Bottom-up Reliability Analysis of a Base Load Diesel Engine Driven Electric Power Unit

E.C. NASIOULAS[1], G.J. TSEKOURAS[1], F.D. KANELLOS[2]
[1]Department of Electrical & Computer Science, Hellenic Naval Academy
Terma Hatzikyriakou, 18539, Piraeus
[2]Production Engineering & Management Department, Technical University of Crete
Technical University Campus, Chania, 73100
GREECE
Email: nasioulas1371@hotmail.com, tsekouras_george_j@yahoo.gr, kanellos@mail.ntua.gr

Abstract: - Power systems are usually based on thermal-electric power units as they have several advantages, such as predetermined installation and operation cost, easy active and reactive power control and high reliability. The reliability of a thermal power unit is usually quantified by the Unavailability or Forced Outage Rate (F.O.R.) indicator expressing the unexpected and unforeseen failure rate. It can be calculated from fault data records obtained during diesel engine lifetime. However, a thermal electric power unit is a sophisticated system with several subsystems. In case of a diesel engine driven electric power unit the respective subsystems constituting the unit are diesel engine, electric generator, frequency controller, automatic voltage regulator, and the circuits of compressed air, oil, fuel, water cooling, air cooling etc. In this paper, the reliability analysis of a ship diesel engine power unit is carried out based on a bottom-up approach and the assumption of having constant expected failure rate and constant repair rates for each sub-system's component. In this way, unavailability of diesel engine can be accurately determined and the most frequently malfunctioning parts of the unit can be identified so as proactive measures for increasing overall reliability of the engine could be decided.

Key-Words: - Forced outage rate, reliability, thermal electric power unit

1 Introduction

In small autonomous electric power systems, such as ships, airplanes, reliability of their power units is a crucial factor affecting even the survivability of their users. For a separate unit reliability is quantified by the Unavailability (U) or the Forced Outage Rate (FOR), which represents the number of hours the unit being in forced outage over the total number of hours of the examined time period. FOR is necessary for the calculation of two major indicators quantifying the unavailability rate of a power system: (1) Expected loss of load power (LOLP), which represents the equivalent time per year in which load demand is not completely satisfied by the generation power system, (2) Expected loss of load energy (LOLE), which represents the amount of active energy not supplied to the load in a year [1-2].

The knowledge of the FOR of each power unit is satisfying regarding design and operation purposes. However, additional information about the most frequently malfunctioning parts of the thermal power unit remains crucial for the operator of the system. This information would enable operator to compare possible proactive-improving measures, such as replacement of a component, ensuring uninterruptible operation of sensitive components with the use of spares connected in parallel, etc. and assess FOR improvement obtained by these measures. Afterwards, the final power system reliability improving measures could be decided based on techno-economical criterions.

Bottom-up reliability analysis is usually avoided, as the data collection required for the modeling of the power unit is a time-consuming process. However, if FOR improvement based on a systematic approach is aimed then this analysis should be carried out.

In authors' previous work bottom-up reliability analysis including two subsystems of a thermal electric power unit has been introduced, assuming constant expected failure rate for all its components [3]. In this paper, the respective reliability analysis is carried out taking into consideration all the subsystems of the power unit and assuming constant expected failure and repair rates for all its components. A diesel engine driven electric power generator has been chosen, as it constitutes the main prime mover in marine applications, autonomous small power systems and also serves as emergency power source in hospitals, large buildings, industrial installations etc.

In section 2, the reliability basic theory and definitions are briefly analysed. In section 3, problem formulation is deployed and the subsystems of a typical diesel thermal electric power unit are presented. Moreover, diesel engine FOR and the subsystems' expected failure rates relation is obtained. Next, the operation of all diesel engine subsystems is described and the respective theoretical reliability analysis is carried out. In section 4, the practical application of the methodology and the respective sensitivity analysis are presented while in section 5 the major conclusions drawn by this work are discussed.

2 Reliability Analysis's Introduction

2.1 General

System reliability deals with the probability a system operating normally during its lifetime under proper quality and operation conditions. Reliability is related with the reparability that is the probability of restoring a system back to normal operation after a failure in a predefined time interval. Major reliability terms are listed next.

- **Expected failure rate λ,** is the ratio of the mean value of the observed failures $K^{/}$ to the respective operation time $T^{/}$ during the observation time period:

$$\lambda = \frac{K^{/}}{T^{/}} \tag{1}$$

The expected failure rate of a component varies during its lifetime and it comprises three separate parts: (1) initial failures, (2) casual failures and (3) decay failures, which occur during initial operation, main life and decay periods, respectively. It is known that the expected failure rate is practically constant during the main life period.

- **Reliability function *R(t)*** of an element is the probability of the element not failing for the time period, [0 *t*]. According to Bayes theorem, *R(t)* is obtained by:

$$R(t) = \exp\left[-\int_0^t \lambda(t)\cdot dt\right] \tag{2}$$

If failure rate λ is constant then reliability function *R(t)* follows the exponential (Poisson) probability distribution:

$$R(t) = \exp(-\lambda \cdot t) \tag{3}$$

- **Mean time to failure *m* (MTTF),** is the mean value of the time intervals between sequential failures during the observation time period:

$$m = \frac{T^{/}}{K^{/}}[h] \tag{4}$$

In case of constant failure rate λ the mean time to failure, *m,* is equal to the inversed expected failure rate λ (m=1/λ).

- **Mean time to repair, *r* (MTTR)**, is the mean duration of the repairing time intervals. In case of constant mean time to repair, *r,* the **expected repair rate,** μ, is constant and equal to the inverse mean time to repair *r* (μ=1/*r*).
- **Unavailability *U*** or **Forced Outage Rate (FOR)** is the ratio of the mean time to repair *r* to the sum of the mean time to repair *r* and the mean time to failure *m*:

$$U = \frac{r}{m+r} = \frac{r}{T} = \frac{\lambda}{\mu+\lambda} \tag{5}$$

Where *T* is the cycle time or the mean time between failures (=*m*+*r*).

- **Availability *A*** is the supplement of the unavailability. It equals the ratio of the mean time to failure *m* to the sum of the mean time to repair *r* and the mean time to failure *m*:

$$A = 1 - U = \frac{m}{m+r} = \frac{\mu}{\mu+\lambda} \tag{6}$$

In case of a complex system comprising *n* components connected in series, system reliability function $R_{series}(t)$ is given by the product of the reliability functions $R_i(t)$ of system components:

$$R_{series}(t) = \prod_{i=1}^{n} R_i(t) \tag{7}$$

Where, *i* denotes the i-*th* system component.

If the failure rates of all components are constant, then the respective total failure rate, λ_{series}, is given by:

$$\lambda_{series} = \sum_{i=1}^{n} \lambda_i \tag{8}$$

Based on Markov methodology and assuming constant repair rates for all components then the respective total repair rate, μ_{series}, is given by:

$$\mu_{series} = \frac{\lambda_{series}}{\sum_{i=1}^{n} \lambda_i / \mu_i} \tag{9}$$

$$r_{series} = \frac{1}{\mu_{series}} = \frac{\sum_{i=1}^{n} \lambda_i \cdot r_i}{\lambda_{series}} \tag{10}$$

Assuming that,

$$\exists i : \lambda_i \cdot r_i >> \underbrace{(\lambda_1 \cdot r_1)\cdot(\lambda_2 \cdot r_2)\cdot\ldots\cdot(\lambda_n \cdot r_n)}_{\text{with any combination of two, three, ... or n combinations}}$$

and that the mean time to failure m_{series} (=1/λ_{series}) is significantly bigger than the mean time to repair r_{series} then the unavailability of the complex system comprising *n* components connected in series becomes:

$$U_{series} = \frac{r_{series}}{m_{series} + r_{series}} \cong \lambda_{series} \cdot r_{series} = \sum_{i=1}^{n} \lambda_i \cdot r_i \tag{11}$$

In a complex system comprising *n* components connected in parallel, if its operation depends on the operation of only one component and each component has very small repair rate then the total reliability function $R_{parallel}(t)$ is given by the following equation:

$$R_{parallel}(t)=1-\prod_{i=1}^{n}\left(1-R_i(t)\right) \tag{12}$$

The development of a general equation for n components connected in parallel is not possible; however for 2 components the following equations stand based on Markov analysis [1]. If the repair rates of the components are constant, then the respective total repair rate $\mu_{parallel}$ is obtained by:

$$\mu_{parallel}=\mu_1+\mu_2 \tag{13}$$

$$\frac{1}{r_{parallel}}=\frac{1}{r_1}+\frac{1}{r_2}\Rightarrow\ r_{parallel}=\frac{r_1\cdot r_2}{r_1+r_2} \tag{14}$$

Also, if the failure rates of the components are constant then the respective total failure rate $\lambda_{parallel}$ is given by:

$$\lambda_{parallel}=\frac{\lambda_1\cdot\lambda_2\cdot\left(r_1+r_2\right)}{1+\lambda_1\cdot r_1+\lambda_2\cdot r_2}\cong\lambda_1\cdot\lambda_2\cdot\left(r_1+r_2\right) \tag{15}$$

