211

GENERAL OVERVIEW ON EXPERIENCE FEEDBACK METHODS IN THE FIELD OF ELECTRICAL EQUIPMENT

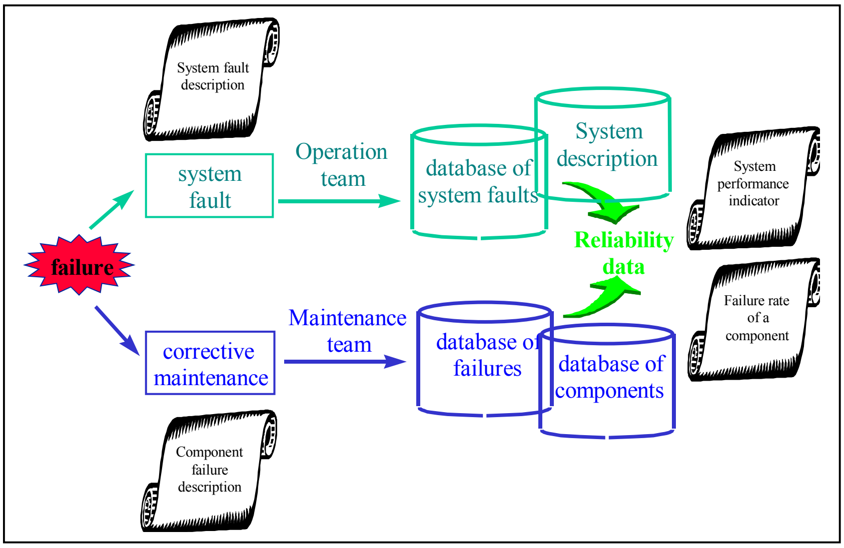
Joint Task Force
23/12/13/21/22.16

October 2002

cigré

211

General overview on experience feedback methods in the field of electrical equipment



Prepared by the CIGRE Joint Task Force 23/12/13/21/22-16
« Preparation of guidelines for collection and handling of reliability data »

Task Force Members :

Mr Robert ATKIN (SC12 - corresponding member of the JTF)
Mr Evaristo DI BARTOLOMEO (SC13 - corresponding member of the JTF)
Mr Eugène FAVRIE (SC 21)
Mr Elias GHANNOUM (SC 22 - corresponding member of the JTF)
Mr Michael ALLISON (JWG 23/39)
Mr Malcolm V. THADEN (WG23/39-14 - corresponding member of the JTF)
Mr Gaëtan DESQUILBET (SC 23 – convenor of the JTF)

Table of contents

1. Introduction

The reliability of network components and systems is a major concern for manufacturers of electrical equipment and utilities. Reliability techniques, derived from the aeronautical and nuclear industries, have been used in the field of electrical systems and have now reached maturity. Thus, CIGRE Study Committees have considered reliability to be an important characteristic of network components and reliability is still the subject of many discussions and exchanges of experience.

A difficulty arose, that the technical discussions and sharing of expertise and data was disrupted by differences in the definitions and formats of data. In 1992, Working Group 23-09 was set up in order to help CIGRE Study Committees to collect reliability data and provide a general overview of reliability. It provided the CIGRE Study Committees with very useful information concerning definitions, maintenance and reliability. However, compiling reliability data is still a difficult task. To add further to the lack of homogeneity in the format of data, it seems that utilities and manufacturers have become more and more reluctant to share data, due to the growth of competition and liberalisation of the market. It is often said that reliability data reveal the performance of the company (both of the manufacturer and/or utility who are involved at the design, manufacturing or maintenance stages), and publishing information on internal performance may lead to a competitive disadvantage. However, the relationship with regulatory authorities who need indicators and benchmarking between utilities is becoming increasingly important in order to assess performance .

The Joint Task Force 23/12/13/21/22-16 was set up in 1998 in order to update the work previously performed, and to help solve these difficulties. The present report is the result of the work of the joint task force, and summarises the 28 answers to the questionnaire that was sent to all CIGRE Study Committees in 1999. The report has several objectives :

- to encourage manufacturers and utilities to use reliability techniques, by showing the benefits of these techniques through examples taken from the latest developments in the field of electrical networks.
- to describe the experience feedback process, as reliability studies need information about equipment behaviour. The goals of experience feedback are given together with practical advice to help utilities in setting up an experience feedback organisation.
- to describe how the data provided by experience feedback have to be processed, in order to qualify and quantify failure modes. The description of the process, and possible uses of the output data in reliability studies are described.
- to encourage utilities and manufacturers to share their experience and data concerning reliability of their equipment and systems. The report provides guidance to bodies such as CIGRE Study Committees who would like to collect and compile reliability data.

This report is not intended to be a reliability data handbook. Several CIGRE Study Committees have already published reliability data. Neither is it a glossary of technical terms in reliability, which have been defined already in Publication IEC 50 (191) or in WG13-09 reports.

This report contains description of reliability concepts (chapter 2), methods (chapter 4) and tools (chapter 5), as an illustration of the possible uses of reliability data. The collection of reliability data, which is the purpose of this guide, is described in chapter 3. An organisation is proposed for the experience feedback collection at the level of a utility or for a CIGRE Study Committee (see §3.3 and 3.4).

2. Dependability in the field of electrical networks

2.1. General considerations about reliability and power systems

This chapter is aimed at describing the main concepts of dependability and to position them in relation to the area of Power Systems.

2.1.1 The « System » approach

Reliability analysis aims to identify the processes of degradation of an object, while describing and quantifying their effects on the reliability of the components of a system.
Thus the consequence of the weakness of a component can be reduced by an appropriate design (e.g. redundancy).

In the case of a power system, several components can be considered (see figure 1) to contribute to the whole :

- a transformer or a circuit-breaker is a system itself, that includes moving parts, control systems, etc...
- an overhead line bay or transformer bay is a system, in which a circuit breaker or a transformer can be considered as a component,
- a substation is a system but can also be considered as a subsystem of the network itself, the network being the biggest system.

The representation of a complete electrical system by all its basic components is too complex. That is why it is necessary to consider the whole system broken down into a number of subsystems. The reliability approach enables the properties of all the basic components to be taken into account in the description of the largest system. The performance and arrangement of electrical equipment in substations or networks determines the continuity of supply to customers. Reliability may be considered as a link between two levels :

- the equipment level (how to design and maintain an item of equipment in order to achieve the best reliability),
- the system level (substation layout arrangement, choice of the operation scheme of the network, types of redundancies...).

Alternative supply systems for sensitive customers can be compared, and the best decision made to reduce the probability of interruption of supply.

