The forecast model for estimating the probability of failure at starting emergency diesel generators of nuclear power plants

R Z Aminov
Saratov Scientific Center of the Russian Academy of Sciences, 24 Rabochaya str., Saratov, 410028, Russian Federation
E-mail: oepran@inbox.ru

Abstract. The main factors that can influence the probable failure of emergency startup of diesel generators at nuclear power plants are analyzed. These factors are defined as general indicators of the state of equipment and service systems, as well as extreme modes for performing basic functions in the case of emergency blackout. A forecast model for estimating the probability of the startup failure of diesel generators at nuclear power plants in emergency blackouts is developed. The proposed model allows for taking into account the main impact factors and can be improved in the process of accumulation of reliability statistics. An example of calculating the probability of startup failures of diesel generators for the determined baseline conditions.

Emergency blackouts at NPPs lead to the need to creating reserve residual heat removal systems of nuclear reactors. Currently these reserve systems are created in the form of 3–4 independent safety channels with installation of a diesel generator in each reactor. Additionally, in case of complete failure at the startup of the main safety channels, the station emergency diesel generator is provided. These reserve systems remain in the waiting mode. Emergency situations with complete NPP blackouts are rare, but failure to perform the residual heat release functions by the shutdown reactor will lead depressurization and melting of the core of the reactor. Under these conditions, there are strict requirements for reliability of these reserve safety systems, and primarily to successful startup of diesel generators.

Consumers of NPP auxiliaries are divided into 4 groups related with the demands for power supply interruption:

– the first group does not allow a break for more than a fraction of a second. These are the control and protection system drives; control and measurement devices and automation; and emergency lighting.
– the second group allows for interruptions of power supply for tens of seconds. These include the mechanisms of reactor cooling;
– the third group allows for breaks during the automatic reserve entry operation;
– the fourth group includes other consumers having no special requirements for the power supply.

Safe cooling of the reactor is ensured by the work of the first and second groups. The first group also includes a DC network, for which a backup emergency power is provided from the batteries. In this case, within 20-45 seconds, the diesel generator used to power the consumers of the first and second groups must be started.

Probability of a reliable start of the emergency safety channel $P_{SC}$ is determined by the probability of the automatic start control system triggering $P_{cont.sys}$, the probability of starting the diesel generator
$P_{DG}$ and the reliability of starting the actuators of the channel $P_{act}$. In the structural scheme of reliability, all these elements are arranged sequentially, when a complete failure of at least one of them leads to the failure of the entire system.

$$P_{SC} = P_{cont.sys} \cdot P_{DG} \cdot P_{act}. \quad (1)$$

A research into reliability properties of such systems is based on many factors and is a rather sophisticated problem. The results of this research should be aimed both at a theoretical study of the possible states of backup equipment in extreme situations when the initial emergency event occurs, and the accumulation of statistical material on equipment failures.

If we consider that reliability of the automatic start-up system is quite high, and the system of executive mechanisms has additional internal reserves by their number, then the diesel generator generates the dominant influence on the reliability of the entire system, and the study of its reliability is of the greatest interest. This is due to little-studied properties of the elements and equipment used in the standby mode, as well as the insufficiency of the necessary statistical material.

Being in long-term reserve, equipment is aging, and the properties of rubber products, plastics, polymers deteriorate. The corrosive processes are observed under the influence of moisture and aggressive components, which leads to the accumulation of hidden defects and failures. The presence of hidden defects can be detected at the startup procedure under preventive testing, or at the onset of the initial event [1].

Reliability of the emergency power supply system is largely determined both by the technical state of diesel generators, their loading modes, and the servicing systems of automation, fuel and oil supply. Moreover, the working capacity of diesel generators depends on the quality of maintenance, repair and recovery works, frequency of inspections and testing, approximation degree of the starting test modes to the actual operating conditions in case of emergency.

