2005 WSEAS/IASME Int. Conf. on ELECTROSCIENCE and TECHNOLOGY for NAVAL ENGINEERING and ALL-ELECTRIC SHIP
Miami, Florida, USA, November 17-19, 2005 (pp17-22)

Optimization of Load Dependent Start Tables in Marine Power Management Systems with Blackout Prevention

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Abstract:- The paper describes optimization of operational procedures embedded in the power management system with regards to an overall vessel's safety and minimization of fuel consumption. Proposed method serves as an aid in a design of power management system but also reflects issues important in the marine power system design. The cost function and constraints have been formulated based on fuel consumption, operational profile of the vessel and blackout prevention in order to select load dependent start tables. The problem is formulated for the influence of generating sets inertia on overall blackout risk when using fast load reduction technology. The same formulation can also be used in the application of flywheel energy storage device technology onboard vessel. The proposed method can be applied to any vessel that requires more generating sets installed and special consideration of related safety issues in operations. With a properly addressed risk, the vessel can operate with closed bus-tie and have a maximum flexibility in operations in order to achieve the maximum fuel savings.

Key–Words: - Marine power system, power management, optimization, fuel consumption, blackout prevention

1 Introduction

In recent years, various methods to improve operability and safety of marine vessels have been developed and successfully applied, see [1] to [9].

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; an overview of marine power management has been given in [3] to [8].

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 reach the under frequency limit. Traditional PMS functions, such as load shedding can disconnect non-essential consumers and unload the network, but in some cases with limited success.

One of the features of frequency converters for thrusters and drilling 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. Thrusters are the largest consumers onboard, and current fast load reduction systems can decrease the total load on thrusters within 0.5 seconds [4].

Optimization of ship components in the design stage has been given in [10] whereas optimal load sharing for equal and unequal sized diesel generators has been analyzed in the [7]. However, optimization of power system components and power management control strategies related to safe operations has not been addressed in the referenced literature. Ref. [1] describes methods embedded in power system configuration and PMS to increase the power plant fault-tolerance and reconfiguration [1].

The goal in this paper is to optimize the load dependent start table in order to minimize the fuel consumption and to increase the resistance to blackout by efficient use of fast load reduction technology. With optimized load dependent start tables it is possible to have lower fuel consumption while running the engines with safe operating margin in the event of single point failures.

Dynamically possitioned (DP) operated anchor handling tug support vessel (AHTS) vessel is used as a case study [12].

2 Safety and black-out prevention

The traditional PMS automatically start and stop generator sets to coincide with the load changes in accordance with the pre-set load dependent start-stop tables. The load dependent start table usually is defined to allow the generator sets to carry a maximum of 110% load in a failure situation. With two engines running, at or above 55% load for longer than some prescribed time, for instance 10 seconds, a third generator set will automatically start and synchronize to the network.

Figure 1 shows the diesel engines capability to maintain the frequency for the load step overload associated with the loss of a parallel running engine [1]. In typical installations, it has been seen that the actions of load reduction and blackout prevention must be effective within less than 500ms in order to not compromise the power system stability and limit the flexibility of operation. Some common conclusions can be made on what is typically required for the blackout prevention functionality [1]:

- *Thruster and thruster drives*: Variable speed FPP thrusters can have a load reduction scheme, either monitoring the network frequency and/or receiving a fast load reduction signal from the PMS. Fixed speed CPP thrusters do not have fast enough response time for blackout prevention. Therefore fixed speed CPP thrusters must be included in the PMS load shedding scheme.
- *PMS*: By class requirements, the PMS must include blackout prevention with load reduction/load shedding functionality. It was observed earlier, that the response time in this system was too long to obtain the desired level of fault-tolerance without a fast acting, stand-alone load reduction scheme in the thruster drives. With the knowledge of today, this has been claimed solved by use of fast acting, and possibly event-trigged load reduction algorithms.
- *DP system*: The DP system is also equipped with a power limitation function, normally based on a permitted maximum power consumption signal from the PMS. Generally, this has shown to be effective in avoiding overloading of the running plant, but not fast enough to handle faults and loss of generator sets. Of importance is also the power limitation in manual and joystick control of the thrusters.

