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Risk-Based Design of Electric Power Systems for Non-Conventional Nuclear Facilities at Shutdown Modes

Borsoi S. S.[1], Baroni D. B.[2], Mattar Neto M.[3], Oliveira P. S. P.[4], and Maturana M. C.[5]

[1]sadborsoi@usp.br, *USP*
[2]douglas.baroni@marinha.mil.br, *CTMSP*
[3]mmattar@ipen.br, *IPEN/CNEN*
[4]patricia@ipen.br, *IPEN/CNEN*
[5]marcos@labrisco.usp.br, *LabRisco*

1. Introduction

Electric power systems reliability is of paramount importance for safe operation of nuclear power plants (NPPs) and impacts the probability of occurrence of a Station Blackout (SBO) event, which is characterized by the loss of all alternating current power supply to plant safety busbars. Since the Fukushima Daiichi accident in 2011, there has been an increase in nuclear scientific community's perception of the need to improve electric power supply reliability level to ensure safe shutdown of nuclear reactors.

According to the General Design Criteria 17 (GDC 17), established by the U.S.NRC in Appendix A of 10CFR50 [1], "*the electric power from the transmission network to the onsite electric distribution system shall be supplied by two physically independent circuits (not necessarily on separate rights of way) designed and located so as to minimize to the extent practical the likelihood of their simultaneous failure under operating and postulated accident and environmental conditions. A switchyard common to both circuits is acceptable*". In Brazil, non-conventional nuclear facilities, such as nuclear reactor prototypes for naval propulsion and shipyards that support nuclear submarines, do not have specific normative design basis defined by the regulatory authority, named CNEN. Consequently, for these non-conventional facilities, codes and standards applicable to nuclear power plants (NPP) have been used, imposing rigorous safety requirements and impacting projects financial feasibility. To comply with GDC 17 [1], power supply from transmission system to NPP must be guaranteed by at least two transmission lines (TL) distributed in different towers. Assembling TL in isolated and difficult to access places, such as hills and slopes, may lead to high deployment costs. In addition, transmission systems are subject to transient phenomena that can be induced, for example, by atmospheric discharges, activation of inductive loads (motors and transformers), switching capacitors, sustained power failure etc. Also, some undesirable events can occur due to component failure, among which TL can be considered the most susceptible items, especially if their physical dimensions and functional complexity are considered. TL travel long distances and, most of the time, are subject to several harsh environmental conditions. Problems associated with monitoring, events location and corrective maintenance are also factors to be highlighted. Based on quality indicators provided by the Brazilian National Electric System Operator (ONS) [2], it is observed that TL contribute, approximately, with 70% of the failures attributed to loss of offsite power.

It is important to mention that loss of offsite power, which may involve transmission systems, is not considered an accident initiating event for non-conventional nuclear facilities operating at-power mode. In this case, the nuclear reactor operates isolated from offsite power systems and power generated from nuclear reaction supplies electric power to plant internal systems. Therefore, a reactor trip induced by loss of offsite power is not a credible event for this operating mode and, likewise, a reactor trip does not affect offsite power system operation. On the other hand, during shutdown mode, non-conventional nuclear facilities depend on offsite power sources to supply their safety busbars and loss of offsite power is considered an accident initiating event for the safety analysis of these facilities. In addition, loss of offsite power is a contributor to an SBO scenario, imposing operational restrictions that may increase plant overall risk. Thus, alternative design solutions must be implemented and submitted to the licensing authority, to prove that such solutions are reliable and may increase electric power availability up to a level compatible with the electric power system architecture established in GDC 17 [1]. This work aims to present a probabilistic approach to assess electric power systems safety for non-conventional nuclear facilities during refuelling outage. Based on the results of this assessment, the risk associated with loss of long-term residual heat removal and loss of cooling in the spent fuel storage can be determined.

