“D8.6.1 – Description of the data center demonstrator and requirement for the reliability analysis”

“Sub Work Package 8.6 : Data Center”

“Work Package 8 : Demonstrator”

MODRIO (11004)

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Executive summary

NOTICE : Only reliability data already published in public domain documents will be used in this document. Degradation models as described in already published works will be taken into account in this study.

The goal of this document is to present the demonstrator “reliability study of Data center structure” of the MODRIO project along with the study on this subject which will be completed subsequently.

A data center is a system with high level of reliability and availability (“Tier I to a Tier IV level” according to the “Uptime Institute” [1]) for electrical supply and air cooling systems. To obtain high levels of availability this system is designed with several redundancies, a stand-by AC power source, and a UPS (Uninterruptible Power Supply) [33]. Probabilistic reliability analysis of such a system has already been done at EDF R&D with the EDF’s KB3 reliability tools [2], [3], [4]. Nevertheless some hypotheses assumed for this type of reliability study were not sufficient mainly in relation to the modeling of the risk of common cause failure.

For example, data centers are usually supplied by two medium voltage lines (20 kV in France) which are supposed to be independent. In reality some common cause failure can affect both these two MV lines simultaneously. Black-out on the HV transmission network, which is a very rare event, can affect the electrical supply of the Data center. These common causes of failure can be trigged by the impact of certain weather events on the electrical distribution or transmission networks. Pertinent meteorological conditions can impact the electrical network and include high (heat wave) or low temperatures (with Ice), extreme, wind speed, or lightning …

To model weather stress on the electrical HV and MV network, physical reliability models of electrical component are needed. The statistical reliability “Cox model” is able to represent the impact of the variation of physical parameter upon the reliability level of electrical component. The degradation of the reliability of each component of a data center may or may not affects, the normal operation of the electrical supply or the air cooling systems.

As one can see from the above, there is a need to model physically the data center in normal operating conditions and for a degraded state of some component. These studies should be done both for electrical supply and air conditioning systems. That is why the use of a tool such as MODELICA will be of great interest to integrate precise representation of electrical and air conditioning component.

EDF has been developing since 2013 a library of electrical component in MODELICA language and has already developed a library for air cooling components. The European “I-Tesla” project (2013-2015 http://www.itesla-project.eu/), in which RTE the French TSO is a partner, is developing MODELICA components to model a transmission network (nevertheless these components will be available only at the beginning of 2016).

Some aspects of the weather constraints that affect the reliability of transmission and distribution networks have already been modeled. These points will be used in the MODRIO project.

The task of the MODRIO project will be to add failure mode to existing EDF’s libraries of components and to realize a reliability study taking into account physical representation of failure mode with MODELICA. The method used to do reliability analysis in MODELICA is to compute in the same time differential equations (DAE) function of the time and “Monte Carlo” simulation to represent the failure occurrence of components of the Data Center.

Benchmarking between reliability studies of the data center were done with FIGARO (existing EDF reliability tool) and new MODELICA libraries component will be completed.

Finally, it is important to position the results of the reliability study with respect to the different perspectives held by either the owner of a future data center or the manufacturer in charge of building this system. In this respect an example of reliability requirements for a data center and example of predicting reliability study will be presented in the document.

Summary

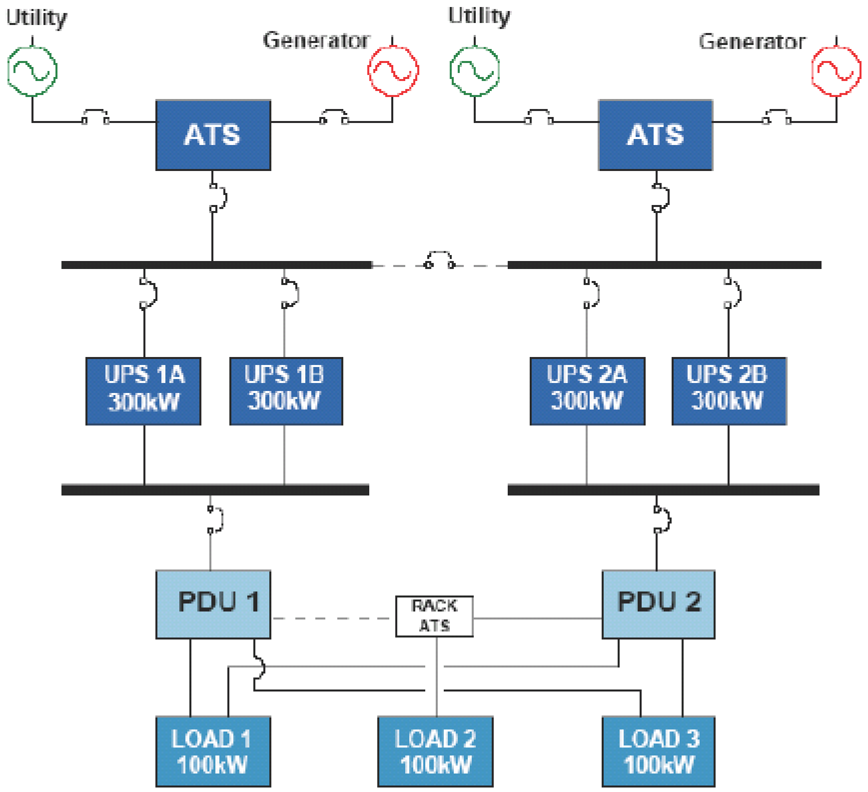
ABREVIATIONS

AC :	Alternative Current
ATS :	Automatic Transfer Switch (component of a Data center)
BDMP :	Boolean Driven Markov Process
BPS :	Back-up Power Source
CIM :	Common Information Model to describe electrical component with the UML standard
DLR (www.dlr.de) :	German research organism on aerospace (member of the MODRIO project)
DLA :	Diffusion Limited Aggregation (type of diffusion process)
EPRI (www.epri.com) :	US organization in charge of R&D in the electrical networks field
EMTP :	Tool to compute the Transient Electromagnetic phenomena
EUROSTAG :	Tool to compute the electrical characteristic of electrical networks with generation sources and the HV and MV networks
FIDES :	Reliability data handbook for electronic components
FORM-L :	Language designed by EDF in the context of the MODRIO project
FMEA :	Failure Mode and their Effect Analysis
GRIF :	Reliability tool designed by TOTAL (Satodev ©)
HV :	High Voltage over 50 kV
IEC :	International Electrotechnical Commitee (for Standard)
I_Tesla :	« I_Tesla » European project directed by RTE (French Transmission system operator
KB3 :	Knowledge Base (third version) - reliability tool designed by EDF R&D and based on the FIGARO language (wrote by EDF R&D) to describe a system including failure modes of its components and the propagation of failures inside the system. This description can be used to compute with other tool (based on markov graph computation for example) the reliability and availability indices of the system
MV :	Medium Voltage between 400V and 50 kV (MV : 20 kV in France)
Object Stab :	Library designed by ABB to model electrical component
TIER :	Classification used by the Up-Time Institute for the Data Center
PDU :	Power Distribution Unit
PAPYRUS :	Tool designed by CEA (France) for the system description with the SYSML standard
RTE :	French Transmission System Operator
SOC :	Self Organized Criticallity
SYSML :	System Modeling standard to describe system
TSO :	Transmission System Operator
Thermosys-Pro :	Library designed by EDF R&D for the thermo-hydraulic components
Utility :	Electrical Company
UPS :	Uninterruptible Power Source (contained Converter , battery ..)
Uptime Institute :	https://uptimeinstitute.com/TierCertification/

1. Introduction

This document presents the reliability study of the electrical network and air cooling part of a Data Center with MODELICA language. In this chapter we present some general information about the data Center and about components for the electrical supply part and cooling system of Data Center.

WARNING : This document will not examine the human factor as a cause of a failure of the components or systems. In this document there is no confidential data.



ATS Automatic Transfer Switch *UPS : Uninterruptible Power Supply*	*PDU : Power Distribution Unit* *Utility : external MV line* *Generator : Back Up AC power source*

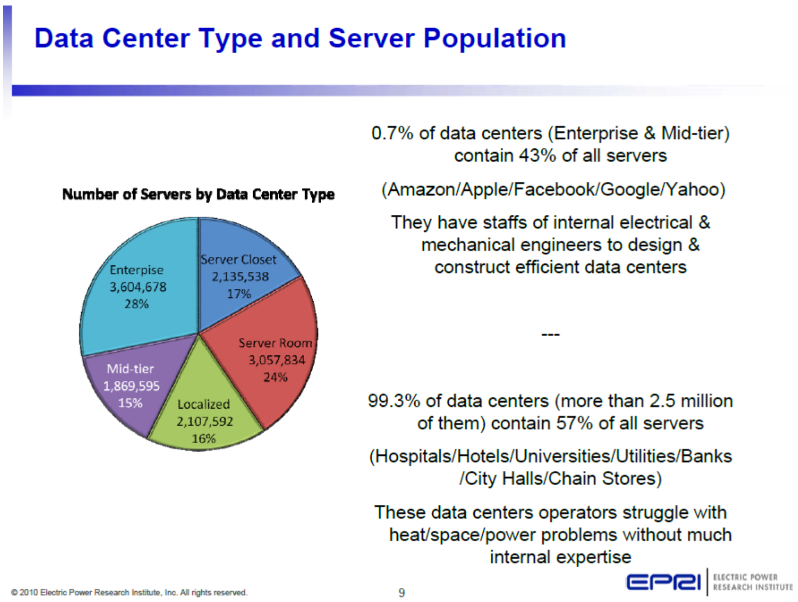
Figure 1.1 Example of the electrical diagram of very reliable data center structure

1.1. General Example of the construction of the Data Center

Data Centers are composed of : servers to compute and store Data, telecommunications links to exchange information with the outside; cooling system to regulate temperature; and electrical network to supply the unit. The electrical network is composed of external lines of the Medium Voltage distribution network and an internal electrical network of high reliability with duplicates, back up power supply, and UPS (uninterruptible power supply).

- **Types of Data centers (information from EPRI- US)**

There are several type of Data centers on different sizes and levels of availability depending of the architecture of the electrical network and air cooling systems. The figure below shows some information, from EPRI US, the types of data center and servers populations.



From: EPA Report to Congress on Server and Data Center Efficiency, 2007. It is estimated that this sector consumed about 61 billion kilowatt- hours (kWh) in 2006 (1.5 percent of total U.S. electricity consumption) for a total electricity cost of about $4.5 billion

Figure 1.2 : Information from EPRI (US) about Data Center

➢ Example of data center made by "Schneider Electric"

The manufacturer Schneider Electric builds Data Centers in lot of countries throughout the world. Here is an example of a data center in France made by Schneider Electric of an electrical network and cooling system. In France the transmission and distribution electrical network has demonstrated high levels of reliability and availability. It is therefore very useful, in France, to compute the global level of reliability and availability of a Data Center taking into account both internal and external electrical networks (such as Distribution and Transmission network)

<table>
<tr>
<td>
Figure 1.3a Example of Tier 4 Data Center made by Schneider Electric</td>
<td>IT space area: 750 sqm IT
> Evolving Concept
> from 160kVA HQ to 2MVA HQ
> Ground Water Cooling
> Backup with Chillers
> Indirect Free Cooling Chillers
Business & Decision Green Data Center
Grenoble, France (phase 2) - 2012
> Tier 4 Datacenter
> Power Usage Effectiveness < 1,35
> Scope:
> Design Elaboration in collaboration with the customer
> Complete Electrical Distribution HV, LV (Okken), IT room Busbar (Canalis), rPDU, UPS
> HVAC Design
> IT Space (Racks, In-row cooling, Hot Aisle Containment, Operation software's)

Figure 1.3.b Technical characteristic of one Tier 4 Data Center made by Schneider Electric</td>
</tr>
</table>

1.2. Information about the EDF's two demonstrators of the MODRIO project

Two demonstrators have been proposed by EDF R&D for the MODRIO project to study the reliability of critical system with MODELICA :

- The reliability of a Data Center with the analysis of the electrical networks which supplies the data center and the air cooling system (figure 1.6)
- The "back up" power system (or stand-by AC power supply) for the electrical networks of a nuclear power plant (figure 1.7) [31]

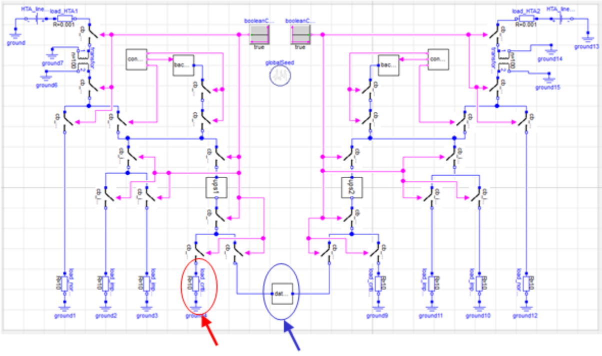


Figure 1.6 : Example of the model of the electrical supply for a Data Center with MODELICA

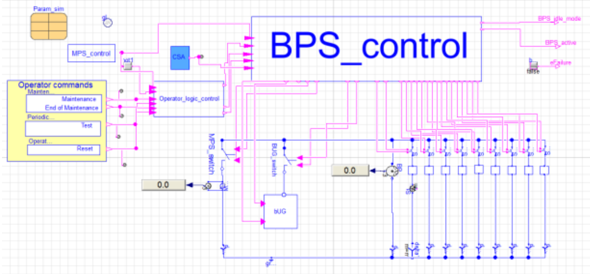


Figure 1.7 : Example a "Back-up power system" (standby AC power supply) in nuclear power plant model with MODELICA for the MODRIO project with Circuit Breaker, loads, and BPS control automatism

As has been indicated above in this document these two demonstrator examples have some common points :

- They represent an electrical networks to supply a critical system.
- **The electrical diagram of the data center includes a back-up power system**

But these two demonstrators have some differences :

- the first demonstrator "back up power system" (figure 1.7) discussed mainly with a deterministic approach for the reliability analysis with precise requirement of the behavior of the system through the "FORM_L" language [30] defined by EDF R&D which can be integrated into the MODELICA Language. The assessment of safety in the nuclear power plant mainly uses deterministic approaches through standards such as IEC 61513 and IEC 62855.
- The second demonstrator for the Data center (figure 1.6) is mainly based on probabilistic approach and the possibility to do reliability analysis through the integration of Monte Carlo simulation into a MODELICA model (differential equation) of the system. The standard such as the classification of the "Uptime Institute" integrates both deterministic and probabilistic approaches for reliability studies.

1.3. Description of some issues for reliability assessment

The issues and items in reliability studies are as follows :

The description of the system adapted to the reliability analysis

- The method used to describe the behavior of the system in order to carry out the reliability analysis : one can use SYSML, KB3 Tools …
- The different precision level for the description of a system

The definition of the reliability requirements for a new system

- The definition of the list of undesirable events of a system : Usually one has to define the "severity scale" concerning the consequences of the failure of component (from S1 to S6 for example). Nevertheless we propose in this document to use several "sets" of undesirable events and each set will have its own severity scale. This type of requirement is a multi-criteria expression for the reliability target.
- The role of the different stakeholders in reliability analysis : the future owner of the system, the project manager who designs of the system; and the manufacturer who makes the component.

The collection of operating behavior of the system and failures reports

- The collection of operating behavior of the system and failures which occur during the lifespan of a system is a main element for reliability analysis. The statistical analysis of this collected data can give information about the reliability parameter of components.
- The management of the failure experience even for very reliable systems such as the electric power supply to a Data Center : this system has redundancy levels but some parts of the system can fail and this event should be registered. The analysis of the causes of the failure system could be very difficult. A tool such as MODELICA can be very helpful to model the system physically and understand the causes of the failure.
- The statistical treatment of the failure can be summarized on a reliability database while taking into account the influence of external or internal factors that can reduce the lifespan of components.
- The management of the company's "know-how" due to staff members aging who are specialized in a particular the technical field. This management has to take into account the lifespan of a system which can be over 30 years for a Data Center.

The choice of methodologies to treat reliability assessment of a system

- The balance between deterministic and probabilistic approaches for dependability analysis in order to design and build a reliable system and the different associated standards or guides (IEC standard 61508, 61513 …, Uptime Institute TIER classification, or IEC 62855).
- The balance between "top down" versus "bottom up" approaches to the reliability analysis of a system.
- The decision making methodology to integrate the probability of failure (the risk of failure). The Bayesian statistical method can be of help in this field (see appendix C).

Tools adapted to the probabilistic assessment of reliability and availability of a system

- The set of tools to estimate the reliability and availability level of a system.

The effect of common causes in the reliability indices of a system

- The risk of common failure cause in the reliability analysis. MODELICA can be used on this subject to model this risk (some examples of common causes for data center or others electrical systems are indicated in appendix B) :

  "Google loses data as lighting strikes" 13 august 2015

  In the August 13, 2015 an incident occurs in the Belgium Google data center due to the loss of energy supply caused by lightning strokes. Detail of this incident are included in the appendix B of this document.

- The reliability model based on Self Organized Criticality (SOC) phenomena could be applied to analyze the reliability of some systems and the electrical networks
- The physical analysis model of the electrical component failure mode : MODELICA can help with this subject.

The maintenance of the component

- The "health Index" type approach based on expert knowledge is challenging classical methodology in the reliability field
- Maintenance based on condition monitoring is a new trend in industrial maintenance aided by the installation of a lot of sensors.

Others items related to reliability or integrated logistical support

- The integrated logistical support (ILS) for the different component represented by the operational availability of component and system through adequate maintenance skills and the availability of the spare parts to maintain the system in nominal operating conditions, also impacts reliability. In the case of subcontracting the maintenance activities, the control of correct maintenance operations is a main element in the management of the system maintenance.
- The new global challenge in the world such as the consequences of climate change (increasing of the average temperature).

