Dependability Modeling of Safety Systems,

Karama Kanoun, Jean-Claude Laprie

DEPENDABILITY MODELING OF SAFETY SYSTEMS

J. C. Laprie, K. Medhaffer - Kanoun

LABORATOIRE d'AUTOMATIQUE et d'ANALYSE des SYSTEMES
du Centre National de la Recherche Scientifique
7, avenue du Colonel Roche - 31400 TOULOUSE - France

ABSTRACT

This paper presents the results of a study[1] devoted to safety systems aimed at preventing the consequences of an incident to propagate. The functions of a safety systems are stated in the first part. How to quantify the accomplishment of these functions is discussed in the second part where the dependability levels of a safety system are defined. The third part is devoted to a detailed study of dependability of simplex, non fault-tolerant, safety systems. This study is necessary due to the very nature of such systems and we emphasize the problem of the masked faults which are of particular importance here. The results of the third part are then applied to the study of fault-tolerant safety systems, in the fourth and fifth parts : a) classical architectures, duplex and majority voting, and b) an example of a distributed safety system with degrated modes of operation, the substations of the extra high voltage French electricity network.

INTRODUCTION

The growth of our industrial society is being accompanied by an increase in hazards, the most disquieting being those for which an incident may propagate and have very severe consequences at diverse levels : economics, environment, human lives. Everybody knows of recent and famous examples which were catastrophic or for which a catastrophe was just avoided (chemical as in Seveso, Italy ; electrical as in the New York and France blackouts ; nuclear as in Three Mile Island).

The increase in the complexity of the industrial processes requiring safety systems leads to an increase in the complexity of these systems themselves. This in turn leads to a realization of safety systems using computers which, due to the very nature of their assigned tasks, are generally fault-tolerant. Although safety systems gave rise from a general point of view to many papers and books[2,3], few papers have been published on the subject of fault-tolerance applied to safety systems[4,5]. This paper is precisely aimed at the study of computer-implemented safety systems.

I. FUNCTIONS OF A SAFETY SYSTEM

A general representation of an industrial process is given in figure 1 which details the terminology which will be used troughout this paper.

In the sequel, the term incident will be exclusively employed for abnormal behavior of the monitored system, which can be due to a malfunction of the control system, of the sensors or actuators, or of the process itself.

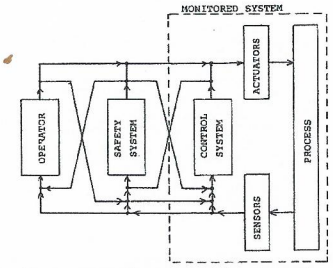


Figure 1- Conceptual view of an industrial system

When an incident occurs, the safety system must detect and process it. Processing of the incident requires two steps :

- confinement : prevent propagation of its consequences,
- elimination : restore the normal working conditions.

The way elimination is performed leads to a distinction between two types of incidents :

- transient incidents : actions carried out by the safety system are enough in order to restore the normal working conditions of the monitored system,
- permanent incidents : the monitored system is shut down and human maintenance intervention is required.

The functions which are generally assigned to a safety system are :

F1) When an incident occurs in the monitored system :
1. detect the incident,
2. warn the operator of the presence and (possibly) the nature of the incident,
3. take corrective actions in order to bring the monitored system back into its normal working conditions.

F2) In the absence of incident in the monitored system : do not have any action which could lead the process into a dangerous state or shut it down.

The statement of these functions of a safety system allows us to infer two important features of such a system : it must be fail safe, and it is a dormant system. Let us explain the latter point. The inputs of the safety system are parameters of the monitored system whose arrival period is generally low (a few milliseconds). The outputs to the process are binary control signals (orders for opening a valve or a circuit-breaker,...) whose period is much higher (several months). Thus, some parts of the safety system can remain unactivated during a long period of time.

