Diesel generator system reliability control and testing interval optimization

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The aim of the current work was to investigate the possibility to change and optimize the testing intervals of the Emergency Diesel Generators System (EDGS) at the Ignalina Nuclear Power Plant (NPP) in such a way that the safety level of the Ignalina NPP would not be decreased. The investigation of EDGS was performed applying the conservative measures related to system reliability. In order to estimate and minimize the reliability data uncertainty, the Bayesian updating approach was also investigated. As these measures and failure data are mainly related to EDGS unavailability, the system unavailability model has been developed and used for testing interval optimization.

The approach, models and the obtained results can be used in the framework of the living probabilistic safety analysis and reliability data updating in order to minimize data uncertainty. Analysis of the results showed that the interval of testing the EDGS at the Ignalina NPP could be increased up to two months, as the average unavailability changes insignificantly and doesn't exceed the acceptable limit.

Key words: unavailability, diesel generators, testing interval optimization, reliability data

1. INTRODUCTION

Diesel Generators (DGs) are usually tested periodically in order to check their condition. In view of their importance, the reliability of DGs must be very high. Since these DGs are standby equipment and operate only on demand or during surveillance tests, their demand failure probability should be very low, and once they operate their operational unavailability should be also very low. However, the testing frequency is chosen mainly by engineering judgment and according to general practices. Having the reliability data, the mathematical modeling can be used to support the decisions related to the testing interval and system redundancy.

The Diesel Generators System of the Ignalina NPP is one of the most redundant EDGS at any NPP in the world. However, the testing frequency is not considered in relation to EDGS redundancy, availability and system reliability data. One month testing interval for EDGS is used at present at the Ignalina NPP [1]. Besides, the decision-making concerning the testing of EDGS is not based on actual statistical data of failures.

In order to prevent the occurrence of failure at an actual demand, the latent and other faults are detected and eliminated on tests. On the other side, too frequent testing may degrade the equipment and cause failures. Through a proper choice of testing interval, the negative and positive effects of testing can be balanced against each other.

2. UNAVAILABILITY MODEL

Reliability analysis focuses on the ability of a system to continue performing its mission without interruptions or failures. Availability analysis (*e.g.*, [2]) focuses on ability to perform a mission at a particular period of time (considering issues such as local equipment failures, testing, maintenance, etc.).

Availability at some point of time t (instantaneous availability) is the probability that a system or component is in operation at the time t. This can be the result of no failure up to time t (*i.e.* reliability) or the combined effect of no failure (reliability) and repair (*i.e.* maintainability). Unavailability is the complement of Availability, *i.e.* the probability that an item does not function when required.

Availability $A(t)$ is the probability that a system is operating at time t, while Reliability $R(t)$ is the probability that the system has been operating from time 0 to t. If we deal with a single unit with no repair capability, then, by definition, $R(t) = A(t)$. If repair is allowed, the reliability does not change but $A(t)$becomes greater than $R(t)$. Periodic testing cannot affect reliability, but does affect availability and at the same time unavailability.

In general, the reliability of stand-by systems is related to the unavailability mean, which is established by assessing the probability that a system cannot perform the designated functions in the case of random demand. EDGS unavailability is mostly influenced by the failure rate and their types. EDGS and other systems at stand-by failures generally are divided into two main types (*e.g.*, [3]): monitored (observed) failures and latent failures, which are also called hidden failures. In addition, according to the safety features, there are critical and non-critical failures (Table 1).

Table 1. **Failure modes of stand-by component**

Occurrence type	**Effect**	
	Prevents the operation	**Does not prevent the operation**
Monitored	Monitored Critical - MC	Monitored Non-critical – MN
Latent	Latent Critical - LC	Latent Non-critical – LN

Unavailability due to critical and non-critical failures unobserved during maintenance is related to the maintenance time, while the latent critical failures influence the unavailability both due to their maintenance and undetected occurrence. When a critical failure occurs, the system cannot perform some of the designated functions until the time when this failure is found, *i.e.* until the testing.

