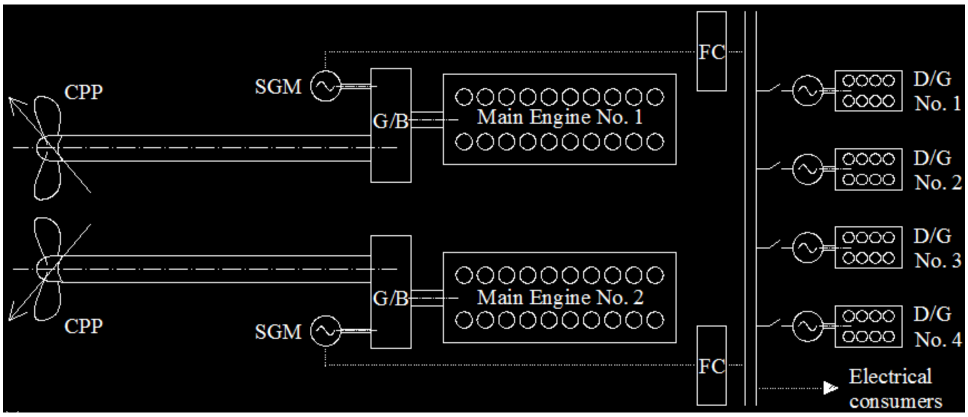

Figure 1. Configuration layout of the hybrid propulsion system with twin screwCPP (concept on OPV 80 m)

Operating 2 x shafts generator to supply electrical power requirements will likely reduce usage load of D/Gs. Thisallows at least one unit of D/Gs to be inactive during patrol or interception condition[16].

C. Mechanical Mode

Same as in the shaft generator mode, in mechanical mode, the main engines take role as the only propulsion engines [5]. The difference between the shaft generator mode and the mechanical mode lies in the LF of each main engine. In mechanical mode, the LF of each main engine is considered as being within the permitted range, that is (60% ~ 90%) MCR [10].Therefore, shaft generators need not to be activated **(Figure 4)**during patrol or interception condition[18].

D. Booster / Power Take In (PTI) Mode

In this mode, both the shafts motor and the main engines become the propulsion engines simultaneously [5]. This allows decrease in LF of each main engine **(Figure 5)**. Synchronization between RPM of the shaft motors and the main engines is absolutely necessary in order to prevent braking condition on either the shaft motor or the main engines. This means the RPM of both the propulsion engines have to be same each other so that power losses during transmission process in gearbox should not be excessive[17].

Same as in the shaft motor mode, the electrical power suppy to shaft motors comes from D/Gs through MSB and FC.Thus more D/Gs need to activated during interception condition.

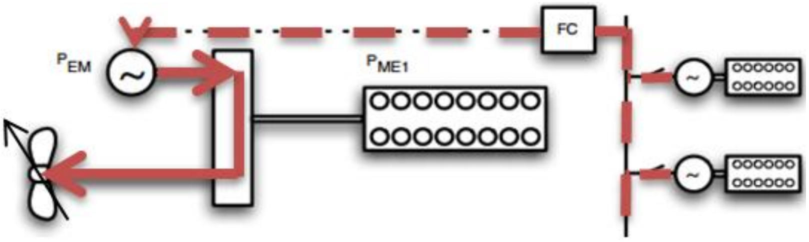

Figure 2. Energy flow in shaft motor / power take home (PTH) mode [5]

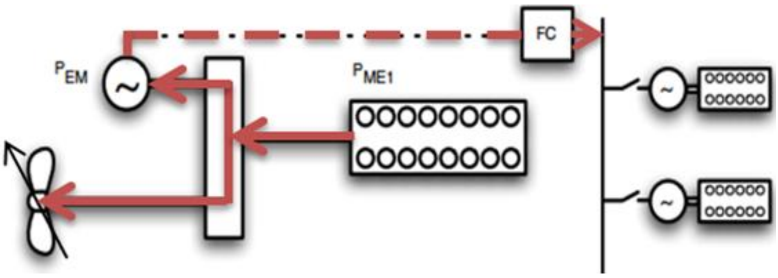

Figure 3. Energy flow in shaft generator / power take off(PTO) mode [5]

