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Importance Of Model Completeness In Reliability Studies Of Electrical Systems In High Temperature Gas Cooled Reactors

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Abstract

Design activities are underway for High Temperature Gas Reactor (HTGR), a IV-generation Nuclear Power Plant (NPP) with unique passive shutdown characteristics. Its greatest asset is its ability to be located near urban areas or industrial installations, allowing for the possibility of cogeneration of electricity and process heat, seawater desalination, or hydrogen production. To confirm its usefulness in co-operating with other chemical plants, it is essential to ensure the high reliability and predictability of all in-house systems. The power supply system is one of the most important systems in any nuclear power plant, therefore, it is vital to have a precise evaluation of the reliability of the power supply and distribution system for this type of plant. This work presents a Probabilistic Safety Assessment (PSA) of the main power supply system of a gas-cooled reactor based NPP. The analysis is based on the canonical approach for modeling such systems and includes equipment that is not typically considered. Additionally, uncertainty calculations and validity of the various component classes are performed, with particular emphasis on equipment not normally included in this type of analysis.

Keywords: gas-cooled reactor, electrical system, fault tree, fussell-vesely, nuclear power plant, probabilistic safety assessment, reliability

1. Introduction

Complex engineering projects such as the construction of a NPP require a PSA (IAEA, 2010). Despite being a mature technology, accidents have occurred in the field (Steinhauser et al., 2014). Therefore, International Atomic Energy Agency (IAEA) enforced nuclear legislation sets very high safety requirements for this type of plant at every stage of its life cycle. The data collected over the years by individual nuclear operators on component failures in nuclear power plants highlights the crucial importance of a dependable electricity distribution system for the successful operation of an NPP (U.S. NRC, 2015). Consequently, specific IAEA guidelines have been developed for the assessment, design and maintenance of this type of plant (IAEA, 2016).

For Generation III NPPs, this conservative approach has proven effective. The result involves increasing system reliability through the use of numerous redundancies (Durga et al., 2009), which is particularly important for units with high generated electric power output. However, for Generation IV power plant design, where unit output is expected to decrease (Pinsky et al., 2020), a standard approach may not be appropriate as it could significantly reduce plant profitability. Various solutions are designed to reduce the number of components, which in turn reduces the margin of error in modeling such systems.

This work proposes a new approach to meet current needs, while also conducting a comprehensive safety analysis. The main objectives of this work are:

- To investigate the existing reliability studies on the electrical systems in High Temperature Test Reactor (HTTR);
- To develop of Reliability models both with basic configuration and extended with often overlooked components of electrical systems and validate the impact of their inclusion on the results obtained;
- To create and compare alternative Reliability models for ability to supply safety-related loads under emergency conditions

- To achieve the objectives, Fault Trees were created using Sapphire 8 code for system performance during Normal Operation (NO) and Reliability Block Diagram (RBD) tool in ReliaSoft's BlockSim software to examine system reliability under Emergency Conditions (EC) electrical mode.
- This paper to achieve the objectives defined above, is organized as follows: Section 2 describes the main Electrical Power Distribution System (EPD) used in the NPP structure analyzed. Section 3 describes methodology that the presented work has been carried out while Section 4 presents calculation results. Related discussion and conclusions are given in Section 5.

Nomenclature

Indices			
i	Indices of system equipment		
Abbreviation			
ABT	Automatic Bus Transfer Switch	IAEA	International Atomic Energy Agency
EC	Emergency Conditions	LV	Low Voltage
EDG	Emergency Diesel Generator	NO	Normal Operation
EPD	Electrical Power Distribution System	NPP	Nuclear Power Plant
FMEA	Failure Mode and Effect Analysis	PSA	Probabilistic Safety Assessment
FT	Fault Tree	RAMI	Reliability, Availability, Maintainability and Inspectability
FTO	Failure To Operate	RBD	Reliability Block Diagram
F-V	Fussell-Vesely	SC	Short Circuit
HTGR	High Temperature Gas Reactor	SEQ	Sequencer
HTTR	High Temperature Test Reactor	UPS	Uninterruptible Power Supply
I&C	Instrumentation and Control		
Symbols			
λ	Failure rate	MV	Medium Voltage
AC	Alternating Current	DC	Direct Current
LV	Lowe Voltage	HV	High Voltage
Other			
ADD	Reliability model with ADDed components	NRC	U.S. Nuclear Regulatory Commission
STD	Reliability model with Standard modeling approach		

2. HTGR system characteristics

HTGR belong to the fourth generation of reactors and, thanks to their parameters and inherent safety (Sato et al., 2018), are a very serious option when it comes to, for example, the generation of process heat (Stewart et al., 2021). This article describes the operation of the EPD of this reactors at example of currently developed TeResa reactor based NPP (Skrzypek et al., 2022).

