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An Analysis of Starting Points for Setting Up a Model of a More Reliable Ship Propulsion

Preliminary communication

This paper considers the important requirement for ship propulsion necessary for its immaculate operation, since any failure can endanger the ship and render it useless. Particular attention is given to the failure of auxiliary engines that can also seriously jeopardise the safety of the ship. Therefore the paper presents preliminary investigations for setting up models of reliable ship propulsion accounting for the failure of auxiliary engines. Models of most frequent implementations of electrical energy generating systems are defined, analysed and their influences assessed. Based on simulation results, analyses of the models and data from relevant data bases on ship machinery arrangements and failures, possible solutions for improving ship propulsion reliability are presented. An analysis of proposed possibilities leads us to the conclusion that it is necessary to define a new model for reliable ship propulsion including auxiliary machines.

Keywords: *electrical energy, generator, main engine, propulsion*

Analiza ishodišta za postavljanje modela sigurnog brodskog poriva

Prethodno priopćenje

Članak razmatra važan zahtjev koji se postavlja pred brodski porivni sustav i njegov besprijekoran rad, budući da njegovo zakazivanje ugrožava funkcionalnost i sigurnost broda. Posebna se pozornost posvećuje mogućim kvarovima i otkazivanjima rada pomoćnih motora što neumitno dovodi do ozbiljnog ugrožavanja sigurnosti broda. Zbog toga su u radu prikazuju ishodišta za postavljanje preliminarnog modela sigurnog brodskog poriva koji uključuje mogućnost otkazivanja i pomoćnih uređaja. Modeli najčešćih izvedbi različitih sustava generiranja električne energije na brodu su definirani simuliranjem a njihov su utjecaji analizirani u radu. Na temelju dobivenih rezultata simulacije, analize postavljenih modela te podataka iz relevantnih baza podataka o izvedbama i kvarovima brodskog strojnog kompleksa, predložena su moguća rješenja povećanja sigurnosti poriva broda. Analizom predloženih mogućnosti zaključeno je da je potrebno definirati novi model sigurnog brodskog poriva.

Ključne riječi: *električna energija, generator, glavni motor, poriv*

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1 Introduction

Any failure of the electrical system can leave the ship without propulsion, even if the main engine is working properly. The inability to establish propulsion when the ship is exposed to harsh conditions at sea can have fatal consequences (loss of ship and cargo, marine pollution, etc.). These are the reasons for the implementation of a reliable propulsion system that will be independent of the primary electrical power supply.

Analysing reliability of ship propulsion requires a block diagram of diesel generator, which is a part of the modern ship machinery system. The model should include status of generators in series and parallel, and operation in series and parallel. Some systems have greater downtime, and some smaller. Some breakdowns are short, almost instantaneous and they influence the reliability of the propulsion system. There are also elements which, while inoperable, do not cause a system stop, but degradation. Complexity of the model is further increased by different operating modes of propulsion in which ship thrust is achieved [1]. Based on specific systems' technical descriptions, their influence on the main engine, and influence of each genera-

tor breakdown, it is possible to construct a model of complete propulsion system. By analysing generators on board ships with slow speed diesel engines, we can single out three main types of systems for generation of electricity:

- Electricity generating system with two or three diesel generators,
- Electricity generating system with two diesel generators and a shaft generator,
- Electricity generating system with two diesel generators and a turbogenerator.

The influence of the electric production systems on the main engine is analysed by simulating breakdowns of specific systems, which enable normal operation of ship machinery. The simulation has been carried out on the simulator "Konsberg Norcontrol PPT 2000". The simulator is equipped with all auxiliary systems of the main propulsion; a two stroke slow speed diesel engine. The engine is one of the MAN B&W type and has the power of 20 000 kW. The engine is built in on board a VLCC, having a deadweight of 200 000 tonnes. It has 5 cylinders, piston diameter of 900 mm, speed of 74 min⁻¹, maximum stroke of 2.9 m and average pressure of 18.2 bar.

2 System with three diesel generators

According to classification society regulations, energy balance must be such that a single generator has the capacity to supply electrical energy during navigation, the second generator is on stand-by, and the third one is a reserve. The emergency generator must also be stand-by. If the need arises, it should be able to supply enough power for emergency steering gear, emergency fire pump, bilge pump, one or more air compressors for the main engine starting, and emergency lighting and control systems. The emergency generator may provide power for additional consumers if ship owner makes such requirements.

All ship's systems, propulsion systems included, rely on flawless performance of diesel generators, i.e. reliability of diesel engine operation [2]. Unfortunately, diesel engines are relatively unreliable due to large number of moving parts which depend on each other. For instance, a typical turbocharger is constructed of 82 elements, while the engine itself has far greater number of parts (shafts, bearings, valves, piston rods, head, seals and gaskets,...). Each of these can cause a breakdown.

The simulator was configured to simulate operation of diesel generator with other generators on standby (Figure 1) [3]. Generator failure was simulated with unexpected overload, which can be caused by deck winches or cargo oil pumps on tankers. When overload of ship's grid occurs, either because of generator failure or power-up of more power intensive consumers, a stand

by generator is turned on automatically (start program), and it is selectively and gradually connected to the main switchboard bus, with automatic voltage and frequency regulation and synchronisation.

Simulation results show that when overload occurs, the alarm is sounded and the primary generator stops working. Two seconds later, the stand by generator powers up, and five seconds later the auxiliary generator starts working. Within nine seconds the generator is connected to the switchboard, and in further 21 seconds load is gradually applied to the generator. After this time the second generator is in process of synchronisation. The analysis of simulation results implies that parallel operation of generators is required because of increased electricity demand. Similar results have been obtained for simulated breakdowns of lube oil system, cooling water system, fuel oil system, or failures of individual generator components.