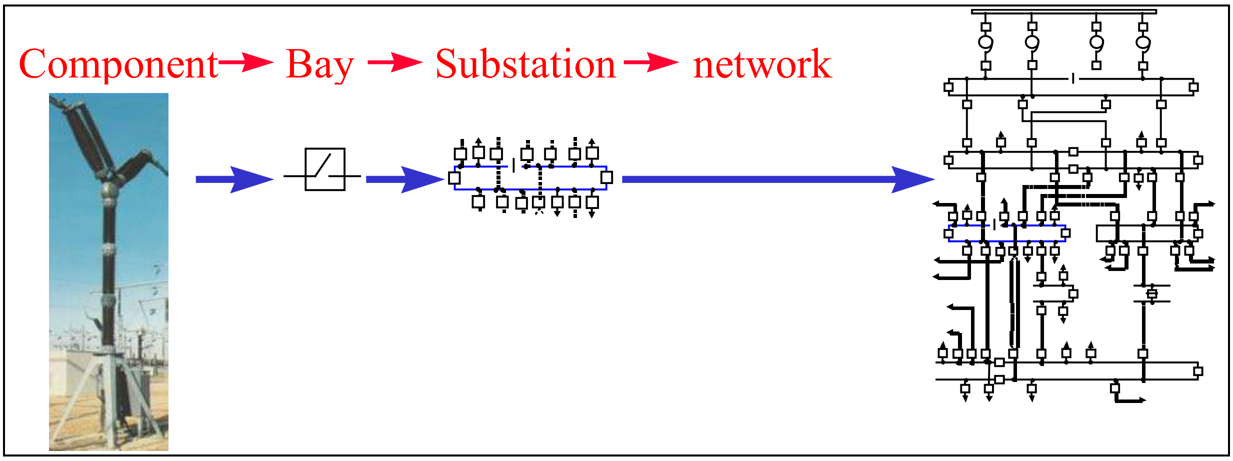


Figure 1 : the « System » approach

The substation is an illustration of the component vs system duality : it is a component of the network, but it is a system itself, made up of several hundred components for the largest substations. As a component in a network study, its failure modes are simply represented (loss of a busbar, of a line or transformer, with associated probability). However, these failure modes are the aggregation of several scenarios from the component point of view. The improvement of the reliability of a substation needs a thorough knowledge of the failure modes, failure rates and links between components of the substation.

2.1.2. Different actors with different points of view

Consideration of components versus systems is linked with a possible difference between the points of view of the utility and the customer.
The customer is interested in global performance, which is expressed in terms of interruptions (frequency, duration...). The utility tries to reduce the number and the impact of failures, from the point of view of an asset manager (reliability of equipment) and a system operator (continuity of supply and transmission capacity).
For the customer, a transient fault is a failure of his supply, even if no damage is sustained by the equipment. On the contrary, a transformer fault usually does not affect customers because of the N-1 rule.

The link between these two approaches is complex because the network is not a serial system. There are numerous failure modes of components but many redundancies avoid interruptions when failures do occur. A purely « customer-oriented » experience feedback would collect only information about supply interruptions. This could give priority to the system point of view. However, in order to improve reliability, the behaviour of components has to be known and the component experience feedback is essential to collect this knowledge.

2.1.3. The life cycle

The life cycle describes the stages of specification, design, manufacturing, use and destruction or recycling of a product.
The reliability of a product is one of its characteristics, in the same way as other technical characteristics. As such, reliability is built in at each stage of the development of the product. At the specification and design stage, minimum failure rates are defined and checked through theoretical reliability studies. The design of the product may then be improved by redundancy or by choosing more reliable electronic components. Logistics needed to comply with the time to repair requirement are also defined at the specification stage. Reliability is checked during the testing process and at the beginning of service life by the feedback of real operational experience. During the life of the product, reliability studies help to define maintenance, incremental improvement and design of new generations of equipment.

A very useful optimisation tool is the Life Cycle Cost (LCC) analysis, which adds the cost of initial purchase, maintenance, failures and other constraints during operational life and possibly dismantling or recycling. The LCC enables a higher investment to be justified in order to purchase equipment with lower failure rates. An example of use of the LCC concept is available in ref [3].

The reliability of a product is managed by a « dependability management plan » which follows the product throughout its life. In the same way as the quality assurance plan, it describes the roles and responsibilities of the actors in the development and use, in the field of dependability, and how dependability is specified, designed and tested.

2.1.4. The « bath-tub curve »

The « bath-tub curve » or « Hazard-rate curve » represents the evolution of the failure rate of a piece of equipment during its operational life. It comprises three periods :

1. decreasing reliability at the beginning of life, the burn-in period, where manufacturing problems are discovered (generic failures, problem in design or with some components)
2. the normal life, during which the failure rate is constant (which corresponds to the hypothesis of an exponential law of the probability of failure)
3. end of life, where the failure rate increases rapidly.

Experience feedback is necessary in the three phases

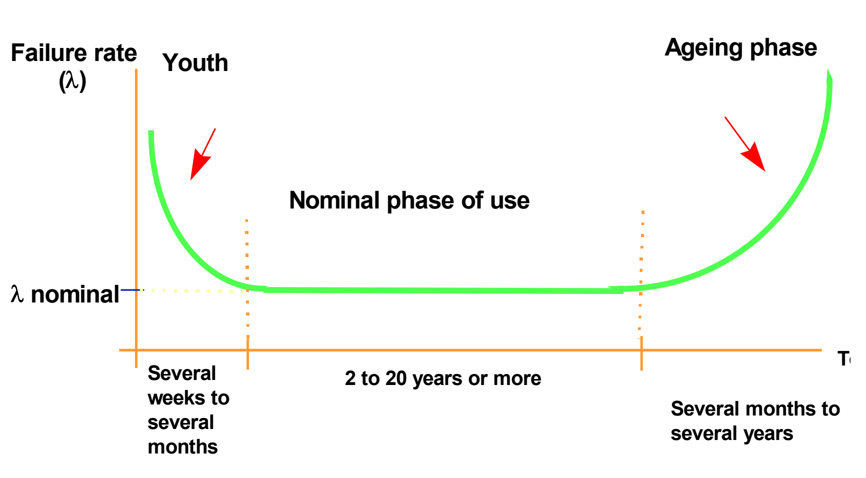


figure 2: bath-tub curve

to :

1. detect early failures, collect information on installation and use by field staff,
2. follow reliability indices in order to detect specific failure modes and the end of life, and to adjust maintenance tasks and intervals correspondingly,
3. decide on replacement if the failure rate is too high.

