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PSA model approaches for asymmetries in the electrical power supply for nuclear power plants

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In the more recent past, several events reported from nuclear power plants (NPPs) indicated that failures caused by asymmetries in the electric power supply can trigger correlated failures of redundant trains of safety related systems. Since the risks from these incidents had been rarely investigated for German NPPs, an existing RiskSpectrum® Level 1 probabilistic safety analysis (PSA) model of a German pressurised water reactor (PWR) has been extended by GRS to include independent and correlated failures caused by asymmetries.

Five different approaches have been developed to model the failures. Four approaches take correlated failures into account. Two of them use the common cause failure groups of RiskSpectrum®. The other two are more complex and need different steps with different computer programs, e.g., for external parameter sampling. The evaluation of the five approaches and the sensitivity study of modelling assumptions led to the following results and conclusions. The core damage frequency (CDF) caused by correlated failures resulting from asymmetries is clearly higher than the overall CDF from plant internal initiating events if no instrumentation and control (I&C) equipment to detect and protect against asymmetries is installed. Hence, the consideration of correlated failures caused by asymmetries in PSA models seems to be relevant. But only one scenario of asymmetries has been considered and more scenarios are necessary to realistically reflect their effects.

Keywords: asymmetry, phase fault, common cause failure, correlated failure, electrical power supply, external hazard, model development, nuclear power plant, PSA model.

1. Introduction

Incidents in the Forsmark (2006, 2013), Grohnde (2011) and Byron (2012) nuclear power plants (NPPs) have demonstrated that failures caused by asymmetries in the electric power supply can lead to correlated failures of redundant trains of safety related systems. Such asymmetries can occur in different scenarios, e.g., static overcurrent in the emergency power supply, or static as well as transient asymmetries in the external power supply. In the aftermath of these scenarios, several studies on failures caused by asymmetries have been performed, e.g., EPRI (2014), VGB (2016). GRS has also conducted various studies, e.g., Brück et al. (2017) and Brück et al. (2018), concluding that the modelling of correlated failures of components caused by asymmetries in the electric power supply is still an open issue. Furthermore, asymmetries in the electric power supply and subsequent accident sequences have not been considered within probabilistic safety analyses (PSAs) for German NPPs. For these reasons, GRS has carried out two research projects outlined in more detail in Berner et al. (2020) and Berchtold et al. (2023). The latter investigated the effects from correlated failures caused by asymmetries. The results of this project are presented hereafter with the focus on a comparison of different approaches used to model correlated failures caused by asymmetries within PSA models.

2. Methodology

2.1. Analysis of operating experience and modelling of component failures

International operating experience comprising about 16,000 reactor years has been analysed to determine the failure characteristics of components when an asymmetry of the electrical energy supply system occurs, see Berchtold et al. (2023) and Stiller et. al. (2023). As a first approximation, a model was conceived that relates the failure probability of components $f(a)$ to the asymmetry it is exposed to. The asymmetry a is defined as the quotient of the voltages of the negative sequence component and the positive sequence component with a strictly monotonously increasing function f, which was specified based on theoretical consideration and limited operating experience data, see Berner et al. (2020). However, it turned out that this approach did not capture the strong correlations of component failures observed in operating experience, where in most cases all or most identical components with identical loads failed or no such components failed. These correlated failures are highly relevant to PSA since multiple redundant components are affected.

Therefore, four different procedures have been developed to model these correlations. They consist of two stages each. Stage I determines if failures occur at all in a group of identical components with identical loads. Stage II determines the number of failed components. For stage I two different procedures have been considered. **Procedure I.1** is based on the direct analysis of the national and international operating experience mentioned above. Based on the numbers of groups of identical components with similar loads exposed to the asymmetry and on the numbers of these groups affected by component failures, an uncertainty distribution μ_{A} of the probability that failures occur was derived:

$$\begin{aligned} & p_{\text{Modell}}(\mu_A): \\ & = \frac{1}{3} + \frac{2}{3}\, p_{\text{Beta}}(\mu_A | 4.35, 178.67) \end{aligned} \tag{1}$$