2. The goal of the case study "Reliability and availability of Data center with MODELICA"

This demonstrator "reliability analysis of Data Center" deals with three technical fields :

- The electrical supply of the critical system,
- The multi-domain model including the electrical system and the air conditioning system of the Data center,
- The reliability approach to study the critical system which integrates different methodologies from the probabilistic method (estimation of the reliability with probability) to the determinist method (add redundancies to the design of a new system without any probabilistic considerations).

There are already some tools to analyze the reliability and availability of a system. Some of these tools have been designed by EDF R&D (KB3 Tool).

The goal of this case study "Reliability and availability of data center" with Modelica is to investigate the benefits and limits of the MODELICA language and associated tools to study the reliability and availability of a critical system such as the data center.

This system requires a very reliable power supply and air cooling system of servers used to compute and to store data. The Data Center merges at least two types of technological fields (electrical components and air conditioning components). That is why is an interesting case study to test the ability to implement reliability and availability analysis into MODELICA representation.

Nevertheless through this demonstrator of the Data Center the goal is to study a more general point linked to engineering design methodology while taking into account the reliability requirement. Some issues on this subject have already been indicated.

The plan of this document is as follows :

- A list of some examples of real failures to illustrate the challenge of reliability analysis of critical electrical supply
- A description of the different architecture of the Data Center according to the TIER classification from the Uptime Institute
- A description of the MV network and HV network where the failure can provoke common cause failure to supply the data center. This section will introduce different tools which are used to model the risk of an electric network black-out in a deterministic way.
- A presentation of different tools already designed or elaborated in the "I-Tesla" European

project or at EDF R&D to model the HV and MV electrical networks based on MODELICA

- A short Presentation of the different departments of EDF R&D which are using, or not, MODELICA language for modeling Electrical systems or other parts of the Data Center.
- A presentation of the others tools used by EDF R&D/MIRE Department to model systems and to do reliability analyses.
- A reminder about different methods and tools to be used to model the normal operating phase of a system.
- The description of the probabilistic methodology applied to reliability analysis including :
    - general points for deterministic or probabilistic approaches in reliability through standards in Data center and in nuclear power plant design
    - Requirement the level and associated severity scale
    - Qualitative study of failure mode
    - Parameters (failure rate and fail on demand) used for the quantitative probabilistic estimation of reliability
    - Parameters of failure depending on the physical parameter presentation of the FIDES reliability database for electronic components
    - Impact of meteorological constraints on the electrical network
    - Tool used for reliability analysis of a system such as KB3 tool designed by EDF R&D
- A description of a hybrid probabilistic and deterministic approach to analyze the reliability of the system including :
    - Method already used by RTE (French TSO) for the electrical system with the ASSESS tool
    - Method using the EMTP tool at EDF R&D
    - New method based on MODELICA to model the reliability of the system
        - DLR Method for electrical network of airplanes
        - Monte Carlo simulation for data center systems (present case study for the data center)
- Examination of the interest of MODELICA for experience feedback experience
- Consideration of different roles of Stakeholders for the reliability of the system
- Description of the study realized in the second document concerning the MODRIO project for the reliability study for Data Center

3. Description of the system studied for the data center

There are different sizes and levels of reliability for a data center. The international “TIER” standard describes several levels of requirement and the structures associated (TIER definition from the Uptime Institute) [1], [33]. Nevertheless the TIER guide do not indicate reliability requirements for the external electrical utility which supplies energy via the medium voltage distribution system.

In this chapter we describe an academic example taking into account both a representation of HV (high voltage) transmission and MV (medium voltage) distribution network and the electrical system of the data center.

3.1. Structure of the Data Center

One can distinguish four main parts in the data center:

- The servers to store and compute information
- The telecommunication links to exchange information with others data centers or peer to peer links
- The air conditioning system
- The electric supply system with stand-by power supply

In this document the telecommunication links will not be discussed.

3.2. Reliability Requirement of the TIER structure for Datacenter

This table from the Uptime institute indicates the deployment of different levels of Data center during the period of the 60’ through to the 90’ and the estimated level of availability.

Tier level	Introduced	Requirements
Tier I	In the 1960s	Single path for power and cooling distribution, no redundant components, *99.671% availability*
Tier II	In the 1970s	Single path for power and cooling distribution, includes redundant components, *99.749% availability*
Tier III	End of the 1980s	Multiple power and cooling distribution paths but with only one active path, concurrently maintainable, *99.982% availability*
Tier IV	1994	Multiple active power and cooling distribution paths, includes redundant components, fault-tolerant, *99.995% availability*

Source: US Uptime Institute: Industry Standards Tier Classification

The tables below give information on the structure of the Data Center depending of their TIER Classification

	Tier I	**Tier II**	**Tier III**	**Tier IV**
Building Type	Tenant	Tenant	Stand-alone	Stand-alone
Staffing shifts Staff/shift	None None	1 Shift 1/Shift	1+Shifts 1-2/Shift	"24 by Forever" 2+/Shift
Useable for Critical Load	100% N	100% N	90% N	90% N
Initial Build-out kW per Cabinet (typical)	<1kW	1-2 kW	1-2 kW	1-3 kW
Ultimate kW per Cabinet (typical)	<1 kW	1-2 kW	>3 kW†,‡	>4 kW*,†
Support Space to Raised-Floor Ratio	20%	30%	80-90+%	100+%
Raised-Floor Height (typical)	12 inches	18 inches	30-36 inches	30-42 inches
Floor Loading lbs/ft (typical)	85	100	150	150+
Utility Voltage (typical)	208, 480	208, 480	12-15 kV	12-15 kV
Single Points-of-Failure	Many + Human Error	Many + Human Error	Some + Human Error	Fire, EPO + Some Human Error
Representative Planned Maintenance Shut Downs	2 Annual Events at 12 Hours Each	3 Events Over 2 Years at 12 Hours Each	None Required	None Required
Representative Site Failures	6 Failures Over 5 Years	1 Failure Every Year	1 Failure Every 2.5 Years	1 Failure Every 5 Years
Annual Site-Caused, End-User Downtime (based on field data)	28.8 hours	22.0 hours	1.6 hours	0.8 hours
Resulting End-User Availability Based on Site-Caused Downtime	99.67%	99.75%	99.98%	99.99%
Typical Months to Plan and Construct	3	3-6	15-20	15-30
First Deployed	1965	1970	1985	1995

	TIER I	TIER II	TIER III	TIER IV
Number of power delivery paths	Only 1	Only 1	1 active 1 passive	2 active
Redundant component	N	N+1	N+1	2 (N+1) or S+S
Utility voltage	208 , 480	208, 480	12 kV – 20 kV	12k V – 20 kV
Year of first construction	1965	1970	1985	1995
Annual IT Downtime due to site	28.8hrs per yr	22.0 hrs	1.6 hrs	0.4 hrs
Site Availability	99.971 %	99.749 %	99.982%	99.995%

	Tier I	Tier II	Tier III	Tier IV
Active Capacity Components to Support IT Load	N	N+1	N+1	N after any failure
Distribution Paths	1	1	1 active and 1 alternate	2 simultaneously active
Concurrently Maintainable	No	No	Yes	Yes
Fault Tolerance (single event)	No	No	No	Yes
Compartmentalization	No	No	No	Yes
Continuous Cooling*	load density dependent	load density dependent	load density dependent	Yes (Class A)

3.2.1. Description of the electrical TIER architectures

➢ Electrical Structure of Tier I and Tier II

The figure below shows the different structures for Tier I and Tier II for the electrical network [1], [33] :

ATS Automatic Transfer Switch

UPS : Uninterruptible Power Supply

PDU : Power Distribution Unit

Utility : external MV line

Generator : Back Up AC power source

TIER I structure

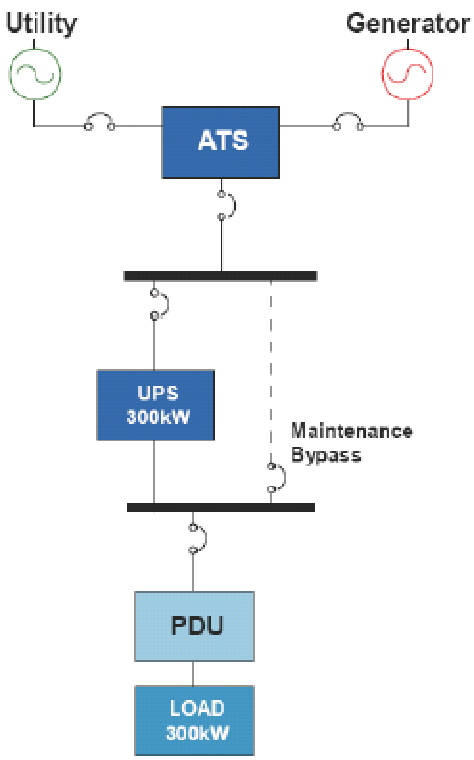


Figure 3.1 : Structure of the electrical network of the Data Center with TIER I

TIER II structure

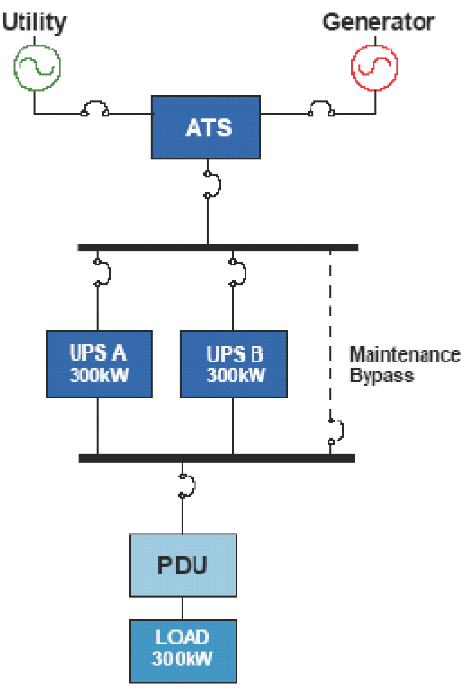


Figure 3.2 : Structure of the electrical network of the Data Center with TIER II

➢ Electrical Structure of TIER III

The TIER III structure has duplicate MV lines for the external supply

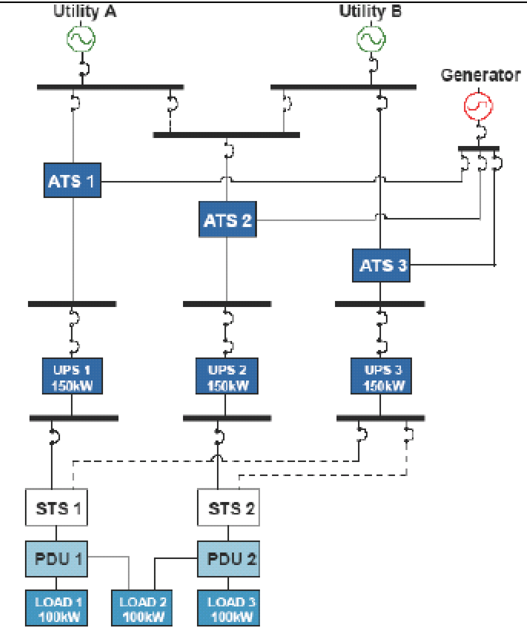


Figure 3.3 : Structure of the electrical network of the Data Center with TIER III

➢ Electrical Structure of TIER IV

The TIER IV is the more reliable and available structure [1], [33].

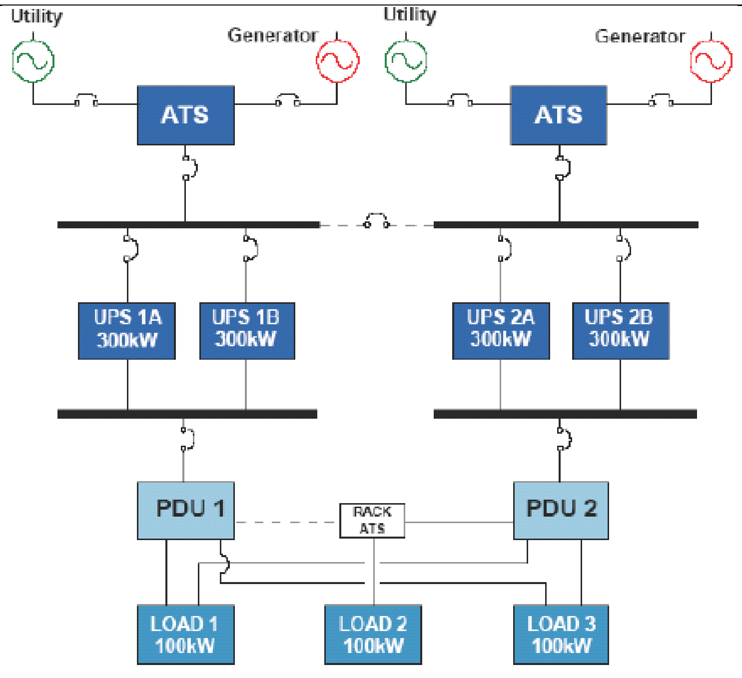


Figure 3.4 : Structure of the electrical network of the Data Center with TIER IV

3.2.2. Library developed by EDF R&D for air cooling system for Data Center

Dedicated MODELICA libraries have been developed at EDF R&D to model cooling system. Nevertheless one will use an other more generic EDF library THERMO_SYS_PRO for thermo-hydraulic component to model Valve Pump and Tube in the Data Center MODRIO demonstrator.

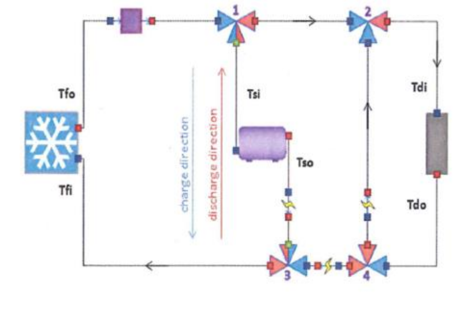


Figure 3.5.a Example of cooling system from EDF R&D / EPI library

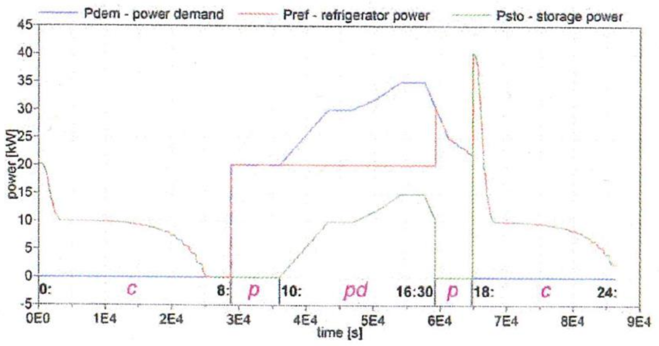


Figure 3.5 b : Result of model of the power for air cooling system

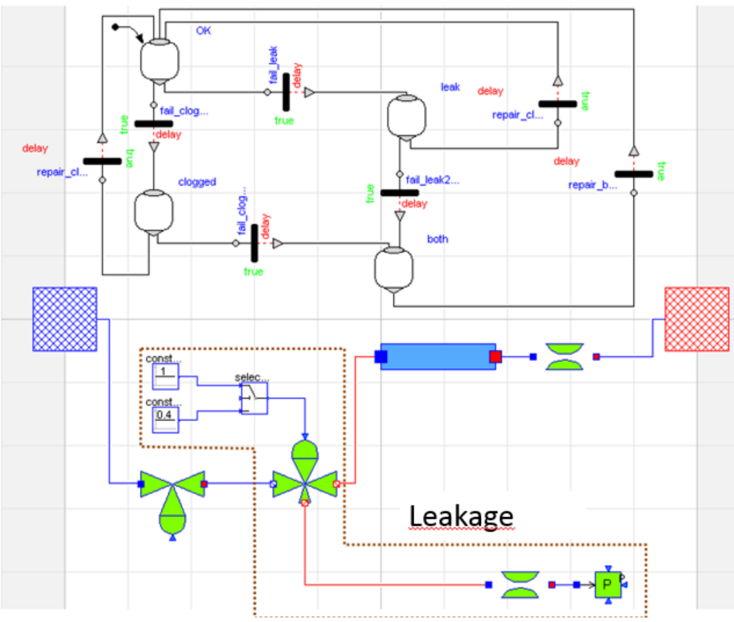


Figure 3.6 : Model of pipe with leakage failure mode integrated into Modelica Thermosys-pro Library
First model with State Graph machine

4. Description of the global electrical network to supply the Data Center

The regional "black-out" of the transmission (HV) or distribution (MV) grid constitutes one of the possible common cause failures which can lead to the simultaneous losses of the two MV lines which supply the Data center.

This chapter focuses on this point and analyzes some of the factor which can lead to a regional black-out. To have a better understanding of this case we describe shortly the structure and organization of the transmission and distribution electrical networks. Some tools available to model the behavior of these structures in nominal condition or failure condition will be presented.

The section examines also the "I-Tesla" European project (http://www.itesla-project.eu/) where RTE (the French TSO) is one of the partners. One task of this project is to model the transmission network and the impact of the renewable energy on stability of this network.

4.1. Global electrical diagram of the system studied

The goal of this chapter is to describe the structure around the data center in order to be able to analyze the common mode failure of the two Medium voltage lines which supply the data center.

The figure below describe a very simple representation of the HV and MV electric networks which supplies the Data Center.

One main hypothesis for the reliability of the DataCenter is that the failures of these lines are independent. Nevertheless the failure of the two lines are not physically really independent because there are connected to the same HV/MV substation.