2.1 Time responses for load reduction

In case of one gen-set sudden failure, the power system loading must be transferred to the remaining generators online. If two equally rated generators are online, each loaded on 80% of rated power, the failure of one generator will result in load increase to 160 % on the remaining one. 110 % is a typical diesel engine limitation. Hence, the frequency will start to drop on the remaining generator. Activating the under frequency limit at –10% of the generator normal speed will initiate opening of circuit breaker and remaining generator will be disconnected. That will have a blackout as a consequence. In order to avoid a blackout, the fast load reduction must act faster than frequency drop. The time before under frequency limit can be determined from the swing equation [11]:

$$\dot{\omega} = \frac{1}{2 \cdot H} T_a \,, \tag{1}$$

where ω is generator shaft speed, H is inertial time constant and T_a is the accelerating torque. For diesel generators, the inertial time constant H is typically between 1.5 and 2 seconds [13]. Solving eq. (1), the time before under frequency is reached or safe time limit can be determined with the following equation:

$$t_{SL} = \Delta\omega \cdot \frac{2 \cdot H}{P_{\max}^{tran} - 100\%} \,, \tag{2}$$

where $P_{\max}^{tran}$ is a maximum transient overload, see fig.1. Load higher then 100% rated power corresponds to gen-set overload and hence practical limits are: $100\% < P_{\max}^{tran} \leq 300\%$. $\Delta\omega$ is the value of under frequency limit and should be set to $\Delta\omega$=10%, according to class rules. The time before under frequency is reached can be determined by prime mover testing, see [4].

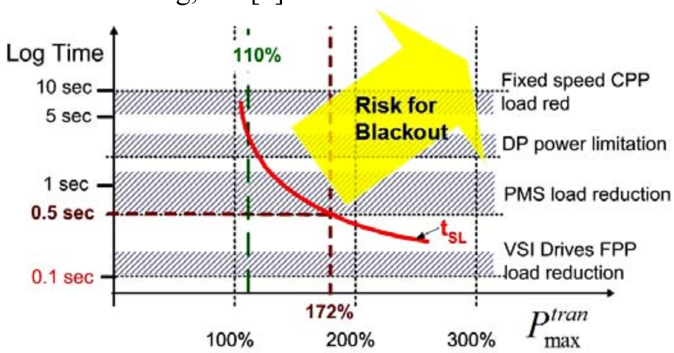


Fig. 1. Regulation time responses for power reduction, with response time of fast load reduction in the order of 500ms [1]-for gen-sets with H=2 sec. and $\Delta\omega$=9% according to equation 2

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

2.2. The distribution system and redundancy

The distribution system is typically split in two or more sections, with the possibility to connect and split the sections by use of bus-ties or bus feeders. The distribution system has the flexibility of operating in a common, closed bus-tie mode for optimizing the energy production, or open bus-tie mode. DP class vessels usually operate with open bus-tie when in class 2 or 3 operations. By automatic splitting and segregation of the system, the faulty parts can be isolated and the intended redundancy obtained without loss of vessel's maneuverability or station keeping ability. When the system is splitted, the loss of any generator can influence only generators in that part of system, but not in the others. Even the system becomes more robust to faults it also becomes less flexible to changing operational requirements, mainly due to segregation of consumers togetheir with generators. The fuel consumption geting increased in open bus-tie mode due to fact that generators becoming unequaly loaded.

It might be important to determine the safe region of operation in case of sudden failure of one or more units and see how that affects the fuel consumption. For equal rated units, the generator continuous loading limit or blackout limit can be defined using following equation:

$$P_{\max}^{\text{cont}}(k, N_{\text{fail}}) = P_{\max}^{\text{tran}} \cdot \frac{k - N_{\text{fail}}}{k}, \qquad (3)$$

where $P_{\max}^{\text{tran}}$ is the maximum transient overload step of each of the equal rated generators, $P_{\max}^{\text{cont}}(k, N_{\text{fail}})$ is the maximum safe continuous loading dependent on the number of units online before failure k and the number of units that are suddenly disconnected due to failure N_{fail}. Hence, the safe operational region is limited within the maximum safe continuous loading according to:

$$P_i(k) \leq P_{\max}^{\text{cont}}(k, N_{\text{fail}}), \qquad (4)$$

where $P_i(k)$ is the power on each unit i when k units are connected online. The most important failure combinations are for the online units that are not in the same compartment since that can affect the decision on operating with a closed or open bus-tie. For instance, with three equal rated units operating online before failure, there can be two possbile limits:

- 1 unit fails: $P_{\max,i}^{\text{cont}}(k=3, N_{\text{fail}}=1) = P_{\max,i}^{\text{tran}} \cdot 2/3$;
- 1 compartment with 2 units fails: $P_{\max,i}^{\text{cont}}(k=3, N_{\text{fail}}=2) = P_{\max,i}^{\text{tran}} \cdot 1/3$.