It should be noted that μ_{A} is event-specific, i.e., is identical to all groups. **Approach I.2** is based on the failure model of individual components discussed above: μ_{A} is calculated as $\mu_{\mathrm{A}} = ef(a)/\sum_{k=1}^{e} k\, w_{k\backslash e}$ with e denoting the number of identical components with identical loads and $w_{k\backslash e}$ denoting the probability that k out of e components fail. Here μ_{A} is specific to an event and a component group since the asymmetry value a is individually calculated for an event and a group of components. For stage II, which models the correlations, again two different procedures have been considered. **Procedure II.1** consists of a direct estimation of $w_{k\backslash e}$ from the operating experience. Here, obviously, only operating experience with a matching number of exposed components e may be used. **Procedure II.2** consists of estimating the transition probabilities of a graphical model from the operating experience data. The $w_{k\backslash e}$ are calculated from the transition probabilities. The model parameters and their uncertainties were estimated by Bayesian statistical methods as described in Stiller (2022). Using these estimations, the probabilities of k of e failures $\mu_{\mathrm{A}} w_{k\backslash e}$ including their uncertainty distributions were calculated. Where necessary, Monte Carlo methods were applied. Part of this calculation can be done implicitly by applying the automated common cause failure (CCF) modelling with the alpha factor model as discussed below.

2.2. PSA Model

An existing RiskSpectrum® Level 1 PSA model of an example German PWR has been used for this study. This PSA model was extended applying five different approaches to consider failures caused by asymmetries. The approaches and their procedures for both levels are called 0 (I.2, without correlated failures), A (I.2, II.1), B (I.2, II.2), C (I.1, II.1), D (I.1, II.2). The approaches 0, A and B can be simply modelled in RiskSpectrum®, while the approaches C and D require several steps with different computer programs. Hence, some simplifications have been made for this study to reduce the computational effort. The simplifications are summarised at the end of the event description. The approaches are detailed in the subsequent subsections. The last subsection describes the methodology used to discuss the assumptions.

2.3. Event description

The accident sequence is assumed to start with the scenario ‘transient asymmetries in the external power supply’. The expected plant behaviour is a reactor trip with a transition to a hot standby state. Hence, the failure of the system functions shown in Figure 1 can lead to transients.

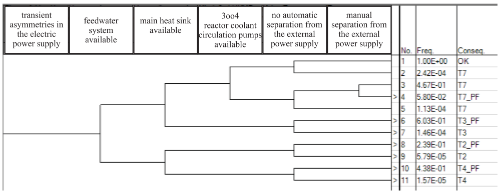

Fig. 1. Event tree used after asymmetries in the electric power supply.

After an asymmetry the plant has to be separated from the external power supply, either automatically or manually, in order to avoid additional failures caused by asymmetries. If the separation was not successful, additional failures have to be considered in the accident sequences of the transients (T2_PF: ‘loss of main feedwater’, T3_PF: ‘loss of ultimate heat sink’, T4_PF: ‘loss of ultimate heat sink and main feedwater, T7_PF: ‘manual shutdown after loss of minimum two reactor coolant pumps’).

In summary, the PSA model for the analysis of failures caused by asymmetries is based on four major simplifications. First, the model does not include I&C equipment to detect and protect against asymmetries, which are commonly applied in NPPs. Second, only a single scenario related to asymmetries has been considered, as mentioned above; others have not been considered. Third, the occurrence of the scenario is a prerequisite for most parts of this study; therefore, the conditional probability is one. Fourth, the study extends only to the so-called ‘hazard state’ of the NPP. A hazard state leads to core and/or fuel damage if no emergency measures, e.g., feed and bleed, have been successfully taken. These simplifications are reasoned by the comparison of different approaches as goal of this study. Particularly, the fourth simplification was made to reduce the computational efforts for the approaches C and D. Therefore, this study was mostly directed to the comparative evaluation of the conditional core hazard probability (CCHP) as consequence of the assumed scenario, but also comprises a discussion of the core hazard frequency (CHF).