2. Methodology

The methodology proposed in this study consists of using the Probabilistic Safety Assessment (PSA) developed for a non-conventional nuclear facility to assess the impact of modifications in the electric power systems configuration on the risk associated with this facility during shutdown mode. In this case, the measure to be adopted to assess the risk is core damage frequency (CDF) and the PSA considered in this study is a Level 1 PSA for shutdown modes. The Shutdown PSA includes the modelling of plant structures, systems, and components that are relied upon to remain functional to maintain plant parameters within a safe-stable state during refuelling outages. The main systems involved are Residual Heat Removal System (RHRS) and Primary Fuel Pool Cooling System (FPCS), as well as support systems, such as electric power and instrumentation and control (I&C) systems. Electric power and I&C systems perform secondary/support functions for the successful operation of front-line systems. Furthermore, at shutdown mode, failures in electric power and I&C systems may lead to accident scenarios during fuel recharging activities, contributing to the frequency of occurrence of accident initiating events.

The Shutdown PSA considered in this work was developed in accordance with procedures recommended in IAEA Specific Safety Guide No. SSG-3 [3]. Besides, modifications to the models originally developed for the facility were evaluated to reflect proposed changes in electric power systems configuration. Therefore, these modifications comprised, mainly, revision of systems fault tree models so that they could represent new configurations proposed for the electric power systems. Review and updating of electric power systems component data, including component failure rates/probabilities and factors associated with common cause failures, were important tasks performed. Revised and updated values were incorporated into the PSA model implemented in CAFTA [4], which was the computer code used in this study. Thus, new estimates for the reliability of electric power systems were obtained, impacting both the failure probability of support functions performed by these systems during an accident sequence as well as the frequency of occurrence of accident initiating events caused by loss of electric power. Reliability data incorporated in this PSA are mainly based on generic data published on U.S.NRC website (https://nrcoe.inl.gov/) [5]. The Idaho National Laboratory (INL) participates in the management of this database, which includes data representative of nuclear industry current practices. Some specific data on equipment failure rates were originally published in NUREG/CR-6928 [6], the most recent edition of which is from 2007 and since then, these data have been periodically updated and made available on U.S.NRC website [5].

Initially, a model for basic configuration of electric power systems based on NPP codes and standards was incorporated to the Shutdown PSA previously developed for the facility. Then, some modifications in electric power systems configuration were proposed and new analyses were carried out. The four distinct configurations proposed in Figure 1 are:

Configuration A = Basic configuration required for NPPs Electric Power Systems (Offsite Power with 2 independent TL);

Configuration B = Configuration A + Modification 1;

Configuration C = Configuration B + Modification 2; and

Configuration D = Configuration C + Modification 3.

Note: Configuration D represents a configuration proposal for electric power systems adequate for a non-conventional facility with one TL.