Recently, an exhaustive study of the lifetime reliability and potential failure modes for the HTTR EPD has been performed by (Kowal, 2022). Lifetime reliability of HTTR EPD was evaluated by different failure modes: Failure to Operate (FTO), Short Circuit (SC) and Age-related. For this analysis, mainly FTO type faults were used as the most representative. The other two modes are also significant in case of system operation and could be extended in other studies. Important part of the those work is also data investigation where by the method described in (Kowal et al., 2021) comprehensive failure rate and repair time of electrical equipment have been gathered. In order to compare other operation modes the same input data have been used in all models presented herein.

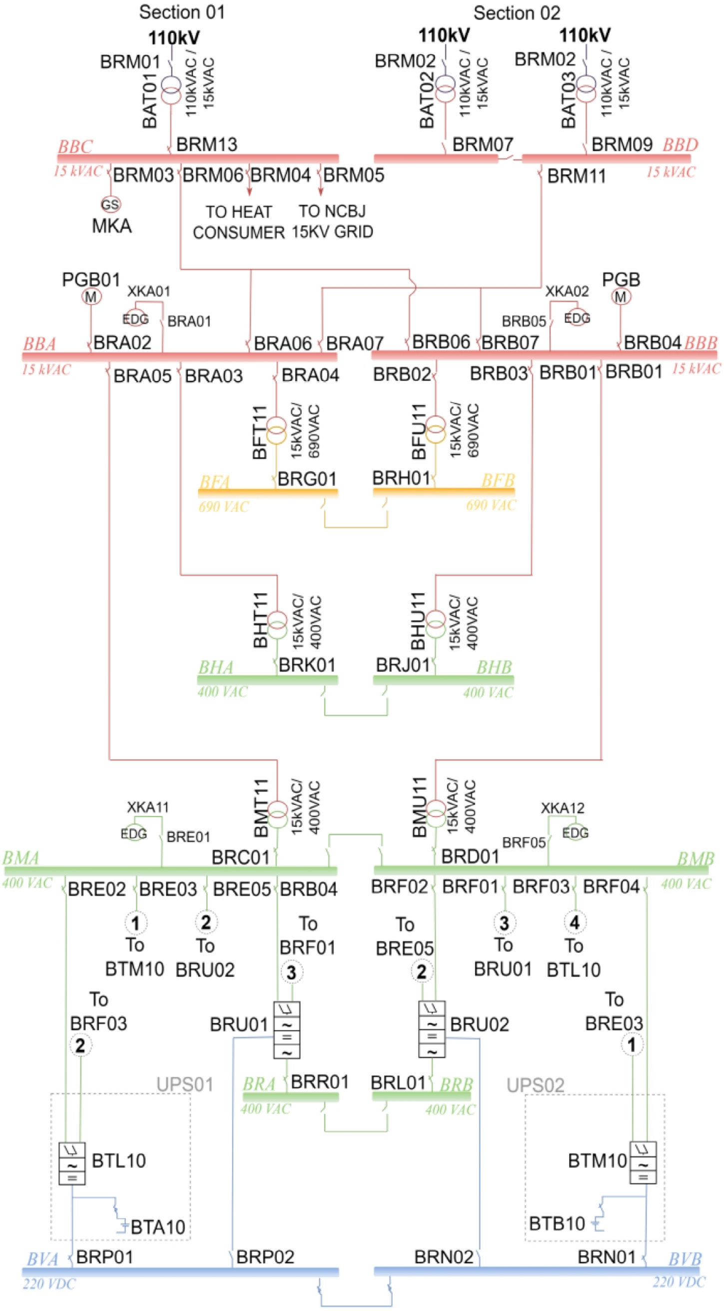

Fig. 1. The configuration of the HTGR electrical facility.

