STOCHASTIC MODELLING OF POWER SYSTEM NETWORK DEPENDABILITY

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Abstract. A power system network has high reliability requirements. The great complexity of generalized Stochastic Petri Nets (GSPN) models, even for simple systems, makes this model difficult to use. A simplified model named Logical Explicite Stochastic Petri Net (LESPN), having the same modelling power as GSPN, but a more simplified structure, will be used for power system network dependability modelling and computation. The paper introduces a reliability comparative study of three different types of power delivery systems: the radial system RDR, the ring system RDI, the loop system RDB. Reliability metrics for modelling alternatives have been computed with the Stochastic Petri Nets Evaluation (SPNE) tool elaborated especially in view of using SPN models and also in particular using LESPN models.

1 Introduction

In performing the design of a power system a reliability analysis of the power system should be done. Considering this, an important task is the system logic representation (specification of all system operational and failure states, as well as relationships between them). There are three approaches for dependability prediction of fault-tolerant systems [3], [5]: combinatorial models, simulation technique (Monte-Carlo), Markov and Semi-Markov models. Combinatorial models have a limited reliability modeling power. A Monte Carlo simulation can be used to calculate system reliability by simulating failure of components at moments in time, distributed according to their failure rates. The disadvantage of this approach appears in case of high reliable fault-tolerant systems, when a very large number of simulation cycles are needed to obtain statistically meaningful results.

Markov models do not posses the above limitations and are capable of handling phased missions, state dependent failure rates, common mode failures, physical interconnection dependencies, time dependent transitions, maintenance policies. To describe the Markov chain (MC) for a complex system is a very difficult task. In this case a Stochastic Petri Net (SPN) equivalent to MC, is usually used in modelling power system failure-repair behavior [6], [7].

This paper uses the power system dependability model based on Generalized Stochastic Petri Nets (GSPN) [1], [8], but having a simplified structure, named Logical Explicit Stochastic Petri nets (LESPN) developed by the authors [2], [4]. The model is used for fault analysis of power systems networks, but not only.

The structural simplified LESPN model is obtained by extracting from inside the GSPN model the logical subnets. As such the logical conditions of system performance are explained outside the GSPN model. Including predicate/transitions nets facilities, a great structural simplification of the model is obtained. The arc label of the colourate Petri Net dictates how many and what kind of "coloured" tokens will be removed from the places or added in there. The GSPN properties and the high level coloured Petri Net facilities (using predicates/ transition set) are combined, to create the set of primitive architectural modules. Primitive architectural modules are used to construct a modular architecture modelling the system behavior [2].

A computerized tool, Stochastic Petri Nets Evaluation (SPNE) using the 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 as well as dependability logical conditions, for candidate architectures of the system, the computation of the availability metrics is straight forward.

The paper exemplifies the LESPN model for simple systems and extends the results for complex power delivery systems. A comparative dependability study of different power delivery systems is performed using the LESPN model.

Section 2 briefly introduces Generalized Stochastic, Logical Explicit Stochastic Petri Nets. Section 3 describes the LESPN models for simple systems. Section 4 describes LESPN models for power delivery radial system, ring system and loop system. Section 5 gives the dependability metrics of the proposed power delivery systems and makes the comparative study.