2. DEPENDABILITY LEVELS OF A SAFETY SYSTEM

Definition of dependability levels requires the definitions of accomplishment levels[6] which may be stated in terms of either fulfilled tasks or classes of

consequences of the various fault sources (the latter is the dual of the former). For our purpose, we define two accomplishment levels referring to functions F1 and F2 :

- level 1 refers to F1 only : the safety system is able to eliminate correctly an incident,
- level 2 refers to F1 and F2 : the safety system is able to eliminate an incident and has no undesirable action on the monitored system in the absence of incidents.

These two levels may be seen as two extremes : avoiding the catastrophe irrespectively of what else may happen (level 1) or everything is going well (level 2).

In order to quantity these levels, let us examine the behavior of a safety system, which results from the combination of two alternating processes[7].

- fault manifestation and maintenance of the safety system, which will be denoted hereafter by the capability alternation process,
- incidence occurrence, incident processing and maintenance of the monitored system, which will be denoted hereafter by the sollicitation alternation process.

Combining both alternation processes leads to the model of Fig. 2, where :

- an inability is the consequence of a fault manifestation in the safety system, the first one in a non fault tolerant system, or after exhaustion of the protective resources in a fault tolerant system ; a declared inability refers to a fault detected by the fault detection mechanisms implemented in the safety system, or perceived by its action on the monitored system ; a masked inability refers to a fault which is neither detected nor perceived,
- it is assumed that when the monitored system is down, incident occurrence is meaningless and no fault can develop in the safety system (shutting down the monitored system leads to shut down of the safety system and vice-versa),
- states 6 and 7 are catastrophic since an incident can propagate ; transitions outgoing from this state are not considered (they may even never occur if the monitored system cannot be restored after a catastrophe).

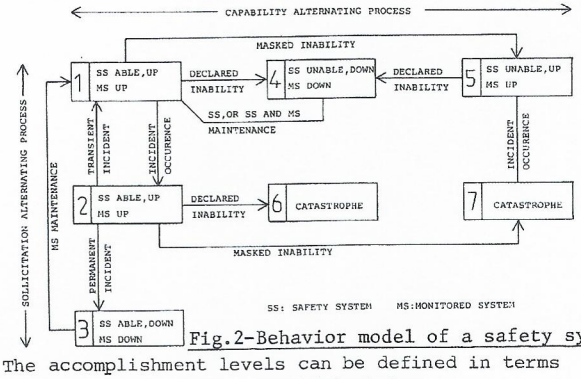


Fig.2-Behavior model of a safety system

The accomplishment levels can be defined in terms of successful and unsuccessful states :

ACCOMPLISHMENT LEVELS	SUCCESSFUL STATES	UNSUCCESSFUL STATES
Level 1	1,2,3,4,5	6,7
Level 2	1,2,3	4,5,6,7

Classification of state 5 necessitates a comment : this state is a dangerous one in the sense that if an incident occurs, the monitored system will be brought into a catastrophic state and this fact is non observable until an incident occurs. However, as mentioned above, the two levels are to be seen as two extremes and that is why we consider it as successful for the first level and unsuccessful for the second level.

The measures of dependability associated with each accomplishment level are "reliability - type" measures, i.e. the unsuccessful states will be absorbing states. Let us denote by D_1 (t) and D_2 (t) the level 1 and 2 dependability and by P_i (t) the probability of the system being in state i. We thus have

$$D_1(t) = \sum_{i=1}^{5} P_i(t) \qquad D_2(t) = \sum_{i=1}^{3} P_i(t) ,$$

the P_i (t) being evaluated on the corresponding transition graphs.

REMARK : from their definition, the dependability levels are close to the usual notions of safety for level 1 and reliability for level 2. We shall however keep the terms "level-1 and 2 dependabilities" in order not to be confusing, particularly concerning the interpretation of state 5 which could be misleading if we use the term "safety".

3. *MODELING OF A SIMPLEX (NON FAULT-TOLERANT) STRUCTURE*

3.1. *Evaluation method*

We shall assume that all the random variables associated with the processes acting on the system are exponentially distributed, i.e. constant rates are associated with the random variables. This assumption

- is widely accepted for the fault rates,
- is in agreement with the concept of incident,
- is, at a first sight, a very rough assumption for maintenance processes ; however, previous studies[8,9] have shown that it is legitimate.