In usual systems it can be assumed that $\forall i:\lambda_i\cdot r_i<<1$. With the additional assumption that the mean time to failure $m_{parallel}$ ($=1/\lambda_{parallel}$) is significantly bigger than the mean time to repair $r_{parallel}$ the unavailability of a system comprising 2 components connected in parallel becomes:

$$U_{parallel}\cong\lambda_{parallel}\cdot r_{parallel}=\lambda_1\cdot\lambda_2\cdot r_1\cdot r_2 \tag{16}$$

In case of three components the following equations stand,

$$\mu_{parallel}=\mu_1+\mu_2+\mu_3 \tag{17}$$

$$\frac{1}{r_{parallel}}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}\Rightarrow$$

$$r_{parallel}=\frac{r_1\cdot r_2\cdot r_3}{r_1\cdot r_2+r_2\cdot r_3+r_3\cdot r_1} \tag{18}$$

$$\lambda_{parallel}\cong\lambda_1\cdot\lambda_2\cdot\lambda_3\cdot\left(r_1\cdot r_2+r_2\cdot r_3+r_3\cdot r_1\right) \tag{19}$$

$$U_{parallel}\cong\lambda_1\cdot\lambda_2\cdot\lambda_3\cdot r_1\cdot r_2\cdot r_3=U_1\cdot U_2\cdot U_3 \tag{20}$$

In addition, it can be assumed that system fails if the 1st element fails followed by the 2nd element and finally the 3rd element fails during the overlapping repair period of elements 1 and 2, or for any other combination of fault occurrence in these elements.

In case of complex systems with components connected in series and parallel, the respective calculations can be realized simplifying the examined system step-by-step into subsystems.

2.2 Generation unit model

The probability of the unit being on forced outage mode is mainly used to assess its reliability. and it is either given by unit unavailability or unit forced outage rate (FOR) as obtained in eq. (5). Alternatively, it is equal to:

$$U=FOR=\frac{\sum \mathrm{t_{down\ time}}}{\sum \mathrm{t_{up\ time}}+\sum \mathrm{t_{down\ time}}} \tag{21}$$

In the case of a base load power unit (with relatively long operating cycles) the two-state model of Fig. 1 can be used.

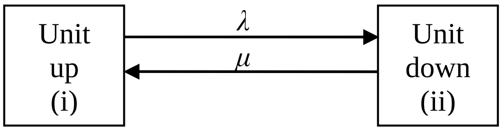


Fig. 1. Two-state model for a base load power unit [4].

3 Sub-systems Reliability Study of A Diesel Electric Power Unit

3.1 General

A diesel engine driven electric power unit is a simple power unit compared with power units employing steam, gas turbines or nuclear power units. It has small initial investment capital but large operation cost. Diesel engines are very common in marine applications used as main or emergency electrical power unit.

Typical configuration of a diesel electric power unit for marine applications includes the sub-systems and major components listed in the following with the respective expected failure rates and mean time to repair given in brackets:

- diesel engine (λ_{DIES}, r_{DIES}),
- electric generator (λ_{GEN}, r_{GEN}),
- frequency controller-governor (λ_{FC}, r_{FC}),
- automatic voltage regulator (λ_{AVR}, r_{AVR}),
- circuit breaker – electrical panel (λ_{CBR}, r_{CBR}),
- compressed air circuit (λ_{AIR}, r_{AIR}),
- lubricating oil circuit (λ_{OIL}, r_{OIL}),
- fuel circuit (λ_{FUEL}, r_{FUEL}),
- treated water circuit (λ_{TW}, r_{TW}),
- sea water cooling circuit (λ_{SW}, r_{SW}).

If the aforementioned rates and times are known then the total failure rate of the system, total mean time to repair and unavailability are calculated as:

$$\lambda_{tot}=\begin{cases}\lambda_{DIES}+\lambda_{GEN}+\lambda_{FC}+\lambda_{AVR}+\lambda_{CBR}\\+\lambda_{AIR}+\lambda_{OIL}+\lambda_{FUEL}+\lambda_{TW}+\lambda_{SW}\end{cases} \tag{22}$$

$$r_{tot}=\frac{\left\{\begin{array}{l}\lambda_{DIES}\cdot r_{DIES}+\lambda_{GEN}\cdot r_{GEN}+\lambda_{FC}\cdot r_{FC}\\+\lambda_{AVR}\cdot r_{AVR}+\lambda_{CBR}\cdot r_{CBR}+\lambda_{AIR}\cdot r_{AIR}\\+\lambda_{OIL}\cdot r_{OIL}+\lambda_{FUEL}\cdot r_{FUEL}\\+\lambda_{TW}\cdot r_{TW}+\lambda_{SW}\cdot r_{SW}\end{array}\right\}}{\lambda_{tot}} \tag{23}$$

$$FOR=U_{tot}\cong\lambda_{tot}\cdot r_{tot} \tag{24}$$

The application of eq. (22) up to (24) constitutes the last step of the bottom-up reliability analysis of a thermal electric power unit and they are based on the assumption that if one system fails, the entire unit fails. It is noted that for this type of reliability analysis the two-state model of Fig. 1 is used.

The calculation of the expected failure rate and the mean time to repair for each sub-system requires good knowledge of each sub-system structure and operation. Next, all sub-systems are analyzed assuming that all failure rates and mean times to repair are constant, and the general assumptions of section 2 are valid. Detailed description of the operation and internal structure of the respective sub-systems can be found in [5]-[8].

3.2 Compressed air circuit

Compressed air circuit is shown in Fig. 2. Next, the elements composing compressed air circuit are listed with the respective numbers used in Fig. 2 given in brackets [3]:

- 30 bar electric air-compressor (1),
- 30 bar non-return valve (2),
- 30 bar pressure regulating valve (3),
- 30 bar air-vessel (4), (two are used in parallel connection),
- 30 bar pipes (5),
- 10 bar regulating-reducing valve (6),
- 10 bar safety valve (7),
- 10 bar air-filter (8),
- 10 bar pipes (9) except pipes between points F and H,
- 10 bar solenoid valve (10),
- 10 bar remote pressure-gauge (11),
- 10 bar non-return valve (12),
- 10 bar slide valve (13),
- 10 bar over-speed solenoid valve (14),
- 10 bar pipe from point F to point H (slide valve (13)) (15),
- 10 bar pressure switch with 6 bar alarm (16),
- 10 bar air-tank (17),
- pneumatic starter (18),
- lubricator (19),
- booster servo-motor (20),
- non-return valve (21),
- air capacity (22),
- 10 bar to 4 bar pressure reducing valve (23),
- start-pilot equipment (24),
- start limiter equipment (25),
- 4 bar pipes (26),
- governor (27).

The supplied to the unit compressed air actuates the pneumatic starter and provides the energy required for engine starting (18). It also controls fuel supply and pressurizes speed governor on engine starting. Finally, compressed air enables engine tripping (in emergencies) when it enters injection pump filling fuel drain chambers after having actuated the slide valve (13).

The 30 bar pressurized air generated by electric compressor (1) is stored in vessels (4), through a non-return valve (2) and a pressure regulating valve (3). Next, the air passes through a pressure reducing and safety equipment including one pressure regulating-reducing valve (6) that reduces the air pressure to 10 bar, one safety valve (7) and one filter (8). The duct connecting filter outlet to solenoid valve (10) comprises a boss allowing the fitting of

(i) a remote pressure-gauge (11),
(ii) an over-speed solenoid valve (14) with a non-return valve (12) allowing the air tank (17) being filled.

The air tank (17) comprises a pressure switch (16) with alarm control activated if air pressure is lower than 6 bars. It is noted that the over-speed solenoid valve (14) feeds the slide valve (13) with air.