2 LESPN Primitive Architectural Modules

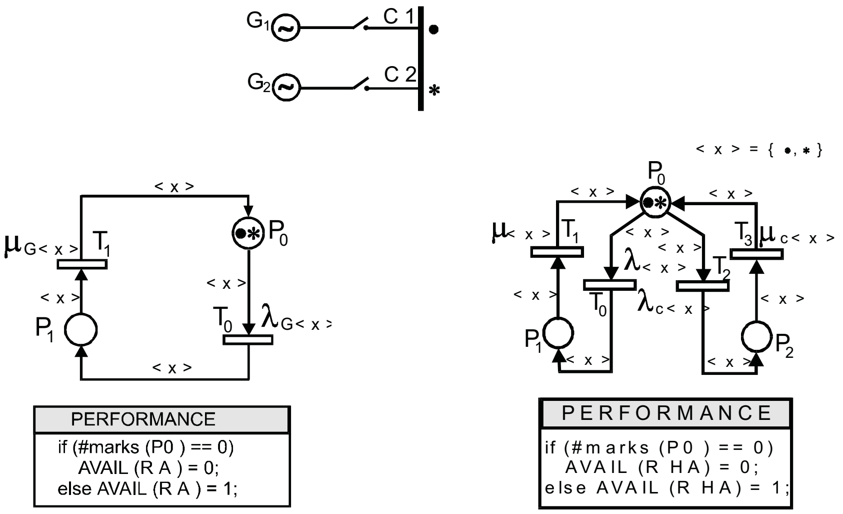
The GSPN model type is situated on top of power-modelling hierarchy. But, this model presents limits because the logical subnet (LS), used in operational dependency modelling and logical performance conditions modelling. This element implies a very large GSPN model even for simple systems and makes very difficult to build the GSPN model for a repairable complex system.

The new proposed model does not use the LS in dependability modeling. The logical performance conditions of the system are modeled outside the SPN, in a SPN associate table. The new SPN structure uses only the events modeling subnet (EMS) [2].

Compared to the GSPN model, the new SPN model, has the following advantages:

- - it uses a higher level PN (coloured and having predicates/transition) implying a very easy to use and intuitive structure;
- - its dimensions are reduced, implying a simplified dependability evaluation;
- - it uses only the EMS modular architecture;
- - the system logical conditions are modeled outside the SPN, in the logical table "PERFORMANCE";
- - the operational dependencies between the system components, associate to EMS different modules, are modeled by the arcs set and the predicates/transition set;
- - the system behavior does not posses the vanishing markings created by the LS of GSPN models;
- - it is easy to extend the model from non repairable systems to repairable systems, by adding the transitions for the repair events of the components.

The primitive architectural modules are used to construct a LESPN structurally 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. LESPN primitive module for a redundancy system (G1, G2), having ideal switches (C1, C2 without failure, RA redundancy modelling alternative) or having real switches (unlimited repairs, R_HA redundancy modelling alternative), are presented in 'Figure 1' a, respectively 'Figure 2' b.



PERFORMANCE
if (#marks (P0) == 0)
AVAIL (R A) = 0;
else AVAIL (R A) = 1;

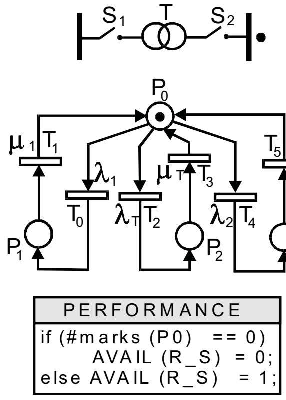
PERFORMANCE
if (#marks (P0) == 0)
AVAIL (R HA) = 0;
else AVAIL (R HA) = 1;

a b

Figure 1. LESPN primitive architectural modules for active redundancy RA (a), active hybrid redundancy RHA (b) alternatives.

The circuit operational state is modelled by the place P0. Generators/switches failure state is modeled by the places P1/P2. Generator fail/repair event is modeled by the stochastic transition T0/T1. The predicates/transition set <x> gives different ways of executing LESPN transitions. Switch fail/repair event is modeled by the stochastic transition T2/T3. The system availability logical conditions are explained, for each model, in the PERFORMANCE associated table.