2.1.5. Risk analysis

Reliability analysis is a theoretical risk analysis approach. Risk is assessed through models that represent the behaviour of the system that is being studied. Each failure mode is considered and quantified. The risk is then assessed in terms of the probability of occurrence. Decisions are made on the basis of figures that are explained by theory. The figures are probabilities which give a measure of the risk, or deduced from probabilities combined with other factors. For example, criticality is often used as a measurement of a risk. It is defined by :

$$\text{criticality} = \text{frequency} \times \text{consequence}$$

Frequency is a probability, and consequence is quantified on a scale, which describes the effect of a failure on the system. Criticality is then a number, which enables failure modes to be classified into major, minor faults etc…

Due to this approach, reliability is sometimes considered to be a pessimistic science, which emphasises failures and worst cases rather than operational success and luck. However this rigorous reliability analysis approach also permits a margin to be established to limit risks to a reasonable level.
The security standard e.g. the « N-1 rule », that is often used as a criterion for investment is the first step of reliability. However, reliability offers powerful tools, described in the following chapter, that permit investment to be contained without decreasing the safety level of the supply. Choices that could be the result of intuition or empirical knowledge of system behaviour are then the result of techno-economical calculations.

2.1.6. Financial benefit of reliability-based decisions

The reliability approach has a cost : it needs the attention of specialists in reliability techniques and power systems. The experience feedback organisation is also expensive. The question of the return on investment of these costs is often asked.
Three types of benefits follow from the use of reliability techniques :

1. reduction in investment costs : some system redundancy may be avoided when the effect on system reliability is not proved. It is possible that the addition of equipment in series with a substation supply decreases the performance measured by the number of interruptions.
2. reduction in maintenance costs : Reliability-Centred Maintenance (RCM) and other techniques enable maintenance costs to be reduced by, for example, reduction of maintenance intervals for expensive maintenance tasks, that would not be necessary in the light of a reliability analysis.
3. reduction of supply interruptions to customers : the increase of the reliability of the system leads to reduced power supply losses for customers and reduced interruptions of their processes.

Many utilities use reliability as a tool for reducing costs. The examples given below intend to prove that the corresponding expenses produce enough cost reductions to justify the production of reliability data of good quality.

2.2. Types of reliability studies and associated reliability data

Reliability studies belong to two families : system studies and component studies. System studies deal with performance of the network in its function of providing supply to customers. Component studies deal with electrical equipment at all the stages of the life cycle.

The following types of reliability studies were considered :

(1) System studies :

- calculation of availability and reliability for customer supply (power quality studies)
- system performance monitoring
- estimation of the risk of voltage collapse
- from system dependability targets derive reliability performance of assets

(2) Component studies :

- testing of new types of equipment
- detection of generic failures, corrective actions
- improvement of equipment
- dependability requirements for the purchase of electrical equipment by utilities
- decisions concerning refurbishment, replacement
- Reliability-Centred Maintenance

Table 1 gives an overview of these types of studies. For each type of study, reliability information and basic data needed to compute this information are listed. Table 1 : Processes Using Reliability/Availability Information

Process	Activity	Area	Reliability/Availability Information	Basic Data
Benchmarking, compliance with legal requirements	Comparison with other utilities, meet statutory requirements.		System availability, planned and unplanned unavailability, system security, loss of supply incidents, energy not supplied, quality of supply, voltage and frequency excursions.	Outages, number of incidents, duration of incidents, demand lost, number of voltage and frequency excursions.
Managing system	Calculation of expected customer reliability, in order to improve the network configuration, substation layout or protection system tuning. Assess system capability at planning stage.		Loss of load frequency and duration determined from equipment failure rates and repair times.	Type of equipment, population, number of failures, date and time of incidents, outage durations, description of the incident, consequences, corrective actions, network configuration
	System performance monitoring		System availability, planned and unplanned unavailability, system security, loss of supply incidents, energy not supplied, quality of supply, voltage and frequency excursions.	Outages, outage costs, number of incidents, duration of incidents, demand lost, number of voltage and frequency excursions.
	Estimation of the risk of voltage collapse and/or system failure, and benefits of new investment to reduce this risk	R&D, planning studies and development of procedures for network operation.	Failure rates and repair times, probabilistic representation of the state of the system	
	From system availability/ reliability performance targets, derivation of reliability performance targets for assets	R&D.	Failure rates and repair times.	
Managing assets	Assessment of asset health, asset reliability performance, decisions on refurbishment or replacement.	Planning and operation of the system.	Equipment failure rates	Failure and defect data, condition monitoring information, direct maintenance costs, outage costs, manufacturer data, equipment age.
	Corrective actions	Operation and maintenance of the system.	Equipment failure rates.	Failure and defect data, condition monitoring information
	Detection of generic failures, improvement of equipment, test and acceptance, comparison between specified reliability performance and actual performance.	Relationship with manufacturers.	Equipment failure rates.	Failure and defect data, manufacturer data.

	Survey of reliability performance of various equipment families to estimate equipment life and assist with predicting future capital investments.		Predicted life	Age, service history (environment, loading of equipment).
	Assessment of life-cycle costs.	Planning and operation	Equipment failure rates.	
Maintenance policy	Reliability-centred maintenance (RCM)		Equipment failure rates.	Strategic importance of the equipment in the network
	Use of reliability data to determine the maintenance interval for individual assets.		Variation of failure rate with time, bath-tub curves.	Failure, direct and outage cost data…
	Circuit maintenance policy			
Spares management			Equipment failure rates, repair times.	Failure data, planned and unplanned outage times, outage costs, and costs of buying and holding spares.

2.3. List of reliability data

2.3.1. « Component » reliability data

Active failure rates (γ)

- Passive failure rates (λ)
- Failure rates per failure mode
- Repair times (μ)
- Predicted life
- Variation of failure rate with time (bath-tub curves)

2.3.2. « System » reliability data

- System availability (planned and unplanned)
- System security
- Loss of supply incidents
- Energy not supplied
- Quality of supply (voltage and frequency excursions…)
- Loss of load frequency and duration determined from equipment failure rates and repair times.

2.4. Limits of the dependability approach

Representation of reality by dependability models is of course an approximation, and reliability studies do not predict the future. The Mean Time Between Failures value does not forecast the exact date and time of the next failure ! Differences are then discovered between the result of a study and the reality of the field.

Four difficulties are particularly important for power systems :

1. representation of large systems (the time to consider all possible states of the system may be far too long)
2. representation of human error
3. consideration of events with low probabilities (very rare events such as system collapse are difficult to model)
4. several failures which appear simultaneously by coincidence

The last three types of incidents are however known as causes of possible catastrophic events.

To cope with these difficulties, it is necessary to take the following measures :

1. only the order of magnitude of the results have to be considered,
2. the comparison of results between two strategies, two network or substation configurations, two maintenance plans etc… is better than an absolute assessment of reliability,

3. input data must be of good quality.

3. Collection and Processing of Reliability Data

3.1. Experience feedback

Experience feedback is the first step of many reliability studies, because it provides reliability data which are necessary for the quantification of system failures, life-cycle costs…
In addition to valid reliability data, experience feedback is also necessary to obtain knowledge about the behaviour of equipment in operation. Experience feedback is a key process in finding improvement actions to important issues such as :

- improvement of quality, security and reliability of equipment
- measurement of installation cost, maintenance cost
- reduction of life-cycle cost
- improvement of the functions of existing equipment, or simplifying equipment
- explanation of failures
- survey of new type of equipment in order to detect generic failures
- replacement of an old type of equipment.