Conceptual design of the research high temperature gas cooled reactor HTGR EPD single-line diagram is shown in Figure 1. Principles of the design of the system on the issue on operation in both NO and EC by characteristic of each subsystems designed in terms of lifetime operation are described below. According to the methodology described by (Brinkmann and Vanvor, 2019), among others, the operation of the electrical system could be differentiated into NO and EC, while from the point of view of the system architecture the following subsystems can be distinguished:

External power lines are performed by two independent Subsections both with doubled power trains. Subsection 1 consist High Voltage (HV) external power line and reactor electric power output provided by generator. Subsection 2 consist two feeder transformers from auxiliary HV external power line.

Medium Voltage (MV) power Sections include two independent Subsections without coupling. The MV Section is connected to the grid by transformers that reduce the voltage to 15 kV, which is most common MV level in Poland which may allows to integrate the installation to existing facilities by not using additional auxiliary transformers. Emergency Diesel Generators (EDG) have already been applied in the MV Section to assess their impact on the reliability of the overall system operation for the EPD considered.

Four general purpose buses are connected to MV via individual transformers. There is two 0,69 kV AC Sections which supply for single loads exceeding 130 kW other not safety-realated equipment are connected to one of the two low-voltage 0,4 kV AC.

Low Voltage (LV) emergency power buses for safety function power loads capable of accepting a break in supply while waiting for the EDG start-up. Emergency power buses are connected to MV Section and there are equipped in individual Section step LV EDG. In addition this Sections are foreseen to be automatic coupling between this Subsections in case of loss of power input of one of them.

DC Sections for 220V direct current drivers like system cabinets or instrumentation supply. The principle of operation of these Sections is the same as for the previously described system and it is for loads required to remain in operation without interruption. In order to achieve that requirement DC Sections are supplied from emergency Sections through the individual Uninterruptible Power Supply (UPS) units.

LV uninterruptible power buses supplying loads related to nuclear and fire safety as well as Instrumentation and Control (I&C). Each Subsection is supplied primarily from an UPS unit and able to be manually switched from the other Subsection. There is also auxiliary power supply from DC Section connected directly to inverters direct current modules.

3. Methodology and models

In view of the rather far-reaching safety analyses of EPD of gas cooled reactors designs and their inherent reliability, it is crucial to make very detailed models to evaluate the various solutions. As the system under study is still in the early stages of design, it is an appropriate opportunity to examine its reliability performance in relation to other studies carried out in this area, which may identify a potential weakness in the solutions used to date. For this purpose, the same input data on failure rates as previously considered was used by (Kowal, 2022) for comparison, using the well-established event tree method.

3.1. Data investigation

One of the main applications of the HTGR is to participate in the upcoming process of heat generators modernization for Polish industrial facilities (Skrzypek et al., 2022). The purpose of conducting risk assessments in addition to ensuring the required level of security is to support investment risk decisions. It is feasible by determining the ratio of NPP operation time to the time in which it will be under service. There is a common practice to develop RAMI (Reliability, Availability, Maintainability and Inspectability) study in order to evaluate Forced Outage Rate of analyzed facility.

Important reason of using event trees approach when collating different systems instead of standard FMEA is possibility of recalculation of models after modifications made to the system. Fault trees advantage in this type of study lies in its probabilistic nature because it allows to simulate basic events individually and when failure occur its impact on system performance is evaluated. A system can fail due to a single failure of critical equipment or multiple occurrences of less important failures, with the cumulative degradation causing system failure. An additional benefit of performing a probabilistic risk assessment is the capability to use tools to estimate the uncertainty of the analysis performed. The failure rates of continuously operating equipment are based on Probability Distribution Functions that could be described also as two-parameter Gamma distributions, while equipment switched on only temporarily to perform specific system functions, such as switching on the EDG on demand in the event of a mains power failure, are based on Beta distributions. This type of component failure record is given for example in U.S. NRC report (NUREG-6928, 2007). This data entry approach enables Monte Carlo simulations to be conducted. For all analyses in this paper, such simulations were run 10,000 times, resulting in the data being presented in terms of lower, middle and upper bounds to characterise the reliability of the overall system under analysis (Kowal et al., 2019). To demonstrate the described methodology, this paper presents the results for NO along with the corresponding uncertainty analysis. Simulation models for complex systems that contain numerous redundancies, which are characteristic of EC modes of operation, generate more complex fault tree scenarios. These scenarios result in extensive computations if high accuracy results are used, which is beyond the scope of this paper, which only demonstrates the use of new methods.