The LESPN primitive module for a repairable series system (R-S) (transformer T, switches S1, S2) is presented in 'Figure 2'. The system operational state and components (S1, T, S2) failure states are modeled by the places P0, P1, P2, P3, respectively. Components fail (repair) events are modelled by the stochastic transitions T0, T2, T4, (T1, T3, T5).



```
PERFORMANCE
if (#marks (P0)  == 0)
      AVAIL (R_S)  = 0;
else AVAIL (R_S)  = 1;
```

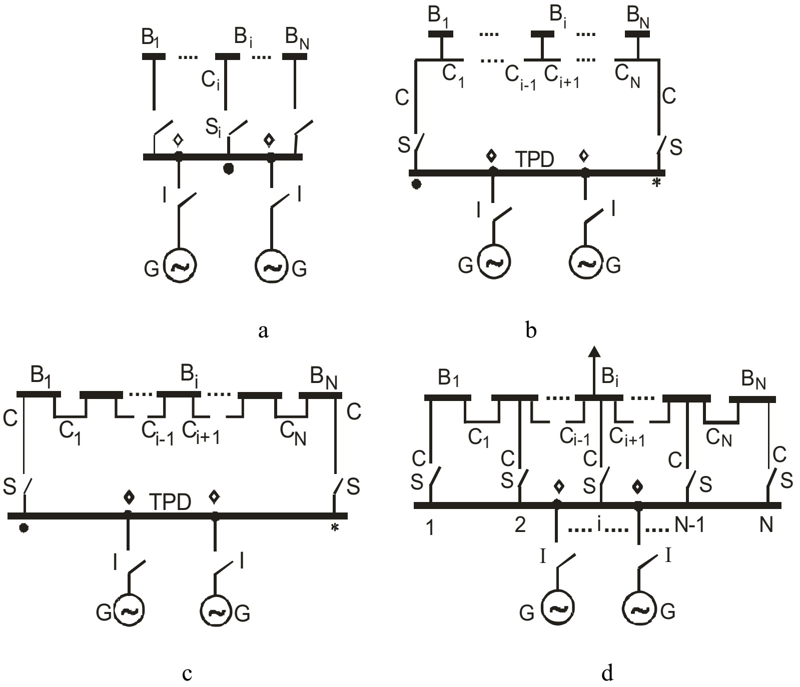
Figure 2. Logical Explicit Petri net primitive module for a repairable series R_S system.

3 LESPN Models for Power Delivery System

Power delivery systems are used to supply the electrical loads. The most common power delivery networks are the radial type, the ring type and the loop type.

Radial power delivery network (RDR) has a separate electrical transport line for each electric load supply (‘Figure 3’ a). Electrical equipments in power delivery network are usually bus bars $B_i, i=\overline{1,N}$, cables $C_i, i=\overline{1,N}$, electrical transport lines C, electrical sources G (electrical generators or electrical transformers), switches S, I. The radial power delivery network type is more reliable but not very economical in regard of electrical materials.

Ring power delivery network (RDI) supplies all the electrical loads from two electrical sources using the cables *Ci* serial connection. This could be done in two distinct networks RDI_A and RDI_B, meaning with or without bus bars serial connection, as we can see in ‘Figure 3’ b, respectively ‘Figure 3’ c. RDI network type is better than the ring type considering economical aspects but not so reliable.



a

b

c

d

Figure 3. Power delivery networks types: radial power delivery network RDR (a), ring power delivery network RDI_A (b), RDI_B (c), loop power delivery network RDB (d).

Loop power delivery network (RDB) is a combination of radial and ring power delivery types, but the network has many electrical transport lines C, in order to increase the network reliability (‘Figure 3’ d).

LESPN high level colored Petri Net model for RDI_B network is presented in ‘Figure 4’. Colour (◊) is for electric generators, colours (•), (∗) are associated to electrical transport lines supplying bus bar B_i, colours C<x>, C<y> are for cables $C_j, j=\overline{1,i-1},$ respectively $C_j, j=\overline{i+1,N}$. The LESPN model has three architectural modules according to the power delivery system in ‘Figure 4’:

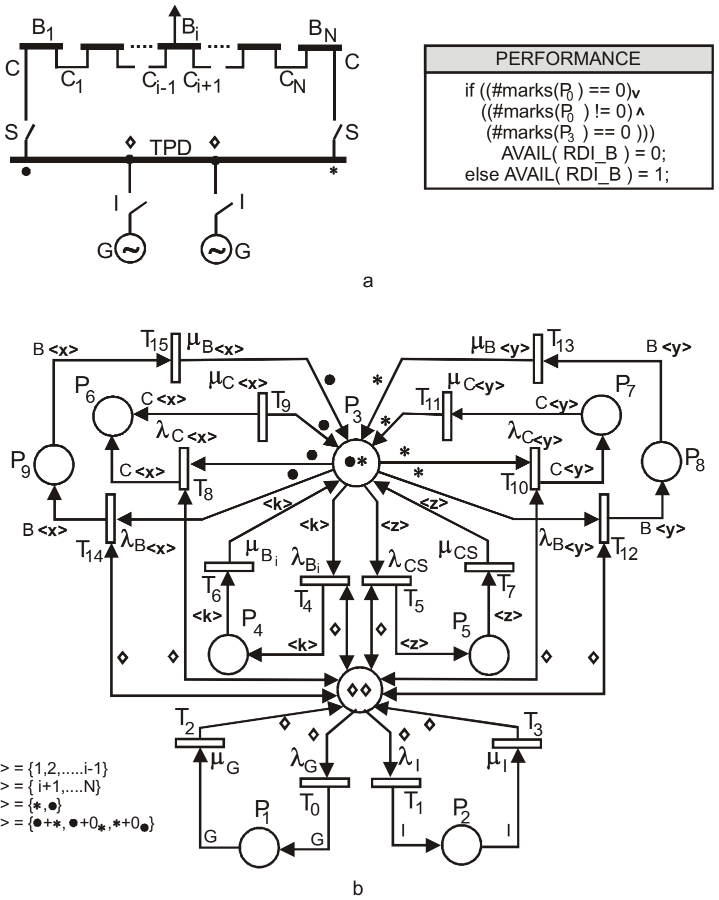
- the G redundant generators system (cold redundancy with hypercritical switches I, having failure possibilities before and after coupling);
- the series system $C_j, B_j, j=\overline{1,i-1}$ or $C_j, B_j, j=\overline{i+1,N}$ feeding bus bar B_i;
- the redundant power system including two electrical transport lines C, and two switches S.

All the architectural modules use transitions modelling fault events (exponential distributed, fault rate λ) and also repair events (exponential distributed, repair rate μ). The architectural modules have the following locations and transitions:

- (P_0, P_1, P_2, T_0, T_1, T_2, T_3) associated to the redundant generators system;
- (P_6, P_7, P_8, P_9,T_8, T_9, T_{10}, T_{11}, T_{12}, T_{13}, T_{14}, T_{15}) associated to the series system;
- (P_3, P_4, P_5, T_4, T_5, T_6, T_7) associated to the redundant electric line system.

The system functional dependencies are modelled by the arcs connecting the architectural modules (P_0, T_4), (P_0, T_5), (P_0, T_8), (P_0, T_{10}), (P_0, T_{12}), (P_0, T_{14}). The predicates/transition sets <x>, <y>, <z>, <k> dictate how many and what kind of tokens are moving in each one of the transition execution type.

Performance logical conditions are presented in the LESPN associated table from ‘Figure 4’ a where AVAIL(RDI_B)=0 means un-availability of supplying electrical load *i*.



```
if ((#marks(P0 ) == 0)v
   ((#marks(P0  ) != 0)^
    (#marks(P3  ) == 0 )))
        AVAIL( RDI_B ) = 0;
 else AVAIL( RDI_B ) = 1;
```

a

<x> = {1,2,.....i-1}
<y> = { i+1,....N}
<z> = {∗,•}
<k> = {•+∗, •+0∗,∗+0•}

b

Figure 4. Logical Explicite Stochastic Petri net LESPN model for ring power delivery network RDI_B.

4 Availability Analysis and Comparative Study

Dependability metrics for the power delivery network types, computed with the SPNE tool (considering a planned operational time T_p= 80000 h) are the following:

1. general dependability indices as system success probability P_S, system failure probability P_F;
2. power system dependability specific indices as, System Average Success Time $M[\alpha(T_p)]$, System Average Failure Time $M[\beta (T_p)]$, System Average Failure Interruptions Number $M[\nu(T_p]$ [9], System Average Interruption Frequency Index SAIFI, Customer Average Interruption Frequency Index CAIFI, Customer Average Interruption Duration Index CAIDI, Momentary Average Interruption Frequency Index MAIFI [10].