As a consequence, we shall be able to evaluate the dependability levels by time homogeneous Markov techniques.

The corresponding Markov transition graphs are generally too complex to allow analytical expressions of D_i (t) to be derived. So, we shall proceed as follows:

- when it is possible, derive the mean time to absorption MTA_i (mean time spent in the non absorbing states) in order to identify the most influent parameters ; let us note that the MTA_i plays the same role for D_i (t) as the MTTF plays for reliability,
- in all cases, compute numerically D_i (t) ; this will be done by using a Markov-based evaluation program developped at LAAS : the SURF program[10].

3.2. *System parameters*

Table of Fig. 3 summarizes the values of the rates associated with the alternation processes which will be considered ; these values have been selected in order to form a coherent set.

ALTERNATION PROCESS	PARAMETERS	LABEL		TYPICAL VALUES
CAPABILITY	Failure rate	λ	one fault developed once every year	10^{-4}/h
	Increase ratio of fault rate during sollicitation	K	From MIL-HDBK-217-B	$1 \leqslant K \leqslant 50$
	Maintenance rate	μ	$10^2 \leqslant \frac{\mu}{\lambda} \leqslant 10^4$	$10^{-2}/h \leqslant \mu \leqslant 1/h$
SOLLICITATION	Incident occurrence rate	γ	$1 \leqslant \frac{\gamma}{\lambda} \leqslant 100$	$10^{-4}/h \leqslant \gamma \leqslant 10^{-2}/h$
	Incident processing rate	ξ	$\frac{\xi}{\gamma} \geqslant 10$	$10^{-1}/h \leqslant \xi \leqslant 10^{+4}/h$
	Maintenance rate	ν	$5 \leqslant \frac{\nu}{\gamma} \leqslant 10^5$	$5.10^{-4}/h \leqslant \nu \leqslant 10^{-1}/h$

Fig.3-Rates associated with the alternation processes

Characterization of the system behavior necessitates additional parameters to be defined, which are expressed under the form of conditional probabilities in fig. 4.

Detection efficiency	p_D= P{Fault has been detected | A fault has occurred}
Masked fault probability	q = P{Masked inability | A fault has occurred} = Q(1-p_D) Q = P{Fault has no action on the monitored system | A fault has occurred and has not been detected}
Maintenance efficiency	p_M= P{Repair leads to a fault-free state | Maintenance has been performed}
Transient incident	= P{Monitored system has returned to normal working conditions under the actions controled by the safety system | End of incident processing occurs}

Figure 4- Conditional probability parameters

3.3 Level-1 dependability modeling

Fig. 5 gives the Markov transition graph deduced from fig. 3, where a) the successive states and transitions occurring in state 5 of fig. 3 are explicitely shown (n is the number of successive masked inabilities which can develop), and b) an imperfect repair is assumed to lead the system into a masked-inability state.

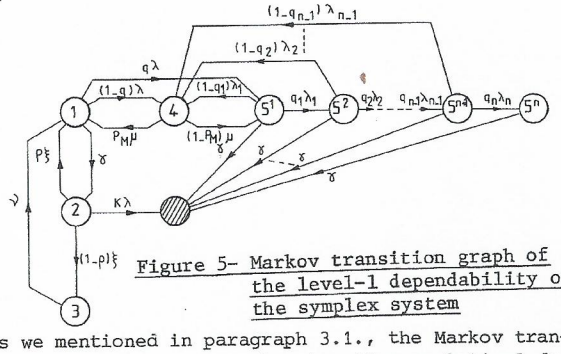


Figure 5- Markov transition graph of the level-1 dependability of the symplex system

As we mentioned in paragraph 3.1., the Markov transition graph is too complex to allow analytical derivation of $D_1(t)$. We have however derived the MTA_1. Using standard techniques for Markov processes and making first-order asymptotic developments with respect to λ/ξ, λ/μ, λ/ν, γ/ξ, γ/μ, γ/ν, q and $1-p_m$, lead to the following results :

