NENE 2022
September 12-15
PORTOROŽ
SLOVENIA
31st International Conference Nuclear Energy for New Europe

RELIABILITY ANALYSES OF EMERGENCY POWER SYSTEMS WITH FOCUS ON MULTI-GROUP DIESEL CONFIGURATIONS

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ABSTRACT / INTRODUCTION

This paper focuses on the reliability analyses of Emergency Diesel Generator (EDG) systems in nuclear power plants and describes possible Multi-Group Diesel (MGD) configurations as a new concept to provide emergency power supply.

In Multi-Group Diesel configuration, several smaller qualified diesel units operate together to replace one large diesel unit. This principal is also used in the industrial sector, especially for higher power ranges.

Further to other technical issues which have to be considered in the general MGD concept and design, the reliability of the system is a very important aspect which has to be investigated.

Reliability analyses are performed as part of the safety demonstration process during the EDG design phase. It is used for overall modernization topics, as well as in new-build projects. The main objective of these analyses is to demonstrate that the reliability targets (the so-called safety goals) imposed on the EDG systems by the customer, regulators, or design authorities are fulfilled. Reliability analyses also aim to identify major contributors that lead to EDG unavailability. Based on this, design improvements are proposed, or even mandatory, to increase the reliability of the EDG design.

One of the main challenges of EDG reliability analyses during licensing is that they are primarily concerned with the reliability assessment of the digital instrumentation and control (I&C) systems, which are nowadays a common part of the EDG control and protection system.

The Framatome methodology uses fault tree modelling to estimate the failure probability of the EDG on demand (unavailability), given by the failure to start or to operate the EDG system. The scope of the analysis includes failures of the EDG as well as their mechanical, electrical, and I&C support systems. The fault tree model includes independent failures and common-cause failures (CCF) of mechanical, electrical and digital I&C components leading to the failure to start or to operate the EDG.

Reliability analyses are considered design guidance for analyzing different MGD configurations from a reliability perspective, with the main objective of maximizing the

reliability of the design. Sensitivity analyses are also conducted to investigate the impact of reliability parameter variations on the Multi-Group Diesel reliability.

The complete paper will therefore describe the reliability analyses of EDG systems in general and then focus on the Multi-Group Diesel configuration, highlighting the increased reliability of this structure and further advantages of the new MGD concept.

1 ADVANTAGES OF MULTI-GROUP DIESEL

Emergency Diesel Generator (EDG) systems at Nuclear Power Plants (NPPs) usually involve large redundant EDG sets. The EDG set consists of the emergency diesel engine delivering the mechanical power and the emergency diesel generator converting the mechanical power into an electrical supply together with the auxiliary systems (e.g. the start air and cooling systems, fuel oil system).

The design capacity of one large EDG set corresponds to the complete emergency power load required in one NPP train, which is typically in the range above 2000 kW up to 10000 kW per diesel aggregate set, depending on the plant design. The design capacity of the EDG system is such that the NPP can be safely shutdown by supplying the essential loads in case of an event of loss of the offsite power (LOOP) using e.g. 2 out of 4 (2oo4) trains, such as in the German NPPs with a "Konvoi" design.

EDG configurations involving MGD operating in parallel are considered to offer a number of installation and operational advantages over a single large EDG set, such as improving the maintainability and the flexibility for possible power expansions. Furthermore, large diesel generator sets are highly complex and require high efforts for integration engineering and erection, very difficult replacement with other brands due to different footprints and time consuming repair activities, requiring extended outages if one large diesel generator set is damaged. In addition, compact EDG sets, as those involved in MGD configurations, have the advantages to require smaller and simpler buildings with the possibility to install complete functional container packages. The more compact EDG sets allow also more innovative concepts than the conservative design which is suitable for new requirements like fuel efficiency or Bio Diesel. These are the reasons why this configuration has been promoted for many industrial solutions for high power ranges.

For nuclear (safety) applications, the most important criterion is the reliability. MGD configurations can involve backup sets, which are able to replace failed sets within the configuration. In order to ensure an improvement of the MGD reliability respect to the single large set, a detailed investigation is presented in this paper.

