Analysis of Turbine Missile & Turbine-Generator Overspeed Protection System Failure Probability at NPPs: A case study from PSA perspective

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Introduction

- Plant-specific analysis on turbine missile probability as well as the failure probability analysis of the turbine-generator overspeed protection system at the NPP Goesgen
- The two general categories of turbine missile failures are considered:
  - **Design** overspeed (up to approximately 120% of the rated speed)
  - **Destructive** overspeed (any speed above the design overspeed)
- NPP Goesgen (KKG):
  - 3-loop KWU PWR 1060 MWe single-unit NPP;
  - The turbine is designed as single stage high-pressure (HP) and 3-stages low-pressure (LP) turbine
  - all 3-LP turbines were replaced by Siemens AG in 2013 (planned maintenance)
  - Plant-specific PSA was performed in order to provide information on rotor burst probability, resulting from hypothetical load case
  - Turbine blades bursts are not considered as a "turbine missile" event since it is proofed that these blades would be contained within the casings
  - Only rotor shaft bursts are accounted as potential for generating turbine missiles
- The benefits of conducting a plant-specific reliability analysis of specific hazards vis-à-vis the option of using the generic databases are emphasized

Design Overspeed Analysis

- The most significant source of turbine missile is a burst-type failure of bladed LP-rotor
- Failures of the HP and generator rotors would be contained by relatively massive and strong casings
- The most critical load case considered for crack growth failure of LP-rotor is that turbine reaches 120% overspeed during each start-up; This case covers the operating speed and all maximum overspeed excursions, which may occur in normal operation of the unit.
- Monte Carlo method is used to evaluate the failure probability

P_{1r} is the rotor burst probability < 120% of rated speed due to critical crack growth after 1000 start cycles;
P_{2r} is the probability of casing penetration given a burst of the rotor up to 120% of rated speed;
P_{3r} is the probability of turbine running up to 120% of rated speed.
It is conservatively assumed that P_{2r} and P_{3r} are 1.0.

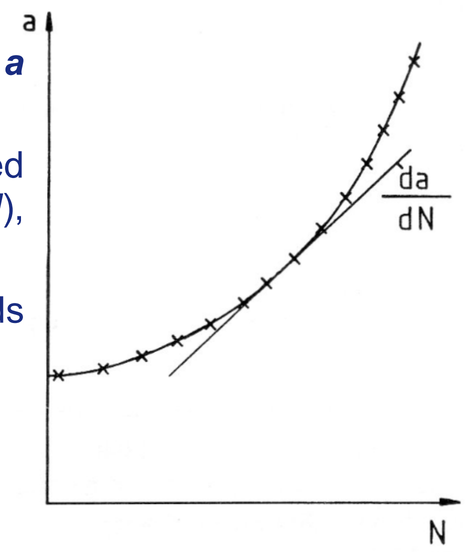
- P_{1r} calculated via a Monte Carlo simulation technique involving successive deterministic fracture mechanics calculations using randomly selected value of fracture toughness.
- The results after 1E7 simulations performed direct a 1E-7 probability for a rotor burst given 1000 start-ups.
- This turbine missile probability given design overspeed conditions was subsequently used by KKG to derive the plant-specific failure frequency. In KKG, the conservatively-assessed failure frequency is:

$(d = demands)$

Design Overspeed Analysis (*cont'd*)