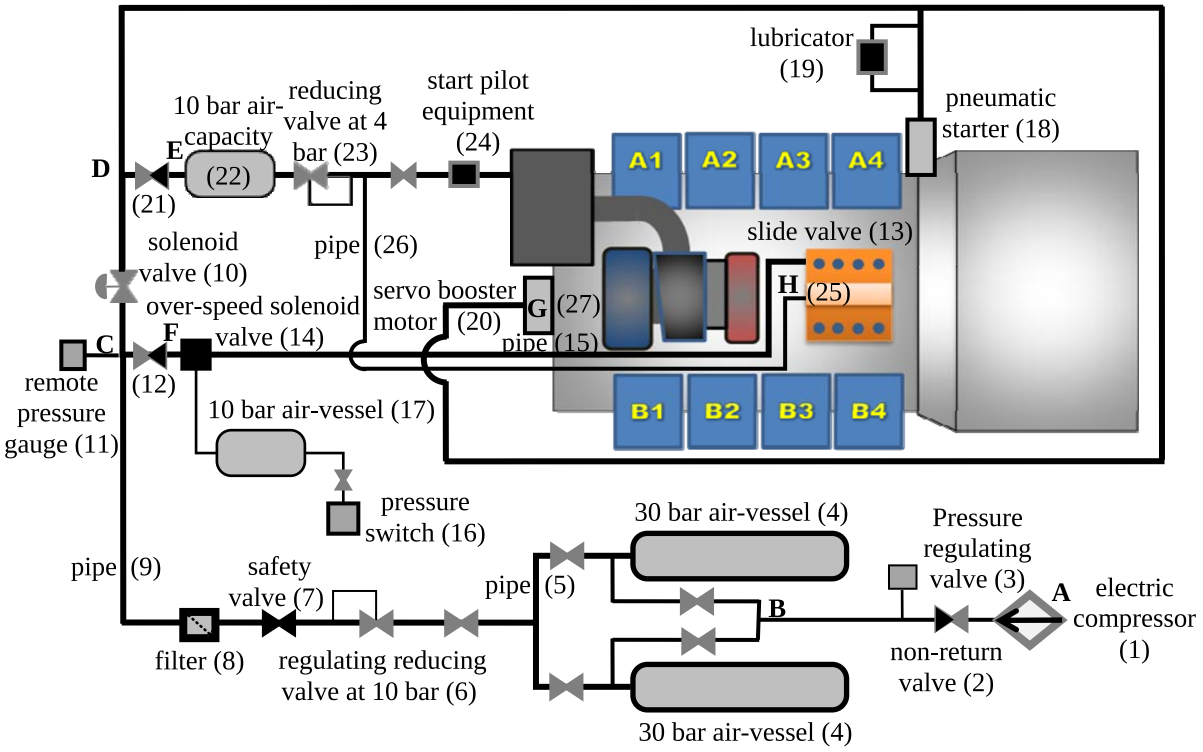
The solenoid valve (10) comprises a device allowing manual handling in case of a 24V current cut-off. After solenoid valve (10) the air is led to two pipes. The first leads air to the starter (18) to lubricator (19) (by-pass) and to the servo-motor (20). The second pipe is connected to a compressed air capacitor (22) via a non-return valve (21) and a pressure reducing valve (23). Pressure reducing valve (23) regulates air pressure at 4 bar and directs it to the start-pilot (24) and start limiter (25) equipment.

When the engine is automatically started, solenoid valve (10) opens and air reaches to the pneumatic starter (18) driving a toothed-crown attached to fly-wheel coupling. This actuates the fuel-limiting device (13) and the booster servo-motor (20). The slide valve (13) moves a rod that reduces the fuel linkage. Boost servo-motor (20) supplies the governor (27) with pressured oil stopping immediately the injection pump fuel leakage. Thus, the engine starts immediately without waiting oil pressurization by the gear pump inside the governor.

The activation of emergency stop, over-speed trip function and lubricating oil low-pressure switch energizes the emergency stop solenoid valve (14). The solenoid valve (14) is provided with air from the air tank (17) in order to supply the safety slide valve (13) that controls the injection pump.

Reliability analysis of the examined subsystem is as follows:

- The expected failure rate of the *i*-th element is denoted with $\lambda_{AIR\text{-}i}$.



(12), (21): non-return valve, (25): start limiter equipment, (27): governor

Fig. 2. Compressed air circuit of a typical diesel thermal electric power unit for ship.

- The mean time to repair of the *i*-th element is denoted with $r_{AIR\text{-}i}$.
- The elements (1) to (3) are connected in series. If one of them fails then the respective section of the compressed air circuit fails. Applying eq. (8) and eq. (10), the equivalent failure rate $\lambda_{AIR\text{-}A\to B}$ and the mean time to repair $r_{AIR\text{-}A\to B}$ are calculated as following:

$$\lambda_{AIR-A\to B} = \sum_{i=1}^{3} \lambda_{AIR-i} \qquad (25)$$

$$r_{AIR-A\to B} = \frac{\sum_{i=1}^{3} \lambda_{AIR-i}\cdot r_{AIR-i}}{\lambda_{AIR-A\to B}} \qquad (26)$$

- The two 30 bar air-vessels (4) are connected in parallel with the set of components between A and B as only one of them is needed compressed air circuit operation. Assuming that the two air-vessels (4) have the same expected failure rates $\lambda_{AIR\text{-}4}$ and the same mean time to repair $r_{AIR\text{-}4}$, the respective equivalent failure rate, $\lambda_{AIR\text{-}p4}$, of the triple air-supply is obtained by eq. (19):

$$\lambda_{AIR-p4} \cong \left\{ \begin{array}{l} \lambda_{AIR-A\to B}\cdot\lambda_{AIR-4}\cdot\lambda_{AIR-4}\cdot \\ \left(r_{AIR-A\to B}\cdot r_{AIR-4}+r_{AIR-4}\cdot r_{AIR-4}+r_{AIR-4}\cdot r_{AIR-A\to B}\right) \end{array} \right\}$$

$$\Rightarrow$$

$$\lambda_{AIR-p4} \cong \lambda_{AIR-A\to B}\cdot\lambda_{AIR-4}^{2}\cdot\left(2\cdot r_{AIR-A\to B}+r_{AIR-4}\right)\cdot r_{AIR-4} \qquad (27)$$

The respective equivalent mean time to repair, $r_{AIR\text{-}p4}$, of the triple air-supply is obtained by eq. (18):

$$r_{AIR-p4} = \frac{r_{AIR-A\to B}\cdot r_{AIR-4}\cdot r_{AIR-4}}{r_{AIR-A\to B}\cdot r_{AIR-4}+r_{AIR-4}\cdot r_{AIR-4}+r_{AIR-4}\cdot r_{AIR-A\to B}}$$

$$\Rightarrow r_{AIR-p4} = \frac{r_{AIR-A\to B}\cdot r_{AIR-4}}{2\cdot r_{AIR-A\to B}+r_{AIR-4}} \qquad (28)$$

- Three compressed air sub-circuits are considered. The first one (between A and G) operates at 10 bar during engine starting and governor operation. Components (5) to (12), (18) to (21), and the equivalent component (p4) are connected in series. Applying eq. (8) and eq. (10) the equivalent failure rate $\lambda_{AIR\text{-}A\to G}$ and the mean time to repair $r_{AIR\text{-}A\to G}$ are obtained as following:

$$\lambda_{AIR-A\to G} = \lambda_{AIR-p4} + \sum_{i=5}^{12}\lambda_{AIR-i} + \sum_{i=18}^{21}\lambda_{AIR-i} \qquad (29)$$

$$r_{AIR-A\to G} = \frac{\left\{ \begin{array}{l} \lambda_{AIR-p4}\cdot r_{AIR-p4} + \\ \left[\sum_{i=5}^{12}\lambda_{AIR-i}\cdot r_{AIR-i} + \sum_{i=18}^{21}\lambda_{AIR-i}\cdot r_{AIR-i} \right] \end{array} \right\}}{\lambda_{AIR-A\to G}} \qquad (30)$$

- The second compressed air sub-circuit (between F and H) operates at 10 bar during engine starting and operation. Components (13) to (17) are connected in series. With use of eq. (8) and eq. (10) the equivalent failure rate $\lambda_{AIR\text{-}F\to H}$ and the mean time to repair $r_{AIR\text{-}F\to H}$ are obtained as following:

$$\lambda_{AIR-F\rightarrow H}=\sum_{i=13}^{17}\lambda_{AIR-i} \tag{31}$$

$$r_{AIR-F\rightarrow H}=\frac{\sum_{i=13}^{17}\lambda_{AIR-i}\cdot r_{AIR-i}}{\lambda_{AIR-F\rightarrow H}} \tag{32}$$

It is noted that the first sub-circuit (between A and G) is an alternative air-supply of components (16)-(17) meaning that the first sub-circuit is connected with components (16)-(17) in parallel and their group in series with (13)-(14)-(15). With use of eq. (15) and eq. (14) the equivalent failure rate, $\lambda_{AIR\text{-}gp}$, and the mean time to repair, $r_{AIR\text{-}gp}$, of the aforementioned group of elements are obtained as following:

$$\lambda_{AIR-gp}\cong\lambda_{AIR-A\rightarrow G}\cdot\lambda_{AIR-16\_17}\cdot\left(r_{AIR-A\rightarrow G}+r_{AIR-16\_17}\right) \tag{33}$$

$$r_{AIR-gp}=\frac{r_{AIR-A\rightarrow G}\cdot r_{AIR-16\_17}}{r_{AIR-A\rightarrow G}+r_{AIR-16\_17}} \tag{34}$$

with

$$\lambda_{AIR-16\_17}=\sum_{i=16}^{17}\lambda_{AIR-i} \tag{35}$$

$$r_{AIR-16\_17}=\frac{\sum_{i=16}^{17}\lambda_{AIR-i}\cdot r_{AIR-i}}{\lambda_{AIR-16\_17}} \tag{36}$$

- The third compressed air sub-circuit operates at 4 bar during the engine starting and it is ignored in this study.
- The governor (27) is not considered here as it is integrated with frequency controller.