To verify the impact of including additional classes of components when modelling EPD for reliability, it is important to perform an importance measures analysis, which provides a qualitative indicator of the impact. To determine the impact, an importance measures analysis is conducted using F-V Importance calculations.

$$FV_i = \frac{F_i(x)}{F(x)}, \tag{1}$$

where: $F(x)$ is the original minimal cut set upper bound and $F_i(x)$ is the minimal cut set upper bound with only the basic event of interest.

The F-V indices provide a measure of the fractional contribution of an event to the overall system failure condition. The objective of this study is to examine the impact of a group of components rather than identifying a specific component in relation to its location in the system. This task is not straightforward as even within a single class of equipment, components may come from different manufacturers resulting in varying failure rates. For the purposes of this study, it is assumed that all components within a given class have identical parameters. Therefore, the importance of each individual component class is characterised sum of single components contribution to system failure cut-sets.

$$FV_i = \frac{\Sigma F_i(x)}{F(x)} 100\% \tag{2}$$

where: FV_i is the importance of component class, $F(x)$ is all system failures occurred in simulations, $F_i(x)$ is the system failure scenario including component class of interest contribution. The framework for the F-V indices evaluation applied in this work is presented in Figure 4.

This paper proposes a novel approach that takes into account procedures that are often neglected in this type of analysis when dealing with the actual operation of EPD, in addition to the procedure described above for carrying out the reliability assessment of an electrical system:

- The Automatic Bus Transfer Switch (ABT) is used to connect buses at the same voltage level. Although often disregarded or depicted as disconnectors in diagrams, it is listed in the system descriptions of modern gas-cooled NPPs electrical systems i.e GEMINI+ (Torabi and Kowal, 2023) and HTGR shown on Figure 1. These devices are frequently included in sources of nuclear power plant electrical component failures. The ABT failure modes are provided in Table 1 and Table 2.
- EDG Sequencers (SEQ) operate on the same principle as ABT, which is described above, and are responsible for connecting EDG to the electrical system during a power loss event. NUREG-6928 outlines how SEQ is implemented in a redundant power supply system.
- To provide protection for the loads, fuse disconnectors are used (Fan et al., 2021), therefore they may be incorporated into consumer circuits of modeled systems. In addition, NUREG-6928 states that fuses share a comparable mission time with circuit breakers, making them a popular choice in nuclear power plants.
- Depending on the type of earthing system utilised, as well as the design of the electrical switchgear and level of direct contact protection, the quantity of supply buses may differ which is not explicitly stated in IAEA SSG-34 document. As the quantity of buses within switchgears can vary and is frequently greater than one, a more accurate method would be to specify the number of buses for each modelled installation. For example, Szulborski et al. (2021) and Yusop et al. (2021) cover the modelling phenomena and potential failure modes linked to busbars in switchgear. To illustrate the impact of adding extra busbars on the present analyses, it has been presumed that MV switchgear contains 4 busbars and LV switchgear contains 5 busbars. The DC buses were not equipped with additional components.

Table 1. Probability of the failure on demand of additional electrical equipment – NUREG-6928.

No.	Component Type	Failure Mode	λmean [d]	λ5% [d]	λ50% [d]	λ95% [d]
1	Automatic Power Transfer Switch	Fails to Transfer	1,13E-03	4,19E-04	1,05E-03	2,13E-03
2	Sequencer	Fails to operate	1,20E-04	1,37E-06	6,51E-05	4,24E-04

Table 2. Frequency of the failure on demand modes of additional electrical equipment – NUREG-6928.

No.	Component Type	Failure Mode	λmean [1/h]	λ5% [1/h]	λ50% [1/h]	λ95% [1/h]
1	Automatic Power Transfer Switch	Transfers Open	9,90E-08	3,89E-10	4,50E-08	3,80E-07
2	Fuse	Transfer to Open State	1,23E-08	2,82E-09	1,07E-08	2,03E+08

3.2. Reliability models

There were four reliability models considered resulting from EPD of HTGR. Standard configuration (STD) considered canonic approach for electrical system modelling while models enhanced according to the assumptions described above will be marked as ADD. Both modelling approaches have been conducted under electrical system NO and EC. The structure of developed fault tree for normal operation is shown in Figure 2(a). Consequently, reliability model of the electrical system under EC is shown in Figure 2(b). As calculations were carried out in two different software tools, due to the higher level of complexity, the HTGR electrical system in the EC was represented using RBD, which is the logical equivalent of the classical fault tree.