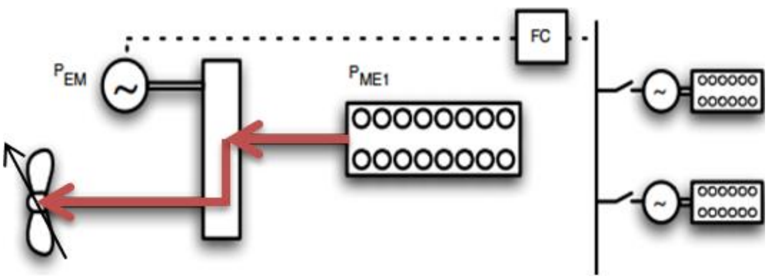

Figure 4. Energy flow in mechanical mode [5]

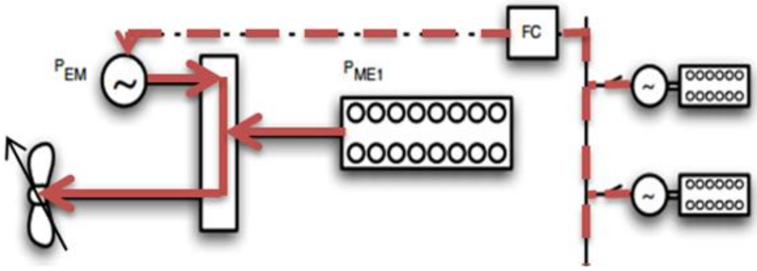

Figure 5. Energy flow in booster / power take in(PTI) mode [5]

III. Method

A. Data Collection

Primary data required for these studies are acquired directly from the OPV 80 m's designer, engine makers, and shipyard company. The primary data that needed are as follows.

a) Principal dimensions ofthe OPV 80 m
b) Maintenance schedule of each component of both DMP and hybrid propulsion systems
c) Maintenance costs including spare parts'prices of each component of both DMP and hybrid propulsion systems

Secondary data required for these studies are acquired from reviewing existing literature. The primary data are as follows.

a) General OPVs'operational profile data
b) The configuration of the existing DMP system on the OPV 80 m
c) Electrical power required during each operation condition of the OPV 80 m including the number of installed and required runningD/Gsduring each operation condition
d) Components and propulsion modes of general hybrid propulsion system
d) Investment cost of each component of both DMP and hybrid propulsion systems
e) Performance diagram of the main engines, D/Gs, and chosen *shaft generator motors* (SGM).

B. Prediction of Total Resistance

The initial step of these studies is the calculation of total resistance of each OPV 80 m's operation condition or each speed (Vs) by using Holtrop method [11]. The total resistance during services is called $R_{T\ service}$acquired by multiplying sea margin (SM) factor with the previously acquired R_T with the Holtrop method.

$$R_{T\ service} = SM \times R_T \quad (1)$$

The SM factor varies among sailing routes. For seas around Indonesia e.g. Indian and Pacific Oceans, the SM factor would vary in range of 1.15 ~ 1.20 [12]. In case of the OPV 80 m, the greatest SM factor is considered to be 1.20.

C. Prediction of Required PropulsivePower

After acquiring the SM factor for everyVs, the prediction of required power for propulsion on each Vs can now be carried out. The required engine power for propulsion (P_B) is a function of the $R_{T\ service}$ and Vs like this following formula [13]:

$$P_B = \frac{R_{T\ service} \times Vs}{\eta_{PTO/PTI\ gearbox} \times \eta_{shaft} \times \eta_{propulsive}} \quad (2)$$

where:

$\eta_{PTO/PTI\ gearbox}$ = power transmission efficiency through the PTO/PTI gearbox, as much as 0.967 [13]

η_{shaft} = power transmission efficiency through the shafting system, as much as 0.98 [13]

$\eta_{propulsive}$ = propulsive efficiency resulted from the interaction of ship hull and the propeller, initially taken as 0.60

D. Propeller Selection

Steps of the propeller selection for hybrid propulsion system taken as follows.