2.4. Modelling of approach 0 as basis for the other approaches

The approach 0 only models independent component failures caused by asymmetries without taking correlated failures into account. The failures caused by asymmetries have been added to the PSA model with a total of 123 basic events. The failure probability is determined applying the procedure I.2. This approach forms the basis for the implementation of further approaches. Hence, a basic event of an independent failure is included together with the house events for the approaches as exemplified in Figure 2.

2.5. Modelling of approaches A and B

The approaches A and B are implemented via exchange events of the independent failure basic event of approach 0 to also consider correlated failures. Their basic events use the same independent failure probability determined by procedure I.2.

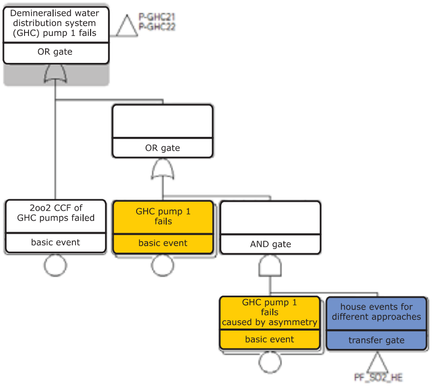

Fig. 2. Implementation of the different approaches in the fault tree of the demineralised water distribution system (GHC) using a transfer to the house events (blue) and exchange events for the failure (orange).

The correlated failures have been included with in total 72 CCF groups of RiskSpectrum$^{®}$. The CCF groups are assumed to be complete. This assumption will be scrutinised in the sensitivity analysis. The alpha factors shown in Table 1 (procedure II.1) and Table 2 (procedure II.2) are used to quantify the correlated failures for the approaches A and B, respectively.

Table 1. Alpha factors from procedure II.1 with a beta distribution (parameters beta 1, 2, oo: out of).

Case	Mean	Beta 1	Beta 2
2oo2	9.50 E-01	9.50 E+00	5.00 E-01
2oo3	7.69 E-02	5.00 E-01	6.00 E+00
2oo4	2.14 E-01	1.50 E+00	5.50 E+00
3oo3	8.46 E-01	5.50 E+00	1.00 E+00
3oo4	7.14 E-02	5.00 E-01	1.00 E+00
4oo4	5.00 E-01	3.50 E+00	3.50 E+00

Table 2. Alpha factors from procedure II.2 with a beta distribution (parameters beta 1, 2, oo: out of).

Case	Mean	Beta 1	Beta 2
2oo2	8.40 E-01	1.85 E+01	3.50 E+00
2oo3	5.90 E-02	1.41 E+00	2.22 E+01
2oo4	4.50 E-02	1.12 E+00	2.39 E+01
2oo6	2.20 E-02	5.40 E-01	2.37 E+01
3oo3	8.40 E-01	1.85 E+01	3.50 E+00
3oo4	4.50 E-02	4.20 E-01	2.76 E+01
3oo6	2.20 E-02	5.40 E-01	2.37 E+01
4oo4	8.40 E-01	1.85 E+01	3.50 E+00
4oo6	7.50 E-03	2.50 E-01	3.28 E+01
5oo6	7.50 E-03	2.50 E-01	3.28 E+01
6oo6	8.40 E-01	1.85 E+01	3.50 E+00

