Availability Assessment of Diesel Generator System of a Ship: A Case Study

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Abstract: The diesel generator set is one of the most critical systems for a ship’s operation. Consequently, the ship preserves four different diesel generators in addition to the power battery packs. This paper describes the generator operation and the main failure conditions. Assuming that the failure rate of the system parts is constant, the paper shows how the diesel generator system can be modelled based on Homogeneous Continuous Time Markov Chains. Actual data are given for the verification of the model, while a specific software is used for the steady-states probabilities extraction. The paper aims to show the advantages of Markov modelling in Maritime Risk Assessment compared to conventional techniques, such as Fault Trees and Event Trees, which are usually applied in risk estimation maritime studies.

Keywords: Diesel generators, reliability, availability, FSA, maritime risk assessment

1. Introduction

In this paper the availability of a diesel generators system operation is calculated. The generators are extremely critical for the ship’s operation, since they supply power to every mechanic and electronic device on the vessel. Any power interruption may be fatal in difficult circumstances (e.g., dangerous weather conditions etc.).

The proposed Markov model examines the generator system of a generic ship, which has four generators, two in operational and two in cold, stand–by mode. The study’s aim is to examine if the redundant elements cover the ship’s needs in failure condition as well as the restoration time duration, especially if the failure comes between two inspections and it has not been detected. Subsequently, the probability of total system failure is measured and a general equation for calculating the financial cost is provided.

The data processing given for the ship, show that generator’s failure rate is constant, so the data distribution is exponential. The next section presents a brief description of the system and some causes leading to a simple or serious failure. Section three describes Formal Safety Assessment and Markov models in shortly. Section four analyzes the Diesel Generator Set modeling, by using Continuous Time Markov Chains. Section five contains a numerical example for the model and derives the failure probability conditions.

Notation

\( \lambda \) Primary generator failure rate.
\( \gamma \) Automation probability failure (activates one of the secondary gen/tors).
\( t_{\text{man}} \) Time for secondary gen/tor manual activation by ship personnel.
\( \mu \) Automation and gen/tor repair rate (it consists of automation and gen/tor repair time symbolized by \( t_a \) and \( t_g \)).
2. Operation in the diesel generator set

In general, electric current from the diesel generator set (DGS) is carried out in two bus bars with voltage at 440 Volt bar for regular use and 220 Volt for emergencies. The first bar supplies all the main electric power and the emergency switchboard, while the second supplies the bowthruster and the deck machinery [4].

If the ship is in anchorage or the auxiliary machinery does not operate, one generator is adequate to cover the ship’s needs, so the electric load is decreased. Stand-by generators are activated for the case of increased electric load, overcharging or system failure. Furthermore, they function in parallel, automatically or manually (by human interference), supporting critical systems such as steering gear, fire pumps, radars and radio, navigation system, electric whistle etc. The importance of the proper operation of the DGS set is obvious, as well as the risks posed by malfunction in sensitive devices, such as the navigation system, fire pumps, the unloading system etc.

Risk assessment in critical areas of the ship is the object of several studies, which try to propose methods for risk reduction and its consequences. One of these methods is called Formal Safety Assessment (Fig.1).

3. Application of Markov Models in the FSA methodology

The structured and systematic methodology, adopted by the International Maritime Organization (IMO), for assessing the risk in maritime safety is called FSA (Fig. 1). According to IMO [7], [8], [9] FSA is a rational and systematic approach of risk estimation, which computes the ratio of cost / benefit for applicable effective risk control measures. The conducted studies (e.g., double side skins on bulk carriers) show the objective evaluation and fertile development of new risk prevention measures. Literature review of the FSA studies shows that Fault Trees (FT) and Event Trees (ET) are the most widely used and reliable methodologies for the risk assessment [15]. They are approachable and easily understood by the users, offering a detailed analysis of the system. Furthermore, the tree methods use simple mathematical calculations for deriving the failure probabilities.

