FUZZY LOGIC IN POWER SYSTEM PERFORMABILITY

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Abstract. The paper proposes a composed model performance-dependability, combining electric-power system dependability measures and electric-power protection/automation safety measures. The paper presents the fuzzy logic aspects of power system performability evaluation. In a fault-tolerant power the failures must be detected and isolated saving the operational state of the system. We propose a Markov reward model. The instantaneous reward (IR) depends of the fuzzy Safety Transition (ST) due to the electric-power protection/automation system action. The fuzzy logic system (FLS) is used for safety analysis of the electric power protection/automation system. We propose a performability comparative study for a fault tolerant system - an electrical power (EP) isolated system. The objective is to minimize the total cost of the system, of energy loss cost due to system defaults.

1 Introduction

Performability modeling is an important topic of research in the area of fault-tolerant systems. Beaudry [1] introduced performance-reliability for degrading fault-tolerant systems. Combining the structure state process (SSP) that describes the system evolution as influenced by failures and repair with the system performance in each state of the SSP means - composite performance-dependability analysis.

In literature performance and dependability issues are dealt separately. Combined performance-dependability studies give the performability model.

The structure state of the system is a vector whose component describes the status of its constituent subsystems. The structure state of the system changes due to failures and repairs as time progresses. The transitional dynamics from one state to another is captured via the SSP. Let $\boldsymbol{Z}(u)$ be the structure state of the system at time u > 0. Then the family of random variables $\{\mathbf{Z}(u),\ u \geq 0\}$ is called the SSP.

2 Performance-dependability model

A continuous-time Markov chains (MC) model or Stochastic Petri Nets (SPN) model equivalent to MC, it is easy to realize for SSP modeling. We assume that the system reaches steady state in each of the structure state and use a performance model to compute the quantitative index of the system performance in a specific structure state (the reward associate with the structure state).

If SSP has the state space S and the generator Q. Let $\boldsymbol{P}(t)$ represent the state probability vector of MC (or SPN) then:

$$\overset{\bullet}{\boldsymbol{P}}(\mathrm{t}) = \boldsymbol{Q} \cdot \boldsymbol{P}(\mathrm{t}) \tag{1}$$

If the steady-state probability vector $\boldsymbol{P} = \lim_{t \to \infty} \boldsymbol{P}(t)$ exists

$$\boldsymbol{P} \cdot \boldsymbol{Q} = 0; \qquad \sum_{i \in S} P_i = 1; \tag{2}$$

Availability is the dependability measure for the analyzed system. We define the indicator random variable:

$$\overset{\bullet}{\boldsymbol{P}}(\mathrm{t}) = \boldsymbol{Q} \cdot \boldsymbol{P}(\mathrm{t}) \tag{3}$$

considering: $S = S_0 \bigcup S_N$ and $\mathrm{S}_0, \mathrm{S}_\mathrm{N}$ operational states set, failure states set respectively. As we well know instantaneous availability of a system $\boldsymbol{A}(u)$ at time $u \geq 0$ is the probability that the system is properly functioning at time u.

$$\boldsymbol{A}(u) = P\{\boldsymbol{I}(u) = 1\} \tag{4}$$

The steady-state availability S of a system is the limiting value of the availability:

$$\boldsymbol{A} = \lim_{u \to \infty} \boldsymbol{A}(u) \tag{5}$$

When MC (or equivalent SPN) describes the SSP we have:

$$A = \sum_{i \in S_0} P_i \tag{6}$$

Considering $\{\mathbf{Z}(u),\ u \geq 0\}$ the SSP of the manufacturing system and S be its state space. Then we have instantaneous reward (IR):

$$X(t) = \gamma_{\mathbf{Z}(t)=i} = \gamma_i \tag{7}$$

The Markov reward model (MR) is a performability model [4] that combine both dependability and performance aspects, using the SSP and IR notions respectively. The performability measure is the expected instantaneous reward (EIR) applicable for repairable systems.