The two compressed air sub-circuits located between F - H and D - G points, respectively, should be in operation when the engine operates while the third sub-circuit should not. With use of eq. (8) and eq. (10) the equivalent failure rate, $\lambda_{AIR\text{-}op}$, and the mean time to repair, $r_{AIR\text{-}op}$, of the compressed air-circuit when engine is in normal mode of operation are obtained as following:

$$\lambda_{AIRop}=\lambda_{AIR-A\rightarrow G}+\lambda_{AIR-gp}+\sum_{i=13}^{15}\lambda_{AIR-i} \tag{37}$$

$$r_{AIRop}=\frac{\left\{\begin{array}{l}\lambda_{AIR-A\rightarrow G}\cdot r_{AIR-A\rightarrow G}+\lambda_{AIR-gp}\cdot r_{AIR-gp}\\ +\sum_{i=13}^{15}\lambda_{AIR-i}\cdot r_{AIR-i}\end{array}\right\}}{\lambda_{AIR-op}} \tag{38}$$

3.3 Lubricating oil circuit

Lubricating oil circuit is shown in Fig. 3. Next, the elements composing oil circuit are listed with the respective numbers used in Fig. 3 given in brackets [3]:

- oil sump (1),
- strainer (2),
- gear driven pump (3),
- thermostatic valve (4),
- temperature-switch (5),
- sea-water heat-exchanger (6),
- pressure regulating valve (7),
- self de-polluting horizontal filter (8),
- 2 bar pressure switch (9),
- 2.5 bar pressure switch (10),
- 3 bar pressure switch (11),
- pipes of the main oil circuit (12),
- service oil tank (13),
- pre-lubricating electric-pump (14),
- safety valve (15),
- lubricating oil / treated water-exchanger (16),
- non-return valve (17),
- 0.5 bar pressure-switch controlling electric-pump (18),
- 3 bar pressure-switch controlling electric-pump (19),
- pipes of the electric-pump oil circuit (20),
- hand-pump (21),
- non-return valve (22),
- pipes of the hand-pump oil circuit (23),
- thermometer (24),
- oil filter drains pipe (25),
- pressure gauge (26),
- differential pressure gauge (27).

Lubricating oil from unit service and the respective leakages are drained in the oil sump (1) located in the lower part of the engine.

Once the engine is started, the oil in the sump is drawn through a strainer (2) by gear driven pump (3) located inside engine frame. This pump (3) delivers oil to thermostatic valve (5) through a pipe comprising two bosses. This arrangement connects temperature switch (4) and thermometer (24). The temperature-switch (4) controls an audible and visible alarm. It also trips the engine if the temperature rises above a threshold, i.e. 90° C.

Thermostatic valve (5) acts as a distribution valve and provides heat-exchanger (6) with the necessary flow in order to maintain the engine inlet oil temperature at its normal value. This is achieved as the non-cooled flow is mixed with the cooled oil at the outlet of the exchanger (6). The pressure regulating valve (7) is connected to the circuit after the heat-exchanger (6). The excess of oil directly returns to oil sump. Then the main oil flow is purified by a self de-polluting horizontal filter (8) and finally distributed to engine moving parts, turbo-charger and fuel injection pump. After the de-polluting filter the lubricating oil returns to the oil sump through a drain pipe (25).

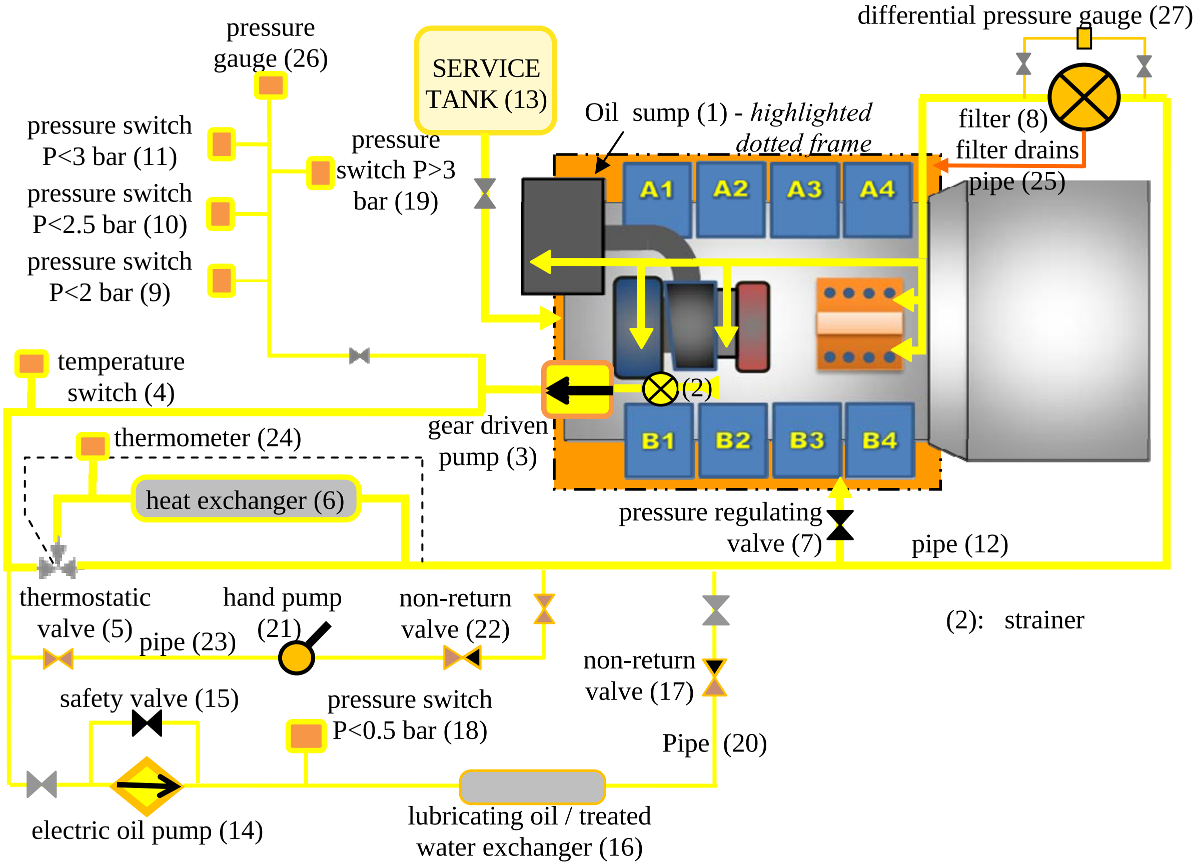


Fig. 3. Lubricating oil circuit of a typical diesel thermal electric power unit for ship.

Oil pressure control sub-system is also connected to a distribution block supplying the following equipment:

- A 2-bar pressure switch (9), which trips the engine immediately after the pressure decreases below 2 bar.
- A 2.5-bar pressure switch (10), which controls an alarm and trips the engine with time delay after the pressure decreases below 2.5 bar.
- A 3-bar pressure switch (11), which controls an alarm after the pressure decreases below 3 bar.
- A 3-bar pressure switch (19), which stops the electric pump if the pressure increases above 3 bar.
- A pressure gauge (26).

In stand-by mode, an electric pump (14) equipped with a safety valve (15) draws the oil from the distribution pipe end through the distribution block and sends it to the lubricating oil and treated water heat-exchanger (16). Then the oil flows through a non-return valve (17) and the oil filter (8) to the engine block. In this way, oil temperature and viscosity are retained in desired levels. Pressure switch (18) controls an audible and visible alarm and turns the starter off, when the oil pressure decreases below 0.5 bar.

Reliability analysis of the oil circuit is as follows:

- The expected failure rate of the *i*-th element is denoted with λ_{OIL-i}.
- The mean value to repair of the *i*-th element is denoted with r_{OIL-i}.
- The oil circuit comprises a major loop with the elements (1) up to (13) that is activated when engine is operating. A second loop (electric pump circuit) of elements (1) up to (4)and (7) up to (20) is activated in stand-by mode. Finally, a third loop (hand-pump circuit) of elements (1) up to (4), (7) up to (13) and (21) up to (23) is activated in trial mode of operation. The last two loops are ignored in the following.
- Elements (24) up to (27) are ignored as their malfunction does not put oil circuit out of operation.