2.6. Modelling of approaches C and D

The approaches C and D to model correlated failures are based on the approaches A and B, but their implementation is more complex. This complexity is caused by dependencies of the independent failure probability f and the uncertain parameter μ_A as well as the parameters $w_{k\setminus g}$ used for the CCF probability, see Eq.(1). These dependencies cannot be modelled in RiskSpectrum®. Hence, the approaches C and D were realised in following steps. **First step**: Monte Carlo simulation with 1,000 samples of μ_A with Eq. (1) for all 123 basic events of failures caused by asymmetries and of the beta-distributed alpha factors in Tab. 1 (approach C) and Table 2 (approach D). The failure probabilities f of all basic events are determined for all 1,000 samples as $f = \mu_A \sum_{k=1}^{g} w_{k\setminus g}\, k/g$. The number of samples was checked with regard to convergence of the CCHP in step 4. **Second step**: Set up of 2,000 PSA models for the 1,000 samples and the approaches C and D with the PSA model described in the previous subsections as template using the GRS tool pyRiskRobot; the PSA models use the deterministic values of the failure probability f in the basic events of failures caused by asymmetries. **Third step**: Consequence analyses of the scenario described in Section 2.1 with each of the 2000 PSA models; the analysis is focused on the transient T7 with a minimal cut-set analysis without uncertainties; these simplifications have been applied to reduce the computational effort (see Section 2.1). **Fourth step**: Text outputs of all consequence analyses are automatically processed to produce the final results for the approaches C and D.

2.7. Method used in the sensitivity analysis

Three major assumptions have been identified in the PSA model and scrutinised using the method by Berner (2016) for more information. According to this method, the assumptions have first been categorised with regard to the following three criteria and their categories. First, the ‘**strength of background knowledge** to the assumption’ can be either weak, moderate, or strong. ‘Weak’ is for example characterised by either strong simplification, a not available or not reliable database, the lack of agreement among experts, or badly understood phenomena. ‘Strong’ can be taken if e.g., the assumption is expected to be reasonable, and reliable data are available, and phenomena are well understood, and models give good predictions. Medium is everything in between weak and strong. Second, the ‘**belief in deviation** from the assumption’ can be categorised with low, moderate, or high. The categorization is done qualitatively regarding the assumption on the basis of the background knowledge. Third, the expected ‘**sensitivity** of the PSA result on a deviation from the assumption’ is categorised with low, moderate, and high using following definitions: low, only unrealistic high deviations have an influence on the PSA result; moderate, only high deviations have an influence; high, small deviations have an influence. In the next step of Berner (2016), the assumptions have been categorised by six different settings S1 to S6 depending on their categories as shown in Table 3.

Table 3. Classification scheme for an assumption to settings S1 to S6 according to its categories (mod.: moderate); adopted from Berner (2016).

Belief in deviation	Sensitivity	Strength of Background Knowledge	
		strong	moderate, weak
Low	low	S1	S2
	moderate, high	S3	S4
moderate, high	Low		
	moderate, high	S5	S6

After the classification, the following treatments are proposed by Berner (2016) depending on the setting of the assumption. The '**law of total expectation**', mostly for S5, means the quantitative description of the uncertainty in the assumption with a probability distribution. The term '**imprecise probability**', used for S6 and sometimes for S4, is the description of the uncertainty in the assumptions with a lower and an upper limit; both do not constitute fixed limits but illustrate the uncertainty. The term '**sensitivity categorization**', used for S3 and sometimes for S4, and also used for the documentation of S1 or S2, is a semiquantitative approach describing the uncertainty of the assumption with the criteria given before. Finally, the '**assumption deviation risk**', used for S3 or for documentation of S4, is a further characterisation of the assumption with the following factors: extents of the deviation, (subjective) probability for the deviation, and effect of the deviation from the assumptions. Different quantitative levels can be defined for each of these factors. After the treatment of all assumptions, the most crucial ones could be further refined with additional information using Bayesian updating.

3. PSA model results

The effects of the different approaches to model the failures caused by asymmetries have been analysed with the PSA model described in Section 2. The focus of this analyses was on the conditional core hazard probability (CCHP) as reasoned in Section 2.3.

Figure 3 shows the uncertainty distribution of the CCHP from all transients in the event tree in Figure 1 by using the approaches 0, A, and B. These analyses showed a clear difference in the CCHP between the approaches A and B in comparison to the approach 0 without correlated failures. This difference is caused by the additional correlated failures with the approaches A and B, namely of the start-up and shutdown pump system, the demineralised water pumps, and the ventilation systems of the diesel generators. The correlated failures of these systems had major contribution to the CCHP. Since the correlated failures are not considered in approach 0, this approach must be considered not suitable.