In comparison with Markov models, Fault Trees and Event Trees have showed structural disadvantages: (a) FT do not permit the return in previous state, so the repair state cannot be taken into account. In contrast, Markov Models comprise the system repairing and make an assessment (based on repair rate) for the returning in safe state. (b) in large systems, the tree becomes extremely complicated while Markov models offer the ability of a more subtractive design of the system. (c) Markov models take into account undetected failures. (d) FT and ET model total failures not partial [3]. Also, the tree based methods assume the independability of the failures [14], [1], whereas Markov models are not limited by these characteristics.
4. Modeling the Diesel Generator Set

In Figure 2, a Diesel Generator System is modeled by Homogeneous Continuous Time Markov Chain [13]. According to experts the following assumptions are adopted: (a) If one generator fails, the expert checks the rest of them. (b) If a main generator fails, the probability of failure in a stand by machine is very close to zero.

Although the state space diagram (Fig.2) is analytical some explanations about certain states might be useful to the reader. In State 2 the main generators fail and the automation is also damaged, so the stand by generator does not start automatically. The crew of the ship activates manually the secondary generator in time $t_{man}$. Two generators operate in State 3, discharging continues, while automation and the second basic generator are under repair. State 6 shows an undetected failure [13] of the stand-by generator. This event determines a series of different states for a second possible failure. In State 8 two generators have failed, but the ship is supported effectively while discharging. Two devices are in repair mode. State 11 represents the possibility that the second s/b generator may also be in failure. This situation continues to be undetected, while the system operates normally.

Completing the risk quantification, which determines the hazards scale, specific risk control options will be chosen for the reduction of risk. A numerical example verifies the model by using actual data from a Greek maritime company.
5. Numerical Example and Sensitivity Analysis

The records in Table 1 are comprised of real data (failure type, frequency and restoration rate) for the most common failures in the DGS.

Table 1: Data given by Greek Maritime Company

<table>
<thead>
<tr>
<th>Type of damage</th>
<th>MTBF (days)</th>
<th>Res/tion (hours)</th>
<th>Type of damage</th>
<th>MTBF (days)</th>
<th>Res/tion (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel oil filters</td>
<td>20</td>
<td>1.5</td>
<td>Dirty water cooler</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Oil filters</td>
<td>20</td>
<td>1.5</td>
<td>Dirty oil cooler</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Air filters</td>
<td>20</td>
<td>1.5</td>
<td>Cover gasket damage</td>
<td>365</td>
<td>3</td>
</tr>
<tr>
<td>Water filters</td>
<td>30</td>
<td>1.5</td>
<td>Exhaust inlet valve</td>
<td>365</td>
<td>7</td>
</tr>
<tr>
<td>Fuel Inj.</td>
<td>60</td>
<td>1.5</td>
<td>Cracking of cylinder heads</td>
<td>240</td>
<td>7</td>
</tr>
<tr>
<td>Leaking of gasket</td>
<td>90</td>
<td>1.5</td>
<td>Piston ring damage</td>
<td>365</td>
<td>7</td>
</tr>
<tr>
<td>Piping system</td>
<td>60</td>
<td>1.5</td>
<td>Turbo charger</td>
<td>365</td>
<td>7</td>
</tr>
<tr>
<td>Water pump</td>
<td>60</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel pump</td>
<td>30</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel injector</td>
<td>180</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the data of Table 1, the failure rates $\lambda$ and $\mu_{op}$ are calculated. The remaining rates, probabilities and times of the model are given approximately by the machine experts.

An HTMC model is solved by the following (Eq. 1) linear system, which computes the steady states of the system (Figure 3b).
\[ \Pi \cdot Q = 0 \]
\[ \sum_{i=1}^{n} \pi_i = 1 \]

The 13 by 13 generator matrix is symbolized by \( Q = [q_{ij}] \) denoting the transition rate from state \( i \) to state \( j \) and \( n \) denoting the number of states (\( n = 13 \)), while \( \Pi \) is the steady state probability vector. The results calculation became in the context of Visual Basic 2006 and specific software was developed called MARitime - REliability (MAR – REL).