1. Determination of number of propeller's blades
2. Calculation of maximum propeller's revolution speed
3. Calculation of allowed propeller's diameter upper limit
4. Calculation of propeller's diameter, initial ηo, and P/D ratio

E. Ship Hull – Propeller Interaction

Thrust produced by propellers (T_{Prop}) is to be same as thrust needed by the hull (T_{Hull}) so that the OPV 80 m could sail at determined Vs with the propulsion engines' LF and speed within permitted operation range.T_{Prop} would be same as T_{Hull}only if T_{Prop}coefficient (Kt_{Prop}) is same as T_{Hull}coefficient(Kt_{Hull}). The Kt_{Hull} is determined by the following formula [13]:

$$Kt_{Hull} = \beta J^2 \quad (7)$$

where:

$$\beta = \frac{1}{2}\frac{\rho\ Ct\ S}{(1-t)(1-w)^2 D^2}$$

where:

Ct $= R_{T\ service}$ coefficient as function of Vs

$$= \frac{2\ Rt}{\rho S\ Vs^2} \quad (8)$$

The Kt_{Hull} vs J curve could be drawn by giving various J numbersin range between 0 to 0.9 into Formula

7.Kt_{Prop}vs J curve is acquired from open water diagram of the previously chosen propeller. The Kt_{Hull} vs J curve is then plotted onto the propeller's open water diagram. From the intersection point between the Kt_{Hull} vs J curve and the Kt_{Prop} vs J curve on the open water diagram, hull – propeller interaction satisfying J number, propeller torque coefficient (Kq), and propeller's efficiency for a given P/D ratioof a given Vs can be acquired. For the type of the propellers used is of Wageningen B series, the J number and Kq are figured out for all P/D ratios in range between 0.5 to 1.4 Vsfor eachVsvarying between 5 knots to 22 knots (maximum) [14].

F. Analysis of Economical Aspects of the Hybrid Propulsion Application

The method used for this analysis is present value (PV). Annual PV of each propulsion system can be determined by using Formula 9 [15].

$$PV_n = {CO_n}/{(1+i)^n}\ ;\ n \in \boldsymbol{N} \quad (9)$$

Di mana:
i = interest factor (10%)
n = yearin natural numbers (1, 2, 3, ...)
CO_n = cash outflow in year n
$= FC_n + MME_n + MAE_n + RME_n + RAE_n + REM_n + BB_n + MCSS_n + PS_n;\ n \in \boldsymbol{N}$ (10)

where:
FC_n = Fuel consumption cost in year n
MME_n = Maintenance cost of the main engines in year n
MAE_n = Maintenance cost of the generator's prime movers in year n
RME_n = Main engines' spare parts replacement cost in year n
RAE_n = Generator's prime movers' spare parts replacement cost in year n
REM_n = Electrical machines' reconditioning costs inyear n
BB_n = Electrical machines' ball bearings replacement cost in year n
$MCSS_n$ = Maintenance cost of CPPs and shaftting systems in year n
PS_n = Price of shafting systems' seals in year n

Annual PV for OPV 80 m's operation period of 30 years of each propulsion system application is then accumulated to acquire total PV of each propulsion system application and the difference between them will be amount of savingsas benefit gained from the hybrid propulsion system application.

IV. RESULTSAND DISCUSSION

A. Data Umum OPV 80 M

Principal dimensionsof the OPV 80 m are as follows [18].