The mean total unavailability can be expressed by a function that depends on the testing interval of length T (period between tests). In general, it is a sum of three components related to the impact of different types of failures, and one component, which defines testing time impact:

$$Q(T) = Q_{LC}(T) + Q_{MC} + Q_{NC} + Q_{TS}(T). \quad (1)$$

The latent critical faults contribute to the expected unavailability during stand-by time, but the operator does not know their presence until the next test or demand. The mean total latent critical failure unavailability, taking into account the impact of the average idle time a_{LC} formed due to the maintenance, is expressed by the formula:

$$Q_{LC} = \frac{1}{T}\int_0^T u(t)dt + \frac{u(T)a_{LC}}{T}. \quad (2)$$

The function $u(t)$ is an instant latent critical failure unavailability. For system modeling it is assumed that all observed failures occur at a constant rate λ_{MC}. The average critical failure unavailability, taking into account the impact of the average idle time a_{MC} formed due to the maintenance, is expressed by the formula:

$$Q_{MC} = \lambda_{MC}\, a_{MC}. \quad (3)$$

If the non-critical failure occurrence rate is λ_{NC} and the average idle time of maintenance is a_{NC}, then the expression for those failures impacting on the unavailability is

$$Q_{NC} = \lambda_{NC}\, a_{NC}. \quad (4)$$

Testing duration impact on the unavailability is defined by the formula:

$$Q_{TS} = \frac{\tau}{T}E, \quad (5)$$

where τ is testing duration, while E is an estimated probability that the system functioning demand will not be fulfilled during the testing.

If during testing the system demand is found and is automatically turned into the normal functioning mode, then the effect of testing duration on the unavailability becomes practically insignificant ($E = 0$). In other extreme cases, when the system during testing was absolutely disconnected, $E = 1$ and the impact of system testing duration was maximum.

Seeking to optimise the DG testing interval T, the mean DG unavailability was analysed. The earlier analysed mean unavailability function $Q(T)$ is expressed as a sum of three terms which describe the impact of different failures and testing duration as follows:

$$Q(T) = \frac{1}{T}\int_0^T u(t)dt + \frac{u(T)a_{LC}}{T} +$$

$$+ (\lambda_{MC}a_{MC}) + (\lambda_{NC}a_{NC}) + (\frac{\tau}{T}E). \quad (6)$$

One of the main parts influencing the unavailability variation, which depends on the testing interval, is related to latent critical failures. The main feature of latent failures is that their existence is unknown until the system is in a stand-by mode.

These failures usually are described by probability, called instant unavailability. Typically, the simplified model is used for the calculation of instant unavailability $u(t)$:

$$u(t) = q + \lambda t, \tag{7}$$

where q is the time-independent unavailability term, λ is the failure rate (depending on time), and t is the time after the previous test or demand.

In the application under consideration, a more precise model was employed, where the failure distribution itself but not its linear approximation was used. In this case the expression of instant unavailability is

$$U(t) = q + (1 - q)(1 - e^{-\lambda t}). \tag{8}$$

The time-independent unavailability parameter q reflects the failures that occur during the testing and are not observed until the next testing or demand, and the failures whose failure mechanism is related to the testing or system functioning and is not manifested in the stand-by mode.

The unavailability part q_{LC}, which is influenced by latent critical failures, does not depend on time. This part is calculated by dividing the number of latent critical failures observed during the testing by the number of testing. The failure rate λ (partly depending on time) for the corresponding types is obtained by calculating the relation between the number of failures during the testing and duration when these failures occurred. The mean idle time a, which as a actually occurs due to maintenance, is calculated by dividing the total maintenance time by a corresponding number of failures.