According to statistics, about half of all faults and failures of diesel engines are caused by fuel quality. The storage conditions of diesel fuel may affect the reduction of its quality. Here are the most important factors affecting the reduction of fuel quality: contact with copper and zinc, contact with air, exposure to elevated ambient temperatures (starting from 20°C), general contamination of tanks, presence of additives in fuel that accelerate the decomposition of diesel fuel. With the introduction of European norms, the sulfur content of diesel fuel decreased, which led to an increase in the activity of microorganisms. All these features lead to the fact that all petroleum fuels start to darken and split over time as a result of evaporation of light fractions and oxidation of heavy fractions. The dark heavy fraction of diesel fuel cannot be utilized, since in this case, black smoke is generated and the engine may fail to start.

At the temperatures of +20÷25°C, during the storage of diesel fuel a suspension of solid particles is formed and the fuel becomes turbid due to reaction of individual components with oxygen. The resulting mixture can lead to filter clogging and engine shutdown.

Thus, the impact of air, water, heat and light is a key point leading to deterioration of fuel quality during its storage.

The presence of water in diesel fuel promotes an active growth of bacteria, which leads to accumulation of dirt. The presence of various additives in the fuel leads to their disintegration starting after a short time span.

Thus, even if all the storage rules are observed, the diesel fuel retains its service-life properties only for one year. After this period, the fuel must be replaced by a new one, and the old diesel fuel must be disposed of.

Reliability of starting a diesel generator depends on the starting mode. Regulated start-up time in the event of an emergency should not exceed 15 seconds, followed by the connection of asynchronous motors actuators channel. The total loading time of the backup safety channel is 20–45 seconds.

Note that for squirrel-cage motors, the ratio of the starting current to the rated current can reach 7, and its inclusion is accompanied by a shock load on the diesel generator, with a short-time increase in the current in the generator circuit to 100–200% of the nominal for the generator. The short duration of
starting the diesel generator due to significant temperature and mechanical stresses affects the reliability of the start negatively [2]. There are a number of concomitant factors that may affect the reliability of the launch [3]. In particular, the nominal oil flow rate is set with a certain delay in comparison with the speed of rotation. In addition, the inertia of the supercharging system does not allow to ensure the required air flow and the complete combustion of the fuel. The low temperature of the surfaces of the cylinders and pistons leads to the condensation of the chemically active components from the combustion products, which activate corrosive processes. According to the data of [3] out of 100 consecutive commands for launch under these conditions, only one failure is permissible.

Another important factor in predicting the reliability of diesel generators start is the essential difference between the control check-ups from the extreme modes that occur in an emergency with de-energizing. It is rather difficult to reproduce these conditions for technical reasons and therefore this is not carried out in practice.

The diesel generator testing start-ups at nuclear power plants are carried out monthly with a duration of work of at least 30 minutes under a load of 50% and up to 30 minutes with idling.

In foreign practice, a certain statistics of failures at start of diesel generators has been accumulated and a technique for calculating reliability based on the empirical Bayesian estimate has been proposed [4]. In [5, 6] describe algorithms and applications to failure data of diesel generators. The failure statistics at start for 195 diesel generators at 63 nuclear power plants in the USA for 4 years of operation from 1988 to 1991 are given [7]. The average probability of failure at startup was 5.0·10⁻³ and failure to load-run – 9.6·10⁻³ [4]. In these studies, the assessment of the influence of various factors and conditions for the use of diesel engines is practically absent.

Taking into account the presence of a large number of important factors that can have a direct impact on the reliability of starting a diesel generator under extreme conditions and the absence of detailed information and statistics on these issues, the task is to build a forecast model for estimating the probability of failure of diesel generators of nuclear power plants when starting them in emergency situations with de-energizing. Such a model should embody the above-mentioned peculiarities of using reserve diesel generators at NPPs and allow it to be adjusted as the statistical data on failures accumulate.