Elements (1) up to (13) that are connected in series are needed during engine starting and normal operation. If one of them fails then the respective section of the lubricating oil circuit fails. With use of eq. (8) and eq. (10) the equivalent failure rate λ_{OIL-op} and the mean time to repair r_{OIL-op} are obtained as following:

$$\lambda_{OILop} = \sum_{i=1}^{13} \lambda_{OIL-i} \qquad (39)$$

$$r_{OILop} = \sum_{i=1}^{13} \lambda_{OIL-i} \cdot r_{OIL-i} \Big/ \lambda_{OILop} \qquad (40)$$

3.4 Fuel circuit

Fuel circuit is shown in Fig. 4. Next, the elements composing fuel circuit are listed with the respective numbers used in Fig. 4 given in brackets [3]:

- fuel tank (1),
- pipes (2),
- solenoid valve (3),
- gear fuel pump (4),
- relief valve (5),
- fuel filters (6), (two connected in parallel),
- remote pressure gauge (7),
- pressure switch - boss (8),
- slide valve (9),
- fuel injection pump (10),
- fuel pipes connecting injection pump with burners (11), (eight fuel pipes are used one for each fuel burner),
- 8 cylinder fuel burners (A1- B4) (12),
- drip tank (13),
- hand-pump (14),
- non-return valve (15).

Fuel circuit operation is briefly described next. Gear fuel pump (4) pumps fuel from fuel tank (1) and delivers it to the duplex filters (6) at a specific pressure (usually not exceeding 1,5 bar). Relief valve (5) discharges the excessive fuel flow at higher pressures.

Fuel is supplied to slide valve (9) by a duct at the outlet of the filter (6). The duct is fitted with two bosses to connect a remote pressure gauge (7) and a pressure switch-boss (8) that activates pressure alarm if pressure decreases below a specific level (usually 0,5 bar). Slide valve (9) allows the fuel reach the injection pump (10) which delivers it to the injectors through two sheathed pipe sets. Both of discharges connected to the barrels are joined for direct return (2) of excess fuel to the daily tank (1). The drain that is connected to the drip tank (13) collects booster pump (4) leakage, duplex filter (6) draining, leakage at injection pipe couplings, injector leakage collected at cylinder-head outlets, slide-valve piston leakage and overflows.

One hand-pump (14), which is attached to the engine at the air-intercooler level, draws fuel downstream the booster pump (4) and delivers it through a no-return valve (15) placed before filter (6). It allows pressurizing and draining on the engine fuel circuit.

Reliability analysis of fuel circuit is as follows:

- The expected failure rate of the *i*-th element is denoted with λ_{FUEL-i}.
- The mean value to repair of the *i*-th element is denoted with r_{FUEL-i}.
- The filters (6) are connected in parallel as only one filter is needed for the circuit to operate. Assuming that the two filters have the same expected failure rates, λ_{FUEL-6} and the same mean time to repair, r_{FUEL-6}, the respective equivalent failure rate of the duplex filter, $\lambda_{FUEL-p6}$ is obtained by eq. (15):

$$\lambda_{FUEL-p6} \cong \lambda_{FUEL-6} \cdot \lambda_{FUEL-6} \cdot \left(r_{FUEL-6} + r_{FUEL-6} \right) \Rightarrow$$

$$\lambda_{FUEL-p6} \cong 2 \cdot \lambda_{FUEL-6}^{2} \cdot r_{FUEL-6} \qquad (41)$$

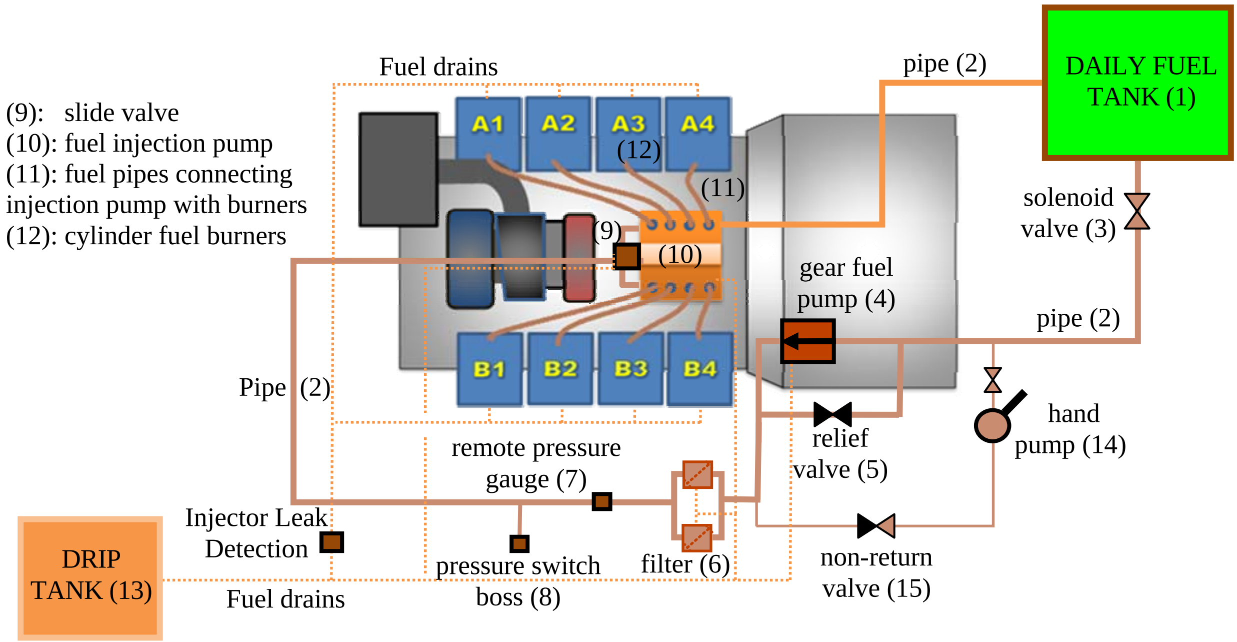


Fig. 4. Fuel circuit of a typical diesel thermal electric power unit for ship.

The respective equivalent mean time to repair of the duplex filter, $r_{FUEL\text{-}p6}$ is obtained by eq. (14):

$$r_{FUEL-p6} = \frac{r_{FUEL-6} \cdot r_{FUEL-6}}{r_{FUEL-6} + r_{FUEL-6}} = \frac{r_{FUEL-6}}{2} \qquad (42)$$

- The eight burners (12) are connected in series as if one burner fails then the diesel engine is immediately shut down for safety reasons. The same also applies in case of fuel pipes connecting injection pump burners (11).
- The drip tank (13) and the hand pump (14) are not considered as crucial elements for the operation of diesel engine and are not included in reliability analysis.
- The isolation valves, the no-return valve (15) and the pipes of the circuit are grouped and referred to as “pipe” (2).

Hence, the equivalent expected failure rate λ_{FUEL} and mean time to repair r_{FUEL} of the fuel circuit are obtained by:

$$\lambda_{FUEL} = \left\{ \begin{array}{l} \lambda_{FUEL-1} + \lambda_{FUEL-2} + \lambda_{FUEL-3} + \lambda_{FUEL-4} + \\ \lambda_{FUEL-5} + 2 \cdot \lambda_{FUEL-6}^{2} \cdot r_{FUEL-6} + \lambda_{FUEL-7} + \\ \lambda_{FUEL-8} + \lambda_{FUEL-9} + \lambda_{FUEL-10} + \\ 8 \cdot \lambda_{FUEL-11} + 8 \cdot \lambda_{FUEL-12} \end{array} \right. \qquad (43)$$

$$r_{FUEL} = \frac{1}{\lambda_{FUEL}} \cdot \left\{ \begin{array}{l} \sum\limits_{i=1,2,3,4,5,7,8,9,10} \lambda_{FUEL-i} \cdot r_{FUEL-i} \\ + \lambda_{FUEL-6}^{2} \cdot r_{FUEL-6}^{2} \\ + 8 \cdot \sum\limits_{i=11}^{12} \lambda_{FUEL-i} \cdot r_{FUEL-i} \end{array} \right\} \qquad (44)$$

3.5 Treated water circuit

Treated water circuit is shown in Fig. 5. Next, the elements composing treated water circuit are listed with the respective numbers used in Fig. 5 given in brackets [3]:

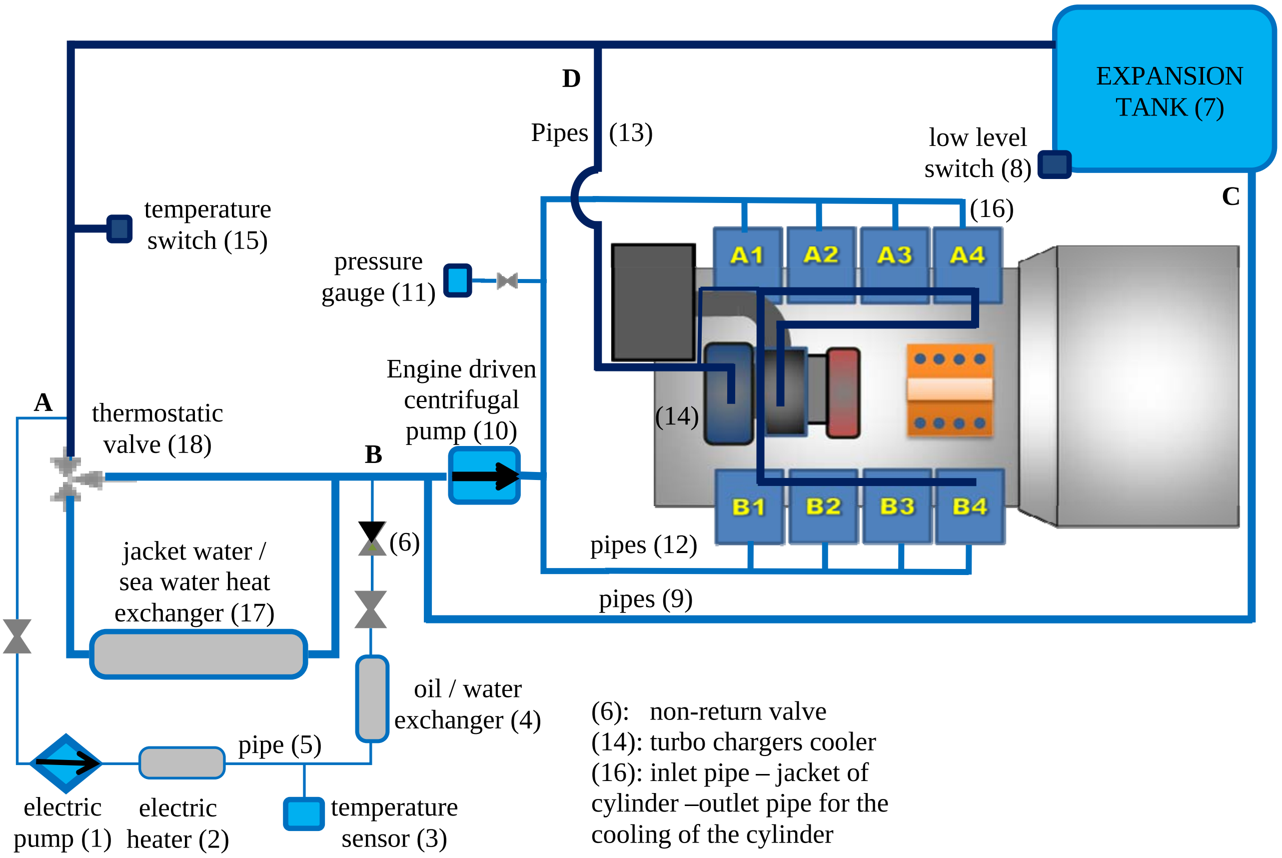
- centrifugal electric pump (1),
- electric heater (2),
- temperature sensor (3),
- oil / water exchanger (4),
- pipe (5) (group of elements between points A and B),
- non-return valve (6),
- expansion tank (7),
- low level switch (8),
- pipes (9) (between points B and C),
- engine driven centrifugal pump (10),
- pressure gauge (11),
- pipes originating from point B and connected to 8 inlet pipe jackets of the respective cylinders (12),
- Set of pipes originating from 8 outlet pipe jackets and terminated to point D (13) including the return-pipe of the cylinder bank, turbo-chargers water inlet and outlet pipes and the central outlet pipe,
- turbo-chargers cooler (14),
- temperature switch (15),
- inlet pipe – jacket of cylinder –outlet pipe for the cooling of the cylinder (16), (eight components, one for each cylinder),
- jacket water / sea water heat exchanger (17),
- thermostatic valve (18).

Treated water circuit cools the cylinders and cylinder-heads, as well as the turbo-charger exhaust casing before it is cooled by the sea water. In engine normal operation, treated water circuit is pressurized by the engine driven centrifugal pump (10) while in stand-by mode of operation by a centrifugal electric pump (1). In the second case, water circulation allows temperature to be maintained at 40°C at the engine inlet by means of electric heater (2). At heater outlet, a temperature sensor (3) provides the measurement so as to maintain water temperature at 50°C. Lubricating oil is circulated by an electric-pump and it is heated within an oil-water heat exchanger (4). The circuit is pressurized by the expansion tank (7) placed outside of the engine. Expansion tank is connected to an engine driven centrifigural pump (10). At the upper point of the circuit (water outlet), a small recycling pipe is connected to the tank (7).

Once the engine is started, pump (10) delivers water into the engine through two main pipes placed alongside outside of the engine. Water flows through short pipes towards the lower part of the jackets, then it circulates within the jackets (16) and flows upwards to the cylinder-heads. The outlets of the cylinder-heads are collected into a return-pipe. Turbo-charger water inlet and outlet pipe, as well as the respective cooler (14), are by-passed with the rightward return pipe bank. Both return-pipes (rightward and leftward) are then joined to deliver the entire water flow to the outlet pipe.

Temperature-switch (15) is located on the outlet of the pipe banks and it trips the engine if water temperature is above 95^{o}C. At the outlet of the pipe, water flow is distributed in two lines, one leading to the jacket water-sea water heat exchanger (17) and the other to the thermostatic valve (18). At heat exchanger outlet, the flow is returned to the thermostatic valve, where high temperature of outlet flow is achieved (i.e. 77^{o}C).

In shut-down mode, the water is delivered by the electric pump (1). The non-return valve (6) allows preheating circuit to be isolated while engine is in operation mode.



(6): non-return valve
(14): turbo chargers cooler
(16): inlet pipe – jacket of cylinder –outlet pipe for the cooling of the cylinder

Fig. 5. Treated water circuit of a typical diesel thermal electric power unit for ship.

Reliability analysis of treated water subsystem is as follows:

- The expected failure rate of the *i*-th element is denoted with $\lambda_{TW\text{-}i}$.
- The mean value to repair of the *i*-th element is denoted with $r_{TW\text{-}i}$.
- The isolation valves and the pipes included in each section of the circuit are referred to as “pipe” ((5), (9), (12) and (14)).
- The elements (1) to (6) located between points A and B are connected in series. If one of them fails then the section of the treated water circuit they belong fails. This group of elements operates if the engine is in standby mode and it is ignored in this study.
- The elements (17) and (18) operate in parallel regarding their hydraulic behavior. However, regarding their effect on the reliability of treated water circuit they should be considered to be connected in series, as, if one of them fails, then the respective section of the treated water circuit fails. This group of elements operates if the engine is in normal operation mode. With use of eq. (8) and eq. (10) the equivalent failure rate $\lambda_{TW\text{-}A\to B}$ and the mean time to repair $r_{TW\text{-}A\to B}$ are obtained as following:

$$\lambda_{TW-A\to B}=\sum_{i=17}^{18}\lambda_{TW-i} \tag{45}$$

$$r_{TW-A\to B}=\frac{\sum_{i=17}^{18}\lambda_{TW-i}\cdot r_{TW-i}}{\lambda_{TW-A\to B}} \tag{46}$$

- The inlet pipe, the jacket of the cylinder and the outlet pipe for the cooling (or pre-heating) of one cylinder constitute the component (13). The above elements are connected in series as if one of them fails then the engine is shut down immediately for safety reasons.
- The elements (7) up to (16) are placed between points B – C – D – A and they are connected in series. If one of them fails then the engine is shut down immediately for safety reasons. With use of eq. (8) and eq. (10) the equivalent failure rate $\lambda_{TW\text{-}B\to A}$ and the mean time to repair $r_{TW\text{-}B\to A}$ are obtained as follows:

$$\lambda_{TW-B\to A}=\sum_{i=7}^{15}\lambda_{TW-i}+8\cdot\lambda_{TW-16} \tag{47}$$

$$r_{TW-B\to A}=\frac{\sum_{i=7}^{15}\lambda_{TW-i}\cdot r_{TW-i}+8\cdot\lambda_{TW-16}\cdot r_{TW-16}}{\lambda_{TW-B\to A}} \tag{48}$$

In engine normal operation the equivalent expected failure rate λ_{TWop} and the equivalent mean time to repair r_{TWon} of the treated water circuit are given by:

$$\lambda_{TWop} = \lambda_{TW-A\to B} + \lambda_{TW-B\to A} \qquad (49)$$

$$r_{TWop} = \frac{\lambda_{TW-A\to B}\cdot r_{TW-A\to B} + \lambda_{TW-B\to A}\cdot r_{TW-B\to A}}{\lambda_{TWop}} \qquad (50)$$

3.6 Sea water cooling circuit

Sea water cooling circuit is shown in Fig. 6. Next, the elements composing sea water cooling circuit are listed with the respective numbers used in Fig. 6 given in brackets [3]:

- sea water inlet (1),
- pipes (2) (from point A to point B),
- filter (3),
- high pressure centrifugal sea water pump (4),
- non-return valve (5),
- pipes (6) (from point B to point C),
- air-intercooler (7),
- lubrication oil-sea water exchanger (8),
- generator air-cooler (9),
- thermostatic valve (10),
- treated fresh water-sea water exchanger (11),
- pilot-valve (12) with sensors and control equipment ($12^{/}$),
- sea water outlet (13),
- pipes (14) (from point D to point B),
- non-return valve (15),
- fire-fighting sea water circuit (16).