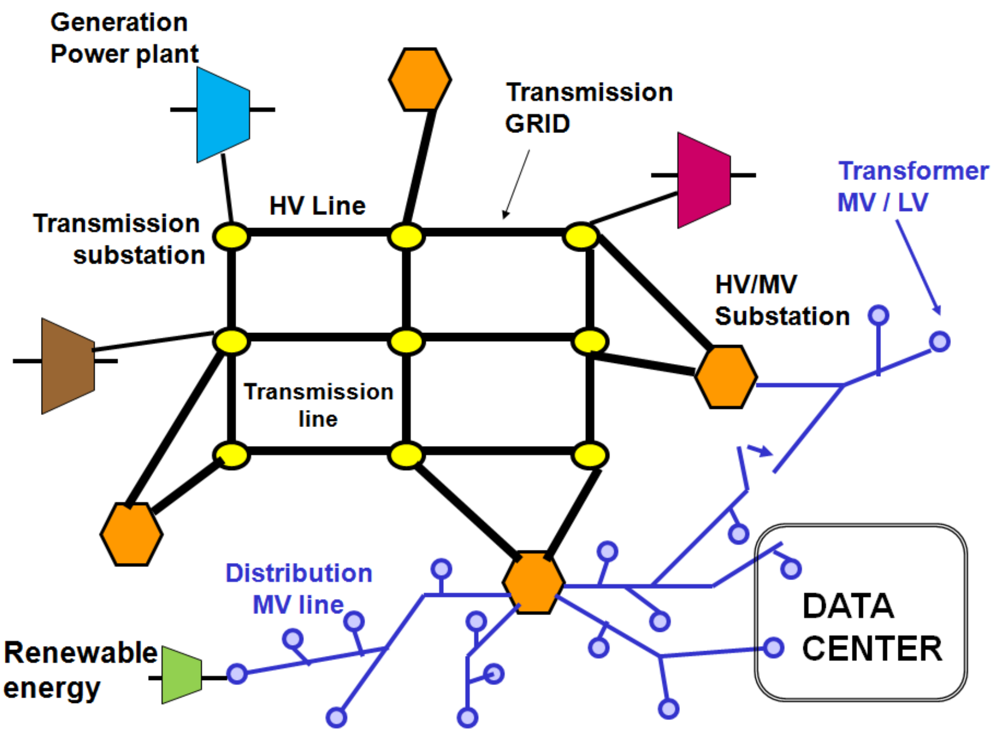


Figure 4.1 : Description of the simplified HV and MV networks

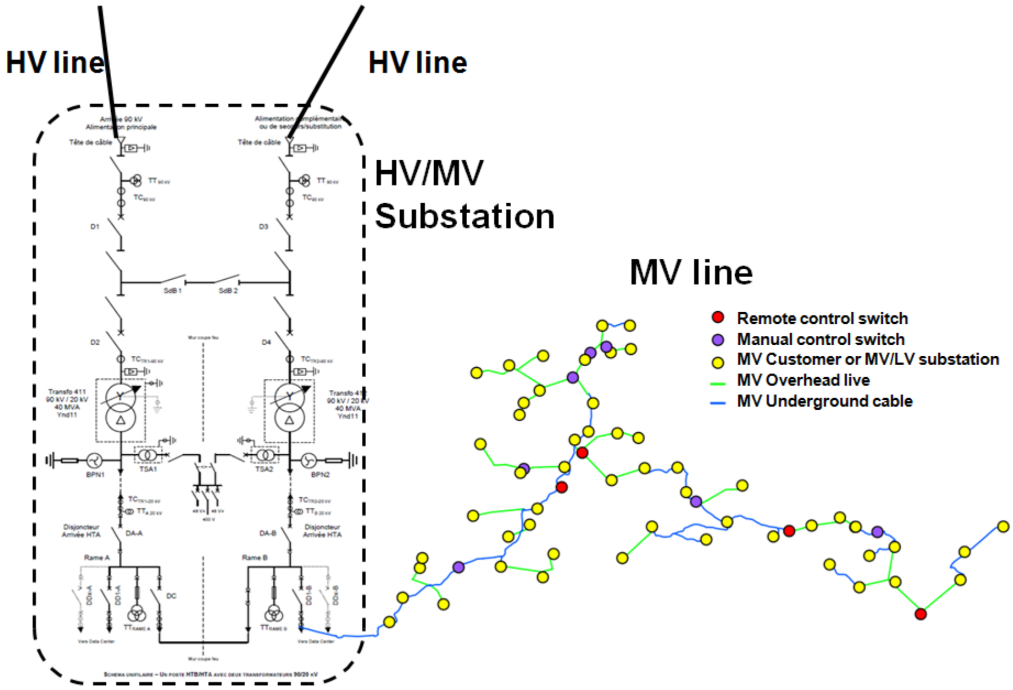


Figure 4.2 : HV/MV Substation with one MV line

4.2. Tools based on MODELICA to model the electrical networks

There are already existing some tools designed or building in 2015 to model the electrical network with MODELICA. This fact is very interesting for the MODRIO project that it indicates a trend to shift from other tools to MODELICA in several technical domains. The goal of this chapter is to give some information about this point.

4.2.1. Example of modeling HV Network with the "object stab" data base component from ABB

The ABB library "Object Stab" [27] for MODELICA is composed of component to represent the HV or MV electrical network which is a version of Eurostag. For example EDF R&D had used this library to implement a simple model of a HV network and to study the ability of the system to operate after an event of loss of load.

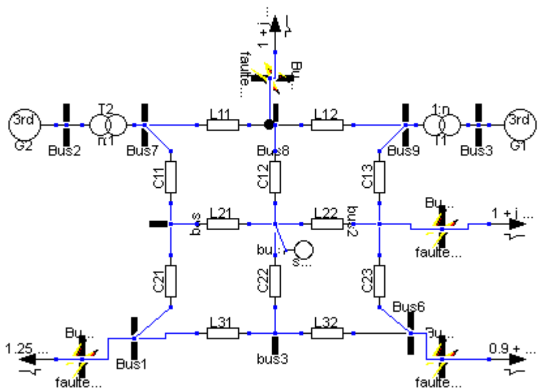


Figure 4.3 : Simple meshed HV electrical system with Generation and HV Line

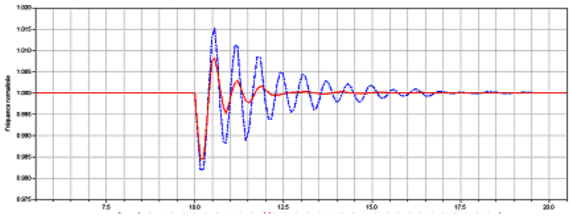


Figure 4.4 : Variation of the frequency after loss of load with and without system of regulation of the frequency

4.2.2. The European I-Tesla Project (2013-2015)

Since 2011 a version of the EUROSTAG tool has been developed with the language MODELICA in the context of the European project PEGASE (http://www.fp7-pegase.com/). A library has been implemented by RTE in an open Tool Scilab /Xcos. There are no reliability study published with these tool. Nevertheless one has to note the activity of the "iTesla" European project 2013-2015 (http://www.itesla-project.eu/). Several European TSO are involved in this project including RTE which is the French TSO.

The European Project "I-Tesla" has used the MODELICA language to model the electrical HV network. The elaboration of a new tool such as EUROSTAG based on MODELICA was main objective of this project .

One has to note the Modelica library that has been developed for electrical component in this "I-Tesla" European project [14] (see also appendix D)

5. Reminder of the description method and model before analyzing the reliability of system or component

Before analyze the reliability of a system or a component, one has to clearly understand the role or function of each component of the system and the way to represent the normal operating phase of the component and to choose the level of detail for the description of the system.

In this chapter the different method to describe system are presented.

5.1. Level of detail for the description of system and component

For example in the representation of the transmission grid as follow the line represent the line feeder with the tower the dot are the HV substation.

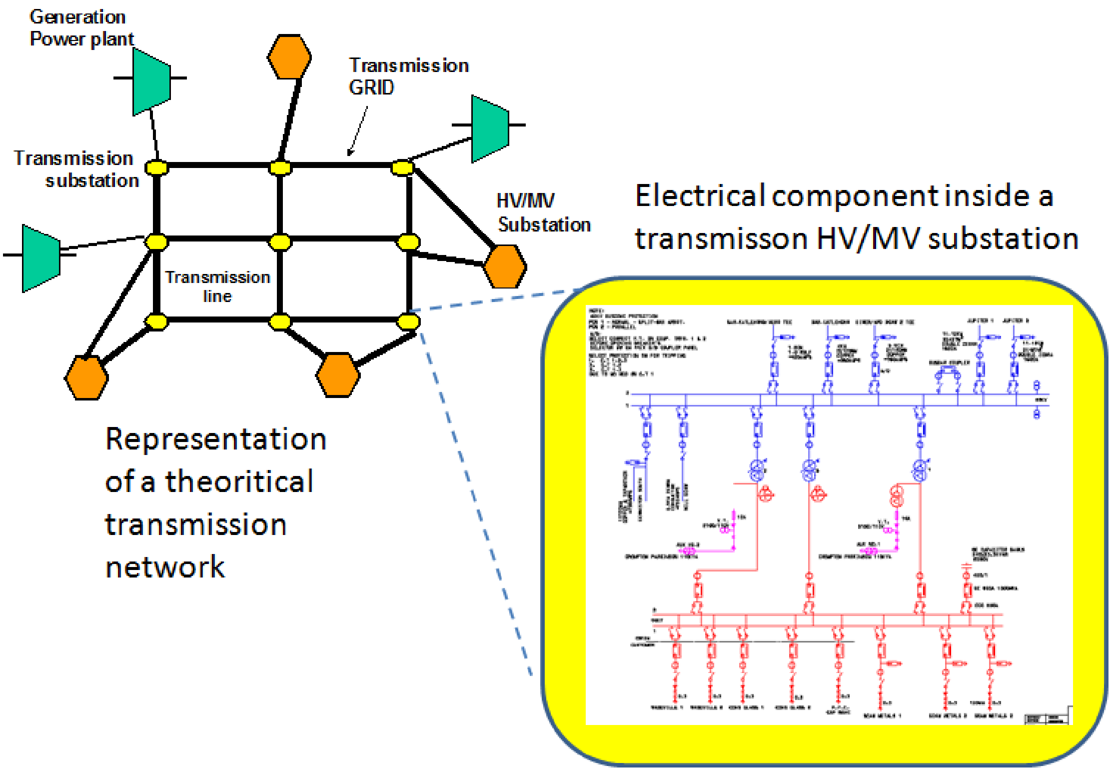


Figure 5.1 : Example of different levels of the description of electrical networks or components

But the HV/MV substation is composed of circuit breakers, busbars, protection relay, transformer, sensor,

And the circuit breaker is composed of the chamber to eliminate fault current due to short circuit, command to operate the circuit breaker; transformer is made of wire, insulated oil, tap changer …

5.2. Description of the operating mode of the component or the system

Different methods are available to represent the operating phases of the electrical system and its components.

In the following section several approaches pertinent to our problematic will be presented. This comparison is particularly important given the difference of granularity and subsequent implication on the phenomena which can be captured.

➢ Electrical Diagram for Data Center structure

The most classical way to describe an electrical system is the electrical Diagram

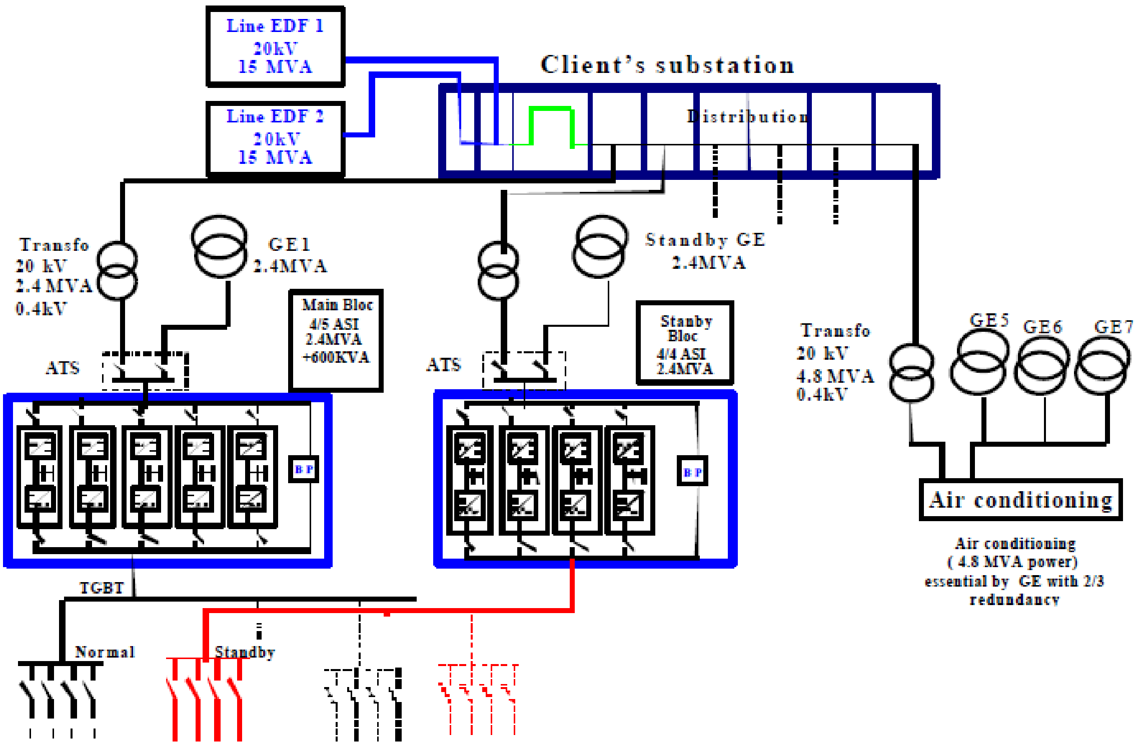


Figure 5.2 : Example of electrical diagram of a Data Center (Carer 2002)

➢ Sysml representation

The SYSML method can be used to model a system. The "Papyrus" tool is based on the SYSML method.

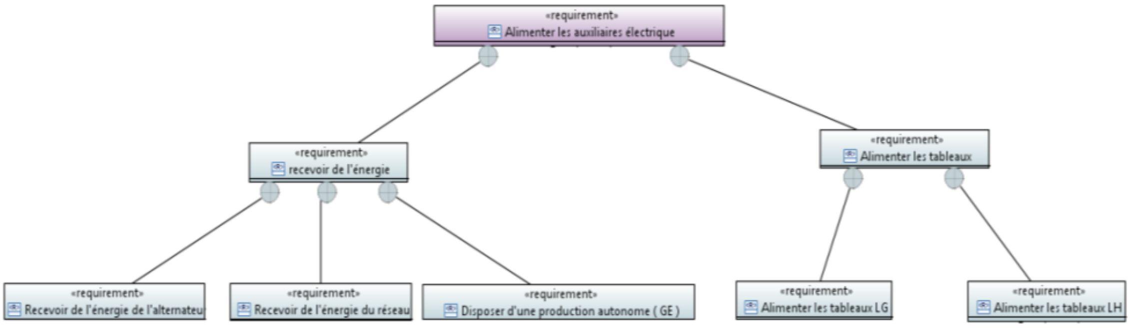


Figure 5.3 : Example of SYSML representation of a part of the DATA CENTER with the PAPYRUS tool (CEA France)

➢ Block Diagram representation

Block diagram is a simple method to represent a system. This method is used by the GRIF Tool (designed by TOTAL and Satodev Companies).

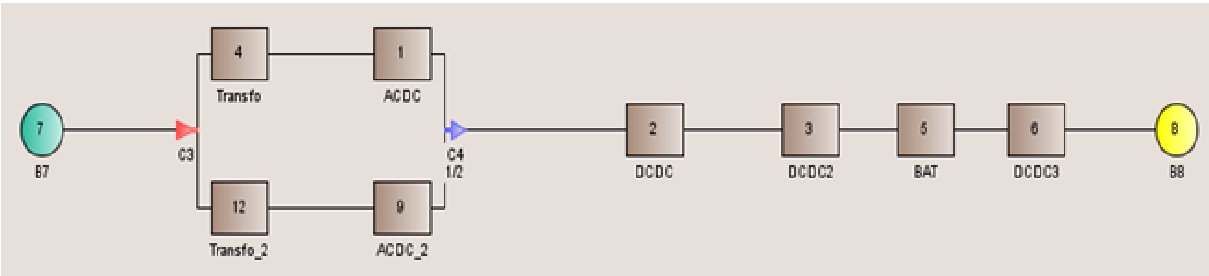


Figure 5.4 :Example of block Diagram representation of an electrical system with parallel component of serie structure

➢ KB3 representation with a first database for electrical network

In the EDF’s KB3 database one can use electrical components to illustrate directly the diagram of the electrical network studied.

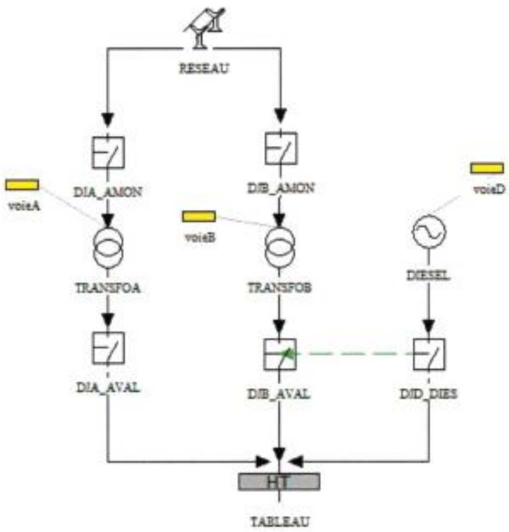


Figure 5.5 : KB3 with the version of database for electrical network

➢ KB3-K6 representation with a third prototype database for electrical network

In the KB3-K6 database the electrical components are described in a more precise detail than in the KB3 database for electrical component.

