Probability Based Generator Commitment Optimization in Ship Power System Design

DAMIR RADAN, ASGEIR J. SØRENSEN, TOR A. JOHANSEN, ALF KÅRE ÅDNANES
[a]Department of Marine Technology, NTNU, N-7491 Trondheim, NORWAY
[b]Department of Engineering Cybernetics, NTNU, N-7491 Trondheim, NORWAY
E-mail: {damir.radan, asgeir.sorensen}@marin.ntnu.no,
E-mail: tor.arne.johansen@itk.ntnu.no, alf-kare@ippconsulting,com
http://www.ivt.ntnu.no/imt/electricship/

Abstract: This paper describes the optimization of marine power system design and power management system (PMS) unit commitment algorithm. The optimization is based on a probabilistic approach to vessel operational conditions with regards to blackout prevention and minimization of fuel consumption. The generator commitment problem has been solved using long term probability of sea states and expected values of wave heights based on weather statistics. The problem is analyzed by taking care of proper selection of vessel's operational profile, total installed power, number of generator sets, power rating of each unit, load dependent start/stop tables and load sharing among generators. The cost function is based on fuel consumption and operational requirements. Minimization of fuel consumption has been analyzed with respect to efficient use of fast load reduction technology where generating sets inertia has important influence on the power system speed of response and direct influence on risk of the blackout. Redundancy requirements with respect to blackout prevention are also included in the optimization. The proposed optimization scheme can be used in marine power plant design and application of any technology that influence power system inertia such as flywheel energy storage devices, batteries and fuel cells.

Key Words: probability-based optimization, power system design, blackout prevention, fuel consumption

1 Introduction

In recent years, various methods to improve operability and safety of marine vessels have been developed and successfully applied [5].

The traditional power management system (PMS) monitors the total power demand and compares it to the available supply. The system can automatically start and stop generator sets to coincide with the load changes in accordance with the pre-set load dependent start-stop tables. In case of one generator set sudden failure, the power system loading will be transferred to the remaining generators online. According to the class rules, transient frequency after step load for marine power system is limited to $\pm 10\%$. Activating the under frequency limit will initiate opening of the circuit breakers for the remaining generator(s) online which can have a total blackout as a consequence. Hence, the online generators must be unloaded before reaching the under frequency limit.

One of the features of frequency converters for propulsors and thrusters and other process motor drives, is the possibility to change the power very fast in less than 50 to 100 ms. That has been utilized in the fast load reduction system. Propulsors and thrusters are typically the largest consumers in ships with electric propulsion and for station keeping vessels, and current fast load reduction systems of modern variable speed drives can control the load within less than 0.5 seconds.

Optimization of power system components in the ship design stage has been given in [2] and [4].

This paper is a result of research on the problem defined previously in [4] where the similar optimization problem was solved for equal rated units. In this paper, we present a more general optimization method that includes more detailed consideration of the operational profile.

2 Unit commitment problem and optimization

Assume k unequally rated units that are connected online. Then, the optimization problem is to find the received load $P_L(k)$ in the moment of starting the next unit k+1 in order to achieve the minimum difference in total instantaneous fuel consumption, according to following formulation:

$$\min_{P_L(k)}\left(\sum_{i=1}^{k+1} FC_i\left(P_i(k+1)\right)-\sum_{i=1}^{k} FC_i\left(P_i(k)\right)\right)\geq 0\,, \qquad (1)$$

where $i \in [1, N]$, $i \in I$, N is the number of installed units. $FC_i(P_i(k))$ is the instantaneous fuel consumption on each unit i with k unequally rated units online, usually indicated in tons per hour. $P_L(k)$ is the received load with k units online and has the same value for k+1 units online. For the unconstrained problem, the optimum is found with setting (1) equal to zero. For negative values of (1) the spinning reserve becomes lower than with positive values. For equally rated units in (1) we have [4]:

$$P_i(k) = \frac{P_L(k)}{k}, \qquad P_i(k+1) = \frac{P_L(k)}{k+1}. \tag{2}$$

The load dependent start table $P_{start,i}$ (k), can be determined according to following equation:

$$P_{start,i}(k) = P_i(k) \quad \rightarrow \quad N_{on} = k+1. \tag{3}$$

where N_{on} is the number of units operating online. The next unit k+1 will be started when P_i (k) becomes equal to the value defined in the load dependent start table $P_{start,i}(k)$. The instantaneous fuel consumption for each unit is calculated according to:

$$FC_i(P_i) = b_{e,i}(P_i)P_i, \tag{4}$$

where P_i is the generated power on unit i, and $b_{e,i}$ is the specific brake fuel consumption (SBFC) for each unit, usually indicated in g/kWh. For medium speed diesel engines b_e is typically a convex curve with a minimum about 80% rated power. $b_{e,i}$ can be determined by the use of polynomial approximation as follows:

$$b_{e,i}(P_i) = \sum_{j=0}^{m} a_{j,i} \cdot P_i^j, \tag{5}$$

where $a_{j,i}$ are approximation constants for each generating unit i. The cost function has to be minimized subjected to the following constraints:

$$\sum_{i=1}^{N} P_i = P_L, \tag{6}$$

$$P_{\min,i} \le P_i \le P_{\max,i}. \tag{7}$$

The constraint in (6) requires that the total generated power on all online generators to be equal to the received load by consumers P_L in all power range. The constraints in (7) impose limitations of prime movers. For diesel engines a continuous operation below 15% rated power and above 100% rated power is not recommended. Overload in the range of 100 to 110% rated power is not allowed for more than one hour continuous running. The following equation determines the load sharing between the online generators:

$$P_i(k) = P_L \cdot L_{share,i}(k), \tag{8}$$

where $L_{share,i}(k)$ is the load sharing ratio of indicated generator i when having k generators online; $L_{share,i} \in [0, 1]$. Class rules require $L_{share,i}(k)$ to be power independent and to have a constant value for the k units online. According to the constraint defined in (6), the load sharing sum for all generators must always be equal to 1:

$$\sum_{i=1}^{N} L_{share,i}(k) = 1. \tag{9}$$

For unequally rated units, the installed power must equal to the total ratings of all units:

$$P_{install} = \sum_{i=1}^{N} P_{rated,i}, \tag{10}$$

and according to the constraint (7) the rated power will correspond to maximum continuous operating power, $P_{rated,i} = P_{max,i} = 100\% \, P_i$.

It is relevant to investigate how the solutions close to the optimal affect the total fuel consumption per year with regards to the spinning reserve, class society rules and design requirements. The proposed optimal control for the whole operating range per year should include the operating profile of the vessel, according to following minimization:

$$\min_{P_L} J_{year} = \min_{P_L} \int_0^{P_{install}} \left(FC(P_L) \cdot OP(P_L) \right) dP_L, \tag{11}$$

where $OP(P_L)$ is the operational profile of the vessel.

2.1 Load dependent start and stop

The load dependent start table has been optimized to obtain the lowest possible fuel consumption, considering the blackout as an important constraint. That has been done for the units of equal rating in [4]. In the load increasing operations, the generator units must be started and connected online, gradually one at the time. In the load decreasing operations, these online units can be disconnected and stopped in order to save fuel and decrease wear and resulting maintenance and overhaul costs due to low running of the diesel engines. However, there is no clear definition when the units should be stopped. The only available criterion is that the load dependent stop tables must not coincide with the load dependent start tables.

This corresponds to the following constraint:

$$P_{L,stop}(k+1) = P_{L,start}(k) + \nu \cdot \left(P_{L,start}(k+1) - P_{L,start}(k)\right)$$
$$\text{for } \nu \in [0,\,1] \qquad (12)$$

where $P_{L,start}(k)$ is the received load when starting the next unit and provide k+1 units online, and $P_{L,stop}(k+1)$ is the received load when stopping the unit and having k online unit as shown in fig. 1. $P_{L,start}(k)$ is determined from (1), since load dependent start is part of the optimization procedure. Fig. 1. shows the corresponding limitation for the load dependent stop table. By stopping the units near the lower limit, $P_{L,start}(k)$, the safety will be increased due to high spinning reserve. However, that will increase the fuel consumption. Stopping near the limits has the tendency to increase the number of starting/stopping due to uncertainty in load increasing and decreasing. When connecting units online, each engine must be started, generator synchronized and connected to the grid, and the load slowly increased until get to the pre-set load sharing value. According to the class rules, generators must be connected online in less then 45 seconds.