3.2.1. Normal Operation

The aim of NO is to sustain continuous state of the system through the operation of all its components. Therefore, the lack of power to any of them causes disruption of the assumed state of the system and shutdown of the reactor for corrective maintenance. Referring to previous studies of similar electrical facilities of HTTR (Kowal, 2022) and GEMINI+ (Torabi and Kowal, 2023) loss of single load means system failure, therefore the construction of the event tree is unambiguous and includes all elements of the system connected by OR gates. EPD is integrated into complex multi-component systems for this reason, the event tree was divided into subdiagrams corresponding to the Sections described above. Redundancy in this model is considered only for the circuit breakers for the power supply of BRU Inverters (Computer Section) and UPSes in DC Section. All other elements labelled in Figure 1 contribute to the top event through OR gates.

The event tree for the HTGR reactor electrical system constructed in this manner can be seen in Figure 2(a). The event tree shown contains a top event defined as "Insufficient power input to the main electrical loads" and subdiagrams in which there are components assigned according to the system configuration shown in Figure 1 and description of the system characteristics. Development of NO conditions is intended to model the most conservative fault tree, where a power failure to any major component will cause the system failure.

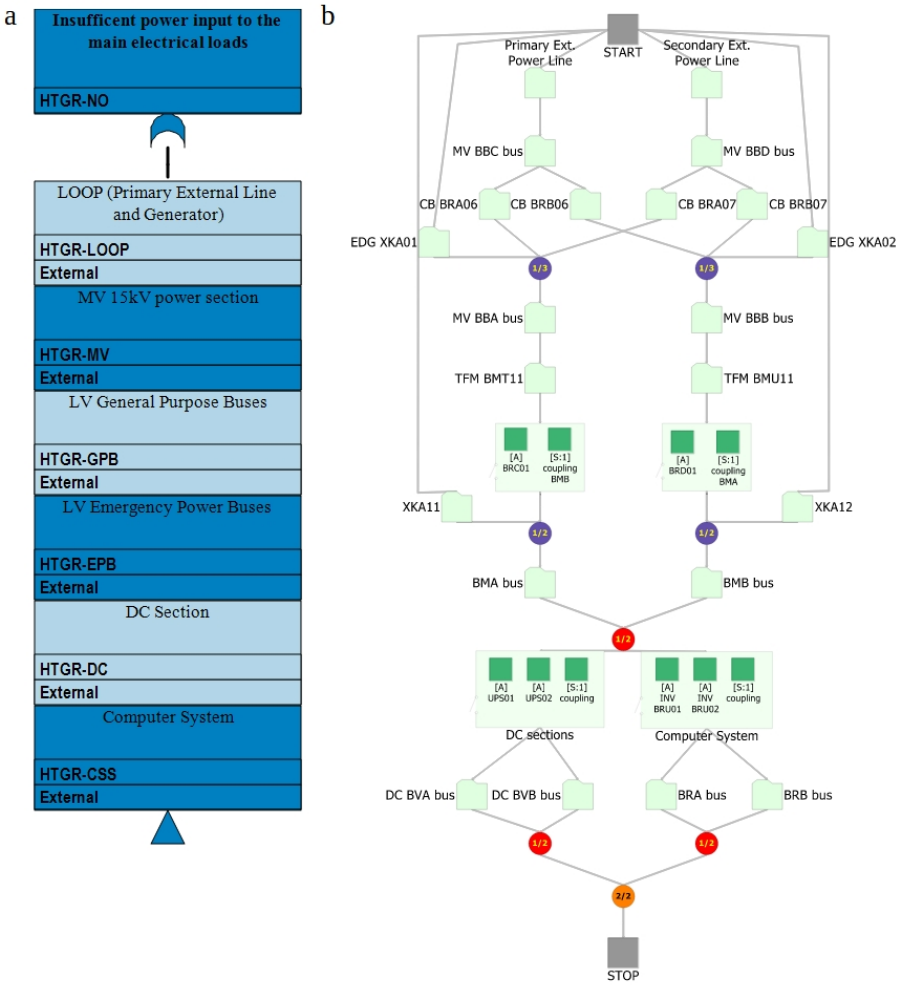

Fig. 2. (a) Fault tree for HTGR electrical system in NO; (b) RBD model for the HTGR electrical system in EC.