The minimum of testing interval for one diesel generator is obtained by solving the equation:

$$\frac{d}{dz} Q(z) = 0\,. \tag{9}$$

3. DATA RELIABILITY STUDIES

EDGS functionality at the Ignalina NPP is controlled by the procedures of three types: testing, technical service and preventive maintenance, the frequency of which is one in a month (TO-1), a year (TO-2) and in five years (TO-3).

Like other systems important for safety, EDGS should have a high reliability. On the one side this reliability is guaranteed by DG construction and technical parameters (*e.g.*, a guaranteed operational period is 30 years) and on the other side by testing, when EDGS is checked, the defects are identified and eliminated. During TO-1 every diesel is started and run for approximately one hour.

EDGS reliability to some extent can be ensured by changing the length of the testing interval, however, it is clear that on the one hand testing increases EDGS reliability, while on the other hand frequent diesel start-up increases EDGS ageing. In addition, the EDGS cannot perform all designated functions during the tests.

From 1998 up to 2002, as an example, there were registered 134 failures of DGs at the Ignalina NPP. During that time there were 85 critical failures. The maintenance took 4548 hours. The amount of critical failures and maintenance time for separate DG during the period 1998–2001 are presented in Table 2.

Table 2. **Critical failures (CF) and corresponding maintenance hours**

DG number	**1**	**2**	**3**	**4**	**5**	**6**
Number of CF	9	13	2	7	14	2
Maintenance hours	316	712	10	364	1126	48
DG number	**7**	**8**	**9**	**10**	**11**	**12**
Number of CF	7	2	4	8	8	9
Maintenance hours	928	22	154	258	258	352

The accumulated number of repair and repair hours through the operating period 1988–2001 are shown in Figs. 1 and 2. From these figures, it would be possible to see the effect of ageing, however, it should be noted that in the considered case the amount of critical failures and repairs still cannot be directly related to DG ageing.

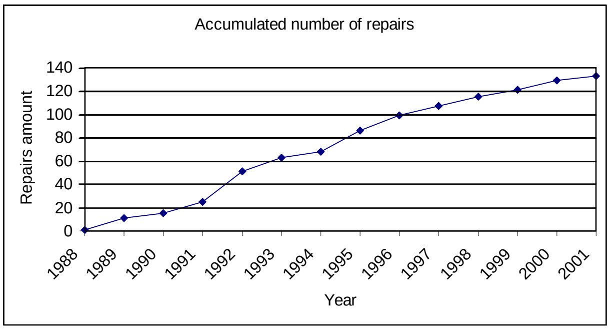

Fig. 1. Accumulated number of repairs

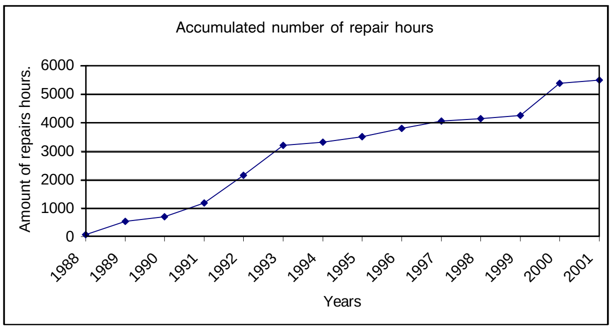

Fig. 2. Accumulated number of repair hours

For the further investigation, the Ignalina NPP DGs statistical data and characteristics for a 10-year period (1 Jan 1990 up to 1 Jan 2000) were analysed. The parameters of the unavailability model calculated using the mentioned statistical data are shown in Table 3. The indices *LC* and others are added to the q, λ and a parameters in order to distinguish between the different modes of failure discussed in the corresponding section.

Table 3. **Estimated parameters and unavailability contributions for DG**

Parameter / contributor	1 DG	Unit
LC faults		
q_{LC}	2.10E-02	(1/demand)
λ_{LC}	29.45E-06	1/h
a_{LC}	31.40	h
MC faults		
λ_{MC}	33.33E-06	1/h
a_{MC}	54.62	h
NC faults		
λ_{NC}	41.89E-06	1/h
a_{NC}	18.60	h

It should be noted that the uncertainty intervals of the parameters are relatively large due to sparse data and inhomogeneities. Using the Bayesian approach, there is a possibility to estimate and decrease the data uncertainty [4] and to model the initiating event frequencies more precisely [5].