Experience feedback is not a uniform process for all types of equipment. The effort to obtain experience feedback of a type of equipment can be adjusted depending on :

- total purchase cost of the equipment
- cost generated by a failure of the equipment
- environmental impact of the equipment
- safety impact
- image of the utility in the public.

3.2. From failures to reliability data

Two types of experience feedback are possible in a utility, as shown in figure 2 :

(1) the « system » experience feedback, which collects information on interruptions, and surveys the quality of the supply of customers

(2) the « component » experience feedback, which collects information on equipment failures, in order to maintain the network in good operating condition and to provide data for the estimation of expected system performance.

Both processes lead to reliability data : in the first case, these data are, for example, average number of customer interruptions, energy not supplied… and in the second case, these data are equipment failure rates.

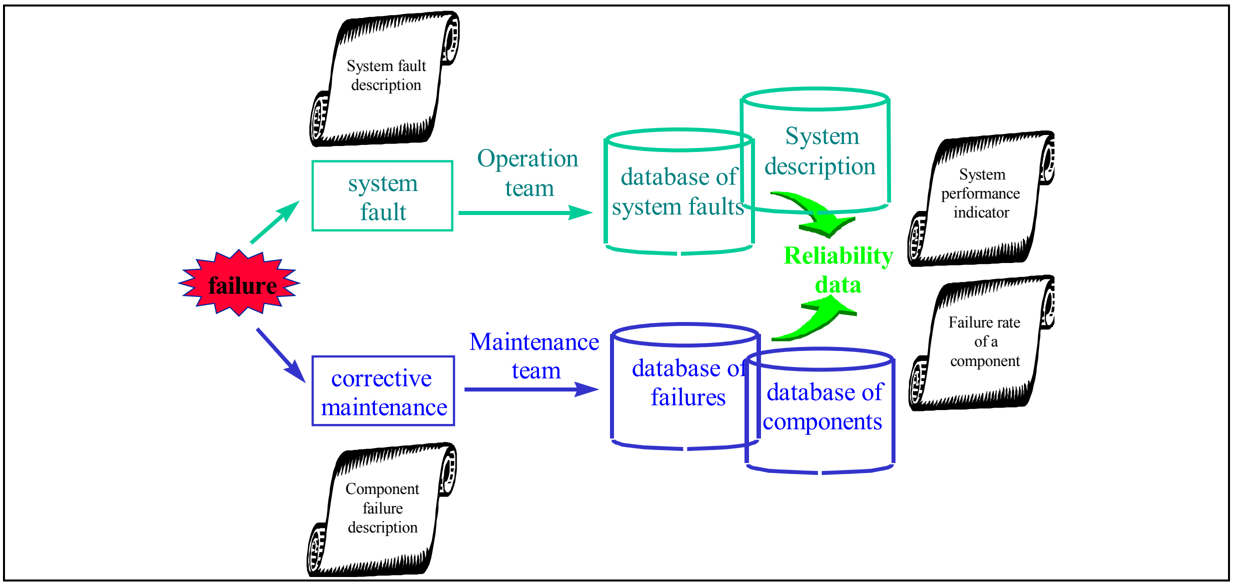


Figure 2 : « system » experience feedback and « component » experience feedback

These two experience feedback processes are not independent. For example, the number of active failures of a circuit breaker (failures on demand) needs to be calculated in relation to the total number of operations of the circuit breaker.
The present report mainly focuses on « component » reliability data.

3.3. Guidelines for the organisation of experience feedback and processing of basic data

Experience feedback collects basic data such as component failure reports and system fault reports .
The quality of the information given in these basic data reports will determine the quality of the reliability data calculated with this basic information. If some information is missing, some computation of specific reliability data will not be possible. For example, if the basic information does not give the age of the defective equipment, then the variation of failure rate with time, and the bath-tub (Hazard rate) curve for the equipment will not be accessible. As a consequence, studies such as those required to replace equipment will not be possible.

3.3.1. Component failure description

A failure report for a component failure should contain the following information :

(a) Information about the device :

- Identification (name, type, manufacturer, serial number, site, nominal voltage)
- Age
- Date of installation in this location
- History of the device (past maintenance, past failures, past locations…)

(b) Information about the failure :

- Date of the discovery of the failure
- Description of the failure : (failure mode, if a list of failure modes exists for this type of device. Is it a spontaneous failure, or a failure on demand ? which component has failed ?)
- State of the device : installation, normal operation, preventive maintenance, curative maintenance
- Environment of the device at the moment of the failure : (meteorological event, loading condition…)
- Repair time : time to repair
- Effect of the fault : e.g. interruption of customers (duration, number, power, energy not supplied), loss of generation, need to start a generation plant, no effect (e.g. in the case of a fault discovered during preventive maintenance), cost of the repair, cost of the consequence.

This information may not be available at the time of creation of the failure report. The failure report must then be accessible for further feeding of some data.

This information can be collected in a table similar to the FMECA (Failure Mode, Effects and Criticality Analysis) table (see § 4.7) :

(a)	(b)			
Description of the device	Failure mode	Possible cause	Effect on equipment	Effect on the system

If possible, in order to help people in the field, a pre-filled FMECA table should be provided, so that the failure mode, the effect would be chosen in a list rather than described each time.

An interest of the use of the FMECA format is the ease of compilation of the failures. The global table derived from this experience feedback process is a very good overview of the behaviour and operation of the considered equipment on the field.

3.3.2. Calculation of a failure rate

There are two types of failures of components, according to the cause of the failure :

1. failures due to time consumption. These failures appear randomly, happen at any time, e.g. loss of insulation of an overhead line. For these failures, the probability of occurrence is described by an exponential law (if we consider that the probability of failure is not time-dependant, that is we are on the flat part of the “bath-tub” curve). For taking into account ageing, Weibull laws are to be used.

2. failures on demand , which happen when a specific function of a device is activated, e.g. failure to open of a circuit-breaker. For these failures, the law of probability is a binomial law.

A failure rate is basically the ratio between the number of failures and a representation of the constraint endured by the set of equipment. The unit of the representation of the constraint is the cumulated duration of the observation period for all equipment concerned for the first sort of failures (random failures). In the case of failures on demand, the denominator is the number of demands on the device made during the period of observation. It should be noted that this type of information may be very difficult to collect.

These two types of failures are not so different. In the first case, the constraint on equipment is hidden behind the time. It is the climate, the night and day cycles, the wear, which cannot be identified as independent elements like in the case of circuit-breaker openings (which are typically of the second type).

In addition to failure reports, two types of data are necessary (for « component » reliability data calculation), in order to calculate the denominator of the reliability data :

- a database of components,
- for failure rates related to demand, the number of operations.