When overload of ship's grid occurs, either because of generator failure or power-up of more power intensive consumers, the stand by generator is turned on automatically, and it is selectively and gradually connected to the main switchboard bus, with automatic voltage and frequency regulation, and synchronisation. Automatic synchronisation of started generator is necessary, and if available power is not sufficient to satisfy the demand of more intensive consumers (windlass engine), the system automatically gathers the data on available power before generator start. If the available power is insufficient, the third generator is turned on;

Figure 1 Diesel generator overload simulation
Slika 1 Simulacija preopterećenja dizelskog generatora

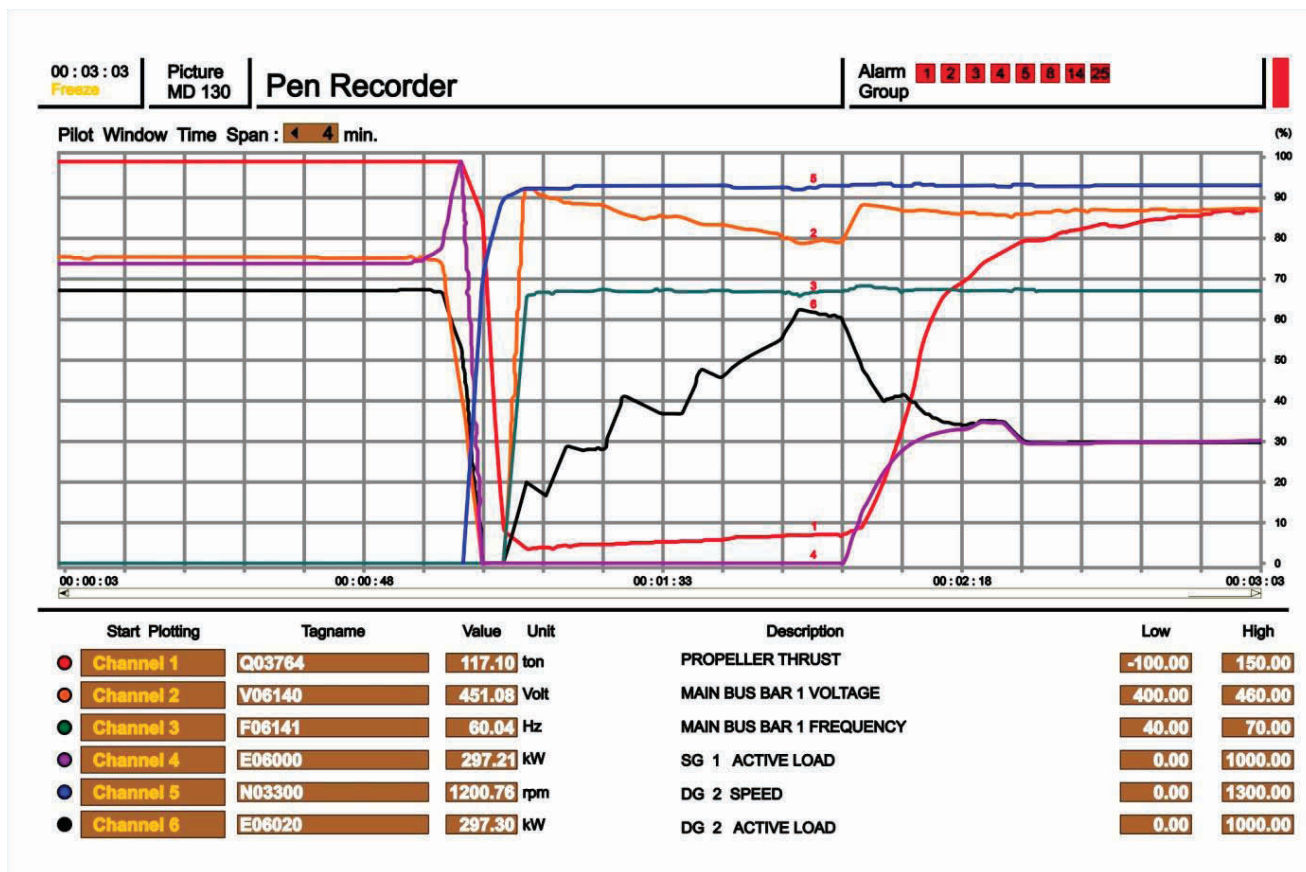
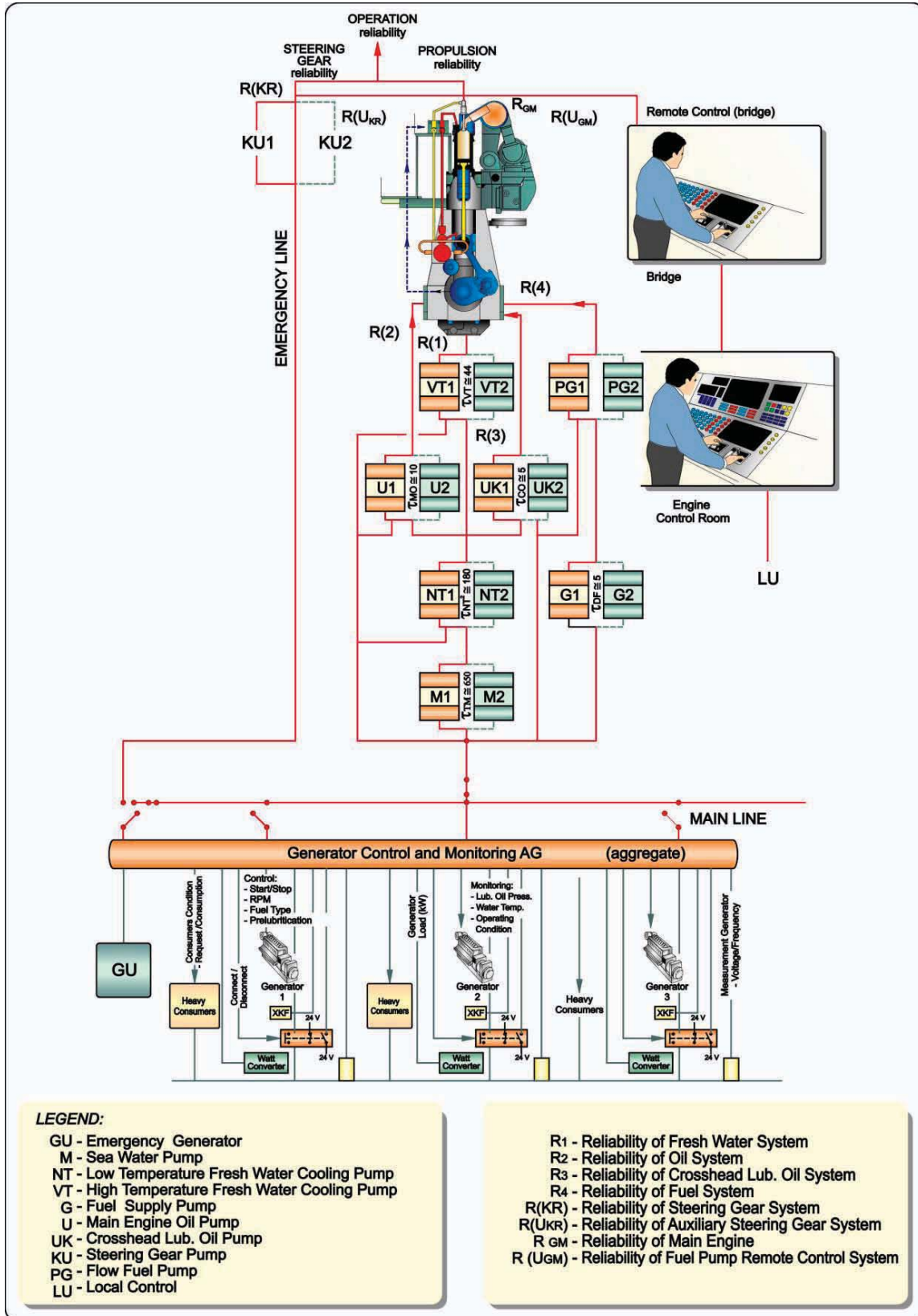