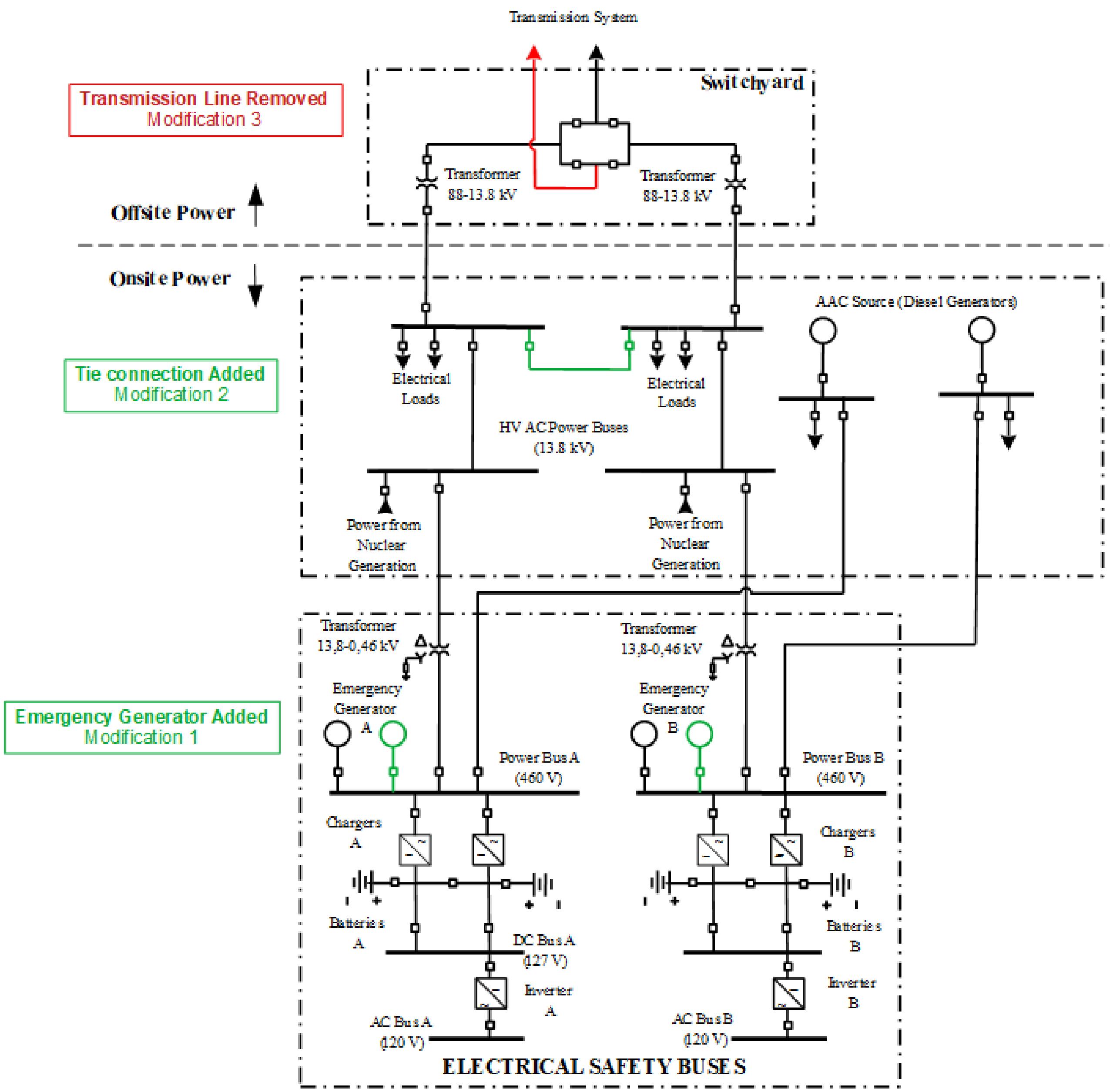

Figure 1 – Basic electrical configuration of a NPP with three modifications to represent the electrical configuration of a non-conventional facility with one TL.

3. Results and Discussion

Generic reliability data from U.S.NRC website [5] were used in the analyses. Additionally, the following assumptions were made:

(i) Refuelling outages were assumed to last 30 days (8.22E-2/yr);
(ii) Test and maintenance for front-line systems were assumed to have an average unavailability of 40-48hrs in a 30-day-outage (5.00E-3/yr). Support systems that have the potential to impact both front-line systems are assumed to have the same average unavailability;
(iii) All components were considered repairable and a mean time to repair (MTTR) of 24hrs was assumed;
(iv) Standby circuits operating time is defined to be 24 hours. Thus, the first system failure (the running component) can be considered as the initiator and the backup systems as the mitigation response; and

(v) Test and maintenance for two components that accomplish the same function in two redundant safety trains must not be performed simultaneously.

Analyses results are shown in Table 1, in which the contribution of SBO to plant total CDF considering the four electric systems configurations are presented. Total CDF reduction comparing configurations B, C and D with A are presented in the last column. Comparison between configuration A (basic NPP) and configuration D (adequate for non-conventional nuclear facilities) shows that there is a 28.42% reduction in total CDF and SBO contribution to CDF in Configuration D (6.30E-6 /yr) is around 4.5 times smaller than in Configuration A (2.72E-5 /yr).

Table 1 – CDF estimates for different electric power systems configurations.

Electrical Configuration	CDF_{TOTAL} (/yr)	CDF_{SBO} (/yr)	CDF_{SBO} (%)	ΔCDF_{TOTAL} (%)
A	7.49E-5	2.72E-5	36.33	-
B	5.47E-5	7.04E-6	12.87	26.95
C	5.16E-5	4.94E-6	9.57	31.12
D	5.36E-5	6.30E-6	11.75	28.42

4. Conclusions

CDF is an adequate risk metric for the objectives of this study and PSA methodology is an important tool to support decision making for the design as well as the licensing process of non-conventional nuclear facilities. In this work, PSA was used to support the selection of alternative configurations of electric power systems design, overriding the standard configurations required for NPPs.

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