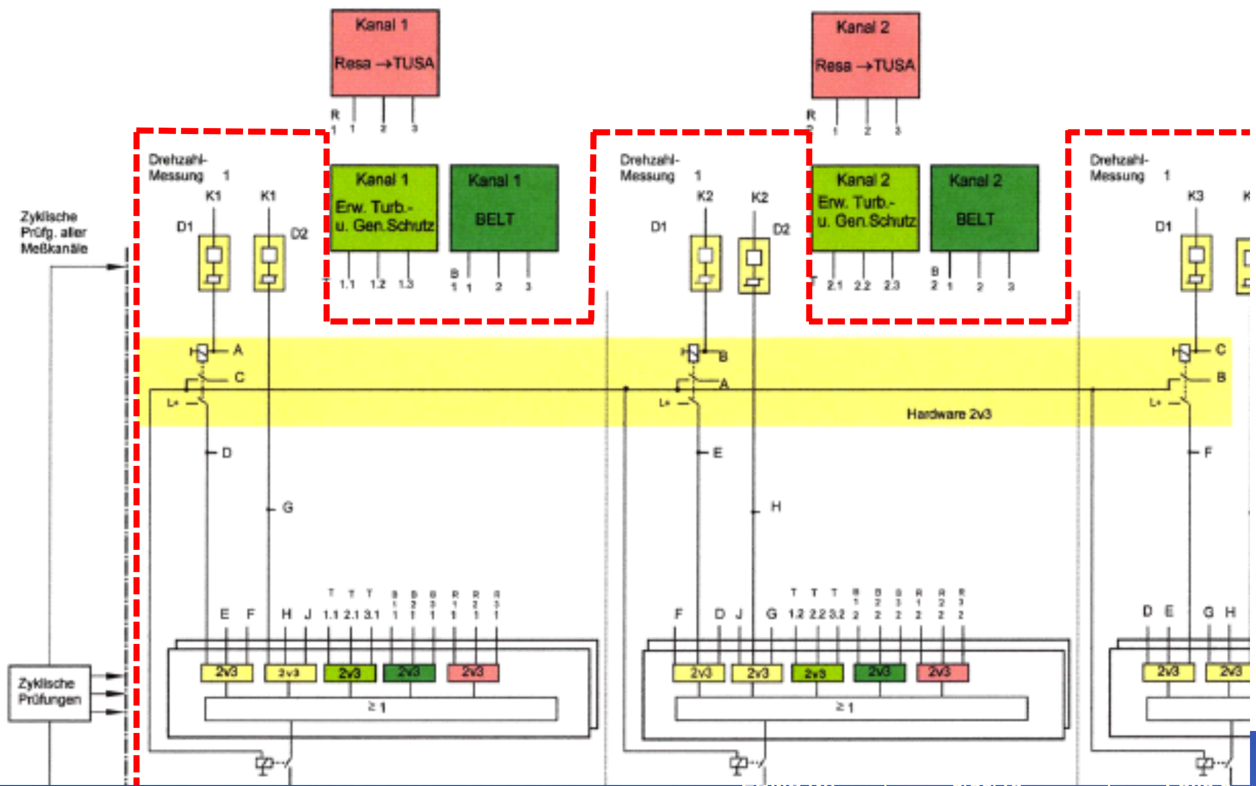
- This conservative estimate is based on the assumptions that not more than 3 relevant transients per year took place on average:
  - Annual startup **1/y**
  - Fault-related transients that lead to load shedding (load shedding to own demand, load shedding by pump failures or faults). **1/y** is calculated from 17 occurrences in 20 years;
  - The operational starting procedure following all power transients. This leads, according to the transients operating manual, starting the system 0-100%, to the above-mentioned 17 operations, i.e. conservatively **1/y**

- The conservative assumption for the calculation of the critical crack size ***a*** is based on the linear fracture mechanics
- The crack growth rate shows a monotone increasing behavior associated with the stress intensity factor, i.e. with increasing number load cycles (***N***), the cyclic stress intensity factors and thus the crack growth rates increase
- Linearization of the crack growth rate over the number of load cycles leads to an overestimation of the crack growth at small numbers of cycles
- The turbine rotor shaft failure frequency at design overspeed
  F_{design} = 1E-7/1000 * 3/y = 3E-10/y



Destructive Overspeed Analysis

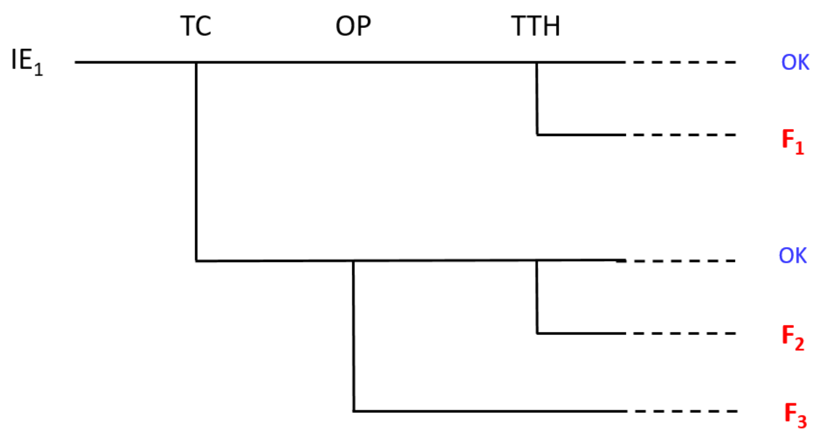
- Analysis of the failure probability of the turbine overspeed protection system is performed – via a FTA (Q = 1.02E-5/d)
- After the refurbishment, the KKG turbine overspeed protection system consists of two redundant channels – hardware and software one
- The high requirements with regard to safety, without sacrificing availability, are fulfilled with the present 2 x 2-from-3 structure

