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Three-loop Monte Carlo simulation approach to Multi-State Physics Modeling for system reliability assessment

Wei Wang[a], Francesco Di Maio[a,*], Enrico Zio[a,b]

[a] Energy Department, Politecnico di Milano, Via La Masa 34, Milano 20156, Italy
[b] Chair on System Science and the Energy Challenge, Fondation Electricite' de France (EDF), CentraleSupélec, Université Paris-Saclay, Grande Voie des Vignes, Chatenay-Malabry 92290, France

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ABSTRACT

Multi-State Physics Modeling (MSPM) provides a physics-based semi-Markov modeling framework for a more detailed reliability assessment. In this work, a three-loop Monte Carlo (MC) simulation scheme is proposed to operationalize the MSPM approach, quantifying and controlling the uncertainty affecting the system reliability model. The proposed MC simulation scheme involves three steps: (*i*) the identification of the system components that deserve MSPM, (*ii*) the quantification of the uncertainties in the MSPM component models and their propagation onto the system-level model, and (*iii*) the selection of the most suitable modeling alternative that balances the computational demand for the system model solution and the robustness of the system reliability estimates.

A Reactor Protection System (RPS) of a Nuclear Power Plant (NPP) is considered as case study for numerical evaluation.

1. Introduction

System reliability assessment relies on a model of the system failure process: the more accurately the model reproduces the system behavior, the more confident the system reliability assessment. Physical knowledge, expert information and data on the system behavior are used to build the model and estimate its parameters [2,3]. The uncertainties in the model and parameters can be propagated by Monte Carlo (MC) simulation [12,47,50,51], Bayesian posterior analysis [46] and Fuzzy methodology [5,18,21,22]. Most commonly, MC simulation is used, consisting in repeatedly sampling random values of the inputs from probability distributions [52].

MSPM is a semi-Markov modeling framework that allows inserting physical knowledge on the system failure process, for improving the system reliability assessment by accounting for the effects of both the stochastic degradation process and the uncertain environmental and operational parameters [17,30,38,40].

In this work, a three-loop MC simulation scheme is proposed for MSPM system reliability modeling. The proposed MC simulation is made of three steps: (*i*) the identification of the components of the system for which a component-level MSPM is beneficial, because of the importance of the component for the system unreliability, (*ii*) the quantification and propagation of the uncertainty, and (*iii*) the selection of the proper modeling details, considering computational demand and robustness of the result.

The first step is achieved by Sensitivity Analysis (SA), which can be informed in three different ways: local, regional and global [16,34]. Global SA, in particular, measures the output uncertainty over the whole distributions of the input parameters and can be performed by parametric techniques, such as the variance decomposition method [10,35,36,43,44] and moment-independent method [7,8,13,42]. The variance-based method measures the part of the output variance that is attributed to the different inputs or set of inputs, without resorting to any assumption on the form of the model [11,31,33–35]. The moment-independent method allows quantifying the average effect of the input parameters on the reliability of the system and provides their importance ranking [48]. In this work, we resort to moment-independent sensitivity measures, such as Hellinger distance and Kullback-Leibler divergence [14,20], for ranking the input variables most affecting the system reliability uncertainty [16,24].

The second step consists in quantifying the uncertainty in the output of the reliability model. The method adopted for this depends on the components modeling approach: for binary-state Markov Chain Models (MCMs), the variance of the transition failure rate is estimated by Fisher Information Matrix [1,15,26,28]; for MSPM component models, the transition rates uncertainty is propagated and, therefore, estimated by MC.

* Corresponding author.
E-mail address: francesco.dimaio@polimi.it (F.D. Maio).

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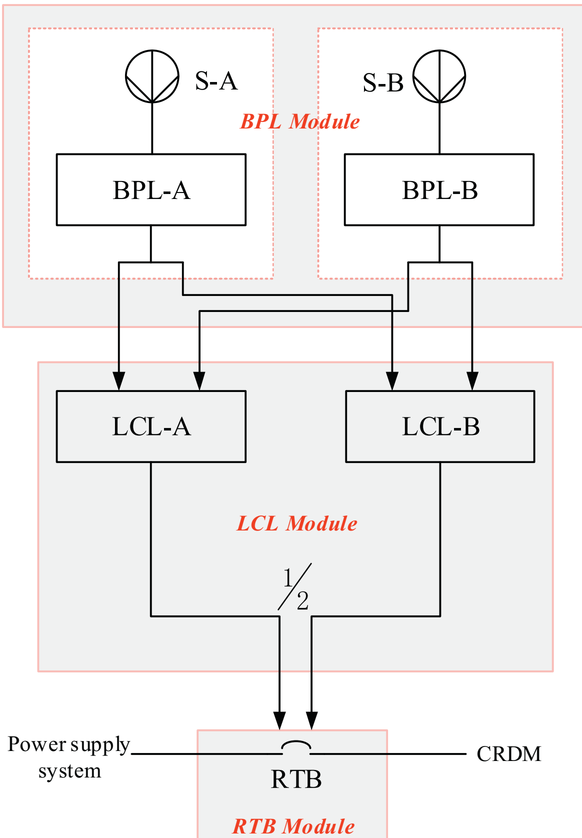

Fig. 1. RPS scheme [41].