Through flow-type tube exchangers the sea water successively cools the charge-air delivered by the turbo-charger, engine lubricating oil, the alternator cooling air loop and engine cooling treated water .

One direction sea-water flow is achieved with one high-pressure centrifugal pump (4) driven by the diesel engine and a non-return valve (5). After the sea water exits the filter (3) is first delivered by the pump to the air-intercooler (7) and then to the lubrication oil-sea water heat exchanger (8), where the sea water chills the lubrication oil. Then it flows through the thermostatic valve (10) and it is partly directed to the alternator generator air-cooler (9), with the remaining water flowing through the pipe (17). According to the temperature measurement obtained by the sensor of the thermostatic valve (10) the flow is directed in the air-cooler (9) and the by-pass pipe (17). The alternator air-cooler outlet and the by-pass pipe are joined together in order to deliver the entire flow into treated water-sea water exchanger (11).

Treated water-sea water heat exchanger (11) outlet is connected to the pilot-valve (12) in order to prevent from undesirable sea water temperature variations at circuit entrance by re-circulating a part of the heated sea water and casting the remaining part out to the sea. The re-circulating pipe is connected to pilot valve equipment ($12^{/}$). This equipment senses and controls the temperature of the cold sea-water mixture inside the engine. If necessary, the fire-fighting electric pump may be used instead of the engine-driven pump (4) by means of the no-return valve (15).

Reliability analysis of sea-water cooling circuit is as follows:

- The expected failure rate of the *i*-th element is denoted with $\lambda_{SW\text{-}i}$.

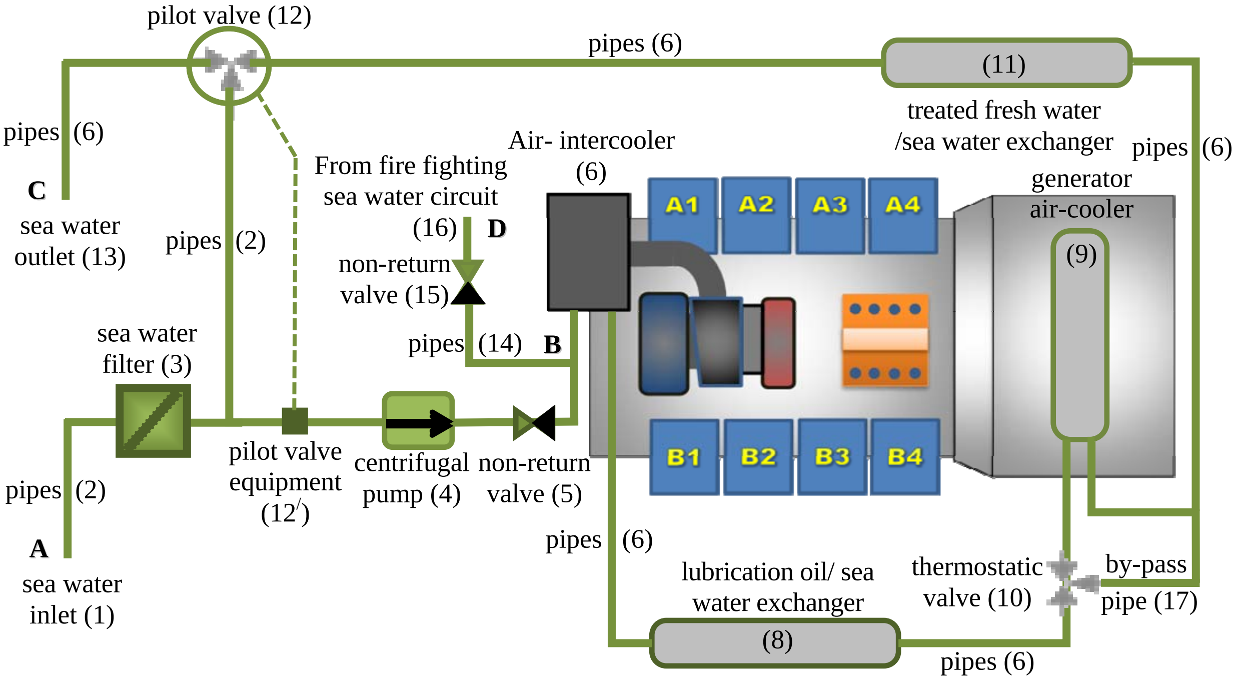


Fig. 6. Sea water cooling circuit of a typical diesel thermal electric power unit for ship.

- The mean value to repair of the *i*-th element is denoted with r_{SW-i}.
- The isolation valves and the pipes of each section of the circuit are referred to as “pipe” ((2), (6) and (14)). Especially, “pipe” (6) corresponds to the by-pass pipe (17).
- The elements (1) up to (5) located between points A and B are connected in series, as if one of them fails then the respective section of the sea-water circuit fails. Applying eq. (8) and eq. (10) the equivalent failure rate $\lambda_{SW-A\to B}$ and the mean time to repair $r_{SW-A\to B}$ are obtained as following:

$$\lambda_{SW-A\to B} = \sum_{i=1}^{5} \lambda_{SW-i} \tag{51}$$

$$r_{SW-A\to B} = \frac{\sum_{i=1}^{5} \lambda_{SW-i} \cdot r_{SW-i}}{\lambda_{SW-A\to B}} \tag{52}$$

- The elements (6) up to (13) located between points B and C are connected in series. If one of them fails then the entire engine is shut down immediately for safety reasons. With use of eq. (8) and eq. (10) the equivalent failure rate $\lambda_{SW-B\to C}$ and the mean time to repair $r_{SW-B\to C}$ are obtained as:

$$\lambda_{SW-B\to C} = \sum_{i=6}^{13} \lambda_{SW-i} \tag{53}$$

$$r_{SW-B\to C} = \frac{\sum_{i=6}^{13} \lambda_{SW-i} \cdot r_{SW-i}}{\lambda_{SW-B\to C}} \tag{54}$$

- In sea water pump (4) malfunction the fire-fighting sea water circuit can be used. The respective elements, (14) up to (16) located between points D and B are connected in series. If one of them fails then the respective section of the sea water circuit fails. With use of eq. (8) and eq. (10) the equivalent failure rate $\lambda_{SW-D\to B}$ and the mean time to repair $r_{SW-D\to B}$ are obtained as:

$$\lambda_{SW-D\to B} = \sum_{i=14}^{16} \lambda_{SW-i} \tag{55}$$

$$r_{SW-D\to B} = \frac{\sum_{i=14}^{16} \lambda_{SW-i} \cdot r_{SW-i}}{\lambda_{SW-D\to B}} \tag{56}$$

- Sea water cooling circuit sections located between points A and B, D and B are connected in parallel as only one of them is necessary for its operation Based on the equivalent expected failure rates estimated with eq. (51) and (55) and using eq. (15) the respective equivalent failure rate λ_{SW-pB} is obtained as:

$$\lambda_{SW-pB} \cong \lambda_{SW-A\to B} \cdot \lambda_{SW-D\to B} \cdot \left(r_{SW-A\to B} + r_{SW-D\to B}\right) \tag{57}$$

Based on the estimated by eq. (52) and (56) equivalent mean time to repair, the respective equivalent mean time to repair r_{SW-pB} is obtained by eq. (14) as following:

$$r_{SW-pB} = \frac{r_{SW-A\to B} \cdot r_{SW-D\to B}}{r_{SW-A\to B} + r_{SW-D\to B}} \tag{58}$$

Hence, the equivalent expected failure rate λ_{SW} and the equivalent mean time to repair r_{SW} of the sea water cooling circuit are obtained by eq. (59) and (60).

$$\lambda_{SW} = \lambda_{SW-pB} + \lambda_{SW-B\to C} \tag{59}$$

$$r_{SW} = \frac{\lambda_{SW-pB} \cdot r_{SW-pB} + \lambda_{SW-B\to C} \cdot r_{SW-B\to C}}{\lambda_{SW}} \tag{60}$$

3.7 Rest sub-systems

Except from the circuits analyzed above the electric power generation unit also includes the main diesel engine, the electric generator, the frequency controller, the automatic voltage regulator and the main electric circuit breaker. Despite the fact that all these components comprise hundreds of elements the correct approach to consider them as a single unit. If the electrical or electronic equipment such as circuit breaker, frequency controller etc. fails, it is preferred to be replaced using identical equipment as its repair requires specialized staff, usually not available facilities and time. The major breakdowns of diesel engines (i.e. ball-bearing damage, main shaft of crack) and electric generators (i.e. windings short-circuit, insulation leaks) require the general inspection and repair of the respective component. Hence, each one of these engine sub-systems is usually treated as one unit with its total failure rate and mean time to repair.

