ABSTRACT

Title of Document: **RELIABILITY EVALUATION OF COMMON-CAUSE FAILURES AND OTHER INTERDEPENDENCIES IN LARGE RECONFIGURABLE NETWORKS.**

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This work covers the impact of Interdependencies and CCFs in large repairable networks with possibility of "re-configuration" after a fault and the consequent disconnection of the faulted equipment. Typical networks with these characteristics are the Utilities, e.g. Power Transmission and Distribution Systems, Telecommunication Systems, Gas and Water Utilities, Wi Fi networks. The main issues of the research are:

A. Identification of the specific interdependencies and CCFs in large repairable networks, and
B. Evaluation of their impact on the reliability parameters (load nodes availability, etc.).

The research has identified

1. The system and equipment failure modes that are relevant to interdependencies and CCF, and their subsequent effects, and

2. The hidden interdependencies and CCFs relevant to control, supervision and protection systems, and to the automatic change-over systems, that have no impact in normal operation, but that can cause relevant out-of-service when the above automatic systems are called to operate under and after fault conditions.

Additionally methods were introduced to include interdependencies and CCFs in the reliability and availability models. The results of the research include a new generalized approach to model the repairable networks for reliability analysis, including Interdependencies/CCFs as a main contributor. The method covers Generalized models for Nodes, Branches and Load nodes; Interdependencies and CCFs on Networks / Components; System Interdependencies/CCFs; Functional Interdependencies/CCFs; Simultaneous and non-simultaneous Interdependencies / CCFs. As an example detailed Interdependency/CCFs analysis and generalized model of an important network structure (a “RING” with load nodes) has been analyzed in detail.

RELIABILITY EVALUATION OF COMMON-CAUSE FAILURES AND OTHER INTERDEPENDENCIES IN LARGE RECONFIGURABLE NETWORKS.

By

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Foreword

The technological systems which supply a service (power, telecom, etc.) to the customers are basically large interconnected networks, organized in several hierarchical levels, with one or more input points and several output points (customers)

The background acquired along many years by the network managers shows that a fault on a single component can sometimes cause an extended out-of-service of an entire part on the network, and therefore the loss of service supply to many customers; typical recent cases have been the power transmission black-outs of New York and of Italy.

The occurrence of Interdependencies and Common Cause Failures (CCFs) is evident in the above cases, because the consequences of a fault on a single component are the out-of-service of many components and the loss of service supply to many users.

The causes of the above mentioned black-outs seem still partially hidden; it is evident that there is need of an effective methodology for the analysis of complex networks, that could take into account not only the out-of-service and disconnection of the faulted components, but also a few basic functionalities that can have impact on interdependencies and CCFs:

- Protections, and their selective operation
- Re-configuration after fault
- Sequential disconnection during the repair times

The long analysis which has been carried out, with a specific focus on the impact of CCFs and interdependencies in large networks, has been an exciting challenge as a starting point to try to solve the above problems. Of course, the analysis had to start from the origins, i.e. a novel approach to the reliability analysis of repairable and re-configurable systems, in order to obtain:

- A new approach to model the repairable networks for reliability analysis, including CCFs as a main contributor
- Detailed interdependencies and CCFs analysis and generalized model of a network structure

Among the questions that needed to be revisited, was: What really is a network?

For the Author, the research has provided the opportunity to re-organize and develop many ideas arising from a working life spent on the design and analysis of large systems.

Summary

The specific objectives of this work are:

1. General methodology to include interdependencies/CCFs in repairable systems
2. A new generalized approach to model the repairable networks for reliability analysis, including Interdependencies/CCFs as a main contributor
3. Detailed Interdependency/CCFs analysis and generalized model of a Power Distribution Load Node
4. Detailed Interdependency/CCFs analysis and generalized model of a network structure: a "RING" with load nodes is analyzed in detail; a generalized model of this classic redundant scheme has not been developed for the time being.

The work is organized as follows:

- General CCFs characteristics and modelization criteria, relevant both to repairable and non repairable systems, are covered in Ch. 1 – Research Background
- Chapters 2 and 3 cover the research issues, objectives and contribution, and the step-by-step sequence to reach the above mentioned objectives
- Chapter 4 describes a new approach to include CCFs in repairable systems (Objective n. 1); main topics (new contributions) are:
  - Distinction between Residence States and Transition States, to define a priori the frame in which CCFs have to be included
  - Ordering of the Transition States, to evaluate separately the CCFs impact
  - Extension to Montecarlo Simulation
- Chapter 5 covers a new approach to networks reliability analysis (Objective N. 2) and to include CCFs; main topics (new contributions) are:

- Generalized models for Nodes, Branches and Load nodes.
- Interdependencies and CCFs on Networks / Components
- System Interdependencies/CCFs
- Functional Interdependencies/CCFs
- Simultaneous and non-simultaneous Interdependencies/CCFs

A detailed analysis, including statistics, of three typical networks is reported in Appendix A)

- Load Nodes are the last sub-systems of the overall network, and they are themselves small networks; Chapter 6 is a detailed analysis of the Load Nodes (Objective n. 3), carried out by means of Montecarlo in accordance with the criteria described at Ch. 5; main topics (new contributions) are:
  - Simultaneous and Non-Simultaneous CCFs: Evaluation of their impact
  - Coupler: Evaluation of the Coupler impact on the overall Load Node reliability
  - Start-Up Time of Already Existing Networks**:** generalized start-up time
  - Control / Protections Systems**:** Evaluation of the impact of their malfunction
  - Load Node Interface with the upper level grid
  - Load Node Equivalent Model: macroblock to be included in network analysis
- The “ring” is a typical upper level network structure; Chapter 7 is covering a detailed analysis of a network composed by a ring and of the interconnection / interdependence with its the load nodes(Objective n. 4), carried out in accordance with the above criteria by means of Montecarlo simulation. Main topics (new contributions) are:

- Detailed Network Analysis, including re-configuration, protections, different failure modes for circuit breakers, system CCFs to reach a comprehensive understanding of the ring performance
- Simplified Mathematical Model, to be used to evaluate reliability parameters even though with a certain margin of uncertainty, but suitable for feasibility studies (compare circuit alternatives etc.) and basic design.

- The last Chapters are covering Accomplishment, Future Contributions and Conclusions.

Dedication

To my wife and my sons.

In memory of “Carlin” Boggia, the first one in our family to design and survey electric networks around the world in the early decades of the past century.

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I wish to express my sincere gratitude to Professor Ali Mosleh for his support and guidance. He helped me so much to clarify many still rough ideas, and he oriented me with top-level knowledge and unbelievable patience to carry out this work.

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- SNE Congo
- Tecnimont / Fiatengineering
- Terna
- Turbomach

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List of Acronyms

CB	Circuit Breaker
CT	Current Transformer
CCF	Common Cause Failure
CTS	Concentratore Telefonia Selettiva (Selective Telephonic Concentrator)
DC	Direct Current
DCL	Double Circuit Line
EHV	Extra High Voltage
F&D	"Frequency and Duration" Reliability Analysis
FT	Fine Tratta (End of the Line)
HV	High Voltage
LAN	Local Area (Computer) Network
MV	Middle Voltage
OF	Optical Fiber
OHTL	Over Head Transmission Line
PRA	Probabilistic Risk Assessment
PT	Potential Transformer
PCM	Pulse Code Modulation
SCL	Single Circuit Line
SPF	Single Point Failure
S/S	Substation
WI FI	Synonym for Wireless LAN
WISP	Wireless Internet Service Providers

1 Research Background

1.1 Importance of Dependence in Reliability and Risk Analysis

(From [11R]) The significant risk contributors are typically found at the interfaces between components, subsystems, systems and the surrounding environment. That is, the risk drivers emerge from aspects in which one portion of the design depends on, or interacts with, another portion, or the surrounding environment. Failures arising from dependencies are often difficult to identify, and if neglected in Risk and Reliability modeling and quantifications, may result in underestimation of risk. A special class of dependent failures is known as **Common Cause Failures (CCF)**, and they are described in the following Chapters.

1.2 Definition and Classification of Dependent Events

(From [11R]) Two events A and B are said to be dependent if

$$\Pr(\mathbf{A} \cap \mathbf{B}) \neq \Pr(\mathbf{A})\Pr(\mathbf{B}).$$

In the presence of dependencies, often, but not always, $\Pr(\mathbf{AB}) > \Pr(\mathbf{A})\Pr(\mathbf{B})$. Therefore, if **A** and **B** represent failure of a function, the actual probability of failure of both will be higher than the expected probability calculated based on the assumption of independence. In cases where a system provides multiple layers of defense against total system or functional failure, ignoring the effects of dependency can result in overestimation of the level of reliability.

Dependencies can be classified in many different ways. A classification, which is useful in relating operational data to reliability characteristics of systems, is presented in the following paragraphs. In this classification dependencies are first categorized based on whether they stem from intended functional and physical characteristics of the system, or are due to external factors and unintended characteristics. Therefore dependence is either ***intrinsic*** or ***extrinsic*** to the system. The definitions and sub-classifications follow. **Intrinsic**. This refers to dependencies where the functional state of one component is affected by the functional state of another. These dependencies normally stem from the way the system is designed to perform its intended function. There are several subclasses of intrinsic dependencies based on the type of influence that components have on each other.

These are:

- **Functional Requirement Dependency**. This refers to the case where the functional status of component **A** determines the functional requirements of component **B**. Possible cases include
  - **B** is not needed when **A** works,
  - **B** is not needed when **A** fails,
  - **B** is needed when **A** works,
  - **B** is needed when **A** fails.

  Functional requirement dependency also includes cases where the load on **B** is increased upon failure of **A**.
- **Functional Input Dependency** (or **Functional Unavailability**). This is the case where the functional status of **B** depends on the functional status of **A**.

An example is the case where A must work for **B** to work. In other words **B** is functionally unavailable as long as **A** is not working. An example is the dependence of a pump on electric power. Loss of electric power makes the pump functionally unavailable. Once electric power becomes available, the pump will also be operable.

- **Cascade Failure**. This refers to the cases where failure of **A** leads to failure of **B**. For example, an over-current failure of a power supply may cause the failure components it feeds. In this case even if the power supply is made operable, the components would still remain inoperable.

Combinations of the above dependencies identify other types of intrinsic dependencies. An example is the ***Shared Equipment Dependency***, when several components are functionally dependent on the same component. For example if both **B** and **C** are functionally dependent on **A**, then **B** and **C** have a shared equipment dependency.

Extrinsic. This refers to dependencies that are not inherent and intended in the designed functional characteristics of the system. Such dependencies are often physically external to the system. Examples of extrinsic dependencies are:

- **Physical/Environmental**. This category includes dependencies due to common environmental factors, including harsh or abnormal environment created by a component. For example, high vibration induced by **A** causes failure of **B**.
- **Human Interactions**. Dependency due to man-machine interaction. An example is failure of multiple components due to the same maintenance error.

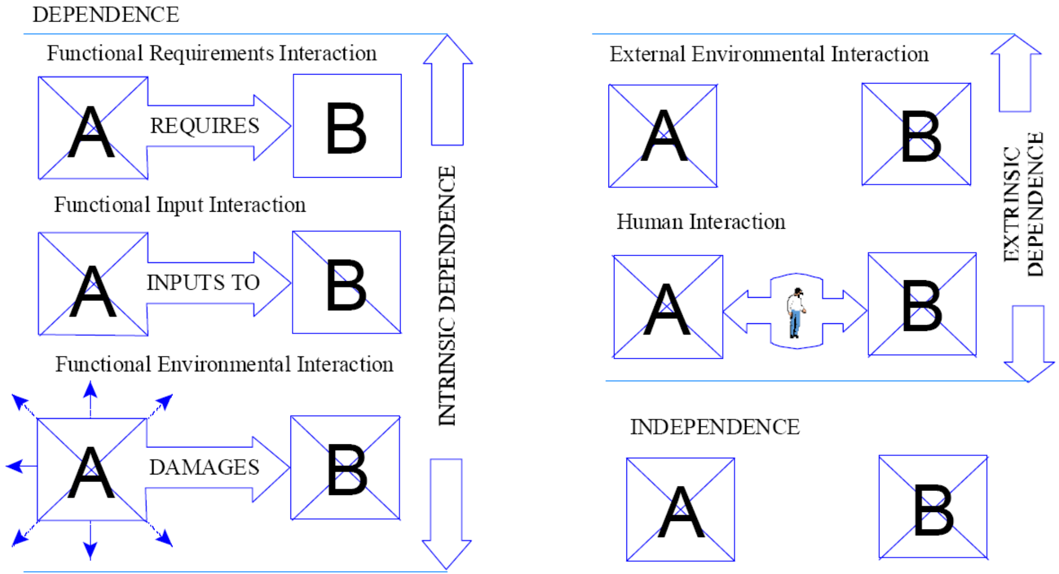


Fig. 1.1 Classification of Sources of Dependency

1.3 Account for Dependencies in Risk and Reliability Analysis

(From [11R]) Risk and Reliability analysts generally try to include the intrinsic dependencies in the basic system logic model (e.g., fault trees). So, for example, functional dependencies arising from the dependence of systems on electric power are included in the logic model by including basic events, which represent component failure modes associated with failures of the electric power supply system. Failures resulting from the failure of another component (cascading or propagating failures) are also often modeled explicitly. Operator failures to respond in the manner called for by the operating procedures are included as branches on the event trees or as basic events on fault trees. Some errors made during maintenance are usually modeled explicitly on fault trees, or they may be included as contributors to overall component failure probabilities.

Extrinsic dependencies can be treated through modeling of the phenomena and the physical processes involved. Examples are the effects of temperature, humidity, vibration, radiation, etc, in the category of Physical/Environmental dependencies. A key feature of the so-called "external events" is the fact that they can introduce dependencies among PRA basic events. Explicit treatment of the external events such as fire etc. may be a significant portion of a PRA study.

The logic model constructed initially has basic events that for a first approximation are considered independent. This step is necessary to enable the analyst to construct manageable models. As such, many extrinsic and some intrinsic dependencies among component failures are typically not accounted for explicitly in the PRA logic models, meaning that some of the corresponding basic events are not actually independent. Dependent failures whose root causes are not explicitly modeled in Risk And Reliability analysis, are known as ***Common Cause Failures*** **(CCF**). This category can be accounted for by introducing ***common cause basic events*** (**CCBE**) in the PRA logic models. A formal definition follows:

A Common Cause Failure event is defined as the failure (or unavailable state) of more than one component due to a shared cause during the system mission.

Viewed in this fashion, CCFs are inseparable from the class of dependent failures and the distinction is mainly based on the level of treatment and choice of modeling approach in reliability analysis.

Components that fail due to a shared cause normally fail in the same functional mode. The term "common mode failure," which was used in the early literature and is still used by some practitioners, is more indicative of the most common symptom of the CCF, i.e., failure of multiple components in the same mode, but it is not a precise term for communicating the important characteristics that describe a CCF event.

The following are some real examples of common cause failure events:

- Hydrazine leaks leading to two APU explosions on STS-9
- Multiple engine failures on aircraft (Fokker F27 -1997, 1988; Boeing 747 -1992)
- Three hydraulic system failure following #2 failure on DC-10, 1989
- All three redundant auxiliary feed-water pumps failed at Three Mile Island nuclear power plant
- Two SSME controllers on two separate engines failed when a wire short
- Failure of two O-rings causing hot gas blow-by in an SRB of Shuttle flight 51L
- Two redundant circuit boards failed due to electro-static shock by technician during replacement of an adjacent unit
- Worker accidentally tripped two redundant pumps by placing a ladder near pump motors to paint the ceiling
- Maintenance contractor unfamiliar with component configuration put lubricant in motor winding of several redundant valves making them inoperable
- Undersized motors purchased from a new vendor caused failure of four redundant cooling fans
- Check valves installed backwards, blocked flow in two redundant lines

Common cause failures may also be viewed as being caused by the presence of two factors: a ***Root Cause***, i.e., the reason (or reasons) for failure of each component failed in the CCF event, and a ***Coupling Factor*** (or factors) which was responsible for the event to involve multiple components. For example failure of two identical redundant electronic devices due to exposure to excessively high temperatures is not only the result of susceptibility of each of the devices to heat (considered to be the root cause in this example), but also a result of both units being identical, and being exposed to the same harsh environment (Coupling Factor). This causal picture of CCF events is depicted in Figure 1.2

Since the use of identical components in redundancy formation is a common strategy to improve system reliability, coupling factors stemming from similarities of the redundant components are often present in such redundant formations, leading to vulnerability to CCF events. CCF events of identical redundant components therefore merit special attention in risk and reliability analysis of such systems.

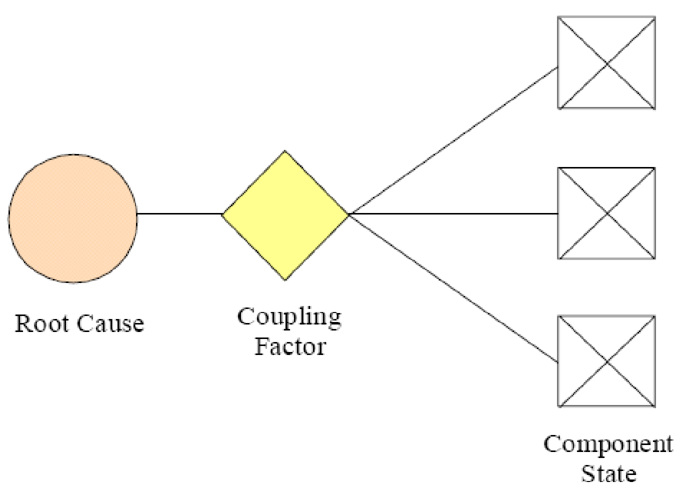


Fig. 1.2 Coupling Factor

1.4 Modeling Dependencies and CCFs in Non-Repairable Systems

(From [11R]) Proper treatment of common cause failures requires identifying those components that are susceptible to CCFs, and accounting for their impact on the system reliability. The oldest and one of the simplest methods for modeling the impact of CCFs is the beta-factor model.

To illustrate the way beta factor treats common cause failures, consider a simple redundancy of two identical components B1 and B2. Each component is further divided into an "independently failing" component, and one that is affected by common cause failures only (see Figure 1-3). It further assumes that

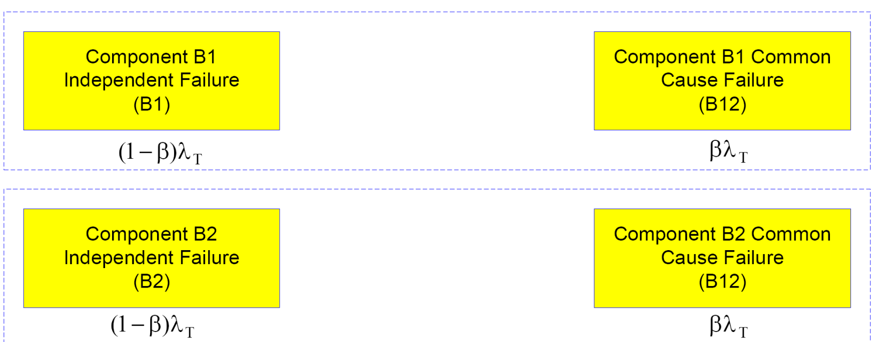
Total component failure frequency = (Independent failure frequency) + (Common cause failure frequency)

A factor, β, is then defined as

$$\beta = \frac{\lambda_C}{\lambda_T}$$

$$\lambda_C = \beta\lambda_T \quad \text{(common cause failure frequency)}$$

$$\lambda_I = (1-\beta)\lambda_T \quad \text{(independent failure frequency)}$$



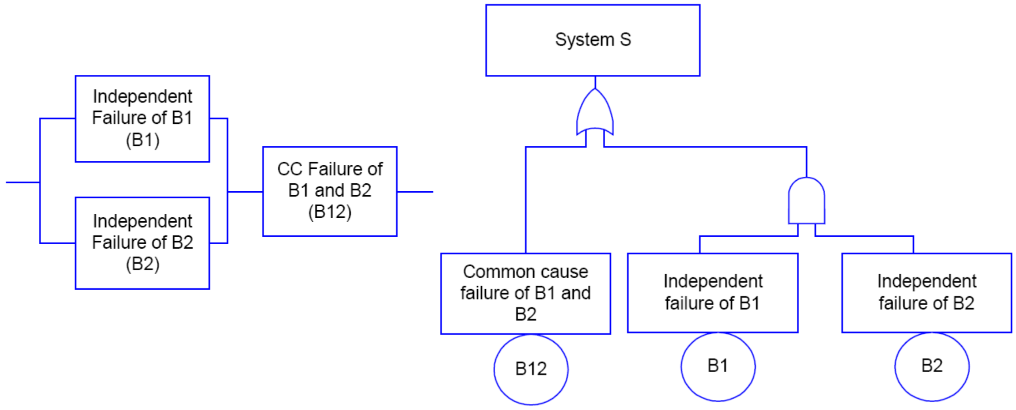


Fig. 1.3 β Factor Fault Tree

Failure probability of the two-unit parallel system of B1 and B2 is then

$$Q_S = (\lambda_I t)^2 + (\lambda_C t) = [(1-\beta)\lambda t]^2 \beta\lambda_T t$$

A point estimate for beta is given by

$$\beta = \frac{2n_2}{n_1 + 2n_2}$$

where:

n1 = Number of independent failures,

n2 = Number of common cause failures

Samples of failure events are then used to obtain values of n1 and n2 for the specific component of interest. The resulting beta factor value, together with the total failure rate, λt, of the identical redundant components, is then used to calculate the reliability of the redundant formation in the presence of CCF events.

Other more advanced models have been developed for Non – Repairable systems, such as Basic Parametric (BP), α model, Multiple Greek Letters (MGL), etc.; a comprehensive treatise is reported in [3R].

1.5 Modeling CCFs and Dependencies in Repairable Systems

The models developed for Non-Repairable Systems, described in the previous Section, are not directly applicable to repairable systems, in fact they do not take into account the repair transitions and rates. Conversely, no specific models have been developed for repairable systems.

A comprehensive survey covering the literature that is available for the time being, led to the following conclusions:

- A repairable system always requires a complex transition model, in which it is possible to include any additional sub-model relevant to CCFs.
- No well-grounded approach exists for CCFs in repairable systems, covering:
  - Real (not simplified) technological systems
  - Large networks

The different impact of CCF on Repairable and Non-Repairable Systems can be summarized as follows:

➢ **Non-Repairable System**

- Mission-specific characteristics: System goal to be reached once on every mission, otherwise the system is lost.
- Typical Reliability Figure: Reliability.
- CCF Impact: Intrinsic/Extrinsic CCF make redundancies useless.
- Example: Rocket with two redundant engines; CCF causes the out-of-service of both of them and mission is aborted.

- **Repairable System**
  - Mission-specific characteristic: Supply of a continuous service to one only user.
  - Typical Reliability Figure: Availability; in case that both the redundant components go out-of-service, there is a temporary service loss.
  - CCF Impact: Intrinsic/Extrinsic CCF make redundancies useless; however, cascade failure has to be very very fast, within the repair time of the first failed component.
  - Example: Pumping system, with two redundant pumps.

1.6 Large Networks Reliability Analysis

The reliability analysis of Power systems networks, as well as of other large networks (telecom, etc) can be carried out by means of analytical methods only if their complexity is limited; the analytical methods are developments of the renewal theory of repairable systems:

- Frequency and Duration (F&D), developed by Ringlee and Wood, and improved by Billinton and Allan
- Tailored Transition Diagrams and Matrices

A previous simplification can be obtained using the "Macrostructures", developed by Birolini at ETH Zürich, which are based too on the renewal theory of repairable systems.

However, the above mentioned methodologies do not allow the analysis of large networks with complex transitions, unless for specific configurations; the following examples can be considered as the upper limits:

- The largest power system analyzed by the Author by means of F&D (Frequency and

Duration) method has been a national power utility in Central Africa; however, in this case the grid configuration was simply a very extended backbone with many power injection points and many load centers, and an extensive use of the "Macrostructures" allowed to simplify so much the reliability model.

- The largest power system analyzed by the Author by means of Transition Matrices is a large power station with different possible configurations; the dimension of the largest transition matrix is 23x23 (including CCFs).

For more complex systems, Montecarlo simulation is mandatory. Application of Montecarlo simulation to large transmission networks started during the decade of 60'; a remarkable contribution has been paid by ENEL (the former Italian Utility), their scientists achieved many international awards (Reggiani – IEEE Award of Excellence, Salvaderi – IEEE Fellowship, etc.). Later, Montecarlo has been adopted by the best specialists in Power systems analysis, such as Billinton, Allan, Li, etc., and all the recent studies in this area have been carried out on the base of this methodology.

Montecarlo Methodologies are:

Simulation approaches:	**Variance Reduction Techniques**:
- State Sampling	- Antithetic Variates
- State Duration Sampling	- Correlated Sampling
- Sequential Sampling	- Control Variates
- State Transition Sampling	- Importance sampling
- Hybrids	- Stratified sampling

1.7 *CCFs and Network Reliability Analysis*

In general, a "network" is an interconnected multi-level set of :

- Nodes: interconnecting points;
- Branches: interconnections.

that provide connection between

- Input
- Users

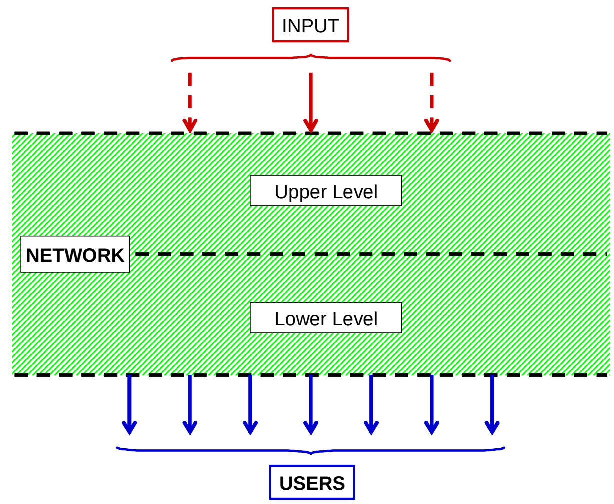


Fig. 1.4 Network Blocks

Large Networks are usually organized in at least 4 levels

- Injection Points, connecting the Input to the network Upper Level
- Network Upper Level : It is usually a meshed network, with intrinsic redundancies, including the several backbones to delivery the service
- Network Lower Level: t is usually a set of non-meshed networks with simple redundancies, connected to the upper level by means of transition nodes
- Load Nodes: They are connected to the lower level, and provide the service to the users.

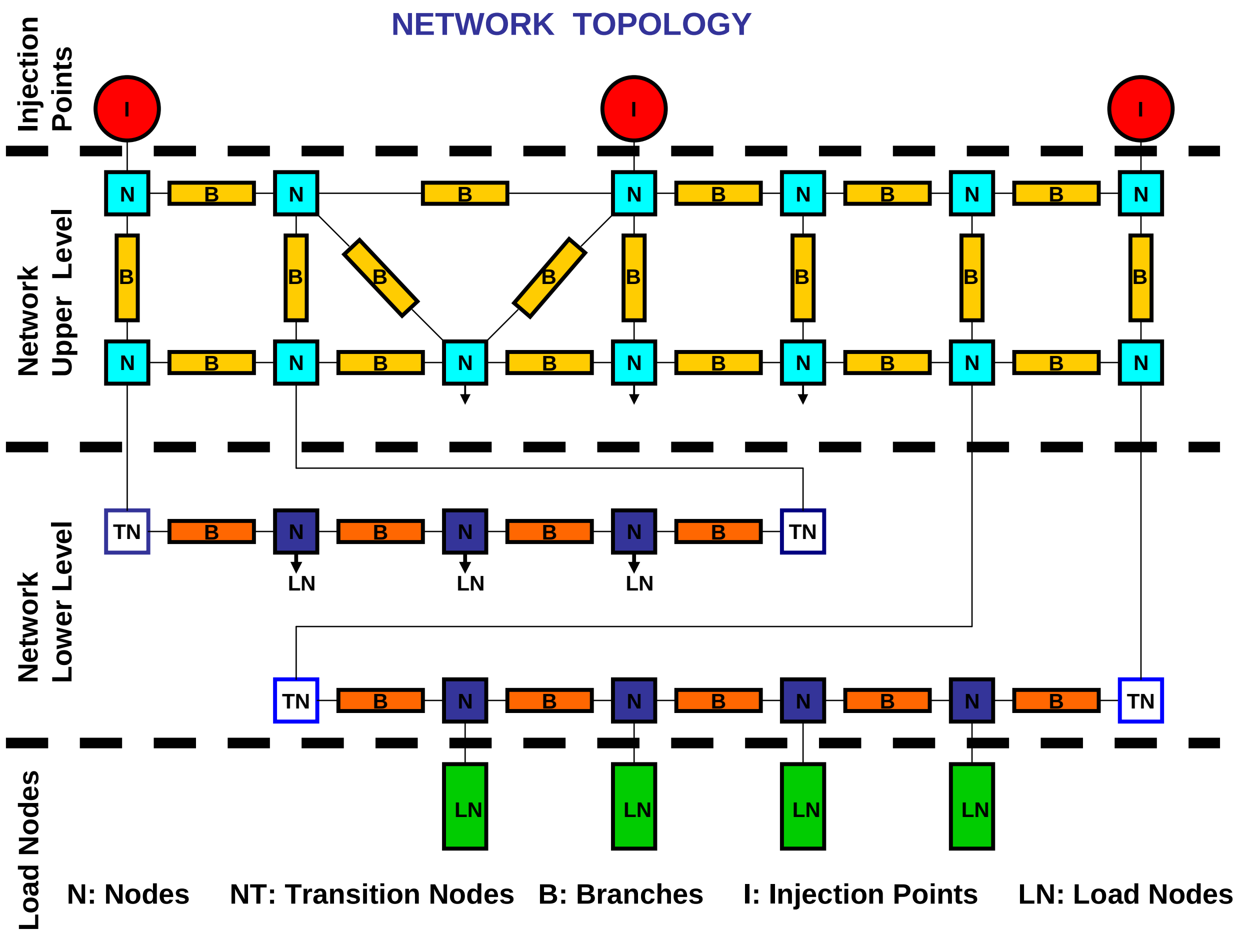


Fig. 1.5 Network Topology

NODES: Interconnecting points of the grid. They can be sub-networks, with internal nodes and branches.
Transition Nodes are specific nodes that provide interconnection between the upper and lower network levels.

BRANCHES: They are the interconnections between the nodes. They usually are a set of series components, such as cables, devices to connect the lines to the nodes, etc.

LOAD NODES: Connections between the Lower Level network and the users. They are themselves networks with internal nodes and branches and re-configuration; they represent the lower level of the overall network, and they are very relevant for the overall network reliability .

INJECTION POINTS: They represent the service supply, that has to be delivered by means of the network.

Differences between Repairable and NON-Repairable Networks:

NON-REPAIRABLE NETWORKS	**REPAIRABLE NETWORKS**
Mission specific characteristics: System goal to be reached once on every mission, otherwise the system is lost.	Mission specific characteristic: Supply of a continuous service to the several Load Nodes. The out-of-service of more load nodes has to be considered a CCF.
Typical Reliability Figure: Reliability.	Typical Reliability Figure: Availability; Loss of supply frequency and duration.
CCF Impact: Intrinsic/Extrinsic CCF make redundancies useless.	CCF Impact: same as for repairable systems.
Network Example: Aerospace on-board telecommunication system	Network Examples: Typical examples are Utilities: • Power Transmission and Distribution Systems • Telecommunication Systems • Gas and Water Utilities • Wi Fi networks Important specific addition: FAULTS PROPAGATION, that cause the extended out-of-service of Load Nodes. Main causes: - Out-of-service of nodes, causing the disconnection of branches and other nodes - Selective operation of the back-up protections, disconnecting up-stream and down-stream nodes/branches in case that the fault has not been cleared at a first attempt.

1.8 Valuable Previous Work

This research is basically an original work, specifically it is not the development / continuation of a previous work by other researchers; its origin are some real problems faced during the analysis of large systems.

Of course, there is an indiscutible background, as follows:

- CCFs: University of Maryland ENRE Department background has been fundamental; and specifically papers and reports by Dr. Mosleh covering CCFs
- Network Montecarlo Simulation: Studies carried out by ENEL (former Italian Utility) Research Center. Main Authors are Reggiani, Salvaderi, Noferi, Paris, Manzoni, Invernizzi, Bertoldi, etc.
- Step-by-step development of reliability analysis of complex systems, by means of macrostructures, etc., to check the congruity of Montecarlo simulation: Former ETH Zurich Reliability Laboratory, directed by Prof. Birolini.
- Cascading Failure Propagation Studies, developed by PSERC (Power Systems Engineering Research Center), mainly covering HV lines overload and consequent failure propagation [23N], [24N].

2 Research Issues, Objectives and Contribution

2.1 Research Issues

In Chapter 1, it has been shown that Interdependencies and CCFs are major causes of networks partial or total out-of-service, therefore they have to be carefully taken into account in network reliability assessment. It is therefore evident the need of a generalized approach to networks reliability, which could specifically consider:

- The overall structure of the network, at its several levels. The focus has to be on the reliability goal, that is to provide through the network a service to the several users downstream of the Load Nodes; in fact, the effect of a failure inside the network can be the simultaneous out-of-service of many Load Nodes, and this consequence has to be considered as a System interdependency.
- The effects of component/equipment interdependencies and CCFs on the network specific characteristics
- The effects of the out-of-service of the networks structure components (Nodes and Branches), that can lead to a simultaneous out-of-service of many end users.

A comprehensive survey of the present practice and of the available literature (see Chapter 10 – Bibliography) led to the conclusion that such a generalized approach has not been proposed for the time being, and this work is an effort to start.

This work is therefore covering the impact of interdependencies and CCFs in large repairable networks.

The large networks considered in this research are "repairable" systems, with possibility of "re-configuration" after a fault and the consequent disconnection of the faulted equipment. Typical networks with these characteristics are the Utilities, e.g.:

- Power Transmission and Distribution Systems
- Telecommunication Systems
- Gas and Water Utilities
- Wi Fi networks

The <u>main issues of the research</u> are:

- Identification of the specific interdependencies and CCFs in large repairable networks
- Evaluation of their impact on the reliability parameters (load nodes availability, etc.)

It has been therefore necessary to analyse:

- The **System and Equipment Failure Modes** that are relevant to interdependencies and CCF, and their **subsequent Effects**
- The **hidden** interdependencies and **CCFs** relevant to control, supervision and protection systems, and to the automatic change-over systems, that have no impact in normal operation, but that can cause relevant out-of-service when the above automatic systems are called to operate under and after fault conditions

Finally, it has been necessary to include interdependencies and CCFs in the reliability / availability models.

2.2 Objectives

The specific objectives of this work are:

1. **General methodology to include interdependencies/CCFs in repairable systems**
2. **A new generalized approach to model the repairable networks for reliability analysis, including Interdependencies/CCFs as a main contributor**
    a. Generalized models for Nodes, Branches and Load nodes.
    b. Interdependencies and CCFs on Networks / Components
    c. System Interdependencies/CCFs
    d. Functional Interdependencies/CCFs
    e. Simultaneous and non-simultaneous Interdependencies/CCFs
3. **Detailed Interdependency/CCFs analysis and generalized model of a Power Distribution Load Node**
4. **Detailed Interdependency/CCFs analysis and generalized model of a network structure: a "RING" with load nodes is analysed in detail; a generalized model of this classic redundant scheme has not been developed for the time being.**

3 Methodology

3.1 Step-by-Step Sequence of Analysis

This work has been carried out in accordance with the following sequence:

1st Step General Methodology to include Interdependency/CCFs in Repairable Systems, starting from transition diagrams and matrices

2nd Step General Models for Reliability Analysis of Large Networks : Load, Branches and Load Nodes.
Analysis of 3 types of networks with different configuration of nodes, branches and load nodes, to assure generalization:

- Power transmission and distribution
- Telecommunication
- Wi Fi

3rd Step CCFs general approach for large networks, including:

- The above general methodology to include CCFs in repairable systems
- The above general models for reliability analysis

4th Step Identification of interdependencies/CCFs, that are specific of networks:

- Equipment CCFs, and impact on nodes, branches and load nodes
- System Interdependencies/CCFs
- Interdependencies/CCFs originated by faults on nodes and branches
- Simultaneous and Non-Simultaneous Interdependencies/CCFs

5th Step Analysis of Interdependencies/CCFs Stastistics, to validate the models

- High Voltage Transmission Statistics
- Wi Fi amateur network statistics

6th Step Identification of the reference network: a two-levels power system network.

- HV network: a HV ring, open in an intermediate point, and re-configurable after fault
- Load Nodes: HV/MV Substations, with two MV bus-bars interconnected by a normally open tie breaker

7th Step Detailed analysis and generalized model of the Load Nodes, by means of Montecarlo Simulation

8th Step Detailed analysis and generalized model of the ring, including the generalized model of the Load Nodes, by means of Montecarlo simulation

3.2 Montecarlo S imulation

Montecarlo simulation techniques has been extensively used for the reliability evaluation.

Two main techniques are usually adopted for large systems:

State Duration Sampling	-	Proved very effective
Random Walk	-	Proved very difficult

The Montecarlo Simulation approach has been as follows:

- A relevant effort has been made to develop a simulation procedure suitable to obtain
  - A sound results interpretation
  - A reliable validation of the calculation results

  The procedure to reach the above objectives is described in Ch. 6.7
- Conversely, no specific techniques to optimize simulation have been adopted, e.g. for computing time limitation, variance reduction, etc; it has been a choice to have as far as possible a easily readable computer program, to facilitate the results interpretation. In other words, the Author preferred to privilege the technical application of Montecarlo simulation instead of to optimize the simulation efficiency.

3.3 Reference Network

The reference network is reported here below; it is a typical High Voltage sub-transmission system fed from two injection points, with a HV Ring feeding many Load Nodes (Sub-Stations).

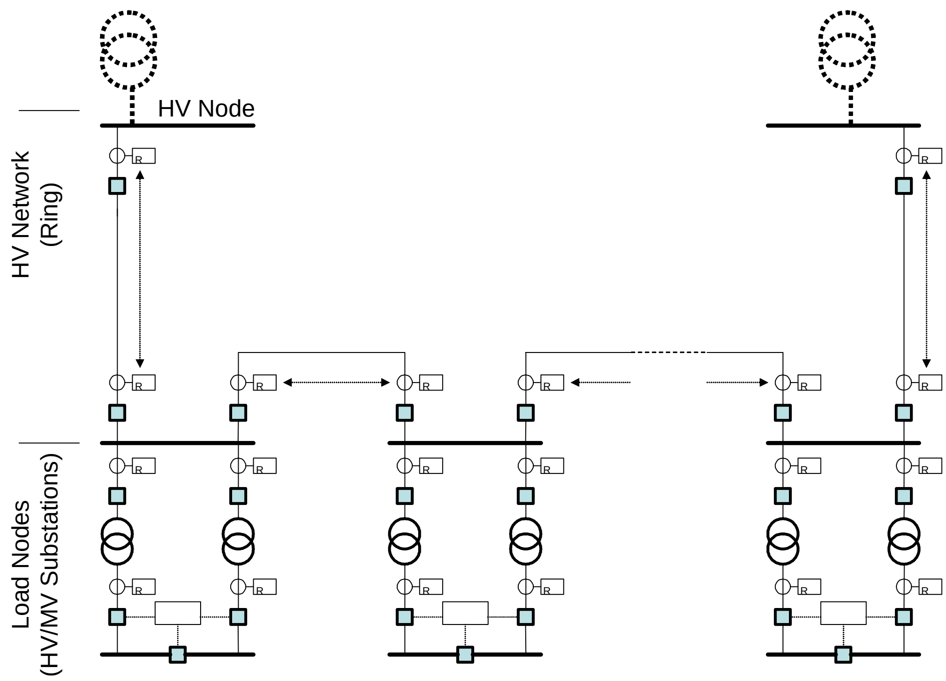


Fig. 3.1 Reference Network

4 1st Objective: CCFs Analysis in Repairable Systems – Proposed Methodology

4.1 *1st Objective - Summary*

What Is Not Necessary:

- A specific math model. Both the Markovian transition diagrams and the Montecarlo simulation can properly model any CCF in repairable systems.
- An "extension" of the system transitions, to take into account CCFs: every system has a limited quantity of out-of-service modes, and CCFs are not increasing them.

What Is Important : A proper methodology:

- To take into account the limited quantity of out-of-service modes, and to include CCFs in this frame
- To easily identify and evaluate the impact of CCs, i.e. the system reliability parameters with and without CCFs

New Contribution: Methodology:

- Distinction between Residence States and Transition States, to define a priori the frame in which CCFs have to be included
- Ordering of the Transition States, to evaluate separately the CCFs impact
- Extension to Montecarlo Simulation

4.2 Generalized Criteria to Include Interdependencies and CCFs in Repairable Systems

The repairable systems have to take into account renewal sequences with failure and repair times, and they can be modeled by:

- Markov processes for limited systems
- Montecarlo simulation for real systems.

In both cases, it is possible to include interdependencies and CCFs within the fault/repair sequences without limitations; specific interdependencies and CCFs models are not required, and conversely they could limit the analysis.

However, a generalized criteria to include Interdependencies and CCFs in repairable systems is necessary; it will be developed first for simple repairable systems by means of Markov processes, then, on the base of the acquired background, it will be **extended to Montecarlo simulation for large systems.**

The impact of Interdependencies and CCFs on the transition diagrams and matrices relevant to Markov models of Repairable Systems is as follows:

The Transition Diagrams relevant to the Markov Processes include:

- Transition States: Transient system configurations, that take into account the up-down states of the components, their interactions, and specific failure-repair transitions
- Residence states: Cumulative states that include one or more of the above defined Transition States, with the same output parameter that is relevant for the reliability goal (e.g. the cumulative output power of a power station with many generating sets).

Interdependencies and CCFs

Add	• New Transition States, included into the Residence States • New Transitions between Residence States, due to the new transition states
Do not add	• New Residence States

Proposed Methodology:

1st Step
- Definition "A Priori" of the Residence States of the repairable system
- Identification of the interdependencies and CCFs, and their Transition States included into the Residence States

2nd Step Ordering the Transition States: the ones relevant to CCFs are with progressive number after the ones without CCFs; finally, there are two areas:
- An internal area, without CCFs
- A peripheral area, with CCFs

3rd Step Solution of the Transition Matrix by means of numerical methods.

Remark on 3rd Step – Numerical Methods: In order to reach a satisfactory precision, it is recommended to adopt standard numerical methods for the solution of the system of linear equations, such as Gauss-Seidel and Newton-Raphsom. In case that a method with matrix inversion had to be used, it is common practice to adopt standard numerical methods for the inversion too, because the transition matrices are including so many "zeros"; the standard Matlab instruction Y=inv(X) is working with numerical methods, and it is actually effective; another alternative can be the Modified Gauss-Giordan Elimination method proposed by matrixlab-examples.com.

Extension to Montecarlo simulation will be carried out with the same methodology:

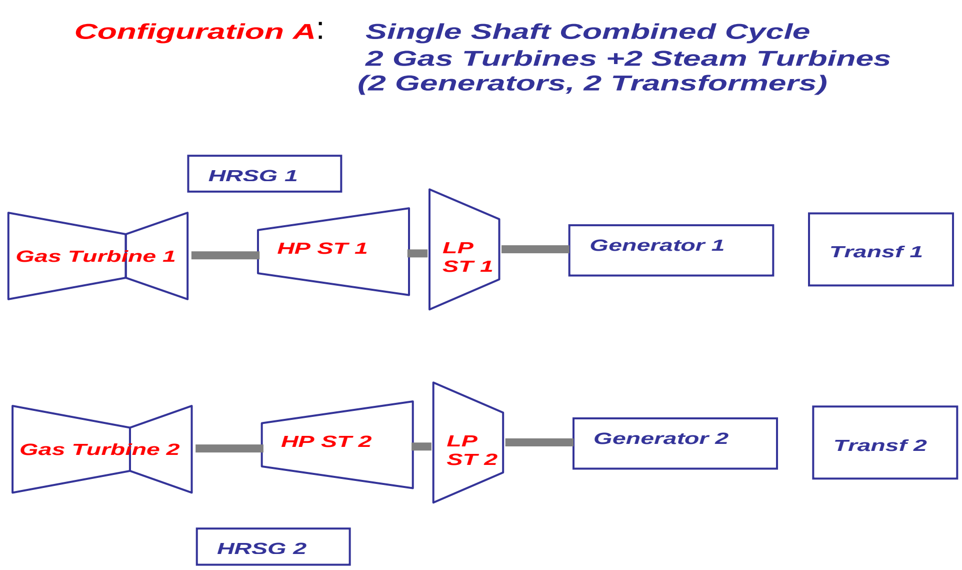
- A priori identification of the Residence States
- Identification of interdependencies and CCFs
- Development of interdependencies and CCFs models and transitions
- Interdependencies and CCFs transition states ordering, in order to evaluate reliability parameters <u>with</u> and <u>without</u> CCFs

4.3 Example – Power Plant Configuration Alternatives and CCFs

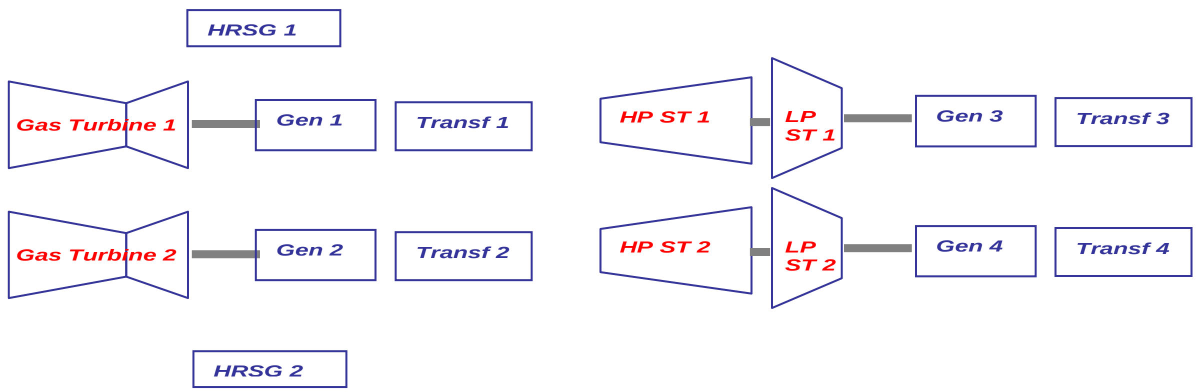
4.3.1 Scope

The objective of this analysis is the comparison of three Combined Cycle (the gas turbine exhaust is used to produce steam) Power Plant Configuration Alternatives A), B) and C), referred to the following parameters:

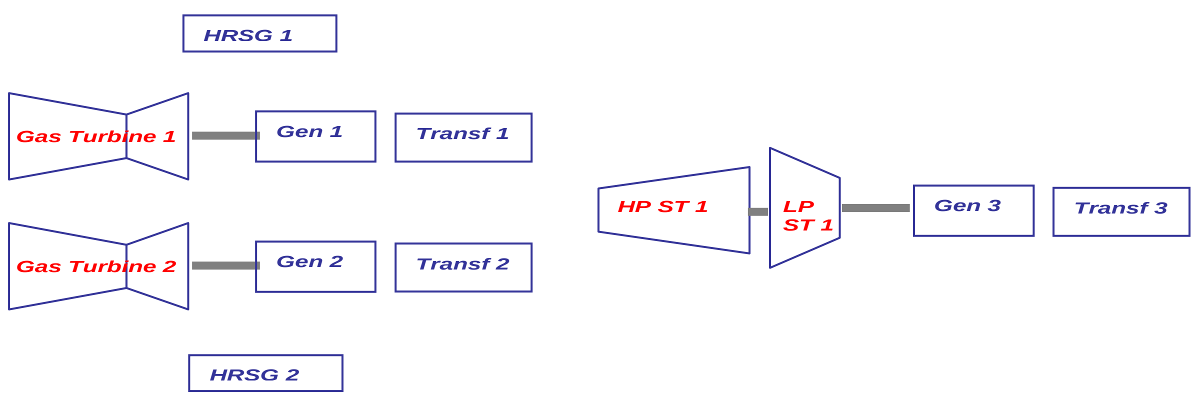
- Power Plant probabilistic evaluation of the average power delivery,
- Quality of the power delivery, i.e. frequency and duration of the faulted conditions



Configuration B: **Multi Shaft Combined Cycle**
2 Gas Turbines +2 Steam Turbines
(4 Generators, 4 Transformers)



Configuration C: **Multi Shaft Combined Cycle**
2 Gas Turbines +1 Steam Turbine
(3 Generators, 3 Transformers)



4.3.2 Steps of the Analysis

- Definition of the Reliability/Availability Indices
- Simplified model of the Generating Sets
- Reliability/Availability data of the generating sets
- Transition Diagrams and Matrices, and power delivery probabilistic evaluation
- Frequency and Duration assessment of out-of-service conditions

4.3.3 Reliability Parameters

The main characteristic of the power station, relevant for a reliability/availability analysis is that it is a set of generating units which can be out-of-service either one by one, or more than one simultaneously.

In this case, the reliability/availability analysis of the three alternatives has to take into account the following parameters, which represent the reliability/availability indices:

- **<u>Average Power Delivery</u>**: It is the weighed mean of the products of the power delivery of each generating state, and the probability of the system to reside in this state, referred to the overall power plant capacity.

$$PE = [(\sum_{i=1}^{n} p_i P_i) / PT]x100$$

where:

PE: Average Power Delivery

PT: Power Plant Rated Power (450 MW)

i: Partial Production Generating States (150 MW, 300 MW, etc)

P_i: Probability of the system to reside in State i

p_i: Power Production at State i (150 MW, 300 MW, etc)

The P_i Probabilities are the ones included in the asymptotic transition matrix; they represent the asymptotic probabilities of the system to reside into the several states.

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -B_1 & \rho_{2,1} & .... & .... & \rho_{n,1} \\ \rho_{1,2} & -B_2 & .... & .... & .... \\ .... & .... & -B_i & .... & .... \\ .... & .... & .... & -B_i & .... \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ ... \\ ... \\ P_n \end{bmatrix}$$

- **Frequency and Duration of System Residence into the "i" States**: This index represent the quality of the power delivery

4.3.4 Simplified Model of the Generating Sets

An exhaustive FMEA allowed us to identify in advance the critical points and the Common Cause Failures (CCF):

- Common Auxiliary Services (Compressed Air, A.C. Power Supply, etc)
- Common Lubricating Oip Circuits
- Common Control and Instrumentation Equipment, etc.

and to adopt suitable preventive measures; it is therefore reasonable to consider that, for sake of comparison of the power plant configuration alternatives, the generating sets can be considered as "blocks" with specified reliability data. In addition to the generating sets blocks, the following blocks relevant to the connection to the HV Substation, have to be considered:

- Step-Up Transformers
- HV Circuit Breakers

The above equipment will be considered "in series" to the generating sets, because their out-of-service will cause the out-of-service of the relevant generating sets.

For all the equipment (generating sets, step-up transformers and HV circuit breakers) it has been assumed that the failure and repair probability density functions will have exponential distribution; this assumption is usual in power systems reliability analysis, and it is recommended by many reliability standards and tutorials.

The overall failure and repair rates of the generating sets can be then evaluated by means of the macrostructures, for series components as follows:

$$\lambda_s = \Sigma \lambda_i$$

$$\mu_s = (\Sigma \lambda_i) / (\Sigma \lambda_i/\mu_i)$$

In addition to the generating sets failures, it is necessary to take into account the impact of the Common Cause Failures (CCF); they have been considered as equivalent cumulative blocks, and included in the transition diagrams.

Furthermore, it is important to highlight that the reliability blocks reported in this work, and specifically the generating sets availabilities, do not take into account forced outages due to preventive maintenance; the reason is that preventive maintenance has a non-negligible impact on the overall availability, but it a “superposed” activity and therefore it has actually no impact on the choice of the optimal power plant configuration.

4.3.5 Sequence to Include CCFs

The sequence is in accordance with the General Methodology proposed in Ch. 4.2, as follows:

1st Step
- Definition of the Residence States : They are the Partial Production Generating States defined in Ch. 4.2.3, and they are indicated in the following transition diagrams
- Identification of Interdependencies and CCFs: An exhaustive FMEA with specific focus on CCFs has been carried out.

2nd Step The Transition Matrices have been ordered in such a way that CCFs fall in an external area; this configuration leads to two sets of equation, with/without CCFs; the separation of the two areas is evident in the following transition matrices.

3rd Step The linear system of equations has been solved by means of numerical methods embedded in MathCad

4.3.6 Transition Diagrams and Transition Matrices

They are reported in the following pages, for the three A), B) and C) Power Plant Configurations.

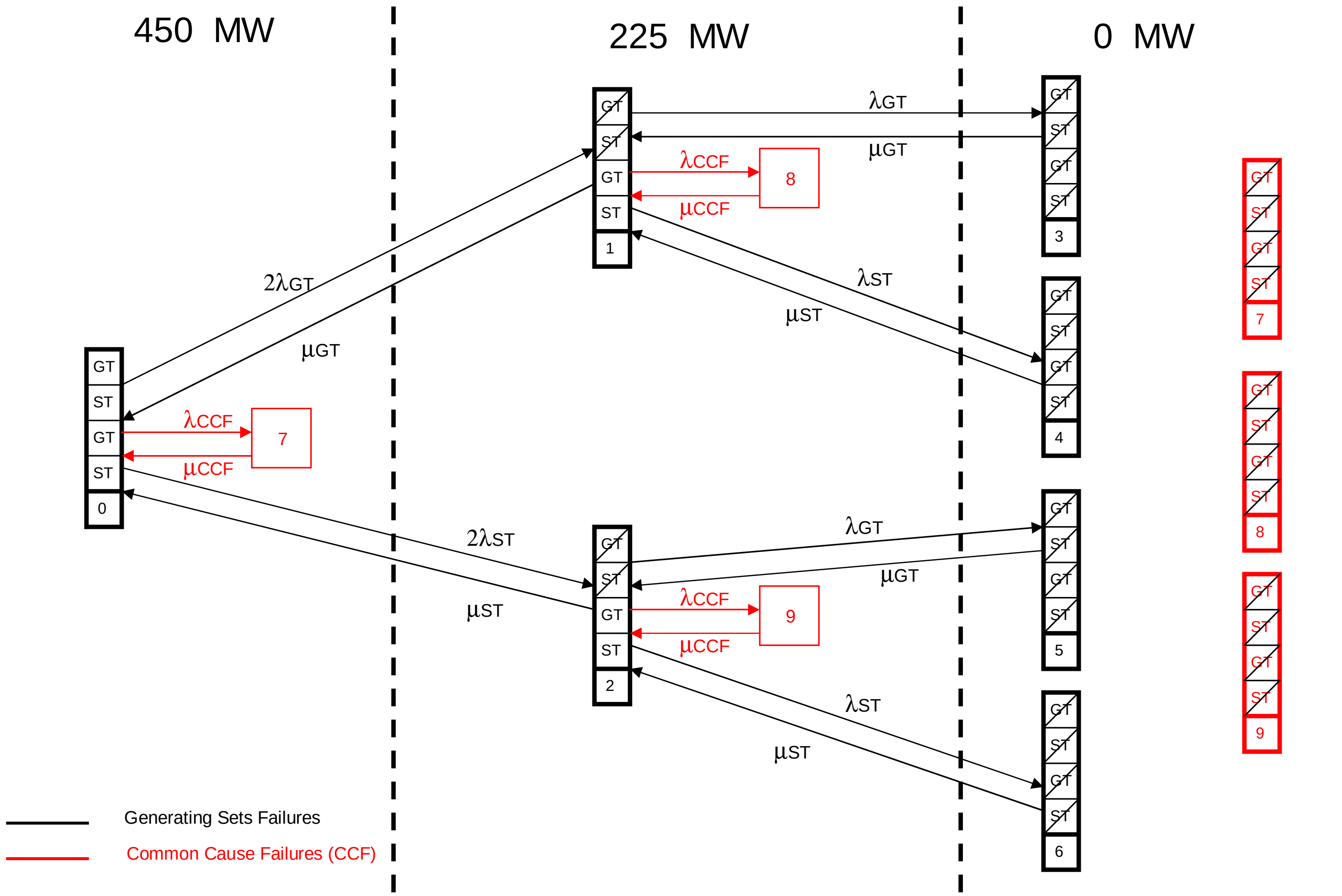
The evaluation of the reliability parameters, both with and without CCFs, is reported for Configuration A), to make an example.

4.4 <u>1st Objective - Conclusion</u>

The above methodology has been tested in some studies (e.g. the example reported at Ch. 4.3) and led to satisfactory results:

- The transition diagrams and the relevant matrices have been developed within the frame of the real “residence states”, therefore the failure states transitions are representing the real system dynamic performance.