1.	Loa	= 80.90	m
2.	Lpp	= 73.15	m
3.	Lwl	= 76.15	m
4.	Moulded breadth (B)	= 13.60	m
5.	Moulded height (H)	= 7.0	m
6.	Moulded draught (T)	= 3.0	m
7.	Block coefficient (Cb)	= 0.48	
8.	Prismatic coefficient (Cp)	= 0.64	
9.	Waterplane coefficient (Cwp)	= 0.75	
10.	Maximum service speed	= 22	knot
11.	Endurance	= 3000	NM

General OPVs' operational profile andthe OPV 80 m's machinery and electrical data are consecutivelypresented by **Table 1**, **Table 2**, and **Table 3** below.

B. Prediction of Total Resistance and Required Propulsion Engines' Power

By giving Vs = 10 knots, 18 knots, and 22 knots into Holtrop formula and Formula 2, $R_{T\ service}$ and P_B can be acquired for each given Vs.

1. Vs = 10 knot (Loitering)
   a) $R_{T\ service}$ = 64.202 kN
   b) P_B = 645.337 kW
2. Vs = 18 knot (Patrol)
   a) $R_{T\ service}$ = 216.727 kN
   b) P_B = 3921.243 kW

TABLE 1.
GENERAL OPVS' OPERATIONAL PROFILE [19]

No.	Operation conditions	Vs [knot]	Duration [hour/year]
1	*At port*	-	3504
2	Loitering	10	1577
3	Patrol	18	2102
4	Interception	22	1577

TABLE 2.
OPV 80 M'S MACHINERY DATA [9]

No.	Components	DMP system
1	Main engines	2 x MTU 20V 4000 M93L 4300 kW @ 2100 rpm
2	D/Gs	4 x CAT C18 ACERT 450 kWe @ 1500 rpm, 380 VAC, cos phi = 0.8
3	Propellers	2 x Wageningen B4-65 D = 1.83 m, P/D = 0.852, ηo = 0.569
4	Gearboxes	2 x single I/O ZF 23560 C 5327 kW/2100 rpm, rasio 3.577 : 1

TABLE 3.
OPV 80 M'S ELECTRICAL DATA [9]

No.	ITEMS		At Port	Loitering	Patrol	Interception
1	Continuous load	[kW]	606.38	797.42	826.13	847.39
2	Intermitten load	[kW]	531.35	447.14	566.98	562.79
3	Diversity factor	[kW]	265.68	223.57	283.49	281.39
4	Total electrical load	[kWe]	872.05	1020.99	1109.62	1128.78
5	Running D/Gs	[unit x kWe]	3 x 450	3 x 450	3 x 450	3 x 450
6	LFof each D/G		64.60%	75.63%	82.19%	83.61%

3. Vs = 22 knot (Interception)
   a) $R_{T\ service}$ = 345.370 kN
   b) P_B = 7637.399 kW

C. Propulsion Engine Loading Analysis during Loitering Condition

The results of shaft motor – propeller matching MPM) analysis presented by **Figure 6**. In **Figure 6** it can be seen that match P/D ratio for Vs = 10 knots is 0.55 with LF of each shaft motor = 87.26% with each shaft motor produces torque = 273.30% its rated torque and speed = 78.30% its rated speed.