2 RELIABILITY ANALYSIS OF MULTI-DIESEL CONFIGURATIONS

The reliability impact of replacing a large EDG set with smaller parallel sets is estimated using fault trees.

The unavailability (failure probability on demand) of one EDG set occurs if:

- The EDG set fails to start or;
- The EDG set fails to operate within a certain mission time.

The failure of the EDG to start can be caused by: a) undetected failures occurring before the demand and remaining latent during the standby period, or b) due to failures caused by the demand. The probability of failure to operate is a conditional probability given that the EDG set started successfully.

The possibility of repairing an EDG set after it fails to operate within the mission time is considered in the fault tree model if the mission time is long enough. Repair activities are only considered for backup sets after failing to operate. These are unavailable during the repair time (mean time to repair, MTTR) and can only affect the system reliability if additional sets fail to operate during the mission time.

The following assumptions are considered in the reliability analysis:

- A large EDG set supplying approx. 6000 kW is considered for the analysis (based on the German Konvoi design).
- The MGD configuration involves small EDG sets connected in parallel, providing at least the same power load supplied by the large EDG set.
- Configurations involving safety concepts with N sets with one (N+1) and two backup sets (N+2) operating in parallel are considered for the replacement of a single large EDG set.
- It is assumed that backup sets can replace any failed EDG connected in parallel.
- A MTTR of 12h is assumed to repair small EDG sets. The possibility to repair a small EDG set is considered for mission times of 24h or longer.
- A periodical test interval of one month is assumed for each EDG train with a staggered testing scheme between trains. For MGD configurations it is assumed that all small sets within one train are tested simultaneously once a month (non-staggered scheme within one train).

The following mission time (TM) scenarios are considered to be interesting for the analysis in nuclear applications [1]:

- Short-term LOOP with a duration of 2 hours (no repair activities are considered)
- Medium-term LOOP with a duration of 24 hours
- Long-term LOOP with a duration of 7 days (168 hours).

Longer mission times (up to 500 h) are also considered to account for the analysis of beyond-design scenarios.

3 COMPONENT RELIABILITY DATA

Component failure data used for EDG reliability analyses are typically estimated with the Bayes method based on the operating experience with such equipment in the nuclear field. Component failure data are followed up and reported in component reliability databases, such as NUREG CR-6928 for US, the T-Book for northern Europe or the Centralized Reliability Database ZEDB for German NPPs [2].

The failure rates for the failure to start/operate of the EDG sets are taken from the ZEDB, based on operating experience of German nuclear power plants collected from 1976 to 2013 [2]. These failure rates consider failures of the main components (engine and generator) and also failures of the supporting systems required to guarantee the EDG set start and operation (avoiding excessive wearing), as well as failures of the electrical and control components. The ZEDB provides failure rates for EDGs distinguishing between two power-rated groups (the so called “collectives”):

- Group 1: EDG sets with a rated power from 320 kW to 1740 kW and;

- Group 2: EDG sets with a rated power from 2682 kW to 7300 kW.

Table 1 lists the failure rates estimated in the ZEDB database for these two EDG groups.

Table 1: Generic failure rates of EDG sets [2]

EDG collective groups (rated power, kW)	Failure to start (1/h)	Failure to run (1/h)
320 – 1740	4.04E-06	8.41E-04
2682 – 7300	8.60E-06	2.49E-03

The reliability data of the EDG group involving the largest electrical rated power (above 2682 kW) is considered for the large single EDG set. The small EDG sets are assigned the reliability data of the collective group involving a rated power below 1740 kW.

Common Cause Failures (CCF) are modelled in the fault trees for configurations involving redundant EDG sets using the Alpha Factor Model. The CCF Alpha parameters for the failure to start and to operate are taken from NUREG/CR-5497 [3].

4 RELIABILITY OF MGD CONFIGURATIONS: ONE TRAIN

This section analyses the impact of replacing one large single EDG set within one train by a set of smaller sets operating in parallel with and without backup equipment. Figure 1 compares the unavailability of the N=1, N+1 and N+2 configurations. As expected, the higher the number of paralleled sets to provide the load, the lower the availability of the configuration.