When operating within the safe operational region, consumers in the other compartments can remain connected online in the case of the system spliting. By using this approach, more flexibility in the design of marine power system can be achieved since consumers need not be necessarily separated in the same compartments as generators.

3 Optimization problem formulation

Assuming k equal rated units are connected online, 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 with k and k+1 units, according to following formulation:

$$\min_{P_L(k)} \left(\sum_{i=1}^{k} FC_i \left(\frac{P_L(k)}{k} \right) - \sum_{i=1}^{k+1} FC_i \left(\frac{P_L(k)}{k+1} \right) \right) \geq 0 \qquad (5)$$

where $FC_i(P_L(k)/k)$ is the instantaneous fuel consumption on each unit i when heaving k equal 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 unconstrained problem, the optimum is found with setting the eq. (5) equal to zero. For negative values of eq. (5) the spinning reserve becomes lower then with positive values.

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

$$P_{start}(k) = \frac{P_L(k)}{k} \quad => \quad N_{on} = k+1. \quad (6)$$

$P_{start}(k)$ is the value of each row in the load depending start table and k allocates the row in the table, $k \in I$. For equal rated engines, the load on each unit i will have the same value in the moment of starting the next unit, hence the load dependent start table will be just one colummn. N_{on} is the number of units online. For $k < 2$ there is no redundancy in the system, and hence the system does not have any resistance to blackout, as defined in eq. (3).

The instant fuel consumption for each unit is calculated according to:

$$FC_i(P_i) = b_{e,i}(P_i)P_i \,, \qquad (7)$$

where $P_i(k)$ is the generated power on unit i and $b_{e,i}$ is the specific brake fuel consumption (SBFC) for each unit, indicated in g/kWh. For medium speed diesel engines b_e can vary among different vendors, but is typically a convex curve and usually is found around 190 g/kWh for loading around 80% of the engine rated power. $b_{e,i}$ can be determined by the use of polynomial approximation as follows:

$$b_{e,i}(P_i) = \sum_{j=0}^{m} a_{j,i} \cdot P_i^j \,, \qquad (8)$$

where $a_{j,i}$ are constants to be adapted in aproximation for each generating unit i.

The cost function has to be minimized subject to the constraint that the sum of the power generated must equal the received load for all power range. Hence, the main constraints of the minimization problem are:

$$\sum_{i=1}^{N} P_i = P_L \,, \qquad (9)$$

$$P_{\min,i} \le P_i \le P_{\max,i} \,. \qquad (10)$$

The constraints in eq. (10) impose limitations of prime movers. A diesel engine manufacturer does not recommend a continuous operation below 15% of rated power and 110% rated for no more then one hour running [13].

The blackout limit from the eq. (4) defines the safe, optimal operating region:

$$P_i(k) \le P_{start}(k) \le P_{\max}^{cont}(k, N_{fail}) \qquad (11)$$

According to eq. (11), if the safety limit is $P_{\max}^{\text{cont}}(2,1) = 75\%$, then the third unit must start when $P_L \ge 150\%$. For optimizing the load dependent start table, the units will get online one by one, as the load power increases.

The optimal load dependent start table for the minimum total instantaneous fuel consumption defined in eqs. (5) and (6) will be optimal for all times. However, it might be important to investigate how solutions close to the optimal affect the total fuel consumtion per year with regards to the spinning reserve. Due to the fact that optimal solution will probably have an active blackout constraint, other more safe solutions, not on an active blackout constraint, may be more beneficial. Hence, the proposed optimal control for the whole operating range per year should include the operating profile according to following minimization:

$$\min_{P_L} J_{year} = \min_{P_L} \int_0^{P_{installed}} \left(FC(P_L) \cdot OP(P_L) \right) dP_L \,, \quad (12)$$

where $OP(P_L)$ is the operational profile of the vessel and $P_{installed}$ is total installed or rated power on the vessel.