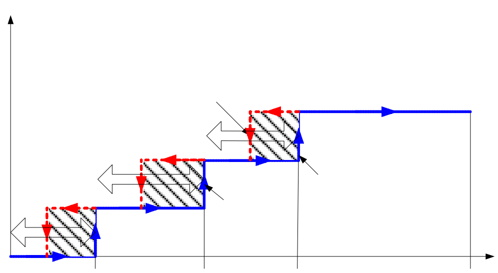

Fig 1. Load dependent start and stop

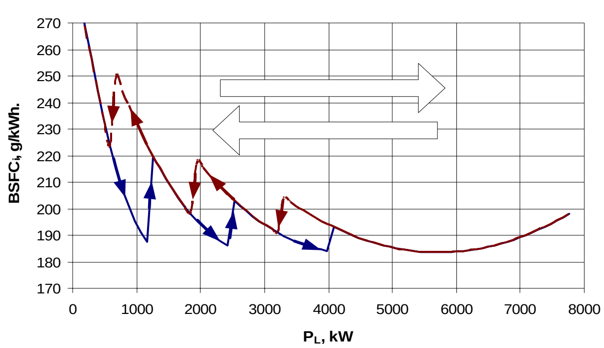

Fig. 2. BSFC for starting and stopping of generators

Usually, engines are started cold and starting procedure can be regarded as one of the worst transients on the generating set. Therefore, higher number of switching units will increase the maintenance costs and increase the risk of blackout. In order to avoid too many unit starting and stopping, the compromise is to set the $P_{L,stop}(k+1)$ around the middle between $P_{L,start}(k)$ and $P_{L,start}(k+1)$, see fig. 1 and that is done in real applications as well. Additional fuel is then required for stopping the units as shown in fig. 2, for $\nu = 0.5$ in (12).

2.2. Switch units when change operational modes

The fuel consumption due to unit stopping can be made lower if the units are stopped closer to the upper limit, $P_{L,start}(k+1)$, see fig. 2. For that reason, we need to examine the circumstances when relatively high certainty in the load change exists. Than we can have higher reliablity of stopping and be more sure that stopped unit will not be required to start back again in the same vessel operational mode. The consumed power in each operational mode has been based on statistics of vessel operations, see table 1. The vessel is naturally assumed to be able to perform operations also in bad weather conditions. Based on table 1, the vessel will operate 58,3% of year in moderate weather conditions, with sea states below number 4 and wave heights less than 2.5 m. More detailed statistics are easily available for the various operating areas and time of the year. The proposed solution includes optimization of the load dependent start based on the probability that the vessel will change to higher load operating mode at the same time. For instance if *DP standby High (Hi)* mode is determined for sea state 6, then one can expect the vessel to operate with wave heights lower then 6 meters for 92.5% of the year, see table 1.

Table 1. Probability of sea states for North Atlantic (Journee, 2000)

Sea State number	Wave height (m)	Probability of Sea State (%)	Cumulative Probability of Sea State(%)
4	1,25 -2,50	28,7	58,3
5	2,5 -4,0	15,5	73,8
6	4 -6	18,7	92,5
7	6 -9	6,1	98,6
8	9 -14	1,2	99,8
9	>14	0,2	100