By clicking the button on the first form of MAR-REL application, the user enters the transition rates for every state (Figure 3a). On completion of this step, the algorithm generates the steady states results in an output text file (Figure 3b).

**Figure 3: Input – Output Data Forms**

In states “two”, “four”, “seven”, “nine” and “twelve” of Figure 3b, the generators cannot support the unloading procedure of the cargo. So the availability of the system is 99.03 \%. Tables 2 and 3 present the variation of availability and unavailability vectors in case of failure rates \( \lambda \) and \( \lambda_s \) variations. The results show a very mild final modification.

**Table 2: Availability and Unavailability Sensitivity in \( \lambda \)**

<table>
<thead>
<tr>
<th></th>
<th>-5%</th>
<th>( \lambda )</th>
<th>+5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>0.9897</td>
<td>0.9903</td>
<td>0.9909</td>
</tr>
<tr>
<td>Unavailability</td>
<td>0.0103</td>
<td>0.0097</td>
<td>0.0091</td>
</tr>
</tbody>
</table>

**Table 3: Availability and unavailability sensitivity in \( \lambda_s \)**

<table>
<thead>
<tr>
<th></th>
<th>-5%</th>
<th>( \lambda_s )</th>
<th>+5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>0.9911</td>
<td>0.9903</td>
<td>0.9895</td>
</tr>
<tr>
<td>Unavailability</td>
<td>0.0089</td>
<td>0.0097</td>
<td>0.0105</td>
</tr>
</tbody>
</table>

The probability vectors for every system state can now be used for computing the realization cost \( C \) of system unavailability and risk control options. In order to identify the costs associated to system unavailability Equation 2 is used [11], [12].

\[ C = \sum_{i \in \text{down states}} (\pi_i \cdot c_i) \]

where,
\( \pi_i \): steady state probabilities of state \( i \).
c. sojourn cost in state I in $ per year

By collecting data for unavailability duration, combined with steady states and the cost for every state, the decision maker possesses an integrated tool, which calculates the realization cost of the new regulation and the total unavailability cost. A specific example is given:

Let’s consider a maritime company, which owns 6 ships of 1000 TEU each. According to the data provided, the mean rate of unloading at the port of Piraeus is 6.26 moves per hour. Consequently, each time the ship will remain at the harbor for 159.74 hours. If the containership berths at the port for 11 times per year and the unavailability probability is 0.0096 % (according to our results), the Total unavailability cost per ship is 47,654.95 USD, assuming that the operational costs of the ship is 2,825.00 USD per hour. Therefore, for a fleet of six ships the total cost is 285,929.71 USD. This amount must be incremented by the terminal cost per move, which is 140 USD, which leads to 876.4 USD per hour. Following the previous calculations the terminal’s cost is 96,723 USD for the whole fleet. Accordingly, the final amount is 382,652.7 USD.

6. Conclusions

The ongoing environmental damage in our century, makes necessary the application of more safety rules, especially in maritime industry. The International Maritime Organization, has conducted a series of studies for the risk localization and confrontation. Risk assessment method has the major role in these studies.

This paper proposes Markov modeling as an effective method for maritime risk assessment, because it takes into account the repair of the system, the possibility of an undetected failure and the system time evolution. Furthermore, Markov modeling derives probability indicators useful for statistical and economic purposes, becoming a powerful, dynamic tool for estimating risk and evaluating risk control options for decision making, by contributing to three of five phases in Formal Safety Assessment.

Future studies could apply Non Homogeneous Markov Models [10], which can be used when the failure rate is not constant. It will be interesting to compare the results of non homogeneous and homogeneous models, alongside a more detailed financial analysis.

References

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