Figure 2 Model of system with three diesel generators
 Slika 2 Model sustava s tri dizelska generatora



it is synchronised and connected to the main switchboard. Only then will the consumers be connected to the grid. If one of the generators fails, remaining generator must be protected from overload. This is achieved by discontinuing operation of lower priority consumers. This allows continued operation of essential systems, like propulsion or steering gear, and other systems which influence ship safety.

Electric circuit begins with the generator, which has sub-systems that monitor and control functions, and enable alarms. Generator controllers may communicate to allow complete automation in the generator control system (Figure 2).

When power demand is reduced, available power increases. To avoid unnecessary reserve power, one of the generators is stopped. This ensures normal operation of remaining diesel generator. Thus, low efficiency and operation at reduced load are avoided.

Apart from regulating working parameters of the generator itself, automation systems have other functions:

- powering up,
- monitoring of lube oil pressure,
- monitoring of cooling water temperature and pressure,
- monitoring of fuel oil pressure and temperature,
- powering down, etc.

Ship's electric consumers are usually classified in groups of essential consumers, high priority consumers, and low priority consumers. The first group contains devices which are essential for safe ship operation and navigation. These include navigation systems, steering gear, alarm systems, fire extinguishing systems, bilge systems, and other essential subsystems which ensure the working condition of the main engine. The second group encompasses systems which are not continuously in operation, and their power-up is always registered. Upon their initialisation, available electrical energy is assessed, and additional generators are started if necessary. The third group covers consumers which are turned on and off automatically, and their operation does not influence the safety of the ship and navigation.

The model has two diesel generators which are on standby. Should the operating generator break down, one of the diesel generators automatically turns on and takes over power production and load of consumers within 15 seconds. In order to keep the main engine in operation, its vital systems must be operational and running or at least have the ability to start.

One of the most important systems is the seawater cooling system with two pumps connected in parallel. Simulation [1] has shown that if they lose power, engine load will be reduced in ten minutes, and main engine will stop working after fifteen minutes.

Seawater is used for cooling the low temperature system (NT) of fresh water directly. Two seawater pumps (M_1 , M_2) are connected in parallel. Water flow and temperature are automatically monitored at inlet and outlet of the heat exchanger. The low temperature fresh water system is driven by pumps connected in parallel (NT_1 , NT_2). The ME high temperature system is cooled by low temperature system by means of two pumps connected in parallel (VT_1 , VT_2). High temperature water flow and temperature at engine intake and outlet are continually indicated and depend on engine load regulation, i.e. engine stop. The low temperature system is connected with the ME and crosshead oil coolers. Water flow is regulated by temperature control valves to keep oil temperature at engine intake constant. ME lube oil system circulates

by means of two pumps connected in parallel (U_1 , U_2), as well as crosshead pumps (UK_1 , UK_2). Oil pressure and temperature are automatically monitored by ME control system. Pressure drop in any of the systems forces the engine to stop and sounds the alarm. A change in temperature causes a reduction in speed until the engine is finally halted. Reaction time of both systems is very short. When one pump fails, the other has to take over within five to ten seconds.