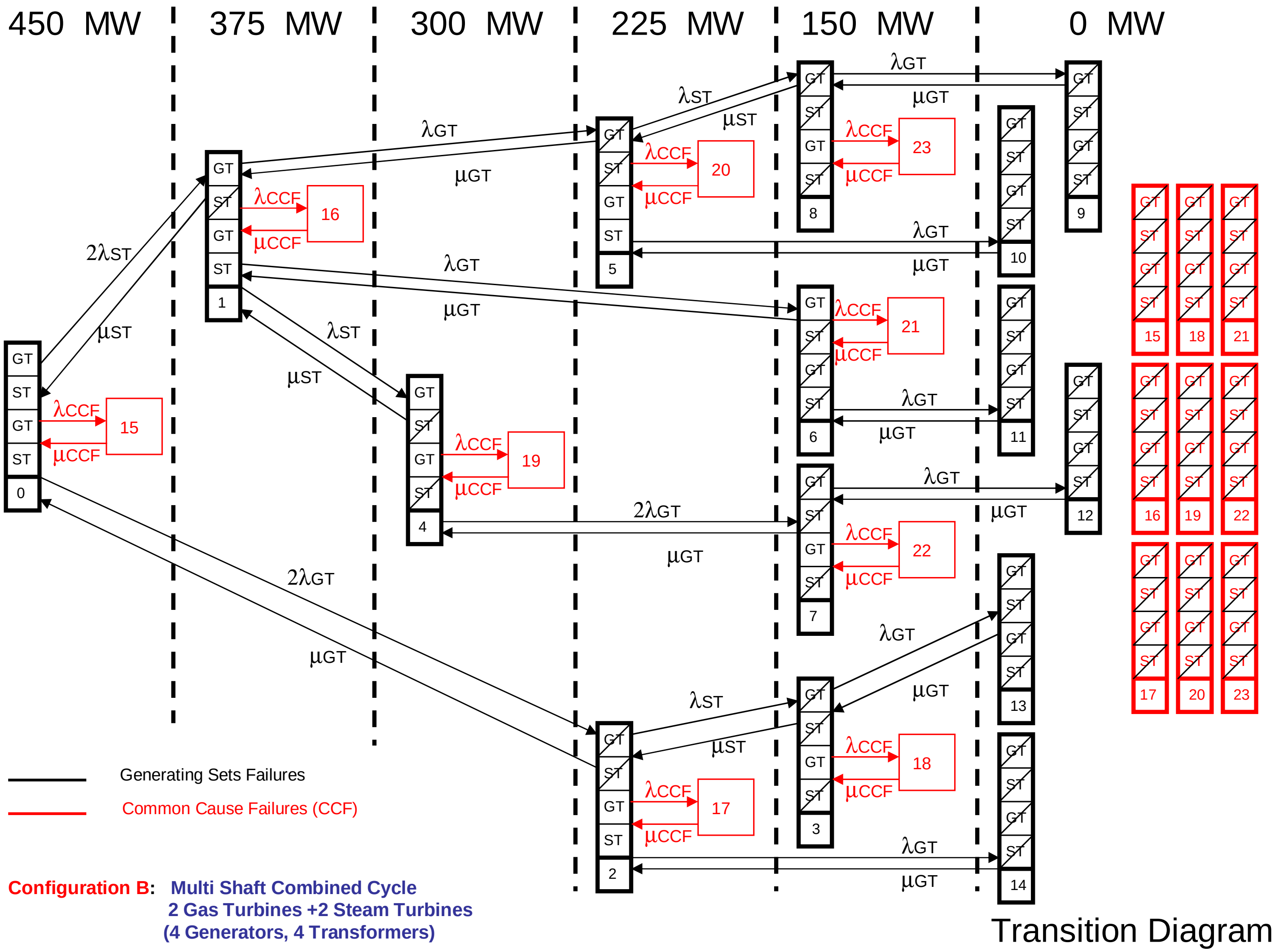
- The addition of the CCFs within the frame of the “residence states” proved easy and clear.
- The calculation of the linear systems relevant to the transition matrices led to correct results, because the a.m. linear systems proved not complex even though the transition matrices are large and sparse.



Configuration A: **Single Shaft Combined Cycle**
2 Gas Turbines +2 Steam Turbines
(2 Generators, 2 Transformers

Transition Diagram

	0	1	2	3	4	5	6	7	8	9
0	-(2λGT+ 2λST +λCCF)	2λGT	2λST	-	-	-	-	λCCF	-	-
1	μGT	-(λGT+ λST+ μGT+λCCF	-	λGT	λST	-	-	-	λCCF	-
2	μST	-	-(λGT+ λST+ μST+λCCF	-	-	λGT	λST	-	-	λCCF
3	-	μGT	-	- μGT	-	-	-	-	-	-
4	-	μST	-	-	- μST	-	-	-	-	-
5	-	-	μGT	-	-	- μGT		-	-	-
6	-	-	μST	-	-	-	- μST	-	-	-
7	μCCF	-	-	-	-	-	-	-μCCF	-	-
8	-	μCCF	-	-	-	-	-	-	-μCCF	-
9	-	-	μCCF	-	-	-	-	-	-	-μCCF


450 MW
375 MW
300 MW
225 MW
150 MW
0 MW
λGT
μGT
λST
μST
2λST
2λGT
λCCF
μCCF
GT
ST
0
1
2
3
4
5
6
7
8
9
10
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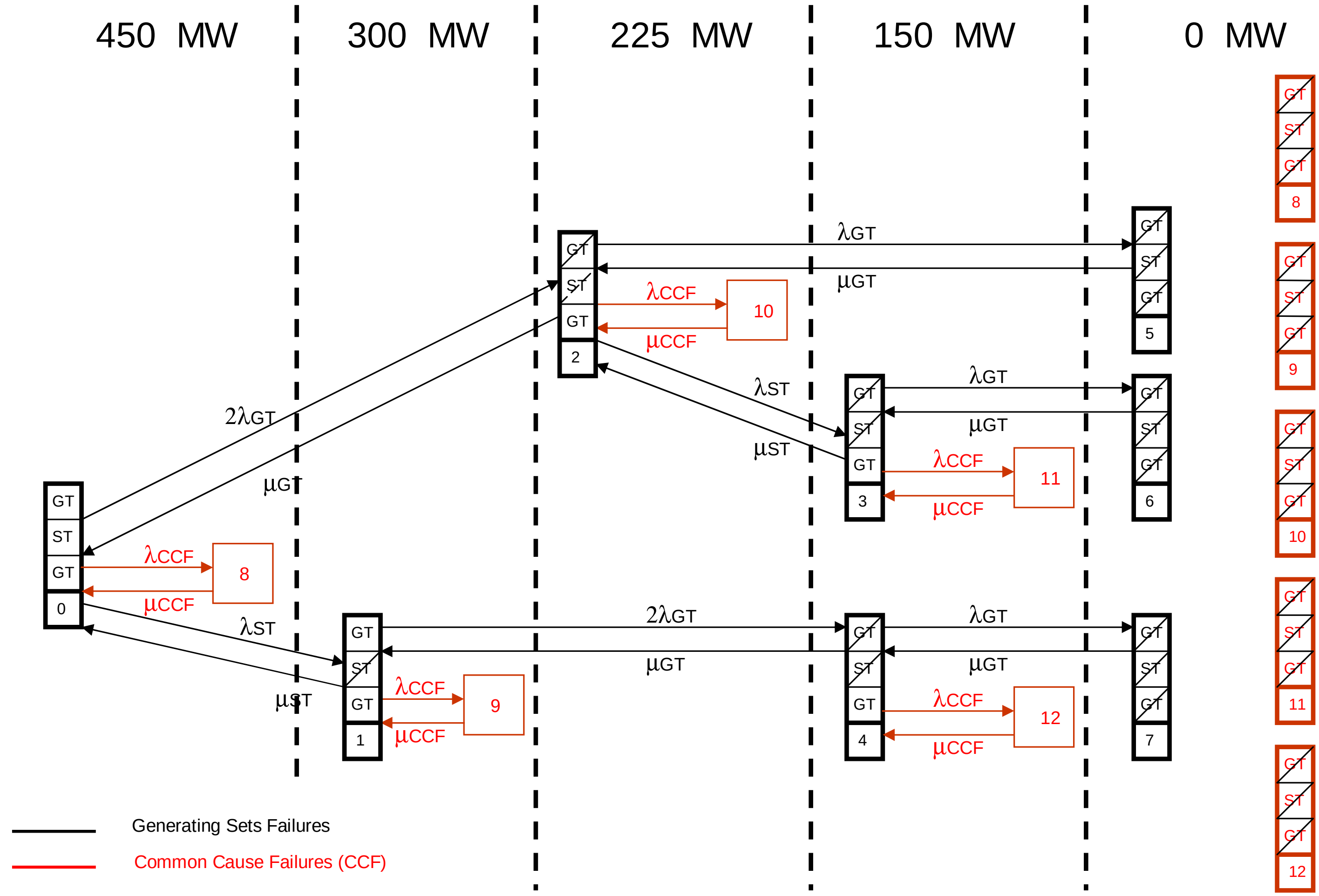
Generating Sets Failures
Common Cause Failures (CCF)
Configuration B: Multi Shaft Combined Cycle
2 Gas Turbines +2 Steam Turbines
(4 Generators, 4 Transformers)
Transition Diagram

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	-(2λGT+ 2λST+ λCCF)	2λST	2λGT	-	-	-	-	-	-	-	-	-	-	-	-	λCCF	-	-	-	-	-	-	-	-
1	μST	-(2λGT+ λST+μST+ λCCF)	-	-	λST	λGT	λGT	-	-	-	-	-	-	-	-	-	λCCF	-	-	-	-	-	-	-
2	μGT	-	-(λGT+ λST+μGT+ λCCF)	λST	-	-	-	-	-	-	-	-	-	-	λGT	-	-	λCCF	-	-	-	-	-	-
3	-	-	μST	-(λGT+ μST+ λCCF)	-	-	-	-	-	-	-	-	-	λGT	-	-	-	-	λCCF	-	-	-	-	-
4	-	μST	-	-	-(2λGT+ μST+ λCCF)	--	-	2λGT	-	-	-	-	-	-	-	-	-	-	-	λCCF	-	-	-	-
5	-	μGT	-	-	-	-(λGT+ λST+μGT+ λCCF)	-	-	λST	-	λGT	-	-	-	-	-	-	-	-	-	λCCF	-	-	-
6	-	μGT	-	-	-	-	-(λGT+ μGT+ λCCF)	-	-	-	-	λGT	-	-	-	-	-	-	-	-	-	λCCF	-	-
7	-	-	-	-	μGT	-	-	-(λGT+ μGT+ λCCF)	-	-	-	-	λGT	-	-	-	-	-	-	-	-	-	λCCF	-
8	-	-	-	-	-	μST	-	-	-(λGT+ μST+ λCCF)	λGT	-	-	-	-	-	-	-	-	-	-	-	-	-	λCCF
9	-	-	-	-	-	-	-	-	μGT	-μGT	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	μGT	-	-	-	-	-μGT	-	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	μGT	-	-	-	-	-μGT	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-		μGT	-	-	-	-	-μGT	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	μGT	-	-	-	-	-	-	-	-	-	-μGT	-	-	-	-	-	-	-	-	-	-
14	-	-	μGT	-	-	-	-	-	-	-	-	-	-		-μGT	-	-	-	-	-	-	-	-	-
15	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-	-	-	-	-	-
16	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-	-	-	-	-
17	-	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-	-	-	-
18	-	-		μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-	-	-
19	-	-	-	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-	-
20	-	-	-	-	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-	-
21	-	-	-	-	-	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-	-
22	-	-	-	-	-	-	-	μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF	-
23	-	-	-	-	-	-	-		μCCF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-μCCF



Configuration C: **Multi Shaft Combined Cycle**
2 Gas Turbines +1 Steam Turbine
(3 Generators, 3 Transformers

Transition Diagram

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	-(2λGT+ λST+λCCF)	λST	2λGT	-	-	-	-	-	λCCF	-	-	-	-
1	μST	-(2λGT+ μST+λCCF)	-	-	2λGT	-	-	-	-	λCCF	-	-	-
2	μGT	-	-(λGT+ λST+ μGT+λCCF)	λST	-	λGT	-	-	-	-	λCCF	-	-
3	-	-	μST	-(λGT+ μST+λCCF)	-	-	λGT	-	-	-	-	λCCF	-
4	-	μGT	-	-	-(λGT+ μGT+λCCF)	-	-	λGT	-	-	-	-	λCCF
5	-	-	μGT	-	-	- μGT	-	-	-	-	-	-	-
6	-	-	-	μGT	-	-	- μGT	-	-	-	-	-	-
7	-	-	-	-	μGT	-	-	- μGT	-	-	-	-	-
8	μCCF	-	-	-	-	-	-	-	-μCCF	-	-	-	-
9	-	μCCF	-	-	-	-	-	-	-	-μCCF	-	-	-
10	-	-	μCCF	-	-	-	-	-	-	-	-μCCF	-	-
11	-	-	-	μCCF	-	-	-	-	-	-	-	-μCCF	-
12	-	-	-	-	μCCF	-	-	-	-	-	-	-	-μCCF

FAILURE AND REPAIR RATES

Gas Generating Set

$\lambda GTa := 700 \cdot 10^{-6}$ h-1 MTTRGTa := 30 h $\mu GTa := \frac{1}{MTTRGTa}$ $\mu GTa = 0.033$ h-1

Steam Generating Set

$\lambda STa := 460 \cdot 10^{-6}$ h-1 MTTRSTa := 72 h $\mu STa := \frac{1}{MTTRSTa}$ $\mu STa = 0.014$ h-1

HV Circuit Breaker

$\lambda CBy := 0.0067$ Failure/y $\lambda CB := \frac{\lambda CBy}{8760}$ $\lambda CB = 7.648 \times 10^{-7}$ h-1

MTTRCB := 2 h $\mu CB := \frac{1}{MTTRCB}$ $\mu CB = 0.5$ h-1

Step-Up Transformer

$\lambda Ty := 0.02$ Failure/y $\lambda T := \frac{\lambda Ty}{8760}$ $\lambda T = 2.283 \times 10^{-6}$ h-1

MTTRT := 3000 h $\mu T := \frac{1}{MTTRT}$ $\mu T = 3.333 \times 10^{-4}$ h-1

Overall Failure Rates

$\lambda GT := \lambda GTa + \lambda CB + \lambda T$ $\lambda GT = 7.03 \times 10^{-4}$ h-1

$$\mu GT := \frac{\lambda GTa + \lambda CB + \lambda T}{\left(\frac{\lambda GTa}{\mu GTa}\right) + \left(\frac{\lambda CB}{\mu CB}\right) + \left(\frac{\lambda T}{\mu T}\right)}$$

$\mu GT = 0.025$ h-1 $MTTRGTT := \frac{1}{\mu GT}$

MTTRGTT = 39.614 h

$\lambda ST := \lambda STa + \lambda CB + \lambda T$ $\lambda ST = 4.63 \times 10^{-4}$ h-1

$$\mu ST := \frac{\lambda STa + \lambda CB + \lambda T}{\left(\frac{\lambda STa}{\mu STa}\right) + \left(\frac{\lambda CB}{\mu CB}\right) + \left(\frac{\lambda T}{\mu T}\right)}$$

$\mu ST = 0.012$ h-1 $MTTRST := \frac{1}{\mu ST}$

MTTRST = 86.321 h

Without CCFs

Configuration A: **Single Shaft Combined Cycle**
2 Gas Turbines +2 Steam Turbines
(2 Generators, 2 Transformers)

Initial Conditions

$P0 := 1 \quad P1 := 0 \quad P2 := 0 \quad P3 := 0 \quad P4 := 0 \quad P5 := 0 \quad P6 := 0$

Given

$$-(2\cdot\lambda GT + 2\cdot\lambda ST)\cdot P0 + \mu GT\cdot P1 + \mu ST\cdot P2 = 0$$

$$2\cdot\lambda GT\cdot P0 - (\lambda GT + \lambda ST + \mu GT)\cdot P1 + \mu GT\cdot P3 + \mu ST\cdot P4 = 0$$

$$2\cdot\lambda ST\cdot P0 - (\lambda GT + \lambda ST + \mu ST)\cdot P2 + \mu GT\cdot P5 + \mu ST\cdot P6 = 0$$

$$\lambda GT\cdot P1 - \mu GT\cdot P3 = 0$$

$$\lambda ST\cdot P1 - \mu ST\cdot P4 = 0$$

$$\lambda GT\cdot P2 - \mu GT\cdot P5 = 0$$

$$\lambda ST\cdot P2 - \mu ST\cdot P6 = 0$$

$$P0 + P1 + P2 + P3 + P4 + P5 + P6 = 1$$

$$\begin{pmatrix} PP0 \\ PP1 \\ PP2 \\ PP3 \\ PP4 \\ PP5 \\ PP6 \end{pmatrix} := \mathrm{Find}(P0, P1, P2, P3, P4, P5, P6) \qquad \begin{pmatrix} PP0 \\ PP1 \\ PP2 \\ PP3 \\ PP4 \\ PP5 \\ PP6 \end{pmatrix} = \begin{pmatrix} 0.87348 \\ 0.04865 \\ 0.06983 \\ 1.35507\times 10^{-3} \\ 1.94476\times 10^{-3} \\ 1.94476\times 10^{-3} \\ 2.79107\times 10^{-3} \end{pmatrix}$$

$PE := PP0\cdot 450 + (PP1 + PP2)\cdot 225 \qquad PE = 419.725 \text{ MW} \qquad \frac{PE\cdot 100}{450} = 93.272 \quad \%$

With CCFs

Configuration A: **Single Shaft Combined Cycle**
2 Gas Turbines +2 Steam Turbines
(2 Generators, 2 Transformers)

Initial Conditions

$P0 := 1 \quad P1 := 0 \quad P2 := 0 \quad P3 := 0 \quad P4 := 0 \quad P5 := 0 \quad P6 := 0 \quad P7 := 0$

$P8 := 0 \quad P9 := 0$

Given

$$-(2\cdot\lambda GT + 2\cdot\lambda ST + \lambda CCF)\cdot P0 + \mu GT\cdot P1 + \mu ST\cdot P2 + \mu CCF\cdot P7 = 0$$

$$2\cdot\lambda GT\cdot P0 - (\lambda GT + \lambda ST + \mu GT + \lambda CCF)\cdot P1 + \mu GT\cdot P3 + \mu ST\cdot P4 + \mu CCF\cdot P8 = 0$$

$$2\cdot\lambda ST\cdot P0 - (\lambda GT + \lambda ST + \mu ST + \lambda CCF)\cdot P2 + \mu GT\cdot P5 + \mu ST\cdot P6 + \mu CCF\cdot P9 = 0$$

$$\lambda GT\cdot P1 - \mu GT\cdot P3 = 0$$

$$\lambda ST\cdot P1 - \mu ST\cdot P4 = 0$$

$$\lambda GT\cdot P2 - \mu GT\cdot P5 = 0$$

$$\lambda ST\cdot P2 - \mu ST\cdot P6 = 0$$

$$\lambda CCF\cdot P0 - \mu CCF\cdot P7 = 0$$

$$\lambda CCF\cdot P1 - \mu CCF\cdot P8 = 0$$

$$P0 + P1 + P2 + P3 + P4 + P5 + P6 + P7 + P8 + P9 = 1$$

$$\begin{pmatrix} PP0 \\ PP1 \\ PP2 \\ PP3 \\ PP4 \\ PP5 \\ PP6 \\ PP7 \\ PP8 \\ PP9 \end{pmatrix} := \mathrm{Find}(P0, P1, P2, P3, P4, P5, P6, P7, P8, P9)$$

$$\begin{pmatrix} PP0 \\ PP1 \\ PP2 \\ PP3 \\ PP4 \\ PP5 \\ PP6 \\ PP7 \\ PP8 \\ PP9 \end{pmatrix} =$$

	0
0	0.87089
1	0.04851
2	0.06962
3	$1.35105\cdot10^{-3}$
4	$1.93899\cdot10^{-3}$
5	$1.93899\cdot10^{-3}$
6	$2.78279\cdot10^{-3}$
7	$2.61267\cdot10^{-3}$
8	$1.4553\cdot10^{-4}$
9	$2.08861\cdot10^{-4}$

$PE := PP0\cdot450 + (PP1 + PP2)\cdot225 \qquad PE = 418.48$ MW $\quad \frac{PE\cdot100}{450} = 92.996$ %

$PCCF := PP7\cdot450 + (PP8 + PP9)\cdot225 \qquad PCCF = 1.255$ MW CCF Impact

5 2nd Objective - Networks Reliability and CCFs

5.1 2nd Objective - Summary

What Is Important

- Network Structure: Networks are composed by Nodes, Branches and Load Nodes, designed, purchased and erected as separated blocks. In terms of reliability, the system is still a network with Nodes, Branches and Load Nodes but the reliability block diagram is quite different from the hardware.
- Network Interdependencies/CCFs: Out-of-service of the network components can lead to fault propagation, with the out-of-service of more than one Load Node; this scenario can be considered a Network Interdependence/CCF.

New Contributions

- Definition of the Network Virtual Components: Virtual Nodes, Virtual Branches, etc.
- Network Interdependencies/CCFs: Evaluation of Interdependencies/CCFs originated by faults on Nodes and Branches
- Definition/Evaluation of:
    - Functional Network Interdependencies/CCFs
    - Simultaneous and Non-Simultaneous Interdependencies/CCFs

5.2 Networks General Analysis

A deep analysis has been carried out on three typical network systems with re-configuration after fault, with quite different specific characteristics but with many characteristics that are also common to all the networks. The analysis is reported in Ch. 6, while the conclusions are summarized in this Chapter.

The objectives of the analysis are:

- To develop **new generalized models** for network reliability evaluation , common to all the networks (see Ch. 5.4)
- To state **general rules** to identify the specific Dependent Failures of the networks (see Ch. 5.5)

The three typical networks that have been analyzed in detail are:

- Extra High Voltage (EHV) and High Voltage (HV) power transmission networks;
- Integrated Selective Phone Communication Networks (STSI – Sistema Telefonia Selettiva Integrata).
- Wireless Networks

The main differences between the above networks are:

- The complexity of the nodes:
  - Simple Real Nodes but Complex Virtual Nodes in Power Systems,
  - Quite complex both Real and Virtual Nodes in Telecommunication Systems
  - The predominant element in Wireless Systems
- The effects of failures:
  - Failures on Power Systems can cause injuries to personnel and equipment; therefore, specific protective equipment is required, and they play a basic role

- Failures on Telecommunication Systems and Wireless Networks have mainly impact on the system performance, therefore protective equipment is less critical than for Power Systems

The analysis of the three above mentioned types of networks, with such different characteristics, seems enough comprehensive to lead to generalized results.

5.3 Identification of Typical Nodes Structures

The structures of the nodes of large networks are basically repetitive, because the networks have to be designed with homogeneous criteria, and have to be expanded in the same way; usually there are no more than 3-4 types of Nodes.

A General Rule for the first step of every network analysis can be stated as follows:

- Assumption: The structures of the nodes of a network will remain the same along the working life of the network. The working life can be short in case of Hi-Tech networks under development (conditioned by technical obsolescence – e.g. Wi Fi) or quite long (e.g. Power Systems); however, the extension of the working life is not affecting in principle the above assumption.
- Rule: The structures of the nodes are basically repetitive; therefore it is not advisable to try to identify a structure for every node; conversely, the analyst has to identify which are the basic structures of the several types of nodes, as well as the design criteria of these basic structures.

5.4 Generalized Models

The detailed analysis of the three above mentioned. typical networks (see Appendix A) led to the conclusion that the usual approach considering the physical structure of the network can have relevant limitations, and it is advisable to develop new generalized models that could take into account all the network functionalities, as follows:

- Nodes and Branches: They are related not only to the physical configuration of the grid, but also to its functional characteristics; therefore they are virtual blocks that take into account both the main hardware and their failure modes.

  Generalized models:

  - Branch between two A and B Nodes: a series connected RBD (Reliability Block Diagram), including all the blocks relevant to the failure modes that can cause the disconnection between A and B. The failure modes can be both equipment failures and other functions, e.g. from protection and control systems.
  - Node A, connected to the B, C, … N nodes by means of the A-B, A-C, …, A-N Branches, that means all the Branches (as defined in the previous paragraph) spreading from A: a series connected RBD, including all the blocks relevant to the failure modes that can cause the simultaneous disconnection / out-of-service of all the A-B, A-C, …, A-N Branches connected to A. Also in this case, the failure modes in general can be both equipment failures and other functions from protection and control systems.

  Remarks:

  - Some components that are part of the physical Nodes (e.g. HV Substations) have to be conversely included, in terms of reliability modeling, into the branches spreading from the relevant Nodes. Typical cases are Line Current Transformers (CTs) and Potential Transformers (PTs) of the HV Substations;
  - There is the possibility that a reliability block, relevant to a specific failure mode, could be included both into a Node and into a Branch. Usually this block

will be included into the Branch, because the disconnection of a branch is always instantaneous, and it will anticipate the disconnection of a Node that normally is delayed (back-up protection) after the tentative disconnection of all the branches.

- Reconfiguration
  - Nodes can be reconfigured, in case that they have possibility of a transference of the branches
  - Branches cannot be re-configured; however, in case that a branch is out-of-service, the grid can be reconfigured, by means of the nodes reconfiguration

➢ Load Centers (Load Nodes): They main characteristics are:

- Small networks inside the overall network
- Their reliability has a relevant impact on the overall reliability of the network
- Goal of the load centers: to assure the service supply continuity to their customers; therefore, the reliability model is very important.
- The reliability "blocks" are related not only to the physical configuration of the load center, but also to its functional characteristics

Therefore, Load Centers are "virtual blocks", composed by virtual nodes and virtual branches of the same Load Centers.

The analysis has been carried out in such a way to allow the superposition of the "Virtual Blocks" of the Load Nodes to the upper level network; calculation and result interpretation has been easier because there has been no need to simulate specifically every Load Node.

Failure Modes in Generalized Models

A FMEA analysis is actually relevant in network studies, and it has to be tailored to take into account all the effects on the system and its virtual nodes and branches. It can be simplified, taking into account the effects on the system only, but it has to satisfy at least the following requirement:

- To identify the several equipment failure modes; for example, in HV systems the CTs, PTs, and mainly the Circuit Breakers, have different failure modes, with different effects;
- To evaluate the impact of the different failure modes on the system, taking into account also the functionalities, such as the operation of the protection and control systems, and the switching sequences; specifically, the analysis has evaluate if the impact is either on the Branches (Lines) or on the Nodes (Sub-Stations);
- To define in which reliability model (either Branches or Nodes) the reliability blocks relevant to the several failure modes have to be included.

It has to be pointed out that the equipment can be split in different Reliability Blocks, and not all these blocks have impact on (and have to be included in) either Branches or Nodes; in fact, there is the possibility that they have to be subdivided between Branches and Nodes.

An example of such a simplified and tailored FMEA is reported in the following tables.

"Repair Modes" in Generalized Models

Two main modes have to be taken into account:

- Usual equipment repair or substitution
- Switching or change – over; the equipment or subsystem is isolated, and the service is restored by means of a switching sequence (e.g. by-pass circuit breaker

closing) or by means of a change-over sequence (e.g. closing the tie-breaker of two bus-bars)

The switching / change – over is a form of not instantaneous redundancy, and of course it is much faster than the repair / substitution.

5.5 Network Interdependencies and CCFs – Generalized Approach

5.5.1 Scope

The scope of this generalized approach is to find the network Interdependencies and CCFs, and specifically the hidden and complex ones that both are due to the network structure, and have a relevant impact on the same network structure.

The objectives are:

- Identification of interdependencies and CCFs on networks components/equipment, and evaluation of their impact on the network reliability,
- Identification of interdependencies and CCFs originated by faults on nodes & branches;
- Identification of "functional" interdependencies and CCFs originated by specific networks characteristics;
- Identification of simultaneous and non-simultaneous interdependencies and CCFs.

HV EQUIPMENT - SIMPLIFIED FMEA					
EQUIPMENT	**FAILURE MODE**	**IMPACT ON**		**INCLUDED IN**	
		BRANCH	**NODE**	**BRANCH**	**NODE**
Line CTs	Insulation breakdown	Out-of-Service. The fault is eliminated by the up-stream and down-stream Circuit Breakers (1)	-	X	
Line PTs	Insulation breakdown	Out-of-Service. The fault is eliminated by the up-stream and down-stream Circuit Breakers (1)	-	X	
Line Circuit Breakers	Opens without command	Out-of-Service.	-	X	
	Internal fault	Out-of-Service. The fault is eliminated by the CB on the opposite site of the line. (No repair activities)	Out-of-Service. The fault is eliminated by the remaining CBs of the node		X
	Stuck on demand (protection)	-	Out-of-Service. The fault is eliminated by the remaining CBs of the node		X
By-Pass Circuit Breakers	Opens without command	Neglected. Low probability of simultaneous - By-Pass operation - Opening without command	-		
	Internal fault	Out-of-Service. The fault is eliminated by the CB on the opposite site of the line. (No repair activities)	Out-of-Service. The fault is eliminated by the remaining CBs of the node		X

HV EQUIPMENT - SIMPLIFIED FMEA					
EQUIPMENT	**FAILURE MODE**	**IMPACT ON**		**INCLUDED IN**	
		BRANCH	**NODE**	**BRANCH**	**NODE**
	Stuck on demand (protection)	-	Neglected. Low probability of simultaneous - By-Pass operation - Fault on a line - CB stuck		
Coupler Circuit Breaker	Opens without command		Neglected. The CB opening will separate the bus-bars but it will not stop the power flow		
	Internal fault		Out-of-Service. The fault is eliminated by the remaining CBs of the node		X
	Stuck on demand (protection)	n.a.	n.a.		
Bus-Bars PTs	Insulation breakdown	-	Out-of-Service. The fault is eliminated by the remaining CBs of the node		X

This generalized approach is taking into account these interdependent factors:

- The Reliability Goal is to provide service to the end points of the Load Nodes
- A Component/Equipment interdependency/CCF can cause the partial/total out-of-service of a Load Node, or of a Network Node
- The out-of-service of a Network Node is a reduction of the network reliability, and there is the possibility of a simultaneous out-of-service of many Load Nodes.

5.5.2 CCFs in Network Component/Equipment

Identification of interdependencies and CCFs

They seem to be very unlikely, and mainly due to environment; the main reason of this low probability is the absence of interdependence between network equipment/components:

Classification: These are mainly Extrinsic

Impact on Nodes and Branches

- Nodes

  Interdependencies and CCFs that can cause the out-of-service of more than one node are very unlikely, because normally there is no functional relationship between the nodes equipment and systems; statistics (see Appendix A)) show that the only CCFs seem to be be extrinsic causes, due to weather (tornados, hurricanes, etc.); a discussion covering CCFs in a HV power system is reported at Ch. 7.5.

- Branches

  The only relevant cases are environmental Interdependencies and CCFs (e.g. environmental failure on double HV circuit lines, or on two HV lines feeding a load node from different sources).

Eventually, these Interdependencies / CCFs usually do not cause subsequent Intrinsic CCFs (no Functional Requirement Dependency, no Cascade)

5.5.3 Interdependencies and CCFs Originated by Faults in Nodes and Branches

- A Node Out-of-Service usually is not leading to the network out-of-service, but it can cause the Out-of-Service of some Load Nodes, and it can reduce the redundancy level assured by the meshed network; the extension of the impact is depending from the network configuration, and in some cases (ring) it can be wide. From the point of view of the Load Nodes, it is a sort of CCF, not related to the equipment but to the system characteristics; therefore in this work this type of failure will be called System Interdependency / CCF.

  Discussion

  - *Comparison with Single Point Failure: there is not only one component failure causing the out-of-ser,vice of many other components; conversely, the Load Nodes out-of-service is due to grid complexity, redundancy level and configuration (open-closed branches and tie breakers, etc.). Conclusion: it is not a SPF.*
  - *Comparison with a usual CCF: there is not a unique root cause for the Load Nodes; therefore it is not a "classic" CCF*
  - *Let us consider two failure probabilities for the Load Nodes:*

    Pint(i): Probability due to equipment failure, inside the Load Node

    Pout(i): Probability due to up-stream failure, outside the Load Node; it is not fixed figure because it depends from the network configurationt

    PT(i)=Pint(i)+Pout(i)

In this case:

Pint(1∩2)=Pint(1)Pint(2) most likely, therefore there is no CCF

PT(1∩2)> Pint(1)Pint(2) because there is the impact of the up-stream failures, which is not a fixed figure.

Conclusion: Pout(i) is acting as a root cause, but it is different node by node, and it is depending from the grid configuration. Eventually, Pout(i) is a sort of CCF, even though it is a bit different from the classic definition.

Classification: This System CCF seems to be Extrinsic, in fact it is due to an external interaction that is causing the out-of-service of redundant branches in case of a fault on Component/Equipment.

- A Branch Out-of-Service has a lower impact than a Node out-of-service; the consequence is usually a lower redundancy level only**.** No Intrinsic Interdependencies / CCFs, due to functional requirement/input and cascade interaction, are expected; Extrinsic Interdependencies / CCFs are very unlikely, and due to weather only.

5.5.4 Functional Interdependencies and CCFs

The detailed analysis of some existing networks led to the conclusion that there is another category of Interdependencies and CCFs, related with the network characteristics; in this work, the term "Functional CCF" has been adopted, however it is open for discussion.

Conditions and relevant steps of the analysis:

- There is a criticality
- There is a bottleneck
- A fault on the bottleneck will "initiate" a process that has consequence on all the centre load substations

Classification: These CCFs seem to be Extrinsic, due to an external interaction related with the system functionality but not with the environment.

5.5.5 Simultaneous and Non-Simultaneous Interdependencies and CCFs

During the development of the preliminary Load Nodes analysis, a problem became evident; it can be stated in a general form as follows:

In a redundant <u>but</u> repairable system, in general an Interdependency/CCF leads to a simultaneous out-of-service of two redundant branches in few cases only; conversely, there are many Interdependencies/ CCFs that lead to <u>non simultaneous faults</u>, which can be "repaired" while the system continues to work. Once the Interdependency/CCF has been identified, there is the possibility to find a proper solution while the system is working, during the repair time of the first failed component, in order to prevent a second fault on the second redundant branch.

Examples:

- Excessive vibration of redundant pumps, due to external factors; during the out-of-service of the first pump, there may be time to eliminate the external cause of vibration.
- Failure in one of two redundant transformer, and consequent overload of the other transformer; during the repair of the failed transformer there is the possibility of a load shedding to avoid the complete shut-down.

Classification: These are Intrinsic (Cascade) Dependencies, but there is the possibility to inhibit them by replacing in service the faulted element before the dependent one is faulted. Specific time-dependent models have to be developed taking into account the cascade process and the fault-repair cycle.

5.6 2nd Objective - Conclusion

The above described methodology has been adopted by the Author to solve some network reliability studies that otherwise could have been faced with simplified methods only, and proved satisfactory to properly model the specific failure modes leading to the out-of-service of Nodes and Branches. It allowed the detailed analysis of the Load Nodes (3rd Objective) and of the Ring (4th Objective), reported in the following Chapters.

6 3rd Objective - Power Systems Load Nodes Analysis

6.1 *3rd Objective - Summary*

What Is Important

- Complex Reliability Model: Power distribution Load Nodes are small networks within the overall network; their reliability model is complex because of change-over (non complete redundancy) and protection sequences.
- Impact on the Upper Level Network: Some specific failure modes of the Load Node can cause the out-of-service of the immediate upper level node, and of other up-stream nodes.
- Necessity of an Equivalent Load Node Model: The reliability analysis of a large network has to take into account also the reliability of the Load Nodes. However, the inclusion of a detailed model for every Load Node would increase dramatically the Montecarlo simulation time; therefore, it is advisable to develop a Load Node equivalent model not requiring a simulation, to be added to the upper level network model.

New Contributions

- Detailed Load Node Analysis, developed in accordance with the network generalized theory
- Non-Simultaneous CCFs: Evaluation of their impact
- Coupler: Evaluation of the Coupler impact on the overall Load Node reliability
- Start-Up Time of Already Existing Networks**:** generalized start-up time
- Control / Protections Systems**:** Evaluation of the impact of their malfunction
- Load Node Interface with the upper level grid
- Load Node Equivalent Model: macroblock to be included in network analysis

6.2 Identification of Typical Load Nodes Structures

The structures of the nodes of large networks are basically repetitive, because the networks have to be designed with homogeneous criteria, and have to be expanded in the same way.

In case of Power Systems Networks, the usual Load Nodes are High Voltage / Middle Voltage Substations with two HV/MV redundant branches, and two MV bus-bars interconnected by a tie breaker.

6.3 Reliability Goal

The reliability goal is as follows:

Continuous load supply at the MV bus-bars.

It is assumed that every semi bus-bar will feed 50% of the total load; therefore, the out-of-service of a semi MV bus-bar will cause 50% load reduction. The reliability goal of every semi bus-bar is to feed the relevant 50% of the overall load of the node.

6.4 Identification of Residence States and Virtual Nodes/Branches

The analysis of the Load Node model is carried out in accordance with the general criteria adopted in this report for the overall analysis of large networks, and reported in the previous Chapters:

- A priori identification of the “residence” states
- Identification of virtual Nodes and Branches

➢ A Priori Identification of the Residence States

 The “Residence” states are the “out-of-service” condition of the Load Nodes delivery points, that means the two MV bus-bars.

  - One MV Bus-Bar Out-of-Service
  - Both MV Bus-Bars Out of-Service

➢ Identification of Virtual Nodes and Branches

- Branches: they include HV / MV bays, with the main equipment; see next chapters

- Nodes: They include the HV bus-bars, and the failure modes of circuit breakers etc. that are not cleared and therefore can cause the disconnection of the HV bus-bars. A detailed analysis is reported in the following chapters.

6.5 The Load Node

6.5.1 Scheme

The scheme of a typical HV/MV Load Substation is reported in the next figures. Two fully redundant HV/MV transformers bays feed the two relevant MV bus-bars.

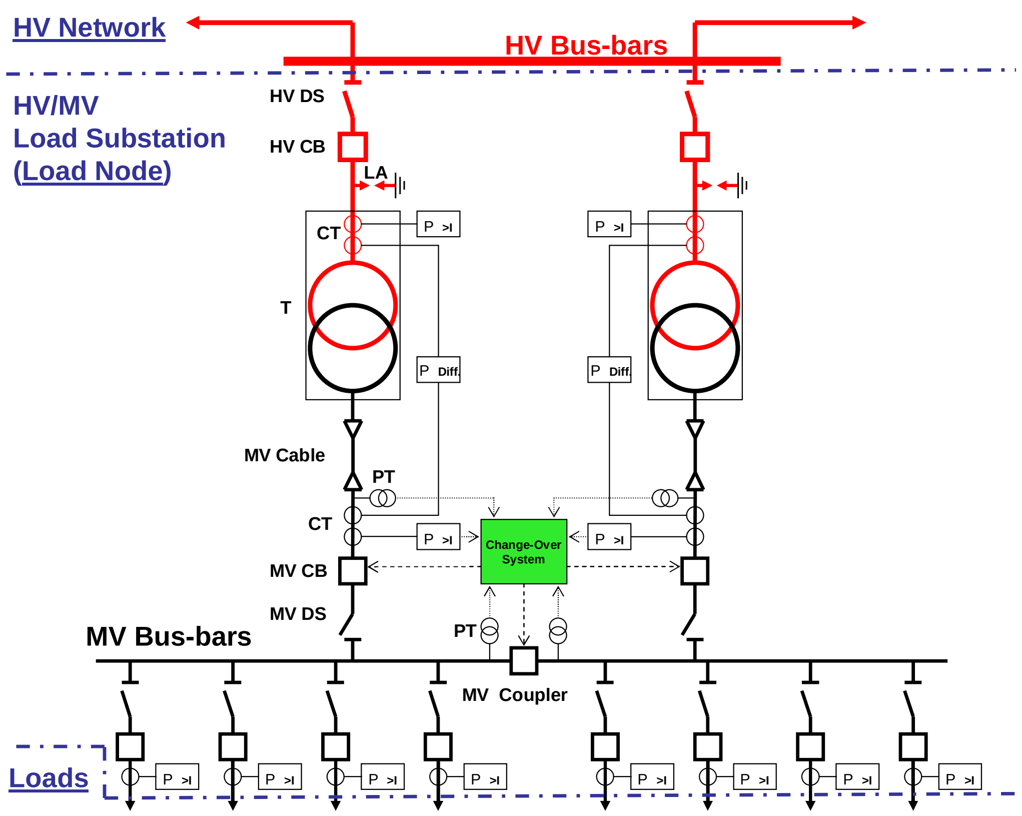


Fig. 6.1 Load Centre HV/MV Sub-Station Typical Scheme

The real load nodes are the MV bus-bars downstream the transformers; however, in this report all the substation has been considered as a load node, because its purpose is only to feed the node and not to interconnect the HV grid.

The Load Node, as above defined, starts downstream a HV interconnecting bus, that is part of the HV grid.

Downstream the MV bus-bars, there is a MV distribution network, that it has not considered in this study; in other words, the downstream limit of this work are the interconnecting nodes of the MV distribution.

6.5.2 Protections

The following typical protections set will be considered:

Location	**Protection Function**
Up-Stream the HV/MV transformer	- Phase and Ground Overcurrent (> I) – Selective (time delayed)
Across the HV/MV transformer	- Differential (Diff) - Instantaneous
Downstream the HV/MV transformer	- Phase and Ground Overcurrent (> I) – Selective (time delayed) - Neutral Grounding Overcurrent (*) (time delayed) - Zero Sequence Overvoltage(*) (time delayed)
MV Feeders	- Phase and Ground Overcurrent (> I) - Instantaneous

Remarks: (*) Not reported on the above single line diagram

Selectivity will act as follows:

- In case that a 3-phase overcurrent relay on the MV feeders could not manage to open the relevant MV Circuit Breaker, the up-stream 3-phase overcurrent relay will open the main MV circuit breaker. The relevant MV bus-bar section (Node) will be put out-of-service, and change-over sequence will be inhibited (see next paragraph); this will be a Single Point Failure for all the feeders

- In case that a ground overcurrent relay on the MV feeders could not manage to open the relevant MV Circuit Breaker, the up-stream neutral grounding overcurrent and the zero sequence overvoltage relays will open. The main MV circuit breaker and the relevant MV bus-bar section (Node) will be put out-of-service, and change-over sequence will be inhibited (see next paragraph); this will be a Single Point Failure for all the MV feeders
- In case that a fault on the HV connections or on the HV/MV transformer would not be cleared both by the differential relay and by the phase and ground overcurrent relay, the up-stream protections on the HV system will isolate the HV busbar up-stream the substation; in this case the MV change-over system (see next paragraph) cannot work. This will be a Single Point Failure for the two redundant transformer bays, and of course a Single Point Failure for all the MV feeders.

The above SPFs have to be included into the reliability analysis

6.5.3 Change-Over System

The Change-Over system plays a basic role in the reliability analysis, because it allows a change in configuration after fault; in this case, the closure of the tie breaker allows the redundancy to work. The automatic sequence will allow to close the tie breaker, under the following conditions:

Reference situation: No voltage on B1

Required conditions to close C:

- Residual voltage on B1 less than 30% Vn, in order to limit the transient residual counter-voltage
- Presence of voltage up-stream B2

- No protections release due to faults on the MV distribution; otherwise, thetie breaker would close on a fault.

6.6 Failures, Repairs, Switching

6.6.1 Failure Rates, and Identification of Components with Low Impact on Reliability Analysis

The failure rates of the several components are reported here below.

The scope of this preliminary analysis is to obtain a simplified scheme, including only the components that are really relevant for the reliability analysis.

Single-Line Diagram Code	**Component**	**Failure Rate (Failures/year)**	**Remarks**
	HV Bus-bars	Rare Event	Negligible
HV DS	High Voltage Disconnecting Switch	$< 10^{-4}$	Negligible
HV CB	High Voltage Circuit Breaker (Overall Failure Rate – see next Ch.)	0.0067	(*)
LA	Lightning Arrester	$< 10^{-4}$	Negligible
CT	Current Transformer	$< 10^{-4}$	Negligible
PT	Potential Transformer	$< 10^{-4}$	Negligible
T	HV/MV Transformer	0.02	
	MV Cable (50 m)	0.0007	
MV CB	Middle Voltage Circuit Breaker (Overall Failure Rate – see next Ch.)	0.0067	(*)

MV DS	Middle Voltage Disconnecting Switch	$< 10^{-5}$	Negligible
MV Coupler	Middle Voltage Tie Breaker (Overall Failure Rate – see next Ch.)	0.0067	(*)

(*) Cumulative failure rate, covering all the failure modes of the HV and MV Circuit Breakers; it is reported in CIGRE Report n. 83, it is accepted by IEEE Std 493 and it is usually accepted both for High Voltage and for Middle Voltage Circuit Breakers. The failure rates relevant to the several failure modes are reported in Ch. 6.6.2

From the above table, it is possible to conclude that the only equipment with relevant failure rates are the circuit breakers, the HV/MV transformers and the MV cables. The MV cables failure rate can be cumulated in the HV/MV transformers failure rate, therefore the scheme can be simplified considering only the following components:

- Circuit Breakers
- Power Transformers

This simplification is usual and commonly accepted in power systems analysis.

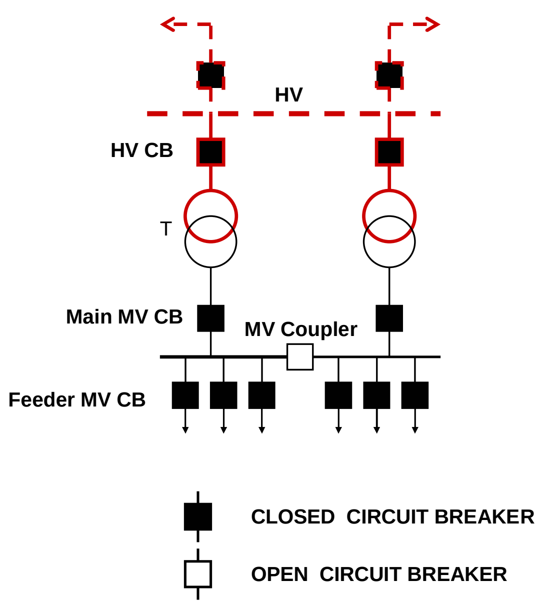


Fig. 6.2 Load Node Simplified Scheme

6.6.2 Circuit Breakers Detailed Model and CCFs

Remark: Part of the following text is an extract from Paper [12N] “EHV Substations Reliability Improvement by means of Circuit Breakers Autodiagnostic”, by the Author and D. Politano, presented at 2003 IEEE Bologna Power Tech Conference; the parts relevant to CCFs are a new contribution.

The work reported in the a.m. paper describes the impact of auto-diagnostic in power systems schemes, and it has been developed in the frame of the overall network analysis covered by this PhD Dissertation.

Circuit Breakers without Auto-Diagnostic

The failure modes general classification adopted in this work is in accordance with the CIGRE Report n. 83, that .is at present the more comprehensive document, and it is used as a reference in IEEE Std 493.

It has to be pointed out that the Circuit Breaker duty is both to open / close the relevant power circuit, and to interrupt faults on down-stream equipment; in other words, it is required to clear faults on other equipment, but itself can be subject to fault. Three main failure modes have been considered, as indicated here below; they are in accordance with the CB model developed by Endrenyi

- M1: Fault cleared by intervention of up-stream c.b. and protections
- M2: Fault cleared without intervention of up-stream c.b. and protections
- M3: Latent Fault, which inhibits fault tripping

Failure	**%**	**Failure Rate** (1/yr)	**Failure Mode**	**CCF** (Preliminary Analysis)
Does not close on command	24,6	0,00164	M2	Control system malfunction (es. CPU failure). This CCF however has to be considered as impossible, because the CBs are never called to operate simultaneously.
Does not open on command	8,3	0,00055	M3	
Closes without command	1,1	0,00007	M2	
Opens without command	7,0	0,00047	M2	
Does not make the current	1,7	0,00011	M2	Choice of Circuit Breakers with characteristics lower than the required ones. It is a very unlikely CCF, because in large networks the C.Bs are usually specified with standardized criteria.
Does not break the current	3,0	0,00020	M1	
Fails to carry current	1,5	0,00010	M1	
Breakdown to earth	3,2	0,00021	M1	
Breakdown between poles	1,5	0,00010	M1	
Breakdown across open poles (internal)	3,6	0,00024	M1	
Breakdown across open poles (external)	1,5	0,00010	M1	
Locking in open/closed position	28,4	0,00190	M3	No CCF
Others	14,6	0,00098	M1-M2-M3	
Total	100,0	0,0067		

HV Circuit Breakers Failure Modes

In this report, the rates of the failure modes have been evaluated as follows:

M1 Rounded sum of the failure rates of the several M1 items

M2 Neglected – see next chapters

M3 On Demand Probability; this is a more suitable figure for CBs, which are working as protective equipment

The classic three-state model developed by Endrenyi is reported in the following figure. Switching of faulted components comprises both their isolation by means of disconnecting switches, and change in S/S configuration (when applicable) to by-pass the faulted components.

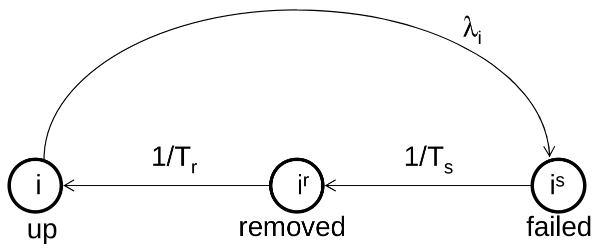


Fig. 6.3 Model of component “i” with three-state cycles

“Switching” in this work is the isolation of a component, after the out-of-service of a HV busbar due to the fault on the same component.

It has to be pointed out that, in substations with automatic change-over between the MV bus-bars, there is no need of a change in configuration both for the MV and for the HV circuit breakers; the operation of the disconnecting switches can be carried out “after” the change over sequence, therefore it has no impact on the system availability. Eventually, the three-state model is <u>not required</u> in this case.

The different failure modes of CBs lead to a more complex switching model, as developed by Endrenyi. The relevant transition diagram is reported in Fig. 6.4; it is relevant to a simple circuit including a component C and a up-stream CB protecting it. The correspondence between the failure rates on the diagram and the ones indicated in the above Tables is as follows:

M1	λ1
M2	λ2
M3	The model takes into account these failures by introducing a probability “p(3)” that the CB would not interrupt in case of a fault on the protected component C

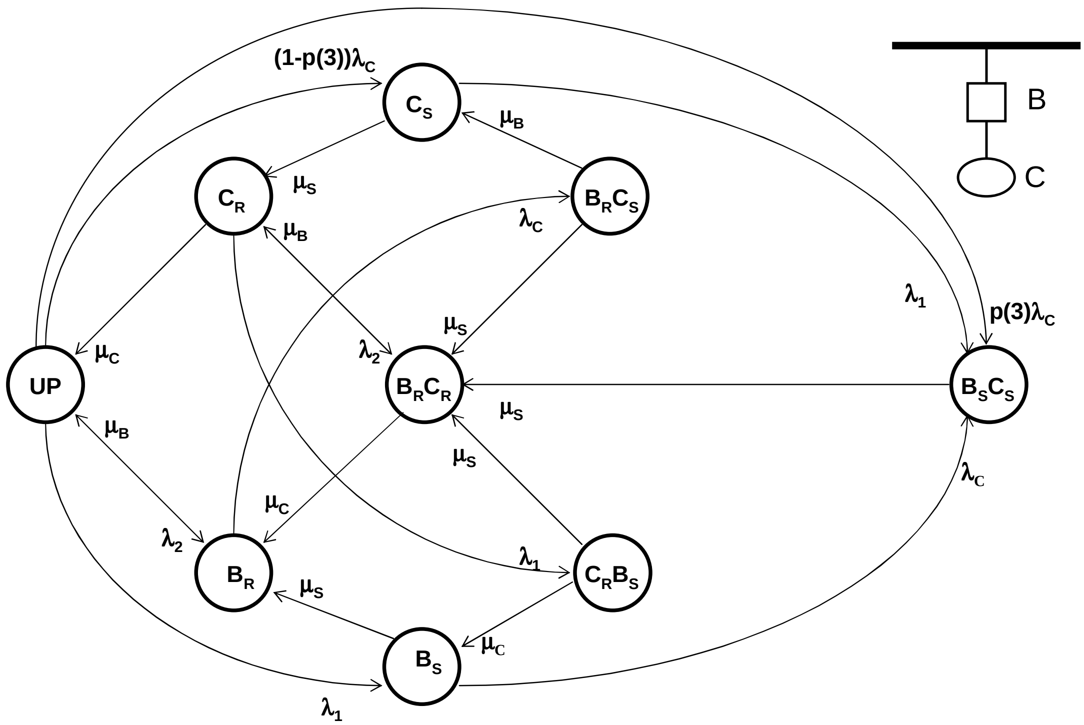


Fig. 6.4 Three-State Circuit Breaker Transition Diagram
WITHOUT Auto-Diagnostic

<u>Circuit Breakers WITH Auto-Diagnostic</u>

The performance of a typical modern, advanced autodiagnostic systems is reported in the following Table. Its condition monitoring unit not only collects and stores data but also employs sophisticated mathematical processing and analysis to provide a complete picture of the breaker condition.

Diagnostic Failure	**Monitored Parameters**	**Prevented Failure Mode**	**Prevented CCFs** (Preliminary Analysis)
Interrupter Wear	• Phase currents • Arcing time • Contact travel	M2	Yes If there is wear-out of the CBs, in case of a fault on one of them the other one has to work with doubled load, and the wear-out can be accelerated leading to the substation out-of-service
SF6 Gas System Integrity & Leakage Rate	• SF6 gas density • Temperature	M1	No No interdependence between CBs relevant to these failures
Mechanical Integrity of the CB	• Position versus time, travel characteristic • Operating times • Supply voltage to the charging motor • Coil energization time • Auxiliary contacts position	M2 M3	
Trip/Close Coil Condition	• Coil impedance • Circuit continuity	M3	
Mechanism Charging System Condition	• Motor supply voltage • Motor current • Number of motor starts • Charging time	M2	
Control Cabinet Heater System	• Heater current • Heater continuity	M2	

The addition of an advanced autodiagnostic system will have the following consequences:

- M1 faults: Some of them can be detected by the autodiagnostic, and there is no intervention of the up-stream CBs; the failure rate portion relevant to these faults is λ_{1ad}. The remaining portion is λ_{1s}
- M2 Faults: Their rate can be reduced ($\lambda'_b < \lambda_b$) by CB monitoring and a proper maintenance program
- M3 Faults: Their probability is reduced by autodiagnostic; the failure rate portion relevant to the detected faults is λ_{3ad}; the residual fault probability is "p_{ad}"

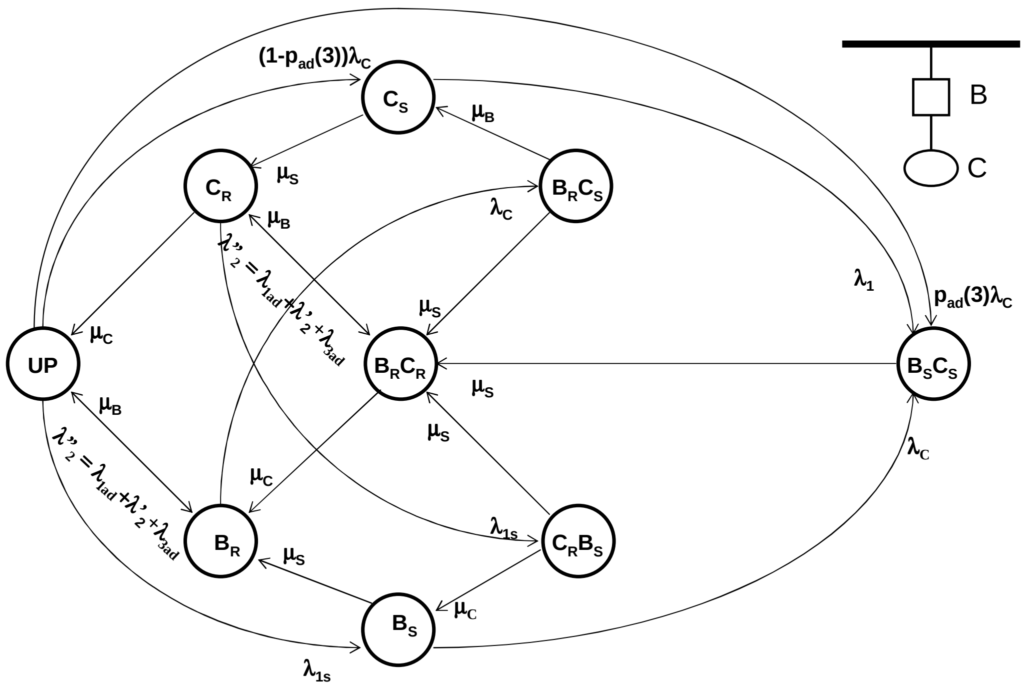


Fig. 6.5 Three-State Circuit Breaker Transition Diagram WITH Auto-Diagnostic

<u>CCFs Detailed Analysis</u>

The CCF analysis reported in the previous paragraphs is preliminary and simplified. However, during the development of the preliminary analysis many problems became evident; the main one can be stated in a general form as follows:

"In a redundant <u>but</u> repairable system, in general a CCF is leading to a simultaneous out-of-service of two redundant branches in few cases only; conversely, there are many CCFs that lead to non simultaneous faults, which can be "repaired" while the system continues to work. Once the CCFs has been identified, there is time to find a proper solution while the system is working to prevent new faults of the same type."

Furthermore, the case of a power substation has this interesting peculiarity that can be a general statement for all the redundant and repairable systems with transfer switch:

The tie-breaker and the automatic change-over sequence don't allow an instantaneous transfer of the load (which is not necessary) but they separate the two load bus-bars, in such a way that a out-of-service of one bus-bar will not cause the out-of-service of the other bus-bar too.