- for n=1, $MTA_1 \simeq \dfrac{1}{\lambda\left[q\tau_M + 1 - \tau_M + k\dfrac{\gamma}{\xi}\right]}$

- for $n \geqslant 2$, $MTA_1 \simeq \dfrac{1}{\lambda\left\{(q\tau_M + 1 - \tau_M)\left[1 - \tau_M(1-q_1)\dfrac{\lambda_1}{\gamma+\lambda_1}\right] + k\dfrac{\gamma}{\xi}\right\}}$

These expressions enable the influence of the various parameters to be weighted and the numerical calculation of $D_1(t)$ with the SURF program has enabled these results to be checked and a precise evaluation of the influences to be derived. However, due the lack of space, fig. 6 gives only the most significant results.

The above results lead to a simplification of the transition graph of fig. 6 through removal of the states whose probability can be neglected [11].

3.4. Level-2 dependability modeling

Fig. 7 gives the Markov transition graph deduced from fig. 2 . Using the same approach as for level-1 dependability, we obtain :

$$MTA_2 \simeq \frac{1}{\lambda}\left[1-(k-1)\frac{\gamma}{\xi} + (1-\rho)\frac{\gamma}{\nu}\right]$$

All the parameters of the model are present in this expression. However they appear as being infinitely small with respect to $1/\lambda$. This is confirmed by use of the SURF program : the curves of $D_2(t)$ and $\exp(-\lambda t)$ cannot be distinguished. It is thus not necessary to account for the sollicitation process for the level-2 dependability modeling.

Number of masked faults	1) Account for two masked faults 2) Values of q_1 and λ_1 with respect to q and λ - the lower number of fault sources leads to $\lambda_1 < \lambda$ if the independance of the fault sources is kept on, and to $\lambda_1 > \lambda$ if the first fault creates dependencies, - Q can be reasonably assumed constant and P_D is likely to be lower after occurrence of a first fault $\Rightarrow q_1 > q$. Thus, we can have $q_1\lambda_1 \gtrsim q\lambda$; the lack of experimental data and the relatively low influence of q_1 and λ_1 leads to assume $\lambda_1 = \lambda$ and $q_1 = q$
Maintenance process	1) μ and ν are of no significant influence over their full range of variation $\Rightarrow$ P{System being in states 3 and 4} can be neglected 2) p_M is of a great influence
Fault manifestation during sollicitation	The values of $k\gamma/\xi$ leads to consider two types of safety systems: 1) $k\gamma/\xi \ll \sup(q, 1-p_M)$: incident processing is of no influence on dependability and P System being in state 2 can be neglected 2) $k\gamma/\xi \sim \sup(q, 1-p_M)$: incident processing must be accounted for
Influence of q	Although of a small value, q is of a primary influence: q represents the ratio of single faults which bring the system into a dangerous state

Fig.6-Main results for $D_1(t)$ of the simplex system

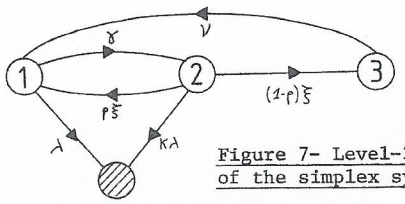


Figure 7- Level-2 model of the simplex system

4. MODELING OF FAULT-TOLERANT STRUCTURES

This paragraph deals with the two most well-known fault-tolerant architectures : duplex and majority voting (TMR). A unified treatment of both architectures is possible through introduction of the two following parameters :