Fuel oil system is connected in series with booster fuel oil pumps (G_1 , G_2) and circulating fuel oil pumps (PG_1 , PG_2), which are connected in parallel. The engine is connected to the fuel oil flow regulator. In case of booster pump failure, the engine will operate until all fuel is used up in the deaerator (mixing tank), heater and piping.

If circulating pumps fail, the engine will still operate, but there will be a decrease in flow by approximately 50 per cent. In case when the system is not fitted with booster pumps, the engine will stop when flow (circulating) pumps fail. All pumps which are connected in parallel have a standby pump which automatically starts operating in case of failure of other pump. Overall reliability of propulsion engine operation equals the reliability of all service systems R(1), R(2), R(3), R(4) and remote control of the main engine. The operation of the propulsion system depends on the reliability of the ME, propulsor and steering gear.

The steering system is considered to be the most important system for ship safety. In case of diesel generator tripping, the emergency generator will start operating within six seconds and engage the steering system (primary consumer). Should power supply fail during navigation, the vessel will maintain relatively high speed. To ensure control of the vessel, steering system and emergency lighting need to be reengaged in a short period of time. This is achieved by means of the emergency generator. Should in that short interval one of the diesel generators be restarted, all pumps which are important for the main engine operation will be automatically started. Fuel oil pumps will force fuel to high pressure fuel oil pumps that will (if the ship's propeller is still rotated by inertia) reactivate the propulsion system if the ME control lever and SHUT-DOWN are reset. If normal working conditions of oil, water and fuel oil systems are present, normal engine operation is achieved. When speed is lowered and blackout reoccurs, essential pumps will stop operating and the main engine is stopped. For restarting the engine, starting air must be used, so the starting procedure lasts longer.

3 System with diesel generators and a shaft generator

A part of the main engine power is used to drive the shaft generator which in turn supplies the power grid or individual consumers with electrical energy. The shaft generator has to deliver full nominal power using nominal voltage, within the range of ME permitted rpm.

On vessels with fixed blade propellers and adjustable speed, shaft generator operation is not constant, so such arrangements are only applied for moving ahead and within a particular range of main shaft rotation (Figure 3). While manoeuvring and at speeds which are inadequate for shaft generator operation, the shaft generator is automatically disengaged and diesel generator started [4].

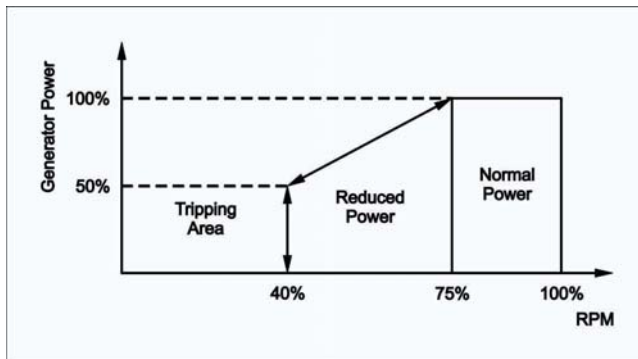


Figure 3 Shaft generator working area
Slika 3 Područje rada osovinskog generatora

With the employment of shaft generators, the operational lifetime of diesel generators is prolonged; fuel consumption and maintenance [5] are reduced. The electrical switch is a shaft generator component that is most prone to failure, i.e. tripping which is caused by abrupt speed change. Thus, tripping will occur in critical situations (“Slow Down” or “Shut Down”), and if the shaft generator is the sole supplier of electrical network, power supply to GPR will be interrupted.

A certain amount of time is required for setting up diesel generator and connecting essential consumers to the grid. If the

diesel generator is not ready for automatic starting, and the ship is without propulsion, moving of the vessel can no longer be controlled which could have destructive consequences.

The navigation scenario during storm or whole gale (Beaufort scale 10) has been simulated (Figure 4). Harsh weather conditions cause the sounding of high and low oil level alarm in the diesel generator crankcase and in the propulsion engine sump. High seas cause engine overload, so the load has to be reduced.

Surfacing of the ship propeller causes a sharp increase in speed and vibration, leading to frequency fluctuation which again causes the shaft generator to trip. Simulation results show time variation of thrust force, frequency, voltage and load of shaft generator, as well as diesel generator speed and load.

When a self-contained shaft generator is engaged during navigation (Figure 5), the circle of dependence in closed system flow passes through the main engine and shaft generator via a main engine subsystem [3]. Under normal weather conditions, this model is reliable. Even more so, it can be said that it is more reliable than the diesel generator model.

Total reliability of propulsion engine operation is similar to the one obtained in the previous analysis, and depends on system service values R(1), R(2), R(3), R(4) and ME remote controlling. The reliability of the whole propulsion system depends on the operation of shaft generator, diesel generators, propulsion engine, propulsor and steering gear. The same principle referring to emergency steering and generator opera-

Figure 4 Shaft generator system simulation in bad weather navigation conditions
Slika 4 Simulacija rada osovinskog generatora u nepovoljnim vremenskim uvjetima plovidbe