$$E[X(t)] = \sum_{i \in S} \gamma_i \cdot P_i(t) \tag{8}$$

The measure used in the paper is the steady-state of the expected instantaneous reward (SEIR)

$$\lim_{t \to \infty} M[X(t)] = \sum_{i \in S} \gamma_i \cdot P_i \tag{9}$$

This paper uses a power system dependability model based on GSPN model, but having a simplified structure. A computerized tool, Stochastic Petri Nets Evaluation (SPNE) using Visual basic software, predicting dependability metrics of complex repairable power system, was developed. Given input data in the form of Petri net structure, elements failure and repair rates and availability logical conditions, for candidate architectures of power system, the computation of the dependability metrics is straightforward [3]. Combining the GSPN properties and high level Petri nets facilities, a structural simplified model Logical Explicit Stochastic Petri Nets (LESPN), having the same modelling power as GSPN, was built.

The primitive architectural modules are used to construct a LESPN structural simplified modular architecture, because the logical conditions of the system performance are explained outside the SPN model. Including predicates/transition set facilities, a great structural simplification is obtained. The arc label of the coloured Petri net dictates how many and which kinds of "coloured" tokens will be removed from or added to the places.

The model needs the IR performance measure for each of the SSP state. The structure state of the system changes due to its elements failure and repair as time progresses. For a power system the failure of an element is detected an isolated by the electric-power protection/automation system. If the electric-power protection/automation system is operational the failure is isolated and the transition to the next SSP state is possible. We propose to use the fuzzy Safety Transition (ST) due to the electric-power protection/automation system action as IR measure of each SSP state.

A fuzzy logic system (FLS) is used for safety analysis of the electric power protection/automation system. The in FLS parameters are Occurrence and Severity of the failure and the out FLS parameter is Safety. Also an adequate rule based is elaborated [2].

3 Fault tolerant power system performability

The energy loss cost (ELC) due to system defaults is an important component in power system function. Performability of a power system must combine the results of the electric- power system dependability analysis with the results of the electric-power protection/automation system safety. The performability measure will be used for ELC evaluation considering the connected electric power- protection/automation system.

For protection/automation system safety is used the event-tree method. Event-trees examine sequences of events and their probability of occurrence. They start with some initiating event (say a failure of some kind) and then develop the possible sequences of events into a tree. For example; is the failure detected?, does a safety relay activate? etc. The result at the end of each chain of events is then determined and the probability of each result calculated from the probabilities of the events in sequence leading to it.

Usually the fuzzy event-tree analysis, has the following steps:

1. fuzzy "failure" probability and fuzzy "function" probability evaluation, for all reliability block diagram elements;

2. fuzzy "occurrence" probability for each path (sequence of events) of the tree;
3. fuzzy " consequence" on power system evaluation, after the events sequence achievement;
4. fuzzy "risk" on power system for each path of the tree evaluation, depending on the path "occurrence" and path " consequence";
5. the tree-paths hierarchy establishing, depending on the path " risk".

The fuzzy probability of an event can be put into following subcategorizes based on the range of probability:

- - very high probability: $P_{vh} > 0.9$;
- - high probability: $0.8 < P_h < 0.9$;
- - moderate probability: $0.4 < P_m < 0.8$;
- - low probability: $0.1 < P_l < 0.4$;
- - very low probability: $0.0 < P_{vl} < 0.1$.