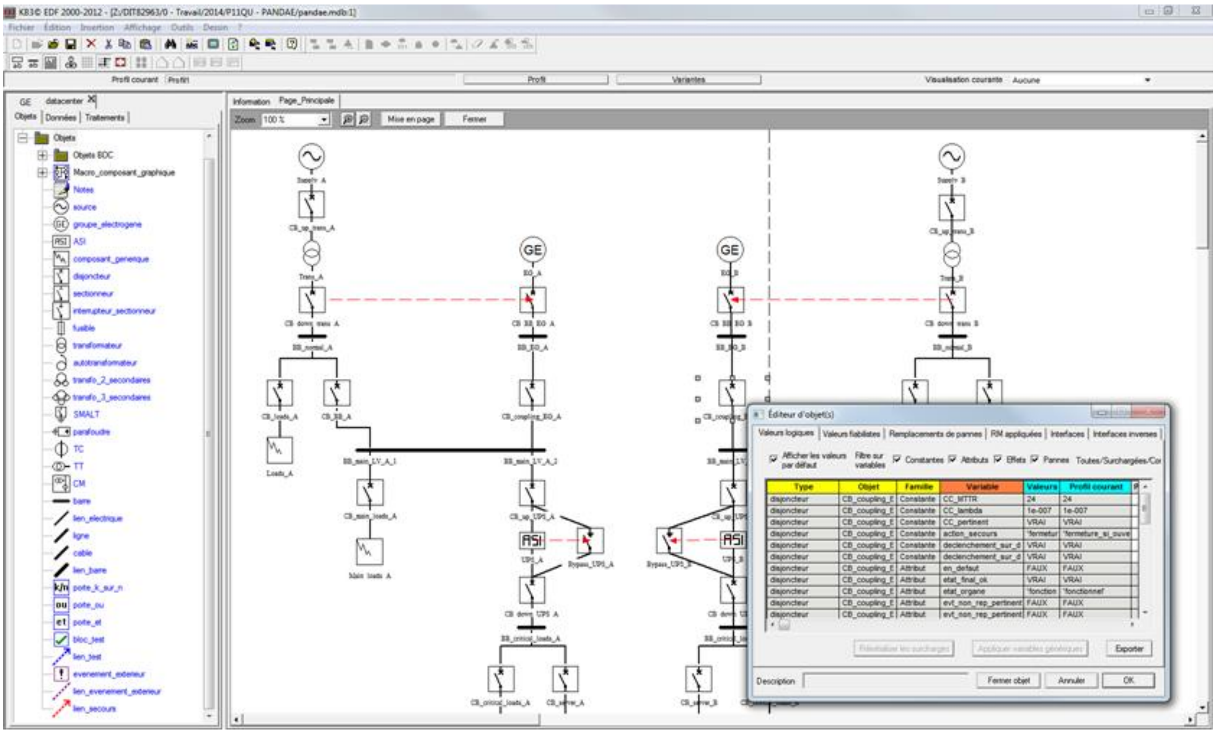


Figure 5.6 : KB3 with a third version of database for electrical network

➢ MODELICA representation of a Data center structure

Here is an illustration of a Modelica representation of the electrical network for a Data Center Tier IV

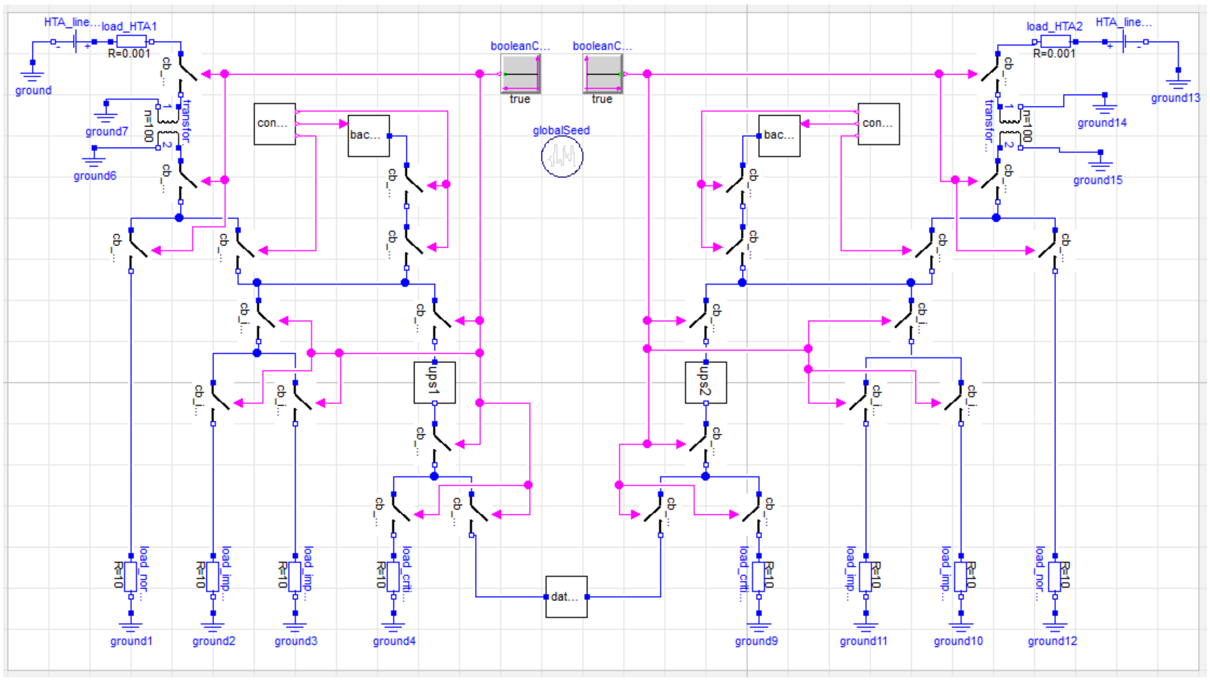


Figure 5.7 : Example of electrical diagram of the Data center with MODELICA tool

5.3. Conclusion

It is necessary to describe a system before doing the reliability analysis of a system. There are different manners or tools to model a system.

The way chosen in a first approach in this document is the SYSML method and the PAPYRUS tool. This tool could be used in the design phase but also to capitalize the information collected about failures in operating phase.

Secondly a more detailed model of the system is realized with MODELICA.

6. Qualitative and quantitative approaches for reliability analysis of a system

The first approach for qualitative failure analysis of a system is the Failure Mode and Effect Analysis (FMEA).

6.1. Primary qualitative reliability approach with FMEA Failure mode and effect analysis

The primary qualitative approach for the reliability approach is the analysis of the different failure mode of the component of the system.

- **FMEA for electrical piece of equipment**

One can organize the failure mode of electrical component

Electrical component which operates continuously such as : line cable, transformer, busbar

- Short circuit due to the electrical breakdown
- Open circuit due to the destruction of the connection

Piece of equipment	Failure mode	Type of parameter
Circuit breaker	Breakdown	Failure rate (f/yr)
Circuit breaker	Fail to operate on demand	Probability
Disconnector	Breakdown	Failure rate (f/yr)
Disconnector	Fail to operate on demand	Probability
Earth switch	Breakdown	Failure rate (f/yr)
CT	Breakdown	Failure rate (f/yr)
Surge arrester	Breakdown	Failure rate (f/yr)
Busbar	Breakdown	Failure rate (f/yr)
VT	Breakdown	Failure rate (f/yr)

Table 6.1 : Example of failure mode for different components

FMEA for air conditioning piece of equipment

Example of the FMEA for component of air cooling system

Element	Failure mode	Cause	Type of parameter
Pump	Fail to operate on demand	Destruction of some comp	Probability
	Operate with Degraded performance	- Leakage - Cavitation	Failure rate
	Fail to operate	Obstruction/ Destruction of component	Failure rate
Tube / Pipe	Fail to operate	Obstruction Leakage	
	Operate with degraded performance	Leakage	

Table 6.2 : Example failure mode and effect analysis

6.2. Quantitative main reliability parameters for component

The different method based on deterministic or probabilistic approaches and Bayesian statistics are detailed in appendix C.

In order to estimate the probability of undesirable event at the level of a system, it is necessary to compute the probability of failure of the component and the system.

Reliability main parameter

In a very simple description of the reliability method, for the failure mode of a system or component the parameters considered for the reliability study are :

- The failure rate during operation (failure in time) : λ [time^{-1}]
- Or the failure rate on demand (failure on demand) : γ (probability)

One other main parameter is the time to repair τ after the failure of the component :

$$\tau = 1/\mu \text{ [time]}$$

Evolution of the reliability parameter with the time

The failure rate λ can evolve with the time $\lambda(t)$. Usually in reliability field this phenomena is represented by the so-called "Bath-tube failure curve" containing three period within the operating life of the component.

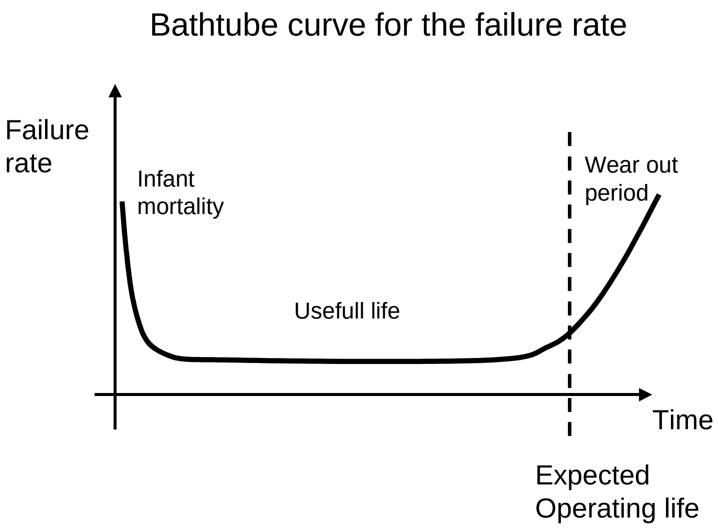


Figure 6.1 : The so-called “Bath-tube Curve” for the failure rate

This fault rate curve can be modeled according a *Weibull* law :

$$\lambda(t) = \left(\frac{\beta}{\alpha}\right)\left[\frac{(t-\gamma)}{\alpha}\right]^{\beta-1}$$

The behavior of function is defined by :

t : age of the component

α, β, γ : parameters to be fitted for b = 1 (useful period life) the failure rate is constant

The λ can vary with the time $\lambda(t)$ and also with some other parameters “Z” due to internal or external constraints $\lambda(t,Z)$. This will be presented latter in this document.

7. Different methods to consider the reliability parameter for the failure of component

One can consider for the failure rate of component via several approaches

- Reliability Black box approach

  In this approach statistics are generated without knowing the physical cause of failure

- Reliability Grey box approach

  In this approach the main physical parameters which influence the failure are known and can be integrated into the reliability model. For example failure rate with Temperature parameter such as Arrenhuis law

- Reliability White box approach
  - In this approach the physical cause of the failure are known and can be modeled with deterministic equation or through Monte Carlo simulation

7.1. Example of the Eireida Database (black box approach)

The following is an example of information of a component from the Eireda Database with failure rate

188 EUROPEAN INDUSTRY RELIABILITY DATA BANK

table 165 of 220	EUROPEAN INDUSTRY RELIABILITY DATA BANK	1998 EDITION

COMPONENT : DIESEL ENGINES
FUNCTION : Auxiliary electric supply

ENGINEERING CHARACTERISTICS :

Type :	4 strokes piston motor (engine)	Safety Class :	3
Generator :			
Power (kVA) :	3,870/5,000	Environment :	Diesel Bld
Voltage (kV) :	6.6		
Engine :		RPM :	1,500
Design :	20V cylinders		
Power (kW) :	4,121/5,000		

OPERATIONAL CHARACTERISTICS :

Operating mode on annual basis :

	- continuous :	intermittent :		standby : ⊗
	⊗ < 100 h	< 1000 h	< 5000 h	> 5000 h
Number of demands :	< 10 ⊗	< 100	< 500	> 5000

Maintenance Policy : 1,000 h, 5R, 15R Test Periodicity : 2 tests/M

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From the Eireida DataBase (see appendix B)

TABLES OF RELIABILITY DATA 189

1998 EDITION	EUROPEAN INDUSTRY RELIABILITY DATA BANK	table 166 of 220

COMPONENT : DIESEL ENGINES

SAMPLE				
1978-1987	plant-years:	144	No components/plant:	2
1988-1993	eqt-years:	174		

	Failure Rate		Probability of Failure on Demand		Mean Active Repair	
	λ/h (E-6)	EF	γ/d (E-3)	EF	MTTR (h)	Man-hours
Prior (78/87), Critical failures	5 900•	1.4	2.7	1.4	30 •• 7 •••	
Likelihood (88/93)	No Failures 33	Cum Time (h) 1.5 E+3 ••••	No Failures 6	No Demands 7.633 E+3	14	59
Post. Mean	3122		1.72			
Prob. Interval	90% 2530	3765	90% 1.16	2.37		
Posterior pdf	Gamma (89 ; 2.21 E+4)		Beta (21.5 ; 1.2516 E+4)			

Mode 1: Loss of perf.: 0.47	Mode 2: Ext. leak: 0.31	Mode 3: Fail to start: 0.22

Other Sources		λ /h. E-6	EF	γ/d. E-3	EF	MTTR (h)	Man-hours
EDF	1995C						
	All (78-93)	9 533	1.1	4.7	1.2	13	35
WASH	Critical	3 000		30			
1400	Sample						
CY	Critical	1 300		5.4			
PRA	All						
	Sample						
T-book 3	Critical	5 500		7.7			
	All						
	Sample						
EUREDATA	Critical	2 250	3.4				
89	All						
	Sample	Engine and generator					

Comments:

- • Short operating time (< 30h/year). All failures (EDF): $\hat{\lambda}$ = 9 533 E-6 /h, EF = 1.1.
  First EPS evaluation of reliability parameters relative to failure of diesel engine, coupling, breaker and generator: $\hat{\lambda}$ = 7700 E-6/h, EF = 1.4.
  With, during operation (EPS): short failure: 4.5 E-3/h, EF = 1.4. Long failure: 3.2 E-3/h, EF = 1.9.
  Pistons and pistons rings modification began in 1986. First generation failures are included.
  Piston; $\hat{\lambda}$ = 53 E-6/h, $\hat{\gamma}$ = 34 E-6/d. Ring; $\hat{\lambda}$ = 37 E-6/h, $\hat{\gamma}$ = 34 E-6/h. Cylinder; $\hat{\lambda}$ = 267 E-6/h, $\hat{\gamma}$ = 34 E-6/d (OMF study).

•• For failures in operation. ••• For failures on demand. •••• Real operating time.

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From the Eireida Database (see appendix B)

7.2. Cox or Eyring reliability model to represent the impact of physical constrains on the reliability of component

In reliability accelerated testing for electronic devices, laws derived from the basis of either chemistry/ physics field or empirical observations are used to represent the variation in the reliability of a component as a function of physical constraints [7].

In reliability test method of a component, it is usual to estimate the variation of the MTTF (mean time to failure) and to use the “accelerator factor” (AF) to represent the impact of external constraints on the component reliability.

The notation used in this paragraph is defined as follow :

$$AF = \frac{MTTF_0}{MTTF_A} \quad and \quad RF = \frac{\lambda_A}{\lambda_0}$$

- AF : accelerator factor which represents the variation of the MTTF versus the variation of parameters considered (in case of failure rate with the exponential law AF=RF)
- RF : reliability factor which represents the variation of the failure rate with parameter considered
- $MTTF_0$: mean time between failure in normal operating conditions
- $MTTF_A$: mean time between failure in accelerating stress test conditions
- λ_0 : failure rate in normal operating conditions
- λ_A : failure rate in accelerating stress test conditions

For example the well known “*Arrhenius* law” (which represents the impact of temperature on the speed if a first order chemical) is used to estimate the variation of the MTTF (mean time to failure) or the failure rate λ of component at different levels of temperature.

$$\lambda(T) = \lambda 0 \,.\, RF(T) \qquad\qquad \lambda(T) = \lambda 0 \,.\, e^{-\left\{\frac{E}{k}\left(\frac{1}{T} - \frac{1}{T0}\right)\right\}}$$

where

T : is the temperature Kelvin ; k : is the Boltzman constant

E : is the Activation Energy

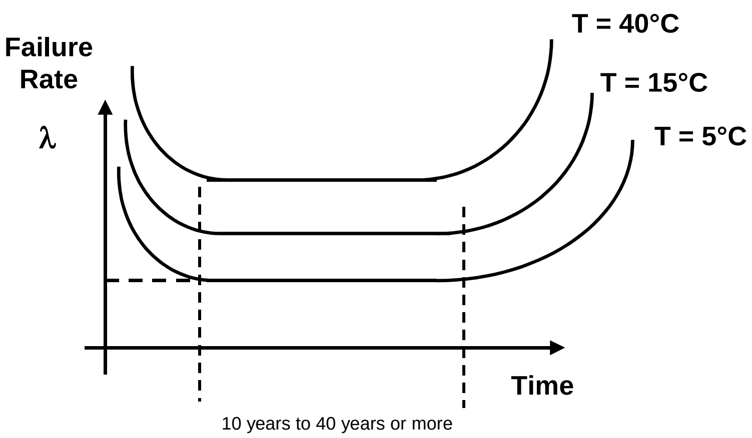


Figure 7.1 : Theoretical variation of the bath tube curve of the failure rate with the increasing of the temperature

Different “accelerator factor (AF)” for the reliability rate can be reviewed from other technical field such as electronic.