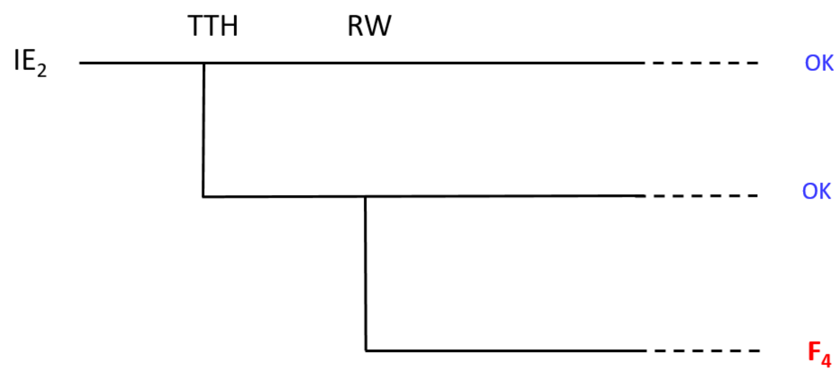


Destructive Overspeed Analysis (*cont'd*)

Initiator groups relevant for accident scenarios related to turbine missile events at destructive overspeed

1. **IE₁** - all transients and system states where the turbine is not synchronized with the grid or disconnected from the grid (conservatively set to 1.25/y):
   a. Faulty (spurious) opening of the generator circuit breaker (GCB);
   b. Faulty (spurious) opening of the block circuit breaker;
   c. All the transients related to opening of the block and / or generator circuit breaker by the protective functions (dominating, 44 such event within 38 yrs. of operation => IE1 set to);
   d. Speed control during the starting process of the turbine
2. **IE₂** - all transients that lead to a turbine trip (conservatively set to 1/y)





TC - the failure probability of the turbine governor; OP - the failure probability of the turbine overspeed protection system; TTH - the failure probability of the non-closure of a control valve and the assigned turbine trip valve of one of the 4 trains; RW - the failure probability of the power reversal protection of the generator;

Destructive Overspeed Analysis (*cont'd*)

- The risk contribution of turbine missile as a result of a overspeed scenario is quantified through the conditional core damage frequency (CCDF)
- Both the F_{design}, related to the turbine missile frequency due to design overspeed scenario, as well as the F_{TZK2}, are negligible in comparison to the F_{TZK1}. Hence, the CCDF is calculated for F_{TZK1}.
- It is conservatively assumed that at a destructive overspeed, the rotor debris will likely penetrate the casing and exit. The affected buildings with safety relevant SSC are the electrical building two emergency diesel generator buildings and the emergency feedwater injection building
- It is conservatively assumed that all three buildings are hit simultaneously and all PSA-relevant SSC are destroyed with a conditional probability of 1.0. The resulting CCDF:
- The CDF contribution is below 1E-9/y. The risk of turbine collision due to a destructive overspeed can be screened out of the PSA according to the Swiss nuclear regulations.

Summary

- Two general categories of turbine missile failures, the design overspeed failures and the “destructive overspeed” failures were considered.
- The most significant source of turbine missile is a burst-type failure of bladed LP-rotor
- To evaluate the failure probability due to rotor burst at speeds up to 120%, a Monte Carlo simulation involving successive fracture mechanics calculations using randomized fracture toughness was used.
- Plant-specific turbine missile failure probability due to destructive overspeed was analyzed:
  - *The failure probability of the turbine overspeed protection system was assessed.*
  - *Two initiator groups are defined as relevant for the accident scenarios that are related to turbine missile events at destructive overspeed*
- Benefits compared with using generic turbine missile failure probabilities (≈ 1E-4):
  - *Minimizes the relatively wide inherent uncertainties of the available generic databases*
  - *The absolute risk values obtained through a plant-specific analysis can be much lower than the generic*
  - *Plant-specific analysis of the turbine missile potential shows that the turbine missile risk can be overestimated by at least three orders of magnitude when using the generic data.*