These two types of data may need a specific experience feedback organisation to be set up.

It is instructive to characterise a failure rate or repair rate by its confidence interval. The confidence interval is obtained by the χ^2 law, in the first case of random failures. The confidence interval gives an indication of the validity of the sample. If the value is too large, it means that the observation period is too short, or the number of devices is too small. For example, if only one failure has been observed, the failure rate range is between one tenth and ten times the estimated value.

3.3.3. Format of reliability data

An item of reliability data should not be just a figure. It needs additional information, that explains the data and enables further calculations, such as the calculation of a reliability index for several areas on the basis of a reliability index for each area.

Thus the format of a reliability index, for exchange, addition, comparison or discussion, should be :

- value of the failure rate (which can be a probability per hour or per year, a probability per demand , a probability per hour or per year and per km or per hundred km (or another distance unit), in the case of line or cable failure rates)
- value of the repair time (in hours)
- the period of time used for the calculation
- the number of failures used for the calculation
- the number of items of equipment, and characteristics of the sample, if need be
- the number of events in case of failures on demand .

This format of reliability data enables the data to be exchanged, but does not permit complex processing such as, for example, variation of the failure rate as a function of the age of the device. This type of complex calculation needs all the basic data and a specific processing.

3.3.4. System reliability data

Joint Working Group 23/39 on Maintenance and Reliability conducted an international survey in 1997/1998 on maintenance policies and trends [1]. Utilities were asked which system performance indices they use. The answers obtained show a great variety in the definitions. However, it appears that the duration of customer interruption is the most commonly used index of performance. Reliability, availability and quality of supply are other indices of performance that are used.

The Joint Task Force responsible for the present report did not attempt to unify the definitions of the indices used to measure system performance. This is a difficult task that would justify setting up a specific task force with System Study Committees to cover this subject alone.

The definitions of system reliability performance indices collected through the present questionnaire had three goals :

- measurement of the reliability of components (line, substations) of the system

- measurement of the quality of supply for customers
- measurement of the availability of transmission capacity.

These three types of definitions represent the three roles of the utility : maintain the assets, transmit power and deliver it to customers.

UNIPEDE is also presently working on this topic, and reference [2] gives definition of indicators for availability of supply.

3.4. Guidance for aggregated reliability data collection and compilation

We recommend to proceed as follows :

1st step : Define why an enquiry for collection of reliability data is organised

It is important to answer this question at the beginning of the process because it may change the way to ask the questions in the enquiry.

The goals of such an enquiry may be :

1. to provide average values for reliability data, calculated on a world wide basis, for the purpose of comparison. A utility will then compare its own performance to the average value. If its performance value is lower than the average, some reasons can be found in the environment (climate), in the operation of the system close to the limit. Best practises could be looked for with the help of utility having the best failure rates.
2. to provide reliability data with reduced confidence interval, for network studies
3. to get better knowledge about the behaviour of equipment on the field : most frequently failing components , comparison between technologies, in order to focus R&D of manufacturers, to provide installation and maintenance guidance.

2nd step : choice of the type of enquiry : failure reports or reliability data ?

Two main types of enquiry may be set up :

1. the collection of reliability data
2. the collection of failure reports.

Obviously the second type of enquiry provides the richest raw material for further statistical processing. However, failure reports for wide spread equipment may be too numerous and then difficult to handle. It is then recommended to set up a collection of reliability data. The question of confidentiality may also be an obstacle to the collection of failure reports.

For collection of failure report, we recommend to use the FMECA table as described in paragraph 3.3.1.

The collection of reliability data, which is the normal type of enquiry dealt with in CIGRE Study Committees, is described in the following.

3rd step : determination of a form for the collection of reliability data

The best example for this type of enquiry is probably the report prepared by Canadian Electricity Association [4]. The proposal described below is greatly inspired by this example.

The form is organised

- a typology of the studied equipment, with the number of pieces of equipment in each type,
- a list of components that may be the location of the fault,
- a list of failure modes associated to the components
- the number of operations for failures on demand
- the number of failures

as shown in the following table :

Type of equipment	Number of equipment of this type	List of main components	Main failure modes	Number of operations (for failures on demand)	Number of failures

The typology has to be defined according to the parameters that discriminate the population. Typical parameters are : the voltage level, the technology, the decade of manufacturing.

If too many parameters are used, then the table becomes long with little failures for each type of equipment.

An example of how the table looks like is given hereafter :

Type of equipment		Number of equipment of this type	List of main components	Main failure modes	Number of operations (for failures on demand)	Number of failures
Voltage level	Technology					
> 200 kV	Tech #1		Component #1	Failure mode #1		
			Component #2	Failure mode #2		
				Failure mode #3		
			Component #3	Failure mode #4		
	Tech #2		Component #1	Failure mode #1		
			Component #2	Failure mode #2		
				Failure mode #3		
			Component #3	Failure mode #4		
200 kV> V>100 kV	Tech #1		Component #1	Failure mode #1		
			Component #2	Failure mode #2		
				Failure mode #3		
			Component #3	Failure mode #4		
	Tech #2		Component #1	Failure mode #1		
			Component #2	Failure mode #2		
				Failure mode #3		
			Component #3	Failure mode #4		
< 100 kV	Tech #1		Component #1	Failure mode #1		
	…					

Grey cells have to be filled, and some lines for Failure modes, or Components, may also be added.

3.5. Examples

This chapter provides examples of how reliability data is collected and how the data is used in various processes and studies.

3.5.1. Examples of calculation of reliability data

The following example shows the sensitivity of the confidence interval with respect to the number of failures.

1. Let us consider a cumulated observation period of 1000 years, during which 10 failures have been observed. The failure rate is then $\lambda=10^{-2}$ per year. The confidence interval given by the application of the χ^2 law is :

- a probability of 90% that $\lambda \in [5.4\ 10^{-3};\ 1.7\ 10^{-2}]$
- a probability of 95% that $\lambda \in [4.8\ 10^{-3};\ 1.8\ 10^{-2}]$

2. Let us consider a cumulated observation period of 10000 years, during which 100 failures have been observed. The failure rate is also $\lambda=10^{-2}$ per year. The confidence interval given by the application of the χ^2 law is :

- a probability of 90% that $\lambda \in [8.4\ 10^{-3}; 1.18\ 10^{-2}]$
- a probability of 95% that $\lambda \in [8.1\ 10^{-3}; 1.21\ 10^{-2}]$

Another classical example is the calculation of a failure rate when no failure has been observed. The χ^2 law leads to $\lambda \in [0 ; 2.3\ 10^{-3}]$ at 90% for an observation period of 1000 years. It is recommended to use a value of 0.7 for the calculation of the mean failure rate, when no failure has been observed. The mean λ is then 0.7/1000 which is in the previous interval.