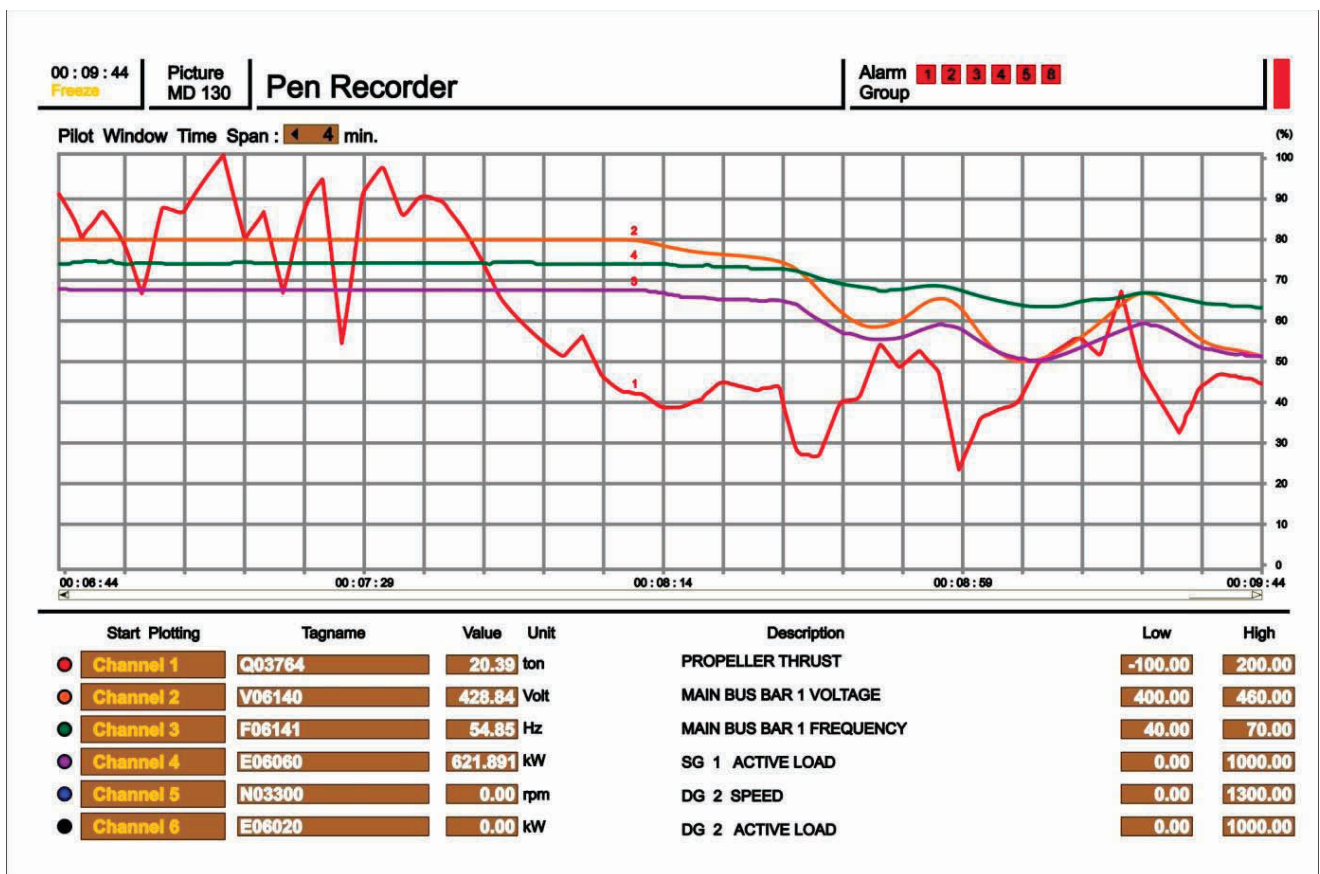
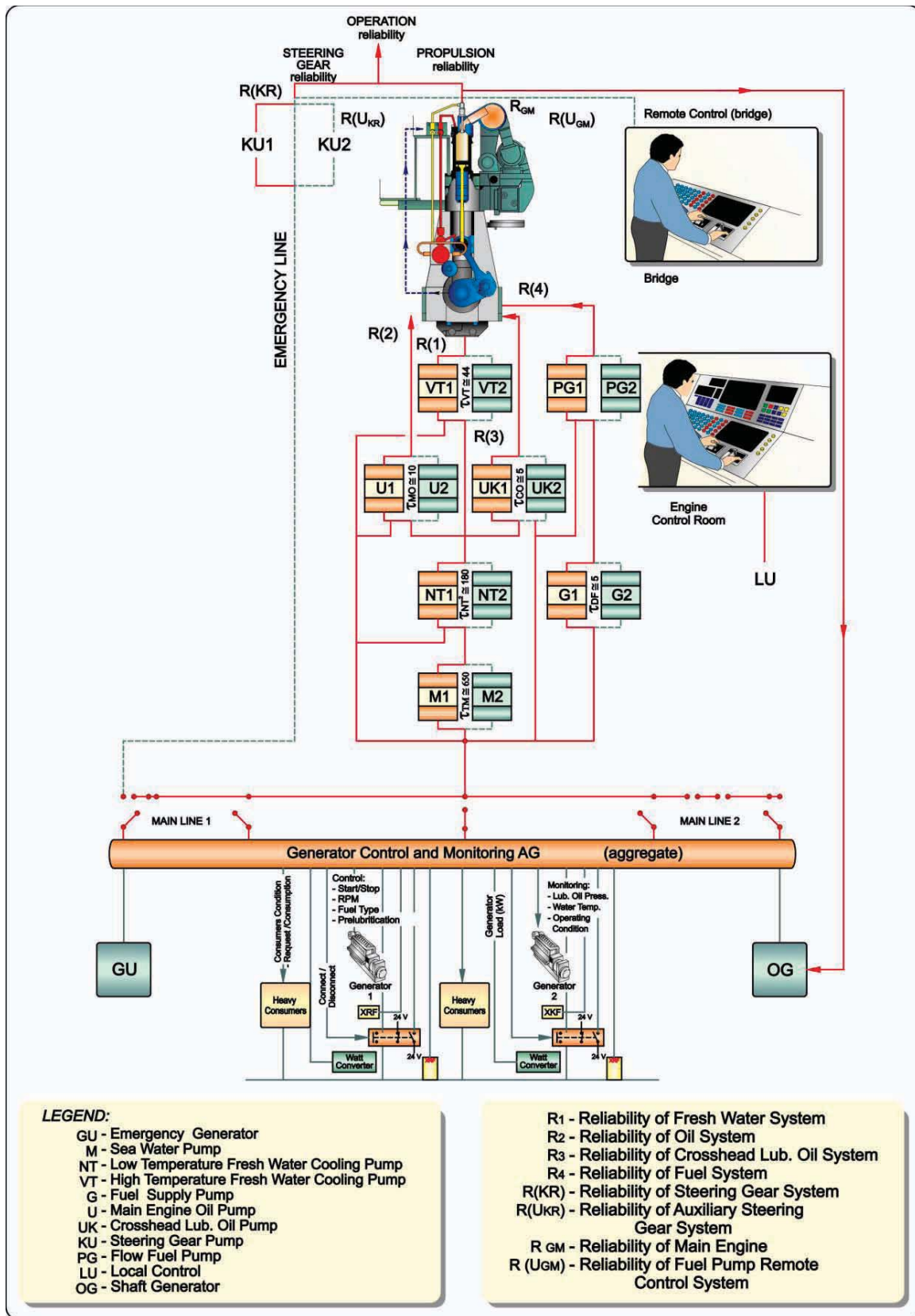