Then the probability that one additional unit will be needed for the vessel to maintain operations in *DP mode* is only 7.5%. Therefore, the following constraint will limit the optimization procedure to start units when changing modes:

$$P_{L,start}(k) \approx P_{L,OP}(m), \;\; m \le N\!-\!1,\, m \in I, \qquad (13)$$

where $P_{L,OP}(m)$ is the received load when modes change, and m is used to distinct modes. The above constraint can be satisfied for $m \le N$–1 since at least one unit should run in order to start the optimization. If this optimization procedure is used to optimize the load dependent start/stop tables, then one can expect units to switch when vessel change mode. The unit can be stopped at almost the same received load P_L as when started and with $\nu \approx 1$ in (12):

$$P_{L,stop}(k) + \varepsilon = P_{L,OP}(m) = P_{L,start}(k) - \varepsilon \,, \qquad (14)$$

where ε has to be smallest possible in order to reduce the hysteresis as identified on figs. 1 and 2. Since units can be started and stopped at almost the same received load P_L, the difference in fuel consumption for starting and stopping can be minimized according to (1), (11) and figs. 2 and 3. Saving fuel for higher load operational modes may not be so efficienct as for lower loads $P_{L,OP}(m)$, see figures 2 and 3.

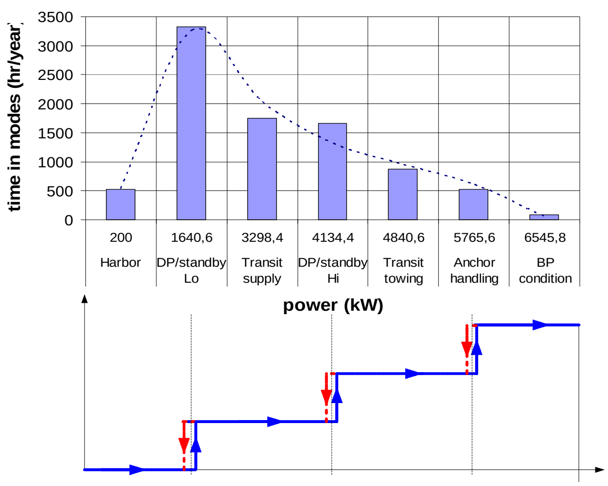

Fig. 3. Swiching units when change operational modes– an example for anchor handling and tug support (AHTS) vessel

3 Blackout prevention

3.1 The distribution system and redundancy

3.1.1 Maximum safe continuous loading

In optimization studies, it is important to determine the safe region of operation for the case of sudden single point failure. According to the class rules, the load percentage of rated power on each unit must be equal for all online units:

$$\frac{P_i}{P_{rated,i}} = \frac{P_{i+1}}{P_{rated,i+1}} \,, \quad i \in [1, k]. \qquad (15)$$

With the above class rule constraint the safe generator continuous loading limit or blackout limit for unequally rated units is:

$$P^{\mathrm{cont}}_{\max,i}(k) = P^{\mathrm{tran}}_{\max,i} \cdot \frac{\sum_{i=1}^{k} P_{rated,i}(k) - P_{rated,f}(k)}{\sum_{i=1}^{k} P_{rated,i}(k)} \,, \qquad (16)$$

where $P^{\mathrm{tran}}_{\max,i}$ is the maximum transient overload step for each unit, and $P^{\mathrm{cont}}_{\max,i}(k)$ is the maximum safe continuous loading for each unit when k units are connected online and one unit fails. Then, the worst case scenario is the failure of the unit that generates the highest power. Thus, $P_{rated,f}(k)$ is the rated power of the largest unit that operates online and:

$$P_{rated,f}(k) = \max_i P_{rated,i}(k) \,, \text{ for } i \in [1, k]. \qquad (17)$$

The safe operational region is limited to:

$$P_i(k) \le P_{start,i}(k) \le P^{cont}_{\max,i}(k, N_{fail}) \qquad (18)$$

3.1.2 Allowable starting sequence combinations

The number of possible combinations, when running one to maximum number of generators, can be calculated according to [6]:

$$\sum_{k=1}^{N} C(N,k) = 2^N - 1 \,, \qquad (19)$$

where:

$$C(N,k) = \frac{N!}{(N-k)!k!} \,, \quad k! = 1 \cdot 2 \cdot 3 \cdot \ldots \cdot k \,. \qquad (20)$$

If four generators are installed, the maximum number of possible combinations is 15. For two units operating online and four installed units, there will be $C(4, 2) = 6$ possible combinations according to (20). (20) can be used to calculate possible combination of modes. In that case $C(M, m)$ where M is total number of modes and m is number of selected modes.