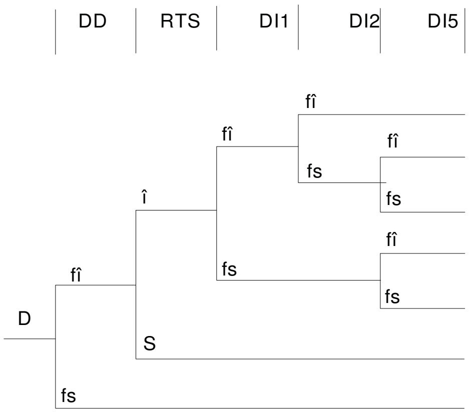
In order to see which one of the outcome has the highest possibility maximum grade of membership in the let the fuzzy probability of each outcome be $\tilde{P}_i$. The possible outcome fuzzy set is noted C_i. The fuzzy risk of each outcome is:

$$\tilde{R}_i = \tilde{P}_i \times \tilde{C}_i \quad , \quad i = \overline{1,n} \tag{10}$$

The tree - paths ranking evaluation is not enough for the electric - power protection system reliability calculation. A methodology to compute a quantitative index "General Safety Degree" (GSFD), for this kind of system, was developed in [2]. For electric power protection system safety evaluation the next algorithm is proposed:

- linguistic variables for the fuzzy logic system (FLS) parameters construction;
- FLS inputs "Occurrence" (OC) and "Severity" (SV) evaluation;
- FLS rule base evaluation and FLS outputs tree - paths " safety" (SF) evaluation;
- fuzzy general conclusion "General Safety" (GSF), for all tree - paths, evaluation;
- GSF defuzzification and "General Safety Degree" (GSFD) crisp value calculation.
- FLS rule base proposal;

'Figure 1a' shows a fuzzy event - tree example. After deducing the event tree, the outcome fuzzy probabilities are calculated as the 'Figure 1b' shown.



	PATH FUZZY PROBABILITY	PATH-FUZZY CONSEQUENC
1	$\widetilde{\text{P1}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pî}} \cdot \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pfî}}$	$\widetilde{\text{C1}} = \widetilde{\text{Cs}}$
2	$\widetilde{\text{P2}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pî}} \cdot \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pfs}} \cdot \widetilde{\text{Pfî}}$	$\widetilde{\text{C2}} = \widetilde{\text{Cm}}$
3	$\widetilde{\text{P3}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pî}} \cdot \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pfs}}$	$\widetilde{\text{C3}} = \widetilde{\text{Cî}}$
4	$\widetilde{\text{P4}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pî}} \cdot \widetilde{\text{Pfs}} \cdot \widetilde{\text{Pfî}}$	$\widetilde{\text{C4}} = \widetilde{\text{Cm}}$
5	$\widetilde{\text{P5}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Pî}} \cdot \widetilde{\text{Pfs}} \cdot \widetilde{\text{Pfs}}$	$\widetilde{\text{C5}} = \widetilde{\text{Cî}}$
6	$\widetilde{\text{P6}} = \widetilde{\text{Pfî}} \cdot \widetilde{\text{Ps}}$	$\widetilde{\text{C6}} = \widetilde{\text{Cî}}$
7	$\widetilde{\text{P1}} = \widetilde{\text{Pfs}}$	$\widetilde{\text{C7}} = \widetilde{\text{Cî}}$

Figure 1. Fuzzy event- tree for differential transformer T1 protection system.

To elaborate the event tree and to use the proposed FLS on each path of the tree, a software tool "Fuzzy event-tree analysis" (FETA) was created. We can obtain a "Safety" fuzzy set on each path of the tree. All the evaluated "Safety" fuzzy sets are introduced in an algorithm to elaborate the fuzzy "General Safety" (SG) of the system. This performance measure is used as ST parameter due to the electric-power protection/automation system action.

We propose the next algorithm for fuzzy IR parameter evaluation starting from the fuzzy Safety Transition ST_i of each SSP state i:

Step1. Inputs parameters are evaluated using FETA software:

- fuzzy general safety for electric power protection system SG_j (associated to the stochastic transition, modeling electric-power element failure, $j \in T_S$, T_S meaning the MC (SPN) stochastic transition set);

- fuzzy general safety for electric power automation system SG_{SA} (associated to each immediate transition, modeling automation system operation, $j \in T_I$, T_I meaning the MC (SPN) immediate transition set).

Step 2. SSP of the electric-power system is elaborated using MC or SPN method [5], [6].