Figure 5 Model of shaft generator system
Slika 5 Model pogona s osovinskim generatorom



tion mentioned in the previous chapter can also be applied in this case.

4 System with a turbogenerator

Modern ships with certain horsepower can produce electricity by means of the so called utilisation turbogenerator, using exhaust gases of the main diesel engine for obtaining steam in the waste utilisation boiler [3]. When the main engine speed is reduced and waste heat is insufficient to supply the boiler, the diesel generator is automatically engaged thus taking over electrical consumers. The waste utilisation boiler can be connected to the fuel oil boiler. The system uses exhaust gases of heavy diesel oil, which leads to system efficiency and cost-effectiveness. The analysis of cost-effectiveness of utilisation plants [1] indicates that the initial investment, which is by 40 per cent greater than for diesel generators, is paid off within three to four years. Operating costs of turbogenerators are lowered, especially fuel consumption (2/3 of saving). Bearing in mind present-day fuel oil prices, the significantly higher initial cost of turbogenerator model is regained in less than a year [3]. The balance depends on the type of ship, ME power, navigation and duration of voyage as well as fuel oil price [3].

Utilisation boiler and turbogenerator production depends on installed main engine power. Capacity to convert exhaust gas

energy into electrical energy is between 8-13 per cent for four stroke engines, and 5-9 per cent for two stroke engines [6].

This system is usually adopted on ships with great propulsion power, navigating on longer shipping lines. This includes bulk carriers, tankers and container ships.

Turbogenerator may be operational during all stages of navigation, including manoeuvring and port services. During open sea navigation, electrical energy generated in the turbogenerator is “costless”, as it is fuelled by waste gasses from the main engine. When the main engine stops working, the utilisation boiler is fuelled by fuel oil. This system, however, has some disadvantages:

- relatively long start-up time (reaching necessary steam temperature and pressure),
- relatively long start-up time of the turbine itself.

Figure 6 shows simulated scenario of turbogenerator breakdown. The turbogenerator produces electricity, and the diesel generator is on standby. For reasons unknown, in given moment, the main engine power drops from 100 to 50 per cent.

With the main engine performance drop, the flow of exhaust gases is reduced, and with it the production of steam in the utilisation boiler. If the boiler can be fuel-oil fired, the alternate process will start within 50 seconds, as pressure drop in the boiler is abrupt. To start up the boiler on fuel oil, ventilation fans must ventilate the boiler, and reaching the full capacity will result in

Figure 6 Simulation of turbogenerator system failure
Slika 6 Simulacija kvara sustava turbogeneratora