A more detailed CCF analysis has been therefore considered as necessary. It has been carried out by means of the frame reported in "A Modified FMEA Tool for USE in Identifying and Addressing Common Cause Failure Risks in Industry", by Mosleh and Childs; the Summary Matrix reporting the coupling factors has been modified by subdividing the faults as follows:

A	Simultaneous or Quasi-Simultaneous Fault; the second fault will surely happen within the repair time of the first one
B	Non - Simultaneous Faults

CIRCUIT BREAKERS IMMEDIATE / INTERMEDIATE CAUSES RELATED TO COUPLING FACTORS						
Type	**Immediate Cause**	**Intermediate Cause**	**Failure**	**Failure Mode**	**Coupling Factor**	
					A	**B**
Common Control System malfunction	No opening / closing signals	Control system power supply out of service; Control / protection equipment malfunction (*)	1 2	M2	3a	-
				M3		4d
Excess short circuit duty	Under Design	Power system short circuit level growth	5	M1	-	4a
			6	M1 M3		
Excess loading	Under Design	Load growth	7	M2	-	4a
Aging, end of life, wear-out, fatigue	NON Repairable part deterioration	Working life exceeded	10	M1	-	1a
	Repairable part deterioration	No spare parts availability due to obsolescence	12	M1	-	4d

(*)This CCF is extremely unlikely, and therefore it will not taken into account, because the CBs are not called to operate simultaneously.

HV CIRCUIT BREAKERS

COUPLING FACTOR

	FAILURE	FAILURE MODE	SIMULT.	1. Oper`l Usage: a. Age	1. Oper`l Usage: b. Maturity	2. Shared Environm.: a. Proximity	2. Shared Environm.: b. Same medium	3. Functional Coupling: a. Energy Source	3. Functional Coupling: b. Shared Input or Output	3. Functional Coupling: c. Load or Load Medium	4. Common Personnel: a. Design	4. Common Personnel: b. Installation Construction	4. Common Personnel: c. Operation	4. Common Personnel: d. Mainenance	5. Documentation: a. Incomplete Incorrect	5. Documentation: a.Steps That Omit Barriers	6. Incomplete Incorrect Labels Displays	7. Component Mfr Issue
1	Does not close on command	M2	A					X										
			B											X				
2	Does not open on command	M3	A					X										
			B											X				
3	Closes without command	M2	A															
			B															
4	Opens without command	M2	A															
			B															
5	Does not make the current	M2	A															
			B								X							
6	Does not brake the current	M1 M3	A															
			B								X							
7	Falls to carry current	M2	A															
			B								X							
8	Breakdown to earth	M1	A															
			B															
9	Breakdown between poles	M1	A															
			B															
10	Breakdown across open poles (internal)	M1	A															
			B	X														
11	Breakdown across open poles (external)	M1	A															
			B															
12	Locking in open / closed position	M1	A															
			B											X				
13	Others	M2	A															
			B															

A: Simultaneous or Quasi-Simultaneous Fault; the second fault will surely happen within the repair time of the first one
B: Non - Simultaneous Fault

6.6.3 Transformer Model and CCFs

Transformers are:

- Passive equipment
- Protected by the up-stream circuit breakers
- Disconnected after the release of the up-stream circuit breakers, in case of an internal fault; anyway, in the simple scheme of a HV/LV Substation there are no by-pass disconnecting switches and circuit breakers, therefore the disconnection is only a safety measure without any impact on reliability / availability.

Therefore, there is no need to consider several failure modalities such as for the HV Circuit Breakers (M1, M2 and M3).

A very exhaustive FMECA for power transformers has been developed by the Author a few years ago; on the base of this analysis, it has been possible to develop a CCF analysis such as for the HV Circuit Breakers.

HV/MV TRANSFORMERS

IMMEDIATE / INTERMEDIATE CAUSES RELATED TO COUPLING FACTORS

Type	Immediate Cause	Intermediate Cause	Subsystem Failure	Coupling Factor A	Coupling Factor B
Conductors insulation deterioration	Overheating	Overload due to load growth	1	4a	-
Oil Deterioration	No oil treatment	Poor maintenance	3	-	4d
On Load Tap Changer deterioration	Thermal overstresses	Load growth	7	4a	-
	Failure on mech/el components	Poor maintenance		-	4d
Aging, end of life, wear-out, fatigue	Repairable part deterioration	No spare parts availability due to obsolescence	1 7	-	1a
	NON Repairable part deterioration	Working life exceeded			

HV/MV TRANSFORMERS

COUPLING FACTOR			1. Oper`l Usage: a. Age	1. Oper`l Usage: b. Maturity	2. Shared Environm.: a. Proximity	2. Shared Environm.: b. Same medium	3. Functional Coupling: a. Energy Source	3. Functional Coupling: b. Shared Input or Output	3. Functional Coupling: c. Load or Load Medium	4. Common Personnel: a. Design	4. Common Personnel: b. Installation Construction	4. Common Personnel: c. Operation	4. Common Personnel: d. Mainenance	5. Documentation: a. Incomplete Incorrect	5. Documentation: a.Steps That Omit Barriers	6. Incomplete Incorrect Labels Displays	7. Component Mfr Issue
SUB-SYSTEM FAILURE		SIMULT.															
1	Conductors	A								X							
		B															
2	Mechanical Parts	A															
		B															
3	Dielectric (Oil)	A															
		B											X				
4	Cooling System	A															
		B															
5	Magnetic Circuit	A															
		B															
6	HV Bushings	A															
		B															
7	On-Load Tap Changer	A								X							
		B											X				

A: Simultaneous or Quasi-Simultaneous Fault; the second fault will surely happen within the repair time of the first one
B: Non - Simultaneous Fault

6.6.4 NON Cleared Fault in a MV Branch

In case that a fault on a MV feeder downstream the MV bus-bars has not been cleared by the feeder MV circuit breaker, the protective relays selective operation will open the general up-stream MV circuit breaker, to isolate the fault; therefore, the relevant half MV bus-bar will be out-of-service, as well as all the downstream MV feeders; this is a CCF for the MV distribution, downstream the disconnected half MV bus-bar only.

The failure / repair sequence is as follows:

Input Data:

- N: Feeders quantity
- λf: Feeder individual failure rate, comprehensive of the feeder MV circuit breaker failure rate in M1 mode
- P: "On Demand" failure probability

Failure (out-of-service) rate a MV semi bus-bars for non cleared fault:

$$\lambda bus = N (\lambda f \times P)$$

Repair / Restoration time: the time to disconnect the faulted feeder MV circuit breaker.

6.6.5 Effects on Nodes and Branches

The failure effects on nodes and branches are reported in the following simplified FMEA.

Remarks:

- The availability of the tie breaker has not been taken into account in the virtual branch analysis, because it has no direct impact on it; however the coupler performance has been included both in the transition diagrams and in the simulation sequences.

- The CCFs relevant to NON simultaneous faults (Type B)) have been cumulated with the non CCF failures because they do not cause loss of redundancy (see output tables)

6.6.6 Overall Failure and Repair Rates

Cumulative Failure	**On Demand Failure Probability**	**Average Failure Rate (Failures/Y)**	**Average Repair / Disconnection Time (h)**	**Remarks**
CIRCUIT BREAKERS				
M1		0.002	720/10	
M2	Not relevant. CB failed closure is not a cause of out-of-service			
M3	0.001		720/10	
CCF M1	Included in M1			
CCF M2	Not relevant. CB failed closure is not a cause of out-of-service			
CCF M3	Included in M3			
MV/LV TRANSFORMERS				
F		0,012	720	
CCF	0,1			CCF: failure of a transformer and overload of the other one.
MV FEEDERS				
F		0.25		
CB M3	0.001			

HV/MV SUBSTATION - SIMPLIFIED FMEA						
EQUIPMENT	**FAILURE MODE**	**IMPACT ON**			**INCLUDED IN**	
		BRANCH	**MV NODE**	**HV NODE**	**BRANCH**	**HV NODE**
HV Circuit Breakers	M1 M3	Branch Out-of-Service	Both MV Bus Bars Out-of-Service, because HV Bus Bars out-of-service	HV Bus Bars out-of-service The fault is cleared by the CBs located upstream the HV bus bars.		X
	M2	Branch Out-of-Service MV Bus-Bar OK – Load transfer activated		-	X	
	CCF M1	B Type only Included in M1				X
	CCF M2	Not Relevant. CB failed closure is not a cause of out-of-service				
	CCF M3	B Type only Included in M3				X
HV/MV Transformers	SubSystem Failure CCF B	Branch Out-of-Service MV Bus-Bar OK – Load transfer activated	-	-	X	
	CCF A		Sequential and quick out-of-service of both transformers. Both MV Bus-Bars Out-of-Service	-	X	

HV/MV SUBSTATION - SIMPLIFIED FMEA					
EQUIPMENT	**FAILURE MODE**	**IMPACT ON**		**INCLUDED IN**	
		BRANCH	**MV NODE**	**BRANCH**	**MV NODE**
MV Main Circuit Breakers	M1 M2 M3	Branch Out-of-Service. MV Bus-Bar out-of-service		X	
	CCF M1	Included in M1		X	
	CCF M2	Branch Out-of-Service. MV Bus-Bar Out-of-Service		X	
	CCF M3	Included in M3		X	
MV Coupler	M1		Both MV Bus Bars Out-of-Service		X
	M3		MV Bus-Bar Out-of-Service.		X
MV Feeders Circuit Breakers	M1 M3	MV Bus-Bar Out-of-Service. The MV Main CB will release			X
	M2	Feeder only out-of-service			
	CCF	Not Applicable There are no redundancies			

6.7 Simulation – Preliminary Approach

6.7.1 Step-by-Step Approach to Simulation

There are two main problems in simulation:

- Results validation
- Results Interpretation

The main idea is to start with a simplified model, for which is possible to find an analytic solution; the simulation process will then be honed up to reach a similar result.

A big effort will be paid to develop simulation in such a way that it will be possible to reach a sound interpretation of the results, with the adoption of specific techniques, markers, etc.

The simplified model relevant to power substations is the one included in the text [9B] "Reliability Engineering", Birolini, and reported here below. The preliminary transition diagram, considering the transition from a pre-defined bus-bar, has been developed by the Author; the final diagram, with the symmetry between busbars, and the analytic solution, have been developed by Birolini.

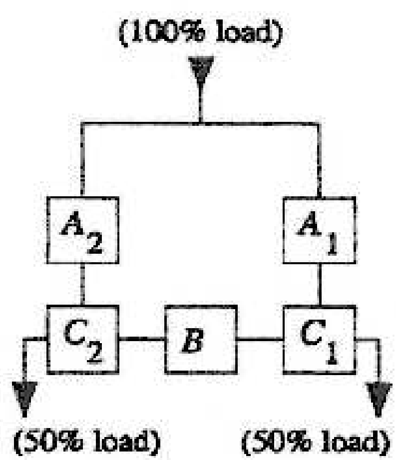


Fig. 6.6 Simplified Sub-Station Model

Once the simplified model will have been solved by simulation, it will be expanded up to reach the substation configuration reported into the previous Chapters.

6.7.2 Simulation Techniques

Two main techniques are used for the simulation of this type of power systems:

- State Duration Sampling
- Random Walk

<u>State Duration Sampling</u>

- Approach:

  Sampling the probability distribution of the component state duration. Each component has an initial state and the duration of each remaining in that state is sampled; the usual choice is from exponential distribution. If the state of a component changes within the time span of the simulation, how long it remains in the next state is sampled repeatedly until the time span is reached.

  The step-by-step procedure is well described in [1M] "Reliability Assessment of Electric Power Systems Using Monte Carlo Methods" Billinton, Li

  1. Specify the initial state of each component. Generally, it is assumed that all components are initially in "up" state; this assumption however will be discussed because it is not fully applicable to large networks
  2. Sample the duration of each component residing in its present state. For example, given an exponential distribution, the sampling value of the state duration is:

     $$T_i = -\frac{1}{\lambda_i}\ln U_i$$

     where U_i is a uniformly distributed number between [0,1] corresponding to the ith component; if the present state is the up state, λ_i is the failure rate of the *i*th component; if the present state is the down state, λ_i is the repair rate of the *i*th component.

3. Repeat Step 2 in the given time span (yr) and record sampling values of each state duration for all components. Chronological component state transition processes in the given time span for each component can be obtained .

4. The chronological system state transition process can be obtained by combining the chronological component state transition processes of all components. The chronological system state transition process for two components is shown in Fig. 6.7

5. Carry out system analysis for each different system state to obtain the reliability index.

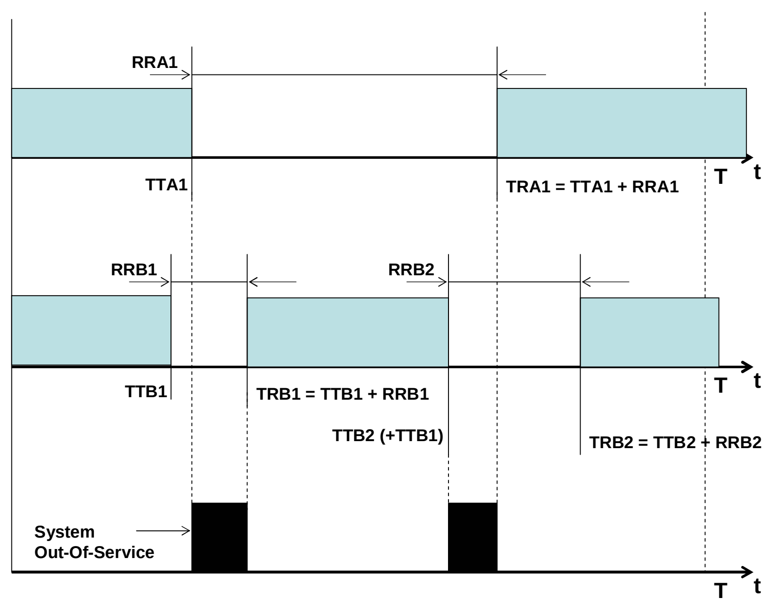


Fig. 6.7 Two independent repairable components, A and B, operate in parallel. System operation requires at least one component in service.

- **Advantages**
  - It can be easily used to calculate the actual frequency index
  - Any state duration distribution can be easily considered
  - The statistical probability distributions of the reliability indices can be calculated in addition to their expected values
  - The "history" and trend of a state can be taken into account

Remark: State Duration Sampling is specifically recommended in the a.m. Billinton – Li textbook for the reliability simulation of power substations.

<u>Random Walk</u>

This technique has been developed to analyze particles collisions on Atomic Physic. It proved very effective in reliability analysis of technological plants (nuclear, chemical, etc.).

A sample of random walk is reported in the following figure; a well detailed theory is reported in [2M] "Basic of the Monte Carlo Method with Application to System Reliability" by Marseguerra, Zio.

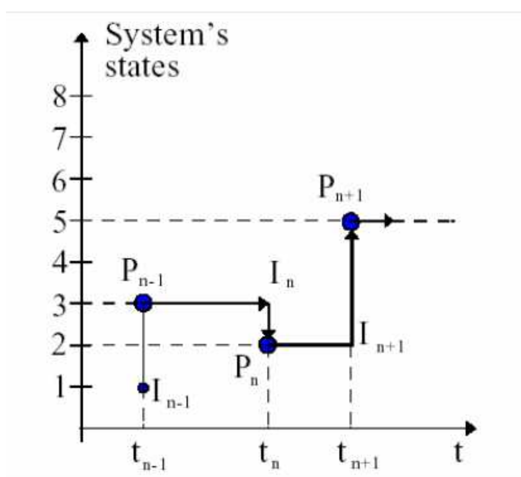


Fig. 6.8 Random Walk, with 8 states(From "Montecarlo Sampling and Simulation for Application to RAM" Marseguerra, Zio)

However, some difficulties arose in the simulation of power substations. The transition diagram of the simplified “first step” scheme reported in Fig. 6.6 is showed in the next figure; the analysis of this “simplified” model leads to the following considerations:

- Although the model is very simplified, the transition diagram is very expanded, with many states.

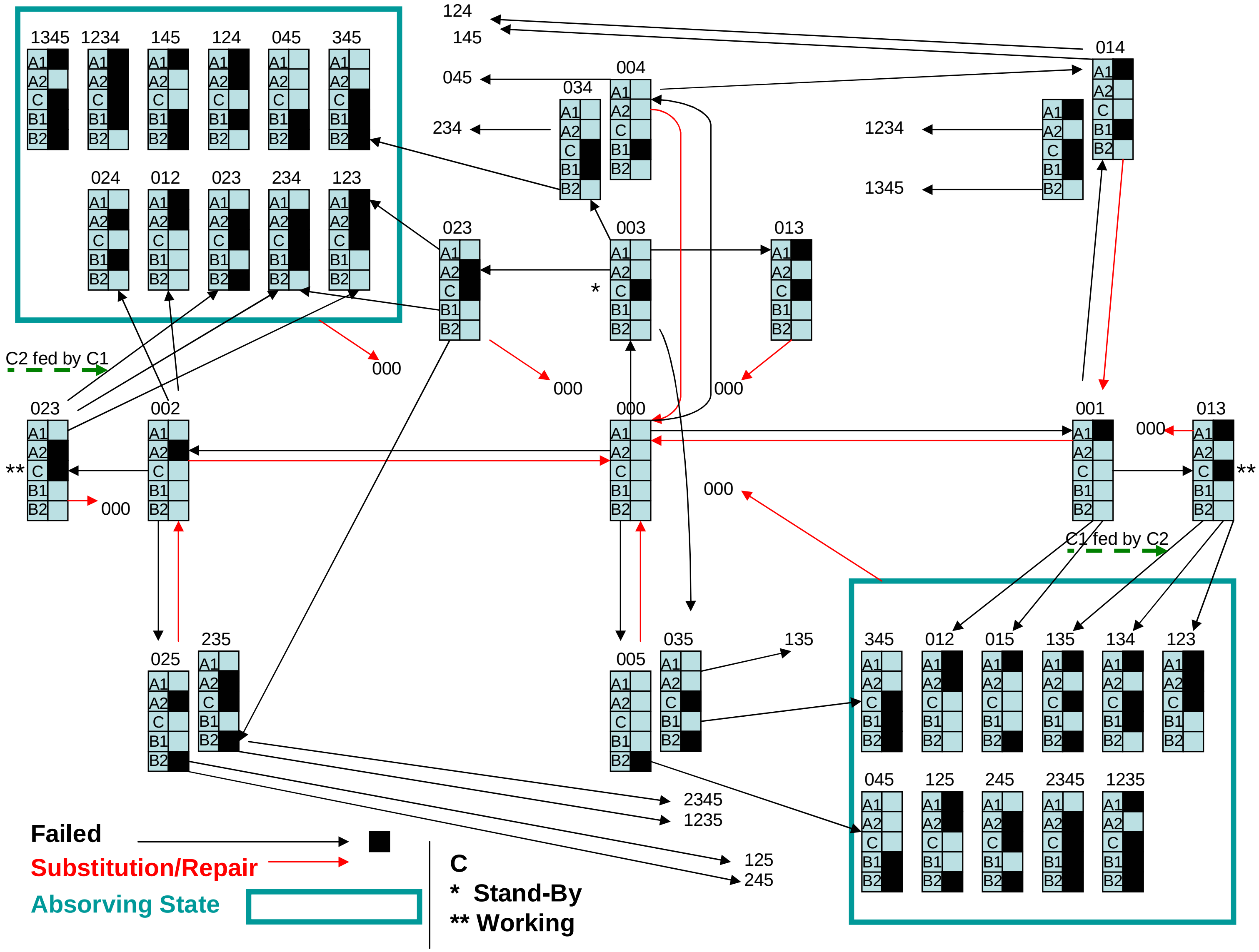


Fig.6.9 Random Walk of the Simplified Model

- The addition of more components (transformers), and mainly of more failure modes related to virtual nodes, protections, CCFs, etc. seems to lead to an excessive quantity of states, that cannot be managed without difficulties;

For the above reasons, for the time being the “Random Walk” has been abandoned, and the “State Duration Sampling” has been preferred.

6.8 Load Nodes Simulation – First Steps

6.8.1 Simplified Substation Simulation

The first step has been to obtain the MTTF of the simplified sub-station scheme, and to compare the results with the analytic calculation.

Objectives of this first step:

- Validation of the simulation model, on the base of the comparison with analytical results; the models relevant to more complex schemes have been built on the frame of the validated model
- Clear understanding of the transition process, and of its performance, on the base of the simulation; for example, the process to reach the steady state will be analyzed by means of a realistic simulation, to understand if the steady state is a reasonable assumption
- Development of specific simulation models to be applied to load nodes; for example, the simulation of the “coupler” has been developed as a general model to be applied in more advanced node schemes

The following assumptions have been taken into account:

- Faults at the “C” bus-bars have been neglected; this is a realistic assumption, because the faults at the bus-bars have to be considered a rare event.

- No CCFs, and specifically no CCFs that can cause the out-of-service of the bus-bars.
- A unique failure rate and a unique repair time for “A” blocks, both of them in accordance with exponential distribution
- The fault relevant to system MTTF is the simultaneous out-of-service of both the “C” load bus-bars
- The repair time after a MTTF is a longer time, taking into account the need to restore service to the whole substation

<u>Simulation Procedure</u>

- Two fault sequences have been modeled, for both “A” branches, with the same renewal cycle reported in Fig. 6.7;
- For both “A” branches, the total out-of-service leading to the MTTF is occurring in case that one of the “A” branches is faulted during the repair time of the other one;
- In this simplified analysis the “on call” failure of the coupler is cumulated within its overall failure rate; it means that it is assumed that the breaker will always close successfully, and the possibility to fail is included within the probability of a failure during the time the coupler is closed.. The change-over sequence is assumed to start successfully once one of the two “A” branches is failed, therefore the working time during which the failure rate is considered is starting and lasting together with the repair time of the failed “A” branch. Eventually, for both “A” branches, another possibility leading to the total out-of-service is that the coupler is faulted after having closed.
- Four MTTFs have been calculated, in accordance with the above procedure:
    - Two MTTFs relevant to faults on A branches

- Two MTTFs relevant to the coupler failure when one of the two A branches is out of service.

The lowest of the above MTTFs is chosen as the MTTF of the system.

- Once reached an overall out-of-service, leading to the system MTTF, no renewal is considered; simulation showed that this situation would not be real, because the MTTF is very long; the average MTTF is obtained simulating many fault sequences leading to the overall fault, and evaluating the average MMTF. This procedure is different from the analytic calculation (Markov models) of the steady-state MTTF, based on the asymptotic renewal process; however, it is much more realistic and it can be obtained by simulation only.
  In this case, simulation is offering the possibility to model a scenario that is much more realistic than the one obtained with Markov processes.
- Availability is calculated simply considering the average MTTF and the previously defined system MTTR.
- The system MTTR is usually longer than the MTTR relevant to a fault in the A branches, because there is to take into account the overall system restoration. The MTTR relevant to the coupler has not been taken into account, because a fault on the coupler is leading to the total out-of-service, therefore also in this case the system MTTR has to be considered.

The simulation has been carried out considering for both A branches:

- High failure rates
- Long repair times
- A long renewal (up-down) chain

This scenario is not realistic, but it has assured that all the types of MTTFs have been reached for every simulation.

Many simulations have been carried out to check which could be the minimum acceptable quantity both of simulations and of renewal cycles; the results reported here below are relevant to a sort of optimization, that means the minimum simulation work to obtain an acceptable result.

MTTF and Reliability for a system with direct redundancy without coupler have been calculated in accordance with the following approximate formulae:

MTTF

Ref.: Hoyland-Rausand formula (6.70) and Birolini (4th Edition) Table 6.6

$$MTTF = \frac{3}{2\lambda} + \frac{\mu}{2\lambda^2} = \frac{3\lambda + \mu}{2\lambda^2}$$

Reliability

Ref.: Hoyland-Rausand formula Ch. 6.6 and Birolini (4th Edition) Table 6.6

R1: Approximate expression

R2: Exact expression

$$r1 := \frac{-(3\cdot\lambda + \mu) + \sqrt{(3\cdot\lambda + \mu)^2 - 8\cdot\lambda^2}}{2}$$

$$r2 := \frac{-(3\cdot\lambda + \mu) - \sqrt{(3\cdot\lambda + \mu)}}{2}$$

$$R1 := e^{\frac{-2\cdot\lambda^2\cdot t}{3\cdot\lambda+\mu}}$$

$$R2 := \frac{r2\cdot e^{r1\cdot t} - r1\cdot e^{r2\cdot t}}{r2 - r1}$$

EVALUATION OF MTTF

The input data and results are summarized here below:

Input Data

Failure rates:

- "A" Branches: 0.1 failures / year
- Coupler: 0.000001 failures / year (i.e. no impact by coupling failure)

Repair Times:

- "A" Branches: 1000 h (very high, and unusually same as system repair time)
- System: 1000 h

Renewal cycles of the "A" branches: 500

Simulations: N = 100000

Results

Successful simulations: 99996 over 100000 (99.996%)

MTTF Validation:

Calculated MTTF: 453.00 years, considering a redundant system without coupler

MTTF from simulation: 453.3831 years

Considering that:

- Simulation precision is of the order of $\sqrt{N}$
- The coupler has a small but not null impact

The simulation result can be considered as very very satisfactory

EVALUATION OF RELIABILITY

The input data and results are summarized here below:

Input Data: as above, with the addition of t = 100 (years)

Results

Calculated R1(approximated) = 0.80192

Calculated R2 (exact) = 0.80207

R from Simulation: = 0.8031

The difference is 0.13%, therefore the result can be considered as very very satisfactory.

Conclusion

The results are very very satisfactory, the (very) simplified model can be considered as validated and it can be used as a basis for further development.

Comments

- The more evident factor is that the renewal cycles are too many, even though the failure rates and the repair times are much higher than real. Therefore, MTTF in accordance with the above formulae cannot be used as an effective reliability index.
- Reliability is not a useful index, because, after the overall system out-of-service, the system can be re-started again.

6.8.2 Evaluation of Failures Quantity and Out-of-Service Time

As above mentioned, MTTF and reliability seem not to be useful indices. In this case of a renewal system, it is more advisable to consider the quantity of failures and the out-of-service time; therefore, the simulation program has been modified to evaluate these figures.

After the simultaneous out-of-service of both bus-bars (out-of-service of the node, that means CCF for the distribution downstream the node) the renewal failure-repair sequence of both A1 and A2 branches has been re-started, after the system repair time.

Assumption: In this simplified model, for the time being the System Repair (Re-Starting) Time has been considered as constant.

The failure–repair sequence of both branches (A1 and A2) has been stopped when reaching the mission time.

The renewal sequence is reported in the following figure.

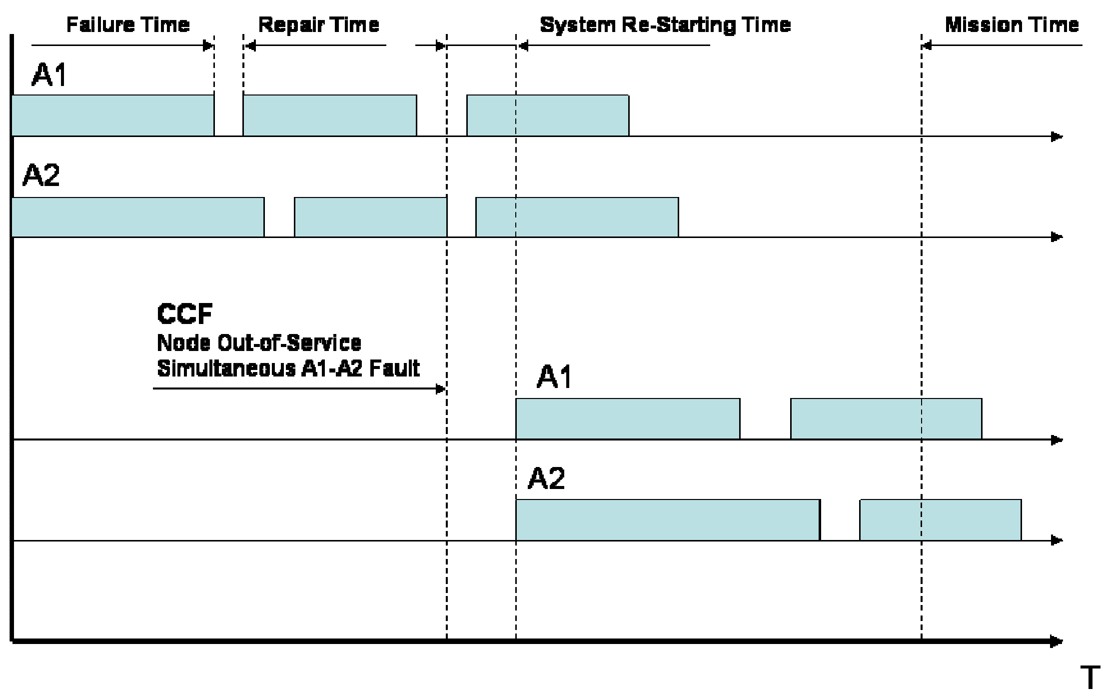


Fig.6.10 Re-starting of Branches Renewal Cycles after a Simultaneous Fault (CCF)

6.8.3 Reliability Assessment of Nodes of Already Existing Networks

This new contribution it is not related with CCF, but it arose from the analysis of the network performance.

Up to now, it has been considered that, at the starting time, the two branches were also starting their working life; this is the situation of a new limited network, e.g. the power distribution system of a new refinery.

In case of a large network, managed by a Utility, the scenario is different: the system is usually existing and periodically refurbished and expanded, therefore there is not a common starting time when all the equipment and sub-systems are new. If the mission time is much shorter that the MTTF, this situation can have a relevant impact on the availability, because of course the probability of having a simultaneous out-of-service of the two branches is much lower during the first renewal cycle of the two branches..

To override this problem, it has been assumed that the starting time will not coincide with the starting of a failure-repair cycle. The procedure is as follows:

- The failure time is computed, both for A1 and for A2 branches. In the previous cases, the calculation of the failure time, assumed in accordance with exponential distribution, is calculated by means of the common expression for exponential distribution as follows:

  AF(1,I)=(-1/L1)*log(rand);

  AF(2,I)=(-1/L2)*log(rand);

- In this case, a 0-1 random coefficient is applied to the first failure time, as follows:

  AF(1,1)=(-1/L1)*log(rand)*(rand);

  AF(2,1)=(-1/L2)*log(rand)*(rand);

The random sequence is reported in the following figure

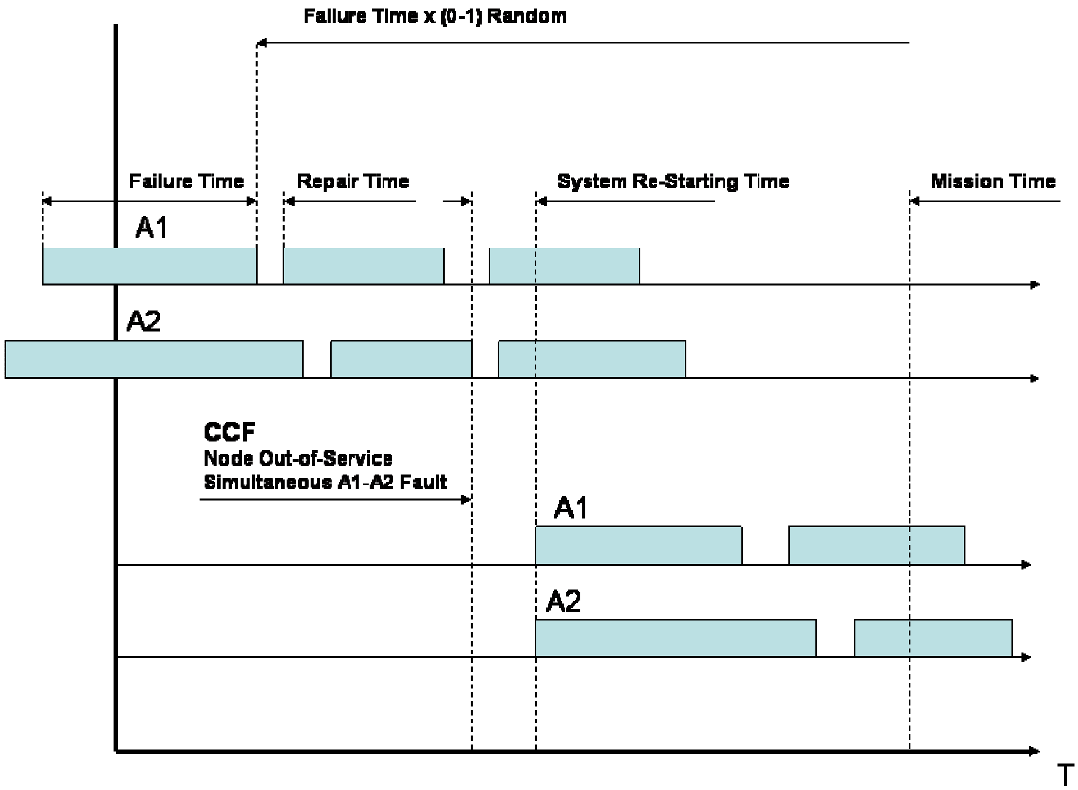


Fig. 6.11 Random Shift of the First Failure Time

It has to be pointed out that the probability to have the first failure is "forced" because the first renewal time is reduced by the coefficient "rand"; therefore, the reliability parameters (quantity of failures, out-of-service time) have also to be reduced considering the same "rand" coefficient for the first cycle.

6.8.4 Convenience to Use Forced Simulation

The very long MTTF suggested to try to adopt Forced Simulation (Importance Sampling); many attempts have been carried out, but always there is a relevant impact on the failure-repair renewal sequence.

The big problem is that two simultaneous sequences have to be simulated, therefore a change in time scale of one of them, or both of them, would affect the system performance.

For the time being, the Forced Simulation has been abandoned.

6.8.5 Coupler Impact on Reliability Indices – Preliminary Evaluation

The analytic evaluation reported in Birolini Textbook, Ch. 6.8.6.3 shows that the coupler reliability has no impact on the overall reliability of this simplified model. A series of simulations has been carried out, to quantify as far as possible this impact; the goal of this further analysis is to make available to the power systems designers a general criteria, without the need of an exhaustive simulation analysis for every specific case.

The coupler impact on the overall reliability is affected by the following factors:

- Coupler reliability, compared with the reliability of the up-stream branches
- Branches repair time, during which the coupler can suffer a failure

Assumptions:

- The coupler on call failure probability has not been taken into account in this preliminary evaluation
- The bus-bars failure has not been considered (rare event)

<u>First Simulation</u>

Input Data:

- Coupler reliability same as branches reliability (0.1 failure/year – very high figure, to obtain reliable simulation); this assumption is very drastic; it is relevant to a change-over circuit with circuit breakers only, without any other equipment.
- Long repair time (1000 h) of the up-stream branches

Simulation results:

- MTTF with coupler: 229.5 years
- MTTF (calculated) without coupler: 453.0 years

Conclusion:

- The MTTF is of the same order of the circuit without coupler, but approximately 50% less.
- The MTTF is however much higher than the one of a single branch, in this case 10 years.
- The solution of a redundant circuit with coupler proved to be very effective, although less then the solution without coupler that in many cases is not advisable for other technical reasons
- The 50% MTTF reduction can be considered as an upper bound, to be used as a very conservative general design criteria.

Simulation Applied to the System Reported on Birolini Textbook Ch. 6.8.6.3

Input Data:

- Coupler reliability 25% of the branches reliability (0.025 failure/year – very high figure, to obtain reliable simulation); this assumption is very drastic; it is relevant to a change-over circuit with circuit breakers only, without any other equipment.
- Repair time of the up-stream branches Rt = 360 h (a reasonable substitution time)

Simulation results:

- MTTF with coupler: 959 years
- MTTF (calculated) without coupler: 1232 years

Difference: 22%

Conclusions as for the first simulation.

A difference of approximately 20% can be considered a preliminary figure to be used as a suitable design criteria.

6.9 Detailed Load Node Model

6.9.1 Simulation Models

The model of the Load Node has to be more detailed, in order to take into account the specific performance of the node components; in fact the aggregation of all the components of a branch in a unique macrostructure is presenting many limitations.

As reported in the previous chapters, the components that will be considered are:

- High Voltage (HV) Circuit Breakers,
- Transformers,
- Middle Voltage (MV) Circuit Breakers,
- Middle Voltage (MV) Coupler,
- Middle Voltage (MV) Feeders,
- Simultaneous CCFs
- NON Simultaneous CCFs

The detailed load model has to take into account that:

- The Circuit Breakers have 3 groups of failure modes, with different consequences on the node reliability
- In this analysis, all the Transformers failure modes have the same consequences; therefore the transformers can be considered as macro-blocks including the up-stream and down-stream connection.
- The Coupler is the only equipment that is “dormant” and it is “called” to work in case of failure on a branch; furthermore, during its working time it is subject to failures.

- Feeders are not relevant for the load node, but a non cleared fault on a feeder can cause the out-of-service of the up-stream bus-bar and of al the other connected feeders; this is a CCF relevant to the MV distribution

6.9.2 Goals of the Load Node Reliability Analysis

The reliability goal of a Load Node is the availability of the MV distribution bus-bars; the detailed model of the Load Node allows a deeper analysis of the reliability performance, and specifically of these two main parameters:

- The overall time of the MV bus-bars simultaneous out-of-service, that means the black-out time of the whole downstream distribution system
- The out-of-service time of the two half bus-bars sections, that means the black-out time of the distribution system downstream the out-of-service half bus-bar.

In order to have a clear idea of the system performance, all the contributions by the several failure modes are individually computed, and specifically, for every failure mode:

- The failure quantities up to the mission time
- The relevant overall out-of-service time

6.10 Circuit Breakers Model

As reported in the previous Chapters, CBs have three main groups of failure modes:

- M1: Fault cleared by intervention of up-stream c.b and protections
- M2: Fault cleared without intervention of up-stream c.b and protections
- M3: Latent Fault, which inhibits fault tripping

6.10.1 M1 – Fault Cleared BY Intervention of Up-Stream C.B. and Protection

In case that a failure occurs on a High Voltage Circuit Breaker, the up-stream protections and circuit breakers installed in other nodes have to isolate the fault; therefore,

- the HV bus-bars up-stream the HV Circuit Breakers will be disconnected, and all the node will be disconnected as follows
- the two HV/MV branches will be both disconnected,
- the down-stream MV bus-bars will be isolated, and there is no possibility to feed the loads.

This situation is a CCF for the MV distribution downstream the load node.

There is no dependence with the downstream equipment (transformers, etc.) and no impact on their renewal sequence.

It is important to highlight that one only out-of-service circuit breaker with M1 failure mode can cause the complete load node out-of-service; therefore, in this case the two renewal sequences of the circuit breakers are fully independent; specifically, there is not a common re-starting time that will reset the renewal sequences. The difference between the renewal sequences of the HV circuit breakers in M1 failure mode and the renewal sequences of the A1 and A2 branches of the simplified model are reported in the following figure.

The repair and restoration times have to be analyzed in detail. The sequence after a M1 fault is as follows:

- The faulted c.b. is disconnected by means of the HV disconnecting switches
- The MV c.b. downstream the transformer, on the branch of the faulted c.b., has been automatically opened by the HV c.b.
- The non faulted c.b. is re-closed, and the relevant branch is re-energized

- The MV coupler is closed,
- The two MV bus-bars are re-energized, and eventually all the load are fed.
- The faulted c.b. is repaired;

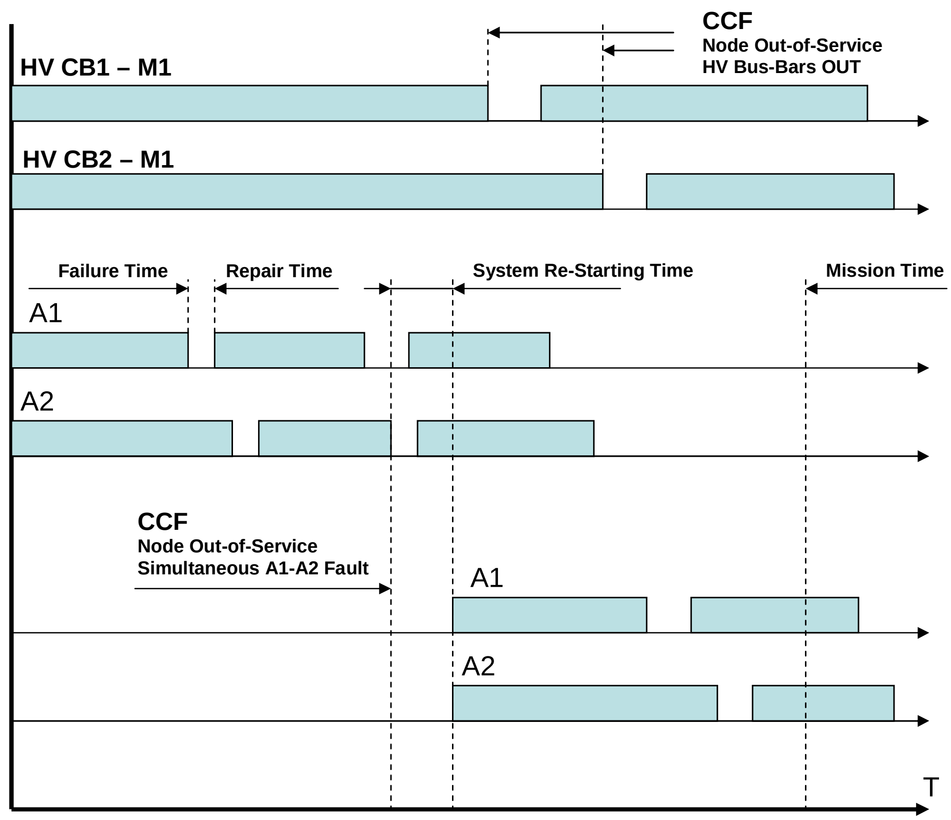


Fig. 6.12 Difference between failure-repair sequences of the HV Circuit Breakers in M1 mode, and the A1/A2 branches of the simplified model.

The detailed failure – repair – restart sequence is reported in the following figure.

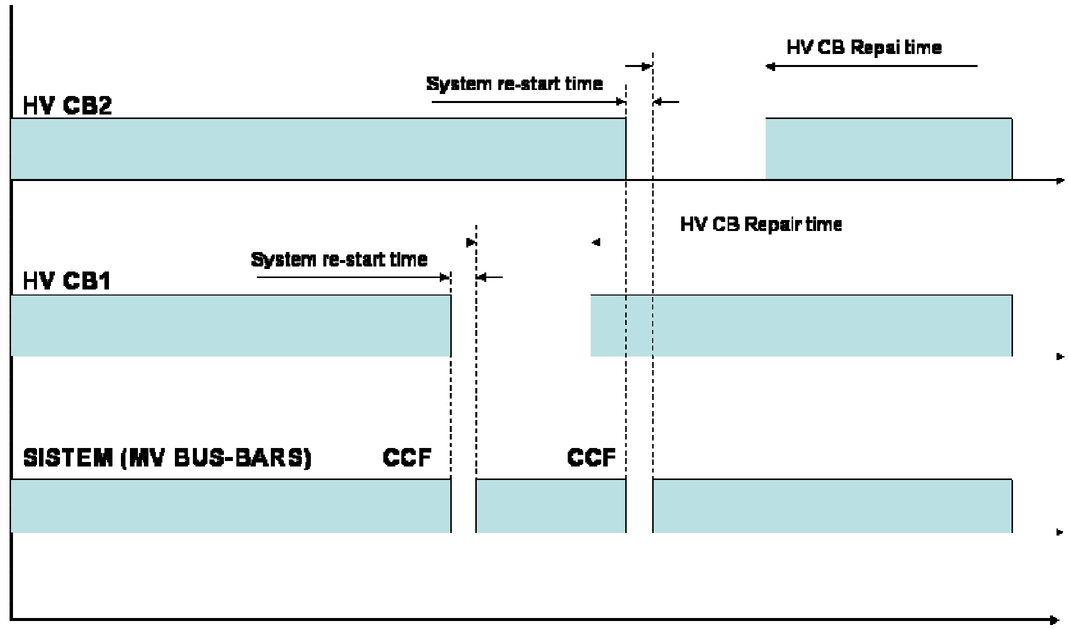


Fig.6.13 System Out-of-Service in case of HV CB Failure in M1 mode

The times to failure, and the two repair – restoring times are computed as random figures, with exponential probability distribution; however, it is possible to change the probability distributions, e.g. the repair times could be in accordance with log-normal distribution.

In this case, the program is computing:

- The number of out-of-services of every HV CB failure in M1 mode
- The total out-of-service, calculated as the sum of the service restoration times.

Of course, the above sequence is possible only if the MC coupler is working properly; therefore it is necessary to check the performance of the coupler. Two conditions have to be verified:

- Coupler working “On Demand” (M3) at the moment of the failure of the HV CB, when there is need to use the change-over sequence

- Coupler working without any failure, during the repair time of the faulted HV C.B.

It has to be pointed out that the repair time of the MV coupler is always shorter than the one of the HV CB.

In case that a Coupler failure would occur, the whole system will remain out of service for all the repair time of the coupler.

This sequence is reported in detail in the following figure.

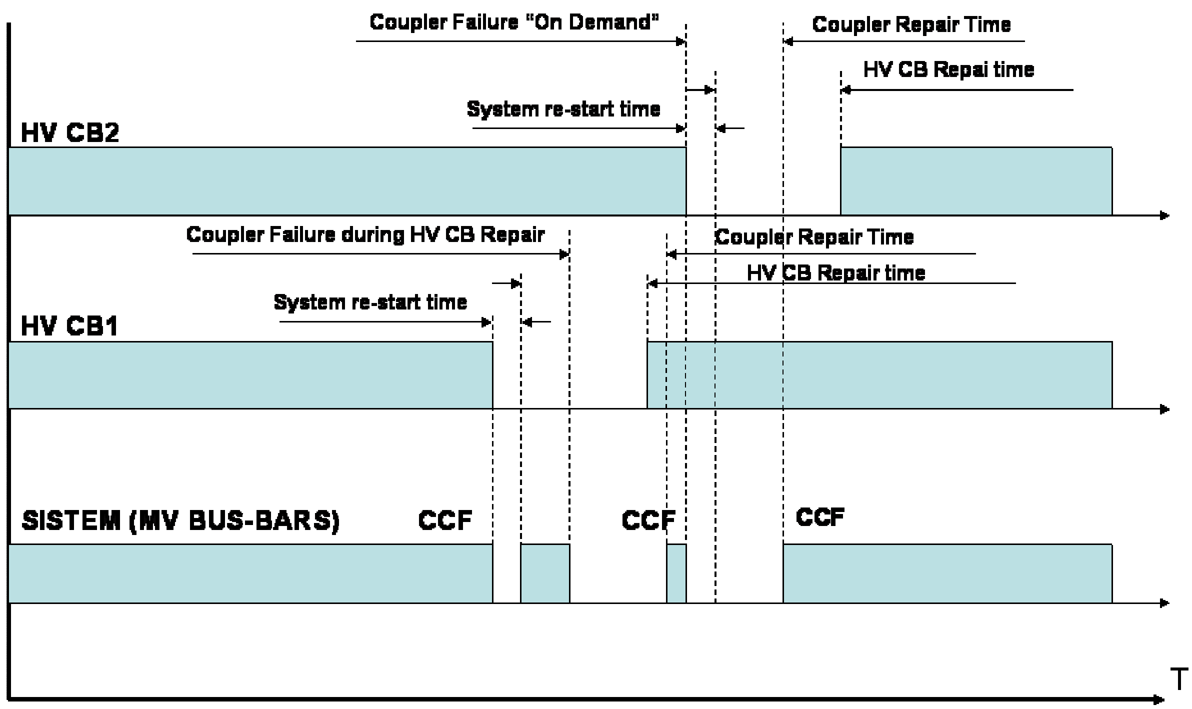


Fig. 6.14 MV Coupler Working Conditions

6.10.2 M2 – Fault Cleared <u>WITHOUT</u> Intervention of Up-Stream C.B. and Protection

M2 grouped failure mode is omitted in this analysis, because it can be considered as <u>negligible</u>.

The detailed M2 failure modes are listed here below, with their discussion.

- Does not close on command: HV circuit breakers in HV Substations are normally closed and there is no need to operate them; 24.6% of the overall failure rate is therefore actually overestimated. The real failure rate, or probability to work on demand, is in this case very very low, i.e. negligible.
- Closes without command: 1.1% of the overall failure rate. The HV CBs are always closed, therefore this failure rate is not applicable.
- Opens without command: I have never observed this failure in HV Substations, in more than 40 years; to me, it is negligible
- Does not make the current: as above
- Fails to carry current: as above
- Others: Negligible

Conclusion:

- M2 mode is negligible
- M2 is not causing CCF

Therefore, in this analysis it is omitted.

Similarity of M2 mode with Transformers failure: It causes the out-of-service of a branch; no impact on the other branch, and no out-of- service of the HV bus-bars ; the fault can be cleared by the same CB on demand (M3).

Therefore, in case M2 could be included into the transformer failure rate, using the transformer as a macro-block.

6.10.3 M3 – Latent Fault which Inhibits Fault Tripping

M3 is a failure “on demand”. It will be taken into account as a probability to be applied to the transformer block (see next chapters).

If the High Voltage CB is not clearing a fault “on demand” (M3) in a transformer block, the fault has to be cleared by the up-stream C.B.s and protections, and the HV bus-bars will go out-of-service; this will be a node CCF such as the M1 mode of a HV CB.

6.11 Transformers and Associated Equipment

The transformers failure sequence is based on the simplified one reported in the previous chapters, with simultaneous re-starting after a simultaneous failure.

Some specific sequences have to be added; it has to be pointed out that these added sequences are not relevant to the transformers and their associated equipment, but they are relevant to their protective and disconnecting equipment (circuit breakers, relays, etc.), as follows:

- Failure "On Demand" (M3) of the up-stream HV Circuit Breaker for a fault in a transformer
- Failure "On Demand" (M3) of the down-stream MV Circuit Breaker for a fault in a transformer; in this case, the opening of the MV circuit breaker is driven by the up-stream HV circuit breaker, to provide a complete disconnection of the transformer
- Failure "On Demand" (M3) of the MV coupler, after that the transformer has been completely disconnected by the up-stream and down-stream circuit breakers.

These added sequences are reported in the following chapters.

6.11.1 Transformer Fault and On Demand Failure of the Up-Stream HV CB

Failure Sequence

- Transformers 1 and 2 failure sequences are same as for the simplified model;
- At the moment of Transformer failure, it is necessary to check the "on Demand" HV Circuit Breaker release (M3 mode), as follows:
  - Definition of P "on Demand" failure probability

- Random number drawing (rand)
- If P>rand, the HV circuit breaker has not cleared the fault. In this case, the up-stream protections and circuit breakers of the HV incoming lines (upper level) while disconnect the whole Load Node. This is a CCF for the whole MV distribution down-stream the MV bus-bars.

Repair/Restoration Sequence

The system (the two half MV bus-bars) out-of-service time is the time to disconnect the HV circuit breaker and the transformer, by opening the HV disconnecting switches and by drawing out the down-stream MV circuit breaker.

The repair time of the branch, for the simultaneous fault of the transformer and of the HV circuit breaker, is assumed to be the transformer repair time, which is 99.9% the longer one; therefore, the transformer failure-repair sequence adopted for the simplified model is not changed.

Remarks:

- After the Load Node black-out, there is no need to restart simultaneously with the two branches in as-good-as–new condition, such as in the simplified model, because in fact one only branch is faulted
- In accordance with REA (Rare Event Approximation) Criteria, no other simultaneous failure is considered, such as MV circuit breaker failure on demand etc.

6.11.2 Transformer Fault and On Demand Failure of the Down-Stream CB

Failure Sequence

Same as for HV circuit breaker, adapted for the downstream MV circuit breaker as follows:

- Transformers 1 and 2 failure sequences are same as for the simplified model;
- At the moment of Transformer failure, it is necessary to check the "on Demand" MV Circuit Breaker release (M3 mode), as follows:
  - Definition of P "on Demand" failure probability
  - Random number drawing (rand)
  - If P>rand, the MV circuit breaker has not disconnected the faulted branch. In this case, it is not possible to close the MV coupler and the MV half bus-bar downstream the faulted branch will remain out-of-service. This is a CCF for the MV distribution down-stream the faulted branch only.

Repair/Restoration Sequence

The restoration time is the MV circuit breaker / Transformer disconnection time.

The repair time of the branch, for the simultaneous fault of the transformer and of the MV circuit breaker, is assumed to be the transformer repair time, which is 99.9% the longer one; therefore, the transformer failure-repair sequence adopted for the simplified model is not changed.

Remarks:

- REA (Rare Event Approximation) Criteria, same as for HV circuit breaker

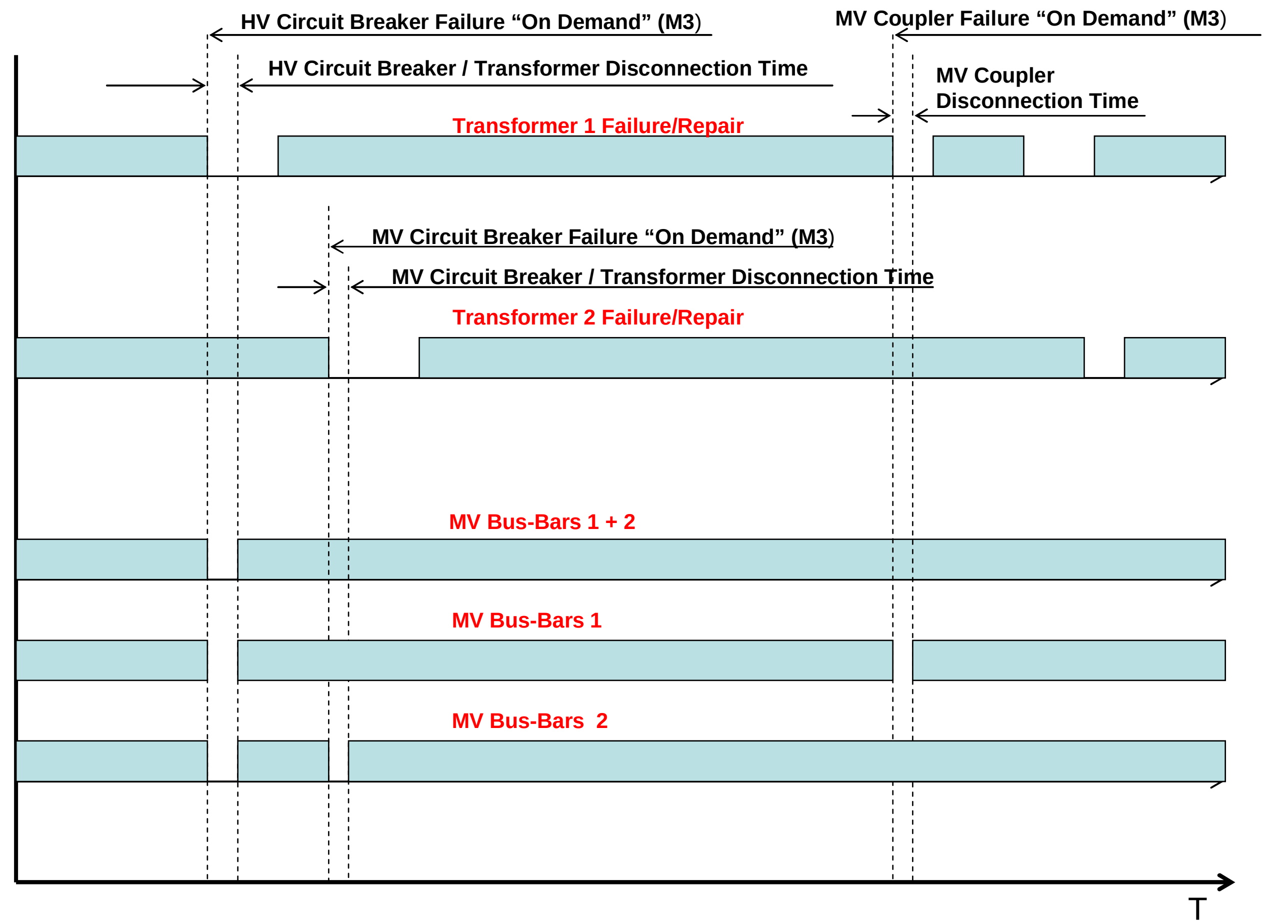


Fig. 6.15 Impact of "On Demand" (M3) Circuit Breakers Failures on Transformers Bays

6.11.3 Transformer Fault and On Demand Failure of the MV Coupler

Failure Sequence

Same as for HV circuit breaker, adapted for the MV coupler as follows:

- Transformers 1 and 2 failure sequences are same as for the simplified model;
- At the moment of Transformer failure, it is necessary to check the "on Demand" MV Coupler release (M3 mode), as follows:
  - Definition of P "on Demand" failure probability
  - Random number drawing (rand)

- If P>rand, the MV coupler has not connected the two half MV bus-bars, and the MV half bus-bar downstream the faulted branch will remain out-of-service. This is a CCF for the MV distribution down-stream the faulted branch only.

<u>Repair/Restoration Sequence</u>

The restoration time is the MV coupler disconnection time.

The repair time of the branch, for the simultaneous fault of the transformer and of the MV coupler, is assumed to be the transformer repair time, which is 99.9% the longer one; therefore, the transformer failure-repair sequence adopted for the simplified model is not changed.

Remarks:

- REA (Rare Event Approximation) Criteria, same as for HV circuit breaker

6.12 Non Cleared Fault on a MV Feeder

As described in the previous paragraphs, in case that a fault on a MV feeder downstream the MV bus-bars has not been cleared by the feeder MV circuit breaker, the protective relays selective operation will open the general up-stream MV circuit breaker, to isolate the fault; therefore, the relevant half MV bus-bar will be out-of-service, as well as all the downstream MV feeders; this is a CCF for the MV distribution, downstream the disconnected half MV bus-bar only.

Remarks:

- The above described failure / repair sequence is actually independent of all the other failure / repair sequences, and there is no superposition to be taken into account
- In accordance with REA (Rare Event Approximation) Criteria, no other simultaneous failures have been considered, such as the failure on-demand of the

up-stream general MV circuit breaker, and other faults on the branch that could lead to the out-of-service of the half MV bus-bar.