- For temperature the *Arrhenius* model (as shown before)

$$AF_{arrh}(T) = \exp\left\{-\frac{E}{k}\left(\frac{1}{T}-\frac{1}{T0}\right)\right\}$$

- For temperature and humidity parameters the *Peck* acceleration is used for electronic device :

$$AF_{peck}(T, HR) = \left(\frac{HR}{HR\,0}\right)^{\eta} .\exp\left\{-\frac{E}{k}\left(\frac{1}{T}-\frac{1}{T0}\right)\right\}$$

Where HR is the relative humidity ; T : temperature ; η : empirical parameter linked to the phenomena

- For the dielectric breakdown one consider the electric field E parameter and the relation as follows is used for electric device :

$$AF\ (E) = \left(\frac{E}{E_0}\right)^{\alpha}$$

With $E = \frac{V}{d}$ where V is the tension applied and d the thickness of the isolator, one can obtain $AF\ (V) = \left(\frac{V}{d.E_0}\right)^{\alpha}$

- For Electric field E parameter some other relation as follows is used for electronic device :

$$AF\ (V) = A_0.\exp[-\gamma.E_{OX}].\exp\left(\frac{E_a}{kT}\right)$$

A arbitrary scale factor

g = field acceleration parameter

Thermal cycle failure mechanical

The model suggested is the Coffin Manson model [7] :

$$N_f = C_0 * (\Delta T)^n$$

The Acceleration factor (AF) is:

$$AF = \left(\frac{\Delta T_{stress}}{\Delta T_{use}}\right)^n$$

Where:
N_f = Number of cycles to failure,
C_0 = a material dependent constant,
ΔT = entire temperature cycle-range for the device,
n = an empirically determined constant.

The acceleration factor (AF) is the ratio of $N_{f(use)}/N_{f(stress)}$.

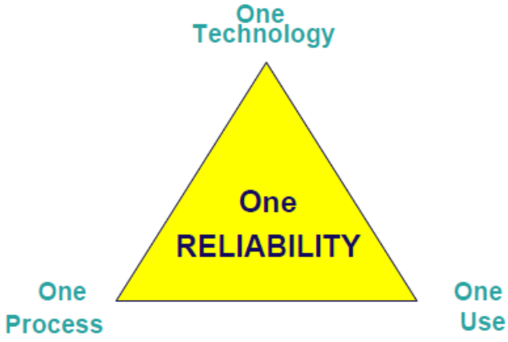
7.3. Example of the FIDES [18] reliability database for electronic component

Previous notions of reliability are used for example in the FIDES [18] reliability data handbook for electronic component. In this document the generic input Data are as follows :

- Data on environments and product usage conditions
- Data on the product definition
- Data of the product life cycle
- Data on suppliers of items used in the product

FIDES approach

The FIDES reliability approach is based on the consideration of three components (Technology, Process and Use). These components are considered for the entire life cycle from the product specification phase until the operation and maintenance phase.



Technology covers the technology for the item itself and also for its integration into the product.
Process considers all practices and the state of art from the product specification until its replacement.
Use takes account of usage constraints defined by the product design and by operation at the final user.

$$\lambda(S) = \lambda_{Physical}(S).\Pi_{PM}.\Pi_{\mathrm{Process}}$$

Where :

- $\lambda_{Physical}(S) = \lambda 0 \,.\, RF(S)$ represents the physical contribution; this parameters can vary with internal or external stresses (S)
- λ_0 : failure rate in normal operating conditions
- RF : reliability factor which represents the variation of the failure rate with parameter considered
- Π_{PM}(PM for Part Manufacturing) represents the quality and technical control over manufacturing of the item
- Π_{Process}represents the quality and technical control over the development manufacturing and usage process for the product containing the item

7.4. Example of possible degradation of electrical MV cable

The origin of the failure of piece of component can be the physical degradation of part of the component.

For electric component the insulation a critical part to insure its reliability. The main parameter to characterize the insulation electrical characteristic is the "Ec (V/m) critical dielectric breakdown field. The nominal electrical field E apply to an electrical component should be lower than the critical field Ec to avoid short circuit.

One will present in this chapter some physical degradation which can reduce this parameter and provoke short circuit and failure of electrical component.

➢ Example of water tree degradation of electrical cable

The figure as follow presents some example diffusion of water inside MV electrical cable. This phenomena is named as "Water Tree" [32]. This phenomena can provoke short circuit.

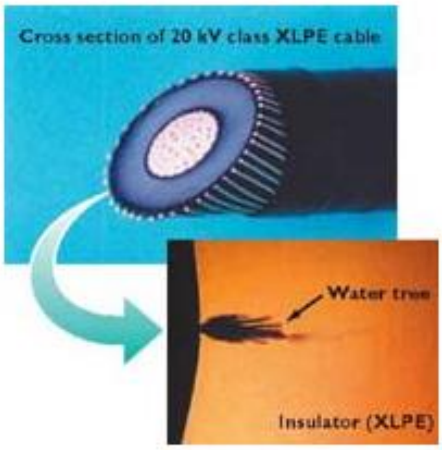


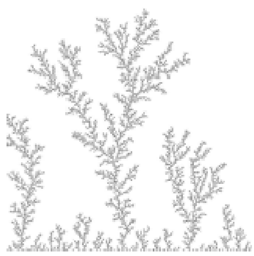
Figure 7.2 : Water tree in electrical cable

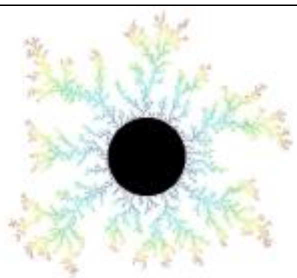

Figure 7.3 : Water tree growing from the inner (bottom) to the outer (top) semiconductor screen of a medium voltage cable

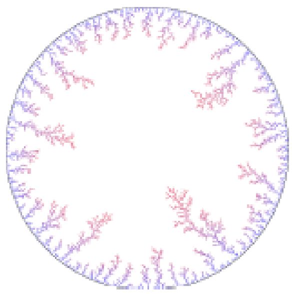
➢ Physical model to represent diffusion phenomena

The degradation of the cable are due to diffusion of the humidity into the insulation of the cable (eventually provoked by external aggression on the cable).

This phenomena can be model with the DLA algorithm (Diffusion limited aggregation).See below example of simulations of the diffusion phenomena with the DLA method [21] , [22].


7.4.a Initial seed is a line


7.4.b initial seed is the outer part of a cercle


7.4.c initial seed is the inner part of a cercle

Globally this phenomena can be represented by diffusion water into the insulation. Diffusion process is modeled with the classical “fick law”

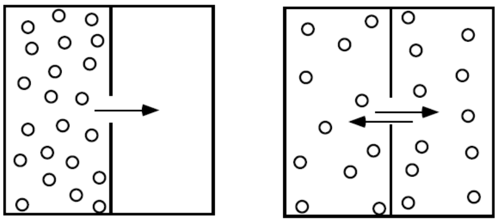


Figure 7.5 ; Illustration of the diffusion process

The mass transport diffusion as consequence of existing of spatial difference of concentration (C)

Flux = Conductivity X Driving force

or Flux (J) = Diffusivity constant (D) X Gradient concentration

First “Fick Law”	Second “Fick law”
$J = -D\left(\frac{dc}{dx}\right)$	$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2}$
The flux is proportional to the exiting gradient concentration With $D = D_o e^{-E_a/RT}$ (D diffusion constant dependant of Temperature T)	Solution $c = c_2 \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$

These type of equations can be modeled with MODELICA.This means that MODELICA could be also used to model the degradation of electrical component and to have a better understanding of the reliability of electrical component.

8. Reliability tool to analyze electrical system

In this chapter we present different tools designed by EDF in order to analyze the reliability of electrical systems. These tools are based on the KB3 platform developed by M. Bouissou at EDF R&D since the 80' [1], [3].

These tool are presented for information because they will be used to illustrate the value and limitations of MODELICA for reliability analysis. These question will be treated in more detail in the second report for the MODRIO project (Deliverable B862)

➢ KB3 electrical component data base (1995)

Some diagrams below are part of the KB3 data base for electrical network. On the left a representation of a simple electrical network and on the right a fault tree which is describing different events that lead to the failure of the system.

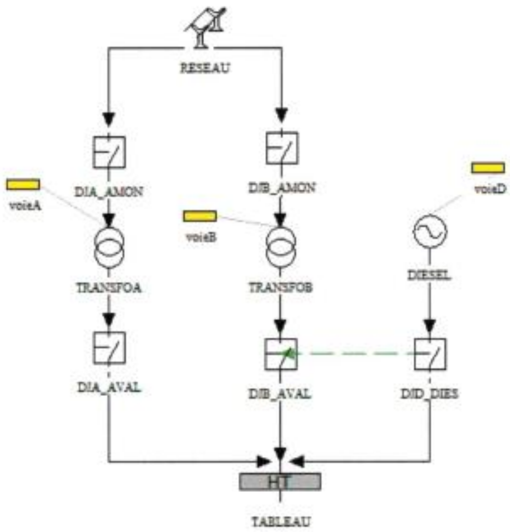


Figure 8.1.a : KB3 Data base for electrical component [34], [35]

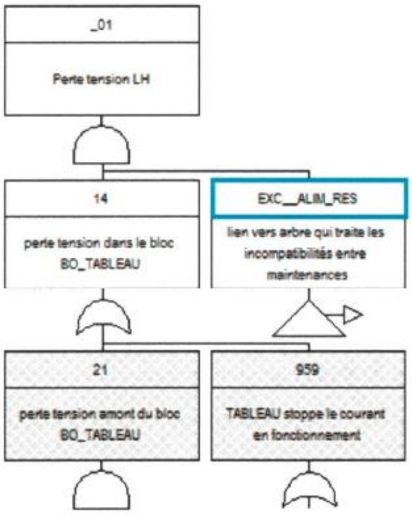


Figure 8.1.b Fault tree generated based on the KB3 Data Base diagram representation [34], [35]

➢ KB3 – BDMP Tool (2001)

An other method to analyze the reliability of a system is via the use of the BDMP (Boolean Diagram Logic Markov Process) methodology. The BDMP is a type of dynamic fault tree in order to represent the solicitation of the back-up power supply when the nominal supply failed.

In this method the BDMP is directly established by the engineer based on the architecture of the electrical network. See below an example of BDMP fault tree [2] for a data center analyzed in 2000 and 2001.

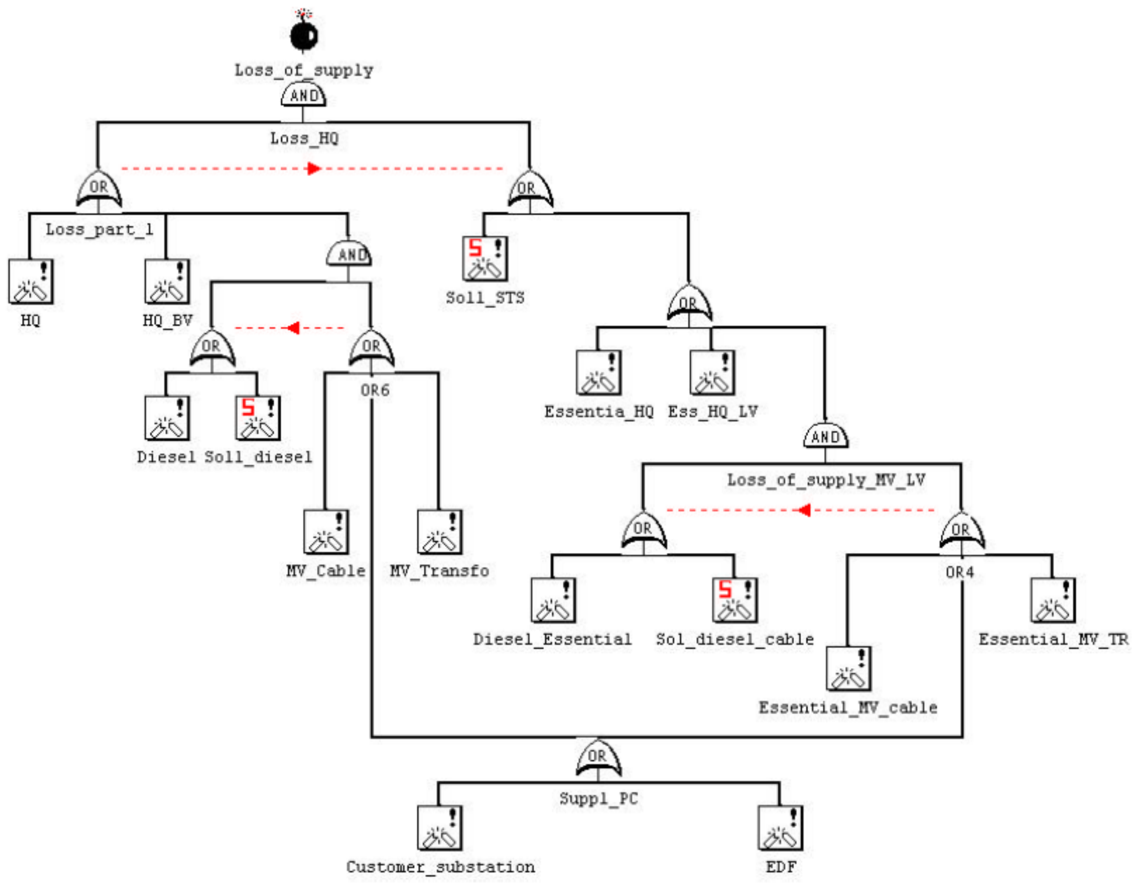


Figure 8.2 : BDMP Diagram for an Internet data center supply [2]

➢ KB3-OPALE Tool (2004)

In 2004 the EDF R&D Tool evolved regarding its treatment of the KB3-OPALE Tool [4] permits the electrical network studied to be directly integrated into the OPALE tool. The failure rates of each component are integrated in the box which represents the component.

Following the tool builds directly the BDMP diagram and computes the reliability and availability indicators for the system and the main sequences leading the failure of the system.

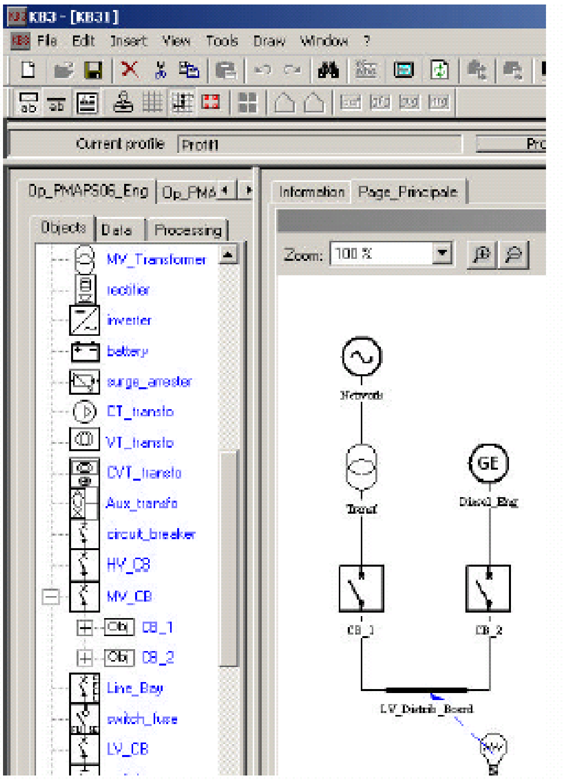


Figure 8.3.a Interface of the KB3-OPALE Tool

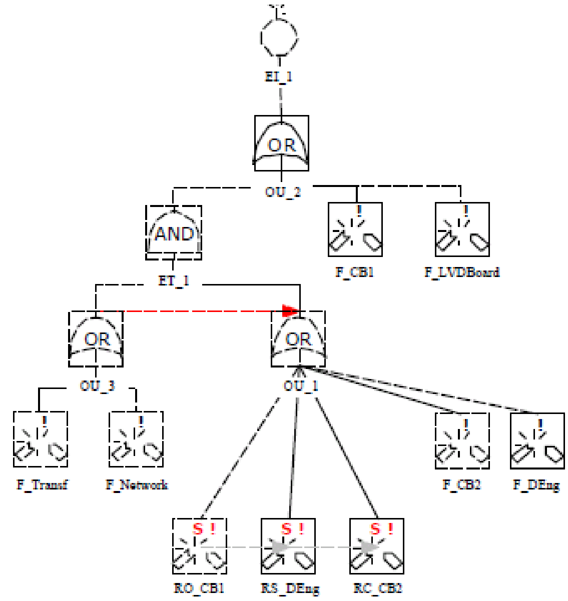


Figure 8.3.b : BDMP fault tree for the failure of the system

Seq.	Name	Rate	Type	Proba Asympt	Contrib in Rel.	Cumulated Contrib	Lambda of the sequence
1	[Network_CC]	2,00E-07	EXP	2,26E-03	49,07%	49,07%	6,80E-10
	[Bon Fct. : CB1_RO,	1,00E+00	INS				
	Bon Fct. : CB2_RF,	1,00E+00	INS				
	Ref. Fct. : Diesel_Eng_DS]	3,40E-03	INS				
2	[Transf_CC]	1,00E-07	EXP	1,13E-03	24,54%	73,61%	3,40E-10
	[Bon Fct. : CB1_RO,	1,00E+00	INS				
	Bon Fct. : CB2_RF,	1,00E+00	INS				
	Ref. Fct. : Diesel_Eng_DS]	3,40E-03	INS				
3	[CB1_CC]	1,00E-10	EXP	3,33E-04	7,22%	80,83%	1,00E-10
4	[LV_Dist_Board_CC]	1,00E-10	EXP	3,33E-04	7,22%	88,05%	1,00E-10
5	[Network_CC]	2,00E-07	EXP	1,79E-04	3,88%	91,93%	5,38E-11
	[Ref. Fct. : CB1_RO,	2,70E-04	INS				
	Bon Fct. : CB2_RF,	1,00E+00	INS				
	Bon Fct. : Diesel_Eng_DS]	9,97E-01	INS				
6	[Network_CC]	2,00E-07	EXP	1,79E-04	3,88%	95,82%	5,38E-11
	[Bon Fct. : CB1_RO,	1,00E+00	INS				
	Ref. Fct. : CB2_RF,	2,70E-04	INS				
	Bon Fct. : Diesel_Eng_DS]	9,97E-01	INS				

8.3.c : Example of sequences leading to the failure of the system

➢ new KB3 – K6 tool for industrial electrical network

In 2012 based on previous KB3 tool a new tools KB3-K6 [35] has been built to model the electrical network. One can see below a very simple representation of an electrical network of a nuclear power plant. On can see clearly the duplicates and the solicitation (red arrows) of the back-up supply when the nominal supply failed.