4 Case study

A case study vessel with diesel electric propulsion AHTS will be used to explain the proposed method [12]:

- Basic configuration is similar to any offshore supply vessel;
- The bollard pull (BP) is approx. 100 metric tons;

The following assumptions has been applied in the model:

1. Total installed load of all consumers is 7770 kW;
2. Installed generating capacity is equal to the total installed load of all consumers and losses in the system;
3. All prime movers are medium speed diesel engines;
4. The number of the gen-sets is four;
5. All the gen-sets are-equally rated;
6. For equally rated units of the same BSFC curve, equal load sharing has been used.

Figure 2 represents typical operational profile of an AHTS vessel. A typical offshore supply vessel is most of the time in DP low or high operating mode. The vessel spends just 1% time per year in the BP mode which is the operating mode with the highest loading.

Table and diagram of results for eight cases with different load depending start tables are presented in fig. 4. Notice that the highest fuel consumption per year is for the case no. 1 which corresponds to the safest case since sudden fail of one generator can not cause more than 110% loading on others, see fig. 1. The minimum time for fast load reduction system to reduce the load on consumers i.e. thrusters is claimed to be 500 milliseconds. Various fast load reduction systems can vary in speed. Hence, it might be better to introduce a safety margin and use some higher value of the time before under frequency, for instance t_{safe}=0.6 sec.

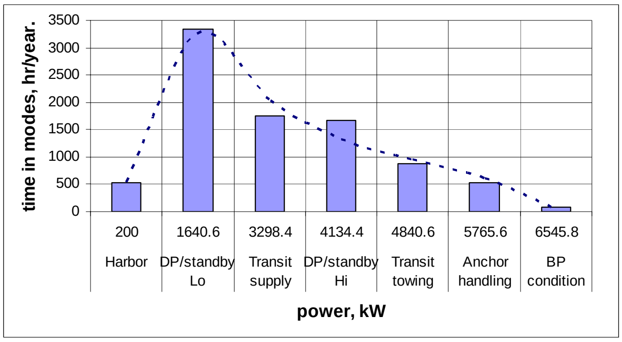


Fig. 2. Typical operational profile of an AHTS vessel [12]

From eqs. (2) to (4) and fig. 1, the one unit can not be loaded more than 160% for longer then 0.6 seconds in the moment of sudden disconnecting the other online unit, see also fig. 3. Hence according to eq. (11):

$$P_i(2) \le P_{start}(2) \le P_{\max}^{cont}(2,1) = 80\%. \qquad (14)$$

Case number 5, shown of fig. 4, corresponds to the unconstrained optimum, when eq. (5) is set equal to yero. However, cases no. 1 to 4 are allowable. Cases no 5 to 8 are not allowable since they are above the safe operational limit set to 80 %. Case 4 can be selected as an optimum with an active blackout constraint $P_{start}(k=2)$=80% for both generating sets.

It is important to notice that the optimization method gives an insight into the costs of the increased safety which means that increasing the blackout resistance can affect the fuel consumption on different ways. For instance, perturbation of the $P_{start,i}$ (k) around selected optimum (for the case 4) will give different cases:

- +9% for k=2 (case 5) the fuel savings can be increased, but just for 0.19% and would shift the system to unsafe region, , t_{SL} = 0.46 sec.
- –10% (case 3) will decrease the fuel savings but just for a 0.69 % and increase the safety of the system, t_{SL} = 0.9 sec. The value of t_{SL} is two times higher than for the case 5.

An interesting feature would be to change the safety limit according to the operational risk, and hence to switch between cases 1 to 4.

Installed generating capacity does not need to be equal to the total installed load of all consumers, see assumption 2 at the beginning of the section. The results of optimization study have been shown in the fig. 5. The cases correspond to the first five cases represented in the load dependent start table on fig. 4. The risk limit may not be changed since the flywheel inertia of the gen-set can be selected to keep approximately the same values of the inertial time constant H for different power ratings, as done in ref. [13].