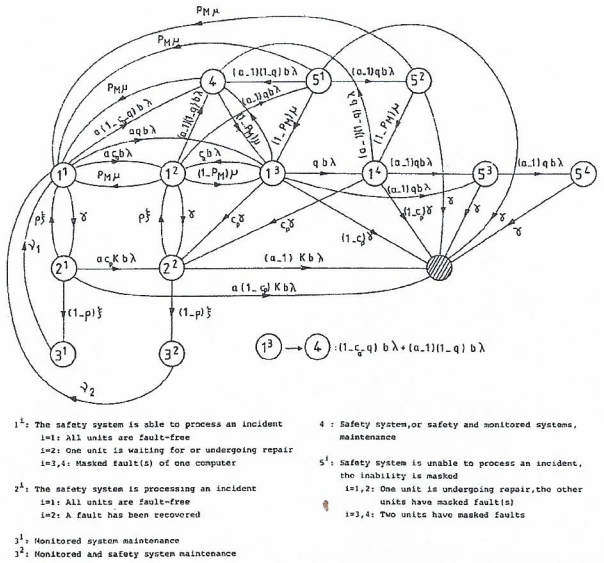
- a is the number of units (a=2 for duplex and 3 for TMR),
- b is the fault-rate ratio between the actual units and a hypothetical non fault-tolerant and non self-detecting unit.

Efficiency of the recovery procedures will be accounted for by the coverage [12,13] : c=P{ the structure is able to recover information processing without loss of ability / a fault has occurred } ; c_a and c_p will respectively denote the coverage in the absence and in the presence of an incident.

The Markov transition graph for level-1 dependability is given by fig.8 ; we have assumed, according to results of § 3.4., that only two successive masked faults can occur.

Model for the level-2 dependability is deduced from fig. 8 when turning states 4 and 5^1 to absorbing states.

Conducting an analysis as extensive as we did for the simplex structure would take much more room and we shall thus restrict ourselves to giving the results of fig.9, which enables the fault-tolerant structures to be compared with the simplex one : both dependability levels are improved ; improvement is however less sensitive for the first level than for the second one.



i^1: The safety system is able to process an incident
- i=1: All units are fault-free
- i=2: One unit is waiting for or undergoing repair
- i=3,4: Masked fault(s) of one computer

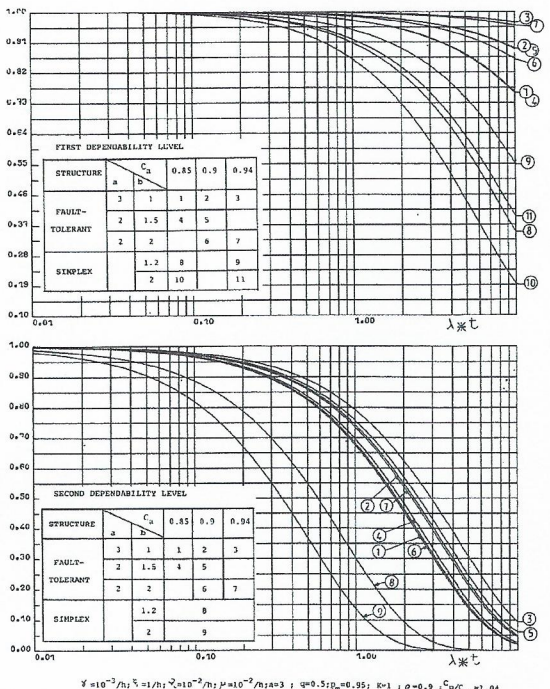
2^i: The safety system is processing an incident
- i=1: All units are fault-free
- i=2: A fault has been recovered

3^1: Monitored system maintenance
3^2: Monitored and safety system maintenance

4 : Safety system,or safety and monitored systems, maintenance

5^i: Safety system is unable to process an incident, the inability is masked
- i=1,2: One unit is undergoing repair,the other units have masked fault(s)
- i=3,4: Two units have masked faults

Fig.8-Level-1 model of the duplex and TMR architectures



$\gamma = 10^{-3}/h$; $\zeta = 1/h$; $\lambda = 10^{-2}/h$; $\mu = 10^{-2}/h$; a=3 ; q=0.5; p_m=0.95; K=1 ; ρ=0.9 ; c_p/c_a =1,04

Figure 9- Dependability of the fault-tolerant vs. simplex systems

5. *MODELING OF AN EXTRA HIGH VOLTAGE (EHV) SUBSTATION*[14,15]