6.13 Equipment CCFs

6.13.1 Simultaneous CCFs

The detailed analysis reported in the previous Chapters led to the conclusion that in this type of Load Node there are no simultaneous Equipment CCFs. However, for sake of completeness, it is possible to image such a CCF, and to evaluate the consequences.

- Failures Sequence: For every component (HV circuit breakers, Transformers, etc.), a CCF failure sequence could be assumed; this sequence should be independent from all the other failure sequences.
- Impact: complete out-of-service of the node (black-out)
- Repair/Restoration Time: System time, to be evaluated; Surely, it would be a long time, taking into account both the equipment repair and the system restoration time. The components (and therefore the two branches too) would be re-started simultaneously, such as in the simplified model.

General Rules

- The simultaneous CCFs could be cumulated in a overall macrostructure, adding their failure rates
- The impact on the renewal sequence is same as the simultaneous fault of the transformers, reported in the simplified model

6.13.2 NON Simultaneous CCFs

The detailed analysis reported in the previous Chapters led to the conclusion that there is the possibility of a CCF in case of a failure on a Transformer, due to the possible overload of the other transformer.

It has to be pointed out that the failure modes of the first failure and of the CCF are different; the first failure can be an internal fault, conversely the CCF is due to an overload that can be caused by a design under-sizing.

The failure sequence is similar with the one of the MV coupler during a fault on a transformer.

- The failure of the second transformer, such as of the MV coupler, has to be checked during the repair time of the first transformer.
- The consequence is the out-of-service of the whole Load Node

A specific model has been developed, as follows:

- It is necessary to evaluate the probability of an overload;

  Pol: Overload Probability

  Rand: random number

  If Pol > rand there is an overload

- The disconnection time for overload is depending from the same overload (high overload -> short disconnection time); a simple linear relationship has been assumed.

  Tmax: Maximum disconnection time due to an overload

  Tmin: Minimum disconnection time due to an overload

  Disconnection Time: $T\min + (1 - \frac{rand}{Pol})(T\max - T\min)$

- The repair time of the CCF is relevant to a load shedding, and usually shorter than the repair time of the first failed equipment

Remark: In this specific case, the CCF could be avoided, anticipating the load shedding on the base of signals coming from:

- Alarms (overcurrent and thermal image relays, etc.)
- Autodiagnostic (temperature, etc.)

General Rule

A NON simultaneous CCF has to be modeled, taking into account that:

- The failure mode of the second fault can be different from the failure mode of the first fault;
- The time of the second failure can be a function of the failure mode;
- It is advisable to check the possibility to avoid the CCF, on the base of alarms and autodiagnostic, during the time between the first failure and the CCF
- The CCF repair/restoration time have to take into account the specific CCF failure mode; it can be very different from the equipment repair time.

At a first glance, it could seem that the NON simultaneous CCF modeling is very complicated; however, it has to be pointed out that all the network models have to be repetitive, therefore few NON simultaneous CCF models only are required; in this case, one only model is sufficient.

The failure /repair sequence is reported in the following figure.

6.14 Simultaneous Re-Starting of the Transformers Renewal Cycles

The Renewal Cycles of the transformers and associated equipment are simultaneously restarted after these type of faults:

- Simultaneous out-of-service of the two transformers, that means the first transformer is failed and the second transformer is failed too during the repair time of the first one;

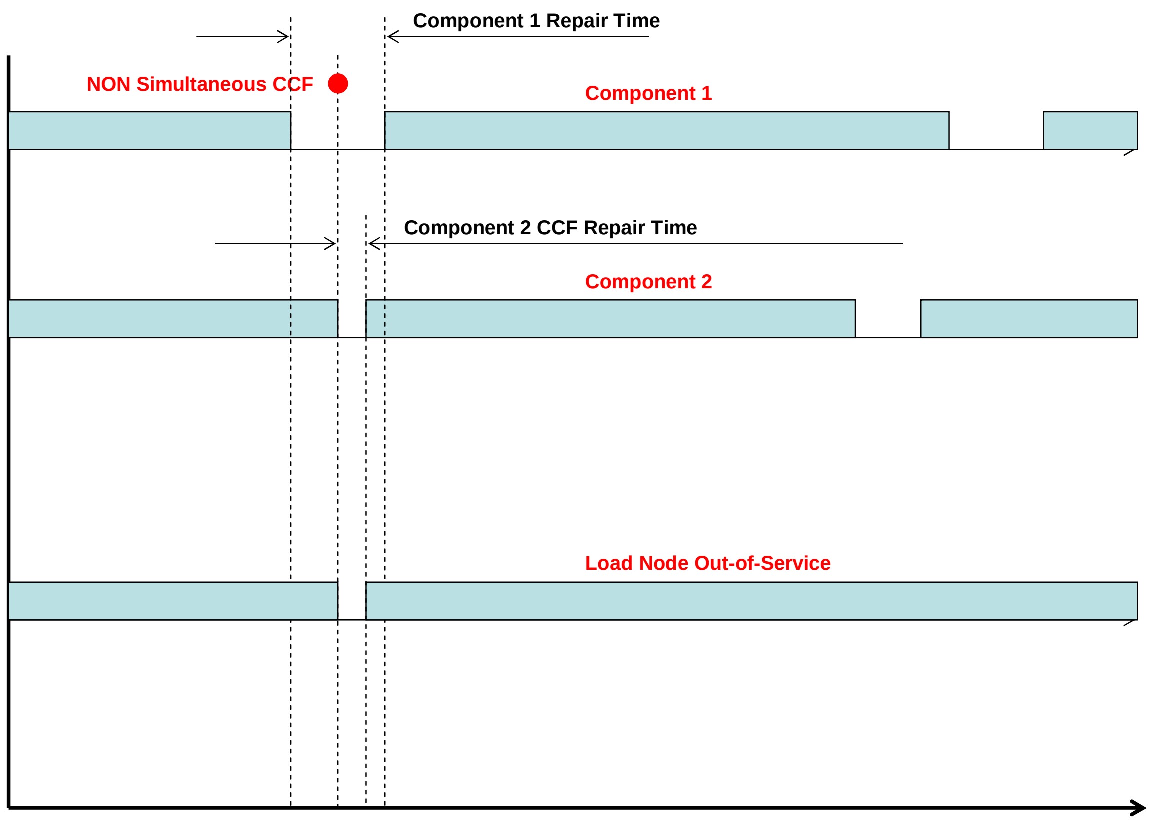


Fig. 6.16 NON Simultaneous CCFs

- NON simultaneous out-of-service of the transformers (NON simultaneous CCF);
- Coupler M1 failure during its closure, after a fault that is causing the out-of-service of a branch and the change-over sequence of the MV bus-bars.

The program is checking which is the first fault among the above ones, and it is restarting the failure-repair sequence, after the system restoration time; the sequence is repeated up to the mission time.

REMARK: The above described simultaneous re-starting is a specific assumption of this work; however, in some real situations it could not be applicable .

6.15 Input Data and Simulation Procedure

In power plants, the MTBF of the transformers and circuit breakers is much longer than the mission type; therefore, it is very unlikely to have more than one renewal cycles for the main components; usually, the renewal sequence is cut before reaching the first fault. In this condition, it is difficult to test all the failure-repair sequences, in order to be sure of the correct simulation of such a complex model.

It seemed therefore advisable to carry out two phases of simulation, as follows:

A) Simulation with higher failure rates and repair times, in order to be sure to check all the sequences described in previous chapters, and to reach a sound interpretation of the results.

B) Simulation with real failure rates and repair times, based on the model developed and debugged during phase A). The results are then compared with the ones of phase A), to check their congruity.

REMARK: The input data and the program sequences are “forcing” the CCFs, in order to highlight them. The simulation results will therefore show a CCFs failure rate and out-service-time that have to be considered at least 10 times greater than the realistic ones.

<table>
<tr><td colspan="2">INPUT DATA</td><td colspan="4">PHASE A)
Higher Failure Rates and Repair Times</td></tr>
<tr><td colspan="2">Component/System</td><td>Failure Rate (Failures/Year)</td><td>Failure Probability</td><td>Repair Time (h)</td><td>Disconnection Time (h)</td></tr>
<tr><td rowspan="2">HV
Circuit Breakers</td><td>M1 Failure Mode</td><td>0.1</td><td>-</td><td rowspan="2">1000</td><td rowspan="2">10</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.01</td></tr>
<tr><td rowspan="2">MV
Circuit Breakers</td><td>M1 Failure Mode</td><td>0.1</td><td>-</td><td rowspan="2">1000</td><td rowspan="2">10</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.01</td></tr>
<tr><td rowspan="2">MV Coupler</td><td>M1 Failure Mode</td><td>0.1</td><td>-</td><td rowspan="2">1000</td><td rowspan="2">5</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.01</td></tr>
<tr><td colspan="2">HV/MV Transformers / Equipment</td><td>0.1</td><td>-</td><td>1000</td><td></td></tr>
<tr><td colspan="2">Transformers Symultaneous CCF</td><td></td><td>0.1</td><td></td><td></td></tr>
<tr><td rowspan="2">MV Feeders
(5 both Busbars)</td><td>Feeder</td><td>0.5</td><td>-</td><td rowspan="2"></td><td rowspan="2">4</td></tr>
<tr><td>CB M1 Failure Mode</td><td>-</td><td>0.01</td></tr>
<tr><td colspan="2">System Restoration after Fault</td><td>-</td><td>-</td><td></td><td>10</td></tr>
</table>

<table>
<tr><td colspan="2">INPUT DATA</td><td colspan="4">PHASE B)
Normal Failure Rates and Repair Times</td></tr>
<tr><td colspan="2">Component/System</td><td>Failure Rate (Failures/Year)</td><td>Failure Probability</td><td>Repair Time (h)</td><td>Disconnection Time (h)</td></tr>
<tr><td rowspan="2">HV
Circuit Breakers</td><td>M1 Failure Mode</td><td>0.002</td><td>-</td><td rowspan="2">720</td><td rowspan="2">10</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.001</td></tr>
<tr><td rowspan="2">MV
Circuit Breakers</td><td>M1 Failure Mode</td><td>0.002</td><td>-</td><td rowspan="2">720</td><td rowspan="2">10</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.001</td></tr>
<tr><td rowspan="2">MV Coupler</td><td>M1 Failure Mode</td><td>0.002</td><td>-</td><td rowspan="2">720</td><td rowspan="2">5</td></tr>
<tr><td>M3 Failure Mode</td><td>-</td><td>0.001</td></tr>
<tr><td colspan="2">HV/MV Transformers / Equipment</td><td>0.012</td><td>-</td><td>720</td><td></td></tr>
<tr><td colspan="2">Transformers Symultaneous CCF</td><td></td><td>0.1 (1)</td><td></td><td></td></tr>
<tr><td rowspan="2">MV Feeders
(5 both Busbars)</td><td>Feeder</td><td>0.25</td><td>-</td><td rowspan="2"></td><td rowspan="2">4</td></tr>
<tr><td>CB M1 Failure Mode</td><td>-</td><td>0.001</td></tr>
<tr><td colspan="2">System Restoration after Fault</td><td>-</td><td>-</td><td></td><td>10</td></tr>
<tr><td colspan="6">REMARK :
(1) Probability to have a CCF after a fault
(2) The above failure rates and repair times are in accordance with the ones reported at Ch. 7.5.1</td></tr>
</table>

The simulation procedure has been based on the following working conditions and constraints:

- Preliminary simulations showed that, for “forced” input data (Phase A)), a reasonable convergence can be reached after at least 100,000 iterations.
- The MathLab program is quite complex, and more than 100,000 iterations cause a continuous running without reaching the end.
- Some results are expected, such as:
    - Failures and out-of-service times of Circuit Breakers and Transformers,
    - Sequential failures and out-of-service times in case of On Demand Failures of Circuit Breakers,
    - Failures and out-of-service times of MV feeders.

  Other results are not expected with a certain precision, due to the complexity of the renewal sequences, but their order of magnitude has to be compatible with the other expected results.

  The check-out of the expected-calculated results congruence is relevant, in order to assure that:

    - The program is working correctly,
    - A reasonable precision has been reached.

On the base of the above working conditions and constraints, the following simulation procedure has been adopted.

- Phase A): 100,000 iterations have been carried out. Taking into account that the Load Node is including two identical branches, with the same failure-renewal sequences, it is possible to evaluate a mean of the results of the two branches, and this is equivalent to the results of 2 x 100,000 = 200,000 iterations.

- Phase B): Preliminary simulations with 100,000 iterations showed a relevant variance of the calculated results, because many times the renewal sequences are cut off before the completion of the first cycle. It has been advisable to carry out four sets of 100,000 iterations, and to evaluate a mean of the results of the branches; this is equivalent to the results of 4 x 2 x 100,000 = 800,000 iterations.

Furthermore, two simulation modes were planned:

X Mode: Normal First Failure Time

Y Mode: Random First Failure Time (see Ch. 6.8.3)

Preliminary simulation tests showed that:

- X Mode - Normal First Failure Time: No problems
- Y Mode - Random First Failure Time
  - ➢ The variance of the results is too high; a much higher simulation quantity seems necessary to reach sound results
  - ➢ A detailed analysis of the simulation sequence led to the following conclusions:
    - In general, for the renewal cycles the adoption of a random first failure time is necessary
    - For the sequences with interdependencies between renewal cycles of more components, the adoption of a random first failure time is NOT necessary

On the base of the above results, it has been possible to revise the procedure relevant to the random first failure time, and Ch. 6.8.3. has been revised.

Conversely, a general revision of the program covering Y mode, that would have required a faster computing language (Fortran), has not been carried out, because this subject is not strictly related to the scope of this analysis (CCFs in large systems).

Eventually, the simulation analysis has been carried out taking into account normal first failure times only (X Mode).

6.16 Output Format

All the possible out-of-service conditions have been associated with an output, in order to have a very comprehensive picture of the Load Node performance; the outputs are listed in the tables here below.

For every output, the following data have been evaluated:

CODE	**OUTPUT**	**REMARKS**
MN	Failures within Mission Time	Quantity of Renewal Cycles within the Mission Time. It is indicating if the system either has reached a steady state condition or it is in the early transient stage
AN	Failures / Year	Failure Rate within the mission time
MT	Out-of-Service Time within Mission Time	Expected overall out-of-service time
AT	Out-of-Service Time / Year	To be used to evaluate the repair rate, and, once cumulated and associated with the failure rate, to evaluate the availability

REMARKS:

- The above Outputs have to be considered as <u>preliminary results</u>, and in fact they are not cumulated to evaluate the overall reliability figures at the MV Bus Bars, which are the goal of this analysis. The overall reliability figures have to take into account also the out-of-service of the up-stream HV Bus Bars due to the HV system dynamics; they will be evaluated in the next chapters.

- In the following table, Item B1- CCFs in Transformers Branches, is a figure cumulating the failures that cause the simultaneous out-f-service of both MV Bus-Bars and the whole system re-starting:

FAILURE	**REMARKS**
Simultaneous Failure of the Transformers, i.e. failure of the second transformer during the repair time of the first one	This is not a CCF, however it is included in this category because it has the same effect (the simultaneous out-f-service of both MV Bus-Bars and the whole system re-starting)
Non Simultaneous failure, i.e. CCF due to the overload of the second transformer during the repair time of the first one	Component CCF
MV Coupler internal fault during the repair time of the Transformer Branch	System CCF

OUTPUT DATA DESCRIPTION						
			Out-of-Service			
N.	Code	Failure	HV Bus Bars	1 MV semi Bus Bar	Both MV Bus Bars	Remarks
A1	HVCB1/2_M1	HV CB Internal Fault (M1)	X		X	
A2	HVCBC1/2_M3	MV Coupler does not close on demand, after fault (M1) and disconnection in a HV CB		X		
A3	MVCBCM1_1/2	MV Coupler Internal Fault, while it is closed after fault (M1) and disconnection of a HV CB			X	
B1	FST	System Out-of-Service due to Transf. Branch Failures • Simultaneous Failure • Non Simultaneous CCFs • MV Coupler internal fault during the repair time of the Transformer Branch			X	Cumulative figure of all the CCFs
C1	TR1/2	Transformer Branch Failures				The out-of-service of a transformer does not cause any out-of-service in the MV bus-bars, because the MV coupler will connect the MV semi Bus-Bar downstream the faulted transformer to the other semi Bus-Bar. This outpour is used for statistics only, to check the program performance
C2	HVCB1/2_M3	HV CB does not open for a Transformer Branch failure	X		X	
C3	MVCB1/2_M3	MV CB does not open for a Transformer Branch failure		X		
C4	CBC1/2_M3	MV Coupler does not close on demand, after fault in a Transformer Branch		X		
D1	B1/2	Feeders failure, not cleared by its own CB, and cleared by main up-stream MV CB		X		

6.17 Simulation Results

The simulation results of the Load Node Model are reported in the following tables; they cover:

Alternative A) – Higher Failure Rates and Repair Times

Alternative B) – Normal Failure Rates and Repair Times

6.17.1 Preliminary Analysis

- The calculated results of Alternative A) are in accordance with the expected figures. Considering that in Alt. A) all the program sequences are working repeatedly, the program can be considered as validated;
- The CCFs failure rates are high figures; this result was expected because, as reported in the previous chapters, the input data and the program sequences are "forcing" the CCFs, in order to highlight them. It is reasonable to assume that these failure rates are at least 10 times higher than the real ones.
- The CCFs out-of-service times are relevant; even though the CCF failure rates are at least 10 times are higher than the real ones, this result is mainly due to the fact that an overall CCF is requiring a longest restoration time. This result is important, because it is demonstrating the relevant impact of CCFs

6.17.2 Generalized Load Node Model

Simulation allowed to clearly identify the hidden structure and interdependencies of the Load Node. Simulation results show that many results could have been directly evaluated without,simulation, and that the other ones, relevant to CCFs and complex sequences with interdependencies, seem to become predictable after a sensitivity analysis.

The important result is that it is possible with very good approximation to assume that the Load Node is a "macrostructure" , i.e. a Generalized Load Model, whose performance is predictable without any interdependence with the up-stream network. On the base of the above assumption, there is no need to simulate the overall system “network + load nodes”; conversely, it is possible to simulate the up-stream network only, and to superpose in a second phase the Generalized Load Node model. The only input data from the Generalized Load Node model to be included in the up-stream network model are the failure modes of the Load Nodes that cause the disconnection of the HV bus-bars (see next chapter).

LOAD NODE SIMULATION									ALTERNATIVE A)					Random Starting: NO Iterations: 1 x 100,000 Failure Rates: Forced Repair Times: Slightly Higher
			Calculated by Simulation				Expected Rounded Figures				Out-of-Service			
N.	Code	Failure	Failures within Mission Time	Failures /Year (Failure Rate)	Out-of_Service Time within Mission Time (Y)	Out-of_Service Time /Year	Failures within Mission Time	Failures /Year (Failure Rate)	Out-of_Service Time within Mission Time (Y)	Out-of_Service Time /Year	HV Bus Bars	1 MV semi Bus Bar	Both MV Bus Bars	Remarks
A1	HVCB1/2_M1	HV CB Internal Fault (M1)	4.9397	0.0988	0.0057	1,13e-4	5.0	0.1	0.0057	1.14e-4	X		X	
A2	HVCBC1/2_M3	MV Coupler does not close on demand, after fault (M1) and disconnection in a HV CB	0.0496	9.94e-4	0.0057	1,13e-4	0.05	0.001	0.0057	1.14e-4		X		
A3	MVCBCM1_1/2	MV Coupler Internal Fault, while it is closed after fault (M1) and disconnection of a HV CB	0.0546	0.0011	0.0063	1.26e-4							X	Expected rounded figures not available, because of too many working conditions
B1	FST	System Out-of-Service due to Transf. Branch Failures • Simultaneous Failure • Non Simultaneous CCFs • MV Coupler internal fault during the repair time of the Transformer Branch	2.1796	0.0436	0.0124	2.49e-4							X	Expected rounded figures not available, because of too many working conditions
C1	TR1/2	Transformer Branch Failures	4.9579	0.0992	0.5639	0.0113	5.0	0.1	0.0057	1.14e-4				For statistics only
C2	HVCB1/2_M3	HV CB does not open for a Transformer Branch failure	0.0505	0.0010	5.84e-5	1.17e-6	0.05	0.001	5.70e-5	1.14e-6	X		X	
C3	MVCB1/2_M3	MV CB does not open for a Transformer Branch failure	0.0488	9.78e-4	5.55e-5	1.11e-6	0.05	0.001	5.70e-5	1.14e-6		X		
C4	CBC1/2_M3	MV Coupler does not close on demand, after fault in a Transformer Branch	0.0495	9.87e-4	2.84e-5	5.68e-7	0.05	0.001	2.85e-5	5.70e-7		X		
D1	B1/2	Feeders failure, not cleared by its own CB, and cleared by main up-stream MV CB	1.2511	0.0250	5.71e-4	1.14e-5	1.25	0.0250	5.71e-4	1.14e-5		X		

LOAD NODE SIMULATION

ALTERNATIVE B)

Random Starting: NO
Iterations: 4 x 100,000
Failure Rates: Real
Repair Times: Real

N.	Code	Failure	Calculated by Simulation				Expected Rounded Figures				Out-of-Service			Remarks
			Failures within Mission Time	Failures /Year (Failure Rate)	Out-of_Service Time within Mission Time (Y)	Out-of_Service Time /Year	Failures within Mission Time	Failures /Year (Failure Rate)	Out-of_Service Time within Mission Time (Y)	Out-of_Service Time /Year	HV Bus Bars	1 MV semi Bus Bar	Both MV Bus Bars	
A1	HVCB1/2_M1	HV CB Internal Fault (M1)	0.0992	0.002	1.14e-4	2.27e-6	0.1	0.002	1.14e-4	2.27e-6	X		X	
A2	HVCBC1/2_M3	MV Coupler does not close on demand, after fault (M1) and disconnection in a HV CB	1.11e-4	2.22e-6	1.04e-5	2.08e-7	1.00e-4	2.00e-6	1.14e-5	2.27e-7		X		
A3	MVCBCM1_1/2	MV Coupler Internal Fault, while it is closed after fault (M1) and disconnection of a HV CB	1.5e-5	3.0e-7	1.22e-6	2.44e-8							X	Expected rounded figures not available, because of too many working conditions
B1	FST	System Out-of-Service due to Transf. Branch Failures • Simultaneous Failure • Non Simultaneous CCFs • MV Coupler internal fault during the repair time of the Transformer Branch	1.1201	0.0224	0.0064	1.28e-4							X	Expected rounded figures not available, because of too many working conditions
C1	TR1/2	Transformer Branch Failures	0.5985	0.012	0.0491	9.81e-4	0.6	0.012	0.0493	9.83e-4				For statistics only
C2	HVCB1/2_M3	HV CB does not open for a Transformer Branch failure	5.39e-4	1.08e-5	6.00e-7	1.12e-8	6.00e-4	1.20e-5	6.85e-7	1.36e-8	X		X	
C3	MVCB1/2_M3	MV CB does not open for a Transformer Branch failure	5.85e-4	1.17e-5	6.76e-7	1.35e-6	6.00e-4	1.20e-5	6.85e-7	1.36e-8		X		
C4	CBC1/2_M3	MV Coupler does not close on demand, after fault in a Transformer Branch	5.71e-4	1.14e-5	3.27e-5	6.53e-7	6.00e-4	1.20e-5	3.42e-5	6.85e-7		X		
D1	B1/2	Feeders failure, not cleared by its own CB, and cleared by main up-stream MV CB	0.0501	0.0010	2.29e-5	4.58e-7	0.5	0.0010	2.28e-5	4.57e-7		X		

6.17.3 Input Data for the Upper Level System

The average failure rates and repair times of the failure modes that cause the out-of-service of the HV Bus-Bars are reported in the following tables.

HV BUSBARS OUT-OF-SERVICE ALTERNATIVE A)			Failure Rate (Failures/Y)	Out-of-Service Time/Y (Y)
A1	HVCB1/2_M1	HV CB Internal Fault (M1)	0,0988	1,30E-04
C2	HVCB1/2_M3	HV CB does not open for a Transformer Branch failure	0,0010	1,17E-06
		Cumulated	**0,0998**	**1,31E-04**
		Average Repair Time (h)		**11,51**

HV BUSBARS OUT-OF-SERVICE ALTERNATIVE B)			Failure Rate (Failures/Y)	Out-of-Service Time/Y (Y)
A1	HVCB1/2_M1	HV CB Internal Fault (M1)	0,0020	2,70E-06
C2	HVCB1/2_M3	HV CB does not open for a Transformer Branch failure	1,08E-05	1,20E-08
		Cumulated	**0,0020**	**2,71E-06**
		Average Repair Time (h)		**11,81**

Considering that there are two HV Circuit Breakers for every Load Node, the failure rates and repair times of the HV Bus-Bars due to faults of the Load Nodes become as follows:

Alternative A)

HV Bus-Bars Failure Rate 0.2 Failures /Year (rounded figure)

HV Bus-Bars Restoration Time 11.51 h

Alternative B)

HV Bus-Bars Failure Rate 0.004 Failures /Year (rounded figure)

HV Bus-Bars Restoration Time 11.81 h

6.18 *Summary and Interpretation of the Results*

The output data relevant to "real" input only are being considered. They have been validated by the coherence with the output data from "forced" input, and with the expected data; they are also coherent with the Ring Analysis output data from "real" input, and therefore they are suitable for an overall "Ring + Load Node" analysis.

The main reliability parameters are evaluates as follows:

Reliability	Sum of the Quantities of Failures / Year
Unavailability	Sum of the Out-of-Service Times (Years) / Year

It has to be pointed out that three failures reported in the former tables have not been considered, for the following reasons:

N.	**Failure**	**Reason to be Neglected**
A1	HV CB Internal Fault	Included as Equivalent Node failure in the Ring Analysis
C1	Transformer Branch Failure	It is not a cause of MV bus-bars out-of-service; it has been reported for statistics only, to check the congruence of the other output data.
C2	HV CB does not open for a Transformer Branch failure	Included as Equivalent Node failure in the Ring Analysis

The overall results are summarized in the following tables.

ONE MV SEMI BUS-BAR OUT-OF-SERVICE

N.	Unit Failures / Year (Failure Rate)	Unit Out-of-Service Time / Year (Unavailability)	Units	Overall Failures / Year (Failure Rate)	Overall Out-of-Service Time / Year (Unavailability)
A2	2.22E-06	2.08E-07	2	4.44E-06	4.16E-07
C3	1.17E-05	1.35E-06	2	2.34E-05	2.70E-06
C4	1.14E-05	6.53E-07	2	2.28E-05	1.31E-06
D1	1.00E-03	4.58E-07	1	1.00E-03	4.58E-07
			Tot.	**1.05E-03**	**4.88E-06**

BOTH MV SEMI BUS-BARS OUT-OF-SERVICE

N.	Unit Failures / Year (Failure Rate)	Unit Out-of-Service Time / Year (Unavailability)	Units	Overall Failures / Year (Failure Rate)	Overall Out-of-Service Time / Year (Unavailability)
A3	3.00E-07	2.44E-08	2	6.00E-07	4.88E-08
B1	0.0224	1.28E-04	1	2.24E-02	1.28E-04
			Tot.	**2.24E-02**	**1.28E-04**

It is evident that the more relevant failure is B1 - System Out-of-Service due to Transf. Branch Failures; this is a cumulative failure, including the following failure modes which are leading to the system out-of-service:

1. Simultaneous Failure,
2. Non Simultaneous CCFs,
3. MV Coupler internal fault during the repair time of the Transformer Branch.

A subdivision of the output results of the above failure modes has not been possible, due to the several intersections of the complex failure sequences; however, few simple calculation allow to reach a sound interpretation as follows:

1) Simultaneous Transformer Failure

$\lambda := 0.012$ failures / year (Failure Mode C1)

$T := 0.000981$ Out-of-Service Time (Year) / Year (Failure Mode C1 - One Transformer)

$MTTR := \frac{T}{\lambda}$ $MTTR = 0.082$ Year $MTTR \cdot 8760 = 716.13$ h Close to 720 h OK

$\mu := \frac{1}{MTTR}$ $\mu = 12.232$

$TUA := \left(\frac{\lambda}{\mu}\right)^2$ $TUA = 9.624 \times 10^{-7}$ Aprox. Tranformer Unavailability
Negligible

2) Non Simultaneous CCF

$pT := 0.1$ Probability to have an overload

$Tmin := 10$ h $Tmax := 100$ h

$AT := \left(Tmin + \frac{Tmax - Tmin}{2}\right)$ $AT = 55$ h Average Time to Overload

$\Delta T := \left(MTTR - \frac{AT}{8760}\right)$ $\Delta T = 0.075$

$CCF\_UA := \lambda \cdot pT \cdot \Delta T$ $CCF\_UA = 9.057 \times 10^{-5}$ Unavailability due to
Non Simultaneous CCF
Rounded Figure 10-4

3) Coupler Failure for a Fault in a Transformer Branch

$pC := 0.001$ Probability of Coupler Failure on Demand

$CT := 5$ h Coupler Replacement Time

$C\_UA := \lambda \cdot pC \cdot \frac{5}{8760}$ $C\_UA = 6.849 \times 10^{-9}$ Unavailability due to Coupler Failure
Negligible

Item 2) is the predominant one and it is of the same order of the overall availability of Failure B1; the difference is due to the inter-dependabilities between the Montecarlo sequences, truncations due to the short mission time and the long MTBF, etc.

Eventually, a rounded figure UA = 1.3 e-4 can be assumed for the Unavailabiliy of both MV Bus-Bars

Discussion:

- Unavailability considering One MV Semi Bus-Bar Out-of-Service: Rounded Figure 5 E-06
- The Non- simultaneous CCFs is the more relevant figure; it means that CCF are very important in this reliability analysis.
- The assumption that the out-of-service time due to a Non -simultaneous CCF is lasting up to the repair of the first failed transformer is very drastic; usually there are some compensation methods to reduce overload, such as load shedding; however:
  - It is very difficult to carry out a load shedding in a public Utility
  - A load shedding is a reduction of power supply availability
- The probability p = 0.1 to have an overload can seem very high, however, in accordance with the Author's experience, it has to be considered as common in developing countries, where:
  - Loads are usually low, but the load forecast is with high increase rates,
  - There is need to wait for a new foreign fund to replace the transformers

  Considering that the B1 Unavailability is predominant, and it is linearly related with the probability to have an overload, the following figures are proposed, for the overall "Ring + Load Node" analysis.

Overload Probability for a Fault in a Transformer Branch	Unavailability of Both the MV Bus-Bars (Rounded Figure)	Remarks
0.1	1.3 e-4	P = 0.1 is likely to happen in developing countries
0.01	1.3 e-5	P = 0.01 has to be surely expected in developing countries
0.001	1.3 e-6	P = 0.001 can be considered as typical of developed countries

- The unavailability of the coupler has an impact of around 10-15% on the overall unavailability of the two bus-bars, but without the non-simultaneous CCFs; this coupler reliability performance has to be considered as more realistic than the one evaluated for the simplified sub-station model, and reported at Ch. 6.7.
- General Criteria: *A predominant CCF has to be expected, in case that a main design conditions is changed;* in this case, the main design condition is the reserve capability of the redundant transformers.

6.19 3rd Objective - Conclusion

The above described Load Node model is very detailed and it is taking into account all the several failure modes; therefore, a sound interpretation of the results has been possible, and specifically of the impact of the several failure modes.

The results interpretation is leading to a simplified math model, reported in Ch. 7.20. This model can be used by the substation designer to easily evaluate, with a reasonable precision, the availability at the MV bus-bars; the simplified math model can be used as an equivalent model to be superposed to the upper level grid, in order to reduce the simulation complexity and to facilitate the overall results interpretation.

7 4th Objective - Upper Level Network – The Ring

7.1 *4th Objective - Summary*

What Is Important

- Ring Structure: A Ring is a (n-1 out of n) redundant structure fed from two extremities, and feeding several load nodes; power systems rings are usually open in an intermediate point. The out-of-service of a Node is causing the cascade out-of-service of other Nodes, therefore this structure is a suitable case study for the generalized network theory.
- Ring General Theory: There is not a general analytic theory of the "ring" although it is a common (n-1 / n) redundant circuit. Conversely, it is possible and not difficult to evaluate the ring performance by means of Montecarlo simulation. The main problem is that a network designer cannot use Montecarlo simulation every time that he has in mind to use a ring circuit.

New Contribution

- Detailed Network Analysis**,** including re-configuration, protections, different failure modes for circuit breakers, system CCFs to reach a comprehensive understanding of the ring performance
- Simplified Mathematical Model, to be used to evaluate reliability parameters even though with a certain margin of uncertainty, but suitable for feasibility studies (compare circuit alternatives etc.) and basic design.

7.2 Network Structure

As mentioned in the previous chapters, two network levels will be considered:

- HV Network: a HV ring interconnecting the Load Nodes, open in an intermediate point and re-configurable (displacement of the open point) after fault
- Load Nodes with two voltage levels: HV/MV substations, with two MV bus-bars interconnected by an open tie-breaker that can be closed in case one of the HV/MV branches is out-of-service.

The simplified overall scheme is reported in the following figure. The upper part is the Ring, that is covered in this section; the lower part are the Load Nodes, that have been covered in Chapter 7.

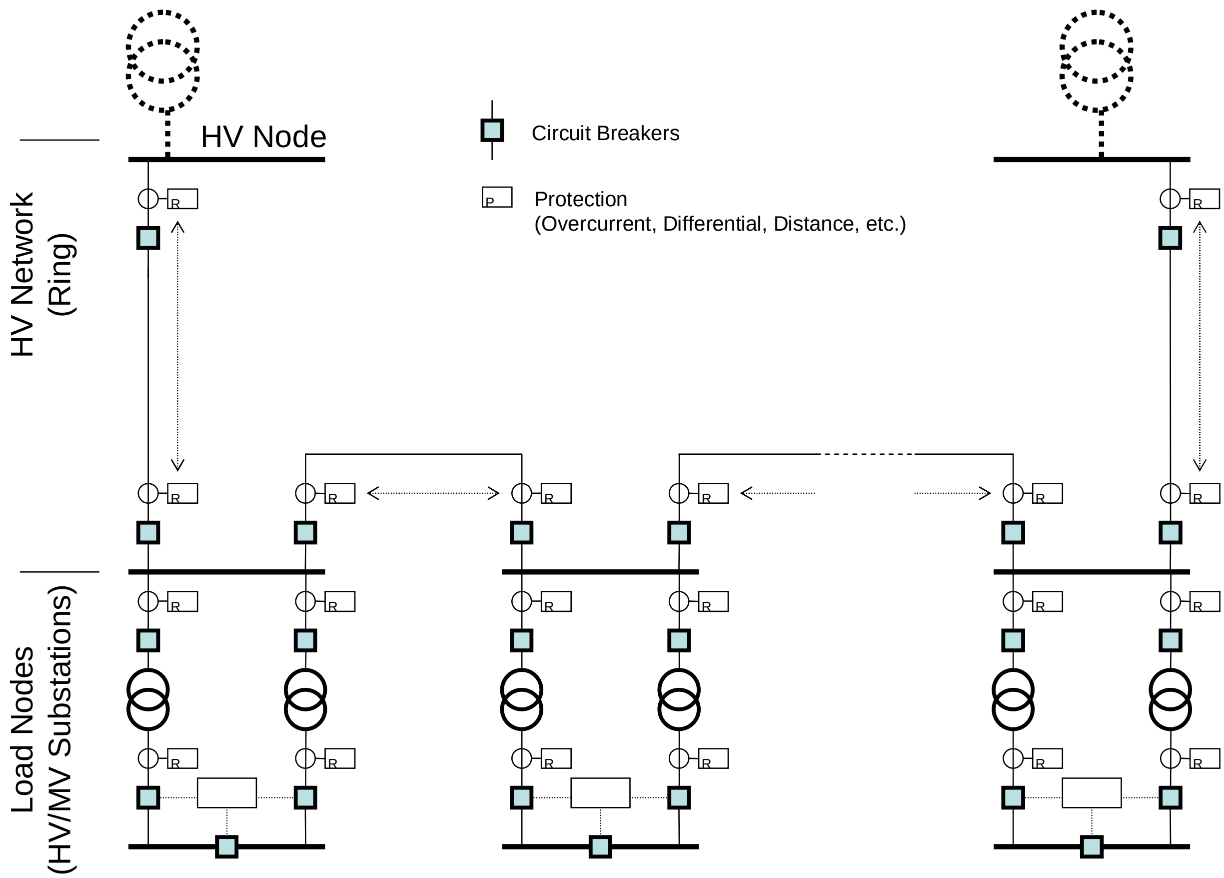


Fig. 7.1 Ring + Load Nodes Simplified Scheme

A Ring is a (n-1 out of n) redundant structure fed from two extremities, and feeding several load nodes. The Ring can be either open or closed; the HV Ring considered in this analysis is relevant to a power transmission system, and it is open in an intermediate point (see next paragraphs).

There is not a general analytic theory of the "ring" although it is a common (n-1 / n) redundant circuit. Conversely, it is possible and not difficult to evaluate the ring performance by means of Montecarlo simulation, the Author has already carried out some reliability analysis of telecommunication and power distribution rings.

The main problem is that a network designer cannot use Montecarlo simulation every time that he has in mind to use a ring circuit; it would be too time wasting, and too complicated. One of the objectives of this analysis is to reach a comprehensive understanding of the ring performance, to be used as general parameters for evaluate circuit alternatives even though with a certain margin of uncertainty; the analysis is being carried out by means of Montecarlo simulation, with specific care paid to the results interpretation.

In this report, the Ring will be identified taking into account:

- The "n" quantity of the "N_i" Load Nodes
- The position of the "Open" Circuit Breaker.

The quantity of "B_i" interconnection HV lines is related to the quantity of Load Nodes as follows:

n Nodes → n+1 Branches

The HV Circuit Breakers up-stream and down-stream the HV lines have been codified with reference to the Nodes codes, as follows:

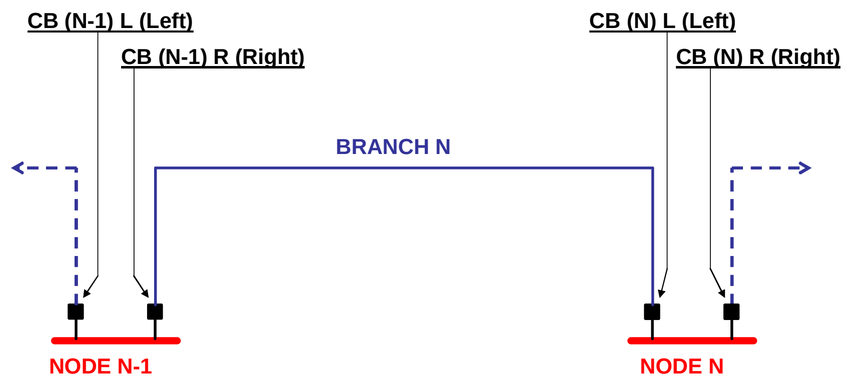


Fig. 7.2 Circuit Breakers Codes

The Ring model adopted for this report is a complex structure, with these specific characteristics:

- It is quite extended, more than in usual networks; the reason is that in this way it is possible to try to reach generalized conclusions;
- It is operated as open, with a pre-determined configuration that can be identified by the position of the open point; after fault, the ring is re-configurated, in order to assure power supply again to all the load nodes but sometimes the ones directly affected by the fault. The reason to work with an open ring is that the short circuit level is lower (feeding from one only side), and there is not a problematic power sharing from the feeding points. Because the open point is only one, and it is an open Circuit Breaker at one only extremity of a branch, there is an intrinsic asymmetry of the model.
- This ring model is including the protection system operation, which clears the faulted branches/nodes in a selective way;

- Two circuit breakers failure modes (M1 and M3, see Ch. 6.6.2) have been taken into account, with different impact on the disconnection of nodes and branches to clear the fault.

Due to the above characteristics, that are typical of rings in advanced power transmission systems, this model can be considered one of the more complex ring structures.

The simplified Ring scheme, without the Load Nodes, is reported in the following figure.

REMARK:

- Codes of the Circuit Breakers, just down-stream the distribution bus-bars in the EHV/HV Substations: CB M (Main) Left and Right

Assumption:

- The HV Ring is relevant to a HV Utility, therefore there is not a “Starting Date” for the system; in this case, the model of the Load Nodes is independent from the model of the Upper Level Network (Ring) (see previous chapters) and it can be superposed in a second phase.

In this model, n = 5 Quantity of Nodes

n+1= 6 Quantity of Branches

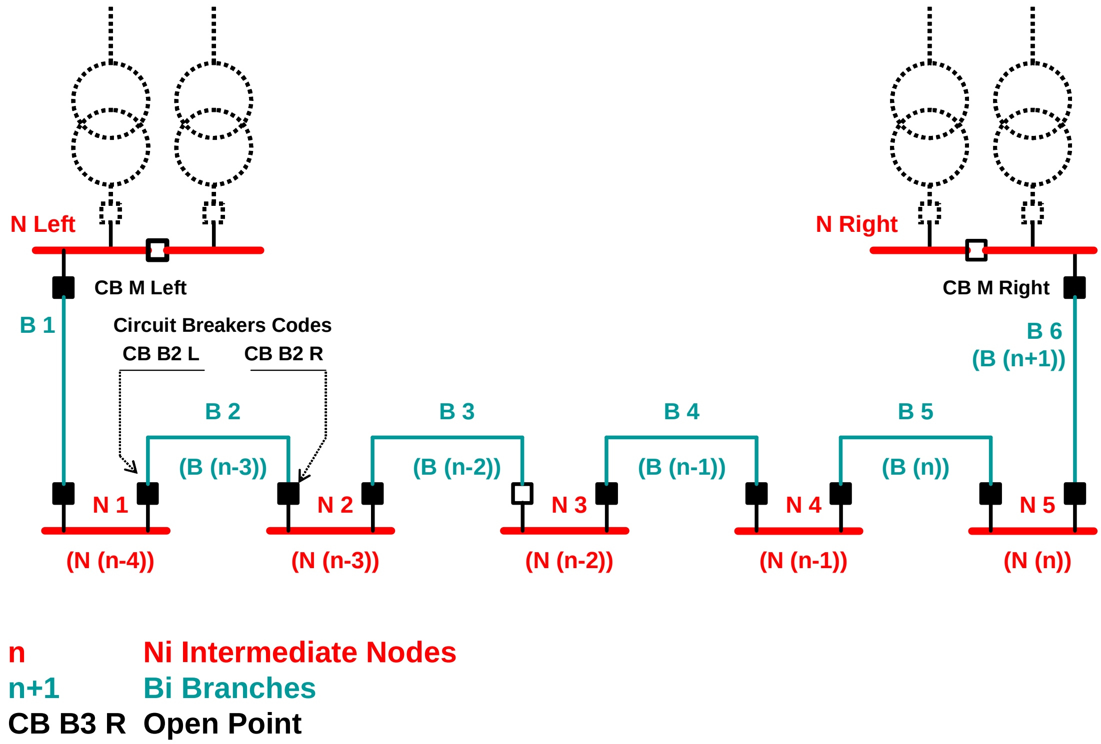


Fig. 7.3 Simplified Ring Scheme

7.3 Network Structure

The analysis of the ring model is carried out in accordance with the general criteria adopted in this report for the overall analysis of large networks, and reported in the previous Chapters:

- A priori identification of the “residence” states
- Identification of virtual Nodes and Branches
- Definition of the starting time for the several renewal cycles

➢ A Priori Identification of the Residence States

The “Residence” states are the “out-of-service” condition of the several Load Nodes

➢ Identification of Virtual Nodes and Branches

- Branches: they include High Voltage Transmission Lines, and all the equipment between the up-stream and down-stream circuit breakers, such as current and voltage transformers, disconnecting switches, lightning arrestors, etc. The failure of these equipment is cleared by the release of the up-stream and down-stream circuit breakers only.
- Nodes: Circuit Breakers failure modes (see previous Chapters, and par. 8.5 of this Chapter) M1 and M3 have been included in the virtual nodes, because they cause the release of the up-stream circuit breakers; M2 failure mode has been neglected. The Nodes Equivalent Model, and its impact on the Ring, are described in the following chapters.

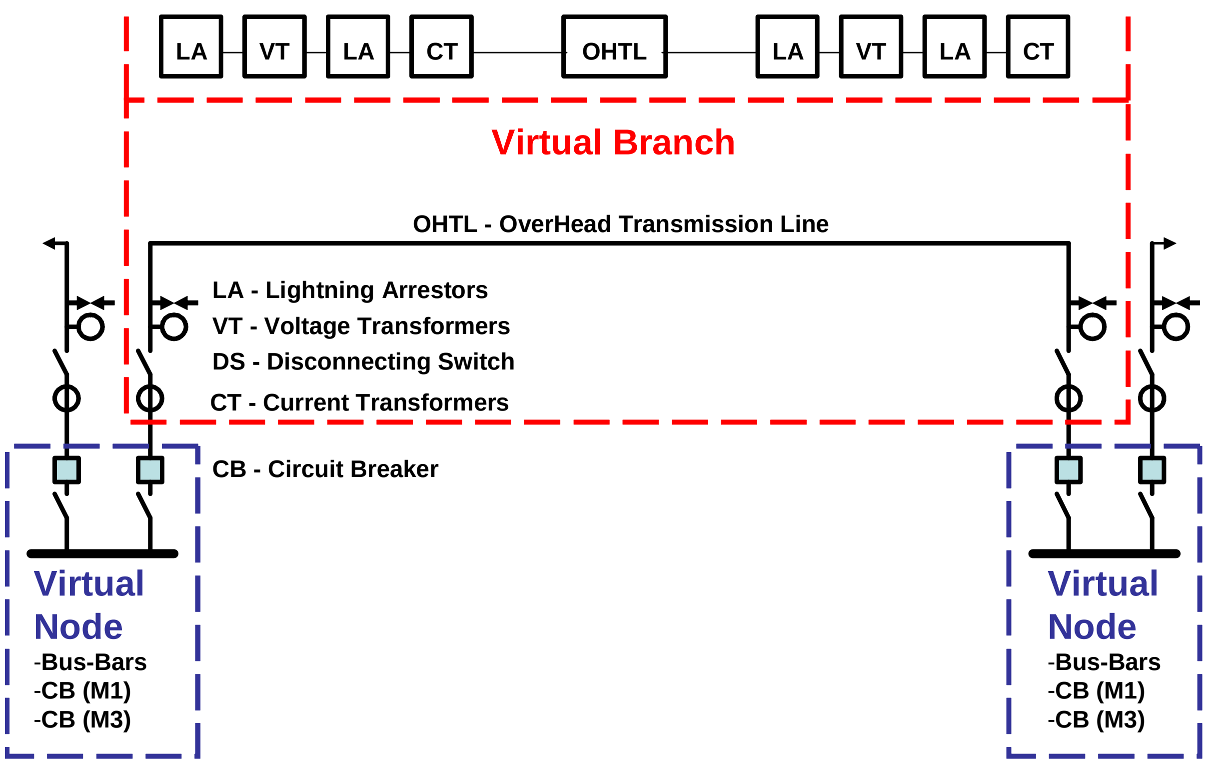


Fig. 7.4 Virtual Branches and Nodes

7.4 *Branches Protections*

It has been assumed that all the HV Lines (Branches) are protected by:

- Main (instantaneous) protections, releasing the upstream and downstream circuit breakers of every line. These protections can be differential, directional overcurrent and distance (1^{st} zone with inter-tripping) relays; they open the faulted line only;
- Back-up (delayed) protections; they do not open the faulted line, but the circuit breakers of the upstream/downstream branches/nodes; in this case, the effect of the fault is more extended, and it is usually a cause of System CCF.

Working Assumptions:

- No more than one back-up step has been considered, that means to limit the analysis to the second order cut-sets (common assumption in power systems reliability analysis)
- Both the HV circuit breakers of the upstream/downstream line will be open, even though one only open CB could be enough in some cases

The above working assumptions are treated in detail in the following sections.

7.5 *Ring Common Cause Failures (CCFs)*

Two main types of CCFs have been taken into account:

- Equipment CCFs: they are only related with the HV Lines, because it has been showed that CCFs between nodes are not realistic (see CCFs Ch. 5.5.2 and Appendix A)). HV lines can be subject to CCFs, mainly due to external factors (see Appendix A)).

  Working assumption: CCFs for HV lines have been considered only for couples of lines connecting a node, because in this case an external factor can be realistic, even though remote. For example, in case of Node 2, only CCFs for B2 and B3 branches have been taken into account.

REMARK: The criteria to consider Equipment CCFs is general, although it is applied to HV lines only; in other words, any other Equipment CCF could be taken into account with the same above procedure, and with the same working assumption.

Discussion about "Equipment CCFs between Nodes are not realistic"

There is actually a "network" redundance, even though it is different node by node, therefore CCFs should be expected. But:

- *Both predictive analysis (FMEA) and statistics do not indicate CCFs between equipment of different (adjacent) Nodes; the main reasons are:*
  - *Distance between Nodes is relevant*
  - *The Nodes equipment are submitted to different stresses within the network, that is not homogeneous*
  - *In a Node, the main equipment are the HV Circuit Breakers, and no CCFs are expected /recorded unless due control and protection systems (see next paragraph)*
- *Control and Protection System could really be CCFs, however:*
  - *Control Systems: Nodes are "static" networks, without automatic changes; therefore, the temporary loss of control functionalities has no impact on the power supply; in other words, a temporary fault on a control system does not cause the opening of the circuit breakers and the loss of supply to the MV bus-bars (reliability goal). The only case that can be a CCF is the coupler*

malfunction, but this failure mode has been treated separately in detail, due to its importance

- *Protection Systems: their malfunction can really be a CCF, and eventually the failure effect is a System CCF. Due to their importance, the protection systems failure modes have been treated separately.*

- System CCFs: In case that either a node or a branch are out-of-service, there is the possibility that the downstream nodes, between the faulted point and the open point of the ring, could remain out-of-service. This is a System CCF.

  Remark: the out-of-service of "nodes" in series with the faulted point is strictly a System CCF, because in this report it has been assumed that the reliability goal is to assure the connection of the Load Nodes; conversely, the simultaneous out-of-service of more than one "branch" can be considered a "Branch" CCF, it is usually leading to the simultaneous out-of-service of more than one node (CCF), but it is not strictly a System CCF related with the reliability goal/index.

- Functional Dependencies and CCFs, in accordance with the definition proposed in Ch. 5.5.4: A typical Functional CCF in power systems is the overload of the HV lines , and the consequent cascade failure; this Functional CCF however has not been taken ino account; the reasons are described in the following discussion.

  Discussion

  - *The disconnection of a HV line, due to overload, can occur in a HV network for the following reasons:*
    - *a load increase;*

- *a line disconnection due to a fault, the subsequent network re-configuration, and the possible overload in the lines which remained active*

- *The network has to be operated as an"interconnected mesh"; this condition is <u>not applicable to our case study</u>, because the ring is in fact re-configurable, but it is an "open mesh", i.e. it is a mesh open in an intermediate poin and working as a radial system. It should be applicable in case that this analysis would have not be limited up to the first upper level.*
- *Along the past 4 decades, several studies have been carried out to develop Montecarlo simulation that could take into account the cascade failure due to overload; e.g. the Author's MS thesis (1981) is covering Montecarlo simulation of sub-distribution systems, with re-configuration after lines overload. The more recent studies, with advanced alghoritms, have been developed for PSERC (Power Systems Engineering Research Center) by Dobson, Carreras, Ren [23N], [24N].*
- *The usual procedure is as follows:*
  - *Probabilistic model of the loads*
  - *Detection of the Overloads by means of Direct Current Load Flow, a simplified alghoritm that does not need of iterations to solve the equatoins linear system relevan to the load flow, and therefore it is suitable to be used in Montecarlo simulation*
  - *Re-configuration of the network, and load shedding*
  - *Evaluation of the reliability index, which in this case is the overall power delivery at the Load Nodes final bus-bars*

- *The network model for the above studies is usually much more simplified than the one developed for this work.*

7.6 *Repair/Reconfiguration Times*

After a fault, there is the following sequence:

- Re-configuration Time: The time to disconnect the faulted equipment, and to –re-configurate the ring; during this time, all the branches and nodes between the faulted point and the open ring point will remain disconnected
- Repair Time: The time to repair the faulted equipment, or to clear the fault in case of an external occurrence (impact of an extraneous object on a high voltage line, such as a tree branch). During this time, the ring will remain in the provisional re-configuration after fault; after this time, the ring will be reset in the original configuration

7.7 *Main Working Assumptions*

- Open Point and Open Branch: It has been assumed that:
  - The ring will be operated as “open”.
  - The HV line connected to the open point will remain energized (common practice, to facilitate the re-configuration)
- Generation at the Load Nodes: In the existing HV (132 kV) Rings, there is the possibility that generators are connected to the Load Nodes; however, usually they are generators of small-medium capacity (up to 40 MVA). In case of a malfunction on the Utility network, all the generators have to be disconnected, in order to avoid damage in case that they are reconnected without a synchronizing check.

Therefore, in this report the generation at the Load Nodes has been neglected, because:

- It has a very limited impact on the network disconnection after fault
- It has actually no impact on the CCFs analysis.

- Limitation of the Analysis to Second-Order Cut-Sets: The analysis will be limited to the second sequential fault occurrence; a third sequential fault occurrence is considered an extremely rare event, that is not affecting the results of this analysis.
- Subsequent fault, during disconnection and before re-configuration: Not taken into account, because the time is very limited and the occurrence is extremely rare without any relevant impact on the analysis

7.8 Fault Scenarios

On the base of the above assumptions and working conditions, the following fault scenarios will be analyzed:

- Fault in a Branch
- Fault in a Branch, and sequential fault on a second Branch during the repair time of the first faulted Branch
- Fault in a Node, CB – M1 failure mode
- Fault in a Node, sequential CB – M3 failure mode (not cleared fault on equipment) after a fault on a Branch or on a CB
- Equipment CCF
- Fault in a Load Node, causing the complete out-of-service of the same Node

7.9 *Faults in the Branches – Preliminary Simulations*

A set of preliminary simulations has been carried out, in order to develop and properly test a correct ring model.

This preliminary simulation is covering the complete ring,

A simplified simulation model has been adopted, with the following characteristics:

- Ring configurated as reported in the above figures, but taking into account faults on the branches only; despite of this simplification, the model is already suitable to identify System CCFs, because the opening of a branch can cause the out-of-service of the downstream nodes and branches up to the ring open point (see FMEA tables relevant to High Voltage Lines)
- Simultaneous simulation of a renewal cycle for every branch
- No ring re-configuration, for the time being

Specific working assumptions of the preliminary simulations:

- Failure rates

- The failure rates of the branch equipment (see the virtual branch model) have been cumulated into one only overall failure rate;
- The above failure rate is larger than real, in order to "force" the MonteCarlo simulation to provide a reasonable quantity of faults during the renewal cycle of every branch;
- The same overall failure rate has been considered for all the branches, in order to facilitate the result interpretation and mainly the differences due to System CCFs; conversely, different failure rates have been considered in the preliminary simulations carried out to test the model, to easily "trace" the simulation output.

- Probability Distribution: The exponential distribution has been considered both for failure rates and for repair/re-configuration rates/times, in order to facilitate the results interpretation;
- Mission Time: a 50 years mission time has been considered for the basic simulation; this mission time is longer than the common figures, but still realistic.
- Renewal Cycles: the quantity of renewal cycles is pre-determined, and so large to be absolutely sure that it is over-passing the mission time

General Input Data

Branches Failure Rate:	0.1 f/year
Repair Time:	24 h
Re-Configuration Time:	2 h
Number of Simulations:	1,000,000

Simulation Results

Legend:

DN	Nodes active disconnection by upstream and downstream circuit breakers of the faulted branch
CN	Passive disconnection by up-stream Out-Of-Service Branches / Nodes in series (System CCF)
AN	Nodes availability, taking into account both DN end SN

:

1st SIMULATION					
SPECIFIC INPUT DATA					
Mission Time (y)			50		
Renewal Cycles			14		
RESULTS					
Nodes	**N1**	**N2**	**N3**	**N4**	**N5**
DN	5.0524	5.7681	5.5099	5.1130	5.2385
CN	-	5.0524	10.3515	5.2385	-
AN	99.9977	99.9951	99.9928	99.9953	99.9976

Check-out: DN (N1) = CN (N2) OK
DN (N4+N5) = CN (N4) OK
CN (N1) = CN (N5) = 0 OK

DN Mean: 5.33638
Failure Rate: 0.10673
DN Standard Deviation: 0.29859

2nd SIMULATION					
SPECIFIC INPUT DATA					
Mission Time (y)			150		
Renewal Cycles			40		
RESULTS					
Nodes	**N1**	**N2**	**N3**	**N4**	**N5**
DN	15.8321	15.4087	15.5556	15.3185	15.8971
CN	-	15.8321	31.2156	15.8971	-
AN	99.9976	99.9952	99.9929	99.9952	99.9976

DN Mean: 15.6024
Failure Rate: 0.10402
DN Standard Deviation: 0.25491

3rd SIMULATION					
SPECIFIC INPUT DATA					
Mission Time (y)			500		
Renewal Cycles			200		
RESULTS					
Nodes	**N1**	**N2**	**N3**	**N4**	**N5**
DN	50.0344	50.7577	50.5020	50.0910	50.2295
CN	-	50.0344	100.3205	50.2295	-
AN	99.9977	99.9954	99.9931	99.9954	99.9977

DN Mean: 50.3229
Failure Rate: 0.10065
DN Standard Deviation: 0.30284

Preliminary Interpretation of the Results

- System CCFs: They have a relevant impact on the quantity of nodes out-of-service occurrences; the impact is more relevant for the nodes that are close to the ring open point, because any up-stream fault will disconnect all the down-stream nodes and branches. Conversely, the impact on the nodes availability is clearly detectable, but it is not so relevant (fifth digit).
- Mission Time: The failure rate, recalculated as DN / Mission Time, is very close (+0.6%) to the expected one (0.1 failures/year) in case of a mission time t = 500 y (50,3229 / 500 = 0.1006), but 500 y is not realistic; conversely, for a real mission time t = 50 y, the recalculated failure rate is 6.7% larger due to the several simulation truncations and approximations (5.33638/50 = 0.1067).
- Nodes Availability: It is very similar for all the mission times.
- Statistical Consideration:

- The estimated precision of a simulation result in general is related with √N, and for 1,000,000 simulations the precision should be of the order of 0.1%; conversely, in our case the precision is around 0.6%, due to the several simulation truncations and approximations;
- The recalculated failure rate, which is a “mean”, is becoming more precise by increasing the mission time;
- The failure rate variance is not reduced by increasing the mission time, it is always in the range 0.25-0.35;
- The Nodes Availability is quite constant for all the mission times.

