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RELIABILITY ASSESSMENT FOR AUXILIARY POWER SUPPLY SYSTEM OF A NUCLEAR POWER PLANT BASED ON THE MONTE CARLO SIMULATION

BY

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Abstract. This paper presents a reliability assessment of the Auxiliary Power Supply System (APSS), Class IV of a Nuclear Power Plant (NPP) using the Monte Carlo simulation method. The paper highlights the important role of the APSS in ensuring safe and efficient operation of the plant. The paper provides an introduction to the concept of reliability, emphasizing its significance in the context of NPP. A description of Monte Carlo simulation method is also provided, including its underlying principles and its application to reliability analysis. The paper then describes the role and structure of APSS. A study case is presented to demonstrate the effectiveness of the proposed method in evaluating system reliability. The results of the study suggest that the Monte Carlo simulation method can effectively method to predict the reliability of the APSS.

Keywords: reliability assessment; Monte Carlo; non-sequential technique; simulation.

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1. Introduction

The notion of reliability concerning a product, part, or system is closely intertwined with the idea of failure. Failures denote instances where a component is unable to execute its intended functions due to various internal or external factors. The origins of these failures are diverse and can stem from deficiencies in design, operation, or the wear-and-tear process.

The understanding of failure is rooted in statistics and lends itself to a probabilistic interpretation. Hence, reliability can be defined as the likelihood that a component will execute its intended functions without encountering failure within a specified timeframe, under specific conditions, and with a certain level of confidence (Ivas *et al*., 2001).

By employing structural reliability analysis, design engineers can undertake both quantitative and qualitative assessments to enhance system reliability. This can involve substituting less reliable elements or components with more dependable ones. Furthermore, they can enhance the design by utilizing additional tools such as implementing redundancy solutions (Felea *et al*., 2001).

One of the industries where the reliability is very well studied is nuclear industry. Reliability is a critical factor in the operation of NPPs. The NPP systems require a high level of reliability to operate safely and efficiently over an extended period.

One of the crucial systems in a nuclear power plant is the Auxiliary Power Supply System (APSS). This system is engineered to distribute power across the entire facility, especially to vital components like the reactor cooling and control systems. Its primary role is to avert accidents and guarantee the reactor's safe shutdown if there's a power outage. For the safe functioning of a nuclear power plant, having a dependable APSS is indispensable, as it ensures that critical systems remain operational even when the main power source fails (Comanescu *et al*., 2005).

The importance of the APSS's reliability was demonstrated during the Fukushima Daiichi nuclear accident in 2011. The power loss caused by the earthquake and tsunami disabled the primary and backup power supplies, including the APSS, leading to a nuclear meltdown. The failure of the APSS, along with other safety systems, highlighted the need for continuous improvements in the reliability of nuclear power plants (David *et al*., 2014).

2. Monte Carlo Method

2.1. Presentation of the method

A Monte Carlo method utilizes random number sequences to address problems, making it suitable for scenarios where there's a correlation between the anticipated result and the expected behavior of a probabilistic system (James, 1980).

The popularity of this method is constantly growing, leading to the development of increasingly complex techniques requiring knowledge in broader fields such as mathematics (to be able to formulate and solve optimization problems), statistics (to analyze the data obtained), probability (to interpret random processes) and programming (to develop the simulation algorithm) (Kroese *et al*., 2013).

2.2. Monte Carlo techniques

Within the Monte Carlo method, there exist two techniques referred to as the sequential and non-sequential approaches.

2.2.1. Non-sequential technique

In this method, the states of a system's components are sampled based on their respective probabilities. When these components are independent, the overall system's state is ascertained by conducting simulations until a sufficient number have been completed. Therefore, the system's state can be derived by evaluating the probabilities of every possible state for each component (Nemeș and Munteanu, 2011).

Every simulation of the system's state operates independently and doesn’t have a chronological connection to the states of other components; these can be represented using random variables.