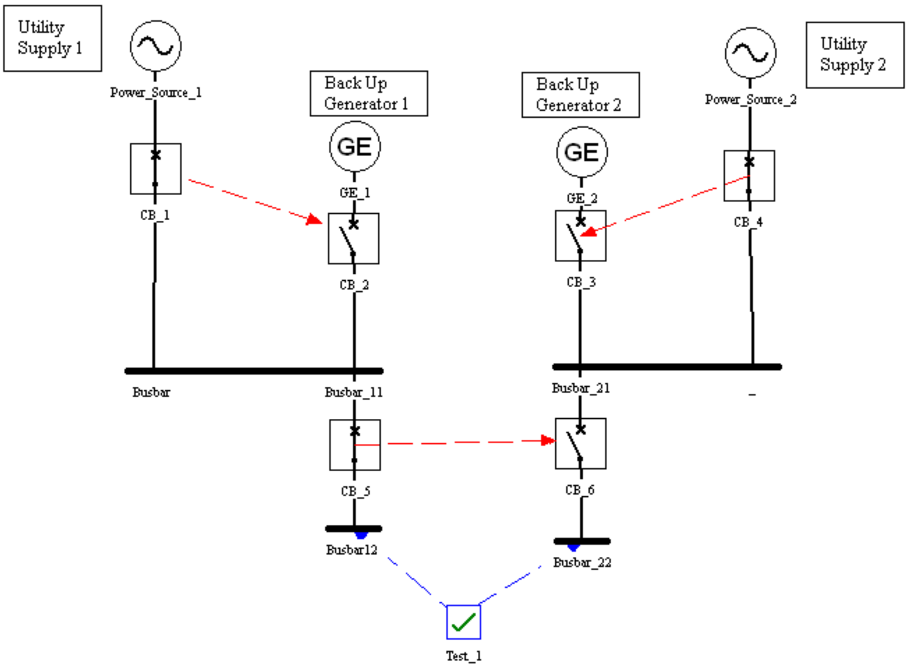


Figure 8.5. Example of representation of the supply of Data Center with the KB3-K6 Tool

(the arrow indicate the dynamic reconfiguration associated to the stand-by components)

9. Potential interests of MODELICA to model the reliability of electrical supply or air cooling system

The potential interests of the MODELICA representation of the Data Center associated with the failure mode to perform reliability analysis are presented. Some example are listed.

These different points will be treated in the Deliverable 8.6.2 for the example of the Data Center.

9.1. Example of the DLR approach for system reliability modeling into MODELICA for electrical supply of plane

DLR [28] has implemented into a MODELICA model of the electrical network of air plane, a reliability approach in order to find out the minimal path set leading to the failure of scenario. The interest of this approach is to merge real physical behavior of system with analysis of different sequence leading to the failure of the system.

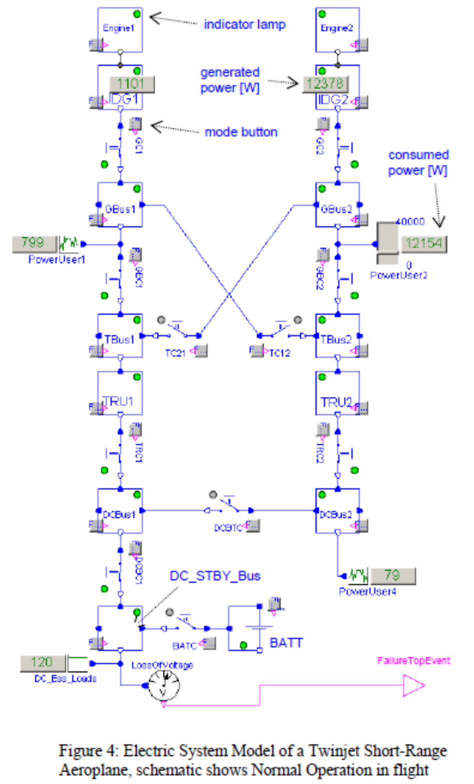


Figure 9.1 : Modelica diagram of an airplane electrical network (from the reference [28])

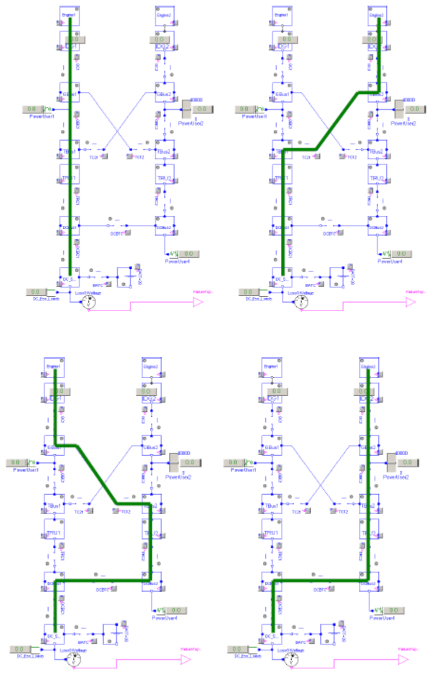


Figure 9.2 : Example of some minimal path set leading to the loss of supply for one scenario

(from the reference [28])

9.2. Approach for reliability analysis with MODELICA

The following is a proposed approach for using MODELICA for reliability analysis of industrial system such as Data Center (electrical network and air conditioning system).

➢ General method

The first step is to do Failure mode and effect analysis (FMEA) for the component studied. Based on this analysis one can choose the main failure which are to be taking into account in the MODELICA reliability analysis.

Therefore one has to add in the nominal model of the component state diagram to model the failure mode with probabilistic transition from nominal operating mode to failure mode.

➢ Reliability model for electrical component with physical influence parameter

The failure rate can vary with the physical parameter such as the temperature and the humidity … The variation of this physical parameter can be due to internal constraints inside the system or from the variation of the external environment due the weather constraints.

The failure database FIDES for electronic component integrates a lot of type of failure rate with physical parameters. For example one presents below the well-known relation due the temperature with the Arrenhuis relation to describe the variation of the failure rate with temperature:

$$\lambda(T) = \lambda 0 \,.\, e^{-\left\{\frac{E}{k}\left(\frac{1}{T} - \frac{1}{T0}\right)\right\}}$$

where

T : is the temperature Kelvin ; T0 reference temperature

k : is the Boltzman constant

E : is the Activation Energy

➢ Reliability model Data Center with Monte Carlo simulation into MODELICA

A classical reliability tool such as KB3 (from EDF) is very powerful to obtain the probability to shift from nominal condition to failure mode of a system.

Nevertheless in the case of a system with temperature regulation which has to operate 100% of the time between two threshold temperatures [T1 ; T2] is not as easily treated with classical type tools (KB3) to compute that the system operates outside these temperature limits due to a failure of temperature regulation.

This case can be treated with MODELICA by taking into account both differential equation to represent the temperature regulation system and the failure of the regulation system;

It is therefore possible to generate by MONTE CARLO simulation several scenario with failure of the regulation system. Nevertheless to obtain relevant statistical estimation of the probability of being outside of the interval [T1 ; T2] one has to generate a lot of scenario.

New function added in MODELICA allows the generation of a large numbers of simulation to obtain relevant estimation probability for abnormal phase of the operating phase (that will be presented in the D862 deliverable)

9.3. Primary conclusion of the interest of MODELICA for reliability analysis of electrical system

In this paragraph the different potential interests of MODELICA for reliability analysis of a system are presented. In a second hand some others conclusion will be given in the other document

- **Interest to model the reliability of electrical system**

  MODELICA constitutes a new tool for the reliability analysis of electrical system which is complementary with the already existing tool (for example the EDF KB3 tool). With MODELICA it is possible to model the probability of occurrence of certain operating mode which can not be estimated as easily with classical reliability tools. For example for Data Center with MODELICA it is possible to represent the regulation of temperature and the estimation of the probability that the temperature will go out a range of temperatures [T1 ; T2].

- **Interest of SYSML, MODELICA and others Tool such as EMTP to organize the experience feedback for the failure**

  - **Experience Feedback of the system failure**

  MODELICA and EMTP tools can be used to understand some complicated failure of an electrical system. The analysis of the incident of FORSMARK 2006 (see appendix B) is an illustration of one failure difficult to analyze. This experience obtained from such an event can be classified with some tool such as SYSML.

  - **Experience Feedback for the component failure**

  Several time the origin of the failure mode of electrical component can be modeled with physical or chemical phenomena. Therefore MODELICA can brought help to model the physical and chemical degradations of electrical component.

- **The use of MODELICA aside other tool such as EMTP for electrical component**

  It will be necessary to keep the use of EMTP in complement to approaches such as the MODELICA language for electro-technical component and electrical network.

- **Role of MODELICA for the exchange between stakeholders and manufacturer for reliability of system**

  The different step of dependability approach for a system are as followed :

  Identification of the different role of each actor for the new system :

  - The owner which will purchase the future system
  - The project manager responsible of design of making of the system
  - Manufacturer subcontractor responsible for realisation of device or component of the system
  - Technical Expert associated to the owner side or manufactory side
  - Eventually for some industrial field (airplane , power generation, telecommunication , …) external public regulatory organisation responsible for quality of service or safety purpose in the industrial field considered

  The use of MODELICA at the different stages of the exchange between stakeholders are indicated in the Appendix F.

10. Conclusion

10.1. Elements presented in this document

The different steps for the reliability study describes in the Data Center Demonstrator (document B8.6.2) will be as follows :

- Studies of the reliability of the data center with software GRIF (Total Satodev) , different tools based on the formalism KB3 (EDF)

In these model one will took into account the two hypothesis with independent Medium Lines or with common mode failure for the two lines due to external weather constrains

- Secondly one can modeled with MODELICA the function of the Data Center for reliability analysis

The study that will be done in the context of the MODRIO project for the demonstrator “data center” has been presented in this document.

Tasks that will be done in the study will be as follows :

- To model both with dedicated EDF’s libraries the normal operating mode of electrical and air cooling parts of a data center structure for the different TIER architecture.
- To model with EDF’s libraries a very simple representation the HV and MV network which will supply the data center
- To integrate in the previous libraries, failure mode of the different component and with focus of physical phenomena which represented the degradation of electrical component or air cooling component
- To integrate in the model representation of external stress on the HV and MV electrical networks due to extreme weather events (high temperature low temperature , wind , lightning …)
- To benchmark (precision of the phenomena studied, time to compute) the reliability study done with the classical type usual reliability Tool (e.g. KB3) and the new libraries developed with the MODELICA language for this demonstrator data center

10.2. Description of the reliability study for the data center presented in the D862 deliverable

The different steps for the reliability study describes in the Data Center Demonstrator (document B8.6.2) will be as follows :

- Studies of the reliability of the data center with software GRIF, and different tools based on the formalism KB3 [36]

In these model one will took into account the two hypothesis with independent Medium Lines or with common mode failure for the two lines due to external weather constrains

- Secondly one can modeled with MODELICA the function of the Data Center for reliability analysis (with Monte Carlo simulation) [37]

10.3. The D742 deliverable, Modelica components with failure mode for the data center

Different component for the data center based on Modelica with failure modes will be presented in the deliverable D742.

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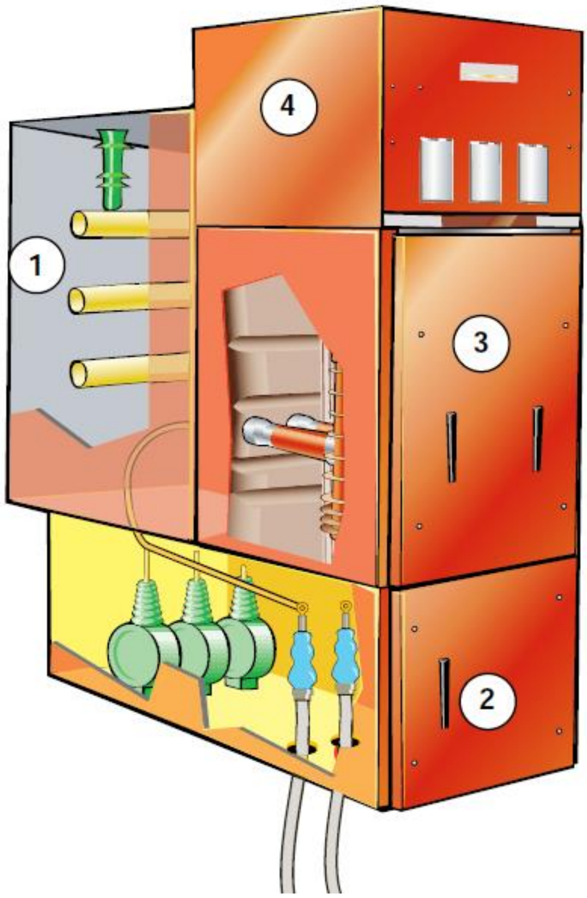
A. Appendix : Examples of electrical components of the data center

➢ Example of components for electrical supply and cooling system for a Data center

In the figure below some components of the electrical Medium Voltage network such as three phases medium voltage Circuit Breaker.

Figure 1.4.a Three phase Medium Voltage (20 kV) circuit breaker



The MV (20 kV) switchboard is composed of :

1 - Medium Voltage Bus Bar

2 - Medium Voltage Sensor

3 - Medium Voltage Circuit Breaker

4 - Relay protection

Figure 1.4.b : MV (20kV) switchboard of HV/MV substation

The picture below presents some components of air cooling of a Data Center

Figure 1.5 a : Cooling system - Chiller

Figure 1.5.b Tank

B. Appendix : Examples of real failures to illustrate the risk associated to common failures for critical electrical supply

To directly illustrate with some examples the difficulties associated to reliability analysis of the reliability of data center of others critical electrical system one can mention some events occurring in 2015 or previously. ***(****All events described below have been presented in conference papers or news published. These examples will illustrate that some events at the level of the system can be very difficult to analyze and model in a simple way).*

➢ "Google loses data as lighting strikes" 13 august 2015

In the August 13, 2015 an incident occurs in the Belgium Google data center due to the loss of energy supply caused by lightning strokes. Detail of this incident are included in the appendix of this document.

The consequence of this incident was some damage on permanent disk and some loss of data. Nevertheless Google gave some recommendations to the end user to have their own storage.

From http://www.bbc.com/news/technology-33989384

Figure B.1

Google says data has been wiped from discs at one of its data centers in Belgium - after the local power grid was struck by lightning four times.

Some people have permanently lost access to the files on the affected disks as a result.

A number of disks damaged following the lightning strikes did, however, later became accessible.

Google compute Engine incident #15056

Google Compute Engine Persistent Disk issue in europe-west1-b

Incident began at **2015-08-13 09:25** and ended at **2015-08-16 09:35** (all times are **US/Pacific**).

Date	Time	Description
Aug 18, 2015	02:18	SUMMARY: From Thursday 13 August 2015 to Monday 17 August 2015, errors occurred on a small proportion of Google Compute Engine persistent disks in the europe-west1-b zone. The affected disks sporadically returned I/O errors to their attached GCE instances, and also typically returned errors for management operations such as snapshot creation. In a very small fraction of cases (less than 0.000001% of PD space in europe-west1-b), there was permanent data loss. Google takes availability very seriously, and the durability of storage is our highest priority. We apologise to all our customers who were affected by this exceptional incident. We have conducted a thorough analysis of the issue, in which we identified several contributory factors across the full range of our hardware and software technology stack, and we are working to improve these to maximise the reliability of GCE's whole storage layer.

Date Time Description

DETAILED DESCRIPTION OF IMPACT:

From 09:19 PDT on Thursday 13 August 2015, to Monday 17 August 2015, some Standard Persistent Disks in the europe-west1-b zone began to return sporadic I/O errors to their connected GCE instances. In total, approximately 5% of the Standard Persistent Disks in the zone experienced at least one I/O read or write failure during the course of the incident. Some management operations on the affected disks also failed, such as disk snapshot creation.

From the start of the incident, the number of affected disks progressively declined as Google engineers carried out data recovery operations. By Monday 17 August, only a very small number of disks remained affected, totalling less than 0.000001% of the space of allocated persistent disks in europe-west1-b. In these cases, full recovery is not possible.