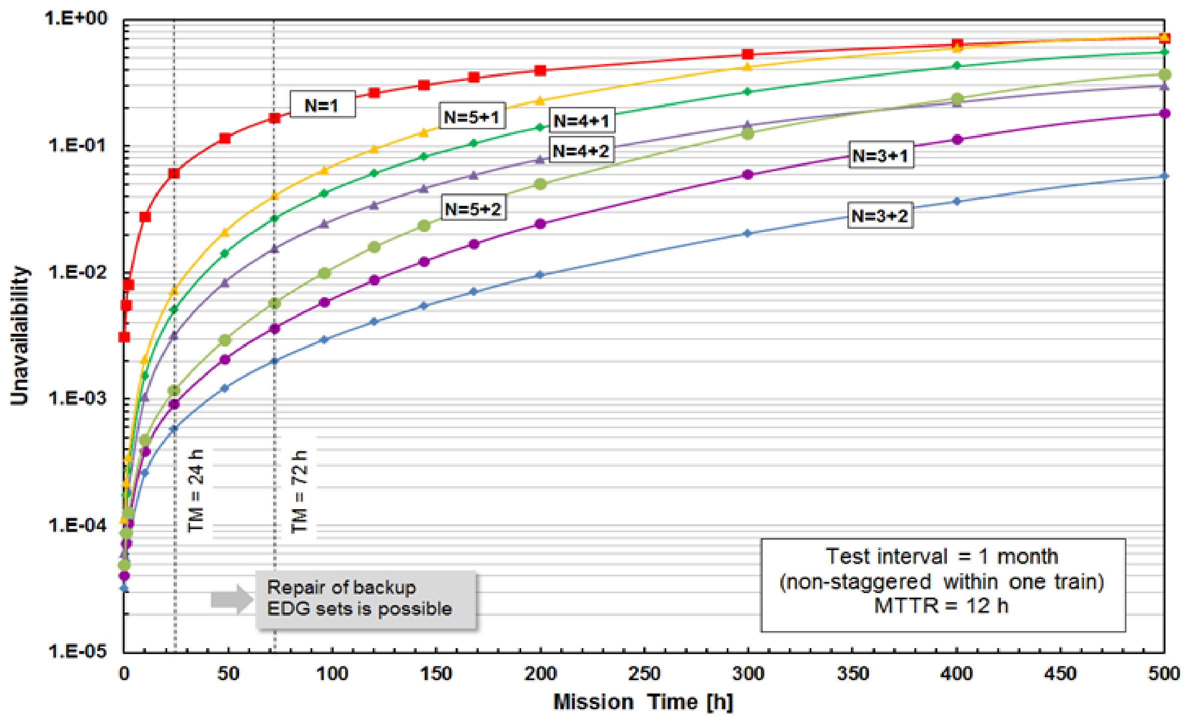

Figure 1: Unavailability of N, N+1 and N+2 configurations as a function of the mission time (one train)

For example, for a required load of approx. 6000 kW the configuration involving 3+1 small sets (each one providing approx. 2000 kW) should be favoured over a configuration with N=4+1 sets (each one providing approx. 1500 kW). For configurations with the same number of sets, the one including two backup sets (e.g. N=3+2) has a higher availability as the one including one backup set (e.g. N=3+1).

Figure 2 shows the sensitivity analysis results for one EDG train for different values of the MTTR considered to repair the failed backup sets. Proceeding with the example of the required 6000 kW and 2000 kW per generator set, Figure 2 shows the N=1, the N=3+1 and N=3+2 configurations.