Provisional Conclusions

- The impact of the System CCFs is clearly detectable; it has to be pointed out that the open and reconfigurable ring is a network structure that is showing easily this result, because it is a double-series structure in which, in case of a fault, all the branches and nodes downstream the faulted point and up to the ring open point are disconnected;
- The simulation model worked well, with a reasonable precision that allows a sound interpretation of the results; however, taking into account the above reported statistical considerations, a uncertainty propagation analysis is advisable;
- The adoption of a real mission time is not assuring the best precision, due to the simulation truncations and approximations; however, it seems that the error is not larger than a few percent points, and therefore acceptable for an interpretation of the grid performance;
- The impact of the System CCFs is clearly detectable both on the nodes out-of-service occurrence quantities, and on the nodes availability; however, the impact on the nodes availability is much less relevant (5^{th} digit). This result is typical in power systems analysis and almost all the hi-tech repairable systems, because the equipment MTBF is much larger than the MTTR. It is therefore advisable to take into account not only the nodes availability as reference reliability parameter, but also the failures frequency and duration, that means the power supply quality.

7.10 Sequential Faults After Reconfiguration

Faults on Branches are the more common and frequent ones; therefore, it reasonable to consider the possibility of a second fault on a Branch during the repair time of the first faulted Branch.

The normal sequence after a fault in a Branch is as follows:

- Failure in a Branch
- Ring reconfiguration (short time)
- Branch repair (more extended time)
- Ring reset to the original configuration

Relevant factors:

- Branches Failure Rate: high
- Branches Repair Time: long

Therefore, a fault on a second Branch during the repair time of the first failed one is not frequent but anyway possible.

The sequence of a second failed branch during the repair time of the first one is reported in the following figure.

Assumptions:

- No further faults during reconfiguration: It is reasonable to assume that during the re-configuration time there will not be another fault on a branch; this assumption is actually in accordance with the operation practice of the HV systems, and the impact of this assumption on the overall analysis is actually negligible. The main reasons are:
  - The reconfiguration time is much shorter than the repair time,
  - During the re-configuration, the part of the ring between the fault and the Open Point is out-of-service
- No possibility of reconfiguration after a fault on a second branch; therefore, the reconfiguration time of the second faulted branch will not be taken into account.

Calculation Procedure

In this stage,

- All the failure-repair sequences have been already evaluated
- The mission time has been stated; usually it is limited to no more than 50 years, therefore there are only few renewal cycles for every branch

For every branch, it is now necessary to check if there is a fault in another branch during the repair times.

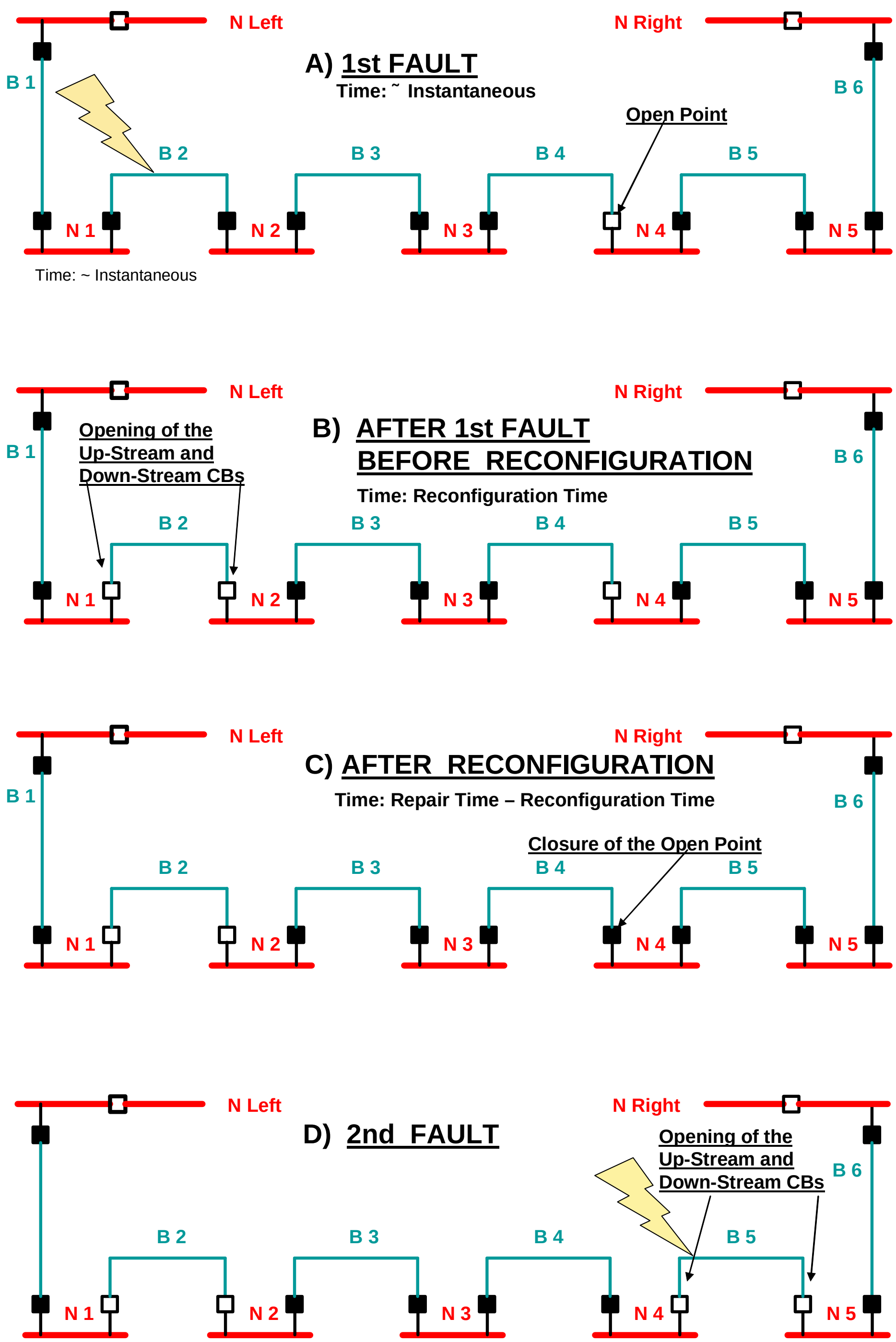


Fig. 7.5 Reconfiguration and Second Faulted Branch

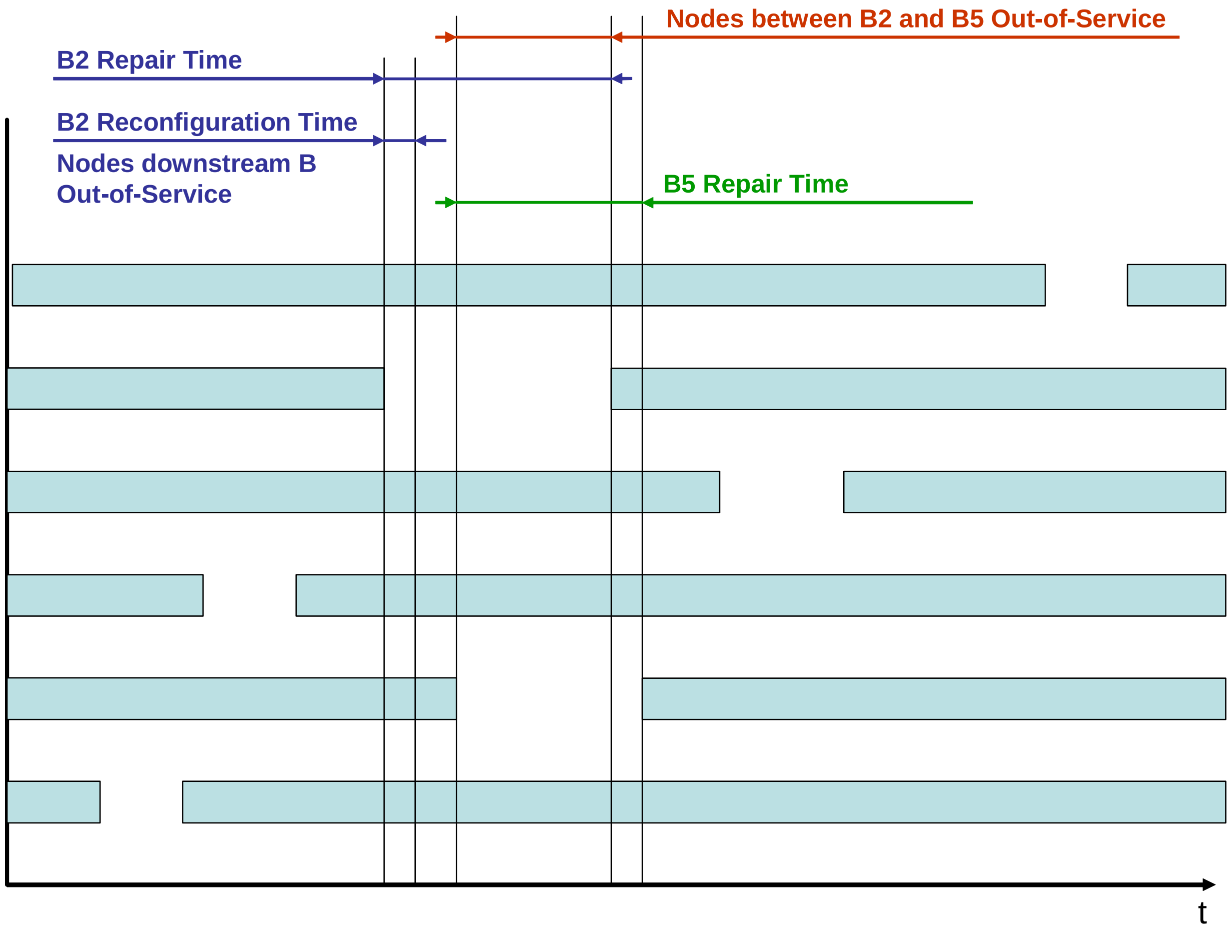


Fig. 7.6 Overall Failure-Repair-Reconfiguration Sequence

The following Nodes will remain out-of-service:

- Nodes downstream the 1st faulted Branch, during the reconfiguration time; in the above example, Nodes N2 and N3.
- Nodes between the 1st faulted Branch and the 2nd one, during the repair time of the 1st faulted branch; in the above example, Nodes N2 and N3.

Conditions to be verified:

- Open Circuit Breaker Availability: The Open Point circuit breaker must be:

- Available; the failure-repair sequence of this CB in M1 failure mode has been already evaluated; it is necessary to check that there is no overlapping between the failure of this CB and the reconfiguration + repair time of the faulted branch
- Ready to close on call (M3 failure mode)

- Left/Right Position of the Open Point: The position of the Open Point CB has a relevant impact on the Nodes that will be put out-of-service. In the above example, the Open Point CB is the left one of the open point node, and during the reconfiguration the N2 and N3 nodes will remain out-of-service; conversely, if the Open Point CB would have been the right one of the open point node, also the N4 node would have been out-of-service during the reconfiguration time. This condition is repetitive for all the other failure modes of the Ring.
- Superposition of the Repair Times: There is the possibility that the repair time of the 2^{nd} faulted Branch would be so short that the restoration of the 2^{nd} faulted Branch could be carried out before the 1^{st} faulted one. The analysis of these overlapping is reported here below.

TR1: Repair Time (instant time) of the 1^{st} faulted Branch

TR2: Repair Time (instant time) of the 2^{nd} faulted Branch

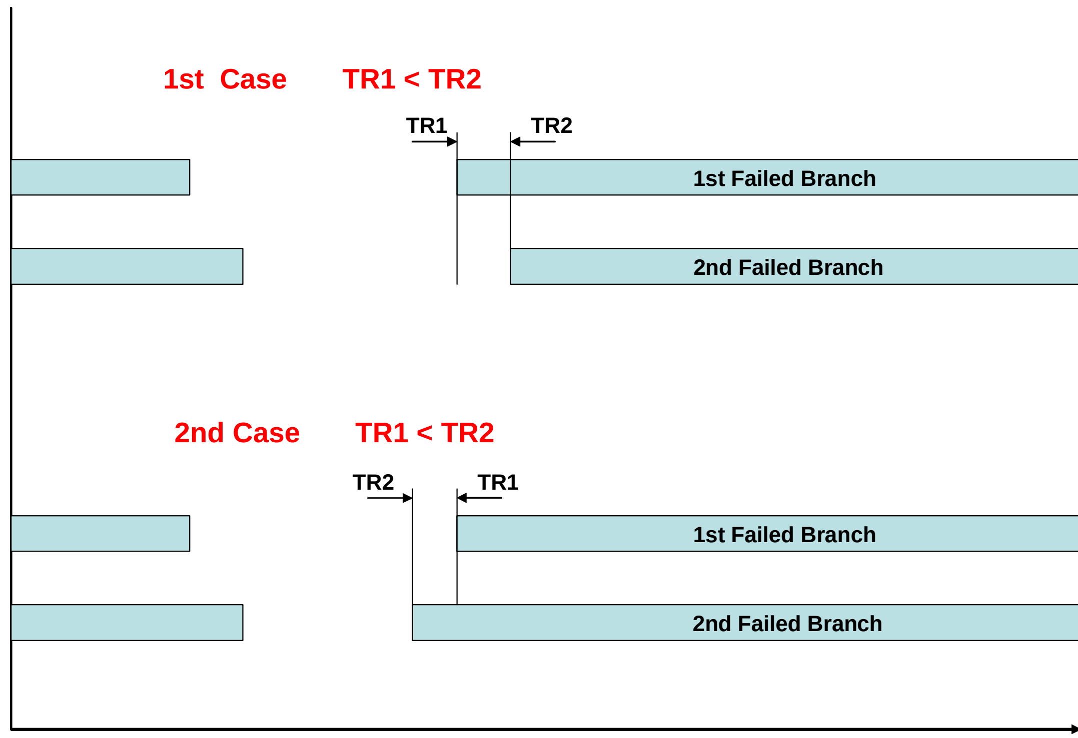


Fig. 7.7 Superposition of the Faulted Branches Repair Times

- 1st Case: TR1 < TR2

  After TR1, the ring is fully fed, but open in correspondence of the 2nd faulted Branch

  The out-of-service time of the intermediate nodes is TR1-$T_{reconfig}$1

- 2nd Case: TR1 > TR2

  After TR2, the ring is fully fed, but open in correspondence of the 1st faulted Branch

  The out-of-service time of the intermediate nodes "should be" TR2-$T_{reconfig}$1, but usually one only repair crew is working, therefore the 1st faulted line will be repaired first. Finally, the out-of-service time of the intermediate nodes is again$TR1-T_{reconfig}1$

The above sequences and conditions have to be verified for all the branches; the analysis has been split in two parts, left side and right side of the open node.

Furthermore, it has been verified that no interference can occur between the sequences, and the analysis can be carried out on "all" the lines without exclusion between 1st and 2nd faulted line; a quick check of the above sequences shows that no interference is possible.

The analysis and the implementation of all the above sequences and conditions, and later their debugging, required a relevant effort.

7.11 Fault in a Node – Circuit Breaker M1 Failure Mode

An internal fault in a circuit breaker (failure mode M1), such as a loss of insulation, cannot be cleared by the same CB, and must be cleared by the up-stream CB; in this case, the Node of the faulted CB is put out-of-service (Node Failure).

The fault-reconfiguration sequence, reported in the next figure and relevant to a "left" CB of a Node, is as follows:

- Internal failure of a CB (failure mode M1);
- Fault cleared by the up-stream (sending side) CBs; there is no need, of course, to clear the fault down-stream too;
- Isolation of the faulted CB, by means of the disconnecting switches
- Re-configuration of the ring, by closing the Open Point CB.

The overall reconfiguration time is longer than the one of a faulted branch, because in this case there is to take into account both the re-configuration time of the ring, that is same as for a faulted branch, and also the isolation time of the CB.

Renewal sequences have to be evaluated for:

- All the “left” CBs of the Nodes
- All the “right” CBs of the Nodes
- The Main Left CB
- The Main Right CB

The mission time has been stated; usually it is limited to no more than 50 years, therefore there are only few renewal cycles for every branch.

<u>Assumption:</u>

No further faults in CBs during the isolation, re-configuration and repair times; in fact, the overall failure-repair interval is much shorter than the expected failure time, and the above assumption is actually in accordance with the present operational practice; therefore, the impact of this assumption is negligible.

The following Nodes will remain out-of-service:

- The Node of the faulted CB, and the Nodes downstream of it, during the isolation + reconfiguration time; in the above example, Nodes N2 and N3.

A complete analysis has to take into account also the impact of:

- The Left/Right position of the faulted CB
- The Left/Right position of the Open Point CB

Furthermore, the consequences of a fault in the Main Left/Right CBs has to be investigated.

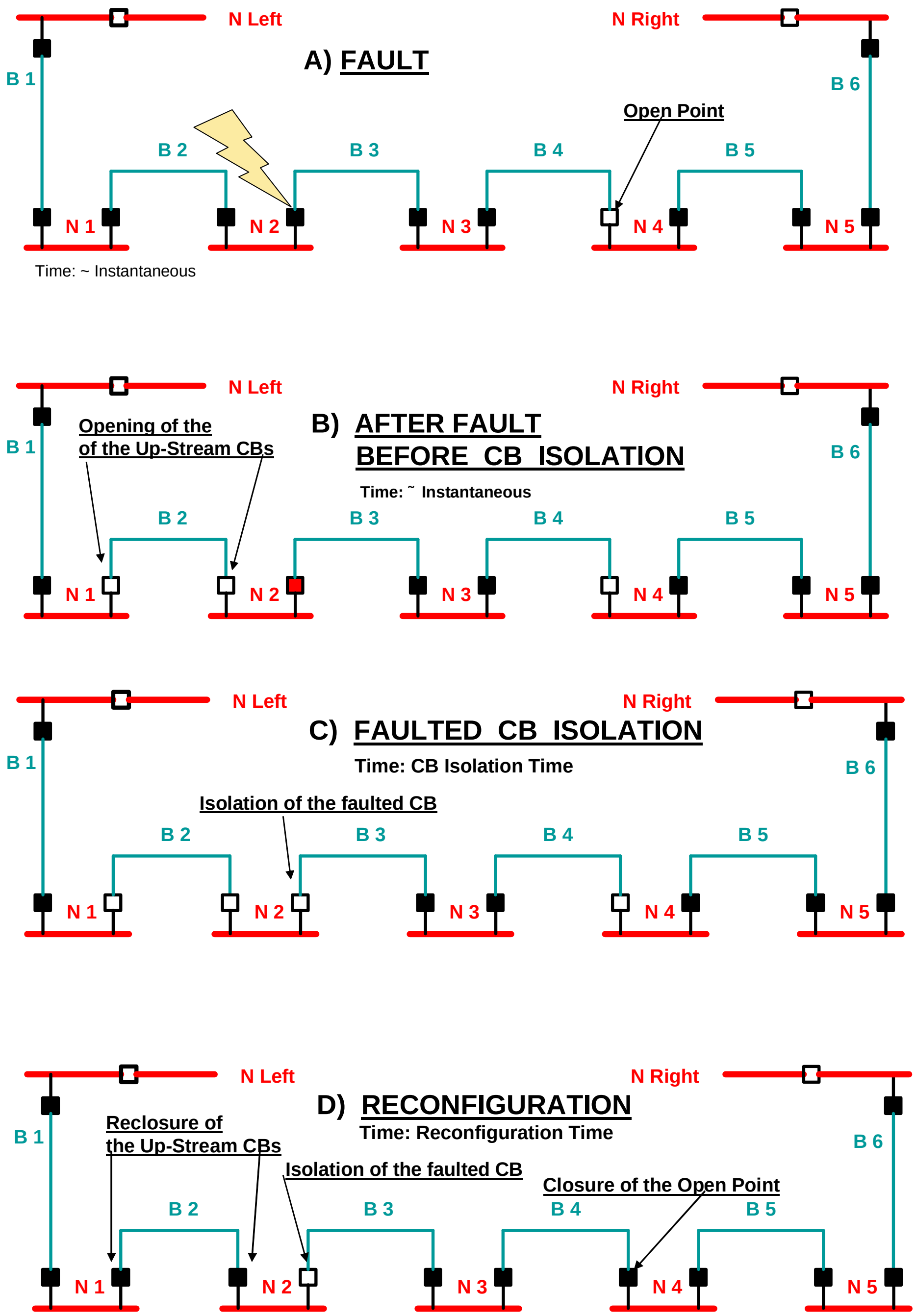


Fig. 7.8 Disconnection of **Faulted Left CB (M1 Failure) and Reconfiguration Open Point Left CB**

Impact of the Left/Right position of the faulted CB

There is no impact, because the fault in the CB can be cleared by:

- Both the CBs of the up-stream branch, in case that the faulted CB of down-stream branch is the up-stream one (see fig. 7.9)
- The up-stream CB of the branch, in case that the faulted CB of the same branch is the down-stream one (see fig. 7.10)

In both cases, the node of the faulted CB and the down-stream ones will be put out-of-service during the re-configuration time (System CCF); in the example of fig. 7.9 and 7.10, the out-of-service nodes are N2 and N3.

Impact of the Left/Right position of the Open Point CB

The Open Point Node will be put out-of-service, in case that the faulted CB is on the same side of the Open Point CB, referred to the Open Point Node.

In the examples of fig7.8 and 7.9, the fault is on the right side of the Open Node, and the Open Point CB is the right one of the Open Node; in this case, the Open Node N4 will not be put out-of-service during re-configuration.

Conversely, in the example of fig. 7.10, the fault is on the right side of the Open Node, but the Open Point CB is the left one of the Open Node; in this case, the Open Node N4 will be put out-of-service during re-configuration.

Consequences of a Fault in the Main Left/Right CBs

An internal fault in the Main Left/Right CB, that is directly connected to the main Left/Right bus-bars, can be cleared only by the Main CB up-stream the same Bus-bars, and this will cause:

- The out-of-service of the bus-bars

- The consequent out-of-service of all the feeders spreading from the bus-bars; in other words, the out-of-service of all the distribution system spreading from the bus-bars.

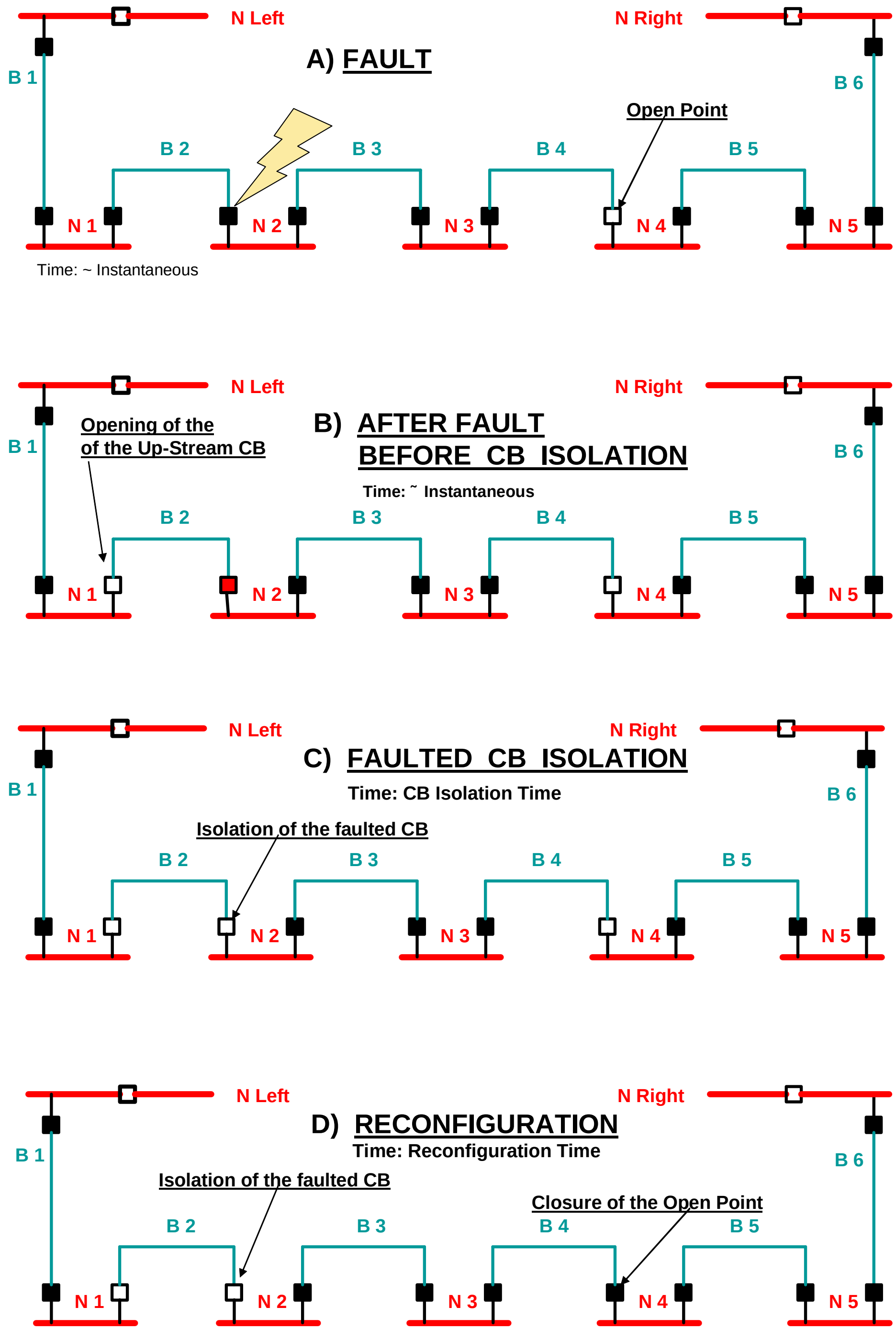


Fig. 7.9 Disconnection of **Faulted Right CB (M1 Failure) and Reconfiguration Open Point Left CB**

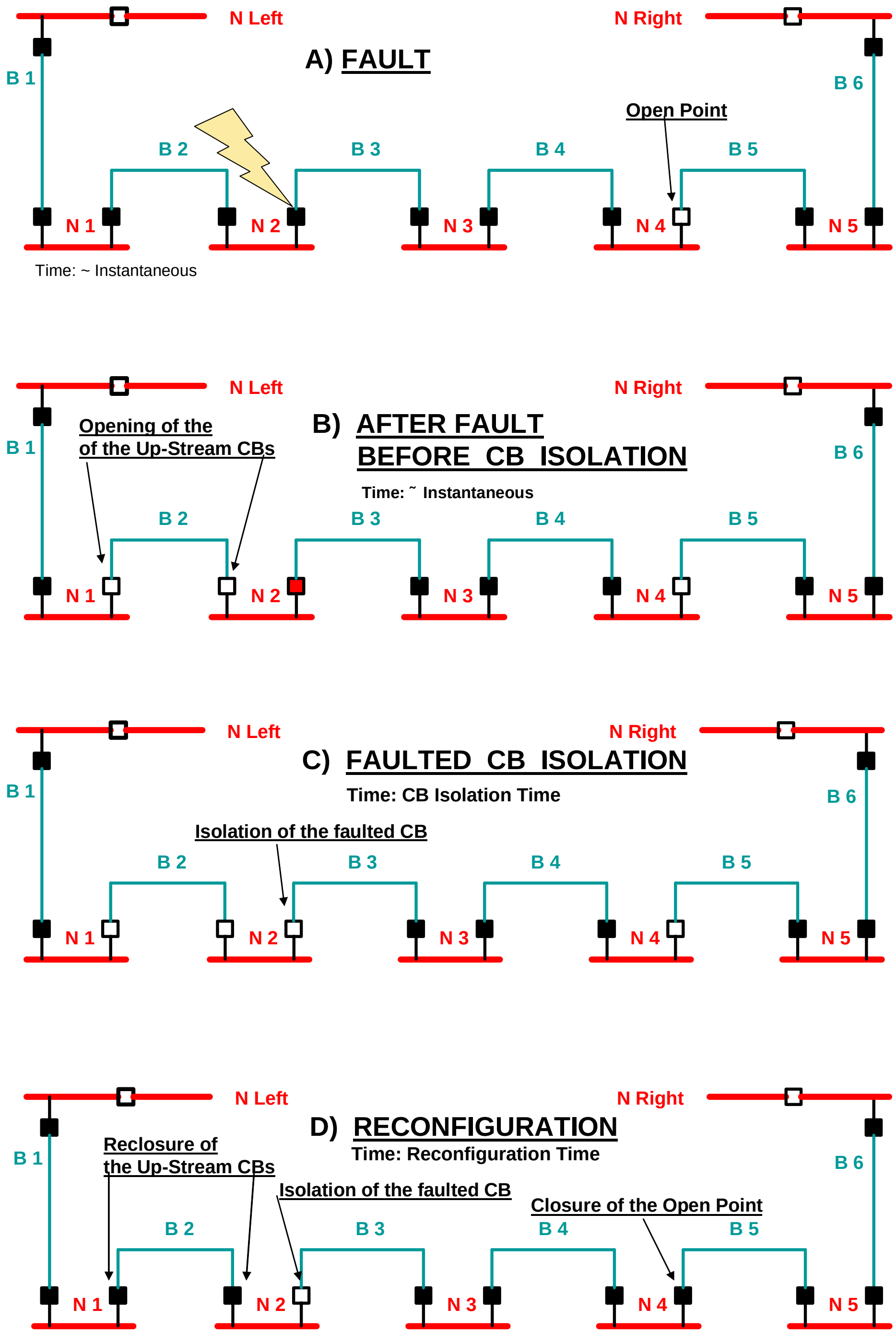


Fig.7.10 Disconnection **of Faulted <u>Left</u>** CB **(M1 Failure) and Reconfiguration, <u>Open Point Right</u>** CB

The fault-reconfiguration sequence, reported in the fig. 7.11 and relevant to the Main Left CB, is as follows:

- Internal failure of the CB (failure mode M1);
- Fault cleared by the up-stream Main CBs, and consequent out-of-service of the Left Bus-Bars
- Isolation of the faulted CB, by means of the disconnecting switches
- Re-configuration of the ring, by closing the Open Point CB.

The overall reconfiguration time is longer than the one of a faulted branch, because in this case there is to take into account both the re-configuration time of the ring, that is same as for a faulted branch, and also the isolation time of the CB.

Renewal sequences have to be evaluated for both the Main Left CB and for the Main Right one.

After the fault clearance, the consequences are as follows:

- Out-of-service of all the nodes downstream the faulted CB, up to the Open Point; this a System CCF, of the same importance of the previously considered ones
- Out-of-service of all the distribution system down-stream the bus-bars. This is a System CCF of greater importance of the above mentioned one; in this work, it has been called Upper Level System CCF.

Therefore, the consequences of the faults due to a failure in the Main Left/Right Node have been evaluated separately, and they have not been cumulated with the other Systems CCFs

Remark: In this case too, the left/right position of the Open Point CB has impact on the out-of-service of the Open Point Node. In the example reported in Fig. 7.11, the Open

Node CB is the left one, and the Open Node N4 will not be put out-of-service; conversely, if the Open Node CB would be the right one, the Open Node N4 will not be put out-of-service.

Other assumptions as described in the previous paragraphs.

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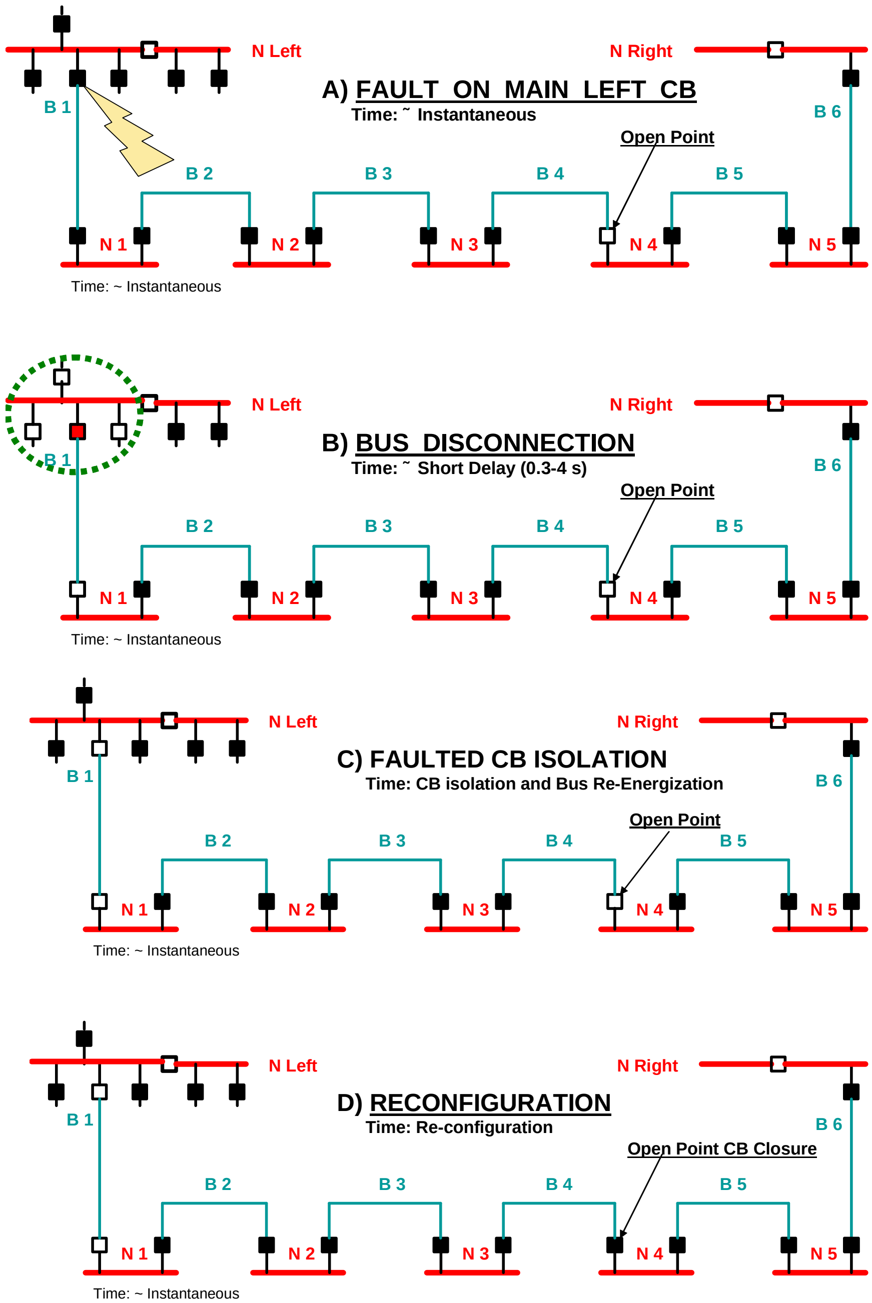


Fig. 7.11 Fault in a Main Left/Right CB

7.12 *Circuit Breaker M3 Failure Mode*

There is the possibility that, in case of a fault in a Branch or in a Node such as described in the previous chapters, the same fault could not be cleared by the immediately up-stream circuit breaker.

The up-stream Circuit Breaker, called to open to clear the fault, is not opening (M3 failure mode); The main reasons are:

- The mechanical driving mechanism of the CB is stalled
- The opening coils are interrupted
- Protections malfunction
- Control and protection circuits malfunction

The final consequence of the CB M3 failure mode is the out-of-service of at least another node up-stream the fault, as follows:

- Fault in a Branch, not cleared: The Node up-stream of the faulted Branch is put out-of-service by the back-up protections of the up-stream Branch,
- Fault in an incoming CB of a Node, not cleared: The Node up-stream of the faulted one is put out-of-service

The sequences of the above faults are discussed here below.

Fault in a Branch, not cleared

A fault in a Branch should have been cleared b the up-stream CB, that conversely did not release. The protections of the up-stream Branch are therefore called to release (selective operation, 2^{nd} zone of the distance protections.

The fault-reconfiguration sequence, reported in fig. 7.12, is as follows:

- Failure in a Branch
- "On-Call" failure of the up-stream circuit breaker
- Release of the protections of the up-stream branch, which "sees" the fault in a selective sequence (2nd zone of the distance protections)
- Isolation of the faulted CB, and also of the faulted Branch in case that the fault has net been self-eliminated (e.g. the wet leaves of a tree on a conductor)

  Remark: more than 85% of the faults on the lines are self extinguishing
- Ring re-configuration by closing the Open Point and the up-stream open branch

Again, the overall reconfiguration time is longer than the one of a faulted branch, because in this case there is to take into account both the re-configuration time of the ring, that is same as for a faulted branch, and also the isolation time of the CB.

No renewal sequences relevant to the M3 failure mode has been considered, because this is an "On-Demand" failure mode; conversely, a "On-Demand" failure probability has been evaluated for the CBs up-stream the faulted Branches.

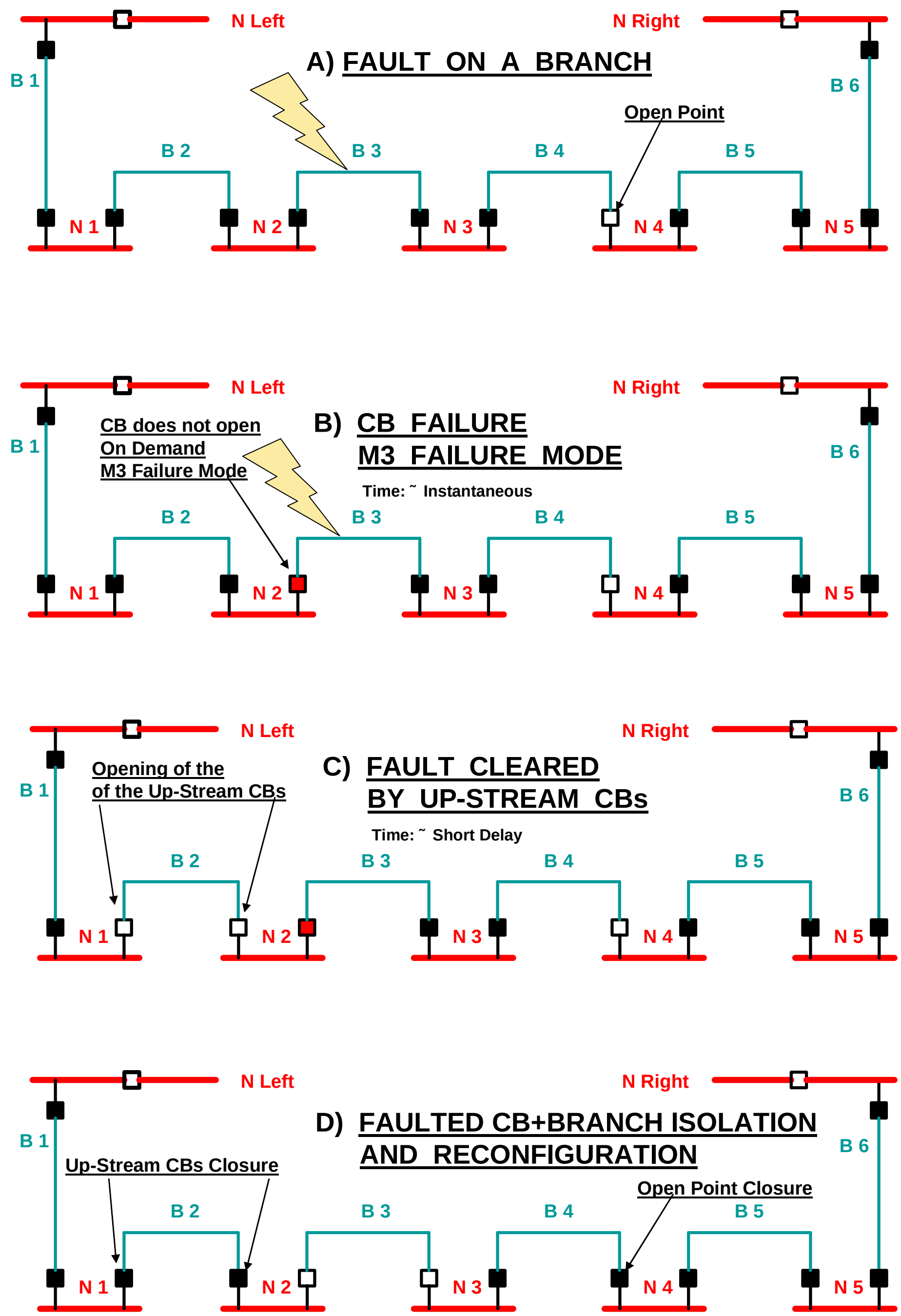


Fig. 7.12 CB Failure (M3 Mode) to Clear a Fault in a Branch

A fault in the First/Last Branch, not cleared by the up-stream Main/Left Circuit Breaker, can be only cleared by the Main CB up-stream the same Bus-bars; the consequences are same as described in the previous chapter:

- Out-of-service of all the nodes downstream the faulted CB, up to the Open Point; this a System CCF, of the same importance of the previously considered ones
- Out-of-service of all the distribution system down-stream the bus-bars. This is a System CCF of greater importance of the above mentioned one; in this work, it has been called Upper Level System CCF.

Fault in a Circuit Breaker, not Cleared

The Left/Right position of the CB has a relevant impact, therefore the two following cases have to be checked separately:

- Fault in a Left CB; fault-reconfiguration sequence reported in fig. 7.13
- Fault in a Right CB; fault-reconfiguration sequence reported in fig. 7.14

➢ Fault in a Left CB

A fault in a Left CB should have been cleared by the up-stream CB of the Branch, that conversely did not release. The protections of the up-stream Branch are therefore called to release (selective operation, 2nd zone of the distance protections.

The fault-reconfiguration sequence, reported in fig. 7.13, is as follows:

- Failure in a Left CB
- "On-Call" failure of the up-stream circuit breaker (Left CB of the Branch, that means the Right CB of the up-stream Node)

- Release of the protections of the up-stream branch, which "sees" the fault in a selective sequence (2nd zone of the distance protections)
- Isolation of both the faulted CBs
- Ring re-configuration by closing the Open Point and the up-stream open branch.

➢ <u>Fault in a Right CB</u>

A fault in a Right CB should have been cleared by the up-stream CB of the Branch, that conversely did not release. The protections of the up-stream Branch are therefore called to release (selective operation, 2nd zone of the distance protections.

Remark: In this work, it has been assumed that there is no bus-bar protection, or any other protection that could isolate the faulted Node; this is a common practice in High Voltage sub-systems, but NOT in the Extra High Voltage systems.

The fault-reconfiguration sequence, reported in fig. 7.13, is as follows:

- Failure in a Right CB
- "On-Call" failure of the up-stream circuit breaker (Left CB of the Branch, that means the Right CB of the up-stream Node)
- Release of the protections of the up-stream branch, which "sees" the fault in a selective sequence (2nd zone of the distance protections)
- Isolation of both the faulted CBs
- Ring re-configuration by closing the Open Point and the up-stream open branch, and by means of a by-pass on the first faulted CB (M1 failure mode)

Remarks:

- Other protection and release sequences could be considered in accordance with specific procedures of the utilities, the above described ones are quite common, and the interpretation of the consequences is not difficult, therefore they have been considered a good compromise for this work
- The introduction of the M3 failure mode “shortened” the ring, as it’s evident from the above figures, and many constraints had to be included in the software sequences, to correctly evaluate the series out-of-service of the Nodes (System CCFs)
- All the assumptions considered in the previous cases had to be taken into account in this case too.

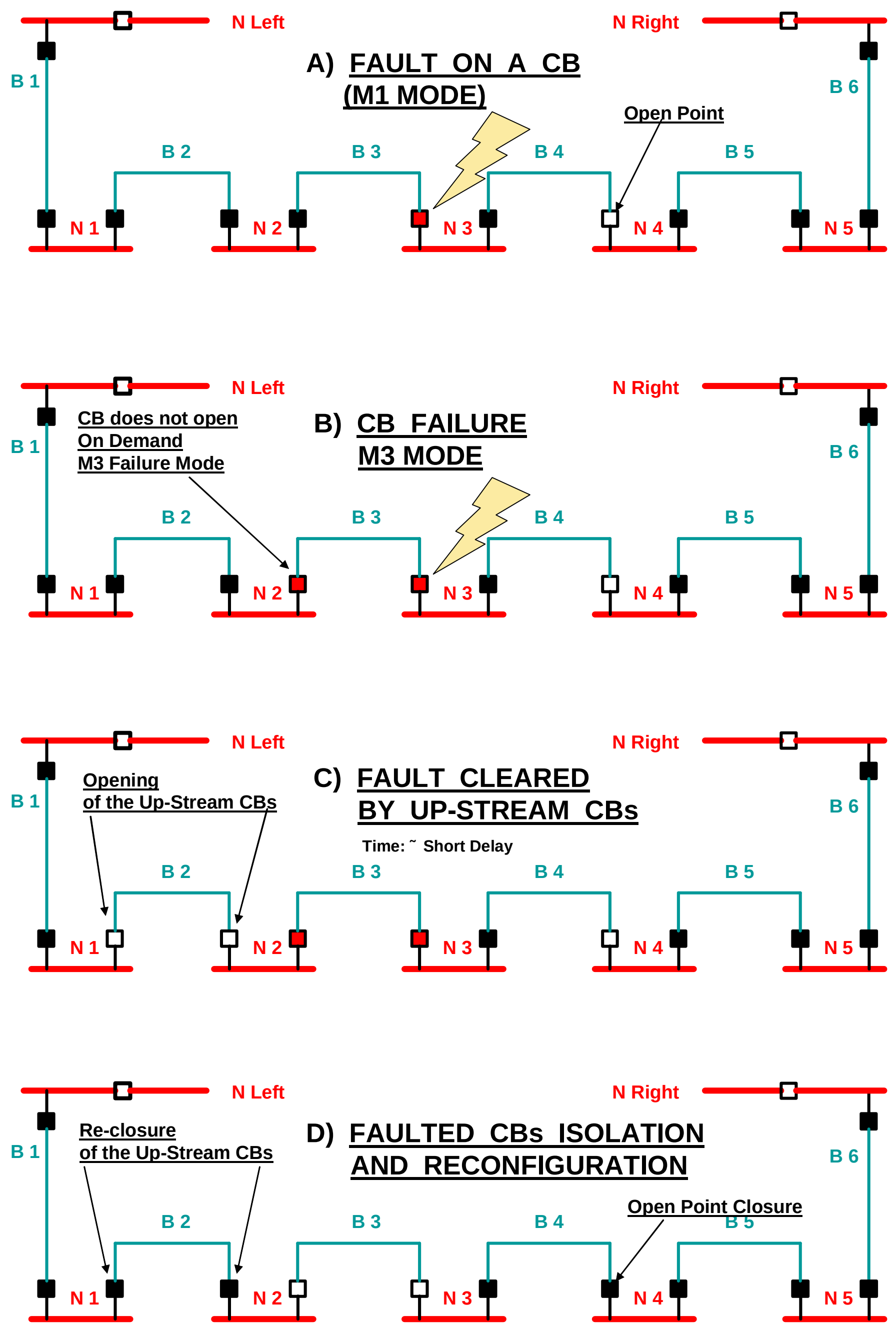


Fig. 7.13 CB Failure (M3 Mode) Clearing a Fault in a Left CB

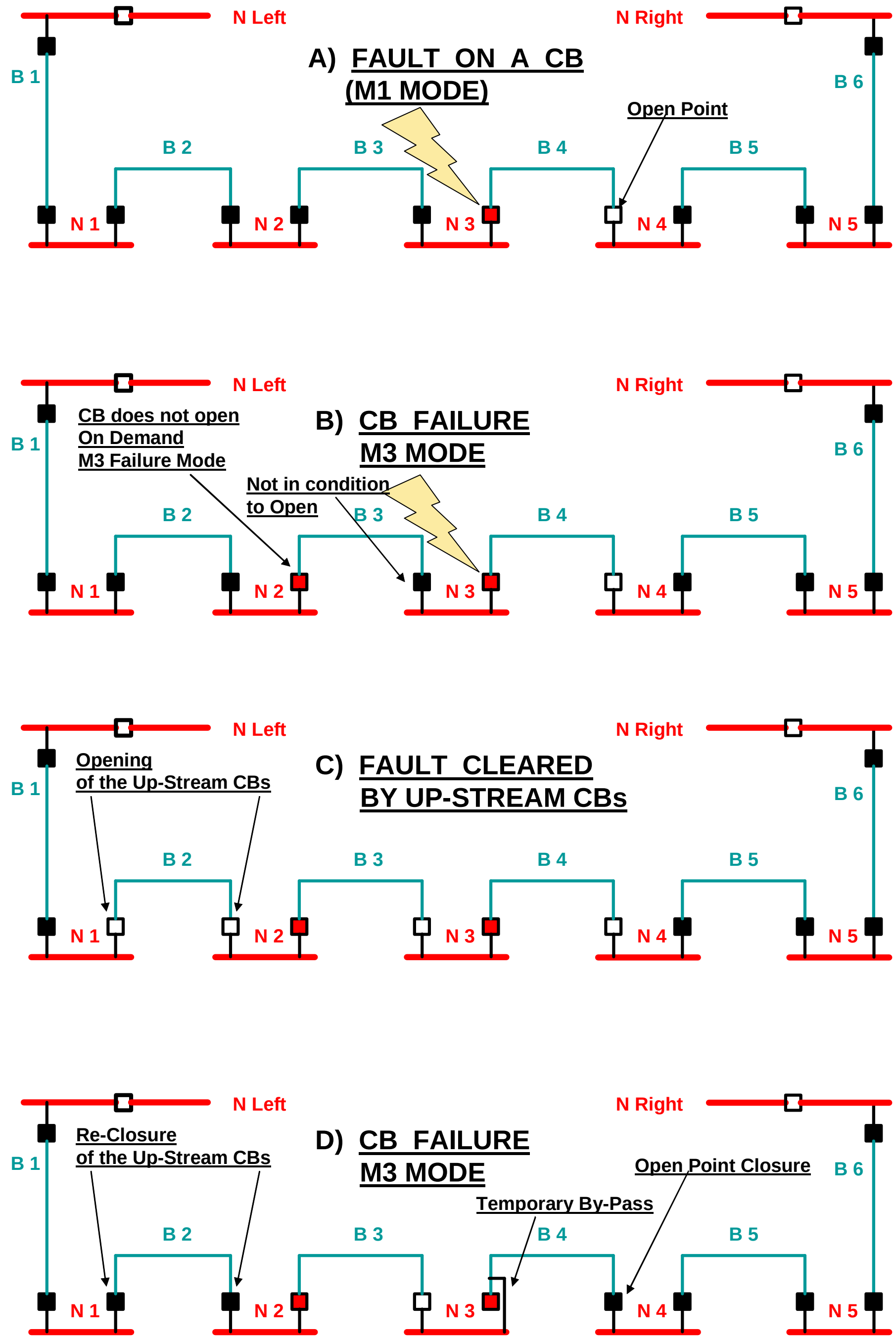


Fig. 7.14 CB Failure (M3 Mode) Clearing a Fault in a Right CB
(One of the possible sequences)

7.13 <u>Ring CCFs</u>

Ring CCFs are the typical, very rare, common events in High Voltage sub-distribution systems; they summarized here below.

- <u>CCFs in Branches</u>: They are mainly due to external factors (environment). It has to be pointed out that the extension of a HV system is of hundreds of kilometers, therefore in this work it assumed that CCFs in Branches can cover a limited area only with no more than two contiguous Branches; the final consequence is the out-of-service of the Node connecting the two contiguous Branches. Conversely, CCFs covering a more extended area, with more than two contiguous branches in series, have not been taken into account.
- CCFs in Nodes: The interdistance between Ring Nodes is of many kilometers, and there are no connections between the Nodes.
  - There are no intrinsic dependencies related to equipment, which can lead to a simultaneous CCF; specifically, there no auxiliary systems, control and protection systems, etc. which are common for two adjacent nodes.
  - There are no intrinsic dependencies that can lead to non-simultaneous CCF, because the nodes are not redundant.
  - Extrinsic dependencies due to external factors such as weather etc. are extremely unlikely due to the long distance between nodes.

  Therefore, CCFs in Nodes have not been taken into account.

Therefore:

- CCFs are due to a simultaneous environmental failure in a limited area; they are independent from the lines (Branches) length. Eventually, it is advisable to associate CCFs directly to the Nodes connecting the two faulted branches.
- The only interested nodes should be the N(1) – N(N) ones, with two connected Branches. However, the Main Left/Right Nodes can be subject to a similar CCF, because the whole EHV/HV Substations (Main Left/Right Nodes) could be out-of-service due to a similar environmental problem.

The above CCFs conditions are reported in fig. 8.15.

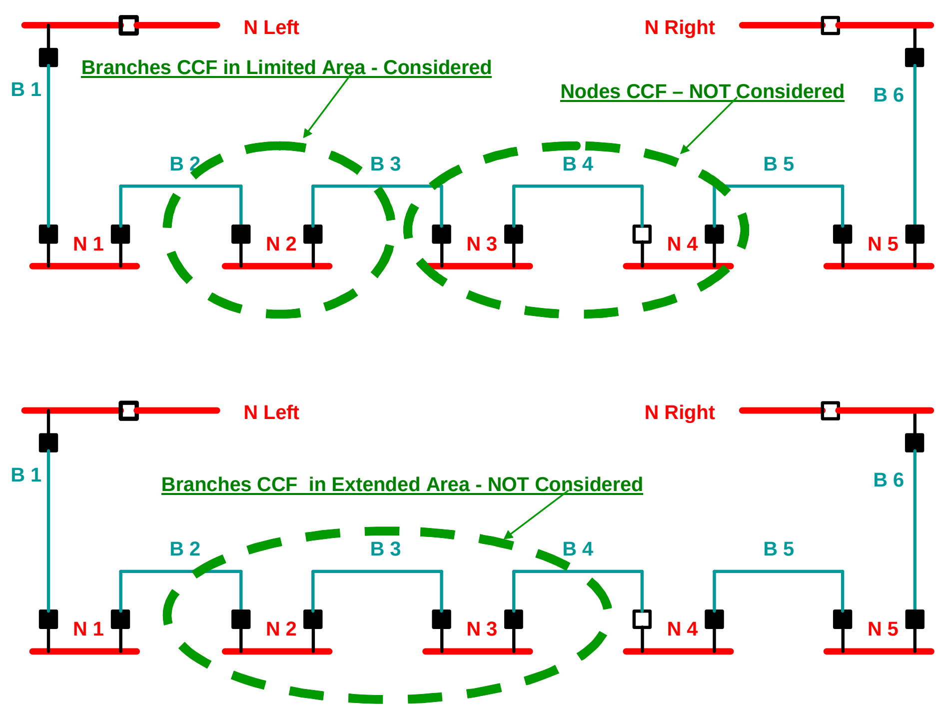


Fig. 7.15 CCFs into the Ring

The fault-reconfiguration sequence, reported in fig. 8.16, is as follows:

- CCF in two Branches

- Out-of-service of the Node interconnecting the two Branches; the two branches are cleared by their protections and CBs on the opposite side of the CCF.
- Re-configuration of the Ring
- “Repair” of the CCF
- Ring re-set to the original configuration

Consequences:

- The Node interested by the CCF will remain out-of-service fo all the “repair” time of the CCF, that is surely longer than the re-configuration time.
- The other Nodes, down-stream the one affected by Branches CCF, will remain out-of-service during the re-configuration time. This is a System CCF.
- In case CCF in the Main/Left Nodes, all the feeders spreading from the HV bus-bars will remain out-of-service during the “repair” time of the CCF; this is a Upper Level System CCF.

Remark: A Branch CCF in the Open Point Node has the same impact of the other Nodes, because the Open Node in anyway has to be disconnected; this situation is different from the ones of the other above analyzed failure cases.