The non-sequential technique consists of sampling the random variables of the components in the system to simulate a large number of trials in order to observe the system states generated by them (Firouzi *et al*., 2022).

Considering these factors, the sequential technique is employed for analyzing complex systems where the components have minimal interdependence or are entirely independent. This method demands less computational effort compared to other approaches. Additionally, it offers the benefit of using fewer resources for data storage (Lei, 2017).

2.2.2. The sequential technique

The sequential approach involves sampling the probability evolution of individual or multiple component states. This methodology entails conducting a simulation in a chronological manner, capturing every transition in the state of one or more components within the system. As a result, the overall system state and the associated time intervals can be ascertained based on the reliability indicators of these components.

To assess system reliability, this technique employs statistical distributions representing the failure and repair rates of equipment encompassed by the system. While the Weibull distribution often effectively characterizes most failure processes, the Lognormal distribution is commonly employed for modeling repair processes.

These aspects are applicable for repairable components, however, if we are talking about components that are usually replaced entirely (modular type), then the repair time is better described by exponentially distribution. This distribution also tends to describe the failure time for electronic components.

When considering economic aspects like repair expenses and the financial repercussions of system outages in the simulations, this method can significantly enhance the optimization of maintenance strategies. The sequential approach has demonstrated its value in evaluating the dependability of composite systems, with the ability to derive multiple reliability indicators from the simulations, such as the failure rates and out of service periods.

Therefore, this technique has the advantage of being able to take into account chronological events and the distributions of reliability indicators in the analyses, but it should be noted that as the complexity of the analyses increases, more computing power will be required. This may translate into higher costs for the purchase of simulation equipment, but also into simulations with longer simulation time (Patel and Deshpande, 2019).

3. Auxiliary Power Supply System

The Auxiliary Power Supply System (APSS) ensures the safe and consistent delivery of electrical power to the power plant's process, control, instrumentation, and lighting loads. It services both the conventional sections of the plant and the nuclear-related functions (AERB, 2020).

The APSS is separated into two independent subsystems, termed the “odd” and “even” subsystems. Systems catering to the “odd” load group are entirely separate, both physically and electrically, from those serving the “even” load group (IAEA, 2007).

The standard electrical power distribution system is divided into distinct power categories, labelled as Class I, II, III, and IV.

The Class I system delivers power to components demanding continuous DC power for safety-critical tasks, equipment monitoring, and the surveillance and management of the nuclear power plant's operations.

The Class II system provides power to loads that require uninterrupted AC power to ensure the protection, monitoring, and control functions of the processes in the power plant. This category includes systems such as reactivity control mechanisms and process computers.

In the Class III system, connected loads can withstand power supply interruptions of up to 3 minutes, the time required for the transition from the primary to the backup power source (standby generators).

The Class IV system is an alternating current power system without on-site backup sources. While an interruption in this class doesn't jeopardize the power plant's safety, it does affect energy production (AECL, 2005). The Class IV power distribution system sources its power directly from either the main generator or a 110 kV station. This philosophy is common with other power plants such as hydro power plants because the main source is the main generator and the alternative source is offsite power source (used for start-up, shut-down etc.) (Costinas *et al.*, 2014).

4. Study Case

For this study case, the Class IV was analysed because even if this class of power may not be directly related to the safety of the nuclear reactor, it may still have an influence on the overall safety of the NPP in some scenarios such as planned maintenance. Another reason to study the Class IV system is from economic point of view. A failure of this system could lead to a loss of production and increased downtime.

In order to conduct this study, Matlab Simulink was used to model real-time scenarios using a generic Class IV auxiliary power supply scheme for a nuclear unit (Fig. 1).