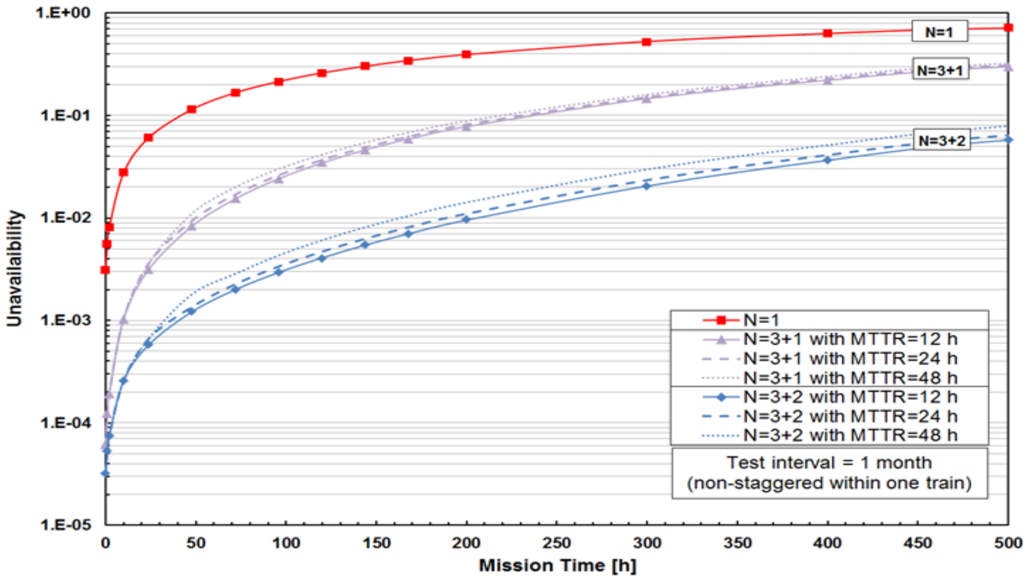

Figure 2: Sensitivity analyses for different MTTR values for the N+1 and N+2 configurations as a function of the mission time (one train)

Note that the reliability results of the N=3+1 configuration are rather insensible to an increase of the MTTR value for the EDG sets. For the N=3+2 configuration the unavailability slightly increases with the increasing MTTR values. The small influence of the increased MTTR values can be justified by the fact that failures of the backup sets are not the most important contributors to the unavailability of the different configurations. The reliability results are dominated by combination of EDG sets failing within the mission time.

5 RELIABILITY OF MGD CONFIGURATIONS: FOUR TRAINS

This section analyses the reliability impact when one large set in each of four trains of the EDG system is replaced by N+1 or N+2 multi-group configurations. The success criterion for the emergency power supply out of the four trains is assumed to be 2oo4, i.e. at least two trains are required to operate during the mission time.

For the configuration involving the small paralleled EDG sets, CCF are modelled for EDG sets within one train (all sets are tested simultaneously once a month) and also between the trains (staggered periodic testing strategy). For mission times longer than 24h repair activities of backup sets are considered.

Figure 3 shows the unavailability of at least three (>3oo4) trains for the configurations involving one single EDG set (shown as N=1 in Figure 3), N+1 and N+2 configurations for N=3, N=4 and N=5 in each train as a function of the mission time.