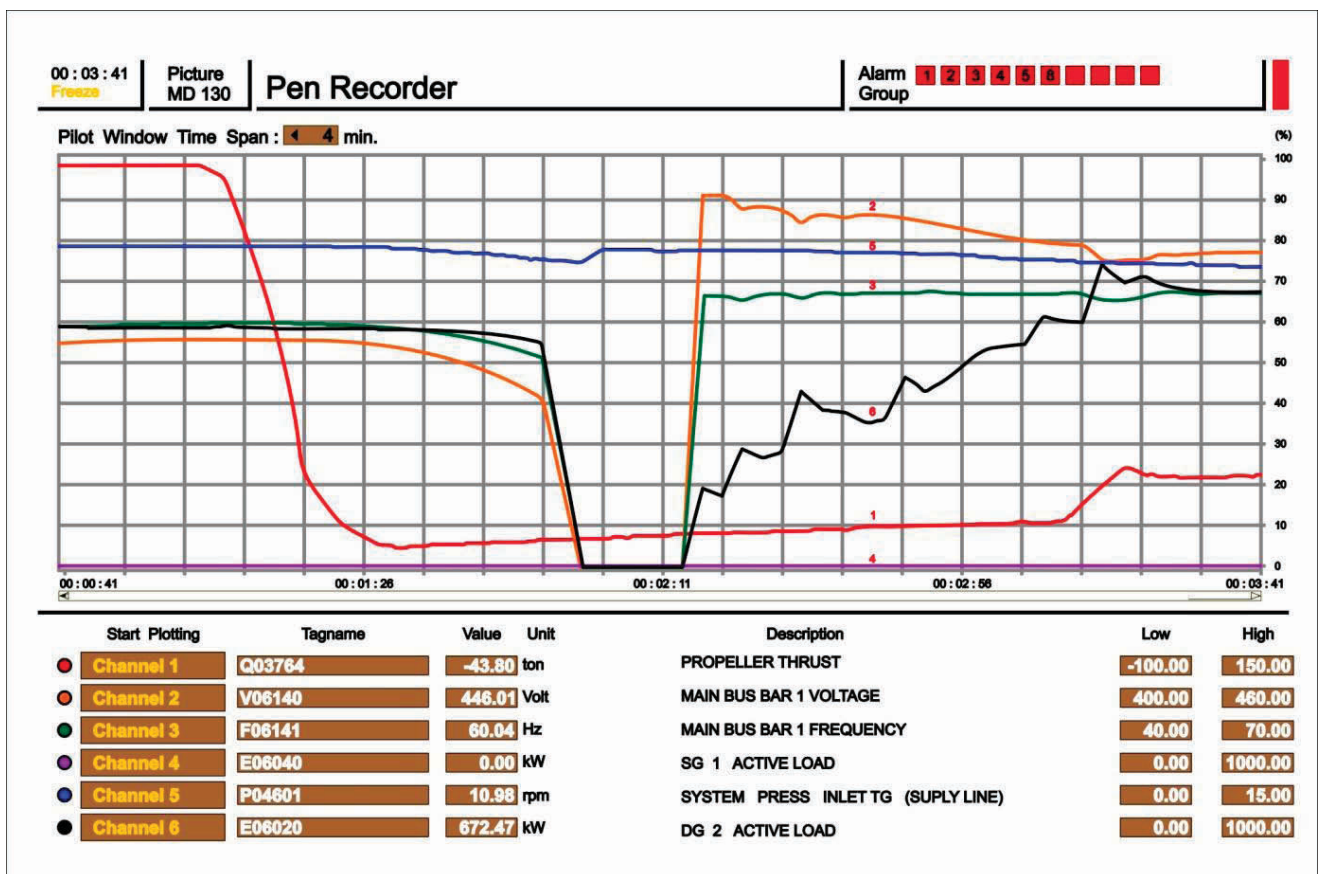
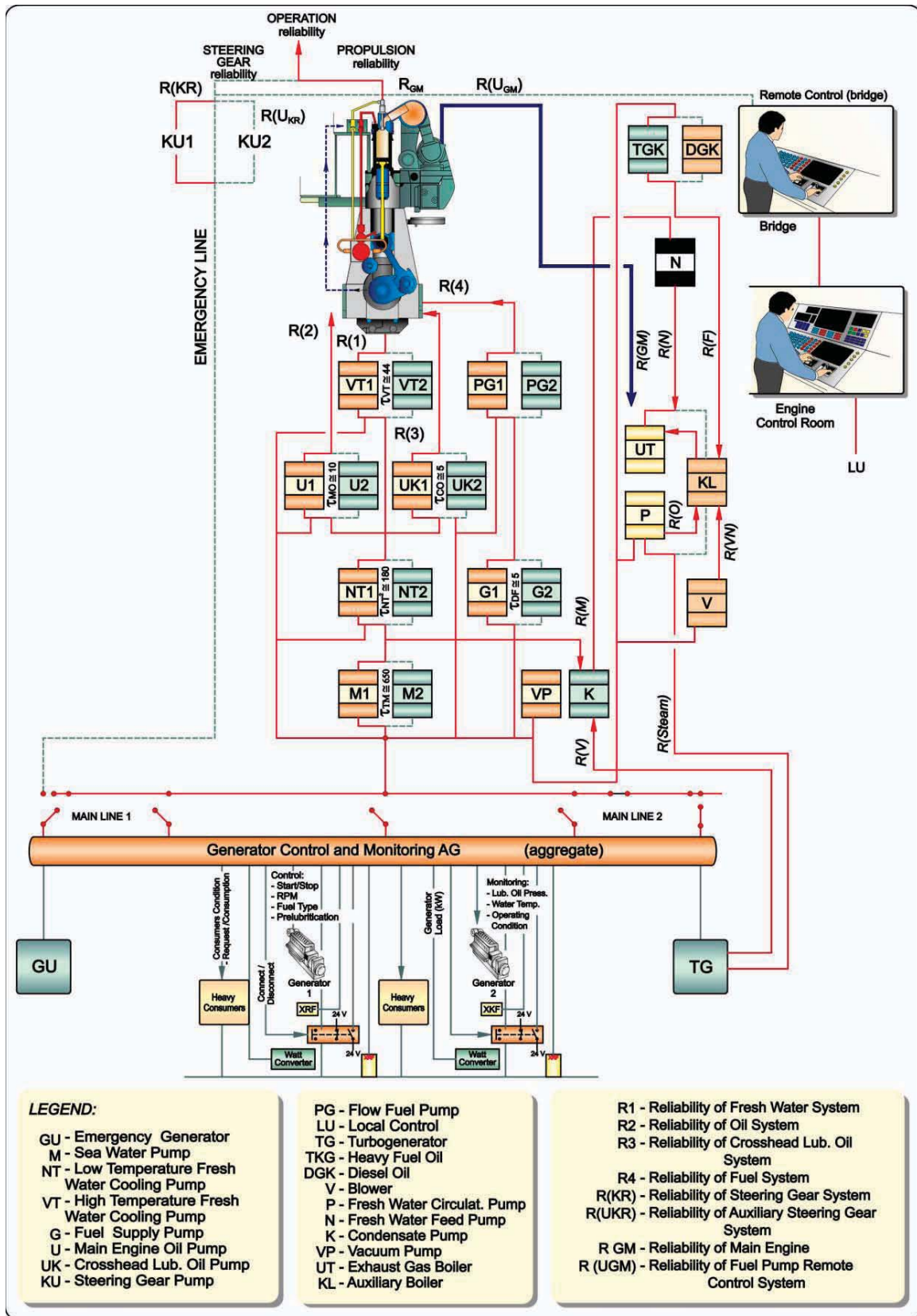