3.2 Generator set inertia and speed responses

The maximum transient overload step for each unit can be calculated according to [4]:

$$P^{tran}_{\max} = \Delta\omega \cdot \frac{2 \cdot H}{t_{SL}} + 100\% \,, \qquad (21)$$

where $\Delta\omega$ is the value of under frequency limit and should be set to $\Delta\omega$=10%, according to class rules. H is the inertial time constant, and for marine diesel generators is typically between 1.5 and 2 seconds. The time before under frequency $\Delta\omega$ is reached, t_{SL}, must be set higher than the time necessary for load reduction, see fig. 4. Load higher than 100% rated power corresponds to gen-set overload and hence practical limits are: 100% < $P_{\max}^{tran} \leq$ 300%.

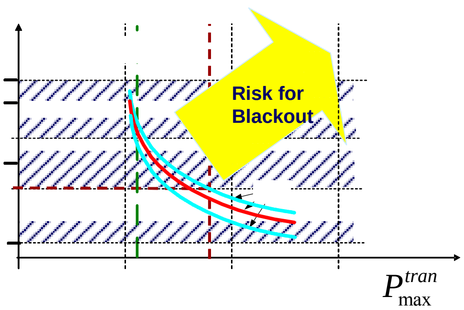

Fig. 4. Regulation time responses for power reduction, with response time of fast load reduction in the order of 500ms [5] for gen-sets with typical inertial constants H

For the diesel engine, the maximum prime mover overload value is typically 110% of rated power. For load steps less than the prime mover maximum overload value, the frequency becomes less dependent on gen-set inertia and more dependent on the ability of prime mover to respond to load.

4 Case study

A case study vessel with diesel electric propulsion AHTS will be used to explain the proposed method [1]:

- Small size Anchor Handling and Tug Support Vessel, AHTS. The basic configuration is similar as for many offshore support vessels;
- Approximately 100 metric tons bollard pull;

The following has been assumed:

1. Total installed load of all consumers is 7770 kW.
2. Installed generating capacity is equal to the expected received load in the highest operational mode which includes all losses: $P_{install} = P\ (m{=}BP)$=6550 kW, see fig. 3.
3. All prime movers are medium speed diesel engines.
4. The number of the installed units is four, N=4.
5. According to the class rules defined in (15), the load percentage of rated power on each unit is equal for all online units: $P_i\,/\,P_{i,\,rated} = P_{i+1}\,/\,P_{i+1,\,rated}$.
6. All gen-set units have the same value of inertial time constant H and the same value of maximum transient overload, $P_{\max}^{tran}$ = 180 %.

The upper part of fig. 3 represents typical operational profile of an AHTS vessel, while the lower part is one possible optimization solution.

ALGORITHM-1

$P_L(k)$ is free (no constraint (13) and (14))

The sequence of optimization procedure should be followed in this order:

1. Select initial ratio of rated power on each unit in total installed power, $P_{rated,\,i}\,/\,P_{installed}$.
2. Find the received load $P_L(k)$ with k units online, use cost function (1) and all other constraints, $P_{rated,i}\,/\,P_{installed}$ is fixed when optimizing.
3. Define starting sequence combinations, C(N, k), (20).
4. Compare the total fuel savings (11) in load increasing operations (for $P_{L,\ start}$) and for load decreasing operations (for $P_{L,\ stop}$) and sum them. The fuel loss due to stopping units can be determined from (12), with ν = 0.5. Select the final solution that gives the highest total fuel savings, fig. 6.

ALGORITHM-2

$P_L(k)$ is fixed (constraint (13) and (14))

The sequence of optimization procedure should be followed in this order:

1. Select the load when start units according to constraint (13): $P_{L,start}(k) = P_{L,OP}(m)$. There can be many possible combinations of modes C(M, m) in (20). For 2 switches to select among 3 distinct modes, there will be C(3,2) = 3 combinations. However, the best is to select modes m for which we can say that are distinct with high probability.
2. For each $P_{L,start}(k) = P_{L,OP}(m)$ combination, find the rated power ratio $P_{rated,\,i}\,/\,P_{installed}$, where $P_{L,start}(k) \approx P_{L,stop}(k)$ is fixed in the optimization;
3. Compare the total fuel savings (11) in load increasing operations (for $P_{L,\ start}$) and for load decreasing operations (for $P_{L,\ stop}$) and sum them. The fuel loss due to stopping units can be determined from (12). With $\nu \approx 1$ in (12) there will be almost no fuel loss due to stopping. Select the final solution that gives the highest total fuel savings, fig. 6.