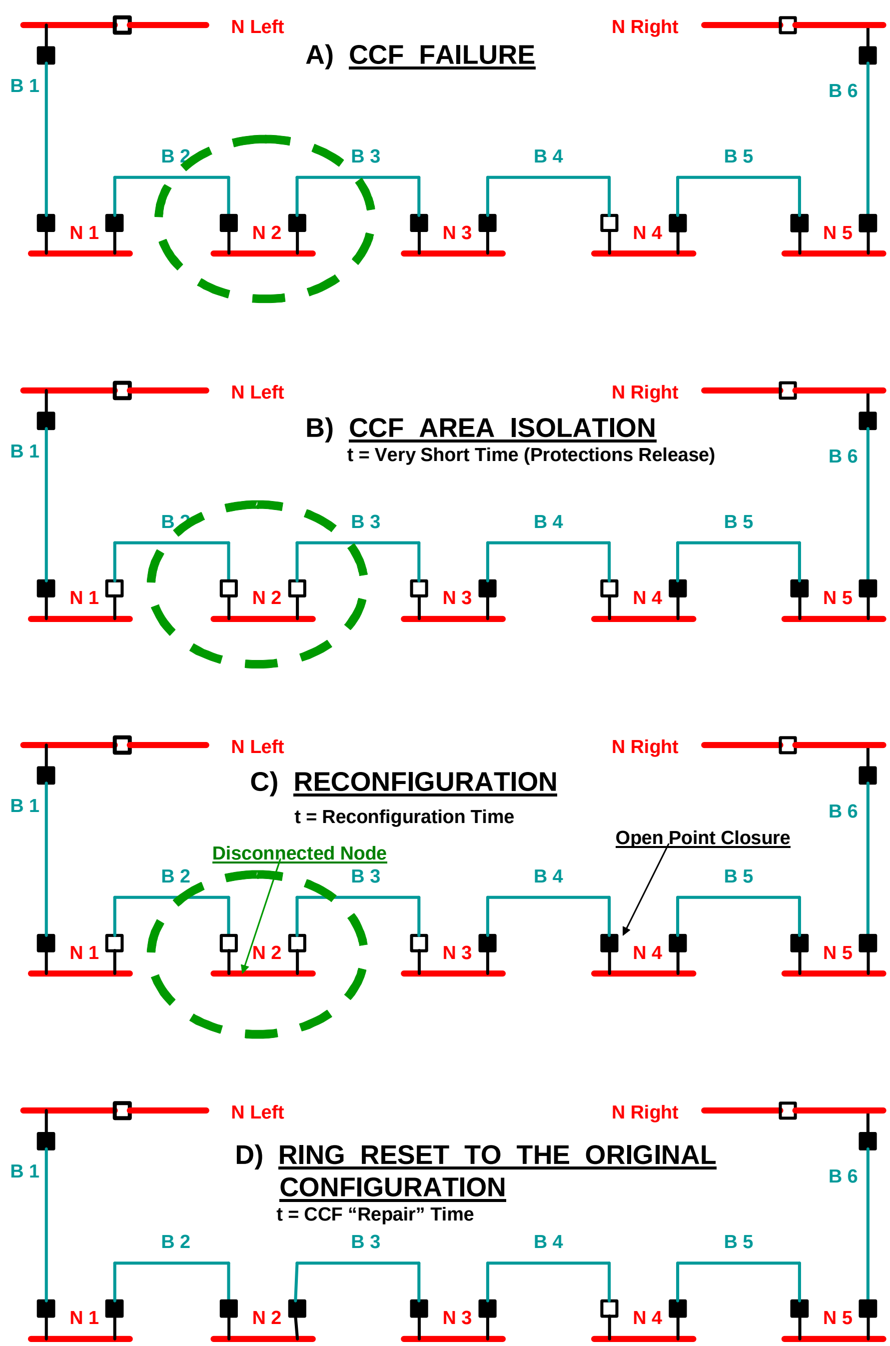


Fig. 7.16 Branches CCFs Fault/Re-Configuration Sequence

CCF failure and "repair" rates have been stated for all the Nodes, included the main /Left/Right ones.

Renewal sequences have to be evaluated for:

- All the intermediate Nodes
- The Main Left/Right Nodes

Working Assumptions:

- No superposition of CCF failures; this assumption is well grounded because the CCF failure rate is extremely low.
- Reconfiguration time same as for the other above considered failures
- No further failures during CCF repair and reconfiguration times.

7.14 Fault in a Node, Causing the Complete Out-of-Service of the same Load

The last failure to be considered is a fault in a Load Node, either in the HV bus-bars or down-steam them, that can cause the complete out-of-service of the same Node.

Such a fault can be for example the internal loss of insulation of a High Voltage Circuit Breaker (M1 failure mode), which can only be cleared by the up-stream CBs; the consequence is the temporaneous disconnection of the Load Node.

Procedure:

- The failure rate of these faults has been already evaluated during the analysis of the Load Node, and there is no need of a further evaluation;
- The above mentioned failure rate is included as an input data into the Ring model;
- The Ring analysis is then covering only the out-of-service of the nodes down-stream the faulted one; this out-of-service is considered as System CCF
- The only nodes considered in this step of the analysis are the intermediate Load Nodes. Conversely, the Main Left/Right Nodes have not been taken into account; in fact, their out-of-service due to internal causes should be part of a upper level

analysis; however, the impact on the overall analysis is negligible, because a fault causing the out-of-service of a main node is really a rare event.

The fault-reconfiguration sequence, reported in fig. 7.17, is as follows:

- Fault in a Load Node, leading to the complete disconnection
- Fault cleared by the up-stream protections; out-of-service of the Load Node
- Isolation of the fault
- Re-configuration of the Ring
- “Repair” of the Load Node
- Ring re-set to the original configuration

Renewal sequences have to be evaluated for:

- All the intermediate Nodes - YES
- The Main Left/Right Nodes - NO

Working Assumptions:

- No superposition of Load Nodes failures; this assumption is well grounded because their failure rate is extremely low.
- Reconfiguration time same as for the other above considered failures

No further failures during Load Nodes “repair” and reconfiguration times.

-

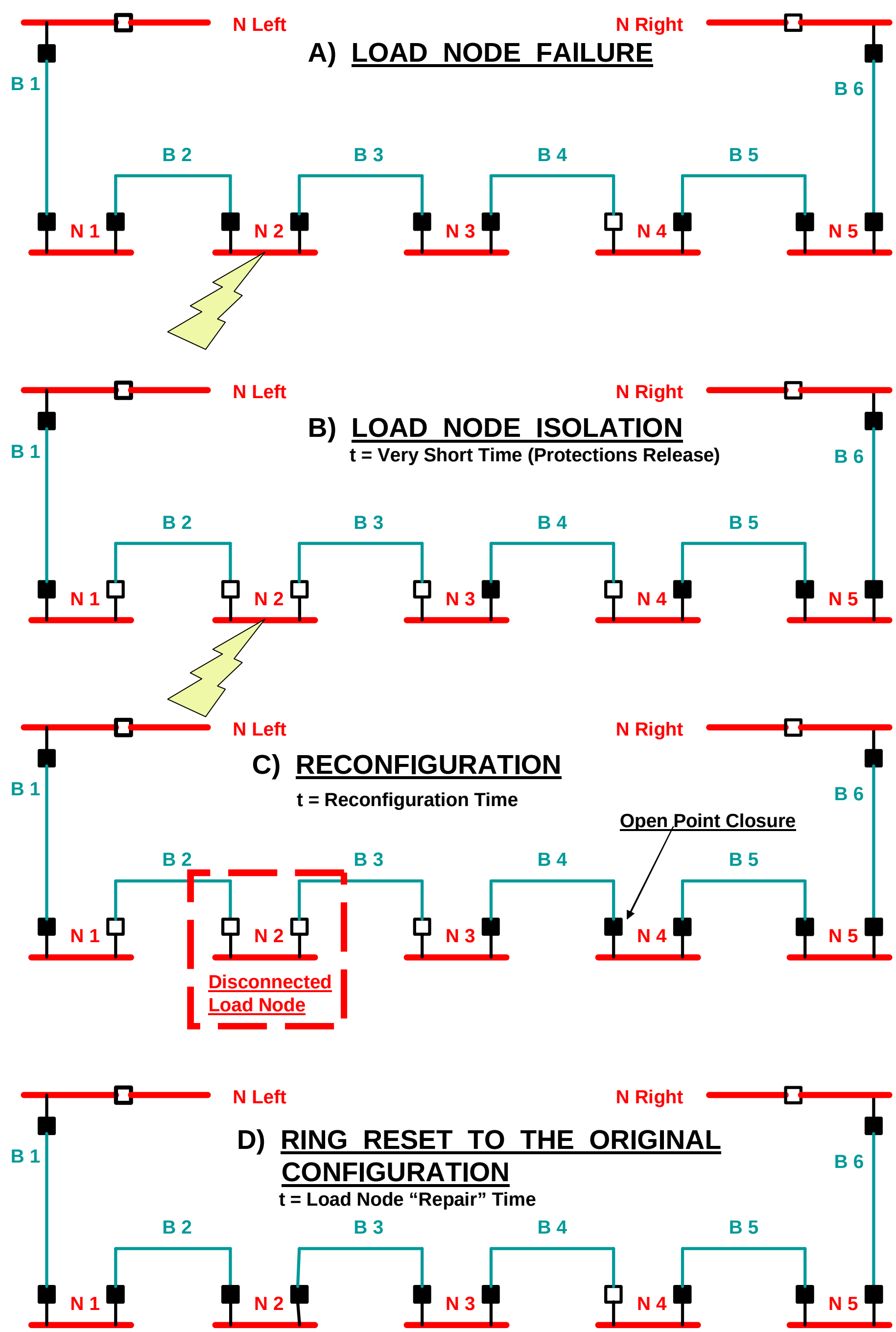


Fig. 7.17 Fault/Re-Configuration Sequence in a Load Node

7.15 *Ring / Load Node Interface*

The reliability index, as stated in the previous Chapters, is the availability of the bus-bars down-stream the Load Nodes.

This reliability index has to take into account, for every Load Node:

- The internal failures of the Load Node;
- The availability of the up-stream Network (Ring), at the Load Node High Voltage bus-bars

The results of the previous analysis of the Load Nodes are the reliability and availability parameters due to internal faults of the nodes. Among the failures into the Load Node, a few of them can cause the out-of-service of the up-stream bus-bars; the failure rate corresponding to these failures is the Interface input data with the Upper Level (Ring) Analysis.

The results of the Upper Level (Ring) analysis are the availability (out-of-service frequency and duration) of the Nodes; of course, the consequence of an out-of-service of the HV bus-bars of a Load Node is the out-of-service of the same Load Node.

The out-of-service quantities and times of every Load Node, due to failures in the Ring, are cumulated to the ones which are due to internal causes of every Load Node.

7.16 *Input Data and Simulation Procedure*

Two phase of simulation have been carried out, such as for the load nodes, in order to reach a sound confidence of the results:

C) Simulation with "forced" failure rates and repair times, in order to be sure to check all the sequences described in previous chapters, and to reach a sound interpretation of the results.

D) Simulation with "real" failure rates and repair times, based on the model developed and debugged during phase A). The results are then compared with the ones of phase A), to check their congruity.

Criteria to "force" the failure rates in Phase A):

- HV Circuit Breakers: As highlighted in the Load Nodes analysis, the MTBF of these equipment is much longer than the mission type; therefore, it is very unlikely to have more than one renewal cycles for the main components; usually, the renewal sequence is cut before reaching the first fault. Therefore, their failure rate has been increased in order to have a reasonable quantity of renewal cycles;
- HV Aerial Lines: Their failure rate is relevant, and they could "cover" the results of the other equipment. Therefore, their failure rate has been slightly decreased.

The Input Data considered in the two simulation phases are reported in the following tables.

Remarks:

- Aerial Lines Parameters
  - Length: a rounded and uniform 100 km length has been assumed for all the lines, to facilitate the results interpretation
  - Failure Rate: In Appendix A) - Ch. A.1.9 covering statistics of HV systems, it has been indicated that HV lines failure rate is < 10 f/y, and only aprox. 6% of the failures is permanent (not eliminated by fast reclosing). Furthermore, considering that the usual length of a HV aerial line is much more than 100 km, and assuming a good maintenance level, a reductive coefficient k = 0.35

can be applied. Eventually, the real failure rate of a HV line can be evaluated as follows: $\lambda = 10 \times 0.06 \times 0.35 \approx 0.002$ failure / (year x km)

HV Nodes: They have been considered as black boxes, whose failure rates and re-connection times are the ones evaluated in the Load Nodes analysis

INPUT DATA		**PHASE A)** Forced Failure Rates and Repair Times			
Component/System		**Failure Rate (Failures/Y)**	**Failure Probability**	**Repair Time (h)**	**Disconnection Time (h)**
HV Aerial Lines (Failures /km) Length: 100 km		0.001	-	240	20
HV Circuit Breakers	M1 Failure Mode	0.1	-	720	10
	M3 Failure Mode	-	0.01	720	10
CCFs		-	0.05	50	-
Equivalent Nodes (From Load Nodes Analysis)		0.2	-	11,51(*)	-

(*) See Ch.6.17.3

INPUT DATA		**PHASE B)** Real Failure Rates and Repair Times			
Component/System		**Failure Rate (Failures/Y)**	**Failure Probability**	**Repair Time (h)**	**Disconnection Time (h)**
HV Aerial Lines (Failures /km) Length: 100 km		0.002	-	12	5
HV Circuit Breakers	M1 Failure Mode	0.002	-	720	5
	M3 Failure Mode	-	0.001	720	5
CCFs		-	0.01	10	-
Equivalent Nodes (From Load Nodes Analysis)		0.002	-	11,81(*)	-

(*) See Ch.6.17.3

The simulation procedure has been based on the following working conditions and constraints:

- Preliminary simulations showed that, both for "forced" (Phase A)) and for "real" (Phase B)) input data a reasonable convergence can be reached after at least 100,000 iterations.
- Some results are expected, such as:
  - Failures and out-of-service times of Circuit Breakers and HV Lines,
  - Sequential failures and out-of-service times in case of On Demand Failures of Circuit Breakers,

  Other results are not expected with a certain precision, due to the complexity of the renewal sequences, but their order of magnitude has to be compatible with the other expected results.

  The check-out of the expected-calculated results congruence is relevant, in order to assure that:

  - The program is working correctly,
  - A reasonable precision has been reached.

On the base of the above working conditions and constraints, the following simulation procedure has been adopted.

- <u>Simulation</u>: All the simulation have been carried out by means of 100,000 iteration
- <u>Grid Scenarios</u>: Four Grid Scenarios have been considered, in order to evaluate the effect of the asymmetry.
  - Two scenarios with central node open, and right/left circuit breaker open
  - Two scenarios with 2^{nd} or 4^{th} node open

Remark: No Random First Failure Time has been taken into account, for the same reasons reported in the Load Nodes analysis.

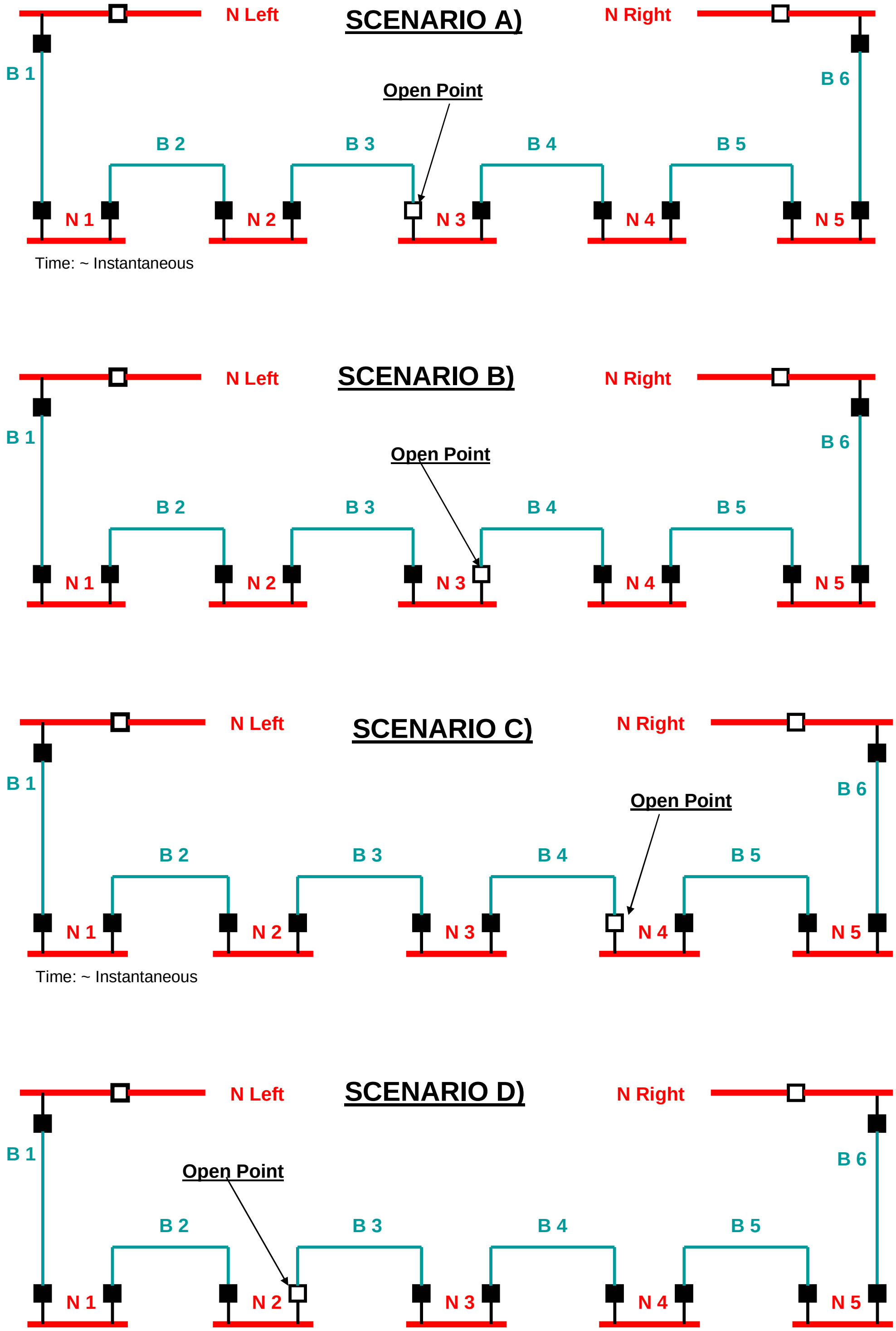


Fig. 7.18   Grid Scenarios for Simulation

7.17 *Output Procedure and Results*

➢ Output Parameters

All the possible out-of-service conditions have been associated with an output, in order to have a very comprehensive picture of the Load Node performance; the outputs are listed in the tables here below. For every output, the following data have been evaluated:

CODE	**OUTPUT**	**REMARKS**
N	Failures within Mission Time	Quantity of Renewal Cycles within the Mission Time. It is indicating if the system either has reached a steady state condition or it is in the early transient stage
T	Out-of-Service Time within Mission Time	Overall out-of-service time
FR_TM	Average Out-of-Service Duration	
FR-Y	Failures / Year	Failure Rate – Usual DEfinition

Wherever applicable, the above figures have been subdivided in:

D	Direct Failures, that cause the out-of-service of the interested node
C	System CCF, that cause the out-of-service of the nodes downstream the one that has been directly disconnected by the fault

The above parameters have been evaluated for all the failures described in the previous analysis, as follows:

N.	**Code**	**Failure**
1	BR	HV Branches
2	CB_M3_BR	HV Circuit Breakers - Failure Mode M3 for Failure on Branch
3	CB_M1	HV Circuit Breakers - Failure Mode M1
4	CB_M3	HV Circuit Breakers - Failure Mode M3 for Failure in a HV CB (M1)
5	CCF	Ring CCF
6	NE	Equivalent Nodes Out-of-Service

The following overall output parameters have been evaluated for the Ring Nodes:

PARAMETER	CODE	CALCULATION METHOD	NODES
Total Failure Rate	TF	Quantity of failures during the mission time, divided by the mission time	Ring Nodes; Main Left and Main Right Node
Average Out-of-Service Time		Overall Out-of-Service time during the mission time, divided by the Failures Quantity during the mission time	Ring Nodes
Total Unavailability	TUA	Overall Overall Out-of-Service time during the mission time, divided by the mission time	Ring Nodes

- Failure rates and availability of the Main Left and Main Right Nodes: They cannot be evaluated in the same way as for the Ring Nodes, for the following reasons:
  - The analysis covered the failures relevant to one ring only, but the Main Left and Main Right Nodes are feeding a distribution system with many rings, and all these rings can indirectly cause the out-of-service and disconnection of the above Circuit Breakers
  - A failure on a Main CB causes the out-of-service ot the whole downstream distribution system; the consequence is much relevant than the one of a failure in a ring.

  Therefore, all the failures and the relevant times of the Main Left and Main Right Nodes have been evaluated and reported in the output tables, but the overall parameters such as total failure rate, total unavailability, etc. have not been computed because they could lead to a misinterpretation.
- Expected Results: As for the Load Nodes, Some results are expected, such as:
  - Failures and out-of-service times of Circuit Breakers and Transformers,

- Sequential failures and out-of-service times in case of On Demand Failures of Circuit Breakers,

Other results are not expected with good precision, due to the complexity of the renewal sequences, but their order of magnitude has to be compatible with the other expected results.

The figures of the expected results are reported in a preliminary output table, covering Scenario A) only.

The check-out of the expected-calculated results congruence is relevant, in order to assure that:

- The program is working correctly,
- A reasonable precision has been reached by Montecarlo simulation.

➢ Output Tables

The first table is summarizing the main parameters of the simulation results; these parameters will be used as input data for the combined "Ring + Load Nodes" analysis.

The other tables report all the output parameters relevant to the several failure modes, both for "forced" and for "real" input data, and for all the considered scenarios, in order to have a comprehensive picture of the ring performance.

Output parameters relevant to CCFs have been highlighted with the following colours:

- System CCFs
- Direct CCFs

RING - Simulation Results Summary

Real Failure/Repair Rates

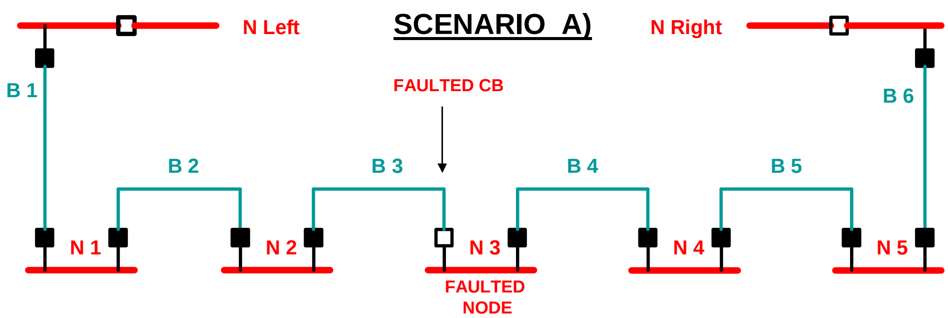
Scenario A	N1	N2	N3	N4	N5
Failure Rate (F/Y)	0.227	0.446	0.661	0.445	0.227
Unavailability	1.33E-04	2.61E-04	3.85E-04	2.60E-04	1.33E-04
Repair Time (h)	5.15	5.13	5.10	5.13	5.14

Scenario B	N1	N2	N3	N4	N5
Failure Rate (F/Y)	0.227	0.446	0.657	0.446	0.227
Unavailability	1.33E-04	2.60E-04	3.87E-04	2.58E-04	1.33E-04
Repair Time (h)	5.15	5.13	5.14	5.12	5.14

Scenario C	N1	N2	N3	N4	N5
Failure Rate (F/Y)	0.227	0.445	0.663	0.442	0.226
Unavailability	1.33E-04	2.61E-04	3.87E-04	2.58E-04	1.33E-04
Repair Time (h)	5.15	5.13	5.12	5.10	5.15

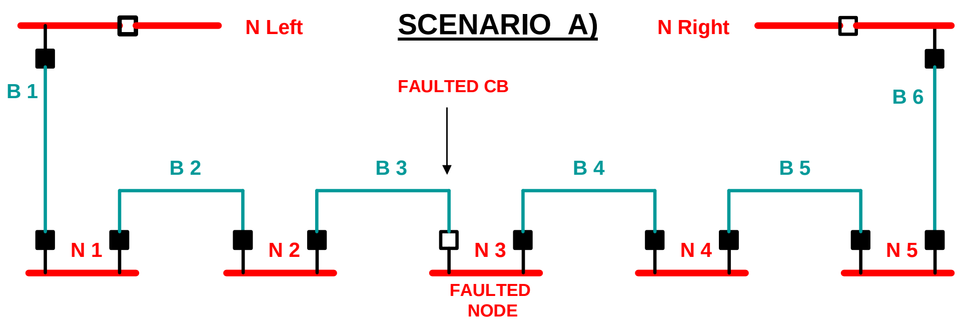
Scenario D	N1	N2	N3	N4	N5
Failure Rate (F/Y)	0.227	0.443	0.663	0.445	0.227
Unavailability	1.33E-04	2.58E-04	3.87E-04	2.60E-04	1.33E-04
Repair Time (h)	5.14	5.11	5.12	5.13	5.15

Remark: The above table is a "summary", therefore the figures are with 3 digits, as usual for reliability data. Conversely, the figures in the following tables are with 4 digits, in order to show clearly the data fluctuation due to Montecarlo simulation.

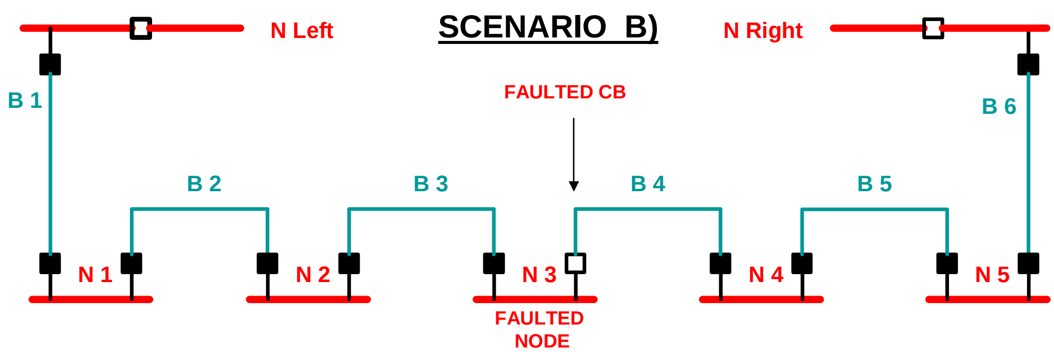


EXPECTED ROUNDED FIGURES

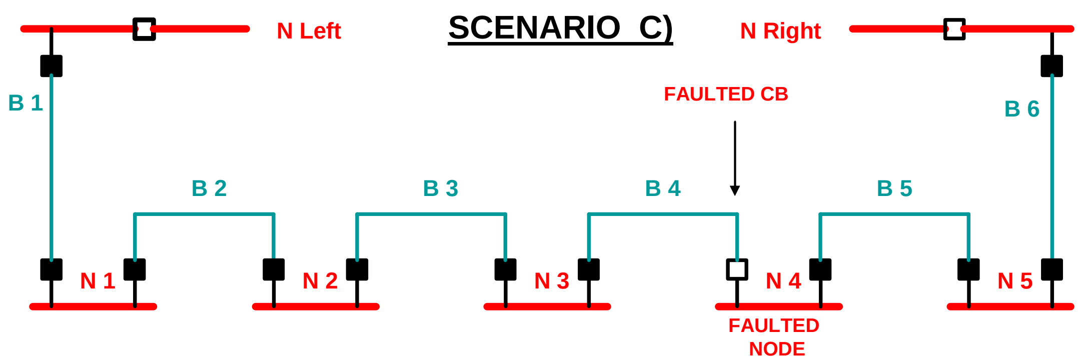
RING SIMULATION				Scenario A)		**<u>Forced</u> Failure and Repair Rates**					
N.	**Code**	**Failure**	**Reliability Parameter**	**Nodes**							**Remarks**
				Main Left	**N1**	**N2**	**N3**	**N4**	**N5**	**Main Right**	
1	BR	HV Branches	D_N		5	5	5	5	5		
			C_N		0	5	10	5	0		
			D_T		0. 0114	0. 0114	0. 0114	0. 0114	0. 0114		
			C_T		0	0. 0114	0.0228	0. 0114	0		
			D_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			C_FR_MT		0	0.0023	0.0023	0.0023	0		
			D_FR_Y		0.1	0.1	0.1	0.1	0.1		
			C_FR_Y		0	0.1	0.2	0.1	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N								
			T								
			FR_MT								
			FR_Y								
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	5	10	10	5	10	10	5	
			C_N		5	15	25	15	5		
			D_T	0.017	0.034	0.034	0.017	0.034	0.034	0.017	
			C_T		0.017	0.051	0.085	0.051	0.017		
			D_FR_MT	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	
			C_FR_MT		0.0034	0.0034	0.0034	0.0034	0.0034		
			D_FR_Y	0.1	0.2	0.2	0.1	0.2	0.2	0.1	
			C_FR_Y		0.1	0.3	0.5	0.3	0.1		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.15	0.15	0.05	0	0.1	0.15	0.15	
			T	1.72e-4	1.72e-4	0.57e-4	0	1.14e-4	1.72e-4	1.72e-4	
			FR_MT	0.0011	0.0011	0.0011	0	0.0011	0.0011	0.0011	
			FR_Y	0.003	0.003	0.001	0	0.002	0.003	0.003	
5	CCF	Ring CCF	D_N	2.5	2.5	2.5	2.5	2.5	2.5	2.5	
			C_N		2.5	5	7.5	5	2.5		
			D_T	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	
			C_T		0.0057	0.0114	0.0171	0.0114	0.0057		
			D_FR_MT	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	
			C_FR_MT		0.5	0.5	0.5	0.5	0.5	0.5	
			D_FR_Y	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
			C_FR_Y		0.05	0.1	0.15	0.1	0.05		
6	NE	Equivalent Nodes Out-of-Service	N		0	10	20	10	0		
			T		0	0.0228	0.0456	0.0.0228	0		
			FR_MT		0	0.0023	0.0023	0.0023	0		
			FR_Y		0	0.2	0..4	0.2	0		
7	TF	Total Failure Rate									
8	TUA	Total Unavailability									



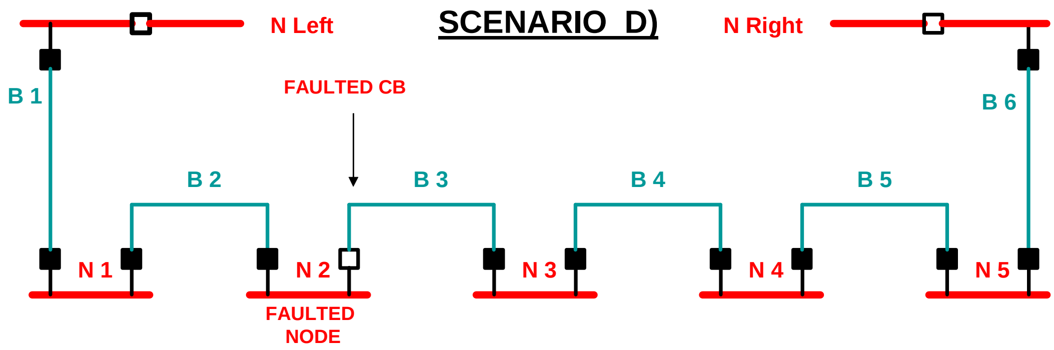
RING SIMULATION				Scenario A)		**Forced** Failure and Repair Rates					
N.	**Code**	**Failure**	**Reliability Parameter**	**Nodes**							**Remarks**
				Main Left	**N1**	**N2**	**N3**	**N4**	**N5**	**Main Right**	
1	BR	HV Branches	D_N		4.9873	4.9960	4.9912	5.0010	4.9908		
			C_N		0	4.9873	9.9919	4.9908	0		
			D_T		0. 0113	0. 0114	0. 0113	0. 0114	0. 0114		
			C_T		0	0. 0113	0.0227	0. 0114	0		
			D_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			C_FR_MT		0	0.0023	0.0023	0.0023	0		
			D_FR_Y		0.0997	0.0999	0.0998	0.1000	0.0998		
			C_FR_Y		0	0.0997	0.1998	0.0998	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.1367	0.2186	0.2450	0.2169	0.1365		
			T		0.0037	0.0059	0.0066	0.0058	0.0037		
			FR_MT		0.0274	0.0270	0.0270	0.0268	0.0270		
			FR_Y		0.0027	0.0044	0.0049	0.0043	0.0027		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	4.9549	9.9030	9.9212	4.9554	9.9126	9.9153	4.9561	
			C_N		4.9549	14.8580	24.7841	14.8715	4.9561		
			D_T	0.0170	0.0337	0.0337	0.0168	0.0337	0.0337	0.0170	
			C_T		0.0170	0.0507	0.0844	0.0507	0.0170		
			D_FR_MT	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	
			C_FR_MT		0.0034	0.0034	0.0034	0.0034	0.0034		
			D_FR_Y	0.0991	0.1981	0.1984	0.0991	0.1983	0.1983	0.0991	
			C_FR_Y		0.0991	0.2972	0.4957	0.2974	0.0991		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.1484	0.1498	0.0502	0	0.0976	0.1470	0.1478	*
			T	1.72e-4	1.73e-4	0.57e-4	0	1.12e-4	1.66e-4	1.69e-4	*
			FR_MT	0.0012	0.0012	0.0011	0	0.0011	0.0011	0.0011	*
			FR_Y	0.0030	0.0030	0.0010	0	0.0020	0.0029	0.0030	*
5	CCF	Ring CCF	D_N	2.4967	2.4955	2.4968	2.5128	2.5000	2.5020	2.4990	
			C_N		2.4967	4.9921	7.5010	5.0010	2.4990		
			D_T	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	
			C_T		0.0057	0.0114	0.0171	0.0114	0.0057		
			D_FR_MT	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	
			C_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			D_FR_Y	0.0499	0.0499	0.0499	0.0503	0.0500	0.0500	0.0500	
			C_FR_Y		0.0499	0.0988	0.1500	0.1000	0.0500		
6	NE	Equivalent Nodes Out-of-Service	N		0	9.9865	19.9748	9.9891	0		
			T		0	0.0228	0.0456	0.0.0228	0		
			FR_MT		0	0.0023	0.0023	0.0023	0		
			FR_Y		0	0.1997	0.3995	0.1998	0		
7	TF	Total Failure Rate			0.5025	1.0501	1.4991	1.0516	0.5029		
8	TUA	Total Unavailability			0.0015	0.0031	0.0042	0.0031	0.0015		



RING SIMULATION				Scenario B)			Forced Failure and Repair Rates				
N.	Code	Failure	Reliability Parameter	Nodes							Remarks
				Main Left	N1	N2	N3	N4	N5	Main Right	
1	BR	HV Branches	D_N		4.9937	4.9711	4.9911	4.9852	5.0034		
			C_N		0	4.9937	9.9648	5.0034	0		
			D_T		0. 0113	0. 0113	0. 0114	0. 0113	0. 0114		
			C_T		0	0. 0113	0.0227	0. 0114	0		
			D_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			C_FR_MT		0	0.0023	0.0023	0.0023	0		
			D_FR_Y		0.0999	0.0994	0.0998	0.0997	0.1001		
			C_FR_Y		0	0.0999	0.1993	0.1001	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.1371	0.2193	0.2453	0.2184	0.1375		
			T		0.0038	0.0060	0.0067	0.0060	0.0037		
			FR_MT		0.0275	0.0274	0.0272	0.0273	0.0272		
			FR_Y		0.0027	0.0044	0.0049	0.0043	0.0028		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	4.9696	9.9212	9.8984	4.9621	9.9334	9.9119	4.9592	
			C_N		4.9696	14.8887	24.7388	14.8711	4.9592		
			D_T	0.0170	0.0338	0.0336	0.0169	0.0338	0.0337	0.0170	
			C_T		0.0170	0.0508	0.0844	0.0507	0.0170		
			D_FR_MT	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	
			C_FR_MT		0.0034	0.0034	0.0034	0.0034	0.0034		
			D_FR_Y	0.0994	0.1984	0.1980	0.0992	0.1987	0.1982	0.0992	
			C_FR_Y		0.0994	0.2978	0.4948	0.2974	0.0992		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.1492	0.1482	0.0973	0	0.0492	0.1487	0.1508	*
			T	1.69e-4	1.70e-4	1.10e-4	0	0.56e-4	1.17e-4	1.72e-4	*
			FR_MT	0.0011	0.0011	0.0011	0	0.0011	0.0011	0.0011	*
			FR_Y	0.0030	0.0030	0.0019	0	0.0010	0.0030	0.0030	*
5	CCF	Ring CCF	D_N	2.4933	2.5097	2.5053	2.5000	2.5055	2.5005	2.5058	
			C_N		2.4933	5.0030	7.5083	5.0063	2.5058		
			D_T	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	
			C_T		0.0057	0.0114	0.0171	0.0114	0.0057		
			D_FR_MT	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	
			C_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			D_FR_Y	0.0499	0.0502	0.0501	0.0500	0.0501	0.0500	0.0501	
			C_FR_Y		0.0499	0.1001	0.1502	0.1001	0.0501		
6	NE	Equivalent Nodes Out-of-Service	N		0	9.9923	19.9936	9.9814	0		
			T		0	0.0228	0.0457	0.0.0228	0		
			FR_MT		0	0.0023	0.0023	0.0023	0		
			FR_Y		0	0.1998	0.3999	0.1996	0		
7	TF	Total Failure Rate			0.5034	1.0514	1.4981	1.0511	0.5033		
8	TUA	Total Unavailability			0.0015	0.0031	0.0042	0.0031	0.0015		



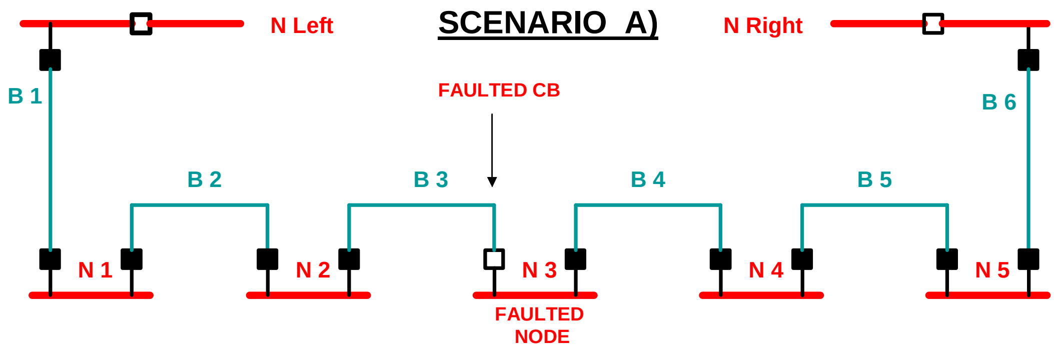
RING SIMULATION				Scenario C)		Forced Failure and Repair Rates					
N.	Code	Failure	Reliability Parameter	Nodes: Main Left	N1	N2	N3	N4	N5	Main Right	Remarks
1	BR	HV Branches	D_N		5.0016	4.9904	5.0006	4.9971	5.0051		
			C_N		0	5.0016	9.9921	5.0051	0		
			D_T		0. 0114	0. 0114	0. 0113	0. 0113	0. 0114		
			C_T		0	0. 0114	0.0227	0. 0114	0		
			D_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			C_FR_MT		0	0.0023	0.0023	0.0023	0		
			D_FR_Y		0.1000	0.0998	0.1000	0.0999	0.1001		
			C_FR_Y		0	0.1000	0.1998	0.1001	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.1374	0.2206	0.2492	0.2217	0.1378		
			T		0.0038	0.0060	0.0068	0.0061	0.0038		
			FR_MT		0.0273	0.0271	0.0272	0.0274	0.0275		
			FR_Y		0.0027	0.0044	0.0050	0.0044	0.0028		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	4.9686	9.9262	9.9102	9.9224	4.9570	9.9193	4.9552	
			C_N		4.9686	14.8848	24.7950	14.8745	4.9552		
			D_T	0.0170	0.0338	0.0337	0.0337	0.0169	0.0338	0.0170	
			C_T		0.0170	0.0508	0.0845	0.0508	0.0170		
			D_FR_MT	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	
			C_FR_MT		0.0034	0.0034	0.0034	0.0034	0.0034		
			D_FR_Y	0.0994	0.1983	0.1982	0.1984	0.0991	0.1984	0.0991	
			C_FR_Y		0.0994	0.2977	0.4959	0.2975	0.0991		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.1492	0.1491	0.1493	0.0497	0	0.0944	0.1506	*
			T	1.70e-4	1.71e-4	1.68e-4	0.58e-4	0	1.13e-4	1.70e-4	*
			FR_MT	0.0011	0.0011	0.0011	0.0012	0	0.0011	0.0011	*
			FR_Y	0.0030	0.0030	0.0030	0.0010	0	0.0020	0.0030	*
5	CCF	Ring CCF	D_N	2.4947	2.5048	2.4902	2.5110	2.5002	2.4980	2.4971	
			C_N		2.4947	4.9995	7.4897	4.9951	2.4971		
			D_T	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	
			C_T		0.0057	0.0114	0.0171	0.0114	0.0057		
			D_FR_MT	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	
			C_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			D_FR_Y	0.0499	0.0501	0.0498	0.0502	0.0500	0.0500	0.0499	
			C_FR_Y		0.0499	0.1000	0.1498	0.0999	0.0499		
6	NE	Equivalent Nodes Out-of-Service	N		0	9.9955	19.9850	9.9731	0		
			T		0	0.0229	0.0457	0.0227	0		
			FR_MT		0	0.0023	0.0023	0.0023	0		
			FR_Y		0	0.1999	0.3997	0.1995	0		
7	TF	Total Failure Rate			0.5035	1.0528	1.5999	0.9505	0.5022		
8	TUA	Total Unavailability			0.0015	0.0031	0.0046	0.0027	0.0015		



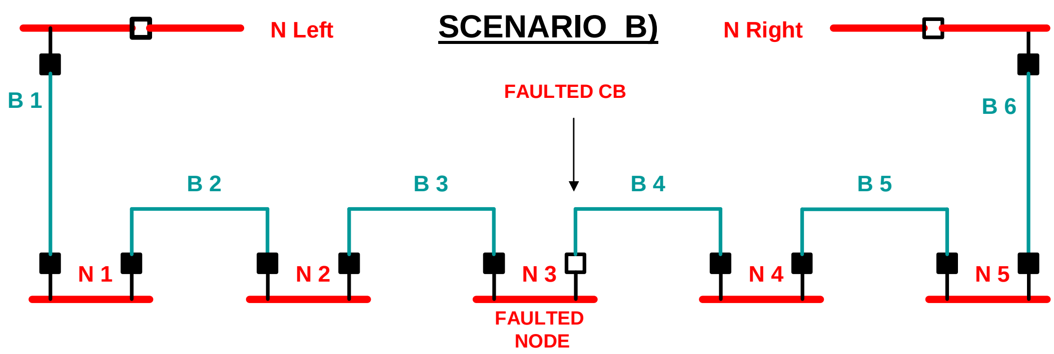
RING SIMULATION

Scenario D) | **<u>Forced</u> Failure and Repair Rates**

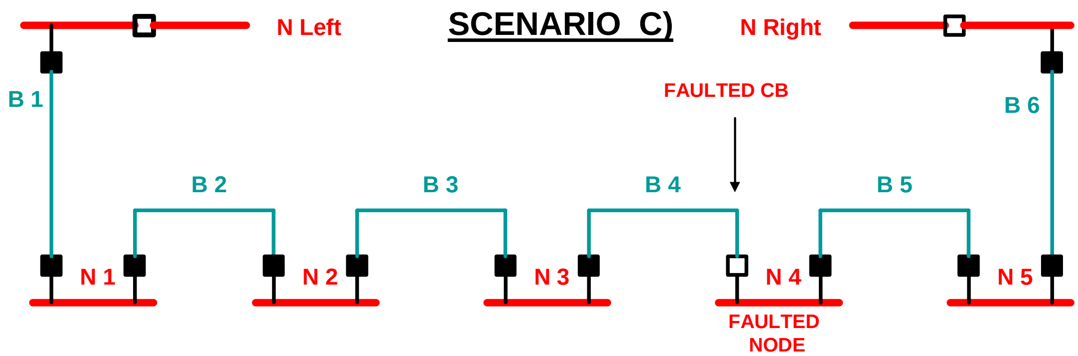
N.	Code	Failure	Reliability Parameter	Nodes: Main Left	N1	N2	N3	N4	N5	Main Right	Remarks
1	BR	HV Branches	D_N		5.0063	4.9866	4.9972	4.9919	4.9902		
			C_N		0	5.0063	9.9821	4.9902	0		
			D_T		0. 0114	0. 0113	0. 0113	0. 0113	0. 0113		
			C_T		0	0. 0114	0.0227	0. 0113	0		
			D_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			C_FR_MT		0	0.0023	0.0023	0.0023	0		
			D_FR_Y		0.1001	0.0997	0.0999	0.0998	0.0998		
			C_FR_Y		0	0.1001	0.1996	0.0998	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.1367	0.2198	0.2469	0.2215	0.1391		
			T		0.0037	0.0060	0.0067	0.0060	0.0038		
			FR_MT		0.0271	0.0272	0.0271	0.0272	0.0271		
			FR_Y		0.0027	0.0044	0.0049	0.0044	0.0028		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	4.9485	9.9231	4.9505	9.9082	9.9333	9.9266	4.9578	
			C_N		4.9485	14.8583	24.8177	14.8844	4.9578		
			D_T	0.0171	0.0338	0.0169	0.0337	0.0338	0.0337	0.0170	
			C_T		0.0171	0.0508	0.0845	0.0508	0.0170		
			D_FR_MT	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	
			C_FR_MT		0.0034	0.0034	0.0034	0.0034	0.0034		
			D_FR_Y	0.0997	0.1985	0.0990	0.1982	0.1987	0.1985	0.0992	
			C_FR_Y		0.0997	0.2972	0.4964	0.2977	0.0992		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.1487	0.0998	0	0.0496	0.1467	0.1482	0.1492	*
			T	1.73e-4	1.11e-4	0	0.58e-4	1.68e-4	1.69e-4	1.72e-4	*
			FR_MT	0.0012	0.0011	0	0.0011	0.0011	0.0011	0.0012	*
			FR_Y	0.0030	0.0020	0	0.0010	0.0029	0.0030	0.0030	*
5	CCF	Ring CCF	D_N	2.4961	2.5062	2.5032	2.5040	2.5044	2.5048	2.5013	
			C_N		2.4961	5.0023	7.5104	5.0060	2.5013		
			D_T	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	
			C_T		0.0057	0.0114	0.0171	0.0114	0.0057		
			D_FR_MT	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	
			C_FR_MT		0.0023	0.0023	0.0023	0.0023	0.0023		
			D_FR_Y	0.0499	0.0501	0.0501	0.0501	0.0501	0.0501	0.0500	
			C_FR_Y		0.0499	0.1000	0.1502	0.1001	0.0499		
6	NE	Equivalent Nodes Out-of-Service	N		0	10.0056	19.9822	0.9959	0		
			T		0	0.0228	0.0456	0.0228	0		
			FR_MT		0	0.0023	0.0023	0.0023	0		
			FR_Y		0	0.2001	0.3996	0.1999	0		
7	TF	Total Failure Rate			0.5031	0.9507	1.6000	10.535	0.5034		
8	TUA	Total Unavailability			0.0016	0.0027	0.0045	0.0031	0.0015		



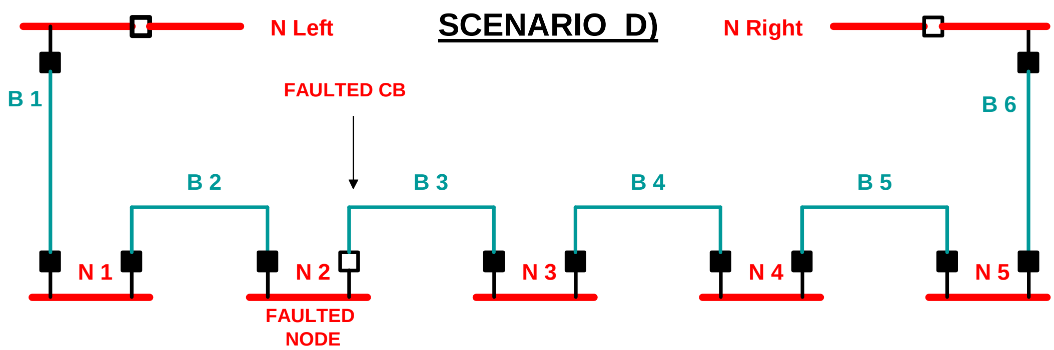
RING SIMULATION				Scenario A)			Real Failure and Repair Rates				
				Nodes							
N.	Code	Failure	Reliability Parameter	Main Left	N1	N2	N3	N4	N5	Main Right	Remarks
1	BR	HV Branches	D_N		9.9968	10.0196	10.0066	0.9939	9.9975		
			C_N		0	9.9968	19.9914	9.9975	0		
			D_T		0. 0057	0. 0057	0. 0057	0. 0057	0. 0057		
			C_T		0	0. 0057	0.0114	0. 0057	0		
			D_FR_MT		5.71e-4	5.71e-4	5.70e-4	5.72e-4	5.70e-4		
			C_FR_MT		0	5.71e-4	5.71e-4	5.70e-4	0		
			D_FR_Y		0.1999	0.2004	0.2001	0.1999	0.1999		
			C_FR_Y		0	0.1999	0.3998	0.1999	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.0315	0.0493	0.0550	0.0497	0.0310		
			T		0.42e-4	0.66e-4	0.73e-4	0.65e-4	0.40e-4		
			FR_MT		0.0013	0.0013	0.0013	0.0013	0.0013		
			FR_Y		0.0006	0.0010	0.0011	0.0010	0.0006		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	0.0996	0.2012	0.2023	0.0991	0.2015	0.1969	0.0097	
			C_N		0.0996	0.3008	0.4980	0.2966	0.0997		
			D_T	1.12e-4	0.24e-3	0.23e-3	0.11e-3	0.23e-3	0.23e-3	1.13e-4	
			C_T		0.11e-3	0.35e-3	0.57e-3	0.34e-3	0.11e-3		
			D_FR_MT	0.0011	0.0012	0.0011	0.0011	0.0011	0.0011	0.0011	
			C_FR_MT		0.0011	0.0012	0.0011	0.0011	0.0011		
			D_FR_Y	0.0020	0.0040	0.0040	0.0020	0.0040	0.0039	0.0020	
			C_FR_Y		0.0020	0.0060	0.0100	0.0059	0.0020		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.0102	0.0101	0.0103	0	0.0102	0.0099	0.0106	
			T	0.60e-5	0.58e-5	0.60e-5	0	0.61e-5	0.57e-5	0.57e-5	
			FR_MT	0.59-3	0.57e-3	0.58e-3	0	0.60e-3	0.58e-3	5.44e-3	
			FR_Y	0.20e-3	0.20e-3	0.21e-3	0	0.20e-3	0.20e-3	0.21-3	
5	CCF	Ring CCF	D_N	0.4969	0.4983	0.4969	0.5045	0.4978	0.4979	0.5033	
			C_N		0.4969	0.9952	1.4990	1.0012	0.5033		
			D_T	2.83e-4	2.82e-4	2.82e-4	2.88e-4	2.83e-4	2.84e-4	2.86e-4	
			C_T		2.83e-4	5.65e-4	85.3e-4	5.71e-4	2.86e-4		
			D_FR_MT	5.69e-4	5.66e-4	5.68e-4	5.71e-4	5.68e-4	5.71e-4	5.69e-4	
			C_FR_MT		5.69e-4	5.67e-4	5.69e-4	5.70e-4	5.69e-4		
			D_FR_Y	0.0099	0.0100	0.0099	0.0101	0.0100	0.0100	0.0101	
			C_FR_Y		0.0099	0.0199	0.0300	0.0200	0.0101		
6	NE	Equivalent Nodes Out-of-Service	N		0	0.2018	0.4000	0.2002	0		
			T		0	1.15e-4	2.29-4	1.14e-4	0		
			FR_MT		0	0.57e-3	0.57e-3	0.57e-3	0		
			FR_Y		0	0.040	0.0080	0.0040	0		
7	TF	Total Failure Rate			0.2267	0.4455	0.6611	0.4450	0.2267		
8	TUA	Total Unavailability			1.33e-4	2.61e-4	3.85e-4	2.60e-4	1.33e-4		



RING SIMULATION				Scenario B)		Real Failure and Repair Rates					
N.	Code	Failure	Reliability Parameter	Nodes							Remarks
				Main Left	N1	N2	N3	N4	N5	Main Right	
1	BR	HV Branches	D_N		9.9938	10.0069	9.9946	0.99884	10.0119		
			C_N		0	9.9938	20.0007	10.0119	0		
			D_T		0. 0057	0. 0057	0. 0057	0. 0057	0. 0057		
			C_T		0	0. 0057	0.0114	0. 0057	0		
			D_FR_MT		5.71e-4	5.71e-4	5.70e-4	5.70e-4	5.71e-4		
			C_FR_MT		0	5.71e-4	5.71e-4	5.70e-4	0		
			D_FR_Y		0.1999	0.2001	0.1999	0.1998	0.2002		
			C_FR_Y		0	0.1999	0.4000	0.2002	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.0306	0.0483	0.0546	0.0492	0.0302		
			T		0.40e-4	0.64e-4	0.71e-4	0.64e-4	0.39e-4		
			FR_MT		0.0013	0.0013	0.0013	0.0013	0.0013		
			FR_Y		0.0006	0.0010	0.0011	0.0010	0.0006		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	0.0994	0.1974	0.2017	0.1001	0.1992	0.1977	0.1022	
			C_N		0.0994	0.2968	0.4984	0.2999	0.1022		
			D_T	1.14e-4	0.22e-3	0.23e-3	0.11e-3	0.23e-3	0.23e-3	1.14e-4	
			C_T		0.11e-3	0.34e-3	0.57e-3	0.34e-3	0.12e-3		
			D_FR_MT	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	
			C_FR_MT		0.0011	0.0012	0.0011	0.0011	0.0011		
			D_FR_Y	0.0020	0.0039	0.0040	0.0020	0.0040	0.0040	0.0020	
			C_FR_Y		0.0020	0.0059	0.0100	0.0060	0.0020		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.0100	0.0100	0.0098	0	0.0098	0.0105	0.0101	
			T	0.55e-5	0.56e-5	0.53e-5	0	0.57e-5	0.59e-5	0.53e-5	
			FR_MT	0.55-3	0.56e-3	0.55e-3	0	0.60e-3	0.56e-3	0.52e-3	
			FR_Y	0.20e-3	0.20e-3	0.20e-3	0	0.20e-3	0.21e-3	0.20-3	
5	CCF	Ring CCF	D_N	0.4966	0.4978	0.4998	0.5021	0.4984	0.4957	0.5031	
			C_N		0.4966	0.9952	1.4990	1.0012	0.5031		
			D_T	2.84e-4	2.85e-4	2.85e-4	2.87e-4	2.82e-4	2.82e-4	2.87e-4	
			C_T		2.84e-4	5.67e-4	8.54e-4	5.69e-4	2.87e-4		
			D_FR_MT	5.71e-4	5.72-4	5.71e-4	5.71e-4	5.66e-4	5.68e-4	5.70e-4	
			C_FR_MT		5.71e-4	5.71e-4	5.71e-4	5.69e-4	5.70e-4		
			D_FR_Y	0.0099	0.0100	0.0100	0.0100	0.0100	0.0099	0.0101	
			C_FR_Y		0.0099	0.0199	0.0299	0.0200	0.0101		
6	NE	Equivalent Nodes Out-of-Service	N		0	0.1994	0.3974	0.1995	0		
			T		0	1.15e-4	2.29e-4	1.13e-4	0		
			FR_MT		0	0.58e-3	0.58e-3	0.57e-3	0		
			FR_Y		0	0.0040	0.0079	0.0040	0		
7	TF	Total Failure Rate			0.2269	0.4455	0.6515	0.4456	0.2271		
8	TUA	Total Unavailability			1.33e-4	2.61e-4	3.85e-4	2.60e-4	1.33e-4		



RING SIMULATION				Scenario C)		Real Failure and Repair Rates					
N.	Code	Failure	Reliability Parameter	Nodes							Remarks
				Main Left	N1	N2	N3	N4	N5	Main Right	
1	BR	HV Branches	D_N		9.9889	10.0015	9.9947	10.0048	9.9976		
			C_N		0	9.9889	19.9904	9.9976	0		
			D_T		0. 0057	0. 0057	0. 0057	0. 0057	0. 0057		
			C_T		0	0. 0057	0.0114	0. 0057	0		
			D_FR_MT		5.71e-4	5.70e-4	5.71e-4	5.72e-4	5.71e-4		
			C_FR_MT		0	5.71e-4	5.71e-4	5.71e-4	0		
			D_FR_Y		0.1998	0.2000	0.1999	0.2001	0.2000		
			C_FR_Y		0	0.1998	0.3998	0.2000	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.0306	0.0483	0.0552	0.0488	0.0307		
			T		0.40e-4	0.64e-4	0.73e-4	0.65e-4	0.41e-4		
			FR_MT		0.0013	0.0013	0.0013	0.0013	0.0013		
			FR_Y		0.0006	0.0010	0.0011	0.0010	0.0006		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	0.1003	0.2004	0.2015	0.1997	0.0991	0.1985	0.0971	
			C_N		0.1003	0.3007	0.5022	0.2956	0.0971		
			D_T	1.15e-4	0.23e-3	0.23e-3	0.23e-3	0.11e-3	0.23e-3	1.09e-4	
			C_T		0.11e-3	0.34e-3	0.57e-3	0.34e-3	0.11e-3		
			D_FR_MT	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	
			C_FR_MT		0.0011	0.0011	0.0011	0.0011	0.0011		
			D_FR_Y	0.0020	0.0040	0.0040	0.0040	0.0020	0.0040	0.0019	
			C_FR_Y		0.0020	0.0060	0.0100	0.0059	0.0019		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.0104	0.0106	0.0098	0.0104	0	0.0098	0.0095	
			T	0.59e-5	0.61e-5	0.58e-5	0.58e-5	0	0.57e-5	0.53e-5	
			FR_MT	0.54-3	0.57e-3	0.59e-3	0.58e-3	0	0.58e-3	0.56e-3	
			FR_Y	0.21e-3	0.21e-3	0.20e-3	0.21e	0	0.20e-3	0.19-3	
5	CCF	Ring CCF	D_N	0.4962	0.5019	0.5020	0.5016	0.5016	0.5004	0.4989	
			C_N		0.4962	0.9981	1.5001	0.9993	0.4989		
			D_T	2.84e-4	2.90e-4	2.86e-4	2.86e-4	2.87e-4	2.86e-4	2.85e-4	
			C_T		2.84e-4	5.74e-4	8.60e-4	5.71e-4	2.85e-4		
			D_FR_MT	5.73e-4	5.77-4	5.69e-4	5.70e-4	5.72e-4	5.71e-4	5.72e-4	
			C_FR_MT		5.73e-4	5.75e-4	5.73e-4	5.72e-4	5.72e-4		
			D_FR_Y	0.0099	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	
			C_FR_Y		0.0099	0.0200	0.0300	0.0200	0.0100		
6	NE	Equivalent Nodes Out-of-Service	N		0	0.2000	0.3992	0.2014	0		
			T		0	1.15e-4	2.28e-4	1.16e-4	0		
			FR_MT		0	0.57e-3	0.57e-3	0.58e-3	0		
			FR_Y		0	0.0040	0.0080	0.0040	0		
7	TF	Total Failure Rate			0.2270	0.4452	0.6630	0.4422	0.2264		
8	TUA	Total Unavailability			1.34e-4	2.61e-4	3.87e-4	2.58e-4	1.33e-4		



RING SIMULATION				Scenario D)			Real Failure and Repair Rates				
N.	Code	Failure	Reliability Parameter	Nodes							Remarks
				Main Left	N1	N2	N3	N4	N5	Main Right	
1	BR	HV Branches	D_N		9.9911	9.9860	10.0002	9.9979	10.0025		
			C_N		0	9.9911	20.0003	10.0025	0		
			D_T		0. 0057	0. 0057	0. 0057	0. 0057	0. 0057		
			C_T		0	0. 0057	0.0114	0. 0057	0		
			D_FR_MT		5.71e-4	5.72e-4	5.71e-4	5.71e-4	5.70e-4		
			C_FR_MT		0	5.71e-4	5.70e-4	5.70e-4	0		
			D_FR_Y		0.1998	0.1997	0.2000	0.2000	0.2000		
			C_FR_Y		0	0.1998	0.4000	0.2000	0		
2	CB_M3_BR	HV Circuit Breakers Failure Mode M3 for Failure on Branch	N		0.0311	0.0508	0.0564	0.0495	0.0308		
			T		0.40e-4	0.67e-4	0.74e-4	0.65e-4	0.41e-4		
			FR_MT		0.0013	0.0013	0.0013	0.0013	0.0013		
			FR_Y		0.0006	0.0010	0.0011	0.0010	0.0006		
3	CB_M1	HV Circuit Breakers Failure Mode M1	D_N	0.0994	0.2000	0.0995	0.1994	0.2021	0.2007	0.1008	
			C_N		0.0994	0.2994	0.5036	0.3015	0.1008		
			D_T	1.13e-4	0.23e-3	0.11e-3	0.23e-3	0.23e-3	0.23e-3	1.15e-4	
			C_T		0.11e-3	0.34e-3	0.57e-3	0.34e-3	0.11e-3		
			D_FR_MT	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	
			C_FR_MT		0.0011	0.0011	0.0011	0.0011	0.0011		
			D_FR_Y	0.0020	0.0020	0.0040	0.0040	0.0040	0.0040	0.0020	
			C_FR_Y		0.0020	0.0060	0.0101	0.0060	0.0020		
4	CB_M3	HV Circuit Breakers Failure Mode M3 for Failure in a HV CB (M1)	N	0.0099	0.0104	0	0.0103	0.0103	0.0103	0.1008	
			T	0.63e-5	0.57e-5	0	0.60e-5	0.57e-5	0.59e-5	0.64e-5	
			FR_MT	0.57-3	0.55e-3	0	0.58e-3	0.56e-3	0.57e-3	0.60e-3	
			FR_Y	0.20e-3	0.21e-3	0	0.21e-3	0.21e-3	0.21e-3	0.22-e3	
5	CCF	Ring CCF	D_N	0.4993	0.4997	0.5076	0.4990	0.4966	0.5015	0.5038	
			C_N		0.4993	0.9990	1.5018	1.0052	0.5038		
			D_T	2.83e-4	2.85e-4	2.89e-4	2.86e-4	2.83e-4	2.85e-4	2.86e-4	
			C_T		2.83e-4	5.68e-4	8.55e-4	5.71e-4	2.86e-4		
			D_FR_MT	5.67e-4	5.71-4	5.69e-4	5.72e-4	5.71e-4	5.68e-4	5.68e-4	
			C_FR_MT		5.67e-4	5.69e-4	5.69e-4	5.68e-4	5.68e-4		
			D_FR_Y	0.0100	0.0102	0.0100	0.0100	0.0099	0.0100	0.0101	
			C_FR_Y		0.0100	0.0200	0.0300	0.0201	0.0101		
6	NE	Equivalent Nodes Out-of-Service	N		0	0.1999	0.3996	0.2006	0		
			T		0	1.15e-4	2.29e-4	1.15e-4	0		
			FR_MT		0	0.58e-3	0.57e-3	0.57e-3	0		
			FR_Y		0	0.0040	0.0080	0.0040	0		
7	TF	Total Failure Rate			0.2269	0.4427	0.6630	0.4451	0.2268		
8	TUA	Total Unavailability			1.33e-4	2.58e-4	3.87e-4	2.61e-4	1.33e-4		

7.18 *Output Results Analysis*

- Ring Analysis

The output results have been summarized in the following table.