For the last step, MC simulation is utilized to propagate uncertainties in the system model and estimate the confidence intervals of the system unreliability.

A Reactor Protection System (RPS) of a Nuclear Power Plant (NPP) is considered as case study. MCM and MSPM are built for the reliability assessment. The Resistance Temperature Detector (RTD) is identified as the most important component. Confidence intervals of the system reliability estimates by RPS-MCM are computed and compared with those of RPS-MSPM that are obtained by the three-loop MC simulation.

The reminder of the paper is organized as follows. Section 2 describes the RPS case study and its MCM reliability model taken as reference. In Section 3, a SA of the MCM is performed and the embedded RTD is identified as the component most affecting the RPS reliability. RPS-MSPM is, then, built for it. Section 4 compares the confidence intervals of the system reliability estimates obtained by MCM and MSPM. In Section 5, conclusions are drawn.

2. The Reactor Protection System

The RPS function is to trigger the NPP emergency shutdown, when an anomaly is detected in the measurements of a relevant signal (here assumed to be a temperature signal). As shown in Fig. 1, the RPS is composed of two redundant channels (A and B). Each channel consists of one signal sensor (S-A and S-B), one Bistable Processor Logic (BPL) subsystem (BPL-A and BPL-B), and one Local Coincidence Logic (LCL) subsystem (LCL-A and LCL-B). Usually, redundancy is applied to sensors and signal processing units of RPS. However, with respect to the development of the methods proposed in the paper, we do not consider this for keeping the modeling complexity at a minimum without loss of generality. Furthermore, the sensors S-A and S-B are considered to be RTDs, because of the importance of these components in NPPs digital Instrumentation and Control (I&C) systems [6,45]. RTDs are safety-

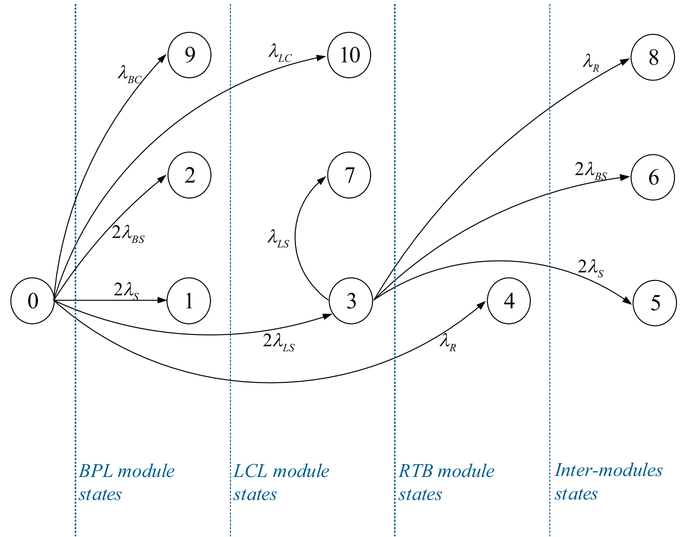

Fig. 2. The RPS-MCM where states are grouped according to their intra-module and inter-modules characteristics.

critical components and their effectiveness of detection of anomalous temperatures is very important for plant operators for monitoring the NPP operational conditions [23]. The reliability and accuracy of RTDs is important for controlling the NPP power rate with confidence, guaranteeing large power rates with sufficient safety margins [40,45].

If any one of the two redundant measured signals exceeds a triggering threshold value, a Partial Tripping Signal (PTS) is sent to the corresponding BPL. The signal processing activates only if both channels produce the PTS: each PTS from a BPL is sent to both LCL-A and LCL-B, which process information by an “AND” gate. In other words, an Emergency Shutdown Signal (ESS) is produced only when receiving two PTSs from different BPLs; ESSs, then, activate the Reactor Trip Breaker (RTB), when at least one ESS is triggered, i.e., the information is processed by an “OR” gate. Once the RTB is activated, the power supply system and Control Rod Drive Mechanism (CRDM) which are connected with the RTB activate to control the power of the reactor.

According to the RPS scheme of Fig. 1, three modules are identified:

- The BPL Module consists of two groups of components: sensor and BPL (i.e., “S-A and BPL-A” and “S-B and BPL-B”); these components are connected in series and their failure effects on the system can be combined.
- The LCL Module consists of the two LCLs (i.e., LCL-A and LCL-B); since the ESS is triggered only when both LCLs simultaneously receive two PTSs from the two BPLs, this module is highly dependent of the BPL module.
- The RTB Module.

2.1. The RPS-MCM

In this Section, a binary-state MCM is built as reference for the reliability assessment of the RPS. To do this, intra- and inter-module states leading to the system failure are identified. Intra-module states refer to events leading to the system failure that concerns components belonging to the same module; inter-module states relate to system failures from combined component events in different modules.

Fig. 2 shows the RPS-MCM, whose states (listed in Table 1) are grouped into four categories that relate to the intra- and inter-module distinction. The following assumptions have been made for the subsequent quantitative analysis:

- Transitions can occur from the system functioning state (state 0) to any of the absorbing failure states of the intra-module category and