Different solutions can be compared in the table 2 and figs. 5 and 6. Solutions under cases 1 to 5 are obtained using algorithm 1 while solutions under cases 6 to 9 are obtained using algorithm 2. When switching units between modes (14), high fuel savings when stopping units can be obtained, see figs. 5 and 6. Total savings are sum of savings with starting and stopping units, as shown on fig. 6.

Table 2. Solutions for algorithms 1 and 2

	engine rating of total installed power								
	1	2	3	4	5	6	**7**	8	9
eng. no.1	0.250	0.358	0.450	0.3	0.3	0.330	**0.322**	0.350	0.333
eng. no.2	0.250	0.128	0.084	0.2	0.2	0.330	**0.226**	0.350	0.200
eng. no.3	0.250	0.257	0.231	0.3	0.3	0.170	**0.352**	0.200	0.368
eng. no.4	0.250	0.257	0.235	0.2	0.2	0.170	**0.100**	0.100	0.100
	load dependent START tables, % rated power								
eng. no.1	80.0	80.00	80.00	80.00	92.14	76.39	**80.00**	73.52	77.36
eng. no.2	88.4	89.68	86.81	90.72	90.72	77.64	**93.58**	90.15	94.55
eng. no.3	84.2	84.73	83.53	81.90	81.90	88.84	**70.84**	97.79	97.79
Modes, *m*:	N/A	N/A	N/A	N/A	N/A	1 2 4	**1 2 3**	1 3 5	1 2 5
fuel saved (START), %	0.0	0.17	-0.46	0.22	0.37	-0.92	**-0.20**	-1.74	-0.46
fuel saved (STOP), %	0.0	1.17	1.91	0.14	0.80	3.91	**4.60**	3.14	4.35
Total fuel saved, %	0.0	1.3	1.5	0.4	1.2	3.0	**4.4**	1.4	3.9

Harbour (*m*=0), DP-standby Low (*m*=1), Transit supply (*m*= 2), DP-standby Hi (*m*=3), Transit towing (*m*= 4), Anchor handling (*m*= 5), Bollard pull condition (*m*= 6)

Fig. 5. Saved fuel in the optimization of unit load dependent start and stop – compared with case 1

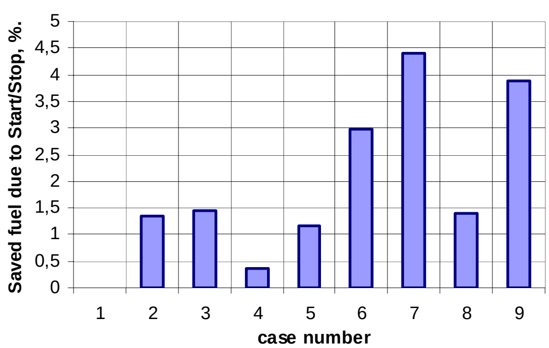

Fig. 6. Total saved fuel in the optimization of unit load dependent start and stop – compared with case 1

5 Conclusion

An integral approach to minimization of fuel consumption and overall safety has been provided following useful guidelines for the future marine power system and power management design:

- Install prime movers of different ratings if necessary, according to vessel operational profile and weather conditions.
- Start/stop the next unit in the sequence when switching between operational modes that can be distinct with high probability.
- For DP vessels minimize the fuel consumption especially for the lower half of the power range.
- Include the calculation of frequency drop in case of one gen-set failure and response of the other(s).
- Find the power rating for each unit accordingly and optimize system inertia.
- For combined power plants, compare responses to sudden change in loading for each prime mover.
- Optimize the load dependent start/stop tables.
- Optimize the load shearing between operating units.

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