The performed scientific researches made it possible to obtain the following dependence for determining the probability of failure when starting the diesel generator, depending on the status of the reserve system and the starting regimes

\[
q_{DG} = 1 - P_{DG} = \exp \left( - \frac{\varphi \cdot K_{\text{life}}^{m}}{K_{\text{start}}^{m} \cdot K_{\text{shock}}} \right). \tag{2}
\]

Here: \( \varphi, n, m \) are the coefficients of reliability indicators, determined on the basis of statistical data on failures;

\( K_{\text{life}} \) is the coefficient of residual life (\( K_{\text{life}} = 0 \div 1 \));

\( K_{\text{start}} \) is the coefficient determined by the speed of the set of loads in the starting mode (\( K_{\text{start}} \geq 1 \));

\( K_{\text{shock}} \) is the coefficient of shock load when connecting asynchronous motors in the generator circuit (\( K_{\text{shock}} \geq 1 \)).

In this case

\[
K_{\text{start}} = \frac{\tau_{0}}{\tau}, \tag{3}
\]

where \( \tau \) is the time of full load acceptance in the real mode of starting and loading the diesel generator, seconds;

\( \tau_{0} \) is the normative time recommended by the manufacturer for taking full load, seconds.

\[
K_{\text{shock}} = \frac{J}{J_{0}}, \tag{4}
\]

where \( J \) is the maximum short-term shock current load of the generator when connecting consumers with asynchronous electric motors, A;

\( J_{0} \) is rated current load of the generator, A.
In formula (2) with $K_{\text{life}} \to 0$, the probability of failure when starting the diesel generator $q_{\text{DG}} \to 1$.

As an experiment, calculations were performed for $q_{\text{DG}}$ for the following conditions: $\phi = 5$, $n = 0.125$, $m = 0.25$. The results of the calculation are shown in figure 1, which shows that with the growth $K_{\text{start}}$ and $K_{\text{shock}}$, the probability of failure when starting the diesel generator also increases. To the same result leads to a decrease in the residual life $K_{\text{life}}$.

![Figure 1](image_url)

Figure 1. Probability of failure at startup $q_{\text{DG}}$: 1 is dependence on $K_{\text{life}}$ at $K_{\text{start}} = K_{\text{shock}} = 1$; 2 is dependence on $K_{\text{start}}$ at $K_{\text{life}} = 0.5$, $K_{\text{shock}} = 1$; 3 is dependence on $K_{\text{shock}}$ $K_{\text{life}} = 0.5$, $K_{\text{start}} = 1$.

In the future, with the accumulation of statistics on failures, the coefficients $\phi$, $n$ and $m$ will be precised.

Conclusions
1. Conceptual bases for calculating specific conditions for the use of reserve diesel generators of nuclear power plants in an emergency situation with de-energization have been developed. These conditions are determined by: general indicators of the state of equipment and servicing systems; resource indices and extreme modes of performing basic functions when the initial event occurs.
2. Forecast model for estimating the probability of failure when launching backup diesel generators of nuclear power plants in an emergency with de-energization is developed. The proposed model allows to take into account the main factors affecting the reliability of the launch and can be corrected as the statistical data on failures accumulate.

Acknowledgments
The reported study was funded by RFBR according to the research project No 18-08-00111 A

References
[1] Ostrejkovskii V A and Shviryaev Yu V 2008 Safety of nuclear power plants. Probabilistic analysis (Moscow: Fizmatlit) p 352
[2] Tokmachev G V 1990 Requirements for emergency power systems for nuclear power plants based on diesel generators *Energy construction* **3** 67–9

[3] Šaban J and Zaharija-Tiska D, Sirbuncej Z 1988 Large diesel generators for nuclear power stations and processing industry *Končar journal* **1** 41–7

[4] Samanta P, Kim I, Uryasev S, Penoyar J and Vesely W 1994 *Emergency diesel generator: maintenance and failure unavailability, and their risk impacts* №NUREG/CR–5994 Nuclear Regulatory Commission p 215

[5] Martz H F and Lian M G 1974 Empirical Bayes Estimator of the Binomial Parameter *Biometrika* **61** 517–23

[6] Copas J B 1972 Empirical Bayes Methods and the Repeated Use of a Standard *Biometrika* **59** 349–60

[7] Letter from Alex Marion NUMARC to H. Lewis, ACRS, Industry-Wide Data on Emergency Diesel Generator Performance March 5, 1992