As an example, analyzing the statistical failure data it is assumed that failures come from a Poisson distribution with the parameter λ. Formally, this parameter is deterministic, but due to the lack of statistical data, computational errors, model assumptions, etc. the parameter λ is supposed to be a random value with the distribution $p(\lambda)$. Usually this distribution is calculated by Bayesian methods, combining the prior distribution based on generic data $p(\lambda)$ and the specific plant data Y, obtaining the final distribution $p(\lambda|Y)$.

The failure rate was expressed as a random value. Its density function p(λ) *a priori* can be assumed to be a lognormal distribution density with the parameters S and R, *i.e.* with the generalized data X, the prior probability density function of the parameter λ is a lognormal distribution with the parameters S and R:

$$p(\lambda) = p(\lambda \mid X) = \frac{1}{\sqrt{2\pi} \cdot S \cdot \lambda} \cdot e^{-\frac{\ln^2 \frac{\lambda}{R}}{2 \cdot S^2}} . \qquad (10)$$

The considered parameter values (S = 0.815 and R = 2.758) are obtained from the generalised operational data. Statistical data on the Ignalina NPP are updated according to the formula:

$$p(\lambda|Y) = \frac{p(\lambda) \cdot p(Y \mid \lambda)}{\int_0^\infty p(\lambda) \cdot p(Y \mid \lambda) d\lambda} , \qquad (11)$$

where $\lambda \in]0;\infty[$, Y is the NPP statistics.

The used algorithm allows to incorporate a new data statistics to the considered model and to estimate the data uncertainty. In case when a new information is available, parameter distributions can be updated using the Bayes procedure. Using distributions obtained in this way, the distribution, 5% and 95% percentiles and the confidence interval of the result can be estimated.

The prior distribution parameters R and S can be estimated using T-Book data (2000) and the prior distribution parameter relations. The prior λ and the posterior λ' as mean values can be calculated using the correspondent distribution $g(\lambda)$ and $f(\lambda)$:

$$\lambda = \int_0^\infty z g(z) dz , \qquad (12)$$

$$\lambda' = \int_0^\infty z f(z) dz . \qquad (13)$$

The corresponding percentiles $\lambda_{0.95}$ and $\lambda_{0.05}$ of λ distribution $p(\lambda)$ can be obtained using the following expressions:

$$0.95 = \int_0^{\lambda_{0.95}} p(z) dz , \qquad (14)$$

$$0.05 = \int_0^{\lambda_{0.05}} p(z) dz . \qquad (15)$$

The results of data updating using the Bayes approach are shown in Table 4. The prior and the posterior distribution $g(\lambda)$ and $f(\lambda)$ are shown in Fig. 3.

Table 4. **Data updating using the Bayesian approach**

R	S	Prior λ	Stat. λ^*	Post. λ'	$\lambda'_{0.05}$	$\lambda'_{0.95}$
2.758	0.815	0.18	0.258	0.21	0.072	0.421

Note: To convert the failure rate per year to the failure rate per hour, it is need to divide it by 365*24, when the mean of the posterior failure rate per hour λ' = 2.385E-05.