The main parameter in the Nodes Availability; the other parameters reported in the output tables, such as failure rates and partial out-of-service times, are necessary as additional information for a sound interpretation of the results.

The Nodes Unavailability has been computed as the average figure of the 4 assumed scenarios; the unavailability increase of the intermediate nodes N2, N3 and N4 has been referred to the average unavailability of the extreme nodes N1 and N5.

Ring Nodes Average Unavailability (x 10^{-3})

Scenario	**N1**	**N2**	**N3**	**N4**	**N5**
A)	0.1334	0.2608	0.3849	0.2604	0.1330
B)	0.1334	0.2607	0.3854	0.2604	0.1333
C)	0.1335	0.2606	0.3873	0.2576	0.1330
D)	0.1332	0.2580	0.3872	0.2605	0.1333
Average	0.1334	0.2600	0.3862	0.2597	0.1332
Δ% over (N1+N5)/2		95	190	95	

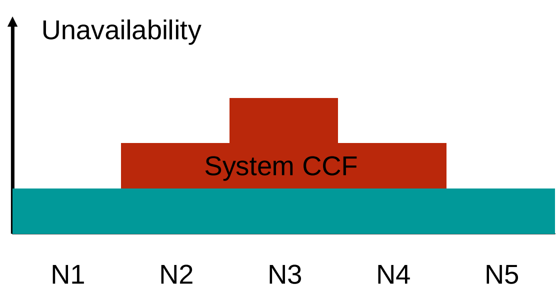
The unavailability difference between N2 and N1 is 95% (same as between N4 and N5), and the difference between N3 and N1 is 195% (same as between N3 and N5). However, there is to take into account that the intermediate nodes N2, N3 and N4 only have been considered as "Open Nodes" , and in these cases failures N.2 (HV Circuit Breakers Failure Mode M3 for Failure on Branch) and N.3 (HV Circuit Breakers Failure Mode M1) are related to only one circuit breaker in the node; the analysis of the output tables shows that the difference due to the above assumption is around 5%, therefore, in case that also the extreme nodes N1 and N2 would have been considered as "Open Nodes", the above differences should be 100% and 200% instead of 95% and 195%.

The assumption to consider the intermediate nodes only as "Open Nodes" is actually sound, because there is no sense to unbalance the grid in normal working conditions; however, a general ring model has to take into account any possible configuration, and the rounded differences 100% and 200% has to be taken as reference parameters. Eventually, the Nodes unavailability are as follows:

Nodes	**Parametric Unavailability**	**Rounded Figure to be used in the Overall "Ring + Load Nodes" Analysis**
Extreme Nodes N1 and N5	UA	1.3 e-4
Second Nodes N2 and N4	2 x UA	2.6 e-4
Central Node	3 x UA	3.9 e-4

Conclusions:

- The Ring proved to be a **symmetrical structure in terms of performance (Nodes Unavailability)** despite of the asymmetry due to the "Open Node" position, and of the Right – Left "Open Circuit Breaker" choice inside the Open Node.
- **The Nodes Unavailabilities are of the same order; they are the product of the Unavailability of the extreme Nodes for the "ranking" (1,2,3, etc.) of the node from the ring extremities**
- **The increase of Nodes Unavailability from the extremities to the Ring Centre is due to the System CCFs, which play an extremely relevant role.**



- CCFs due to component failures are not relevant, because of their very low failure rate.

Consideration:

The results of the Ring analysis, and specifically the “Parametric Unavailability” of the Nodes, now seem to be intuitive, conversely they where actually “hidden”. This is a typical result of the Montecarlo Analysis: what was hidden becomes clear, evident.

The sound interpretation of the results is possible because:

- All the possible failure sequences have been examined thoroughly and modeled in detail, and this is supplying a strong background to the analyst.
- A previous simplified analysis has been carried out, to evaluate rounded expected figures (see Ch. 7.17, Output Tables – Expected Rounded Figures – Ring Simulation)
- The output have been subdivided in all the possible failure modes and reliability parameters

The above procedure is a starting point for a general procedure for the sound interpretation of the Montecarlo results.

➢ **Overall “Ring + Load Nodes” Analysis**

The simplified but reliable criteria to carry out a clear analysis of the overall “Ring + Load Nodes” performance is to use the REA (Rare Events Approximation) and simply to add the unavailabilities of the Ring Nodes and of the Load Nodes. In fact, REA is applicable because unavailabilities are of the order of 10 e-4.

In accordance with the Load Nodes analysis (see previous Chapter), 3 alternatives have been considered, with different probability of overload in case of a non simultaneous CCF on a transformers branch; the results are summarized in the following table.

Ring Nodes + Load Nodes Unavailability (x e-3) Dependence from Load Nodes CCF Overload Probability					
Nodes CCF P = 0.1	**N1**	**N2**	**N3**	**N4**	**N5**
Ring Nodes	0.1300	0.2600	0.3900	0.2600	0.1300
Load Nodes	0.1300	0.1300	0.1300	0.1300	0.1300
Total	**0.2600**	**0.3900**	**0.5200**	**0.3900**	**0.2600**
Nodes CCF P = 0.01	**N1**	**N2**	**N3**	**N4**	**N5**
Ring Nodes	0.1300	0.2600	0.3900	0.2600	0.1300
Load Nodes	0.0170	0.0170	0.0170	0.0170	0.0170
Total	**0.1470**	**0.2770**	**0.4070**	**0.2770**	**0.1470**
Nodes CCF P = 0.001	**N1**	**N2**	**N3**	**N4**	**N5**
Ring Nodes	0.1300	0.2600	0.3900	0.2600	0.1300
Load Nodes	0.0053	0.0053	0.0053	0.0053	0.0053
Total	**0.1353**	**0.2653**	**0.3953**	**0.2653**	**0.1353**

<u>Analysis of the alternatives</u>

- Nodes CCF P = 0.1: The contribution of the Load Nodes to the overall unavailability is same as the contribution of the Ring Nodes;
- Nodes CCF P = 0.01: The contribution of the Load Nodes is evident, but not relevant;
- Nodes CCF P = 0.001: The contribution of the Load Nodes is negligible

<u>Interpretation</u>

The Load Nodes, as considered in this report, are fully redundant (1 out of 2) structure, therefore their redundancy level is higher that the one of the upstream network (Ring). However, there is no alternative, because:

- A Load Node with one only branch, that means without redundancy, would be too week and in fact it is not a standard structure;

- A Load Node with three branches (2 out of three redundancy) has been sometimes adopted, but it is not usual, because it is requiring more space and conversely there is not a cost reduction.

A comparison with a Wi-Fi system, analyzed in the previous chapter, leads to interesting consideration. In this case, the upper grid has a certain degree of redundancy due to the overlapping of the "cells"; conversely, the Load Nodes (the access points, the cellular phones, etc) have no redundancy. The overall grid performance in this case is of course quite different; it is interesting that it is not usual to carry out by the users a comparison between the cost due to the Utility (redundant system, therefore non critical), and the cost of a cellular phone (non redundant, and therefore critical)

7.19 *4th Objective - Conclusion*

CCFs play a relevant role:

- System CCFs are predominant for the unavailability of the Ring Nodes, that are the main availabilities of the Ring + Load Nodes system
- CCFs in the Load Nodes (i.e. Non simultaneous CCFs in transformers branches): If there are CCFs in the Load Nodes which have a relevant impact, the Load Nodes unavailability has a relevant impact too on the overall unavailability; this is a typical scenario in developing countries. Otherwise, the Load Nodes unavailability is negligible

7.20 *Proposed Simplified Formulae to Evaluate the Ring Nodes Unavailability and Failure Rate*

A project engineer, who has to design a Ring structure, should rely on a simplified but sound method to evaluate the Ring Performance, without the support of a complicate method such as the Montecarlo Simulation.

The proposed formulae are based on the following criteria:

- Overall failure rate based on the addition of the several failure modes but the ones relevant to the coupling, whose quantification is without simulation; in fact, the "Node" block is treated as a series of reliability blocks.
- Overall Unavailability as above, considering REA – Rare Event Approximation
- Introduction of coefficients relevant to the coupler impact; a range is suggested, and the correct choice is left to engineering judgment,
- Introduction of a conservative coefficient, taking into account REA as well as the minor effects that simulation only can evaluate,
- Utilization of simplified formulae failure rate and unavailability for the parallel of the Transformer Branches; they are reported in [9B] Birolini Textbook.

The formulae here below have to be also considered as a synthesis of Ring analysis.

LOAD NODE

A) <u>WITHOUT Non-Simultaneous CCFs</u>

A.1 1 Bus Bar Out

$$\lambda_{LN\_1B} = K_{\lambda\_LN\_1B} \sum \lambda_{(LN\_1B\_FM)i}$$

$$UA_{LN\_1B} = K_{UA\_LN\_1B} \sum UA_{(LN\_1B\_FM)i}$$

$$K_{\lambda\_LN\_1B} = 1.3 \div 1.7$$

$$K_{UA\_LN\_1B} = 1.3 \div 1.7$$

where:

λ_{LN_1B}	Failure Rate – 1 Bus Bar Out
UA_{LN_1B}	Unavailability – 1 Bus Bar Out
$\lambda_{(LN\_1B\_FM)i}$	Failure Rate of the “i” Failure Mode leading to 1 Bus Bar Out, excluding Coupler Failures
$UA_{(LN\_1B\_FM)i}$	Unavailability of the “i” Failure Mode leading to 1 Bus Bar Out, excluding Coupler Failures
$K_{\lambda\_LN\_1B}$	Failure Rate Coefficient taking into account Coupler Failure Modes
$K_{UA\_LN\_1B}$	Unavailability Coefficient taking into account Coupler Failure Modes

A.2 Both Bus Bars Out

$$\lambda_{LN\_2B} = K_{\lambda\_LN\_2B} \frac{2\lambda_{Tr\_Branch}^2}{\mu_{Tr\_Branch}}$$ (Parallel of the Transformer Branches)

$$UA_{LN\_2B} = K_{UA\_LN\_2B} \frac{\lambda_{Tr\_Branch}^2}{\mu_{Tr\_Branch}^2}$$ (Parallel of the Transformer Branches)

$$K_{\lambda\_LN\_2B} = 1.4 \div 1.8$$
$$K_{UA\_LN\_2B} = 1.4 \div 1.8$$

where:

λ_{LN_2B}	Failure Rate – Both Bus Bars Out
UA_{LN_2B}	Unavailability – Both Bus Bars Out
λ_{Tr_Branch}	Failure Rate of the Transformer Branch
μ_{Tr_Branch}	Repair-Substitution-Disconnection Rate of the Transformer Branch
$K_{\lambda\_LN\_2B}$	Failure Rate Coefficient taking into account Coupler Failure Modes
$K_{UA\_LN\_2B}$	Unavailability Coefficient taking into account Coupler Failure Modes

B) <u>WITH Non-Simultaneous CCFs</u>

Same Formulae,

$$K_{\lambda\_LN\_1B} = K_{UA\_LN\_1B} = K_{\lambda\_LN\_2B} = K_{UA\_LN\_2B} = 1.05$$

LOAD NODE + RING NODE

$$\lambda_{(TLN)j} = \lambda_{(RN)j} + \lambda_{LN}$$
$$UA_{(TLN)j} = UA_{(RN)j} + UA_{LN}$$

$$\lambda_{(RN)j} = KK_j \sum \lambda_{(RN\_FM)i}$$
$$UA_{(RN)j} = KK_j \sum UA_{(RN\_FM)i}$$

$$KK_i = \begin{cases} j & \text{if} \quad j < N/2 \\ N - j + 1 & \text{if} \quad i \geq N/2 \end{cases}$$

Where:

N	Quantity of the “j” Ring Nodes
$\lambda_{(TLN)j}$	Overall Failure Rate of the Load Node connected to the “j” Ring Node
$UA_{(TLN)j}$	Overall Unavailability of the Load Node connected to the “j” Ring Node
$\lambda_{(RN)j}$	Failure Rate of the of the “j” Ring Node
$UA_{(RN)j}$	Unavailability of the “j” Ring Node
λ_{LN}	Failure Rate of the Load Node as above evaluated
UA_{LN}	Unavailability of the Load Node as above evaluated
KK_j	Position Coefficient of the “j” Ring Node
$\lambda_{(RN)i}$	Failure Rate of the “i” Failure Mode of the Ring Node
$UA_{(RN)i}$	Unavailability of the “i” Failure Mode of the Ring Node

8 Accomplishment, and Future Objectives

8.1 Reached Objectives

A) A new generalized approach to model the repairable networks for reliability analysis, including CCFs as a main contributor

- Generalized models for Nodes, Branches and Load nodes.
- Interdependencies and CCFs on Networks / Components
- System Interdependencies and CCFs
- Functional Interdependencies and CCFs
- Simultaneous and non-simultaneous Interdependencies and CCFs

The new approaches have been developed and used in the advanced models adopted for Montecarlo simulation; although they have to be more and more refined, they proved to be effective, and applicable as general methodologies for repairable networks, of course with some specific adaptations.

Specific contribution relevant to the above mentioned new approaches:

- New methodology to include Interdependencies and CCFs in transition diagrams and matrices;
- New concept of "Virtual" Nodes, Branches and Load Nodes in network reliability analysis. This concept is very relevant to evaluate the impact of the out-of-service of a "virtual" node (more extended than a real node) on the network performance, because it can cause a System Interdependency/CCF;
- System Interdependency/CCFs, caused by the out-of-service of virtual nodes and branches. The new definition of System Interdependency/CCF is relevant to the simultaneous out-of-service of more load nodes, that are considered the final points

(the more important ones) of a network. This approach seems more comprehensive than the concept of “vulnerability region” developed by Allan et. al.

- New definition of Functional Interdependency/CCFs, and procedure to identify them;
- New concept of simultaneous and non-simultaneous Interdependency/CCFs, and procedure to identify them.

B) **Generalized Model of a Network Structure (Ring) on the Base of a Detailed Interdependency and CCF Analysis**

The results of the analysis lead to a sound interpretation of the Ring performance and to a simplified mathematical model.

A generalized model of this classic redundant scheme was not been developed for the time being.

8.2 Other Contribution Along the Way

Some other contributions came along the way, because the development of advanced simulation models required new approaches, as follows:

- Procedure to identify the typical network structures
- Load Nodes: Procedure to correlate protections selective operation and System Interdependency/CCFs
- Existing Networks and difficulty to evaluate the mission time: definition of random starting time of the renewal cycles
- Generalization of the Load Nodes model, and evaluation of the relevance of the impact on the overall network performance.

8.3 *Future Possible Contribution*

After the completion of this work, it would be interesting to go ahead with some new contribution, as follows:

- Montecarlo simulation variance reduction techniques, applied to the above described simulation models for Interdependencies/CCFs and networks
- Montecarlo simulation methods to facilitate the results interpretation
- Reward Models related with Network Performance and CCFs Impact
- Detailed Interdependency/CCFs analysis of telecom and protection systems with ring configuration, that is widely used.
- Detailed Interdependency/CCFs analysis of Wi Fi systems, with application to industrial processes.

9 Conclusions

The four objectives of this work have been reached, as follows:

1. <u>General methodology to include interdependencies/CCFs in repairable systems</u>

The above methodology has been tested in some studies (e.g. the example reported at Ch. 4.3) and led to satisfactory results:

- The transition diagrams and the relevant matrices have been developed within the frame of the real "residence states", therefore the failure states transitions are representing the real system dynamic performance.
- The addition of the CCFs within the frame of the "residence states" proved easy and clear.
- The calculation of the linear systems relevant to the transition matrices led to correct results, because the a.m. linear systems proved not complex even though the transition matrices are large and sparse.

2. <u>A new generalized approach to model the repairable networks for reliability analysis, including Interdependencies/CCFs as a main contributor</u>

The above methodology has been adopted by the Author to solve some network reliability studies that otherwise could have been faced with simplified methods only, and proved satisfactory to properly model the specific failure modes leading to the out-of-service of nodes and branches. It allowed the detailed analysis of the Load Nodes (3rd Objective) and of the Ring (4th Objective).

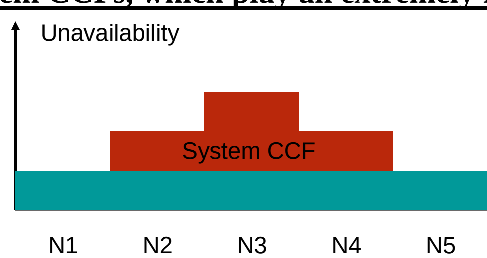
3. **<u>Detailed Interdependency/CCFs analysis and generalized model of a Power Distribution Load Node</u>**

The Load Node model is very detailed and it is taking into account all the several failure modes; therefore, a sound interpretation of the results has been possible, and specifically of the impact of the several failure modes.

The results interpretation is leading to a simplified math model, reported in Ch. 7.20. This model can be used by the substation designer to easily evaluate, with a reasonable precision, the availability at the MV bus-bars; the simplified math model can be used as an <u>equivalent model</u> to be superposed to the upper level grid, in order to reduce the simulation complexity and to facilitate the overall results interpretation.

4. **<u>Detailed Interdependency/CCFs analysis and generalized model of a network structure: a "RING" with load nodes is analysed in detail; a generalized model</u>**

    - The Ring proved to be a **<u>symmetrical structure in terms of performance (Nodes Unavailability)</u>** despite of the asymmetry due to the "Open Node" position, and of the Right – Left "Open Circuit Breaker" choice inside the Open Node.
    - **<u>The Nodes Unavailabilities are of the same order; they are the product of the Unavailability of the extreme Nodes for the "ranking" (1,2,3, etc.) of the node from the ring extremities</u>**
    - **<u>The increase of Nodes Unavailability from the extremities to the Ring Centre is due to the System CCFs, which play an extremely relevant role.</u>**



- CCFs due to component failures are not relevant, because of their very low failure rate.
- **CCFs play a relevant role**:
  - System CCFs are predominant for the unavailability of the Ring Nodes, that are the main availabilities of the Ring + Load Nodes system
  - CCFs in the Load Nodes (i.e. Non simultaneous CCFs in transformers branches): If there are CCFs in the Load Nodes which have a relevant impact, the Load Nodes unavailability has a relevant impact too on the overall unavailability; this is a typical scenario in developing countries. Otherwise, the Load Nodes unavailability is negligible
- A mathematical model has been obtained for the Ring + Load Nodes System; this model is suitable to be used in feasibility studies and basic design, in order to evaluate network configuration alternatives.

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Appendix A) - Networks Examples

Foreword

A deep analysis has been carried out on three typical network systems with re-configuration after fault, with quite different specific characteristics but with many characteristics that are also common to all the networks.

The objectives of the analysis, reported in Ch. 5, are:

- To develop **new generalized models** for network reliability evaluation , common to all the networks (see Ch. 5.4)
- To state **general rules** to identify the specific Dependent Failures of the networks (see Ch. 5.5)

The three typical networks that have been analyzed in detail are:

- Extra High Voltage (EHV) and High Voltage (HV) power transmission networks;
- Integrated Selective Phone Communication Networks (STSI – Sistema Telefonia Selettiva Integrata).
- Wireless Networks

The main differences between the above networks are:

- The complexity of the nodes:
  - Simple Real Nodes but Complex Virtual Nodes in Power Systems,
  - Quite complex both Real and Virtual Nodes in Telecommunication Systems
  - The predominant element in Wireless Systems
- The effects of failures:

- Failures on Power Systems can cause injuries to personnel and equipment; therefore, specific protective equipment is required, and they play a basic role
- Failures on Telecommunication Systems and Wireless Networks have mainly impact on the system performance, therefore protective equipment is less critical than for Power Systems

The analysis of the three above mentioned types of networks, with such different characteristics, seems enough comprehensive to lead to generalized results.

Failure statistics have been considered too, in order to validate the network analysis.

A.1. High Voltage (HV) and Extra High Voltage (EHV) Power Systems

Power Systems are the background of the Author, and a power system is the reference network of this job; therefore, they have been analyzed in detail.

A.1.1. System Description

The purpose of a Power Grids is to transport the power produced by the several generating plants, and to make it available to the final customers.

There are many voltage levels, as follows:

- MV (Middle Voltage) Power Generation: The generators of the power stations work at 11-20 kV, that is the typical range suitable for the insulation of a large rotating machine. The generators are connected to the higher voltages networks by means of step-up transformers;
- EHV (Extra High Voltage) Grids: The operating voltage is in the range 330 – 500 kV. These grids collect the power generated by the main power stations, and are dedicated to the power transmission over large distances (300 – 500 km), in order to feed the

load areas by means of step-down EHV /HV transformers. They are usually meshed, and they really work as a closed mesh; in principle, there are no radial connections;

- HV (High Voltage) Grids: The operating voltage is in the range 110 -132 kV. These grids are connected to the EHV systems by means of EHV / HV Transformers; they are dedicated to feed the HV load centres, that distribute the power to the local MV systems by means of HV/MV transformers; they also collect the power generated by the medium size power stations. These grids are usually simplified meshes (typically they are rings); in normal operation these meshes are open, and the HV systems are working as radial systems;

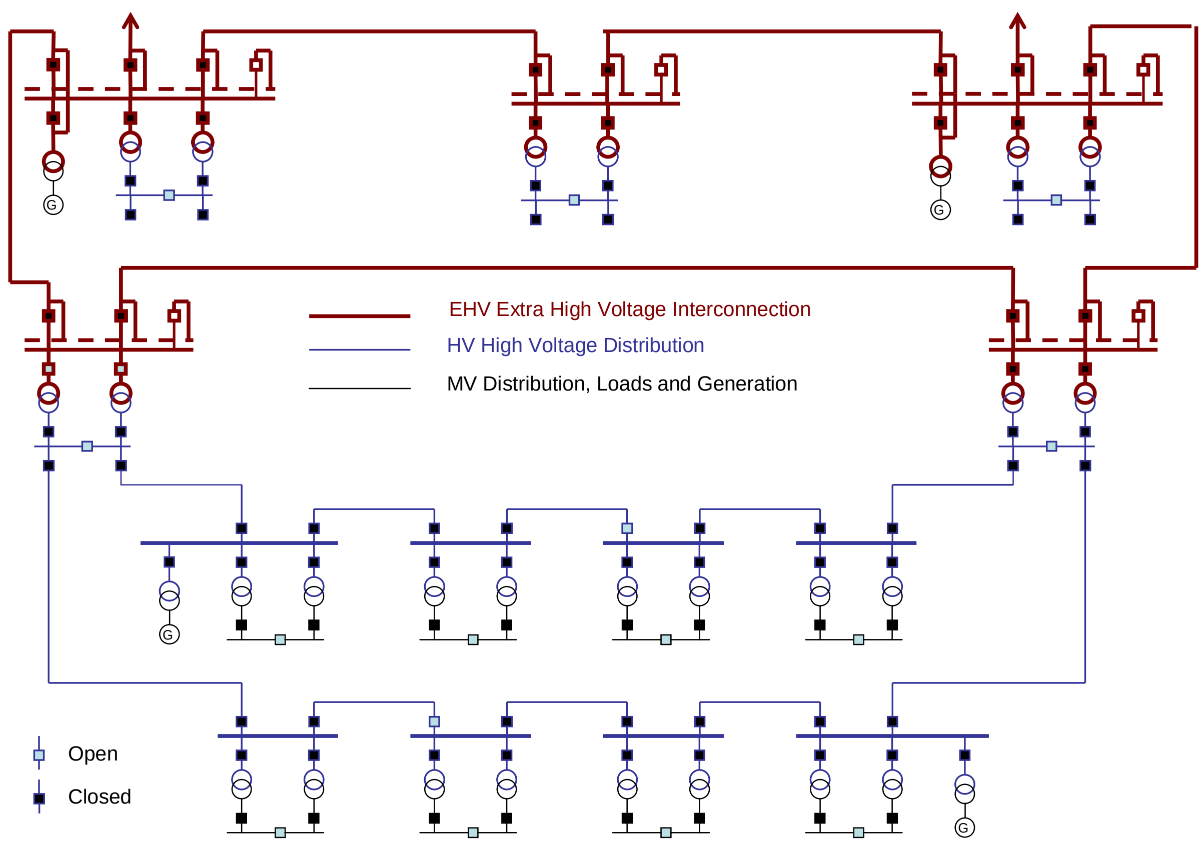


Fig. A.1 Typical EHV / HV Grid

- MV Middle Voltage) Distribution: The loads are fed at MV, by means of HV / MV substations.

The reliability goal has to be clear: to provide an optimized power supply to the MV distribution nodes. However, the optimization can be different considering the different points of view of the producers and of the customers, and the specific characteristics of the loads; therefore, several specific reliability indices have been defined for power systems.

The simplified diagram reported in fig. A.1 is showing a typical power transmission and distribution network, similar to the Italian and German systems, with all the above listed voltage levels; this typical system will be used as a reference for the following analysis.

A.1.2. Redundancies

Redundancies are relevant in this work, because CCFs are usually related with them as described in Ch. 1.

This work will focus on HV transmission and HV/MV Substations, therefore only the redundancies of these systems have been described.

- HV Substations: Usually, there are two fully redundant HV/MV (High Voltage / Middle Voltage) branches, that feed the two MV bus-bars; these two MV busbars can be interconnected by means of a tie-breaker (coupler) that is closed by an automatic control system in case of a fault on one of the two branches. The two HV/MV branches are connected up-stream to a main HV bus-bar, without tie-breaker. Two incoming feeders, relevant to the HV lines, are connected to these main HV bus-bars, therefore there is a redundancy of incoming feeders.

- HV Lines: They form a ring between two EHV / HV Substations; the ring is always open at one of the HV substations, in this case only one circuit breaker of the two incoming feeders is closed. The ring is a [n-1]-out-of-n redundant circuit. After the first fault, the damaged line or substation is sectionalized and the HV system is re-configurated to feed all the HV Substations; the system re-configuration is not automatic, and it needs a certain time. In case of a second fault, the HV system will be again re-configurated, but it could be not possible to feed all the HV Substations.

A.1.3. Protections, Telecommunication and Reclosures

Protections and associated devices (circuit breakers, etc.) play an extremely important role in power systems operation; the main reason is that a fault in an electrical system is always disruptive, and it is necessary to isolate as soon as possible the faulted branch in order to avoid injuries to the personnel and heavy damages to the equipment.

There are two main types of protective equipment:

- Interrupting devices, such as circuit breakers and fuses (fuses are installed only on secondary feeders of MV systems), that are suitable to interrupt the high fault currents in a very short time;
- Protective relays that detect the fault conditions and drive the opening mechanism of the above mentioned circuit breakers.

It has to be pointed out that the same protective equipment, and mainly the circuit breakers, can be a cause of fault. In other words, a circuit breaker has to interrupt a fault current on a up-stream faulted equipment, but at the same time it can have an internal fault and in this case another up-stream circuit breaker has to isolate this faulted circuit breaker. This is a specific characteristic of power systems only.

The intervention of the protective devices has to be selective:

- The fault has to be cleared in the minimum possible time, and the faulted branch only has to be isolated
- In case that the first attempt to isolate the fault would not succeed, a further protection intervention will isolate the fault as follows:
  - In radial grids (i.e. substations, etc.), the protections will open the up-stream circuit breaker
  - In meshed networks, the protections will open the up-stream and down-stream circuit breakers

In both cases, more feeders and bus-bars will be isolated, and the out-of-service will be more extended; this is important because in meshed grids the branches can be considered as redundant elements, and the malfunction of a protective device can cause a sort of Common Cause Failure.

Some typical protective schemes are reported in the following figures, as follows:

HV/MV Substation Protections

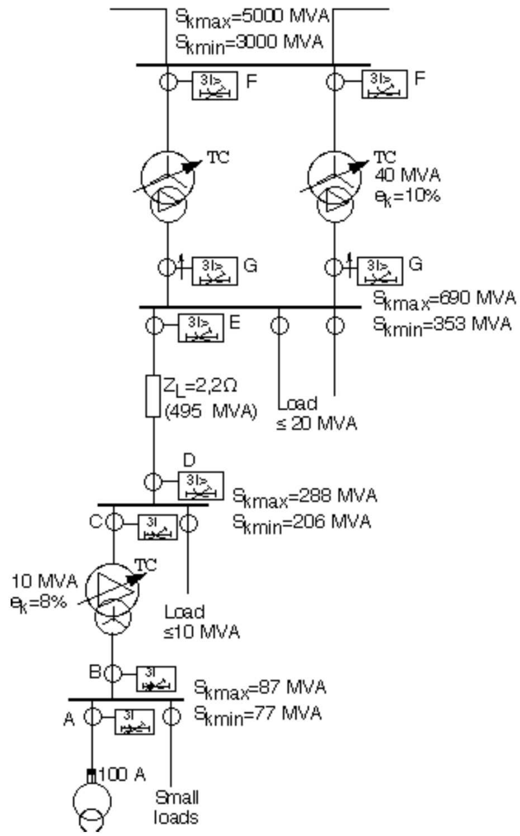
Fig. A.2 is showing a typical protection scheme for HV/MV substations. The selectivity diagram is including time (vertical) – current (horizontal) operating characteristics of the protective relays; the operating characteristics are set in order to be selective, i.e. for the same fault current the up-stream protection is operating always with a short delay.

HV Lines Protections

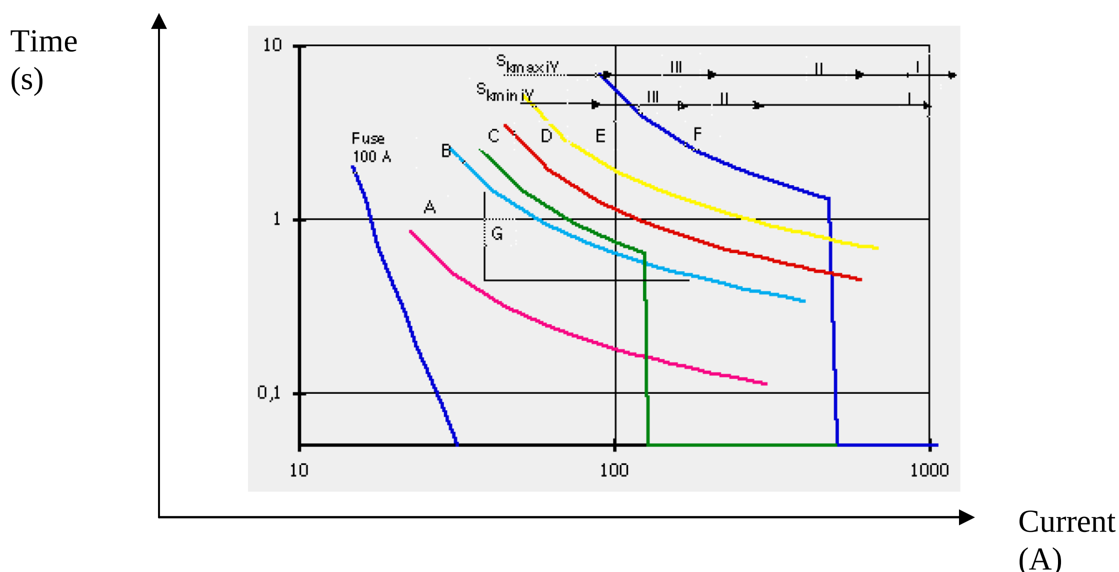
Fig. A.3 is showing a typical protection scheme for HV lines, including distance (under-impedance) protections, and a typical accelerating – blocking scheme with protections interconnected via telecommunication system.

The faulted line is detected by the up-stream and down-stream protections; the logic scheme is assuring that only the faulted line is interrupted, and within the shortest possible time (1st Zone). In case that the either protections or the circuit breakers would not work, the other protections will detect the fault on the successive operating Zones, and the fault will be cleared after a short delay (0.2 – 0.3 s); selectivity will be therefore used in this case too.

It has to be pointed out that sometimes faults on aerial lines are temporary and self-extinguishing; the typical case is a wet branch of a tree touching a HV conductor during a storm; in this case, after opening the HV line, a reclosure system will automatically reclose the circuit breakers that cleared the fault; this after-fault sequence however has to be considered as a system restoration, and not as a change in configuration after fault.



a) Typical HV/MV substation scheme, including protections
(3I > : Three-phase Overcurrent Relay)



b) Selectivity Diagram

Fig. A.2 Protection scheme and selectivity diagram of a typical HV//MV Substation

(From ABB Protection Application Handbook)

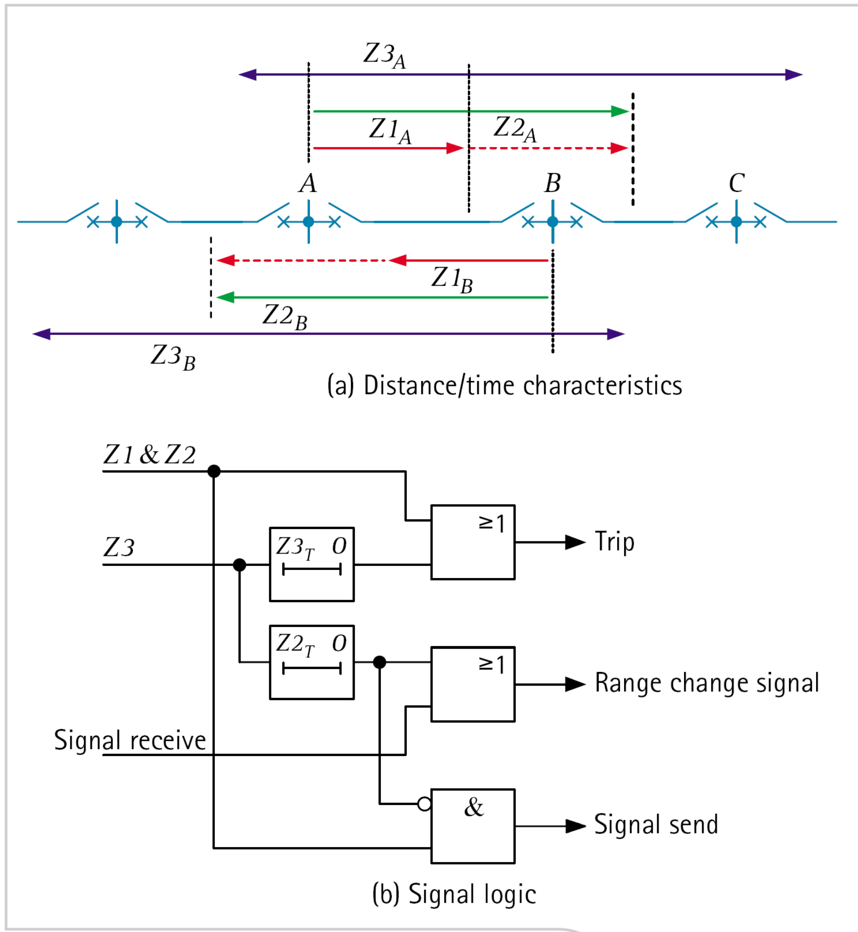


Fig. A.3 Distance protections for HV lines, with PUTT (Permissive Underreaching Transfer Trip) Telecommunication Scheme (From AREVA Protective Relay Application Guide)

A.1.4. Re-Configuration After a Fault

Power systems are redundant, but usually not Hot-Stand-By redundant; there is always need of a re-configuration, which is not instantaneous. Re-configuration modalities and times have to be taken into account in the reliability analysis of this type of networks.

The general criteria for the system re-configuration after fault are reported here below (HV and MV levels):

HV Nodes of a Ring

In case of a fault both on a branch (HV line portion) and of a node (HV busbars of a HV load centre substation), the following actions have to be taken:

- Isolation of the faulted branch or node,
- Re-configuration of the HV ring, in order to feed all the other HV nodes.

Usually the HV ring is open in one intermediate point of the HV line; it means that all the HV circuit breakers of the HV load centre sub-stations are closed with the exception of the ones in correspondence of the ring opening. The HV ring re-configuration is carried out by opening only the circuit breakers that isolate the fault, and closing all the other ones

MV Nodes

- There are usually two sections of MV bus-bars, with a normally open tie breaker between them (see next chapters); in case of loss of supply of one of the two bus-bars sections, an automatic transfer switch sequence will open the circuit breaker upstream the out-of-service bus-bars section, and it will close the tie breaker in order to assure continuity of power supply to both bus-bars sections.
- The failure cause must be automatically checked, and the change in configuration is allowed, by logic sequences, only if it will not cause the repetition of the fault. A simple example will clarify this problem: a fault on a feeder downstream a substation bus-bar has not been cleared by the feeder protections, therefore the protections up-stream the busbar had to open the main circuit breaker that is feeding the bus-bar; in this case, the bus-bars out-of-service, but it is not possible to close the tie-breaker (change in configuration to restore the service), because it would connect again the

faulted feeder whose protections are not working, with a successive and definitive out-of-service of the whole substation.

A.1.5. Virtual Nodes, Branches and Load Nodes

Virtual Nodes and Branches

The Substations are commonly considered the “Nodes” of the Network, and in fact they are designed, purchased and erected as fully independent projects, to be interconnection nodes; is it also common practice to consider the distribution lines as the “Branches” interconnecting the Substations. The real situation is different, as follows:

- The real nodes, i.e. the interconnecting points, are the substations bus-bars; they are simply aluminium pipes or ropes, with a extremely high reliability because there is little aging both in the conductors and in their ceramic insulators;
- The real branches are the lines, and the up-stream and downstream substation bays which interconnect them to the substation bus-bars.

However, failures in some components of the substation bays, and mainly in the circuit breakers, can cause the out-of-service of the bus-bars and as a consequence all of the node; therefore, these failure modes have to be included into the virtual nodes and not into the virtual branches.

A detailed analysis is reported in Ch. 6 (Load Nodes) and Ch. 7 (Upper Level Network); however, a scheme covering the boundaries of the virtual nodes and virtual branches in a HV ring is repeated here below, for sake of clarification.

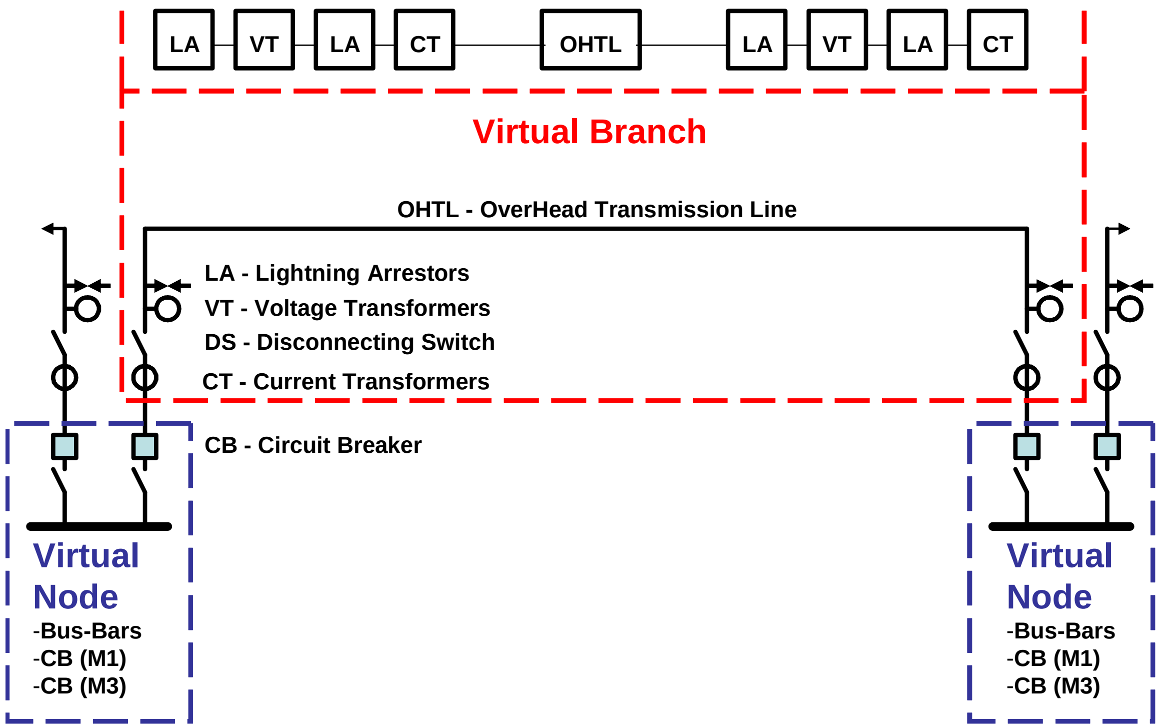


Fig.A.4 Example of Virtual Nodes and Branches in a HV Ring

Load Centers

The goal to create large interconnected grids is mainly to dispatch the energy to the load centers, and the goal of the load centers is to assure the energy supply continuity to their customers; therefore, the reliability model of the load centres is very important.

Typically, the load centres are High Voltage / Middle Voltage Substations with redundant HV/MV transformers bays; a very simplified single line diagram, as well as the relevant block diagram, are reported in the following figure.

Again, the "blocks" are related not only to the physical configuration of the Substation, but also to its functional characteristics; in other words, the blocks are not only referred to HV and MV equipment and to their interconnections, but they are virtual blocks that take into account both the main hardware internal failures and their functional failure modes.

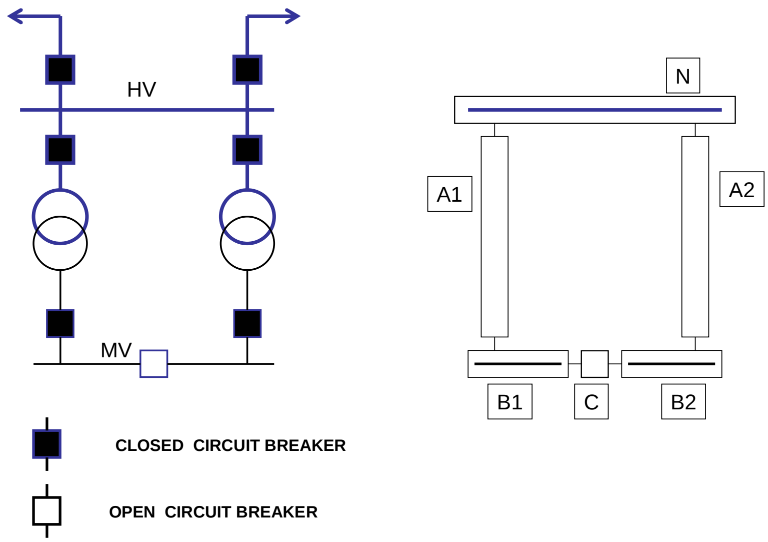


Fig. A.5 HV/MV Load Center

- **Block N** is a HV "virtual" node, in accordance with the definition reported in the previous paragraphs.
- **Blocks A1 and A2** are relevant to the HV/MV bays, but with some functional conditions described here below
- **Blocks B1 and B2** are relevant to the MV bus-bars, but with some functional conditions described here below. Both bus-bars usually can feed 100% of the load with a fully redundant distribution, or >50% of the load with a partially redundant distribution
- **Block C** is relevant to the MV Coupler (Tie Breaker)

Examples of the "functional conditions" of the "virtual" blocks:

- Out-of-service of A1: The fault is cleared by the HV and MV circuit breakers of A1. The consequence is the out-of-service of B1 only; in this case, C can be closed and B1 can be fed by A2+B2

- Out-of-service of B1: The fault is cleared by the MV circuit breaker in A1. It is not possible to close C and to feed B1 by A2+B2, because the fault that causes the out-of-service of B1 would operate the protections to open C and likely the MV circuit breaker in A2.

  Remark: A fault on a bus-bar is a rare event, and it is not the main cause of a bus-bar out-of-service; in other words, if a bus-bar is out-of-service, the cause is most likely out of the same bus-bar.

  For example, a fault on a MV feeder could have not been successfully cleared by its up-stream MV circuit breaker; in this case, the main MV circuit breaker up-stream the bus-bars is operated in a selective (delayed) mode by the protections, and the bus-bars is put out-of-service; in this case, it is not possible to close C, because the faulted feeder would be fed again and the protections would operate once again.

In this report, the blocks of the Load Centres will be defined as follows:

- **Blocks A – Virtual HV/MV Bays**: They are "Branches", as defined for the interconnected grids, because a fault in one of the blocks has no impact on the up-stream and down-stream nodes
- **Blocks B – Virtual Bus-bars**: they are "Nodes", as defined for the interconnected grids. B1 is connected to the following branches:
    - A1
    - A2+B2+C

  The B1+C+B2 overall block is a "reconfigurable node", similar to a HV node with double-bus and coupler arrangement.

- **Block C – Virtual Coupler**: It can be considered as an internal branch between B1 and B2 nodes

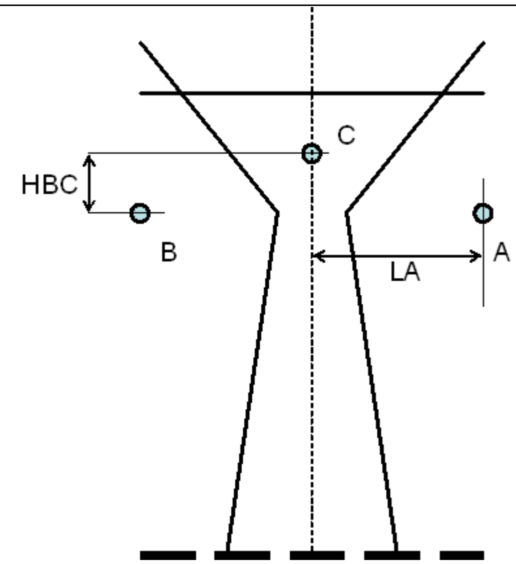
A.1.6. CCFs in Network Components/Equipment – Preliminary analysis

The following Equipment / Components will be analysed:

- HV Lines
- HV Equipment and Transformers
- Auxiliary systems (Control, protection systems, etc.)

➢ HV Lines

There are two main typologies:

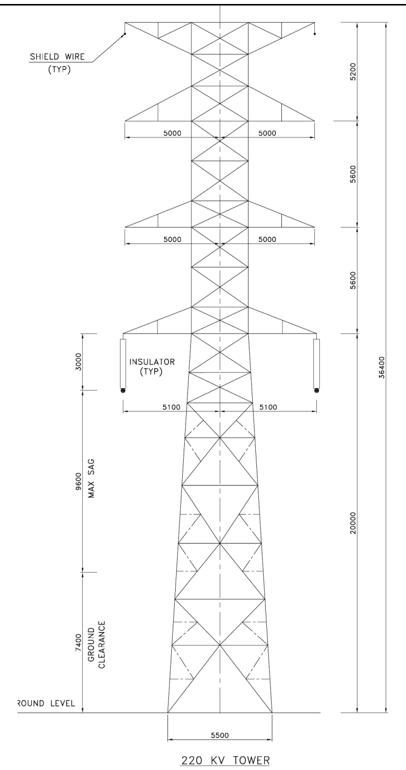
Single Circuit Lines CCF is exceptional (extremely unlikely), because there is no direct interference / relationship between different lines. Therefore, CCFs are assumed to be mainly due to natural events that cover a large area including many Single Circuit lines	

Double Circuit Lines

They are usually very important lines. For example, some large power generating plants are connected in antenna to the HV transmission grid because they are located “out” of the grid, nearby the fuel (coal, gas, etc.) source; in this case, the common practice is to provide a redundant Double Circuit Line between the power generating station and the nearest substation of the HV transmission grid, with every circuit designed for the full capacity pf the power station.

Remark:

- Common Component: Common to both circuits
- NOT Common Component: Relevant to one only of the two circuits



CCFs in Double Circuit Lines can be due to:

- Under-sizing of line components
    - Conductors [not common component; if the conductors are under-sized, in case of a fault on one circuit (NOT a conductor), the other one will be overloaded and it will be disconnected too]
    - Tower [common component]
    - Foundation [common component]
    - Lightning Protection [common component]
- Natural events that cover the area of the Double Circuit Line; this area is much more limited of the area for CCFs of Single Circuit Lines.

A classification of common mode outage causes of overhead transmission lines is proposed in [6B] paper "Common Mode Forced Outage in OHTL. A brief discussion is reported in the following table:

- Original proposed classification: blue characters

- Comments and remarks: red characters

SCL: Single Circuit Lines DCL: Double Circuit Lines

CAUSES		**Applicable to**		**REMARKS**
		SCL	**DCL**	
Natural Events				
1	Fire in Right-of-Way (forest, tall grasses; Agricultural: cane)	X	X	Such an event on a large area can affect both SCL and DCL lines
2	Foundation or Anchor Failure (flood, landslide, ground subsidence)		X	The failure can affect many tower of the same line, but it is unlikely that it will affect more than one line; it is therefore a CCF of the two circuits of a DCL line
3	Severe Environmental Conditions (hurricane, tornado, icing)	X	X	Same as 1
Interference				
4	Interference with other circuits. HV crossing of LV circuits		X	It is very unlikely that the design / erection would make the same mistake on two lines; the event is therefore a CCF of the two circuits of a DCL line
5	Aircraft interference		X	Same as 4
6	Rail and road vehicle interference		X	Same as 4
Additional Data Suggested				
The area isokeraunik level (*) should be added to the information kept on record to isolate future storm plagued areas			X	Simultaneous lightning strokes on two lines are very unlikely; the event is therefore a CCF of the two circuits of a DCL line

(*) Isokeraunik level: frequency of lightning strokes

- HV Equipment
  - CTs and PTs (Current Transformers and Potential Transformers): They have no connection between them; both a simultaneous fault and a sequential fault is actually impossible.

    However, CTs can become undersized in case of expansion of the generating park and the fault current can damage all the ones on the same fault current path. This situation is quite unlikely.
  - Circuit Breakers: As above.

    However, they also can become undersized in case of expansion of the generating park; in this case, if they have to clear a fault, the short circuit current is too high and all the circuit breakers that have to interrupt it can be damaged. This situation is quite unlikely.
  - Transformers: They have no connection between them, and a simultaneous fault is actually impossible.

    However, in case of load centre substations, if the load is growing so much that there is no more full redundancy, if there is a fault in a transformer the load on the other one will be higher than its capacity, and either it will be disconnected or a load shedding sequence will be started. This situation is quite likely and is considered as a specific case of Non – Simultaneous CCF.
  - Other HV Equipment: They have no connection between them; both simultaneous faults and sequential faults are actually impossible.
- Auxiliary Systems

  They are placed in the HV Substations; the main ones are:

- Control Systems
- Protections and Telecommunications
- AC and DC Auxiliary Power Systems

<u>Control Systems</u>

The HV systems usually work in a static way; control systems are used to open / close the circuit breakers and disconnecting switches, and to provide the relevant safety and operational interlocks. Furthermore, control systems drive the automatic change-over sequence on the MV bus-bars of the HV/MV substations.

Other control systems are alarm and measuring circuits; however, their malfunction is not a cause of service interruption, therefore they will not be taken into account in this report.

In case of fault on the HV systems, the control systems drive the operating mechanism of the circuit breakers; if the control systems are nor working and they do not open the circuit breaker nearby the fault, all the other upstream and downstream circuit breakers have to open in order to clear the fault. However, it has to be pointed out that:

A) The protection circuits that release the circuit breaker in case of a fault usually are not mixed with the control circuits; in fact they by-pass the interlock sequences;

B) In normal working conditions, the manual control command of the circuit breakers is not habilitated, and an undue operation is quite impossible;

C) The opening and closing commands of the circuit breakers and disconnecting switches are not automatic, with the only exception of the automatic change-over sequence of the MV bus-bars of the HV/MV load centre substations.

Therefore:

An undue opening / closing command is extremely unlikely, and it should not cause a CCF, because it would only case an out-of-service downstream the operated equipment, i.e. in a branch only. Conversely, CCFs due to control circuits can occur as a consequence of a not cleared fault only in case that condition A) is not satisfied.

Some more considerations about the change-over sequence on the MV busbars of a HV/MV Substation: In case that, after a loss of supply on a bus-bar, the change-over sequence would not succeed due to a fault on the relevant control system, the consequence will be the loss of supply of all the feeders spreading from the bus-bar; this can be considered a CCF on the distribution system downstream the bus-bar, but not a CCF on the HV system and on the HV/MV load centre substations.

Protections

This is an essential item. Main causes of malfunction:

- Undue operation: This is not a CCF, because the relay will open one circuit breaker only
- Failed operation: Two main causes, as follows:
  - Protection Malfunction
  - Failure not detected, for either specific characteristics or location of the failure

All the protection systems have to work with "selective" release, and a failed operation of a protection will cause the operation of other up-stream and downstream protections; therefore the effect of the failure is streaming up to an higher level; typically, the node connecting the faulted branch will be placed out-of-service, together with all the other branches connected to the same node, and this is a CCF.