3.5.2. Examples of use of reliability data

3.5.2.1. Electronic meter

Electronic meters have now been used for several years, in replacement for electromechanical meters. They enable more complex functions, such as the metering of power quality, and changing the characteristics of the tariff. However, these important components of the power system are presumed less reliable than the older and more mature electromechanical meters.

In order to control the reliability of these new meters, a utility has set up a specific experience feedback process. It used a sample area, extending to roughly 10% of the utility, and after two years provided reliability data of very good quality, that enabled :

- discrimination between internal failures and incorrect installation,
- computation of failure rates of each manufacturer.

During the following years, the market share of the manufacturers was determined partially as a function of the reliability of its product during the previous market period.
The use of a sample was possible in this case because the device was widely used and had a relatively high failure rate.

3.5.2.2. HV circuit-breaker replacement

A utility performed calculations of failure rates for different generations of HV circuit breaker. It showed a higher failure rate for oldest technologies. The corresponding circuit breakers were replaced by new ones on the basis of an economic calculation that took into account a reduction of the expected loss of load due to the increase of reliability of the circuit breakers.

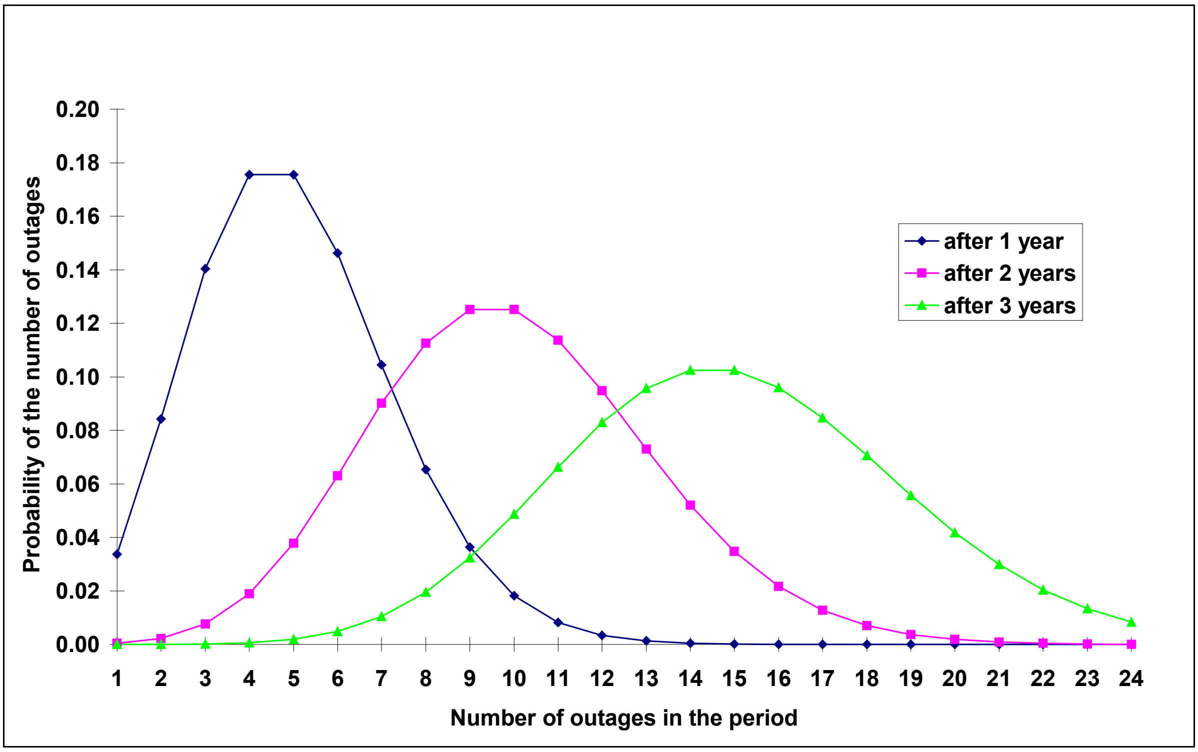
3.5.2.3. Assessment of the risk of exceeding a given number of interruptions

The Poisson Law gives the number of failures n(t) which is supposed to happen during a time interval [0, t], in terms of probability, given a failure rate of λ (average number of failures per year pear equipment) :

$$P(n(t)=k)=\frac{(\lambda t)^k}{k!}e^{-\lambda t}$$

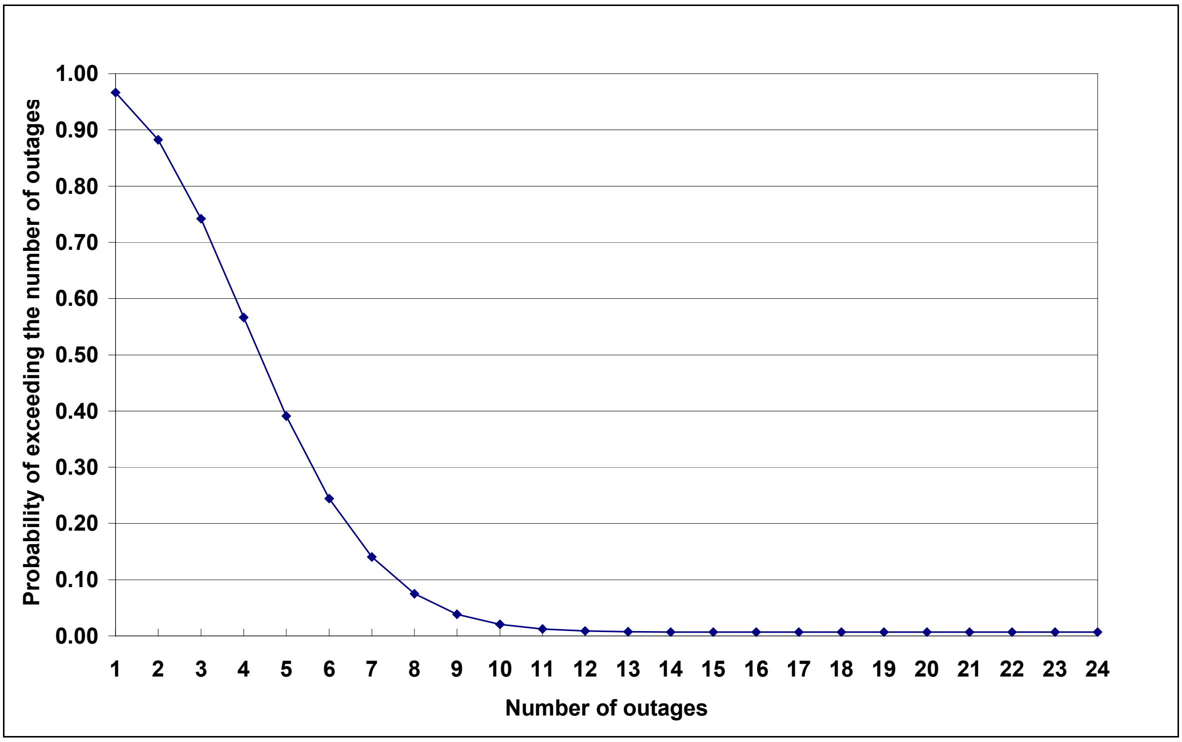
n(t) is the number of failures observed between time = 0 and time = t
P(n(t)=k) is the probability that n(t) equals k
The total number of in one year is supposed to be λ times the number of equipment considered. For example, for a set of 3000 equipment and a failure rate of $\lambda=10^{-2}$ / year, we should observe 30 failures per year. It is obvious that this number is a mean value, that may not be matched. The Poisson Law describes how many failures are likely to be really observed.