When data uncertainty is evaluated, it can be decided whether or not a new information is needed for further uncertainty reduction. It is obvious that when the data amount N $\rightarrow \infty$, a ran-

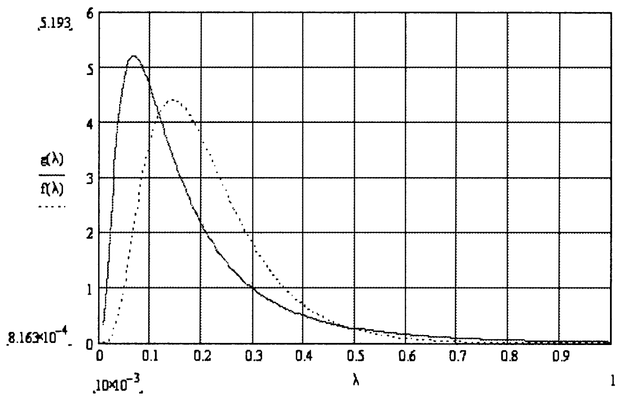

Fig. 3. Prior and posterior distribution of failure rate per year

dom variable (*e.g.*, λ) converges to a constant (*e.g.*, variance Var(λ) → 0).

4. SYSTEM MODEL AND CALCULATIONS

An active on demand parallel system (Fig. 4) of n components designates a redundant system (a system with more units than are absolutely necessary to function as required) in which all units are active on demand. At first, a system of this type is a system with all 100% parallel units:

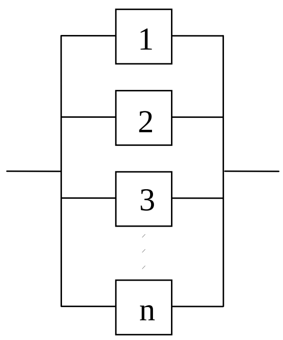

Fig. 4. Active-on-demand parallel system

A redundant system assumes that the individual elements are of full (100%) capacity in accomplishing the designed objective. So, since all elements must fail for the system to fail, the system unavailability

$$U(t) = \prod_{i=1}^{n} u_i(t)\,, \tag{16}$$

where $u_i(t)$ is i element unavailability.

Analysing the success criteria of system operation, this work considers a scheme which consists of elements connected in parallel and performing the functions of a system. In a redundant system, it is assumed that separate elements can perform the designated functions independently of the other elements. Analysing the system of n identical elements parallelly interconnected, when for the system function performance only k elements are required and when the instantaneous unavailability of separate elements is q, the total system unavailability is generally expressed by binomial distribution:

$$F_{k/n}(q) = \sum_{m=k}^{n} n!/m!(n\text{-}m)!\,q^m(1-q)^{n-m}\,. \tag{17}$$

The “non-success criterion” of the EDGS system for one Ignalina NPP unit with six DGs is the failure of four DGs, while the “success criterion” is three out of six DGs. In the case when four DGs would fail, the EDGS system cannot ensure the functioning of the safety system and exceeds the limits of safe NPP operation.

Considering the EDGS “success criterion”, the following redundant EDGS unavailability levels were analysed:

- 4 of 6 DGs failure on demand;
- 3 of 5 DGs fail during one month testing interval T.

Within one month, one of 12 DGs cannot perform the designated functions, because the annual preventive test is performed. Thus, for one unit only 5 of 6 DGs are available.

Trying to assess the mean unavailability of the entire system, one DG mean unavailability model can be used. If one DG mean unavailability conservatively is $Q(T)$, then the entire system’s mean unavailability $U(T)$ in a particular case conservatively can be expressed on analogy with instant unavailability:

$$U_{k/n}(T) = \sum_{m=k}^{n} n!/m!(n\text{-}m)!\,Q(T)^m(1-Q(T))^{n-m}\,. \tag{18}$$

Then the minimum of mean unavailability can be obtained. The optimal testing interval is the solution of the following equation:

$$\frac{d}{dz}U(z) = 0\,. \tag{19}$$

The optimum value of mean unavailability for the whole system $U(T)$ as for each DG $Q(T)$ is not very clear, as shown in Fig. 5.

In particular cases, the system redundancy has no significant influence on the optimum value of the testing interval. An increase of the system redundancy decreases the mean unavailability level, however, it exerts no considerable influence on the shape of the unavailability function curve and at the same time the value of the optimum testing interval.