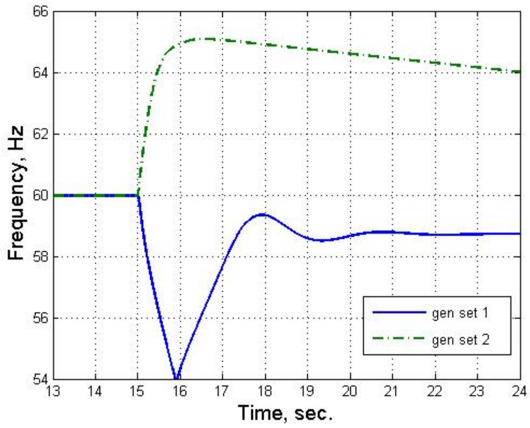
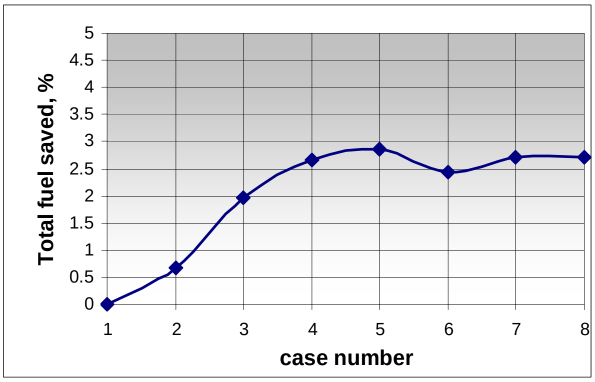


Fig. 3. Frequency drop in case of sudden disconnecting of one gen-set and fast load reduction on thrusters to avoid under frequency limit on 54 Hz. Load on gen-set 1 is 160 %, H=2 sec. (Marine Systems Simulator, MSS)



Case no.:	1	2	3	**4**	5	6	7	8
Gen online, k:	Load dependent START tables Gen-set loading in the moment of starting the next unit, $P_{start,\,i}\,(k)$, %							
2	55	60	70	**80**	89	90	90	100
3	68	70	80	**85**	85	100	90	100
	total fuel savings per year, %							
	0.00	0.67	1.96	**2.66**	2.85	2.43	2.72	2.72

Fig. 4. Tradeoffs between fuel consumption and safety

6550 kW is a maximal loading according to the vessel's operational profile for BP mode whereas the 7770 kW covers all consumers that operate on 100 %. Results show that installing 6550 kW to cover only expected consumption in the BP mode of operation could save from 0.5 to 1 % of fuel per year. Reduced installed power will impose higher risk for vessel to perform high load operations on very bad weather conditions. Hence, obtained low fuel savings might not be justified with regards to operability and safety.

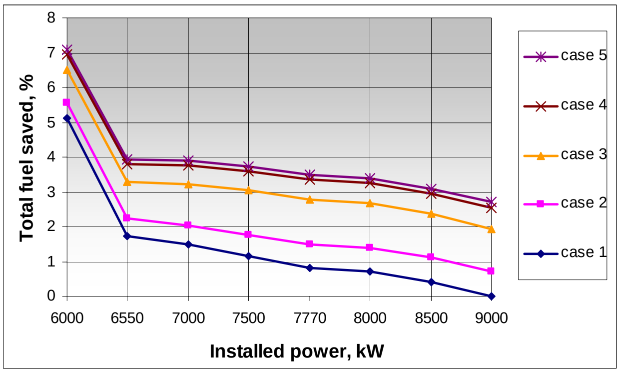


Fig. 5. Optimization with different installed generating power

5 Conclusion

This paper has presented an optimization of load dependent start tables to minimize the overall fuel consumption and to improve the operability and blackout prevention of DP vessels. The method describes efficient use of fast load reduction system and outlines possibilities to use energy storage devices which can control the inertia of the power system.

With operational risk properly addresed, several issues embedded in the power management system and power system design can be optimized and decisions can be based on clear defined criteria. One of the possibilities that might be achieved is that the vessel can operate with closed bus-tie to obtain the maximum savings in fuel consumption. Safe operation with closed bus-tie can give more flexibility to different possible configurations in power system design regarding fault–tolerance and reconfiguration.

The optimization method has been tested in simulation for an AHTS vessel and can be applied to any vessel that requires several generating units installed and special consideration of safety issues in operations.

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Acknowledgements

This work has been carried out as apart of the research project on Energy-Efficient All-Electric Ship (EEAES). The Norwegian Research Council is acknowledged as the main sponsor of EEAES.