Auxiliary Services

They are always physically referred to a HV Substation, and easily referred to the relevant virtual node.

- A.C. (Alternate Current) Aux. Serv. : In case of loss of supply, it is necessary to restore the service as soon as possible, but the loss of supply is not causing the out-of-service of nodes and branches, or the undue opening of circuit breakers. In fact, all the emergency services are fed by D.C. Aux. Serv. (see next paragraph) therefore the temporary out-of-service of the A.C. Aux. Serv. will not cause the out-of-service of a SubStation, and of the relevant virtual node; eventually, the A.C. Aux. Serv. are not a CCF.
- D.C. (Direct Current) Aux. Serv. : the D.C. systems are usually redundant, with different sources (Redundant Rectifier + Battery, etc.), therefore a loss of supply of the D.C. distribution is a rare event. However, in case that there is no D.C. supply, if there is a fault the protections (working on D.C. circuits) cannot release the circuit breakers (opening coils fed at D.C.); the Substation (or the MV bus-bar) will be disconnected because all the protections connected to the opposite sides (upstream) of the branches spreading from the node will operate and disconnect the same node. This is a CCF, but it is very unlikely (3^{rd} Order cut-set).

A.1.7. Interdependencies and CCFs Originated by Faults in Nodes and Branches – Preliminary analysis

NODES

- HV Node

  This section covers the HV/MV substations fed by the HV lines (see the simplified single line diagram – fig. A.1); conversely, the out-of-service of the HV main nodes fed by the EHV/HV substations in not considered here, because it is same as described in theta above paragraph (EHV Node – Effect on the HV system).

  Impact on the HV System: The HV lines (branches) upstream and downstream the faulted HV bus-bars will be disconnected, and a part of the HV ring will be temporarily out-of-service.

  Conclusion:

  - The out-of-service of a HV Node is a HV CCF
  - This CCF is not causing the out-of-service of the whole HV system, but only of a part of it, i.e. the part within the faulted bus-bar and the point where the HV ring was open. It is therefore possible to have some isolated sections in the HV line and consequently a loss of supply to the relevant MV nodes, that means the reliability goal has not been reached; a detailed description of this scenario can be found in Ch. /.4, covering CCFs in a Ring..
  - Reconfiguration of the HV line, or of the HV node (closure of the coupler) will eliminate or reduce the loss of supply to the MV nodes; conversely, the redundancy level of the HV distribution is reduced

Impact on the Generating Park and Power Supply: All the generators connected to this bus-bars will be disconnected to avoid re-synchronization problems; it has to be pointed out that usually the generators directly connected to the HV system are medium size turbo-sets, their loss of production is limited and will have no relevant impact on the overall power supply.

Impact on the MV System: In case that the HV bus-bars of a HV/MV substation are out-of-service, all the MV feeders fed by the MV bus-bars will be disconnected; This is a MV system CCF, relevant to only one MV main bus-bar.

- MV Node

MV Distribution: The out-of-service of a node means that there is no supply to all the MV lines spreading from this same node, and this is a Single Point Failure. However, in all the MV distributions (both public and industrial systems) there is always the possibility of a re-configuration.

Conclusion:

- The out-of-service of a MV Node is a MV distribution CCF
- Reconfiguration of the MV lines will eliminate or reduce the loss of supply to the MV customers; conversely, the redundancy of the MV distribution is lost during the system reconfiguration.

Remark: The MV bus-bars are normally subdivided in two sections, interconnected by a tie breaker (coupler); usually, an automatic change-over system is installed, to close the tie breaker in case that one of the two bus-bar sections has lost its supply. All the causes that prevent the tie breaker closure have to be considered as CCF; for example, as above described, it is not possible to close the tie breaker in case that it will feed again the fault, and this is a Single Point Failure.

BRANCHES

- HV Branches: A failure on a HV line will interrupt the supply to part of the HV ring (see Ch. 7), from the point of the failure to the point where the ring is open; therefore, before the line re-configuration, the MV nodes connected to the HV/MV substations in this part of the line will not be fed, and this is a Single Point Failure.
- HV/MV Bays: The disconnection of a HV/MV bay is compensated by the closure of the MV tie breaker, therefore this is not a Single Point Failure; of course, the MV tie breaker has to close on demand.

  Remark: The two sections of the MV bus-bars can be both out-of-service, in case that the two HV/MV bays are out-of-service. It is a remote possibility, because the two HV/MV bays form a redundant circuit; however, in this case it is necessary to investigate if there is the possibility of CCFs between these two HV/MV bays.

  - In case of a fault on a HV/MV transformer, the other transformer can be disconnected if it is overloaded; this is a Non Simultaneous design CCF.
  - A quasi-simultaneous insulation damage occurred in two transformers in a HV Substations some decades ago; this is a design CCF (mistake to design a provisional insulated connection to allow change in windings configuration), but it is limited to the "infant mortality".
  - It is possible to have the same type of fault on the two HV/MV bays, due to a design mismanagement; anyway, it is quite impossible that the fault is either

simultaneous or during the repair time of the first failed bay. This is a Non-Symultaneous CCF, described at Ch. 6.13.2.

A.1.8. Functional CCFs

Functional CCFs in two large power systems have been investigated in detail, in order to try to find general rules.

- Congo (DRC) HV Grid
  - Situation: The grid is very large, but non-uniformly loaded; specifically, the North Area is very extended, but with light loads for the time being. There is only a main backbone between Pointe Noire and Brazzaville; in normal conditions, the inductive voltage drop is compensated by the high line capacitance and relevant capacitive voltage drop; conversely, if the backbone is fully loaded, the inductive voltage drop is prevailing and it is becoming excessive. The connection of the North Area, with high capacitance and light load, is acting as a capacitor, and the voltage drop is compensated; the problem is that the North Area at present is connected to only one point, and with a single link
  - Criticality: The 220 kV backbone from Pointe Noire to Brazzaville is very long (> 400 km), and it is exceeding by far the typical length of a HV line (1 kV / km); therefore, a critical voltage profile along the line has to be expected
  - Bottleneck: There is only one connecting point and one link between the North Area and the above mentioned HV backbone

  In case that there is fault on the bottleneck (both on the connecting point [Node] and on the link [Branch]), the capacitance of the North Area would not compensate the inductive voltage drop, and it could be difficult to restore a satisfactory voltage profile in a short time; the consequence could be the disconnection of many loads fed by the load centre substations.

- Italian EHV Grid
  - Situation: The grid is heavily loaded, and the generating park is not able to feed the maximum potential load. In case of a overload, it is not possible to adopt a load shedding sequence on a public Utility
  - Criticality: There is need to import energy form neighbouring countries
  - Bottleneck: There are only few links with the grids of the neighbouring countries

  In case that there is fault on the bottleneck (both on the connecting point [Node] and on the link [Branch]), the generating park will not be able to feed all the loads. It is likely that the generating stations would operate in "under frequency" and that they have to be disconnected; as well if one generating station will be disconnected, the other ones will be more and more overloaded, and the disconnection process is accelerated with a risk of black-out.

Similarities

- There is a criticality
- There is a bottleneck
- A fault on the bottleneck will "initiate" a process that has consequence on all the centre load substations

The above similarities represent the proposed sequence to identify Functional CCFs, reported at Ch. 5.5.4.

Is such a Functional Out-of-Service a CCF?

We have to consider that:

- There is no simple connection with the grid reliability, that means the reliability on Nodes and Branches; in other words, there is no direct connection with the grid reliability model
- There is no condition to supply energy at the Load Centre Substations, although they continue to work

However, there is to take into account this basic assumption:

- The reliability goal of the grid is the energy supply at the Load Centre Substations (Nodes)

Conclusion:

- It is a functional CCF
- It is related with the grid model described in the previous chapters (Nodes – Branches), because the final effect is the loss of energy supply at many “Load Nodes”.

A.1.9. Failure Statistics

These statistics cover the failures in the HV Grid of a main Utility in North Italy. They are relevant to all the faults that caused the automatic opening of at least one HV circuit breaker on

- Lines
- EHV/HV Interconnecting transformers
- HV/MV Transformers on Load Centres
- Generators Step-Up Transformers
- HV Bus-Bars

The results have been organized into four paragraphs, as follows:

- Perturbations	Relevant for CCF analysis (*)
- Protections	Relevant for CCF analysis (*)
- Tele-Protections	Relevant for CCF analysis (*)
- Automatic Reclosing	NOT Relevant for CCF analysis

(*) In case that a node is put out-of-service, there is at least a loss of redundancy, and it is likely that more than one branch connected to the node is going out-of-service, therefore. The out-of-service of a node is considered as relevant for CCFs analysis (see previous chapters)

- Perturbations

EHV System: 91.4%

HV System: 8.6%

Perturbation Type	%	**Remarks**
Transient	89.5	Fast Reclosing Cleared in 0.3 s < t< 2 s
Semi-Permanent	4.6	Slow Reclosing Cleared in t < 30 s
Permanent	5.9	

Permanent Perturbations due to adverse weather conditions:85.6%

Remark: adverse weather conditions can be a CCF

Lines Failure Rates:

- EHV System: 3.6 faults / year

- HV System: 9.8 faults / year

A diagram showing percentages of failure causes is included in the following Fig. 6.6.

Adverse weather condition (Meteo in the Table) is largely the more frequent cause; the main factors are:

- Ligthning Strokes
- Snow or Ice
- Wind

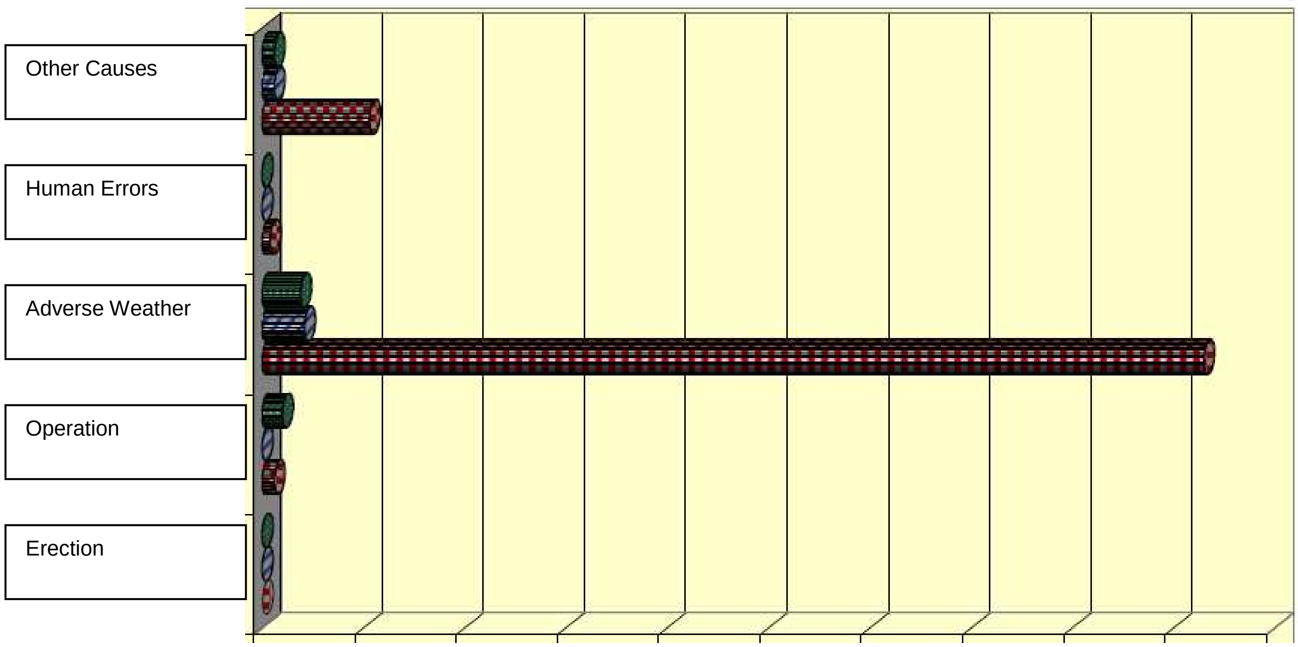


Fig. A.6 – Percentages of Failure Causes in HV Systems

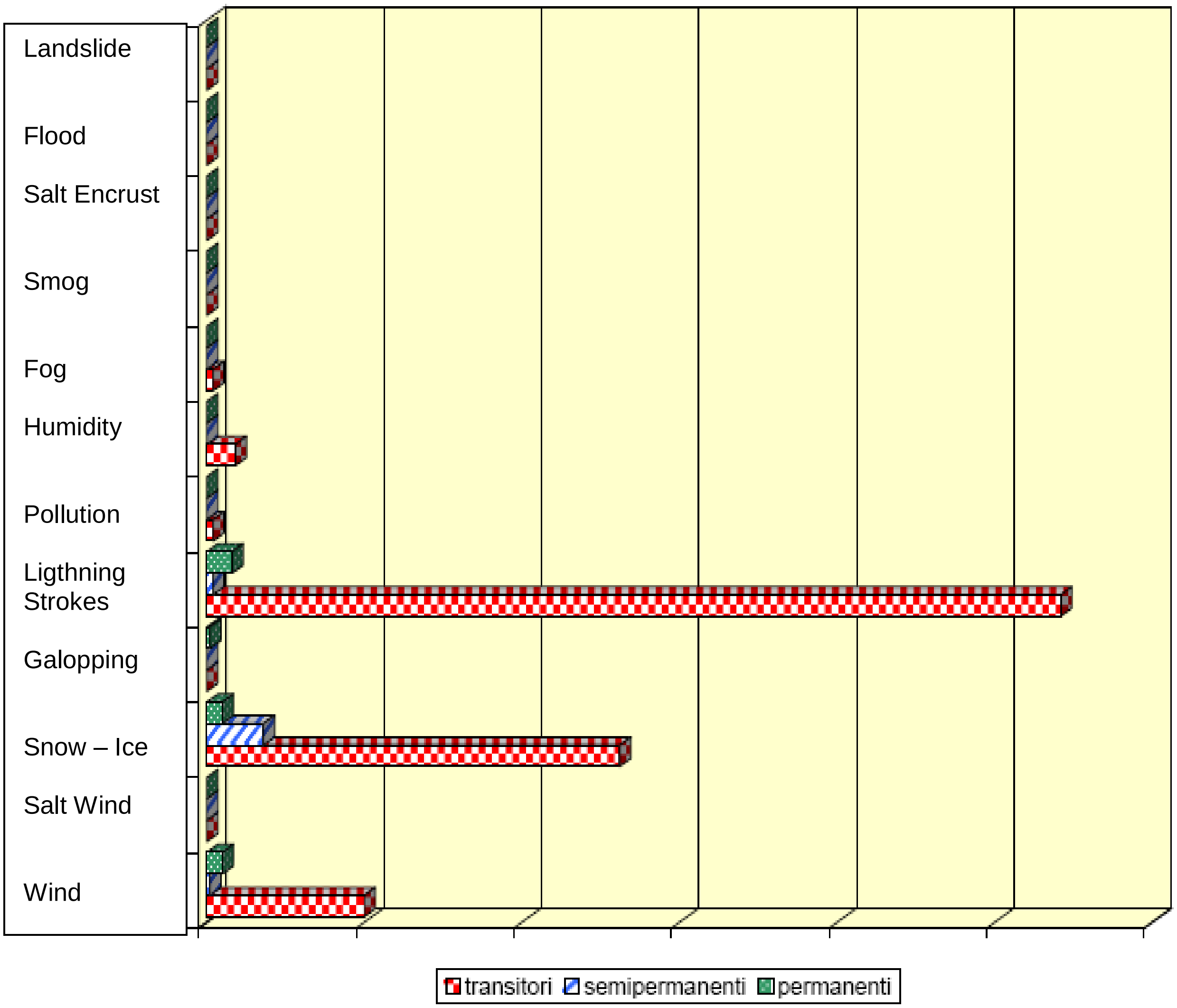


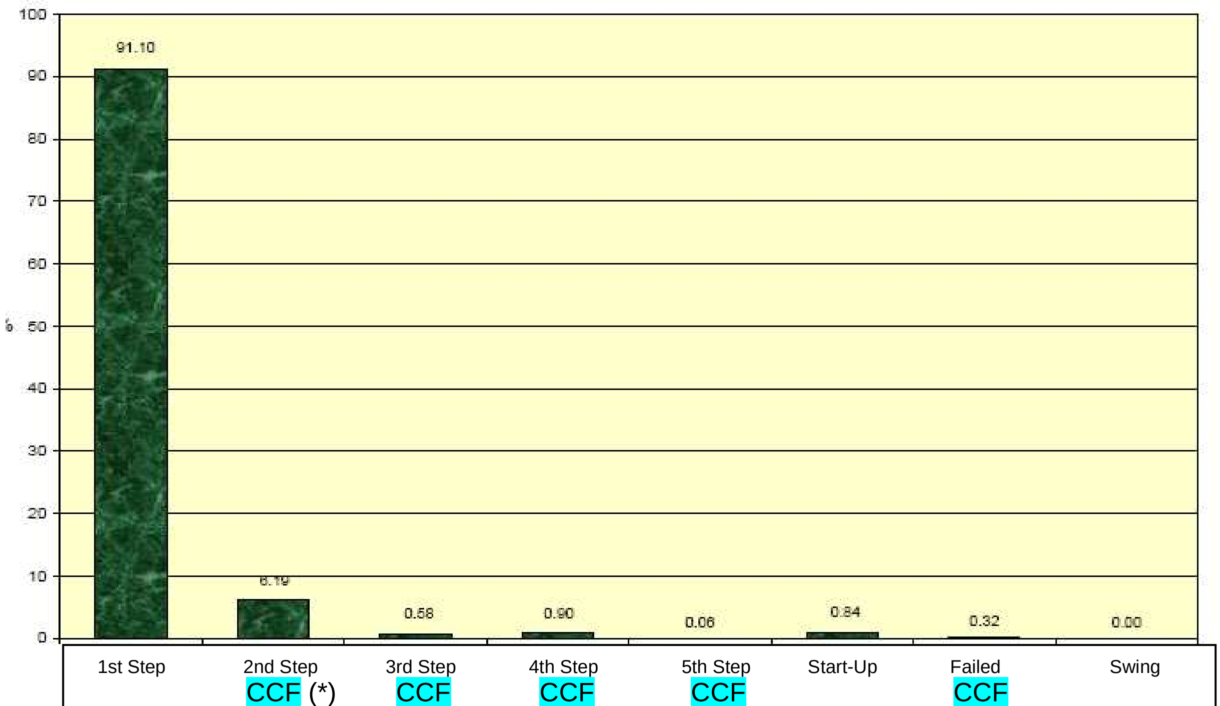
Fig. A.7 – Adverse Weather – Failure Causes Splitting

- <u>Protections</u>

Protections operations, every 100 failures:

Protection	**Operations Base: 100 failures**	**Out-of-Service of a node**	**Remarks**
Line Distance	262,88	YES	In case of a fault on a circuit breaker or associated protection circuit, the protection selective operation can cause the opening of all the up-stream and down-stream circuit breakers, with the consequent isolation of their nodes.

			Remark: Operations figure is > 100 because at least two circuit breakers will operate for every fault
Generator Distance	1,02	NO	Generator protection only
Line Overcurrent	4,41	YES	Same as Line Distance
Generator Overcurrent	2,37	NO	Generator protection only
Transformer Differential	0,34	NO	Differential Prot. is operating on a limited zone
Bus-bar Differential	0,00	YES	It causes the out-of-service of a set of bus-bars, which physically is a "Node", and the possible out-of-service of the lines (Branches) connected to the Node, if they are not fed from the other side
Line Differential	0,17	NO	Differential Prot. is operating on a limited zone
Voltage and Frequency Prot.	0,34	NO	Machine protection only
Buchholz Relay	1,36	NO	Transformer protection only
Breaker Failure	1,86	YES	In case of failure of a circuit breaker (does not open on command) the fault has to be cleared by the the opening of all the up-stream and down-stream circuit breakers, with the consequent isolation of the Nodes.
Transformer Other Prot.	3,39	NO	Transformer protection only
Generator other Prot.	0,34	NO	Generator protection only



(*) It can be caused either by the fault position (not CCF), instead of by the protection malfunction (CCF)

Fig. A.8 - Line Distance Protection Release

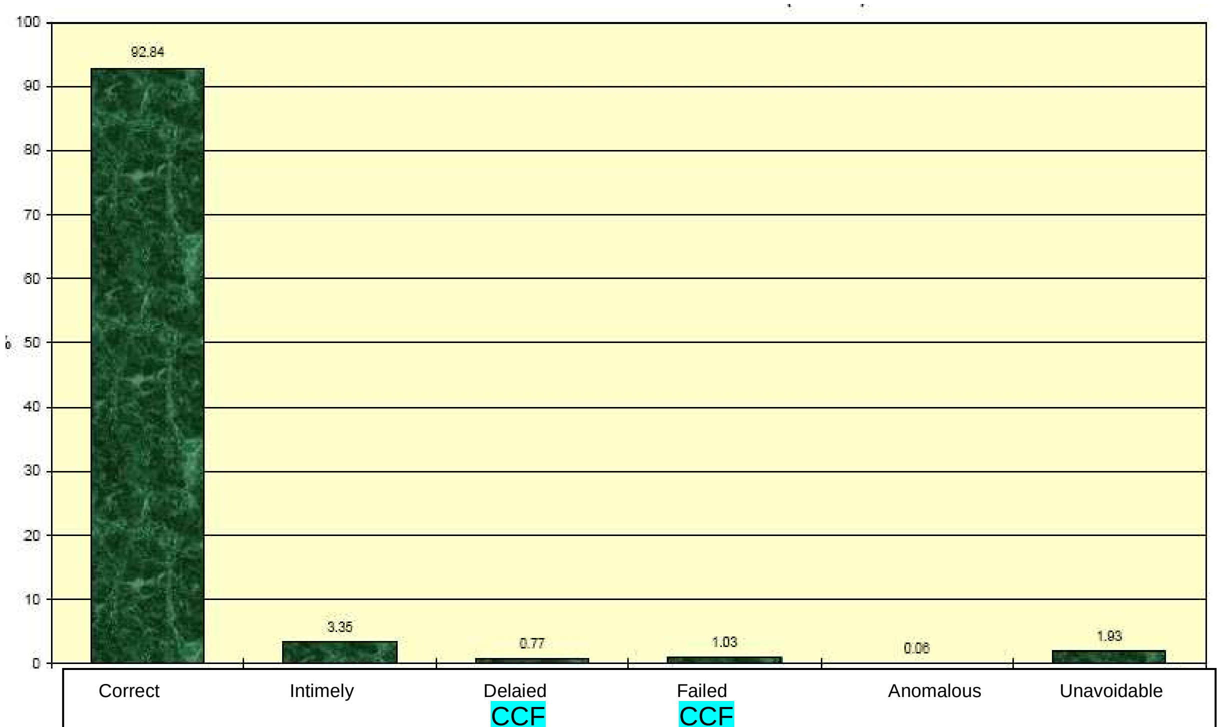
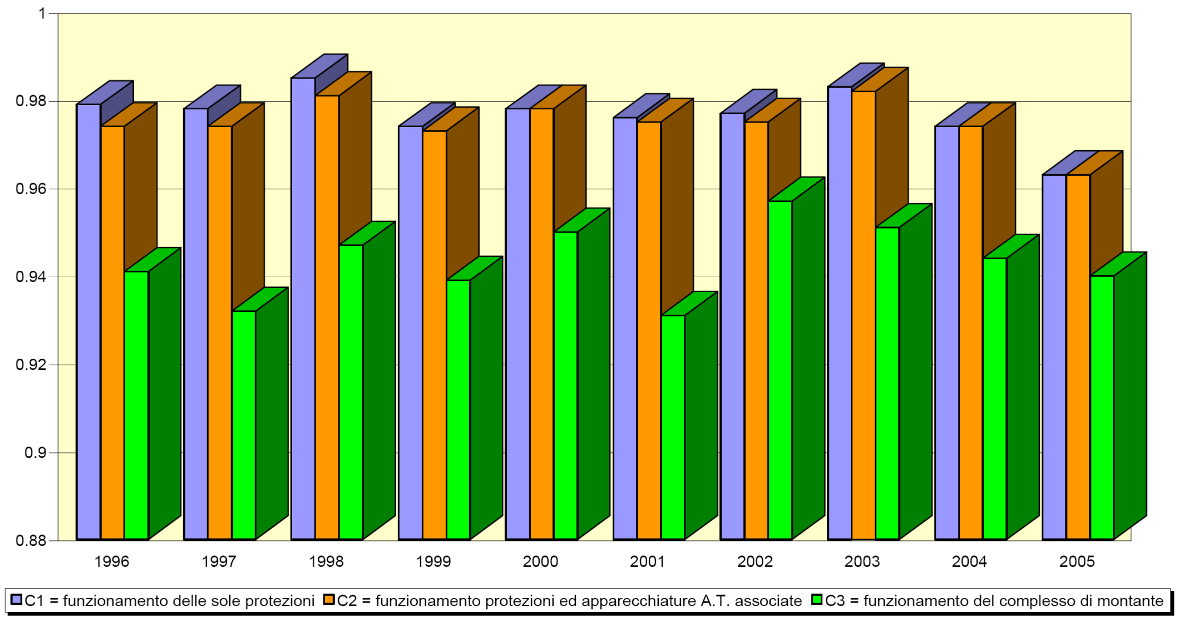


Fig. A.9 - Line Distance Protection Operation

Remark: The above figures are an extract from a report of an Italian Utility; it has not been possible to re-arrange (log) the "scale" of the percentages.



C1= Protections Only C2 = Protections + HV Equipment C3= Protections + HV Bay

Fig. A.10 – Efficiency of Line Distance Protections and Associated Equipment

Remark: Line Distance Protections are multi-zone protections specifically designed for the HV lines. The zones and the logic ptotection diagram are reported in fig. A.3.

Discussion of Fig. A.10

- 1-C1: Protections malfunction: it is of the order of 2-3%
- C1-C2: HV Equipment malfunction: it is a very low rate
- C2-C3: Auxiliary and Control Systems, and other systems: it is of the order of 3-4%

- <u>Tele-Protections</u>

  They work in conjunction with Line Distance and Overcurrent protections; therefore, their failure has the same effect of a protection failure, and can be a cause a CCF (see previous paragraph “Protections”)

  Teleprotection Efficiency: 96.2%

  Teleprotection malfunction (Cause of CCF): 3.8%

- <u>Automatic Reclosing</u>

  This operation attempts to restore the service in case of temporary faults (they are the majority, 79.8%); therefore, they cannot be cause of an extension of the fault. Finally, they are not cause of CCF.

<u>Comparison between Statistics and Predictions</u>

Overall results of the analysis of the failure statistics:

A. <u>Failures on Branches</u>: Failures on EHV/HV systems are mainly on the lines (branches); the main cause is adverse weather.
   - Prediction: It is possible to have CCFs between lines, due to adverse weather;
   - Statistics: it is impossible to detect these CCFs from the statistics in our hands, because there is not a failures chronology

B. <u>Failures on HV Bays</u>:
   - Prediction: The probability of out-of-service of HV bays is very rare if compared with the probability of out-of-service of a High Voltage line, because the failure rate of a HV line is mainly due to external factors (weather), and conversely the failure rate of a HV bay is due to equipment failure only; therefore, it is very difficult to find a CCF that could cause the simultaneous fault of more than a bay.

- Statistics: The very low failure rate is confirmed: it is due to the operation of the Transformer Differential, Buchholz and Other Transformer Protections Relays (see above table), and the sum of their operation frequency is much lower than the operation frequency of the line protective relays.

C. Out-of-Service of a Node, due to Internal Failure:

- Prediction: The out-of-service of a "node", due to both the failure of the node core (bus-bars) and of a simultaneous failure of the HV bays connected to the bus-bars, is very unlikely, because it is quite impossible to find a failure common mode
- Statistics: The internal failure of a node is cleared by the bus-bars differential protection; statistics show that this protection NEVER released; the failure is isolated by the Bus-Bars Differential Relay, whose peration frequency is 0 (zero).

D. Out-of-Service of a Node, due to External Failure: The out-of-service of a "node" can be caused by the malfunction of the protection system, that has not been able to clear the fault on a line

The main criteria to detect the occurrence of CCFs in the system is to check if there has been the simultaneous non-operation of more than one circuit breaker, to clear the faults.

There are two cases:

➢ Simultaneous failures either on more than one branch, or on more than a HV bay in a "Node":

  - Prediction: This situation has been considered very unlikely
  - Statistics: There is no evidence that such a situation has occurred

  Conclusion: Prediction and statistics are in accordance

- Release of more than one circuit breaker, due to the operation of the line distance protections, in 2nd, 3rd, 4th step (zone) (see fig. A.8 showing line distance relay operation zones): this situation occurred, and it is reported into the above described statistics (see fig. A.8 and A.9)

  - Prediction: This situation has been considered as possible
  - Statistics: This situation occurred, and it is reported in fig. A.8 and A.9

  Conclusion: Again, prediction and statistics are in accordance

  Discussion:

  - If the protections release correctly in 1st zone, the fault is isolated and the out-of-service is limited to the disconnection of the branch;
  - If the protections release in 2nd zone, the reason can be a malfunction in the 1st zone, but more likely the position of the fault nearby the end of the branch requires the operation of the 2nd zone. Therefore, it is possible, but not sure, that the nodes upstream and downstream the faulted branch could be put out-of-service;
  - If the protections release in 3rd or higher zone, surely there is a malfunction, and the nodes upstream and downstream the faulted branch will be put out-of-service.

  In fact, Fig. A.8 shows that:

Line Distance Protection Release	%
3rd Zone	0.58
4th Zone	0.90
5th Zone	0.06
Delayed	0.32
Tot.	1.86

Which is very close to the results of Fig. A.9, relevant to protections malfunction.

Remark: An operation malfunction is causing the selective operation of the up-stream protections, that means the protections covering 3rd Zone and 4th Zone (5th zone is very rare)

Line Distance Protection Operation	%
Delayed	0.77
Failed	1.03
Tot.	1.80

The importance of the protection system in CCF analysis is very high; Fig. A.10 shows that the malfunction can be caused both by same protective equipment, and by the associated control and auxiliary systems; conversely, it is very unlikely that the protection release is unsuccessful due to HV equipment malfunction.

Conclusion: there is a close correspondence between CCFs predictions and statistics, and the CCFs prediction model can be considered as validated.

A.2. Telecommunication Systems

A.2.1. System Description

The STSI (Sistema Telefonia Selettiva Integrata – Integrated and Selective Telephone System) is the present standard for the selective telephone systems along the Italian railroads.

The overall architecture of STSI is shown in fig. A.11 that is highlighting the two main hierarchical levels:

- A “Local” level, relevant to all the station and inter-station users connected to railroad station “Concentrators” ; Two inter-station circuits are provided: IA and IB
- A “Omnibus” level, interconnecting all the station “Concentrators”; two omnibus circuits are provided: OA and OB

The system reliability analysis has to cover:

- The availability of the upper (Omnibus) level backbones, i.e. of the OA and OB circuits
- The availability of the lower (Local) level backbones, i.e. of the IA and IB circuits
- The availability of the CTS station telephone concentrators

Equipment and functionalities that are relevant for the reliability analysis are listed here below.

- Both the Omnibus circuit and the Inter-Station circuit are provided with two hardware circuits, that can be shared; in case of an out-of-service of a backbone, all the telephonic traffic cab be deviated on the other backbone, but with a reduction / degradation of the service
- The Omnibus system is provided with a ring link, with OF (Optical Fiber) cable, between the first CTS (CTS-0) and the last one CTS – FT (Fine Tratta – Line End)) indicated as CTS – 3 in fig. A.11
- Main equipment provided for the signal transmission at Omnibus level is listed here below; the order is following the “ring”:
    - CTS – 0 (Starting Point)
    - Omnibus Level Telephonic Cables Backbones (OA and OB)

- CTS –FT (Branch End), in our case CTS-3
- PCM (multiplator + line connection) of the OF line, CTS-FT side
- OF line
- PCM of the OF line, CTS-0 side
- CTS INT A (Intermediate, Amplified), if any
-

- Main equipment provided for the signal transmission at Local level is listed here below.

  - N.2 intermediate and adjacent CTS
  - Local Level Telephonic Cables Backbones (IA and IB)

The system is designed, with suitable redundancies,

- to work even if some components are out-of-service
- to be repaired in a very short time

It is therefore a "repairable" system, with the following characteristics:

- Repairability even during normal operation
- Capability to supply a continuous service to the users

Remark: the system has to be able to provide its service, even if one CTS is out-of-service; for this reason it has been designed in such a way that a fault on a CTS will not cause the out-of-service of others CTS; this means than no CCFs are expected between CTS.

The reliability goals, in accordance with the above described systems performances, are:

- At upper level (Omnibus): Availability of the several CTS to be connected to the overall telephone system, through CTS-0
- Al lower level (Local): availability of the several CTS, and availability of the connection to the Station and Inter-Station Users

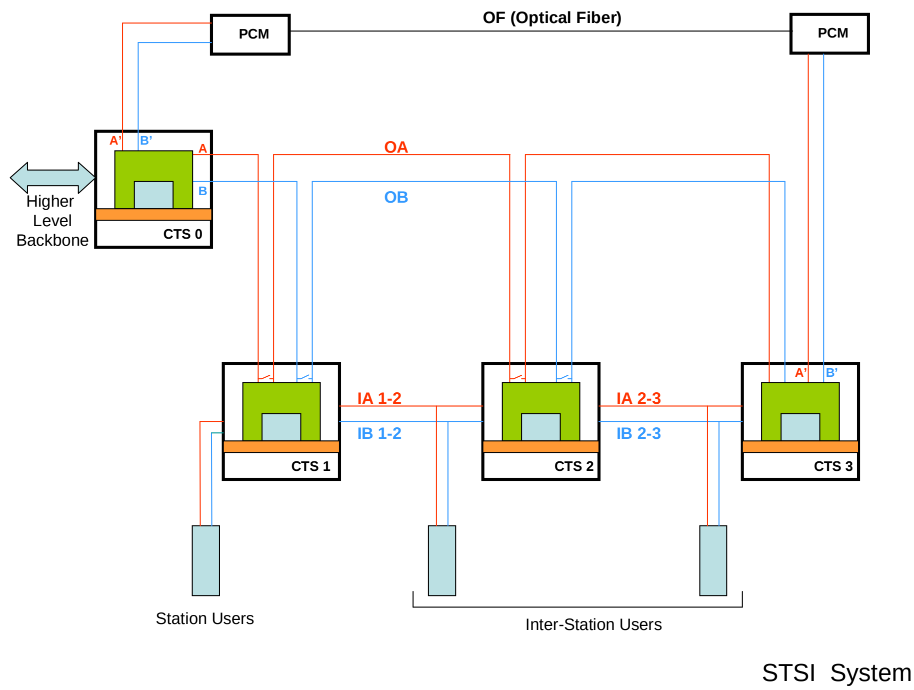


Fig. A.11 STSI System – Overall Scheme

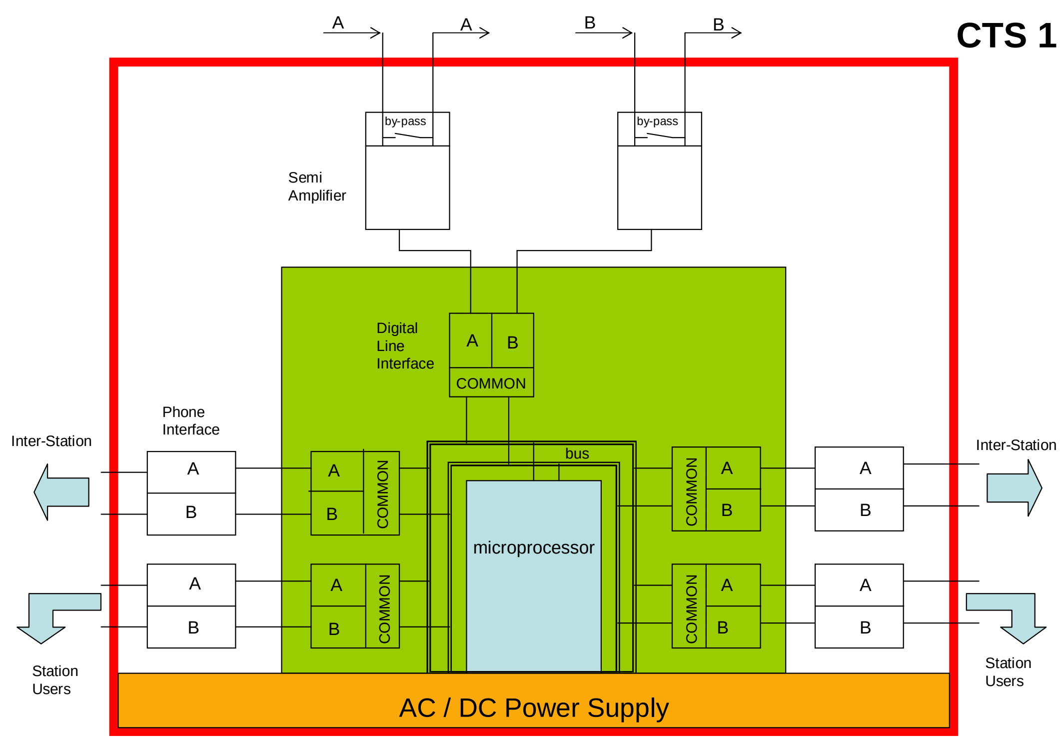


Fig. A.12 STSI - CTS1 Scheme

A.2.2. Re-configuration

At the Omnibus level, in case of a failure of a part (half board) of the line amplifier of a CTS-I, there is the possibility to isolate this equipment and to restore the backbone continuity by means of a by-pass switch (see fig. A.12) that will automatically close.

Therefore, the following functionalities have been provided:

- Auto-diagnostic;
- Automatic sequence to close the by-pass switch.

A.2.3. Hardware Bottlenecks

All the control system is composed by electronic cards, installed in wired racks.

Hardware bottlenecks are summarized here below.

- Many cards, relevant to the connection to two lines (see Fig. A.12), are provided with two separate circuits on the same PCBs (Printed Circuit Boards); in a few cases, on these cards there are some common components (see COMMON part of the equipment in Fig. A.12). A failure of the common components of these boards will cause the impossibility of connection of both circuits outgoing from the same boards, and this is a bottleneck
- Some boards are connected to all the other boards, such as the Control Logic boards; for example, the microprocessor of a CTS-I (see Fig. A.12) is controlling all the satellite boards. A failure on this microprocessor will put out-of-service all the functionalities of the CTS-I.
- Some boards have a vital connection with the other boards, such as the power supply; a failure on these boards will put out-of-service all the functionalities of the CTS-I

- There is also hardware that is common to many boards, such as for example the "buses"; a fault on this hardware will put out-of-service all the functionalities of the CTS-I

A.2.4. Similarities and Differences with Power Systems Networks

SIMILARITIES

- Reliability Goal: The network has to provide a "service" to several Users, downstream the last level nodes
- Interference between Nodes: There is no interference between nodes
- Overall Branch and Nodes model: The structure in different levels, with final connection to distribution nodes, is quite similar; conversely, the branches and nodes models show some differences (see next paragraph)

DIFFERENCES

- Protective Equipment: Faults are not disruptive, with injures to persons and equipment; in this case, the protections do not play a very important role; conversely, Autodiagnostic plays a very important role because it drives the system re-configuration.
- Nodes: The typical real node is more complex, because it includes specific equipment such as microprocessor, etc.
- Double Circuit Lines: Usually not installed in telecommunication system; the redundant systems are installed on separate cable ways

The definition of Branches, Nodes and Peripheral Nodes (equivalent to Load Centres in Power Systems) can be applied also to this system.

A.2.5. Virtual Nodes, Branches and Peripheral Nodes

"Virtual" Nodes include all the equipment whose failure can cause the out-of-service of the node; conversely, the peripheral equipment (outside the "buses") that is connected to the outgoing/incoming lines, although physically installed into the node, is not included in the virtual node.

Equipment included into a Virtual Node:

- Microprocessor
- Power supply
- Buses
- Rack

"Virtual" Branches include not only the transmission lines, but also the equipment installed in the nodes that is connected to the lines.

Equipment included into a Virtual Branch:

- Common parts of the boards connected to the transmission lines
- Parts (circuits) of the boards connected to their specific transmission lines
- Transmission lines

SIMILARITIES AND DIFFERENCIES WITH POWER SYSTEMS

Branches and Nodes

➢ Similarities

  - *Some components that are part of the physical Nodes have to be conversely included, in terms of reliability modeling, into the branches spreading from the relevant Nodes.* In this case, the sections of the cards connecting the lines, which are physically included into the nodes, in terms of reliability modeling have to be included into the branches

- *There is the possibility that a reliability block, relevant to a specific failure mode, could be included both into a Node and into a Branch.*

➢ Differences

- *Nodes can be re-configured*. In this case, it is not possible; Re-configuration is limited to the by-pass on the Omnibus line (branch)
- *Branches cannot be re-configured.* In this case, the by-pass is extending a branch and it is eliminating a node; therefore, the branch is re-configured
- The "Local" level lines that connect the inter-station users are not re-configurable, but they are redundant without any switching sequence so there is no need of re-configuration

Peripheral Nodes

Also in this case there are "Users", that need a service. The model of the peripheral nodes (not of the users) is extremely simple, in practice is a connection point

➢ Similarities

- The goal is the same: to assure the service to all the peripheral nodes and to their users. Also in this case, it is not possible to develop a clear RBD because the users (final point of the RBD) are many
- Also in this case, the "blocks" of the peripheral nodes and of the branches connected to them are related not only to their physical configuration but also to their functional characteristics

➢ Differences

- The NODE structure is different. "Inside" the buses, there are very important but not redundant components: the microprocessor and the power supply (it can be considered as "inside" the bus-bars, because it is relevant to all the boards"
- The boards relevant to the Omnibus and Local level line redundant connection have some parts that are common to both redundant circuits

A.2.6. CCFs in Network Components/Equipment

The system has been designed in such a way to avoid any interference between the several components, as follows:

- There is no physical connection between the several nodes, except the transmission lines
- The transmission line cable ways are separate, therefore a catastrophic event only can have impact on more than one line
- The power supply source is redundant, and there are batteries to supply DC power in case of loss of the main AC supply along the line

It is possible to image the same type of failure on different boards, both in the same node and in different nodes, due for example to a design problem; however, the probability that such a simultaneous fault would occur is very close to zero and will be neglected.

A further investigation has been carried out, on the base of a Sample Check List (drawn from "Estimation and Evaluation of Common Cause Failures in SIS" , Angela E. Summers, Kimberly A. Ford, SIS-TECH (www.SIS-TECH.com); the investigation confirmed that CCFs are extremely rare; however, some points have been highlighted as follows:

- Operator Interface: This is a very likely CCF; however, in this case the interface is very simple, just a keyboard and a display, and operations are very easy in order to be carried out by any personnel; therefore, for STSI the probability that operator interface could become a CCF is very remote;
- Environment: Excessive vibrations and temperature can become CCFs; a proper design managed to reduced as far as possible these factors, anyway it is advisable to monitor them along the system life cycle. Environment CCFs can cause the simultaneous out-of-service of more than one node / branch, and it is possible that some users could result not connected to the system

A.2.7. Interdependencies and CCFs Originated by Faults in Nodes and Branches

NODES

- CTS-0

  The out-of-service of the CTS-0 can be caused by the failure of the following components / sub-systems only:

  - Microprocessor
  - Power supply
  - Buses (extremely rare – neglected)
  - Rack (collapse is extremely rare – neglected)

  Consequence: all the CTS-I will be out-of-service, and therefore all the station and inter-station users too will loose their connection. Therefore, this is a CCF both for the CTS-I and for all the users

- CTS-I

  The out-of-service of the CTS-0 can be caused by the same failure of CTS-0.

Consequences:

- The Station Users of the faulted CTS-I will be out-of-service;
- The inter-station users will be fed by the CTS-I at the other extremity of the lower level transmission lines;
- No impact on the Omnibus ring level:
  - It is a ring fed at the two extremities
  - The ring in some conditions can also be re-closed by means of the by-pass

Therefore, this is a CCF for the station users only

BRANCHES

- ➢ Omnibus Level – Optical Fiber Cable

  In case of failure, the ring will be open, but the system will continue to work; the consequence is a loss of redundancy only

- ➢ Omnibus Level – Copper Cable Transmission Line

  The Omnibus circuit has two redundant transmission lines; in case of failure of one of them, there is only a reduction of the redundancy level

- ➢ Lower Level: The distribution to the inter-station users is redundant; in case of failure of one transmission line, there is only a loss of redundancy

SIMILARITIES AND DIFFERENCIES WITH POWER SYSTEMS

- ➢ Similarities
  - The out-of-service of a node can have impact on many final users.
- ➢ Differences
  - The out-of-service of a branch cannot have impact on the final users.

A.2.8. Functional CCFs

A typical functional CCF of a High-Tech system is obsolescence; it will mainly affect:

- The provision of spare parts;
- The hardware-software interface

The analysis is carried out in accordance with the procedure proposed at Ch. 5.5.4

1st Step - Identify Criticalities: Obsolescence

2nd Step - Identify Bottlenecks

- Provision of Spare Parts: After for example 20 years, it could be difficult to find spare parts to replace the damaged ones; therefore, it is possible that more than one board of the same type could be not in condition to work inside the system
- Hardware-Software Interface: After for example 20 years, it could be difficult that the same software be installed and maintained on the several nodes

3rd Step - Verify the impact of a fault on a bottleneck, and specifically the consequences on the reliability goal

The out-of-service of more than one board, due either to the impossibility to provide spare parts or to software malfunction, could inhibit the overall functionality of the system; in this case, many nodes and many station and inter-station users could be disconnected for a too great time (very high MTTM), and this will be a CCF

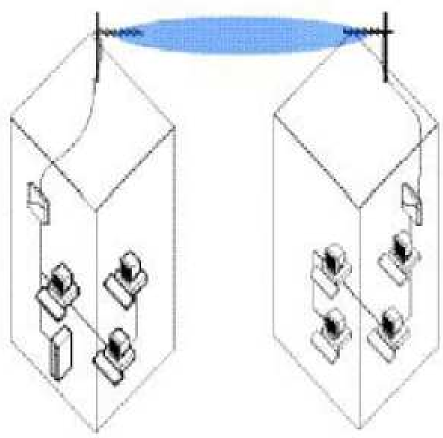
A3. <u>WISP – Wireless Internet Service Providers</u>

A.3.1 System Description

WISP (Wireless Internet Service Provider) is a fixed wireless service between central nodes and clients, with low power radios and high gain antennas; direct line of sight is required between the connected points.

There are 3 main levels as follows:

- Upper Level - Main Backbone, between the main nodes (repeaters)
- Intermediate Level - Interconnections between the main nodes and the user nodes
- Lower Level - User nodes and downstream connections



Fig[redacted]t-to-Point Link

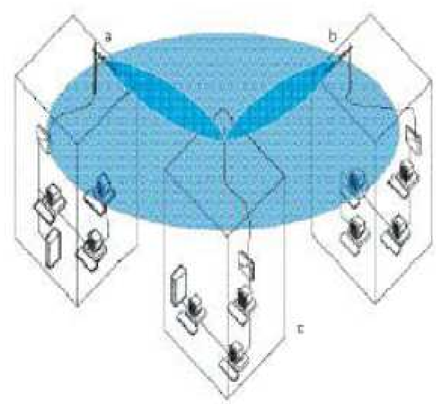


Figure [redacted]-Multipoint Network

Fig. A.13 – WiFi Network Intermediate and Lower Level

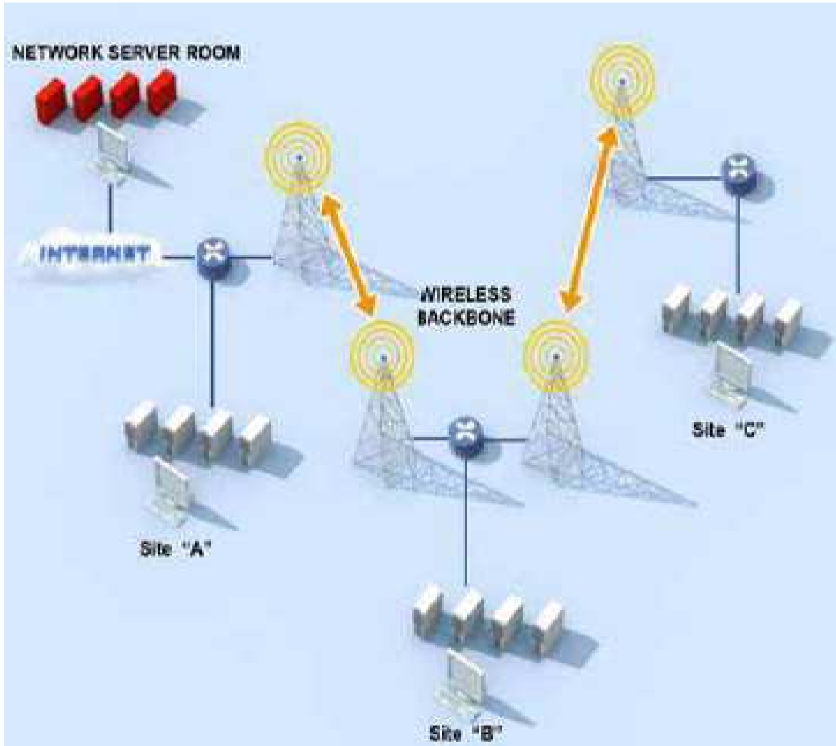


Fig. A.14 – WiFi Network Upper Level

The system is designed

- to work even if some components are out-of-service
- to be repaired in a very short time

Also this system is therefore a "repairable" system, with the following characteristics:

- Repairability even during normal operation
- Capability to supply a continuous service to the users

No redundancies are usually provided for this system; in fact, it is usually a quite "poor" system.

Furthermore, the system designed in such a way that a fault both on a base unit and an access point will not cause the out-of-service of other base units and access points; this means than no CCFs are expected between access points and between base units.

The reliability goals, in accordance with the above described systems performances, are:

- At upper level (Backbone): Availability of the several Base Units to be connected to the overall backbone
- Al lower level (Users): availability of the several access points, and availability of the connection to the Users

A.3.2. Main Equipment

NODES

- <u>Backbone Main Nodes</u>
  - Omni-directional antenna
  - Base Unit
  - Router
- <u>User Nodes</u>
  - Directional antenna
  - Router
  - Hub
  - Access point
  - PC with wireless card

BRANCHES

No physical equipment; sky only. However, for this same reason the environment has a very relevant impact.

A.3.3. Re-Configuration After Fault

For these networks, no reconfiguration is provided

A.3.4. Hardware Bottlenecks

All the components of the backbone nodes are bottlenecks, because there are no redundancies; in the RBDs, they would be series blocks.

A.3.5. Similarities and Differences with Power and Telecom Systems

SIMILARITIES

- Reliability Goal: The network has to provide a "service" to several Users, downstream the last level nodes;
- Interference between Nodes: No direct interference. Adverse weather can cause the out-of-service of many nodes, because the area covered by the system is limited and can be affected by local adverse weather conditions;
- Overall Branch and Nodes model: The structure in different levels, with final connection to distribution nodes, is quite similar; conversely, the branches and nodes models show some differences (see next paragraph).

DIFFERENCES

- Protective Equipment: Faults are not disruptive, with injures to persons and equipment; in this case, the protections do not play a very important role;
- Nodes: The nodes are more complex both compared to the ones of power systems and to the ones of telecom systems. The nodes include many bottlenecks;
- Branches: The model is very different. There is no equipment, and the failure rate is due to the environment (see next Chapters);
- Double Circuit Lines: There are no double circuit branches;
- Redundancies: The system is quite "cheap" and "poor"; usually there are no redundancies.

A.3.6. Branches, Nodes and Peripheral Nodes Models

The definition of Branches, Nodes and Peripheral Nodes (equivalent to Load Centres in Power Systems) proposed in Ch. 5 can be applied also to this system.

VIRTUAL NODES AND BRANCHES

"Virtual" Nodes include all the equipment whose failure can cause the out-of-service of the node; in practice, all the nodes

"Virtual" Branches include only the air links between the nodes; there is no equipment.

Remark: Antennas could seem to be part of the "branches", conversely they have been included among the node equipment for the following reasons:

- In the backbones, antennas can provide connection to many links; therefore, they are part of a node
- They are the last equipment in series with the other equipment of the node; a separation is therefore not coherent.

Peripheral Nodes

Again, there are "Users", that need a service. The model of the peripheral nodes (not of the users) is including many equipment, but there are no redundancies and there are no change-over sequences

SIMILARITIES AND DIFFERENCIES WITH POWER AND TELECOM SYSTEMS

- Similarities
  - The goal is the same: to assure the service to all the peripheral nodes and to their users. Also in this case, it is not possible to develop a clear RBD because there are

many injection points (starting points of the RBD) and many users (final points of the RBD).

- Differences
  - In this case, the concept of "virtual" nodes and branches in not so important, because there is a very clear distinction between nodes – equipment and branches – air link.

A.3.7. Out-of-Service of Nodes and Branches – CCFs Analysis

NODES

- Nodes in the Back-Bone

  The out-of-service of a node of the back-bone will cut the same back-bone; the lower level nodes connected to the node of the back-bone will loose their connection.

  Consequence: many users will be disconnected, and it is likely that also some upper nodes on the backbone will be disconnected. Therefore, this is surely a CCF for the lower level, and on a case by case basis for the upper level

- Lower-Level Nodes

  The users connected to the node will be put out-of-service

  Consequence: many users will be disconnected; therefore, this is a CCF for the lower level.

BRANCHES

As reported in the previous paragraphs, the out-of-service of the air links (branches) is mainly due to environment conditions. In case that a connection on the upper level backbone would be interrupted, surely many users could be disconnected and it is likely that also some upper level nodes could loose their connection. Therefore, this is surely a CCF for the lower level, and on a case by case basis for the upper level

SIMILARITIES AND DIFFERENCIES WITH POWER AND TELECOM SYSTEMS

- Similarities
  - The out-of-service of a node can have impact on many final users.
  - The out-of-service of a branch can have impact on the final users, such as in power systems
- Differences

- The out-of-service of a branch can have impact on the final users, and this is different from telecom systems

A.3.8. Functional CCFs

A typical functional CCF of a High-Tech system is obsolescence, such as for telecom systems ; in fact , obsolescence will mainly affect:

- The provision of parts to be replaced;
- The hardware-software interface; this is a very relevant factor, in fact hardware-software packages are in continuous development (e.g. 802.11a/b/etc protocols)

The analysis is carried out in accordance with the procedure proposed in Ch. 5.5.4.

1st Step - Identify Criticalities: Obsolescence

2nd Step - Identify Bottlenecks

- Provision of Parts to be Replaced: After for a few years, it could be difficult to find parts to replace the damaged ones; therefore, it is possible that more than one board of the same type could be not in condition to work inside the system

- Hardware-Software Interface: After for a few years, it is likely that different software be installed and maintained on the several nodes

3rd Step - Verify the impact of a fault on a bottleneck, and specifically the consequences on the reliability goal

The out-of-service of more than one board, and the software malfunction, could inhibit the proper functionality of the system; in this case, many nodes and many station and inter-station users could be disconnected, and this will be a CCF.

A.3.9. Statistics and Predictions

The failure records reported here below are relevant to the operation of the Wi Fi network of ARI Novara (ARI: Italian Amateur Radio League; Novara: my town).

It has to be pointed out that an amateur network cannot be considered a reliable source for a comprehensive survey, due to its limited extension and to the non-industrial implementation and erection of the system; conversely, in this case it is much easier to obtain real data, due to the remarkable background and to the typical availability of radio amateurs.

Main Failures occurred during the first years of operation:

FAILURES	REMARKS
Adverse weather, and specifically winter humidity, affected sometimes the transmission performance.	This failure can become a simultaneous CCF for all the network
Firmware failure, due to persistent re-booting.	This failure is mainly due to software bugs. It can be a system CCF if the failure is occurring in a transmission node. Conversely, the possibility to be a simultaneous or quasi-simultaneous CCF on two or more apparatus is extremely unlikely.
Firmware failure, with necessity to restart the electronic equipment (access points, etc.)	This failure is mainly due to equipment overstress. It can be a system CCF if the failure is occurring in a transmission node.
Failure of a DC supply converter and out-of-service of a peripheral node.	Most likely human error. The out-of-service of a peripheral node caused the black-out of a whole peripheral area
Failure of a router in a central node, and out-of-service of another node	The out-of-service of a second node caused the black-out of the whole system.

Expected failures:

FAILURES	REMARKS
Overall network shutdown, due to an extended power supply Utility black out	System CCF, due to external factors (power supply disconnection)
Electronic Equipment failures	After a few years of operation, and with a further extension of the grid, it is reasonable to expect a few equipment failures, taking into account the typical failure rates of the electronic equipment. No CCFs
Obsolescence both of software and hardware, after a few years of operation, and impossibility to assure a simultaneous replacement.	Functional CCF

All the above failures have been considered in the previous analysis, although with some differences.

Summary of main results:

- A peripheral Node out-of-service caused the out-of-service of a whole area.
- A second Node out-of-service led to a complete black-out.
- Out-of-service of links (Branches) caused the out-of-service of individual Load Nodes only.
- No CCFs between nodes have been detected; this result was expected

Conclusion:

- The predominance of Nodes over Branches is evident: a Node out-of-service is causing the put-of-service of many users; conversely, the impact of a branch out-of-service is much lower.

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