Figure 7 Model of turbogenerator system
Slika 7 Model pogona s turbogeneratorom



a long power-up time. This will manifest in a frequency drop, which will cause the turbogenerator to trip. After 3 seconds, the diesel generator will engage, and after additional 50 seconds it can take over supplying essential consumers.

In case of self-contained turbogenerator (Figure 7), circle of dependence in closed-system diagram passes through the main engine and turbogenerator, over the utilisation boiler and the main engine subsystems.

5 System reliability

Through defined reliability models of specific propulsion systems, it is obvious that reliability of a specific system cannot be a measure of entire ship's reliability, if the ship is seen as a single system. Even so, propulsion reliability [7] is often taken as reliability measure for the whole ship. Ship availability is therefore usually defined in terms of time during which the ship's systems will be available at satisfactory level. As availability represents the probability of function of system as a whole within a certain time, it follows that all subsystems must function as well.

It is possible that a specific component fails [8], and the system keeps functioning, in systems with redundancy of specific components. There are also examples of all components working within parameters, but marginally, which results in a breakdown. These breakdowns are common with electrical equipment.

If reliability is defined as a measure of system's proper function while in exploitation, depending parameter of reliability is time. If the component works periodically, in regular or irregular time intervals, this parameter can be the number of operations, or a combination of number of operations and time. Functioning of a system in most cases depends on two components: random failure or time interval breakdown. Both components work independently from each other, and at least one is necessary for a breakdown. For this research, reliability during navigation is relevant [9].

Reliability during navigation depends on propulsion system reliability, which is in turn dependant on main engine reliability and main engine auxiliaries, including the following systems:

- sea water M ,
- low temperature cooling system NT ,
- high temperature cooling system VT ,
- lube oil system U ,
- crosshead lube oil system UK ,
- fuel oil supply G ,
- fuel oil circulating system PG .

Control and monitoring system of the main engine U_{GM} has three control subsystems:

- local main engine control LU ,
- control room control KB ,
- bridge control KM .

Propulsion reliability additionally depends upon:

- steering gear reliability KU ,
- steering gear remote control reliability UKR ,
- propulsor reliability P .

All systems mentioned depend on the reliability of the generator GEN , or power unit AG . Thus it follows that reliability of diesel generator propulsion R_p is a function of limited systems, i.e.:

$$R_p = f(GEN; AG; M; NT; VT; U; UK; G; PG; U_{GM}; KU; UKR; P), \quad (1)$$

where:

$$R_{thrust} = R(GM) \cdot R(U_{GM}) \cdot R(P), \quad (2)$$

$$R_{steering} = R(U_{KR}) \cdot R(KU). \quad (3)$$

Reliability of main engine $R(GM)$ equals the product of specific subsystem's reliabilities ($R1 \dots R4$), and reliability of the engine components $R(KE)$.

$$R(GM) = R_{(1)} \cdot R_{(2)} \cdot R_{(3)} \cdot R_{(4)} \cdot R(KE). \quad (4)$$

Propulsion reliability equals engine and steering gear reliability:

$$R_p = R_{thrust} \cdot R_{steering} \quad (5)$$

The analysis [3] shows three possible ways of increasing reliability:

1. **Reliability increases with more parallel connections in the system. This means that additional generators increase the reliability of the system, as additional device increases the redundancy of the system. Increased price and additional maintenance are downsides to this model.**
2. **Reliability will increase with the increase in technical quality of system components, which reduces frequency of breakdowns and increases reliability. However, the issue at hand is how to increase quality.**
3. **Reliability will increase with bypassing of certain unnecessary components. Restructuring the system in such a way poses an obstacle to this design.**

After analysing the given possibilities, it is concluded that the first option is the most viable one. However, the necessity for additional investment must be justified.

6 Conclusion

It is evident from the analysis which was carried out on data based on failures and propulsion reliability that marine auxiliary systems and engines are most prone to failure (54 per cent of failure). Therefore, a systematic development of machinery system is necessary for safe operation. The development includes increasing redundancy of particular subsystems and alternative solutions that will enhance overall system reliability. Unforeseen breakdowns of the propulsion system cause complete inability to navigate for a particular period of time. Ship builders and ship owners are trying to reduce that risk by increasing system redundancy, especially when losses and ecological consequences must be avoided at any cost.

The paper has shown that higher reliability of the propulsion system requires greater maintenance and more staff. But it should also be noted, that a more redundant system increases reliability and safety. By comparing the results acquired by modelling redundancy of parallel systems of ships' generators, together with data from databases, it is evident that enhancing reliability leads to increased maintenance effort and decreases maintenance efficiency, especially after increasing redundancy from second to third level. This shows that increased redundancy may have negative impact on the crew, as it requires greater effort and with it a negative impact on the entire machinery complex.

It is certain that ship owners or operators are not likely to hire more staff on account of more maintenance work. This contributes greatly to the answer about the right approach in increasing reliability, and it becomes obvious that adding generators and increasing redundancy is not the right path. Increasing safety and reliability must therefore be done by improving the quality of machinery components, and by defining a new reliable propulsion model.

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