3.8 Bottom-up reliability analysis

In order to obtain the total failure rate and the mean time to repair, eq. (22), (23) should be applied for diesel-engine operation mode:

$$\lambda_{tot-op} = \left\{ \begin{array}{l} \lambda_{DIES} + \lambda_{GEN} + \lambda_{FC} + \lambda_{AVR} + \lambda_{CBR} \\ + \lambda_{AIRop} + \lambda_{OILop} + \lambda_{FUEL} + \lambda_{TWop} + \lambda_{SW} \end{array} \right. \tag{61}$$

$$r_{tot-op} = \frac{\left\{ \begin{array}{l} \lambda_{DIES} \cdot r_{DIES} + \lambda_{GEN} \cdot r_{GEN} + \lambda_{FC} \cdot r_{FC} \\ + \lambda_{AVR} \cdot r_{AVR} + \lambda_{CBR} \cdot r_{CBR} + \lambda_{AIRop} \cdot r_{AIRop} \\ + \lambda_{OILop} \cdot r_{OILop} + \lambda_{FUEL} \cdot r_{FUEL} \\ + \lambda_{TWop} \cdot r_{TWop} + \lambda_{SW} \cdot r_{SW} \end{array} \right\}}{\lambda_{tot-op}} \tag{62}$$

In case of a base-load electric power unit eq. (61) and (62) are compatible with the two-state reliability model of Fig. 1.

4 Case Study

4.1 General

In this case study all expected failure rates and the mean time to repair are assumed constant for all engine elements. The respective typical values of 97 basic elements of the examined diesel engine driven electric power unit have been used. The target of this analysis is to study the behaviour of the forced outage ratio estimated by eq. (5) for a base-load electric power unit. The obtained value for FOR_{base} is equal to 1.1287% for our case study. It is noted that the respective elements have been enumerated as following:

- 1st up to 26th elements are the 26 elements composing the air-circuit,
- 27th up to 46th element are the 20 elements composing the oil-circuit,
- 47th to 58th element are the 12 elements composing the fuel-circuit,
- 59th up to 76th element are the 18 elements composing the treated water -circuit,
- 77th up to 92nd element are the 16 elements composing the sea water-circuit,
- 93rd element is the main diesel engine,
- 94th element is the electric generator,
- 95th element is the frequency controller,
- 96th element is the automatic voltage regulator
- and the 97th element is the main electrical circuit breaker.

4.2 Sensitivity analysis

Next, an analytical sensitivity analysis is carried out, where the expected failure rates and the mean times to repair of the major unit elements are varied. Specifically, the expected failure rate of each element is varied from 10% up to 200% of its typical value with a step of 10%. Moreover, the mean time to repair of the same element is varied with the same manner. This means that 400 scenarios are examined for each element and the respective 3-D graphic plots are obtained for each statistical index. As an example, the F.O.R. of a base-load electric power unit with respect to the failure rate and the mean time to repair of the 11th element of the fuel circuit (fuel pipes connecting injection pump with burners) is shown in Fig. 7. FOR relative variation because of the variation of j^{th} element reliability indices is calculated, as:

$$\mathrm{var}_j = \frac{\mathrm{max\_FOR}_j\text{-}\mathrm{min\_FOR}_j}{\mathrm{basic\_FOR}_j}, \forall\left(\lambda_j, r_j\right) \qquad (61)$$

This process is repeated for the entire group of the 97 major elements of the diesel power unit resulting in 38800 scenarios. The target of this analysis is to assess FOR sensitivity to major elements and detect the most affecting ones. In Fig. 8, F.O.R. sensitivity with respect to the examined major elements of the electric power unit is shown. According to this analysis, 57th element (fuel pipes connecting injection pump with burners) results in the biggest FOR variation (55%).

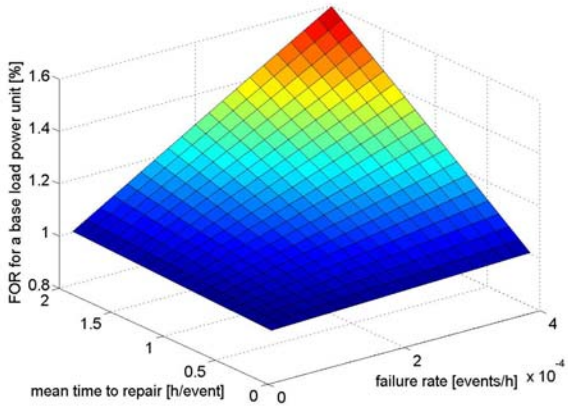


Fig. 7. F.O.R. of a base-load electric power unit, FOR_{base}, with respect to the failure rate and the mean time to repair of the 11th element of the fuel circuit

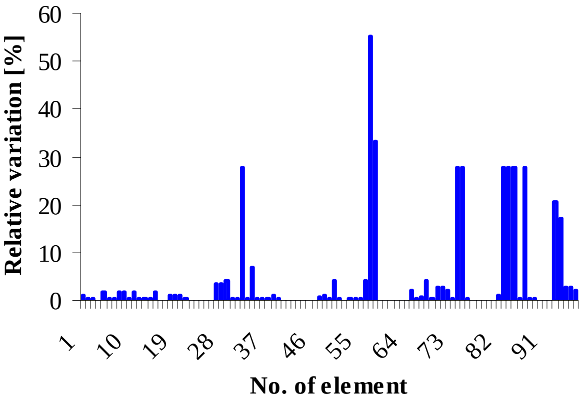


Fig. 8. FOR_{base} sensitivity with respect to the major elements of the electric power unit.

In Table 1 the ten elements affecting most the FOR of a base load electric power unit according to the obtained results, are registered. It becomes evident from the above analysis and the obtained results that the proposed method provides the operator with a tool for the detection of the equipment mostly affecting FOR. In this way, the operator can set up an effective maintenance schedule or timely decide any precautionary action. The above technical analysis can be completed with the economic evaluation of any action the method proposes in order to come up with the final decisions.

TABLE 1
ELEMENTS AFFECTING MOST THE FOR OF THE BASE LOAD ELECTRIC POWER UNIT

Element	Relative variation (%)
Fuel pipes connecting injection pump with burners (11th fuel circuit's element – 57th from 97 elements)	55.11
Cylinder fuel burners (12th fuel circuit's element – 58th from 97 elements)	33.11
Heat exchanger using sea water circuit (6th oil circuit's element – 32nd from 97 elements)	27.60
Inlet piper – jacket of cylinder – outlet piper for the cooling of the cylinder (16th treated water circuit's element – 74th from 97 elements)	27.60
Jacket water / sea water heat exchanger (17th treated water circuit's element – 75th from 97 elements)	27.60
Air intercooler (7th sea water circuit's element – 83rd from 97 elements)	27.60
Lubrication oil / sea water exchanger (8th sea water circuit's element – 84th from 97 elements)	27.60
Generator air-cooler (9th sea water circuit's element – 85th from 97 elements)	27.60
Treated water / sea water exchanger (11th sea water circuit's element – 87th from 97 elements)	27.60
Main diesel engine (93th from 97 elements)	20.71

5 Conclusions

This paper presents the bottom-up reliability analysis of a diesel engine driven electric power unit assuming constant expected failure and repair rates of the components of the unit. First, reliability analysis of the major subsystems of the electric power unit, such as air, lubricating oil, fuel, treated water and sea water circuits, is provided. Next, the forced outage rate of a base-load electric power unit is calculated using the failure rates and the mean times to repair of each element of the unit. The proposed sensitivity analysis can help the operator to identify the elements mostly affecting unit availability. FOR variation assessment for common pre-determined range of failure and repair rates of each element can be used for this purpose. This also may allow the operator to determine a set of precautionary actions in order to improve the unit reliability. Future possible expansion of the method is to be completed with the economic assessment of any action it proposes in order to enable the operator of the electric power unit to make its final decisions.

Acknowledgements

The authors would like to thank Dr. N. Mastorakis, Professor at Hellenic Naval Academy and ex-president of WSEAS for his overall support and scientific guidance.

References:

[1] E.N. Dialynas. *Power System Reliability*. Athens, 1996 (in greek).

[2] R. Billinton, R. N. Allan. *Reliability Evaluation of Power Systems*. Plenum Press, New York and London, 1996.

[3] E.C. Nasioulas, G. J. Tsekouras, F.D. Kanellos. *Reliability analysis of a diesel engine driven electric power unit*. WSEAS-NAUN, August 28, 2013, Chania, Greece.

[4] IEEE Task Group on Model for Peaking Units of the Application of Probability Methods Subcommittee. A four state model for estimation of outage risk for units in peaking service. *IEEE Transactions,* PAS-91, 1972, pp. 618-627.

[5] D.A. Taylor. *Introduction to Marine Engineering*. Elsevier Butterworth-Heimann, UK, 2nd edition, 2006.

[6] G. Daniil, K. Mimikopoulos. *Ship auxiliaries machines*. Eugenidou Foundation, Greece, 1988.

[7] L. Klianis, J. Nikolos, J. Sideris. *Internal combustion machines – volume 1*. Eugenidou Foundation, Greece, 2002.

[8] L. Klianis, J. Nikolos, J. Sideris. *Internal combustion machines – volume 2*. Eugenidou Foundation, Greece, 2003.