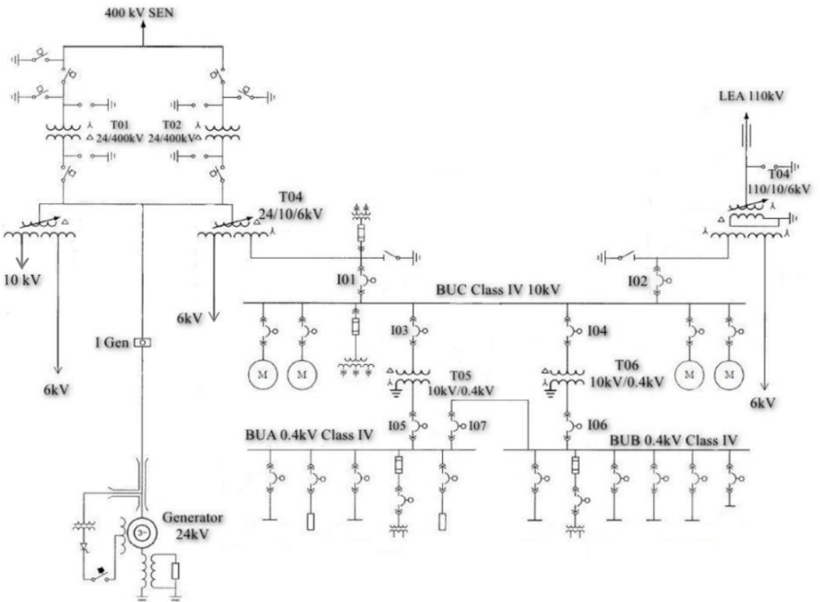

Fig. 1 – Class IV APSS for a Nuclear Power Plant.

The Auxiliary Power Supply System provides power to all essential auxiliary loads and equipment, which are crucial for both the safety and economical operation of the power plant. Hence, it's important to assess the likelihood of adverse events occurring. In this study, we consider the failure rates of the primary auxiliary supply equipment to evaluate the reliability of different levels within the auxiliary supply systems. The primary failure data for this equipment can be found in Table 1, as per (NTE 005/06/00, 2006):

Table 1
Failure rates of electrical equipment from Auxiliary Supply System

Equipment/System	Failure rate λ (h^{-1})
Bus-Bar	0.4×10^{-7}
Low Voltage Breakers	3×10^{-7}
Low Voltage Cables	0.5×10^{-4}/km
Medium Voltage / Low Voltage Transformer	1.7×10^{-7}
Medium Voltage Cables	$1.14 \times 10^{-5} \div 2.28 \times 10^{-5}$/km
Medium Voltage Breakers	$1.14 \times 10^{-6} \div 2.28 \times 10^{-6}$
Bus Ducts	1.14×10^{-5}/km
Bus Transfer System	1.2×10^{-5}
>30 MVA Transformers	$2.28 \times 10^{-6} \div 5.7 \times 10^{-6}$
800 MVA Generator	1×10^{-5}
Offsite Source	1.14×10^{-5}
110 kV Overhead Line	0.97×10^{-4}/km

For the simulation of the Monte Carlo method, the non-sequential technique was chosen.

4.1. Results

The results of the simulations are shown below. In order to validate these are correct, the results found using the MC method were compared to those gotten using another method, namely, the Fault Tree Analysis. Further details on how the fault tree was developed can be found in (Ghidu *et al.*, 2021).

In the Fig. 2 is depicted the reliability value on the 0.4 kV busbar, BUA, after 15 years of operation.

In Fig. 2, the blue mark depicts the reliability of the 0.4 kV bus determined with the Fault Tree method, on a 15 years interval and the red lines represent the reliability of the bus simulated using the Monte Carlo method. It can be seen that the results are very similar, which means that both methods can be used as tools in assessing operational reliability.