The issue only affected Standard Persistent Disks that existed when the incident began at 09:19 PDT. There was no effect on Standard Persistent Disks created after 09:19. SSD Persistent Disks, disk snapshots, and Local SSDs were not affected by the incident. In particular, it was possible at all times to recreate new Persistent Disks from existing snapshots.

ROOT CAUSE:

At 09:19 PDT on Thursday 13 August 2015, four successive lightning strikes on the local utilities grid that powers our European datacenter caused a brief loss of power to storage systems which host disk capacity for GCE instances in the europe-west1-b zone. Although automatic auxiliary systems restored power quickly, and the storage systems are designed with battery backup, some recently written data was located on storage systems which were more susceptible to power failure from extended or repeated battery drain. In almost all cases the data was successfully committed to stable storage, although manual intervention was required in order to restore the systems to their normal serving state. However, in a very few cases, recent writes were unrecoverable, leading to permanent data loss on the Persistent Disk.

This outage is wholly Google's responsibility. However, we would like to take this opportunity to highlight an important reminder for our customers: GCE instances and Persistent Disks within a zone exist in a single Google datacenter and are therefore unavoidably vulnerable to datacenter-scale disasters. Customers who need maximum availability should be prepared to switch their operations to another GCE zone. For maximum durability we recommend GCE snapshots and Google Cloud Storage as resilient, geographically replicated repositories for your data.

REMEDIATION AND PREVENTION:

Google has an ongoing program of upgrading to storage hardware that is less susceptible to the power failure mode that triggered this incident. Most Persistent Disk storage is already running on this hardware. Since the incident began, Google engineers have conducted a wide-ranging review across all layers of the datacenter technology stack, from electrical distribution systems through computing hardware to the software controlling the GCE persistent disk layer. Several opportunities have been identified to increase physical and procedural resilience, including:

Continue to upgrade our hardware to improve cache data retention during transient power loss. Implement multiple orthogonal schemes to increase Persistent Disk data durability for greater resilience. Improve response procedures for system engineers during possible future incidents.

➢ Regional black-out in the west of France end June 2015

In the end of June 2015 (June 30, 2015) during a heat wave in France several failures occurred in HV instrument transformers (sensors) in less than 8 hours in several HV substations in the west of France. This results in almost one million of customers being without electrical supply for a day.

About 40 instruments transformers failed in 17 substations due to the high level of temperature and the cycle between the upper and lower of temperature during the June 30, 2015.

Figure B.2: Number of customers with power cuts the June 30, 2015

Breizh-info.com // ouest.France.com // www.letelegramme.fr

Figure B.3 : High voltage Instrument transformer

This example indicates that for a Data Center which be located in this region and be supplied by two medium voltage lines, this event could provoke the simultaneous loss of the two MV lines. This means that the probability to lose simultaneously the two MV lines is more important than the hypothesis of independent failures for the two lines.

➢ Forsmark 2006 incident for electrical network of nuclear power plant

An incident occurred at 13.20 on Tuesday 25th 2006 at Forsmak 1 (nuclear power plant in Sweden), which was then in operation at full power 900 MW. The origin of the incident lay in a short circuit in the 400 kV switchyard outside the plant. It resulted in severe voltage fluctuations which in a complicated spread into several of the electrical systems in the plant.

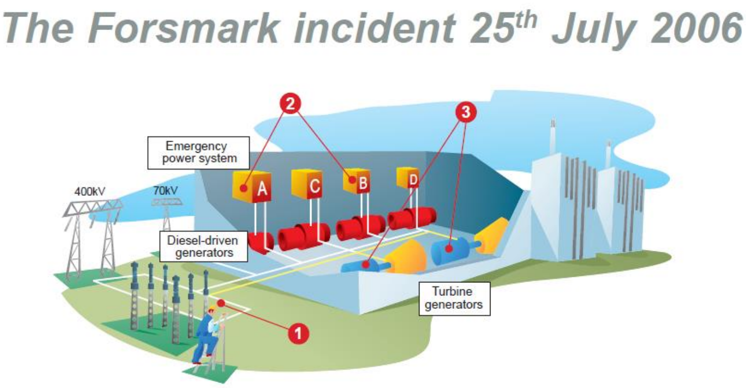


Figure B.4 : Incident of the Forsmark (Sweden) nuclear power plant

The voltage fluctuation resulted in Forsmark 1 being disconnected from the external grid and the reactor being scrammed. Parts of the battery backed AC internal distribution network were knocked out and only two of the four diesel driven generators started automatically. After 22 minutes power was restored manually from the control room after which the two other diesels units started. Some of the control room equipment had also been partially knocked out, with the result that, initially the control room operators were obtain a full overview of the situation

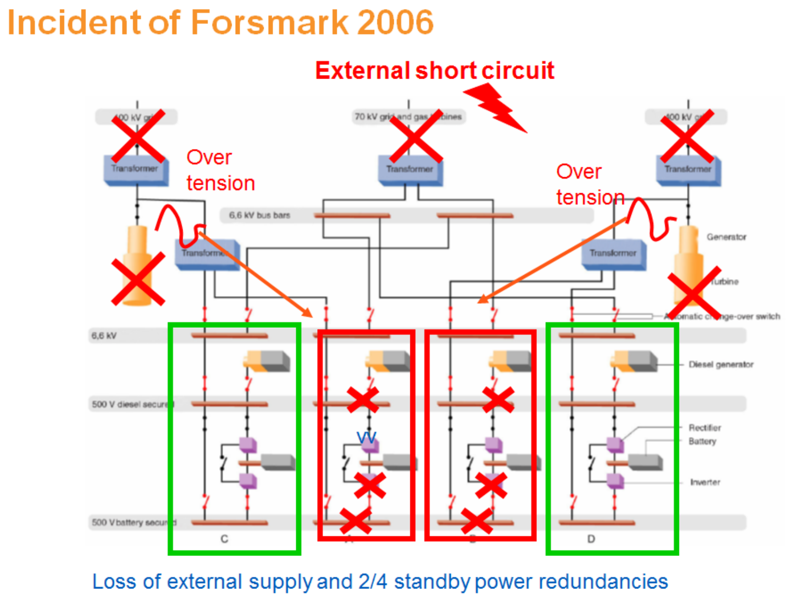


Figure B.5 : Description of the incident for the electrical network in Forsmark 2006

The reactor core, however was an adequacy cooled throughout the incident and the reactor pressure vessel was not subjected to any abnormal pressure or temperature loads. What makes the Forsmark incident serious in terms of safety is instead that the defense –in –depth reactor safety systems that are intented to operate satisfactorily. Several safety systems that are intended to operate independently of each other failed to do so as the result of a common external fault. An important principle for reactor safety – that safety systems are designed and intended to minimize the risk of such common cause failure was not maintained.

Nevertheless the diversity of automatically operating safety systems was sufficient to ensure that the reactor was shut down automatically and independently of the operators, and that sufficient cooling was maintained throughout the duration of the incident. In addition through following special incident instructions, the control room personnel were able to act in a rational manner and retain control over the situation throughout the incident.

The worst situation that has been taking into account during safety analysis in the loss of the external lines HV the shut down of the main generator and the loss of one diesel of the four. **In Forsmark 1 the incident was over serious because two diesels to four were lost instead of only one.**

This incident was classified at level 2 of the international severity scale for incident for nuclear power plant with 7 level.

Others types of constraints for electrical networks

Different types of common cause failure

The hypothesis of the different architectures of DATA CENTER is the independence of the failures of different parts of the system. It means for example for the TIER IV structure, that the failure of the two of electrical MV lines from the utility and the failure of the stand –by generator of the data center are independents.

Nevertheless in reality the failure of the two MV lines from the utility are not totally independents due for example the reasons below:

- The risk of a major black-out on the HV transmission network
- The risk of black out of the HV/MV substation in the case of the two MV lines which are supplying the data center are linked to the same substation

Other causes such as meteorological constraints could affect simultaneously several MV lines feeders such as :

- Major storm with high speed wind
- Heat wave in summer during several weeks could affect both electricity generation and MV overhead lines or MV underground cables while the increasing load due to air conditioning system of customers.
- High temperature level increase the failure rate of all electrical equipment of the network
- Lightning : can affect transmission and distribution line and can generate electrical perturbation which can be introduce through the MV electrical network into the data center and propagate electrical (over-tension) disturbance into the electrical network of the data center
- Cold temperature : can affect transmission and distribution networks with ice

Other factors which could potentially impact reliability include :

- Modification of the nominal electrical diagram network
    - the load on the different piece of equipment and modify the failure rate of some electrical equipment
    - the direction of the electrical current and modify the action of the protection relay

- Structural issue with renewable generation of energy :
    - Renewable generation of energy such as wind energy depending of the wind are not constant. Their impact on reliability requires further study

- Others specific phenomena (rare or theoretical causes) with potentially important impact includes :
    - Earth quakes : can affect towers lines and substations
    - Solar Wind : can affect transmission network

Several issues needed to model precisely the impact on the network (or the electrical component) of physical constraints. That is why the study of the common cause failure for duplicates in the electrical network could benefit from the use of physical model with the Modelica language and tool associated.

Potential consequence of self-organized criticality (SOC) phenomena for the reliability of a system

Usually in model to estimate the probability of local or regional black out we assume that the occurrence of components failures are independents.

Nevertheless some publications [24] examining "black out" in HV electrical networks show that this phenomena can appear to obey "power law" distribution. This means that the black out are the result of several stochastic events that are no independent events.

This phenomena named "cascading failure" or "self organized criticality (SOC)" is shows from statistics applied to the "black outs" in North America.

The consequence is that the probability of "black out" event in much higher than the estimation model with independent failures of components.

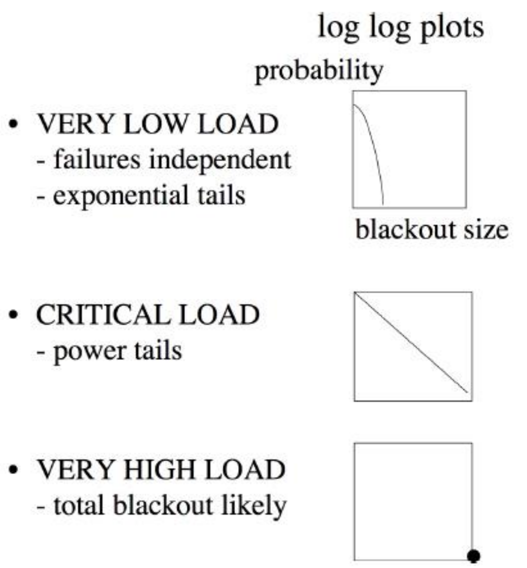


Fig. 2: Log-log plots sketching idealized blackout size probability distributions for very low, critical, and very high power system loadings.

Figure B.7 from the reference [24]

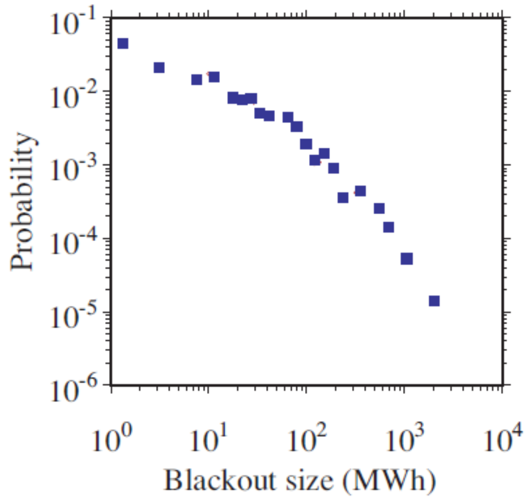


Fig. 1: Log-log plot of scaled PDF of energy unserved during North American blackouts 1984 to 1998.

Figure B.8 from the reference [24]

C. Appendix : Different approaches for reliability analysis of critical system

Probabilistic versus deterministic approaches for reliability analysis of a system

The reliability analysis of a system can be done with deterministic or probabilistic approaches. In this document one has to consider that these two approaches are complementary. Nevertheless some standard for reliability analysis are much more for one side or for the other side. For example :

- **Probabilistic**

  IEC 60300 : General application of reliability method

- **Probabilistic and deterministic**

  IEC 61508 : General application for Control command system

  Up-time Institute standard for Data Center

  NUREG : Guide used in US for nuclear power plant (US)

- **Deterministic**

  IEC 61513 : Control command system for Nuclear power plant (Europe and France)

  IEC 62855 : Electrical network for nuclear power plant (Europe and France)

Example of the SIL (Safety Integrity Level) from the IEC 61508

In order to illustrate the concept of mixed approaches including both deterministic and probabilistic the IEC 61508 defined the Safety Integrity Level (SIL) from 1 to 4 with effort of requirement realization elements test and control are much more important for SIL 4 than SIL 1.

This standard associates through the SIL level, a probability value (see tables below) for failure on time or failure on demand.

Safety integrity level : target failure measures for a safety function operating in low demand mode of operation

Safety integrity level	Average probability of dangerous failure on demand
1	≥ 1E-2 to < 1E-1
2	≥ 1E-3 to < 1E-2
3	≥ 1E-4 to < 1E-3
4	≥ 1E-5 to < 1E- 4

Safety integrity level : target failure measures for a safety function operating in high demand mode of operation or continuous mode of operation

Safety integrity level	Dangerous failure rate of the safety function (hr-1)
1	≥ 1E-6 to < 1E-5
2	≥ 1E-7 to < 1E-6
3	≥ 1E-8 to < 1E-7
4	≥ 1E-9 to < 1E-8

One has to notice even the IEC 61 513 come from the IEC 61508 there is no SIL level in the IEC 61 513. There is no SIL level in the IEC 61 855.

Standard associated to the electric network for Data center

The main standard for the Data Center is a guide from the Uptime Institute which give four typical architectures from 1 to 4 depending the level of availability and cost of the system

Classical statistic versus Bayesian statistic for the reliability parameter λ and γ

The two reliability parameters are as follow

- The failure rate to operate (failure in time) : λ [time^{-1}]
- Or the failure rate on demand (failure on demand) : γ (probability)

These parameters can be determined with statistical analysis of operational failures. We usually take into account the average value $<\lambda>$ and $<\gamma>$ of the statistical analysis.

Classical statistical approach

In addition of the average value of the parameter $<\lambda>$ and $<\gamma>$ one has to consider the interval of estimation (lower and upper values) for these parameters. For example for the $<\lambda>$ the lower and upper values are given by the Khi2 law with a certain level of confidence (90% or 95% for example)

Bayesian Statistical approach

In the bayesian statistical approach we do not use directly the average value of the reliability parameter but the density distribution. One has to define prior $\pi(\theta)$ distribution for the parameter and define the likelihood of the observation and apply the Bayes theorem (continuous version) to obtain the posterior law $\pi(\theta|x)$ for the parameter.

Continuous version of the Bayes Theorem

$$\pi(\theta|\mathrm{x}) = \frac{\ell(\theta|\mathrm{x})\pi(\theta)}{\int_{\Theta} \ell(\theta|\mathrm{x})\pi(\theta)\,\mathrm{d}\theta}$$

The table as follows summarized the two classical and Bayesian statistical method

	Classical statistical approach	Bayesian approach	
		Prior	Posterior
Failure in time	Average value $<\lambda>$ Lower and upper value through Khi2 Law with level of confidence x%	Gamma law (a,b) for the λ parameter	Gamma law (a',b') for the λ parameter
Failure on demand	Average value $<\gamma>$ Lower and upper value through binomial Law with level of confidence	Beta law (c,d) for the γ parameter	Beta law (c',d') for the γ parameter

Conjugate laws for reliability parameters with bayesian approach are as follow :

Reliability parameter	**Priori**	**Model Likelihood**	**posterior**
Failure rate λ	Gamma	Exponential	Gamma
Failure on demand γ	Beta Law	Binomial	Beta law
Other	Inverse gamma law	Gaussian or Cox Model	Inverse gamma law

D. Appendix : Some results of the "I-Tesla" European project

Some result of the "I-Tesla" European project are presented in this appendix from references [14] and [15].

[14] L. Vanfretti, T. Bogodorova, M. Baudette "**A modelica power systems Library for model validation and parameter identification"** Proceeding of the 11th International Modelica Conference March 10-12, 2014 Lund Sweden

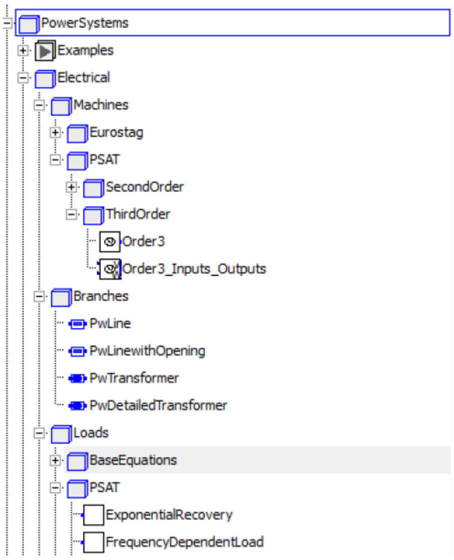


Figure 1. Partial screenshot of the library

Figure D.1 : List of component with MODELICA from the I-Tesla project

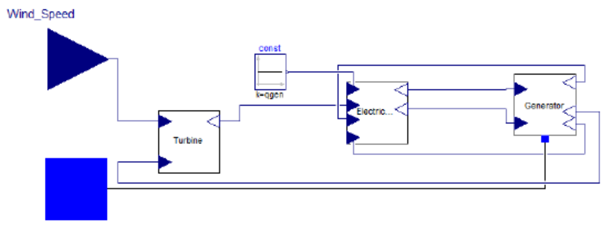


Figure 2. Modelica implementation of the GE Wind Turbine-Generator Model

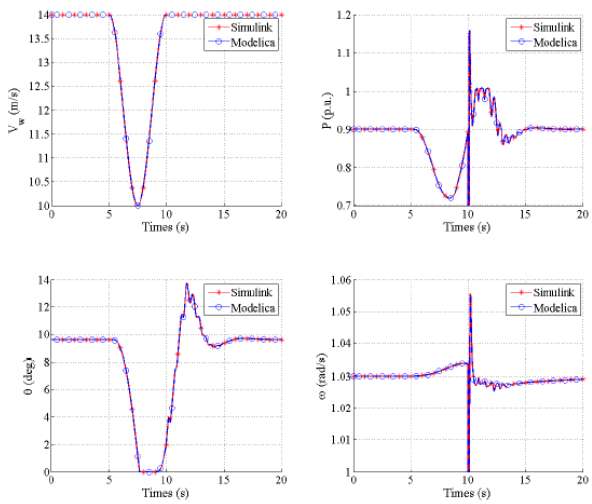


Figure 4. Comparison Modelica vs Simulink for the GE Wind Turbine-Generator Model

Figure D.2 : Example of simulation of electrical network with the I-Tesla library of electrical component

The CIM (common information model) is a standard based on UML data model which has been developed to represent the electrical component. The "i-Tesla" project has created links between CIM standard and Modelica library for electrical components; see below one reference of the "I-Tesla" project and figures associated.