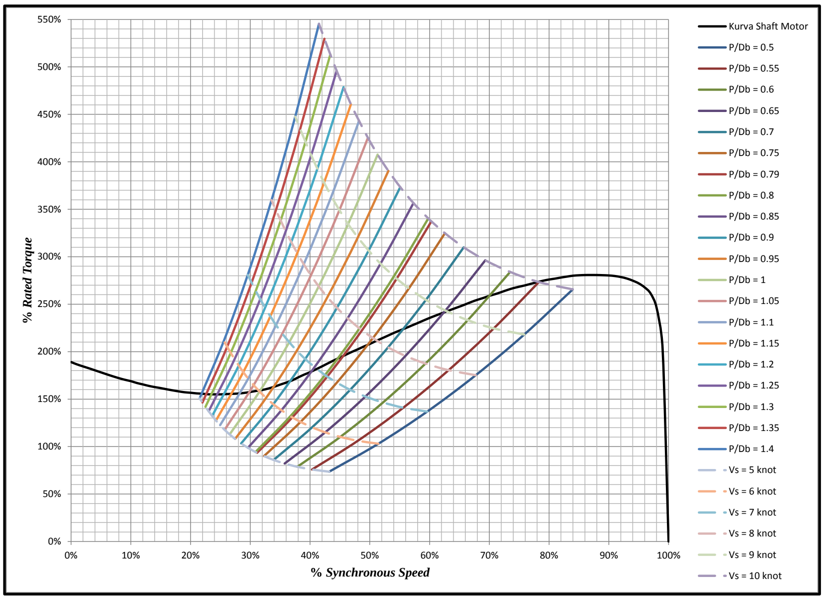

Figure 6. The results of SMPM analysis for various P/D ratios of each Vs varying between 5 knots to 10 knots

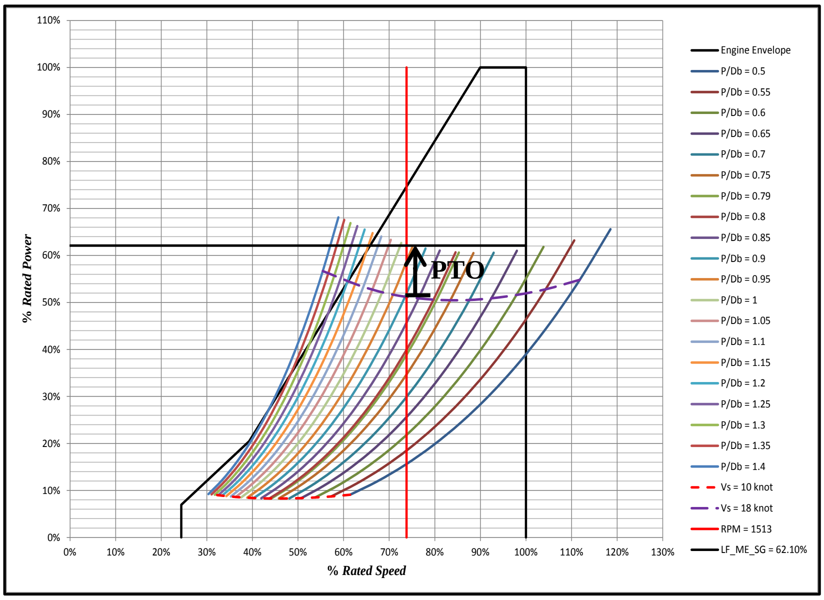

Figure 7. The results of DEPM analysis for patrol condition with 355 kWe shaft generator loading

D. Propulsion Engine Loading Analysis during Patrol Condition

The results of diesel engine – propeller matching(DEPM) analysis for patrol condition presented by **Figure 7**. In **Figure 7** can be seen that after being loaded by 355 kWe shaft generator, LF of each main engine increases from 51.55% to 62.10% at 1513 rpm with match P/D ratio for Vs = 18 knots is 0.9