5.1. Description of an EHV substation (fig. 10)

The reference station consists of two bus-bars coupled by a circuit-breaker ; each bar is connected by circuit-breakers to five EHV lines. The control system has the same architecture as the substation : a computer is associated with each three-phase circuit-breaker, which detects the occurrence of an incident through voltage and current measurements and processing on each phase. The computers communicate in order to derive which circuit-breaker(s) are to be

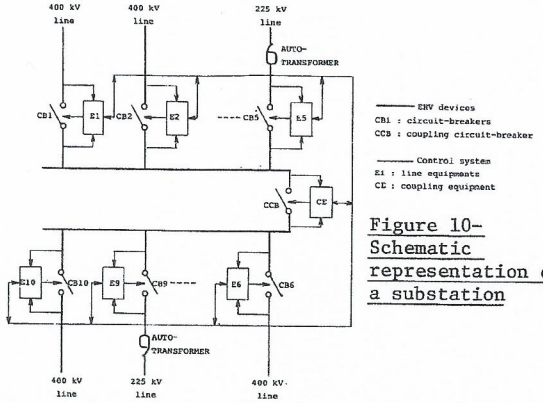


Figure 10- Schematic representation of a substation

opened, depending on the origin of the incident (on a line or on a bar), and due to the fact that when an incident occurs, all the computers associated with the circuit-breakers "see" it : a diagnosis is necessary, which is based on the results of the above-mentioned measurements and processing. In the sequel, computer associated with a circuit-breaker and the interfacing electronics will be refered to as an "equipment". The system presents an inherent functionnal redundancy : if an incident occurs on a line and the circuit-breaker of this line does not open (due to the failure of the equipment or to the failure of the circuit-breaker itself), opening of all the circuit-breakers connected to the same bar and of the coupling circuit-breaker enables the incident to be eliminated in a degrated mode.

5.2. Functions of the system

The function of this safety system is to prevent an incident that occurs on a line or a bar from being propagated on the EHV network.

When an incident occurs, three situations may happen:

S1) the incident is correctly eliminated through opening of the circuit-breakers strictly required by the nature of the incident,

S2) the incident is eliminated in a degraded mode through opening a larger number of circuit-breakers than those strictly required by the nature of incident,

S3) the incident is propagated over the network.

In the absence of incident occurrence, opening of a circuit-breaker leads to the loss of a line or the lines connected to a bar. This is not catastrophic since the network is strongly meshed.

5.3. Definition of the dependability levels

The above discussion leads to consider only the first dependability level. However, accounting for the functionnal redundancy leads to distinguish two sub-levels:

- nominal dependability, defined as $ND(t)=P\{\overline{S_1}$ is successful$\}$,
- degraded dependability, defined as $DD(t)=P\{S_1$ or S_2 is successful$\}$.

5.4. Substation modeling

Modeling of the system was performed using a bottom-up approach : equipment of a circuit-breaker, equipments of a bar, substation.

In the current system, the equipments are non fault-tolerant and fault-detection is based on each equipment checking the coherence of the states of the other circuit-breakers. In order to lower the influence of the masked faults, equipments are periodically inspected.

The value of those system parameters for which field experience data exist are given in fig.11

PROCESS	PARAMETER	LABEL	VALUE
SOLLICITATION	Incident occurrence rate on a line	γ_ℓ	$10^{-4}/h \leq \gamma_\ell \leq 10^{-3}/h$
	Incident occurrence rate on a bar	γ_b	$10^{-5}/h$
	Incident processing	ζ	$\zeta \geq 10^{+3}/h$
FAULT MANIFESTATION	Fault rate of an equipment	λ	$10^{-4}/h$
MAINTENANCE	Inspection rate	δ	$10^{-4}/h \leq \delta \leq 4\ 10^{-4}/h$
	Repair rate	μ	$10^{-2}/h \leq \mu \leq 4\ 10^{-2}/h$

Figure 11- Parameters of the substation

For the first two steps (equipment of a circuit-breaker, equipments of a bar), an approach similar to the one we exposed in paragraph 3 was followed.
The complete model of an equipment is given by fig.12 It is directly deduced from fig.5 and is unique since the nominal dependability only has to be considered for a single equipment.