[15] F-J Gomez, L. Vanfretti, S.H. Olsen "**Binding CIM and Modelica for consistent power system Dynamic model Exchange and simulation**" IEEE PES General Meeting Denver Colorado 26-30 July 2015

A. CIM RDF Schema

The data base of components and connections represented by the CIM data model are stored in a single file, using eXtensible Markup Language (XML) serialization, based on the Resource Description Framework (RDF). With the RDF schema, objects and relations between them are stored in graph-like data structures (see Fig. 1 and Fig. 2). Serialization, checking and making files for storing topology changes are easier to interpret by XML processing tools, like XML Spy [17] that are able to read graph-like structures.

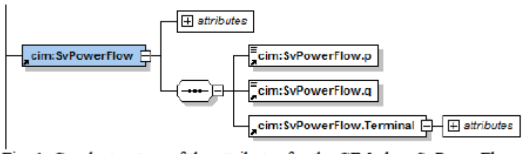


Fig. 1. Graph structure of the attributes for the CIM class SvPowerFlow.

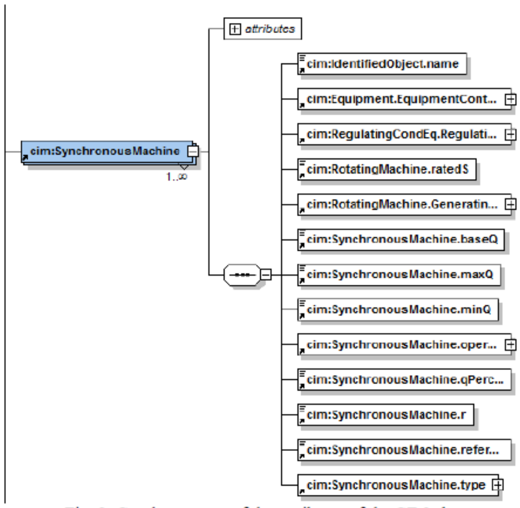


Fig. 2. Graph structure of the attributes of the CIM class SynchronousMachine.

This kind of representation makes it easy to understand the attributes and the associations that CIM classes have between them. In case of Fig. 1, the CIM class **SvPowerFlow** has attributes *p* and *q* and an association with a CIM class Terminal. This class is used to store the power flow solution for *P* and *Q* and the connection terminal to which these values are associated with.

Figure D.3 : CIM (UML) standard used in the I-Tesla for the electrical component [15]

B. Modelica Code Representation

A model implemented in the Modelica language is comprised of three parts. First a specialization keyword, indicating which kind of class should be represented, and the name of the class, open the model declaration. Second, there

is the variable section where all the attributes of the model are defined, with their proper visibility, variability, name, value and comments. The variability indicates the kind of variable; and visibility indicates the level of protection of the variable. Third there is the equation section where the mathematical model is represented. An implementation of a Pi-equivalent model for a Line for the iPSL is represented by next lines of code, with attributes and equations:

```
class Line "Pi-Line"
  PowerSystems.Connectors.PwPin p ;
  PowerSystems.Connectors.PwPin n ;
  parameter Real R "Resistance p.u.";
  parameter Real X "Reactance p.u.";
  parameter Real G "Shunt half conductance p.u.";
  parameter Real B "Shunt half susceptance p.u.";
equation
  R * (n.ir - G * n.vr + B * n.vi) - X * (n.ii - B
* n.vr - G * n.vi) = n.vr - p.vr;
  R * (n.ii - B * n.vr - G * n.vi) + X * (n.ir - G
* n.vr + B * n.vi) = n.vi - p.vi;
  R * (p.ir - G * p.vr + B * p.vi) - X * (p.ii - B
* p.vr - G * p.vi) = p.vr - n.vr;
  R * (p.ii - B * p.vr - G * p.vi) + X * (p.ir - G
* p.vr + B * p.vi) = p.vi - n.vi;
end Line;
```

The variability of a certain variable will explicitly indicate how to assign the start value of the variable. A variable with no variability indicates that its value is able to change during the simulation, so a start keyword should be indicated for assigning the initial value of the variable:

```
Real P (start=0.25) "active power injection";
```

For other kind of variability such as the **parameter** variability indicates that its value does not change during simulation, but can be changed between simulations. The starting value of a variable will be assigned as an equation:

```
parameter Real S = 100 "Base apparent power of the
component";
```

The remaining attributes from other classes will have *parameter* variability.

Figure D.4 : Example of MODELICA electrical component from the I-Tesla project [14]

E. Appendix : Example of components from the EIREIDA Data Base

144 EUROPEAN INDUSTRY RELIABILITY DATA BANK

table 121 of 220	EUROPEAN INDUSTRY RELIABILITY DATA BANK	1998 EDITION

COMPONENT : **BREAKERS, AC, 6.6 kV**
FUNCTION : Power supply: All motor driven pumps

ENGINEERING CHARACTERISTICS :
Type : Electric supply — Safety Class :
Voltage (kV) : 6.6/7.2
Intensity (A) : 90/1,250 — Environment :
Poles : 3

OPERATIONAL CHARACTERISTICS :
Operating mode on annual basis :
- continuous : ⊗ intermittent : standby :
< 100 h < 1000 h < 5000 h ⊗ > 5000 h
Number of demands :
< 10 ⊗ < 100 < 500 > 5000
Maintenance Policy : 1R Test Periodicity : 1R

TABLES OF RELIABILITY DATA 145

1998 EDITION	EUROPEAN INDUSTRY RELIABILITY DATA BANK	table 122 of 220

COMPONENT : **BREAKERS, AC, 6.6 kV**

SAMPLE 1978-1987 plant-years: No components/plant:
1988-1993 eqt-years: 458

	Failure Rate		Probability of Failure on Demand		Mean Active Repair	
	λ/h (E-6)	EF	γ/d (E-3)	EF	MTTR (h)	Man-hours
Prior (78/87), Critical failures	0.49 *	1.7	0.36	1.7	3	5
Likelihood (88/93)	No Failures 1	Cum Time (h) 3.525 E+6	No Failures 2	No Demands 1.718 E+4	4	8
Post. Mean	0.46		0.28			
Prob. Interval	80%	0.29 0.66	80%	0.16 0.37		
Posterior pdf	Gamma (10.2 ; 2.23 E+7)		Beta (10.5 ; 4.0 E+4)			

Mode 1: Overheating: 0.375	Mode 2: Won't close: 0.25

Other Sources		λ /h. E-6	EF	γ /d. E-3	EF	MTTR (h)	Man-hours
EDF	1995C	0.6	1.4	0.2	1.6	3.3	
	All (78-93)	0.5	1.4	0.3	1.5	6	7.5
WASH 1400	Critical			1			
	All						
	Sample						
CY PRA	Critical	1.5					
	All						
	Sample	Won't open γ=0.16 E-3/d, won't close: 0.34 E-3/d					
OCONEE PRA	Critical	0.1					
	All						
	Sample	Won't open γ = 0.3 E-3/d, won't close: 0.9 E-3/d					
T-book 3	Critical	0.18**	4			4	
	All						
	Sample	4 failures, 2.8 E+7 h					

Comments:
- * First EPS evaluation: All during operation: 6.4 E-7/h, EF = 1.7. Spurious: 1.3 E-7/h, EF = 4.2. All failures: 0.4 E-6/h.
- ** Spurious charge of position: λ = 2.1 E-7/h.

Breaker 6.6 kV/250 A: $\hat{\lambda}$ = 0.11 E-6/h, EF = 3.
Breaker 6.6 kV/1100 to 2900 A: $\hat{\lambda}$ = 0.49 E-6/h, EF = 2.
Breaker of reactor coolant pump motor: $\hat{\lambda}$ = 0.97 E-6/h, EF = 3.3.
OREDA : 10 E-6/h, EF = 2, MTTR = 12h.

table 113 of 220	EUROPEAN INDUSTRY RELIABILITY DATA BANK	1998 EDITION

COMPONENT : **BATTERIES, Nickel - Cadmium**
FUNCTION : Auxiliary, regulation, protection and power supply

ENGINEERING CHARACTERISTICS :

Type :	Ni-Cd battery banks	Safety Class :	
Rated capacity :	50/520 AH		
Nominal voltage :	48/125 V	Environment :	Control room Bld
Autonomy (MN) :	60/300		

OPERATIONAL CHARACTERISTICS :

Operating mode on annual basis :

	- continuous : ⊗	intermittent :		standby :
	< 100 h	< 1000 h	< 5000 h ⊗	> 5000 h
Number of demands :	< 10	< 100 ⊗	< 500	> 5000

Maintenance Policy : 1R   Test Periodicity : 26W

1998 EDITION	EUROPEAN INDUSTRY RELIABILITY DATA BANK	table 114 of 220

COMPONENT : **BATTERIES, Nickel - Cadmium**

SAMPLE	1978-1987	plant-years:	79	No components/plant:	4 banks
	1988-1993	eqt-years:	104		

	Failure Rate		Probability of Failure on Demand		Mean Active Repair	
	λ/h (E-6)	EF	γ/d (E-3)	EF	MTTR (h)	Man-hours
Prior (78/87), Critical failures	1.47 •	4.2	0.04	2	6	
Likelihood (88/93)	No Failures 0	Cum Time (h) 9.08 E+5	No Failures 0	No Demands 1.752 E+4	6	13
Post. Mean	1.2		0.04			
Prob. Interval	60% 0.7	1.7	80% 0.02	0.08		
Posterior pdf	Gamma (3.98 ; 3.2 E+6)					

Mode 1: Loss of performance: 0.5	Mode 2: Maintenance: 0.2

Other Sources		λ /h. E-6	EF	γ /d. E-3	EF	MTTR (h)	Man-hours
EDF	1995C	0.9	2.5				
	All (78-93)	2.5	1.6			7	18
IEEE	Critical	0.26	9.5				
	All						
	Sample						
EG&G	Critical	10	5	0.4	3		
	All						
	Sample						
T-book 3••	Critical	1.1	6			21	
	All						
	Sample	12 failures, 1.2 E+7 h					
OREDA	Critical	0.85	2.1			18	
	All	29	1.9				
	Sample	Ni-Cd 35 to 350 Ah ; 24/48/110 V					

Comments:
- • All during operation: 1.5 E-6/h ; EF = 3.15
  - capacity: 7.5 E-7/h ; EF = 4.2
  - open circuit: 3.8 E-7/h ; EF = 10
  - short circuit: 3.8 E-7/h ; EF = 10
- •• Generic data

126 EUROPEAN INDUSTRY RELIABILITY DATA BANK

table 103 of 220	EUROPEAN INDUSTRY RELIABILITY DATA BANK	1998 EDITION

COMPONENT : **VALVES, Electric Motor Operated Stop Valves, Service Water**
FUNCTION : Service water stop valve

ENGINEERING CHARACTERISTICS :

Type :	Stop valve, electric operated, paraslide	Safety Class :	2
Size (mm) :	100/350	Environment :	Aux. Bld
Temp (°C) :	50		
Pressure (bar) :	10		
Medium :	Demineralised water		

OPERATIONAL CHARACTERISTICS :

Operating mode on annual basis :

	- continuous : ⊗	intermittent :		standby :
	< 100 h	< 1000 h	< 5000 h ⊗	> 5000 h
Number of demands :	< 10 ⊗	< 100	< 500	> 5000

Maintenance Policy : 1R Test Periodicity : 1R

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TABLES OF RELIABILITY DATA 127

1998 EDITION	EUROPEAN INDUSTRY RELIABILITY DATA BANK	table 104 of 220

COMPONENT : **VALVES, Electric Motor Operated Stop Valves, Service Water**

SAMPLE	1978-1987	plant-years:	103	No components/plant:	2
	1988-1993	cpt-years:	370		

	Failure Rate		Probability of Failure on Demand		Mean Active Repair	
	λ/h (E-6)	EF	γ/d (E-3)	EF	MTTR (h)	Man-hours
Prior (78/87), Critical failures	0.44 •	10	2 ••	3	10	
Likelihood (88/93)	No Failures 3	Cum Time (h) 7.91 E+5	No Failures 3	No Demands 3.303 E+3	6	13
Post. Mean	1.44		1.16			
Prob. Interval	60%	0.86 1.95	60%	0.72 1.56		
Posterior pdf	Gamma (4.5 ; 3.15 E+6)		Beta (4.97 ; 4.29 E+3)			

Mode 1: Fail to open: 0.50	Mode 2: Fail to close: 0.22	Mode 3: Blockage: 0.17

Other Sources		λ /h. E-6	EF	γ /d. E-3	EF	MTTR (h)	Man-hours
EDF	1995C	2.3	1.3	0.22	1.3		
	All (78-93)	11	1.5	1.44	1.5	9	
CY PRA	Critical			0.375			
	All						
	Sample						
OCONEE PRA	Critical	0.23		4			
	All						
	Sample						
ZION PRA	Critical	0.112		1.14			
	All						
	Sample						
	Critical						
	All						
	Sample						

Comments:
- • Internal leak: 2.2 E-7/h, EF = 10. External leak: 2.2 E-7/h, EF = 10. Rupture or severe leak: 3 E-9/h, EF = 10.
- •• Won't open: 1.5 E-3/d, EF = 3. Won't close: 5 E-4/d.

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F. Appendix : Phases of reliability exchanges between stakeholders

The different step of dependability approach for a system are as followed :

Identification of the different role of each actor for the new system :

- The owner which will purchase the future system
- The main manufacturer responsible of design of making of the system
- Manufacturer subcontractor responsible for realisation of device or component of the system
- Technical Expert associated to the owner side or manufactory side
- Eventually for some industrial field (airplane , nuclear, telecommunication , …) external public regulatory organisation responsible for quality of service or safety purpose in the industrial field considered

First in the call for tender phase the owner has to define the requirement for the future system. Expert associated with the owner side will write the different points

- the different functions of the system
- the life time target for the system
- the environment of the system with external stresses and hypothesis of frequency solicitation of the system
- The reliability, availability (quality of service) and safety target. These target can be define with deterministic or probabilistic expression
- Requirement for the logistical support during the operating phase of the system
- The life cycle cost target of the future system (purchase price and maintenance price during the life time of operating of the future system)

Based of the expression of target for the future system exchanges will take place between the owner and the tender manufacturers.

When the main manufacturer and subcontractor have been chosen by the owner the “V cycle” to realize the system will begin.

Design phase of the system

One assumes that : System = Sum of function

Each function of the system has to be described by the owner of the system and after has to be précised and built by the manufacturer

That at the end of the design phase one can describe each function with several items.

Proposal of items adapted for the reliability study are presented as follows

For example :

Function

Target

Type (Real time, Database, Measurement Regulation , I/O ..sensor ..)

Role of Energy supply for the system (Y / N)

Mathematical representation

Complexity level of the function

Real implementation of the function

Supply energy

Hardware

Software

- Firmware
- Dedicated software application

Telecommunication

Human resource

External constrains

Spare parts number

Life cycle cost for the function

<u>Reliability level of the function</u>

- Failure mode and effect analysis
- Fault tree or markov graph representation
- Model checking of the function
- Functional Failure rate for the function
- Level of redundancies for the different part of the implementation of the function
- Hardware failure rate for component
  - Degradation model due to physical stress
- Software and/ or telecommunication failure rate
  - Reliability growth process for the bug software
- Complexity level of the function from the point of view of reliability

<u>Maintenance of the function</u>

- Spare parts number
- Maintenance human resource skill

Description of the system can used MODELICA ML or others similar method such as TOPCASED (SYSML) to describe the function and their physical or software implementation

Mathematical or physical algorithm for the function can be described with Modelica

Reliability degradation mode which integrated physical stresses or software error design can be described with Modelica Language

Test phase or experimentation phase

During unitary test or integrated test the result of the test phase had to be collected.

All failure or error will be collected and compared with the reliability study done in the design phase

Decision analysis to accept or reject the system regards to the reliability and availability requirement

Based on previous task one has to propose the Bayesian statistic to integrated all the different information collected

Feedback from experience during operating phase has to be organized and data will be statistically treated :

Power cur data base

Meteorological database METEO FRANCE, METEORAGE …

FIDES reliability database for electrical component

MIL HDBK 217 for electrical component

Statistical treatment will be made by the "R" tool