Since the transient T7_PF 'manual shutdown after loss of minimum two reactor coolant pumps' contributed with nearly 50 % to the overall CCHP in the analysis of approaches 0, A, and B the complex evaluation of the approaches C and D was focused on it. The mean CCHP point estimates from the minimal cut set analyses are shown in Table 4. The number of samples led to convergence of the CCHP with less than 1.5 % relative error in a bootstrap analysis. Again, the approach 0 leads to the lowest CCHP among all approaches. More importantly, the approaches A, B, C, and D, which all explicitly consider correlated failures, lead to similar results with the highest CCHP of approach B. Hence, one of these four approaches can be chosen in the PSA model to represent the four approaches for failures caused by asymmetries. This assumption is considered in the sensitivity analysis.

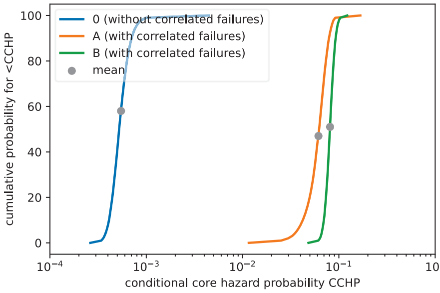

Fig. 3. Cumulative distribution of the probability for a hazard state after asymmetry for the approaches 0, A and B.

The contribution of failures caused by asymmetries on the overall CHF of the NPP was also analysed. The frequency of 7.75 E-04/a for the scenario and the CCHP of 0.081 using approach B led to a CHF of 6.28 E-05/a. This CHF is remarkably higher than the CHF from the internal events PSA without asymmetries. However, two limitations have to be taken into account: first, only a single scenario described in Section 2.1 was assumed in this PSA model; second, the PSA models a plant without I&C equipment to detect and protect against asymmetries. If such equipment, which has been retrofitted in many plants, is available, the CHF given here must be considered conservative. The effect of the first assumption is determined in the sensitivity analysis.

Table 4. Results from the hazard state-analysis of transient T7 using the PSA model with the different approaches.

Approach	Procedures	CCHP (point estimate)
A	I.2, II.1	0.059
B	I.2, II.2	0.077
C	I.1, II.1	0.055
D	I.1, II.2	0.019
0	I.2	0.00065

4. Discussion of assumptions

Three major assumptions in this PSA model have been investigated with the method of Berner (2016).

With the first assumption in Section 2.3 it is stated that the CCF groups are complete. There are 36 CCF groups for each approach and three of them contribute to nearly 50 % of the CCHP as outlined in Section 3. The categorization was therefore based on the following arguments: the belief in deviation is low for two reasons: first, deviations in only three of 36 CCF groups have clear effects on the CCHP; second, the definition of the relevant CCF groups is obvious from the system information; the sensitivity is moderate since only deviations in several CCF groups at the same time can affect the CCHP effectively; the strength of the background knowledge is strong because the definition of the CCF groups is based on precise system information. These categories lead to the categorisation with setting S3 according to Table 3, which can be treated with the ‘assumption deviation risk’: the extent of deviation is defined with the split-up of two relevant CCF groups; the probability of this deviation is estimated with about 0.01; regarding the minimal cut sets, the deviation is expected to result in a reduction of 25 %. Consequently, the deviation leads to a reduction of 0.25 % of the CHF, namely from 6.28 E-05/a to 6.24 E-05/a.

According to the second assumption in Section 3, one approach can be chosen in the PSA model to represent all four approaches for modelling correlated failures. This assumption is categorised as follows: The belief in deviation is high because due to sparse operating experience it is not clear which of the four approaches represents best the correlated failures caused by asymmetries; even further approaches are possible. The sensitivity is high because the choice of the approach directly affects the CCHP. The strength of the background knowledge is weak because different experts can choose different approaches. Hence, the assumption is categorised with setting S6 and treated with the ‘imprecise probability’. Depending on the approach, the CCHP can vary between 0.02 and 0.08 according to Table 4. A range of CHF between 1.6 E-05/a and 6.3 E-06/a therefore seems to be plausible; However, other CHF values regarding the concept of imprecise probability are still possible.