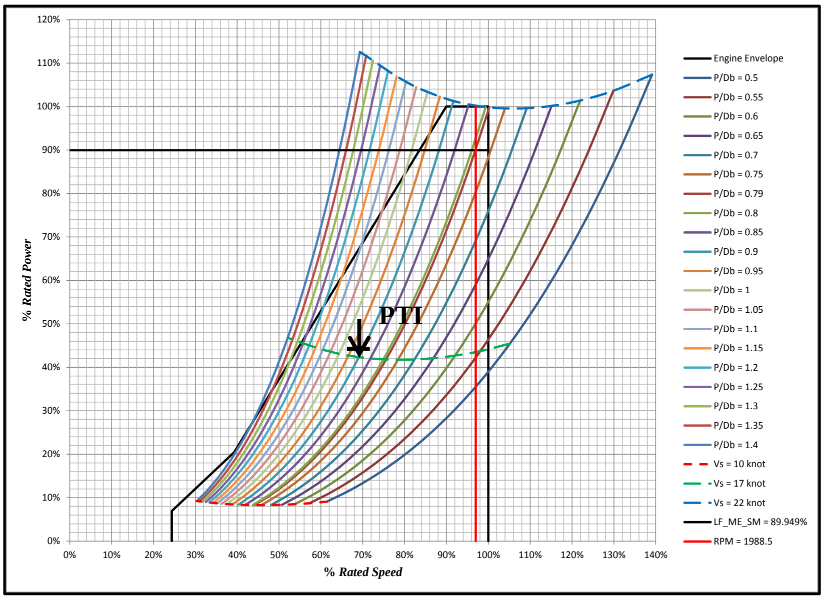

Figure 8. The results of DEPM analysis for interception condition with 355 kW shaft motor synchronization

E. Configuration of the Hybrid Propulsion System

Based on the previous results of the propulsion engine loading analysis, propulsion modes meeting the OPV 80 m's required propulsion and electrical power as well as D/Gs loading condition during each operation condition can now be determined as presented by **Table 4**.

TABLE 4.
SELECTION OF THE HYBRID PROPULSION CONFIGURATION WITH LOAD CALCULATION AND ELECTRICAL SYSTEM

Subsystems	ITEMS	At Port	Loitering	Patrol	Interception
Propulsion System	P_B [kW]	-	645.337	3921.243	7637.399
	Main engines' rating [unit x kW @ rpm]	-	-	2 x 3600 @ 2100	
	LF of each main engine	-	-	62.10%	89.949%
	Rev. speed of each main engine [rpm]	-	-	1513	1988.5
	Shaft motors' rating [unit x kW @ rpm]	-	2 x 355 @ 1500	-	2 x 355 @ 1500
	Shaft motors' frequency [Hz]	-	50	-	65.709
	Propeller chosen	Wageningen B4-55			
	Match P/D ratio of CPP	-	0.55	0.9	0.79
	Mode propulsi	-	PTH	PTO	Booster/ PTI
Electrical System	Total electrical load [kWe]	872.05	1020.99	1109.62	1128.78
	Running D/Gs [unit x kWe]	2 x 720	3 x 720	1 x 720	3 x 720
	Running *shaft generators* [unit x kWe]	-	-	2 x 355	-
	LF of each generator	60.56%	80.14%	77.60%	85.13%

F. Propulsion Engine Loading Analysis during Interception Condition

The results of diesel engine – propeller matching(DEPM) analysis for interception condition presented by **Figure 8**.**Figure 8**can be seen that after being syncedwith 355 kW shaft motor, LF of each main engine decreases from 99.81% to 89.949% at 1988.5 rpm with match P/D ratio for Vs = 22 knots is 0.79.

G. Analysis of Economical Aspects of Hybrid Propulsion Application

In this analysis, there are 2 types of cost to be considered: constant and variable costs. The constant cost includes investment cost (IC). IC itself includes purchasing and installation costs of components of both the propulsion systems. Variable cost (VC) includes fuel consumption costs and all maintenance related costs for these costs are time dependent.

Results of calculation and the comparison of IC, VC, ΣCO, ΣPV, and ΣPV difference of both the propulsion systems up to the 30^{th} year are presented by **Table 5**.