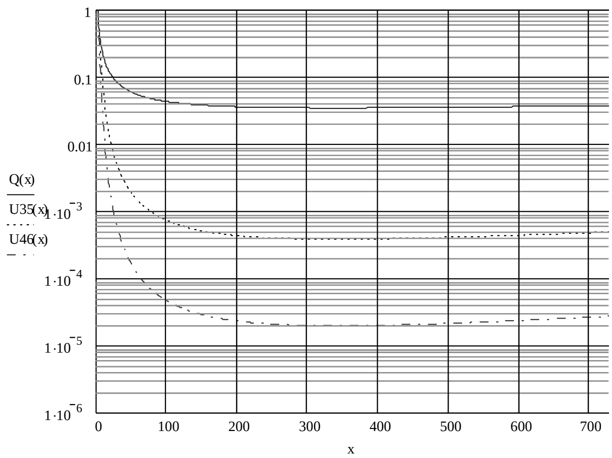

Fig. 5. Unavailability for different redundancy of DGs system

The separate unavailability function with respect to the testing interval and corresponding unavailability level (Table 5) for the failure of 4 out of 6 DG is shown in Fig. 6.

Table 5. **Test interval and corresponding unavailability for different DG system redundancy**

DG system	Testing interval, hours	Mean unavailability	Note
1 DG:	340.57	0.034	Min. unavailabil.
Q(x)	730	0.037	1 month testing
3|5 DG:	345.8	$3.82 \cdot 10^{-4}$	Min. unavailabil.
U35(x)	730	$4.87 \cdot 10^{-4}$	1 month testing
4|6 DG:	345.8	$1.96 \cdot 10^{-5}$	Min. unavailabil.
U46(x)	730	$2.71 \cdot 10^{-5}$	1 month testing

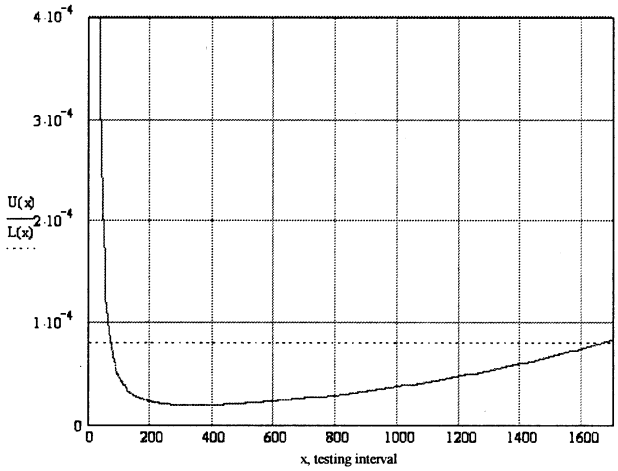

Fig. 6. Unavailability function and unavailability limit in case of failure of 4 out of 6 DGs

There is no criterion to define the allowable unavailability of EDGS at the Ignalina NPP, however, it is stated that the design failure rate for one DG $\lambda_D = 1.4 \cdot 10^{-3}$, from which the limiting unavailability of a system can be assessed.

Unavailability corresponding to one and two months of testing intervals, as well as the minimum unavailability is lower than conservatively determined for 4 out of 6 DGs failures limiting unavailability $L_{4/6} = 8.05 \cdot 10^{-5}$.

Table 6. **Comparison of testing interval and unavailability for 4|6 DGs system**

Testing interval hours (days)	Mean unavailability	Note
345.8 (14.41)	$1.96 \cdot 10^{-5}$	Min. unavailabil.
730 (30.42)	$2.71 \cdot 10^{-5}$	1 month testing
1460 (60.83)	$6.43 \cdot 10^{-5}$	2 month testing

The limiting unavailability corresponds to the following extreme testing interval values:

- ~100 hours (4.17 days) – the shortest testing interval;
- ~1650 hours (68.75 days) – the longest testing interval.

This unavailability model is most sensitive to the parameters related to a latent critical failure. In order to decrease the minimal unavailability, it is reasonable to decrease the time-independent unavailability part or the latent critical failure rate.