Step 3. For *i* SSP state is selected the precedent states set *Ami* from SSP.

- if we find a transitory state *k* (followed by an immediate transition, modeling electric-power automation system action), its *Amk* set of precedent states is selected;
- if don't find a transitory state *k,* jump to step 4.

Step 4. Fuzzy IR parameter is evaluated for each *i* SSP state:

- if there is no transitory state *k* in *Ami* set then

$$\tilde{}IR = \bigcap_{j=1}^{AMi} SG_j \tag{11}$$

$j = \overline{1, AMi}$, *j* meaning an *Ami* state;

- if there is a transitory state *k* in *Ami* set then

$$\tilde{}IR = \left(\bigcap_{j=1}^{AMi} SG_j \right) \cap SG_k \tag{12}$$

$$SG_k = \bigcap_{r=1}^{AMk} SG_r \cap SG_{SA} \tag{13}$$

$r = \overline{1, AMk}$, r meaning an *AMk* state, SG_{SA} meaning the fuzzy number SG of automation system.

Step 5. IR parameter defuzzification is realized and ST_i crisp value for *i* SSP state is obtained.

The proposed Markov reward model gives the performability measure of the power system. Computing the steady-state probability vector $\mathbf{P}(t)$ and the instantaneous reward for the SSP states the steady-state of the expected instantaneous reward is obtained:

$$SEIR = \sum_{i \in S} P_i \cdot ST_i \tag{14}$$

4 A power system prformability comparative study

Naval power plant is an isolated system, usually having a single sectioned busbar system. The fault tolerant power system has automatically coupled Diesel generators to different busbar sections, improving the system availability ('Figure 2'). The Diesel generators and the most important consumers are coupled to the main busbar (MB), with three sections, section S3 having the shore coupling board (SCB) system. The 220Vac consumers are coupled to the secundary busbar (SB).

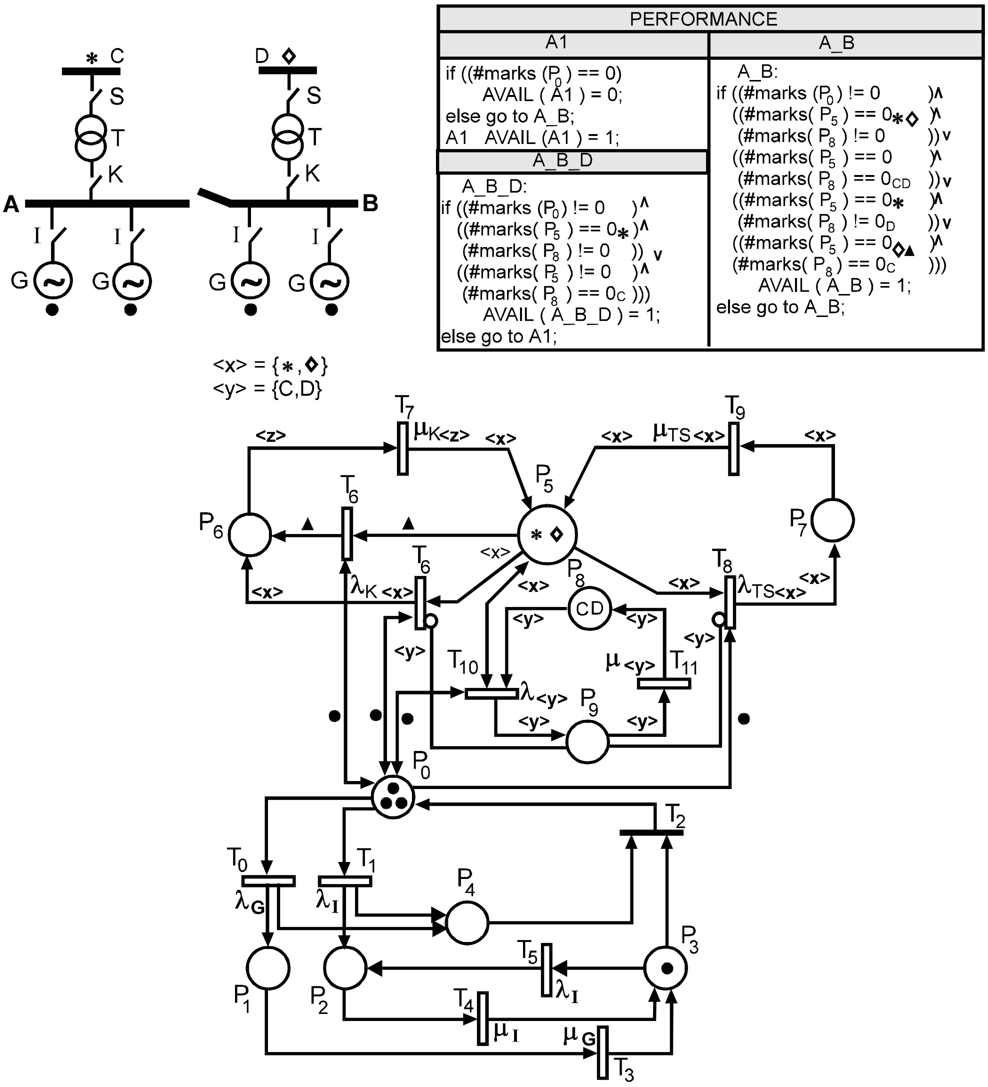
Two distinct alternatives, using four 800 KVA generators (A), or using six 500 KVA generators (b), can cover the most loaded stage of the system. The 220 Vac secundary busbar (SB) supply may by obtained in three different alternatives (1, 2, 3).