TABLE 5.
COMPARISON OF IC, VC, Σ CO, Σ PV, AND Σ PV DIFFERENCE OF BOTH PROPULSION SYSTEMS UP TO THE 30TH YEAR

Costs	Propulsion systems	Result of calculation
IC	DMP	IDR 106,639,410,143,-
	Hybrid	IDR 107,302,399,186,-
FC_{30}	DMP	IDR 44,428,640,001,434,-
	Hybrid	IDR 41,115,632,805,620,-
MME_{30}	DMP	IDR 90,351,067,638,-
	Hybrid	
MAE_{30}	DMP	IDR 23,052,183,770,-
	Hybrid	IDR 32,951,832,487,-
RME_{30}	DMP	IDR 455,035,124,076,-
	Hybrid	
RAE_{30}	DMP	IDR 200,316,231,484,-
	Hybrid	IDR 300,556,635,718,-
REM_{30}	DMP	IDR 2,424,822,133,-
	Hybrid	IDR 4,678,053,678,-
BB_{30}	DMP	IDR 3,096,831,802,-
	Hybrid	IDR 9,251,495,406,-
$MCSS_{30}$	DMP	IDR 602,749,061,-
	Hybrid	
PS_{30}	DMP	IDR 117,734,062,-
	Hybrid	
Σ CO	**DMP**	**-IDR 45,643,758,623,812,-**
	Hybrid	**-IDR 42,339,809,312,190,-**
Σ PV	**DMP**	**-IDR 8,113,250,298,313,-**
	Hybrid	**-IDR 7,534,045,002,681,-**
	Σ PV difference	**-IDR 579,205,295,632,-**

V. CONCLUSION

The application of the hybrid propulsion system on OPV 80 m with CPP is really advantage both in terms of technical and economical things. This conclusion is made based on the several results as follows.

1. During loitering condition (Vs = 10 knots), with DMP system application, LF of each main engine is just 7.08%. But if the DMP system is replaced bythe hybrid propulsion system, shaft motor / PTH mode is activated resulting in no load condition of main engines for they are completely inactive during this condition. This also results in much less noise and vibrationand creates more environmentallyfriendly condition.
2. During patrol condition (Vs = 18 knots), with DMP system application, LF of each main engine is just 7.08%. But if the DMP system is replaced by the hybrid propulsion system, shaft generator / PTO mode is activated resulting in increase of main engine’s LF up to 62.10%. In such configuration, the P/D ratio capable of propelling the OPV 80 m up to 18 knot so that each shaft generator produces 355 kWe electrical power is 0.9.
3. During interception condition (Vs = 22 knots), with DMP system application, LF of each main engine is 77.67%. But if the DMP system is replaced by the hybrid propulsion system, booster / PTI mode is activated with shaft motor – main engine synchronization. Being synced with355 kW shaft motors, LF of each main engineis 89.949%.
4. At 1988.5 rpm, shaft motor – main engine synchronizationis achieved so that the combined power of the shaft motors and of the main engines to propel the OPV 80 m up to 22 knotsis2 x 3593.164 kW (twin screw).

5. Investment cost of the application of DMP system is IDR 106,639,410,143,- while of hybrid propulsion system is IDR 107,302,399,186,-. Therefore, the difference between them is IDR 662,989,042,-.
6. The application of the hybrid propulsion system on OPV 80 m decreases amount of HSD consumedsignificantly, that is from 6817.339 ton/year to 6308.976 ton/year. Such significant decrease means a more economical and environmentally friendly operation condition.
7. Up to 30th operational year of OPV 80 m, total fuel consumption cost for the application of DMP system is IDR 44,428,640,001,434,-while forofthehybrid propulsion system is IDR 41,115,632,805,620,- so that the difference between them isIDR3,313,007,195,813,-.
8. Up to 30th operational year of OPV 80 m, total maintenance costs for the application of DMP system is IDR 326,177,757,012,- while for of the hybrid propulsion system is IDR 817,804,656,701,- so that the difference between them isIDR491,626,899,689,-.
9. The total PV of the application of the hybrid propulsion system is significantly lower than of the DMP system, with the difference between themisIDR579,205,295,632,-.

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