For availability metrics evaluation, the SPNE tool constructs the reachability graph RG of the bounded SPN, the reduced RG (obtained by reducing the vanishing markings) and the isomorphic MC with reduced RG, both modelling the failure-repair behavior of the system. Also the SPNE tool constructs the subset: success states, failure states of the system structure states process.

'Table 1' shows the number of total states NT, number of success /failure states (NS/NR), system success probability P_S and also system failure probability P_F, associated to the power delivery networks types. 'Table 2' shows power delivery networks dependability specific indices, considering parameters N=3, i=2.

	NT	NS/NR	P_S	P_F×E-03
RDR	9	3/6	0.9963145	3.68541
RDI_A	48	14/34	0.9987014	1.29854
RDI_B	75	18/57	0.9986927	1.30732
RDB	225	118/107	0.9998417	0.15828

Table 1. . General dependability metrics of power delivery network types: radial power delivery network (RDR), ring power delivery network (RDI_A), (RDI_B), loop power delivery network (RDB).

	$M[\nu(T_P)]$	$M[\alpha(T_P)]$ ×E+04 h	$M[\beta(T_P)]$ h	SAIFI	SAIDI h	CAIDI h	MAIFI
RDR	24.3509	7.970515	294.832	8,12	98,24	12,23	79,45
RDI_A	10.8902	7.989541	104.585	3,63	34,86	14,93	27,34
RDI_B	10.5931	7.986165	103.883	3,63	34,86	14,93	27,34
RDB	1.66225	7.998733	12.6627	0,55	4,33	8,56	4,92

Table 2. . 2 Specific dependability metrics of power delivery network types radial power delivery network (RDR), ring power delivery network (RDI_A), (RDI_B), loop power delivery network (RDB

The comparative study of the analyzed power delivery networks gives the following results:

- RDR power delivery network model, for parameters N=3, i=2, is less complex. MC has only 9 states but the dependability metrics P_S and $M[\alpha(T_P)]$, in the planned operational time $T_{p,}$ are the lowest of the investigated networks. This conducts to the highest Average Failure Interruptions Number $M[\nu(T_p]$.

- both RDI_A and RDI_B power delivery networks (N=3, i=2) have almost the same dependability metrics. System success probability P_S and, System Average Success Time $M[\alpha(T_p)]$ are smaller for RDI_B case because of the series bus bars B_j, $j=\overline{1,i-1}$ and B_j, $j=\overline{1,N}$ failure/repair events modelling. Also the model complexity in RDI_B case is bigger than in RDI_A case, but dependability metrics P_S, $M[\alpha(T_p)]$ are not much more reduced, because failure rate of the bus bars is generally low. For proposed N=3, i=2 parameters RDI network is more available than RDR network.

- RDB is the most available power delivery network of all studied cases, for N=3, i=2 proposed parameters. Also RDB has the most complex MC of all, having NT=225 states, obtained using LESPN model. Number of success states is very high NS=118, so success probability P_S and, System Average Success Time $M[\alpha(T_p)]$ are important.

5 Conclusions

Extracting the logical subnets from inside the GSPN model, the vanish markings and the immediate transitions associate to logical conditions does not appear in the reachability graph RG. Obviously the states number NT, modeling the behavior of the analyzed system is very small, compared to GSPN model. This leads to smaller computational effort and also to the possibility of increasing the complexity of the analyzed systems. The first conclusion is: the structural simplified model LESPN, having the same modeling power as GSPN, is more practical for engineering applications, easier to understand and also very adequate in power system dependability modeling. The analysis of the delivery system dependability is an important task for electrical engineers and LESPN model gives an easy tool to obtain the important practical results presented in the paper.

6 References

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