The six NPP design alternatives A1, A2, A3, B1, B2, B3 need to be economically analyzed. Many terms are used in the economical analysis computing, but one of the most important is represented by energy loss cost due to system defaults. This term is obtained using he performability metrics, evaluated in the six design alternatives.

The simplified LESPN model for the A1 design alternative in the most loaded naval function stage (3×800 KVA operating, 1×800 KVA stand- by) in shown 'Figure 2'.

The LESPN model has three architectural modules: the (P_0, P_1, P_2, P_3 P_4, T_0, T_1, T_2, T_3) module associated to the redundant generators system (cold redundancy with hypercritical switches, having failure possibilities before and after coupling); the (P_5, P_6, P_7, T_6 ,T_7, T_8, T_9) module associated to the series system (switches K, S, transformer T); the (P_8, P_9, T_{10}, T_{11}) module associated to the secondary sectioned busbar system C, D. The main sectioned busbar system is not modelled, because it is common to all the alternatives. The system functional dependencies are modelled by the arcs coupling the architectural modules. Performance logical conditions are shown in the PN associated table.

Using FETA software we compute the fuzzy *SG* for the generators G, transformers T, bus bars C, D and breakers I, S, K protection system. The obtained values are associated to the SSP stochastic transitions, modeling the failure events of the protected electric-power elements G, I, S (K) T, C (D) having the failure intensity $\lambda_G, \lambda_I, \lambda_{S(K)}, \lambda_T$, $\lambda_{C(D)}$ respectively. Also we compute the fuzzy *SG* of the generator automation system $SG_{AA\text{-}G}$ and associates to the SSP immediate transition, modeling the automation system action. Table 2 presents the computed SG values.