Based on the third assumption in Section 3 only one scenario described in Section 2.1 was considered. GRS had however identified five further scenarios in previous studies of Berner et al. (2020). Two characteristics for each of these scenarios could be derived from the available information: first, the expected occurrence of correlated failures (for one scenario), independent failures (one), or no failures (three); second, the scenario frequency based on U.S. operating experience. These characteristics allow conclusions on the contribution to the CHF. The assumption is thus categorised as follows: The belief in deviation is high because other scenarios have already been observed. The sensitivity is high since the one scenario linked to the occurrence of correlated failures has a non-negligible frequency. The strength of the background knowledge is low because the scenario frequency was derived from U.S. American operating experience and the CCHP was based on calculations from scenario 2. These criteria lead to setting S6 and the treatment with the method of imprecise probability. For the scenario prone to correlated failures, namely, static asymmetries in external power supply, the scenario frequency is expected to range between 1 E-03/a and 1 E-02/a, and its CCHP is expected in between 0.067 to 0.096 (5 % and 95 % quantiles of scenario 2 using approach B). The scenario prone to independent failures has negligible additional contribution and is not shown here. Accordingly, the lower and the upper boundaries for the CHF have been derived ranging from 7 E-05/a to 1 E-03/a being added to the CHF derived for the scenario described in Section 2.1 of 6.28 E-05/a. Finally, the results of the three sensitivity studies are summarised in Table 5. The third assumption can lead to the highest uncertainties in the CHF.

Table 5. Results from the sensitivity study for the three selected assumptions (Cat.: category).

Assumption	Cat.	Treatment	Effect on CHF
1. CCF groups	S3	assumption deviation risk	reduction from 6.28 E-05/a to 6.24 E-05/a
2. single approach	S6	imprecise probability	between 1.6 E-05/a and 6.3 E-05/a
3. only one scenario	S6	imprecise probability	6 E-05/a + (7 E-05 … 1 E-03)/a

5. Conclusions

Five different approaches to model failures caused by asymmetries in the electric power supply of NPPs have been included in an existing PSA model of an example NPP. The approach 0 models only independent failures caused by asymmetries, the other four approaches A, B, C, and D allow the consideration of correlated failures. It is expected that the analysis of other NPPs will qualitatively give similar results.

The results show that there is a non-negligible difference between the results of the approaches with and without explicit modelling of the correlated failures. Moreover, the four approaches for explicit modelling of the correlated failures lead to rather similar results. In addition, a large contribution of correlated failures caused by asymmetries to the internal events CHF can be expected if no I&C equipment for detection of and protection against asymmetries is installed. Consequently, asymmetries in the electric power supply should be considered in PSA models. The quantification of the effect of the I&C equipment for the detection and control of asymmetries will be subject of intended future research.

Furthermore, three assumptions made in the PSA model have been scrutinised in a sensitivity study. As a result, the focus on a single approach for the evaluation of correlated failures is suitable because different approaches lead to similar results. Hence, the use of approach B is recommended since it leads to conservative results and is less complex than the approaches C and D. Thus, the restriction to one approach only leads to a low uncertainty in the PSA. In the present study, only one scenario was considered. It is therefore recommended to consider further scenarios, e.g., static asymmetries in external power supply. For this purpose, it is essential to increase the knowledge on these.

The study presented here involves two limitations. First, I&C equipment for detection of and protection against asymmetries have not been modelled yet. Second, the study was mainly focused on the conditional core hazard probability which is suitable for a direct comparison of the different approaches, particularly with the high complexity in the approaches C and D. The scenario was therefore taken as a prerequisite with a conditional probability of one, and emergency measures not being included. The results are however qualitatively transferable to the core damage frequency.

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