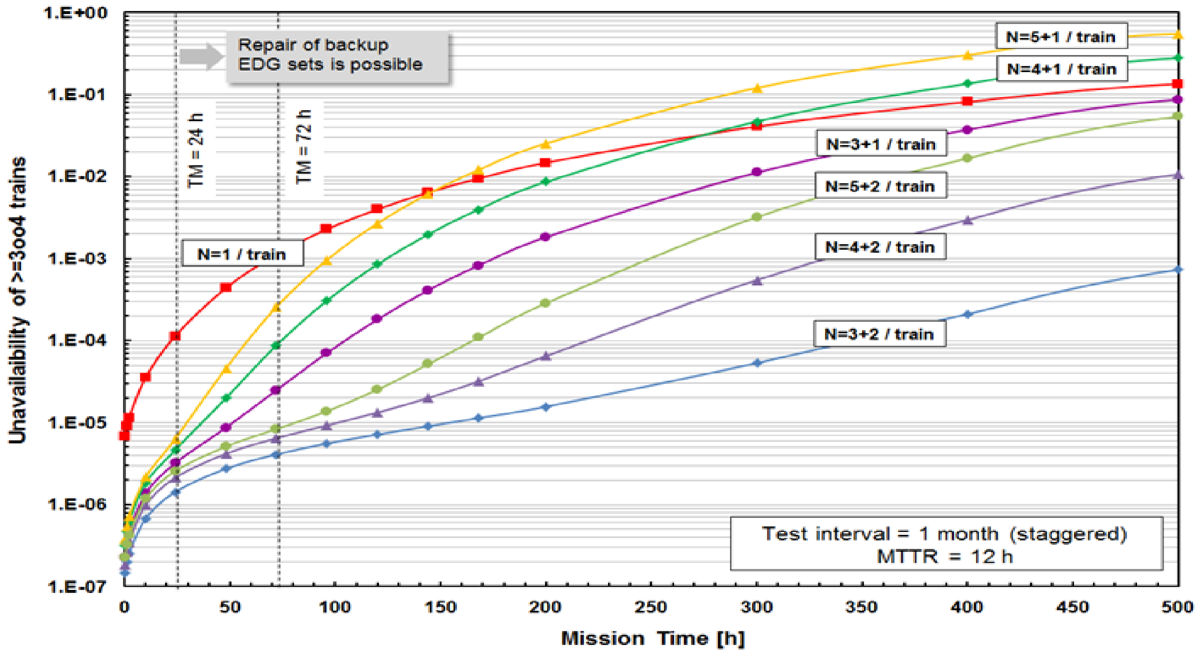

Figure 3: Unavailability of >=3oo4 trains for the configurations with N=1, N+1 and N+2 EDG sets

The system with the N=3+2 configuration in each train is the one involving the highest availability. The unavailability of the configurations involving two backup sets (N+2) in each train increases smoothly with the increasing mission time (see Figure 3). On the other hand, the unavailability of the configurations with only one backup set (N+1) in each train is much more sensible to the increasing mission time.

The system with N+2 sets in each train are unavailable if three trains fail. Each train fails if three EDG sets fail, i.e. combinations of nine failed EDG sets lead to the failure of > 3oo4 trains. The system with N+1 EDG sets/train are also unavailable if three trains fail, but each train fails if two EDG sets fail. This means, combinations of six failed EDG sets lead to the failure of > 3oo4 trains. According to this, the system with N+2 sets/train requires a larger number of failures (9) than the N+1 configuration/train (6) to be unavailable.

The results of the N+2 configuration are dominated by CCF failures, which have a higher probability than the combination of nine failed sets (three in each train), even for long mission times. The results of the N+1 configuration are dominated by combinations of six failed sets (two in each train), which have a higher probability than the CCF failures, especially for long mission times.

Finally, the availability improvement obtained by replacing one single large EDG by the multi-diesel configurations is shown in Figure 4.