PERFORMANCE

A1

```
if ((#marks (P0) == 0)
      AVAIL ( A1 ) = 0;
else go to A_B;
A1   AVAIL (A1 ) = 1;
```

A_B_D

```
   A_B_D:
if ((#marks (P0) != 0      )^
   ((#marks( P5 ) == 0*  )^
    (#marks( P8 ) != 0    ))  v
   ((#marks( P5 ) != 0    )^
    (#marks( P8 ) == 0C )))
      AVAIL ( A_B_D ) = 1;
else go to A1;
```

A_B

```
   A_B:
if ((#marks (P0) != 0         )^
   ((#marks( P5 ) == 0*◇     )^
    (#marks( P8 ) != 0       ))v
   ((#marks( P5 ) == 0       )^
    (#marks( P8 ) == 0CD     ))v
   ((#marks( P5 ) == 0*      )^
    (#marks( P8 ) != 0D      ))v
   ((#marks( P5 ) == 0◇▲     )^
   (#marks( P8 ) == 0C       )))
      AVAIL ( A_B ) = 1;
else go to A_B;
```

Figure 2. The LESPN simplified model for A1 design alternative.

Function stages	Required Capacity [KVA]	Installed Capacty [KVA]		Loading factor [%]	
		A	B	A	B
1	725.274	1×800	2×500	90.659	73.48
2	13117.750	2×800	3×500	82.359	87.21
3	1391.547	2×800	4×500	86.972	70.57
4	608.595	1×800	2×500	76.074	60.81
5	2235.526	3×800	5×500	93	89.15
6	1298.438	2×800	3×500	81.152	86.29
7	928.150	2×800	3×500	57.947	62.75
	Total Installed Capacity	3200KVA (4×800)	3000KVA (6×500)		

Table 1. . Required Capacity, Installed Capacity in the naval function stages.

	λ_G	λ_I	$\lambda_{S(K)}$	λ_T	$\lambda_{C(D)}$		
					A1, B1	A2, B2, A3, B3	AAR-G
Fuzzy *SG*	î 0.611 fî 0.841	î 0.6499 fî 0.8782	î 0.5238 fî 0.7613	im 0.053 i 0.7365 fi 0.7833	î 0.5238 fî 0.7613	i 0.67577 fi 0.71269	im 0.1730 î 0.8420 fî 0.6347
Crisp *SG*	9.3121	9.3049	9.30452	9.06945	9.30452	9.04064	9.30934

Table 2. . Fuzzy SG for the generators G, transformers T, bus S, bars C, D, breakers I, S, K and automation system AA-G.

'Figure 3'presents performability measure (SEIR) for all six EP alternatives used in the proposed performability analysis, a very important component of the economic comparative study. Alternative A performability is generally better than alternative B performability. For the same A or B alternative type, A is better.

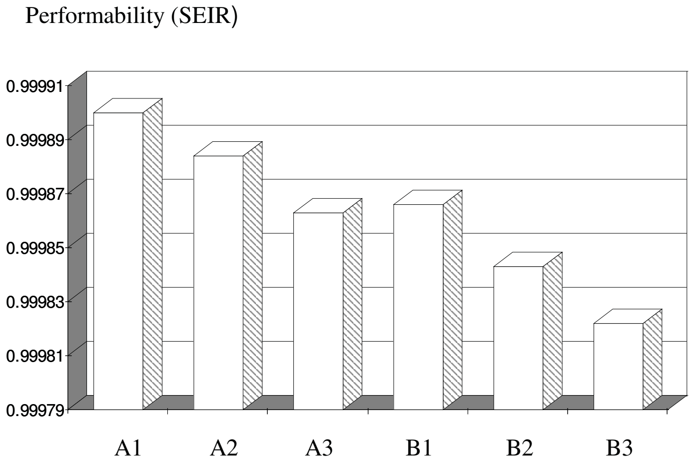


Figure 3. Performability measures for design alternatives.

5 Conclusions

Composite performance-dependability analysis combines the structure state process (SSP) which describes the system evolution as influenced by failures and repair with the system performance in each state of the SSP influenced by the electric-power protection/automation safety.

The reward model uses an adequate fuzzy logic system for electric-power protection/automation safety evaluation providing an intuitively appealing way of handling the uncertainty, by treating the probability of failure as a fuzzy number.

The model allows computing the steady state of the expected instantaneous reward, the proposed performability measure for the power system. This new parameter it is very important for a precise economic comparative study used for the fault-tolerant power system analysis.

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