5. CONCLUSIONS

The limit of unavailability allows to increase the interval of DG testing at the Ignalina NPP up to two months. Due to changing the testing interval from one month to two months the average unavailability changes insignificantly (from $2.7 \cdot 10^{-5}$ up to $6.4 \cdot 10^{-5}$) and doesn't exceed the considered limit of unavailability $8.05 \cdot 10^{-5}$. An economical benefit can be obtained from implementation of the two-month testing interval.

The suggested models and the performed analysis will be especially useful when due to the decommissioning of Unit 1 there would be a need to decide how many DGs should be left for the safe operation of Unit 2 at the Ignalina NPP.

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DYZELINIŲ GENERATORIŲ SISTEMOS PATIKIMUMO KONTROLĖ IR TESTAVIMO INTERVALO OPTIMIZAVIMAS

S a n t r a u k a

Šio darbo tikslas buvo ištirti galimybę pakeisti ir optimizuoti Ignalinos atominės elektrinės (AE) avarinės dyzelinių generatorių stoties (ADGS) testavimo intervalus tokiu būdu, kad Ignalinos AE saugos lygis nebūtų sumažintas. ADGS tyrimas atliktas panaudojus rodiklius, susijusius su sistemos patikimumu. Siekiant įvertinti ir minimizuoti patikimumo duomenų neapibrėžtumus, taip pat buvo tirtas duomenų Bajesinio atnaujinimo metodas. Kadangi nagrinėti rodikliai ir gedimo duomenys daugiausia susiję su ADGS neparengtumu, testavimo intervalui optimizuoti buvo sudarytas ir panaudotas sistemos neparengtumo modelis.

Nagrinėtas metodas, modeliai ir gauti rezultatai gali būti panaudoti nepertraukiamos tikimybinės saugos analizės programoje bei patikimumo duomenims atnaujinti siekiant minimizuoti duomenų neapibrėžtumus. Analizės rezultatai parodė, kad ADGS Ignalinos AE testavimo intervalas gali būti padidintas iki dviejų mėnesių. Dėl testavimo intervalo pakeitimo nuo vieno iki dviejų mėnesių vidutinis sistemos neparengtumas pasikeičia nereikšmingai ir neviršija priimtinos neparengtumo ribos.

Raktažodžiai: neparengtumas, dyzeliniai generatoriai, testavimo intervalo optimizavimas, patikimumo duomenys

Робертас Алзбутас

КОНТРОЛЬ НАДЕЖНОСТИ СИСТЕМЫ ДИЗЕЛЬНЫХ ГЕНЕРАТОРОВ И ОПТИМИЗАЦИЯ ИНТЕРВАЛА ТЕСТИРОВАНИЯ

Р е з ю м е

Целью данной работы явилось изучение возможности изменения и оптимизации интервала тестирования аварийной дизельной электростанции (АДЭС) на Игналинской атомной электростанции (АЭС) таким образом, чтобы безопасность Игналинской АЭС не была снижена. Исследование АДЭС выполнено с помощью показателей, связанных с надежностью системы. Наряду с оценкой и минимизацией неопределенности данных надежности был исследован Баесовый метод обновления данных. Поскольку показатели и данные отказов в большинстве случаев связаны с неготовностью АДЭС, для оптимизации интервала тестирования была создана и использована модель неготовности системы.

Исследованный метод, модели и полученные результаты могут быть использованы для программы непрерывного вероятностного анализа безопасности и обновления данных о надежности в целях минимизации неопределенности данных. Результаты анализа показали, что интервал тестирования АДЭС на Игналинской АЭС может быть увеличен до двух месяцев. Из-за изменения интервала тестирования с одного месяца до двух средняя неготовность системы изменяется незначительно и не превышает допустимый предел неготовности.

Ключевые слова: неготовность, дизельные генераторы, оптимизация интервала тестирования, данные о надежности