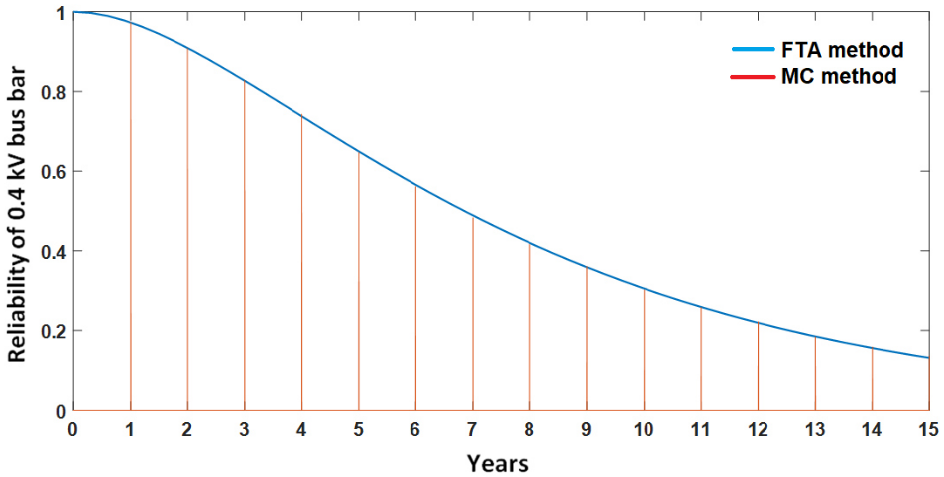

Fig. 2 – The reliability of 0.4 kV busbar after 15 years of operation.

In Fig. 3, the reliability obtained in the time interval between 0 and 3 years has been extracted in order to identify the maximum deviations obtained between the two methods.

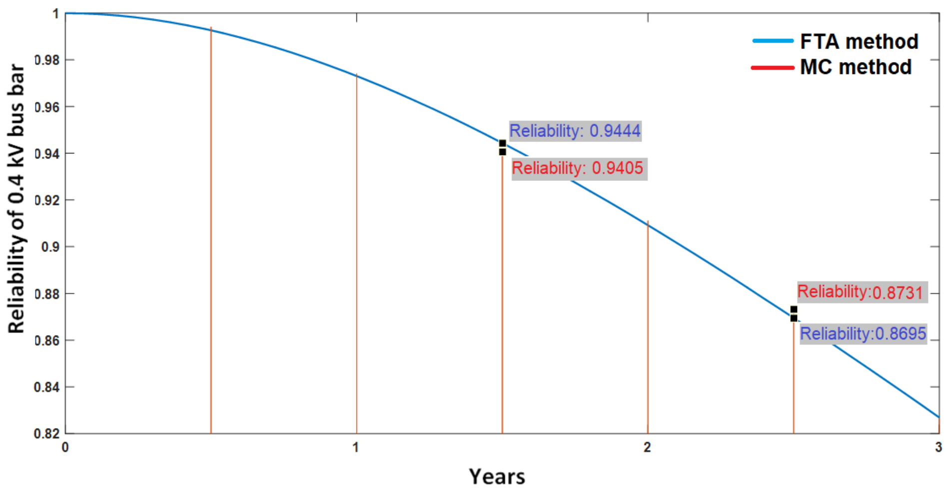

Fig. 3 – The reliability of 0.4 kV bus for 0-3 years interval.

With the Monte Carlo method, were obtained values which closely follow the uniform trend of the reliability curve obtained with Fault Tree method. We can see that are alternating periods when the value of the reliability (using MC) is above the FTA curve or below FTA curve.

In order to determine deviations between the two methods, some points on the graph have been chosen.

The maximum deviation obtained between the two methods is - 0.39%, read at point t = 1.5 years. Since the MC method is based on generating random numbers, different results will be obtained in each simulation, but they will not deviate much from simulation to simulation. The maximum deviations between the two methods did not exceed 0.5% in any case. This is due to the high number of iterations used.

The number of iterations for this case study was 10000, which is large enough so that the reliability values for each element converge to a very constant value.