For example in the next figure, we consider that the number of interruptions of customers is an exponential law of parameter $\lambda=5$. The figures shows the probability of the number of outages after 1 year, 2 years and 3 years.



A particular use of the Poisson Law is the estimation of the risk of exceeding a given number of failures. Let us consider a utility that defines an upper limit λ_{lim} to the annual number of interruptions that customers endure, with a risk that for a given percentage of customers the number of interruptions exceeds the limit λ_{lim}/year. If we suppose that the annual number of interruptions follows an exponential law of parameter λ, then the probability of having more that λ_{lim} failures is $P \Rightarrow 1 - \sum_{i=0}^{\lambda_{lim}} \frac{(\lambda t)^i}{i!} e^{\lambda t}$ after time t.

In the following figure, we take $\lambda_{lim} = 5$. The number of interruptions which is exceeded by less than 10% of the customers is 8.



4. Methods for reliability studies

This chapter describes the main methods used in the industry for reliability studies, and possible applications in the field of power systems.

4.1. Fault trees

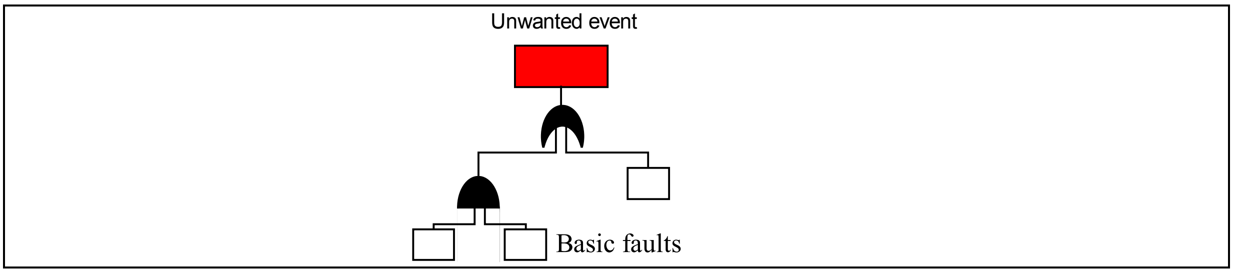


Figure 3 : fault tree

To estimate the probability of occurrence of the « unwanted event », the causes of faults are sought (inductive approach). Basic faults are determined, which give the unwanted event by logical combination. From the value of probabilities of the basic faults the probability of the unwanted event can be deduced.
This very basic technique can be used for the improvement of supply to a sensitive customer.

4.2. Event trees

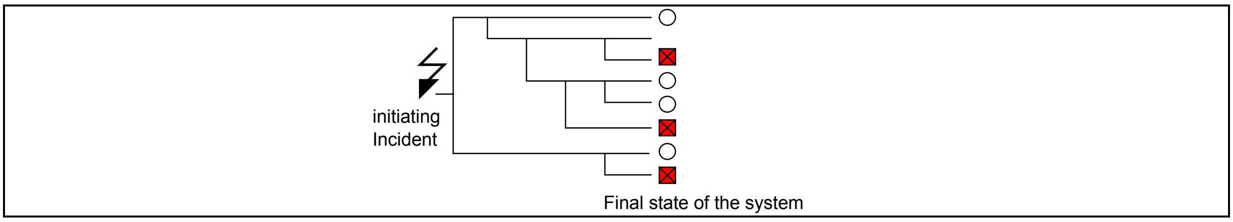


Figure 4 : event tree

For each incident that may affect the system, scenarios of how the system will respond are simulated. These scenarios represent all possible operations of the components, including failures. For each operation, a probability is calculated, using the failure rates of the components. For each scenario, the final state of the system is compared to the unwanted event (deductive approach).
This technique is particularly suited to the definition of the protection scheme and tuning.

4.3. State graphs

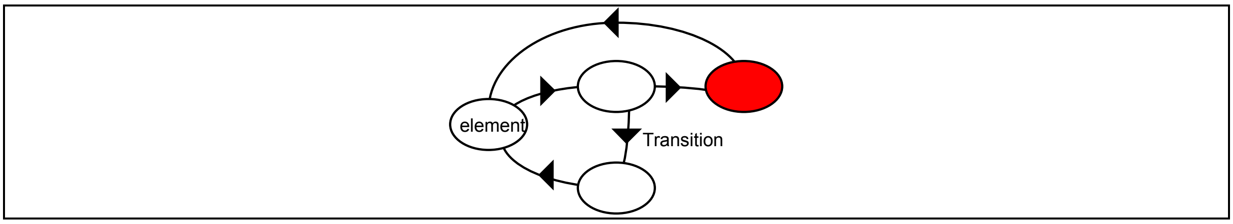


Figure 5 : state graph

Each element of the graph represents a state of the system that is being studied. For transitions, that change the state of the system, represent failures, repairs etc, each transition has a probability of occurrence quantified by a rate. Knowledge of these rates enables the calculation of the probability of each state of the system.
This technique is adapted to the study of systems with several failure modes, including system redundancy. For example, it is useful for substation design in the case of complex substation schemes (typically urban areas).

4.4. Stochastic Petri networks

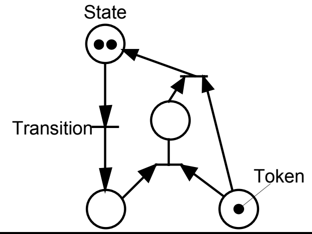


Figure 6 : Stochastic Petri network

This technique was invented to represent the operation of robots . The « states » represent the states of components. The « transitions » represent events that affect the components. A transition is drawn by the move of a « token ». If the transition happens randomly and under certain conditions, this representation can be used for the calculation of the probability of occurrence of certain states of the system, represented by specific tokens.

4.5. Monte Carlo simulations

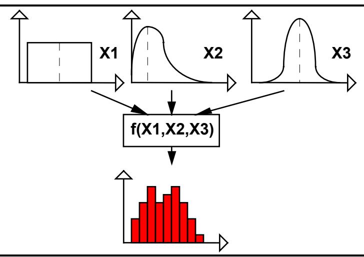


Figure 7 : Monte Carlo simulation

The index is intended as a function of random input variables (for example, the law of failure of components of the system). Knowing this relation, the input variables are simulated by a large number of random values that follow the probability of their occurrence. An estimator of the index is built according to the function that links its value to the input variables.