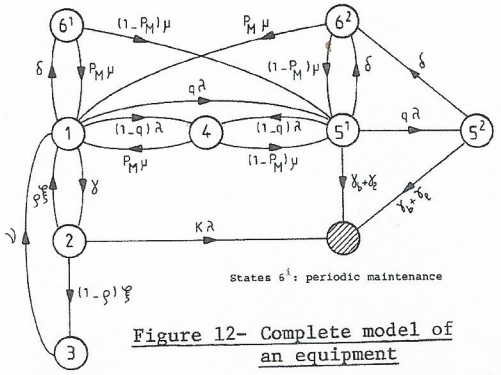


Figure 12- Complete model of an equipment

A sensitivity study showed that the repair actions and incident processing can be considered as instataneous, which led to the simplified model of fig.13.

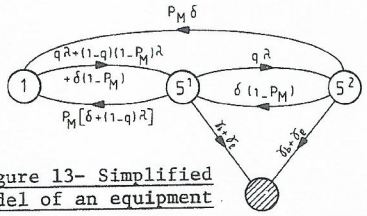


Figure 13- Simplified model of an equipment

This model allowed the model of a 5-equipment bar to be derived. It is a 23 state graph for which a sensitivity study with respect to the number of the faulty equipments and of the number of masked faults to be accounted for led to the simplified models of fig. 14.
Finally, the model of a substation was built : it is a 35 fully interconnected state graph which cannot be displayed here due to space limitation.

CONCLUSION

The results exposed in this paper can be classed into three categories :
- dependability modeling of a complex system,
- safety system evaluation,
- study of EHV substations.

Concerning the dependability modeling the approach we followed can be applied to every type of complex system, and we can sum up as follows :

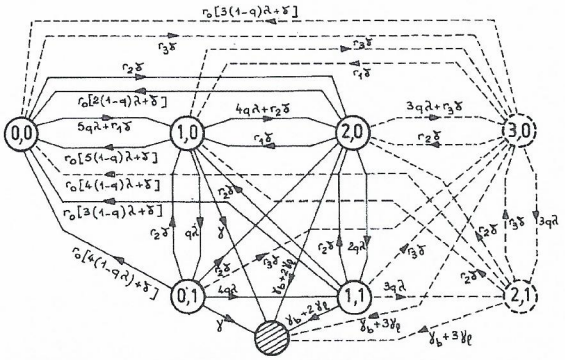


Figure 14- Simplified model of a 5-equipment bar

- definition of dependability levels which are meaningful for the end-user, directly from the statement of the functions assigned to the system,
- definition of probabilistic measures of the dependability levels which can easily be physically interpreted, and verification of their validity through sensitivity studies,
- model construction by agregating the subset models, performing at each step sensitivity studies in order to keep onto only those parameters that are actually influent.

Concerning the evaluation of safety systems, results fall into two categories :
- safety system modeling : we have quantified the two disruption sources : fault manifesting during incident processing, incident occurring after a masked fault has developed ; we have shown that the latter is more important than the former,
- consequence of the evaluation on architecture :
  - . extreme importance of the fault detection mechanisms,
  - . in the maintenance procedures, repair efficiency has to be emphasized more than repair duration.

Concerning finally the EHV substations, the overall results that we obtained constitute a data base (models, processes, parameters,...) which is a reference in the search for new architectures currently carried out at LAAS.

ACKNOWLEDGEMENTS

The results exposed in this paper have been sponsored by Electricité de France (EDF). They are a synthesis of work to which several people of the Direction des Etudes et Recherches from EDF and of the research team "Dependable Processing Systems" from LAAS have significantly contributed. The authors want to thank particularly F. Cereja and A. Costes from LAAS and J.L. Boussin from Electricité de France.

REFERENCES

1 K. Medhaffer-Kanoun, "Evaluation de la sûreté de fonctionnement des systèmes de sécurité. Application à la commande des postes à très haute tension", Docteur-Ingénieur thesis, INP Toulouse, Jul. 1980, 150 p, in French.