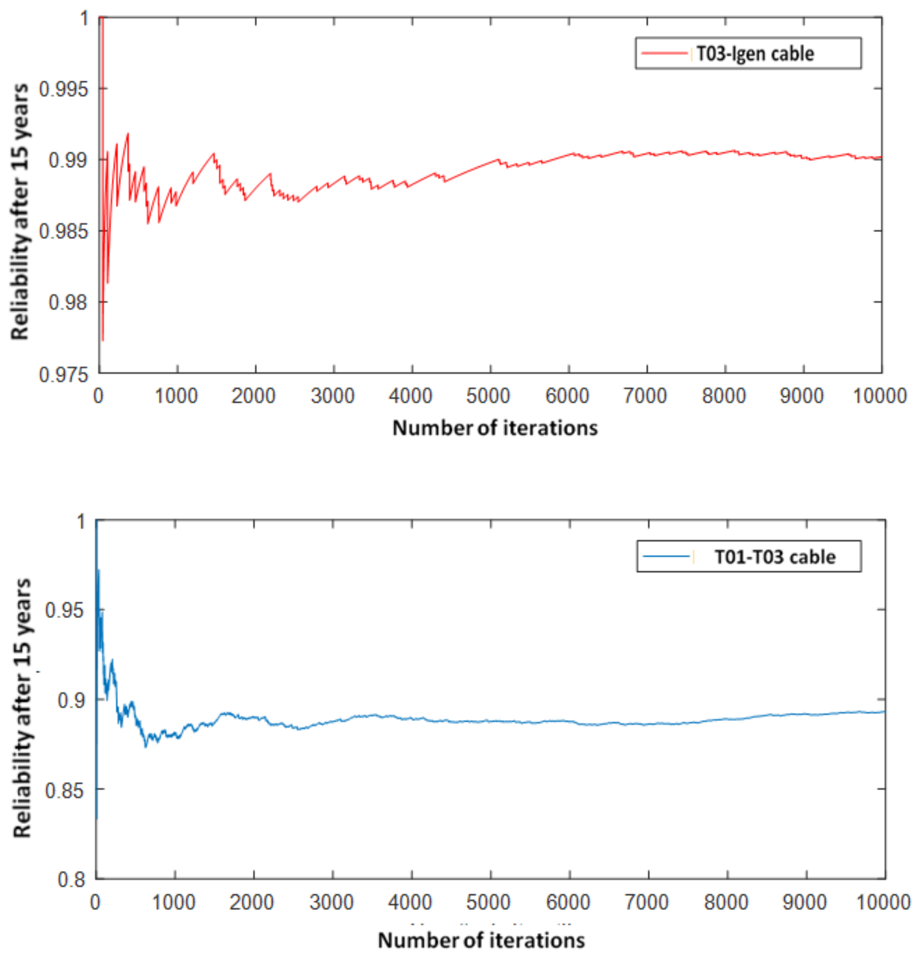

Fig. 4 – Convergence of the components reliability.