4.6. Bayesian method

As there is no existing calculation code or model, Bayesian techniques are used. These subjective techniques collate the data obtained from experience feedback with the data from expert assessments.
A Bayesian technique is used by a utility to adapt the maintenance interval of RCM maintenance plans.

4.7. FMECA

The FMECA (Failure Mode, Effects and Criticality Analysis) technique is widely used in the reliability field.
It is now covered by IEC standard 812.

Component	Function	Failure mode	Possible causes	Effect on equipment	Seriou sness	Av no.	Failure rate in 10 –3 /year	Database frequency	Manage ment Freque ncy	Frequency used for analytical purposes	Criticality
Contacts	Function 1 Function 3	Heating	Corrosion, poor assembly	Risk of destruction	4	20	0,7	2	2	2	**8**
	Function 2 Function 3	Loosening Blocking Breaking	Corrosion, poor assembly	Risk of destruction	4	5	0,2	2	2	2	**8**

Figure 8 : FMECA Table (example)

This table summarises all the available information about the failure modes of the device that is being studied. It makes a link between the causes and consequences of failures. Tables for frequency and consequence have to be defined, and criticality is deduced by multiplication.
It is used at the design stage, but also for maintenance optimisation and explanation of failures.

4.8. Choice of a reliability method

The methods introduced above form a toolbox. Each tool has to be used properly. The criteria for the choice of the appropriate tool are :

- size of the system
- complexity of the system
- phase in the life-cycle

The first step is the definition of the system : its limits, size and functions. The functional approach is very useful at this stage. Then the size of the system and the possible number of states give indications of how to choose between Monte Carlo techniques on the one hand , for complex and large systems, and the first four methods that describe the whole system.

5. Tools for reliability studies

The survey conducted in 1999 by the Joint Task Force collected information about tools for reliability studies. There were three main types of tools :

1. general tools for reliability studies (not devoted to power system or electrical equipment). These tools implement the methods discussed in the previous chapter. They are used in several fields of industry : aeronautics, electronics, car industry. These general tools are not considered in the present report.
2. tools for system studies. These tools make network calculations on the basis of the description of a network (topology and failure rates of components). The outputs are mainly frequencies and durations of interruptions, and system indices such as Expected Loss of Load . Although these tools are not really reliability tools, but more network planning tools, they are listed below.
3. reliability tools : these tools implement reliability methods in the field of power systems (substation or network studies). These tools are recent and rare. They are detailed further in the references given in the bibliography.

The tools listed below have not been tested by the Joint Task Force neither are they recommended by CIGRE. They have been quoted in answers to the 1999 survey. The list provides bibliographical references when available, and names of users for further information. The tools are briefly described in the following table :

Package	Owner	Purpose of package	Input Data Requirement	Output	Reliability model
ALERT	Risk Decision Ltd	Long term asset replacement forecasting	Asset life distribution, costs, replacement strategies	Capital costs, failures, replacement	Analytical and simulation probabilistic model
COMPAC	NGC	Optimisation of circuit maint. Strategy			Analytical probabilistic model
ESCORT	NGC	Simulation of system operation	Network, generation merit order, generation and transmission availability, contingency list, annual demand variation	Vast amount of statistics on costs, load flows, losses, etc…	
APTMAIN	The Woodhouse Partnership	Asset maintenance optimisation	Failure information, costs, maintenance requirements	Costs, maintenance intervals	Analytical probabilistic model
RAMESES	Aachen University of Technology	Reliability analysis methods for electrical power systems	Network description. Failure rates	Frequency and duration of interruptions, unavailability, LOLE ; LOPE	
TOPASE	EDF	Substation and network design	Description of the substation(s) (HV and LV equipment), failure modes and failure rates	Probability of interruption at each bus, contribution of each component to the probabilities	Complete event tree calculation
TRIP	NGC	Reliability of transmission connections to a power station	**Fault data:** transient/ sustained active & passive component failure rates for normal & adverse weather **Circuit Composition:** Series main/subsidiary Series components Common mode elements **Run data:** normal/ stormy weather rates maintenance frequency & duration study parameters	Frequency, Duration and unavailability for 2 cct, 2 cct, 3 cct and 4 cct losses Transient & sustained failure rates. Outage duration (hours) Unavailability (hours/year)	Combination of series and parallel components to obtain reliabilility graph. Analysis to obtain frequency & duration of first, second, third & fourth order failure modes.

6. Recommendations

The traditional experience feedback organisation tends to collect information on each failure. Experience shows that this information is partial. The problem is mainly a human problem : how can an operator be motivated by a task (filling a report form after a failure), if he is unable to see the results of this work ?

This report gives examples of uses of dependability in the field of power systems. It shows a growing concern for the use of this modern technique when considering investment optimisation and operating costs. The purpose of these examples is to persuade utilities to set-up an effective experience feedback organisation. However, these examples do not provide an answer to the question of motivating an operator in the field, who has to complete a form in a computer after his intervention. It would be misleading to believe that each failure report could result in feedback to its author. Unfortunately, much collection, storage and processing work has to be performed before arriving at useful conclusions.

Experience shows that operators tend to formalise failure reports in the following cases :

- the failing device is important
- restoration of supply has been particularly difficult
- replacement cost of the failing equipment is high (the failure report helps to justify the replacement)
- equipment or the failure is new.

To obtain statistically valid data, all the other events have to be reported. Staff motivation is required which will be enhanced if a strong organisation for the processing of the failure reports is set up i.e. if the staff obtains quick answers to its questions and requests for help, if information is made on the main failure modes and possible preventive actions, if emergency measures discovered after a failure report are advertised.

It is advised that Cigre should set up a specific task force, mainly related to the System Study Committees, that should attempt to standardise the definitions of the indices used to measure system performance. Besides, in order to create a useful feed back and information loop regarding both system as equipment failure information, all Cigre groups intending to organise this process are asked to regard the contents and the approach (system versus component) of this report.

Bibliography

[1] « An international Survey of Maintenance Policies and Trends », CIGRE Brochure 1999, by CIGRE Joint Working Group 23/39 on Maintenance and Reliability.

[2] « Availability of Supply (update of the SYSTQUAL report « Quality of Supply from Electric Power Systems ») », 1997, by UNIPEDE - Large Systems and International Interconnections Study Committee - Group of Experts on Quality of Transmission Services

[3] “Renovation of old Air Insulated Substations Utilising GIS-Technology”, CIGRE 1996, paper 23-104 by T. Sezen and K. Pettersson

[4] “Forced outage performance of transmission equipment” edited by the Canadian Electricity Association, December 1996