3.2.2. Emergency conditions

A more complicated operational state of EPD in NPP is the EC, where the principal function is to provide power to safety-critical loads. To perform this, all the safety functions of the system could be used. However, applying safety measures such as increased redundancy, it should be borne in mind that the requirements for the operation of the EPD in the EC are dependent on the initiating event, so there are no universal solutions for creating reliable systems, and they are adapted depending on the characteristics of the entire facility. Among the most typical design procedures used to improve the reliability of EPD in ECs are primarily additional external power sources, EDGs for switchgears supplying safety systems, coupling breakers and UPSs for loads requiring uninterruptible power supply. All of these systems have been applied in the designs of the HTGR electrical systems.

In terms of EPD reliability models in EC, non-safety related power consumers such as AC generators and general purpose buses in the cases under consideration can be omitted from the analysis as non-essential for system operation in EC. Another issue to be considered is the duration of operation of backup power sources such as EDG or UPS, but herein it is assumed at the further design stage fuel tanks and battery units will be selected so that supply individual safety related systems until reactor safety shutdown. The additional initial assumption is that the system operates correctly if at least one of the redundant devices is available. By harnessing the RBD-based modelling technique along with voting nodes, the model is highly flexible to changes in success criteria depending on the adopted requirements. Considering all the above assumptions, the reliability model for HTGR is presented in Figure 2(b).

3.3. Simulation frameworks

According to (Shiozawa et al., 2004) a standard lifetime for a gas-cooled NPP before general audit is approximately 20 years. Thus, this time frame was utilised as the boundary for assessing reliability. Another crucial boundary is the duration of the fuel campaign, which determines the plant's availability for electricity production. Identifying this time frame is essential and could have a significant impact on operational safety in terms of possible inspection intervals as well as the cost-effectiveness of NPP. As there is currently only one design in operation, the HTTR, availability analyses cannot be conducted due to the unavailable information on the duration of a single fuel campaign at this design stage. Additionally, the assumption has been made that the facility will operate continuously for 20 years, which can be adjusted to reflect real operating conditions. This is intended to test the reliability of the system under non-service conditions to its limits.

4. Calculations and results

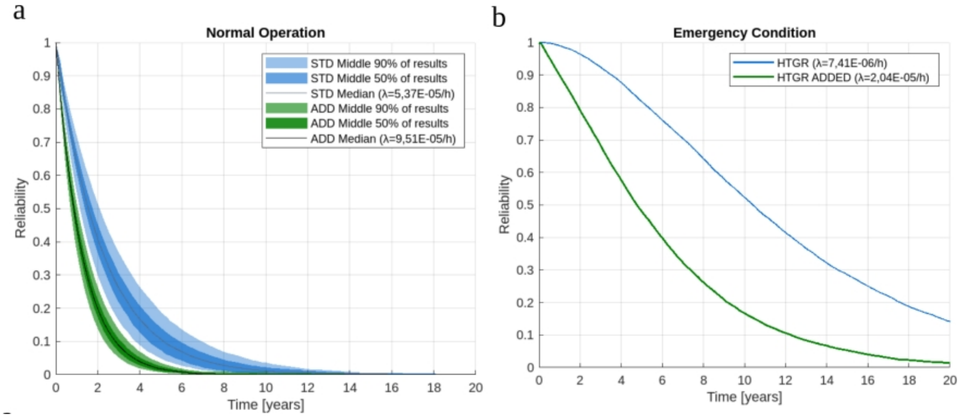

Fig. 3. (a) Lifetime reliability of the HTGR electrical system for NO; (b) Lifetime reliability of the HTGR electrical system for EC.

Figure 3(a) shows the reliability characteristics for the normal operation of the HTGR electrical system. The graph illustrates a standard reliability model and contrasts it with modes that take into account commonly excluded components, which for these purposes include only fuses and additional busses in the switchgears. The graphs also include uncertainty analyses.

As observed in the examined case, higher reliability was achieved with the conventional models. The reliability results of the HTGR reactor showed significant deterioration, ranging from 5.37E-06/h (STD) to 9.51E-06/h (ADD), when considering the reliability of EPD based on the FTO failure mode.

This deterioration in the reliability parameters is all the more striking as the system under study appears to be highly optimised in terms of the amount of complex equipment such as inverters and transformers. The importance of the buses is further emphasized by the proposed modelling approach. Even in the basic model, the buses accounted for 20% of the system, as shown in Figure 4.