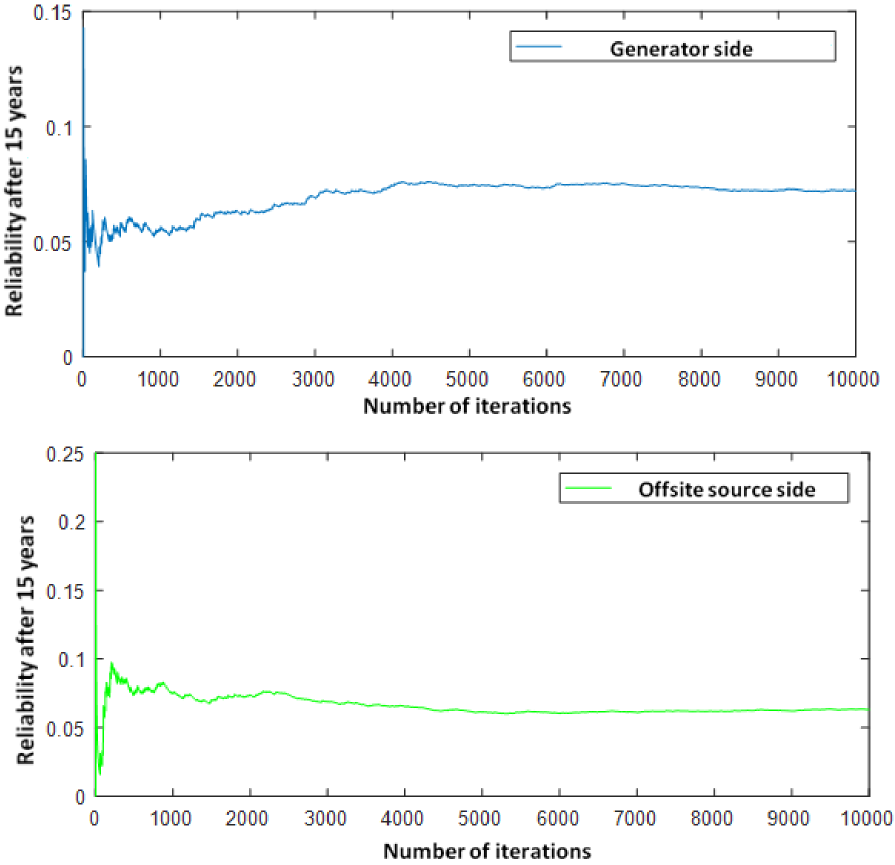

Fig. 5 – Convergence of the reliability for subsystems.

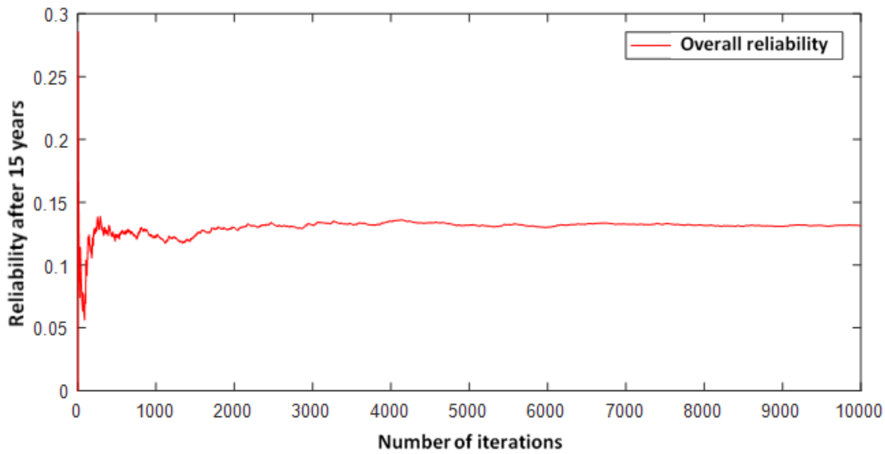

Fig. 6 – Convergence of overall reliability.

From the graphs shown in Figs. 4, 5 and 6 it can be seen that a higher number of iterations, will generate more linear results due to convergence. However, a very large number of iterations may have the disadvantage of too much simulation time, so a balance must be found between the desired accuracy and the available computational power.

5. Conclusions

Although different methods were used, the final results were very similar, thus validating the correctness of the Monte Carlo and Fault Tree simulation programs.

The results from this study case will be analysed, in future papers, in relation to the reliability obtained using data from operation of the APSS.

Depending on the complexity of the analysed system, the desired accuracy and the available computational power, one of the two methods can be chosen to assess reliability of the power plant. If the factors mentioned above do not represent constraints and a validation of the results is wanted, then the simulation of the system can be carried out with both methods.

The advantages of Fault Tree Analysis are the simplicity of adding new elements to the system under analysis, the speed of the simulations and the accuracy of the results obtained.