2 C. Lievens, "Sécurité des systèmes", Cepadues Edition, Toulouse, 1976, in French.

3 J.R. Taylor, "Safety assessment", in *Proc. of the Seminar "Automatic Shutdown Systems"*, Aberdeen, UK, Feb. 80, p.2-1 to 2-18.

4 H.F. Frey, "Safety evaluation of mass transit systems by reliability analysis", *IEEE Trans. on Reliability*, vol.R.-23, n°3, Aug. 74, pp.161-169.

5 C.J. Kenward, "Computer based safety systems", United Kingdom Atomic Energy Authority, Report AERE-R-7809, Oct.74, 31p.

6 J.F. Meyer, "On evaluating the performability of degradable computing systems", *Proc. of the 8th International Symposium on Fault-Tolerant Computing, FTCS-8*, Toulouse, June 78, pp.44-49.

7 F.A. Gay, "Performance modeling for gracefully degrading systems", Ph.D. Dissertation, Northwestern University, Evanston, Ill, June 79.

8 J.C. Laprie, "Reliability and availability of repairable structures", *Proc. of the 5th Int. Symposium on Fault-Tolerant Computing*, Paris, June 75, pp.87-92.

9 A. Costes, C. Landrault, J.C. Laprie, "Reliability and availability models for maintained systems featuring hardware failures and design faults", *IEEE Trans. on Computers*, vol.C-27, n°6, June 78, pp.548-560.

10 A. Costes, J.E. Doucet, C. Landrault, J.C. Laprie, "SURF : Système d'évaluation de la sûreté de fonctionnement ; 1ère Partie : Méthode", Note Technique 79.T.37 ; J.E. Doucet, "2ème Partie : Notice d'utilisation", Note Technique 79.T.38, L.A.A.S., Toulouse, Sept. 79, in French.

11 J.C. Laprie, "On reliability prediction of repairable redundant digital structures when neglecting repair times", *IEEE Trans. on Reliability*, vol.R-20, n°4, Oct. 76, pp. 256-258.

12 W.G. Bourricius, W.C. Carter, P.R. Schneider, "Reliability modeling techniques for self-repairing computer systems", in *Proc. of the 12th ACM National Conference*, Aug. 69, pp.295-309.

13 T.F. Arnold, "The concept of coverage and its effect on the reliability model of a repairable system", in *Proc. of the 2nd Int. Conf. on Fault-Tolerant Computing*, Newton, Massachussetts, June 19-21,1972, pp.200-204.

14 Le plan de protection "palier technique 1975". Les principes.E.D.F. Nov. 75, 48 p., in French.

15 J.C. Laprie, F. Cereja, K. Medhaffer, "Etude de nouvelles architectures sûres de fonctionnement pour les automatismes de protection et de reprise de service des postes à très haute tension", E.D.F. Contract n°47559, Final-report, LAAS publication n°1894, Toulouse, Feb. 79, 149 p., in French.

BIOGRAPHIES

J.C. Laprie was born in Paris, on December 22, 1944. He received the Engineer degree from Ecole Nationale Supérieure d'Ingénieurs de Constructions Aeronautiques in 1968 ; he defended his theses of Docteur-Ingenieur and Docteur és-Sciences in 1971 and 1975 resp, both at Université Paul Sabatier, Toulouse. He has been with LAAS since 1968 and he is currently the head of the research team "Dependable Processing Systems". His research interest are the fault-tolerant systems, from two points of view : architecture and evaluation. He has served as the chairman of FTCS-8, held in Toulouse in June 1978.

K. Medhaffer-Kanoun was born in Sfax, Tunisia, on October 10, 1953. She received the Engineer degree from Ecole Nationale de l'Aviation Civile in 1977. She defended her Docteur Ingenieur thesis at Institut National Polytechnique de Toulouse on July 4, 1980. She has been with the research team "Dependable Processing Systems" since October 1977 and she is actively engaged in research on safety systems under sponsorship from Electricité de France.