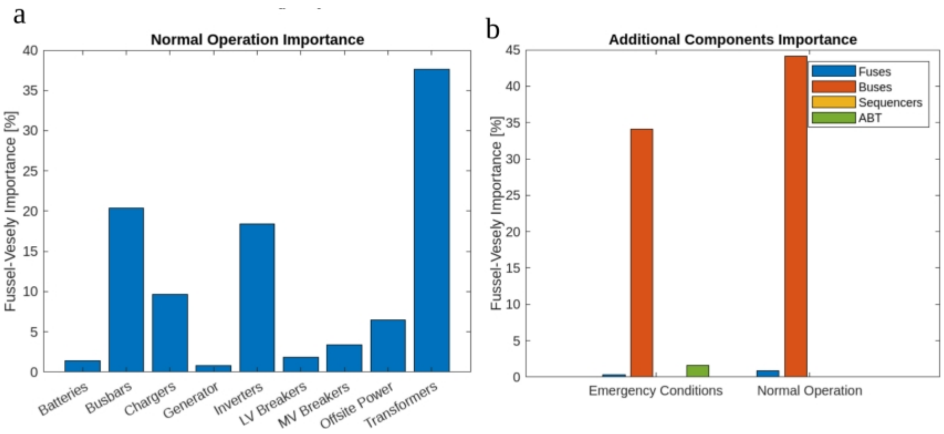

Fig. 4.(a) F-V importance of electrical components of HTGR in NO; (b) Importance of HTGR additional electrical equipment in EC.

Comparing the two modeling approaches which supplement models with given component groups, it is crucial to examine their impact on system reliability. From the obtained results, it is evident that additional buses take the dominant role over fuses added. However, this was only examined in FTO fault mode and more impact on system performance could manifest in other failure type characteristics.

Regarding the operation of EPD in EC, analyzed model was adjusted for the system's operating conditions in such situations. This includes elements not activated during NO, such as secondary external power line, EDGs, and ABT. However, components considered non-essential for reactor safety shutdown were excluded from this analysis. The success criterion is the operation of only one of the redundant Sections, as stated in the technical description. Nevertheless, the approach to system modelling used here is so flexible that the models created can be easily adapted to any success criteria, depending on the needs that arise.

The simulations for EC gave the results shown in Figure 3(b). The reliability results of the NPP EPD have been studied taking into account all additional components mentioned in Table 1.

In the case of sequencers, it is justifiable to omit these elements from safety analyses as their importance in HTGR reactors was 0%. However, the results obtained after taking into account the ABTs are more significant and contributed to system failure in 1.57% of the simulated scenarios. This suggests that a full safety analysis may lead to a significant bias in the results if components of this class are not considered, whereas their influence is insignificant in analyses of systems with comparable complexity as herein. The effect of adding additional fuse links and busbars has already been outlined during NO.

5. Summary and conclusion

The electrical systems within nuclear power plants serve a very important function as they are directly involved in all the installations and are responsible for the power output of the plant, which is its primary task. Equally important is their key role in providing safety and preventing dangerous accidents by powering the safety systems responsible for, among other things, residual heat removal. Consequently, the reliability of the electrical system is crucial not only for the efficient operation of the power plant but also for its safety.

In recent years, the technical and conceptual design of new nuclear power plants with gas reactors has evolved at various stages. This work further develops the scope of general reliability research by presenting new findings on previously unaddressed topics. The obtained results will act as a reference for future studies, including subsequent updates and project phases.

The EPD integrated approach to testing in the RAMI framework provides for two modes of system operation which are NO and EC. The approach proposed in this article is to model these states separately, as different components are involved and different success criteria are required depending on the system mode. Lifetime reliability traits are consequently established on this premise. In a subsequent stage, the forced outages caused by the individual installations can be determined in order to determine the availability of the systems.

Alternative reliability models were formulated utilizing frequently disregarded components of the EPD. This approach led to the following conclusions. Among all the supplementary components deemed, the incorporation of additional buses in the three-phase circuits in the distribution boards has by far the greatest impact. The F-V importance in NO was 44,12 % while in EC it was 34,1%. The other elements did not exceed 3% Importance in any case. The Sequencers are a prime example supporting the omission of certain devices from reliability analyses. These devices demonstrated no importance in the analyzed systems. However, this article's results demonstrate the possibility of further elaboration on EPD models for lifetime reliability studies. Further research is required to evaluate the reliability of electric systems in HTGRs. Additionally, an expanded examination of extending the models of these systems to include remaining modes of potential failures is necessary.

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