The MC method has the advantage that the introduction and construction of the simulation program is done quickly. The main disadvantages are: lower accuracy of the results in case of a small number of repetitions and high simulation time if the number of repetitions is increased too much.

REFERENCES

AECL CANDU, *CANDU 6 Technical Summary,* 2005.

Atomic Energy Regulating Board (AERB), *Design of electrical power systems for nuclear power plants, Mumbai*, 2020.

Comanescu Gh., Costinas S., Iordache M., *Partea Electrică a Centralelor și Stațiilor. Seria "Cursuri Universitare",* Ed. Proxima, București, 2005.

Costinas S., Georgescu S.C., Opris I., *Smart solutions for the auxiliary power supply schemes in hydro-power plants*, U.P.B. Sci. Bull., Series C., Vol. 76, Iss. 3, 2014.

David L., Lyman E., Stranahan S.Q., The Union of Concerned Scientist, *Fukushuma: The Story of a Nuclear Disaster*, 2014.

Felea I., Coroiu N., *Fiabilitatea și mentenanța echipamentelor electrice*, Tehnica, 2001.

Firouzi M., Samimi A., Salami A., *Reliability evaluation of a composite power system in the presence of renewable generations*, Reliability Engineering & System Safety, Vol. 222, 2022.

Ghidu M.A., Nemeş C., *Reliability Assessment of Auxiliary Power Supply Systems for a Nuclear Power Plant (NPP)*, 2021, 9th International Conference on Modern Power Systems (MPS).
International Atomic Energy Agency, *Design of Electrical Power Systems for Nuclear Power Plants*, Specific Safety Guide No. SSG-34, 2007.
Ivas D., Munteanu F., Rotariu M., Voinea E., Nemeş C., *Ingineria fiabilităţii sistemelor complexe*, Editura Perfect, Bucureşti, 2001.
James F., *Monte Carlo theory and practice*, Rep. Prog. Phys., Vol. 43, 1980, Great Britain.
Kroese D.P., Taimre T., Botev Z., *Handbook of Monte Carlo Methods*, John Wiley & Sons, Inc., 2013.
Lei H., *Non-Sequential Monte Carlo Simulation for Cyber-Induced Dependent Failures in Composite Power System Reliability Evaluation*, IEEE Transactions in Power Systems, 32(2), 1064-1072 (2017).
Nemeș C., Munteanu Fl., *Producerea și distribuția energiei electrice*, Editura Politehnium, Iași, 2011.
NTE 005/06/00 (2006-10), *Normativ privind metodele și elementele de calcul al siguranței în funcționare a instalațiilor energetice*, 2006.
Patel H., Deshpande A., *Reliability Evaluation of Power Systems using Monte Carlo simulation in Pspice*, International Journal of Applied Engineering Research Vol. 14, 2019.

EVALUAREA FIABILITĂȚII SISTEMULUI DE SERVICII PROPRII A UNEI CENTRALE NUCLEARE FOLOSIND METODA DE SIMULARE MONTE CARLO

(Rezumat)

Această lucrare prezintă o evaluare a fiabilității sistemului de servicii proprii clasa IV, dintr-o centrală nucleară, folosind metoda de simulare Monte Carlo. Articolul evidențiază rolul important al serviciilor proprii în asigurarea unei funcționări sigure și eficiente a centralei. Articolul oferă o introducere în conceptul de fiabilitate, accentuând importanța sa în cadrul operării unităților nucleare. De asemenea, este prezentată o descriere a metodei de simulare Monte Carlo, inclusiv principiile sale de bază și cum poate fi aplicată în evaluarea fiabilității. Lucrarea descrie rolul și structura sistemului de servicii proprii, iar în final este prezentat un studiu de caz pentru a demonstra eficacitatea metodei propuse în analiza fiabilității sistemului. Rezultatele studiului sugerează că metoda de simulare Monte Carlo poate fi eficientă pentru a evalua fiabilitatea sistemului de servicii proprii.