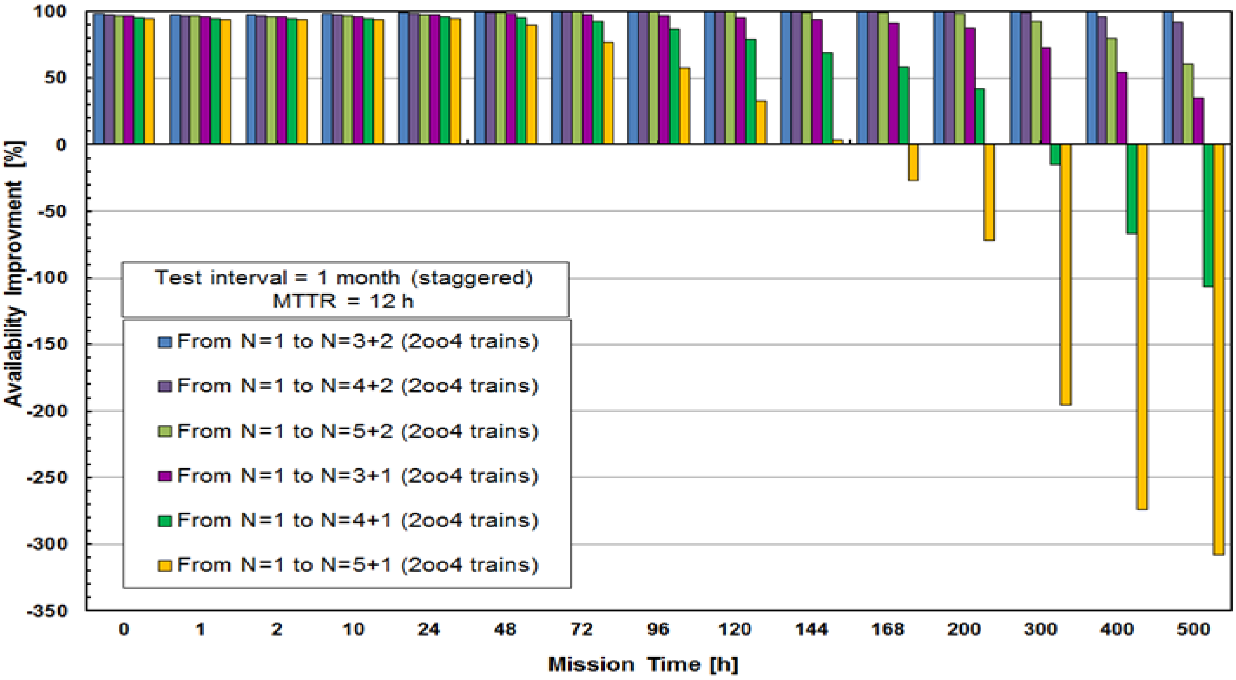

Figure 4: Availability improvement by replacing one single EDG set by N+1 and N+2 multi-group configurations in each of the 2oo4-trains

Note that for the N=3+1 and N=3+2 configurations in each train the availability of the 2oo4 system is improved more than 80% for relevant mission times in nuclear applications (approx. below 200h).

For the N=4+1 configuration an improvement of approx. 80% is obtained for mission times up to 120h. For longer mission times the improvement decreases rapidly given the dominance of the combination of sets which fail to operate. For a mission time of 200h an availability improvement of approx. 40% with respect to the single large EDG set can be achieved. For mission times longer than 200h, the system with single sets in each has a larger availability than the multi-diesel configuration. If one backup set is additionally added in each train, i.e. N=4+2, the availability is greatly improved (see Figure 4). Concluding, the system with four trains and a success criterion of 2oo4 with multi-diesel configurations N+1 and N+2 with N=3 and N=4 in each train has higher availabilities than with single large EDG set in each train for mission time relevant in nuclear applications (approx. up to 200h).

6 CONCLUSIONS AND OUTLOOK

This paper summarized the MGD configuration and analysed the impact of replacing one large, single EDG by smaller EDG sets operating in parallel with and without backup equipment.

The reliability analysis performed for a single train and for a 2oo4 EDG system concluded that a multi-diesel configuration for the replacement of one large EDG set should involve:

- The minimum possible amount of EDG sets in each train needed to provide the required output load, and;

- At least one backup set in each train, otherwise the system availability is downgraded by the replacement. Two backup sets are recommended from the reliability point of view. These backup sets can be integrated easily within the MGD configuration.

If at least one backup set is involved in the configuration, the availability of the system is greatly upgraded after the replacement of the single EDG set. The more backup sets involved in the multi-diesel configuration, the higher the availability of the configuration. Backup sets add redundancy into the system and allow for repairing activities, especially for the long missions, without affecting the system availability.

As analysed for single EDG trains, an increase in the MTTR values for backup sets, does not influence the reliability results significantly.

The selection of a multi-diesel configuration also depends on the cost trade-offs (e.g. investment, maintenance, periodic testing), which have to be considered in the configuration selection alongside reliability.

Furthermore, in addition to the increased reliability, the MGD has several advantages for the plant itself. The installation on site is simplified as the main auxiliaries are mounted on the genset and are not installed on different parts of the building.

The maintenance can be planned more effectively during the complete lifetime of the equipment. Therefore, instances of one emergency power train being unavailable can be almost completely avoided. While EDGs are usually conservatively sized, the MGD consumption during test and emergency runs would be more efficient, as e.g. one genset can be shut off when not required. Additionally, there is also no danger in damaging the equipment while running in low load for an extended period of time.

The concept of the MGDs can be extended for more efficiency while e.g. using a qualified common rail controller on the generator set itself. As the Multi-Group Diesel concept is independent from the plant type, there is no limit in the general use of this configuration!

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