SAPIENZA
UNIVERSITÀ DI ROMA

Facoltà di Ingegneria Civile e Industriale

Dottorato di Ricerca in Ingegneria Elettrica
XXVI Ciclo

SSD ING - IND33

Service Continuity in Complex Power Systems: Safety, Operation and Maintenance

Luigi Parise

Tutor

Prof. Ing.
Carlo Mazzetti di Pietralata

2010-2013

A Valeria

Index

Chapter 1.5: Switching Procedures in Multiple Source Systems: The Flock Logic of Multi-Set Systems

Chapter 1.6: Architecture Impact on Critical Power Systems Exposed to Seismic Hazard

Part 2
Specific Issues of Mission Critical Power Systems

Chapter 2.1: Distribution Architecture in Data Centers: Inrush Currents of Electronic Equipment

Chapter 2.2: Distribution Architecture in Hospitals: Complete & Medical IT-System

Chapter 2.3: Interference of Ground Systems near Critical Power System

Introduction

The research aims to define electrical architectures based on the rationalization of the distribution structure and of power sources with the achievement of the primary objectives of service continuity, power quality, safety and safe maintenance.

Given the importance of electrical systems within the industrial and commercial installations, especially within the critical systems as hospitals and data center, their complexity is increasing with the inclusion of main, alternate, stand-by and emergency sources, as well as with the applications of switchable varying configurations. The high availability and integrity requirement of all the loads, or part of them, is satisfied by means of a system architecture that adopts more power sources and or modeling the system structure suitably for more configurations and so allows safe maintenance and overcoming fault conditions.

Briefly, the architectural measures can be applied in actions on the redundancy of the supply systems adopting multiple ended configuration (availability); of the distributors adopting multiple poles configuration (integrity); of the equipment supplies adopting dual corded equipment. Actions mixed are practically put on the distributors and sources adopting the criterion of partitioning and making redundant.

The electrical service continuity guaranteed by sources reliability and by power system integrity requests an effective business continuity management. The management of a complex system with multiple sources has to be planned with guidelines and strategies that consider the different reliability of the utilities sources, the actual system configuration in its parts and the loads exigencies of the buildings. The operation of the complex system must not be organized with an overall approach (macro approach) that studies all the links among the system nodes in the transitions of the authorized statuses, it has be organized node by node with a local approach (micro approach). Each node must only respect the constraints with the adjacent nodes by applying a “flock logic”.

The level of complexity influences the system design stage, but also its commissioning, operating and maintenance procedures. The design of a power supply system has to be permanent and comprehensive for the aspects of traditional design configuration as well as its safety of operation, i.e. the management and maintenance. The overall design must detect and define both aspects during the various stages of design and during the operational life cycle of the system. In fact the design of a power system requires a comprehensive and permanent design and highest consideration of competence of system operators. At this aim a business continuity management (BCM) is an essential component to be considered since the preliminary system design. The BCM is as much effective as it recognizes the importance of analyzing its objectives and the organization’s needs; implementing and operating controls, measures and procedures reducing the loss continuity risks; monitoring and reviewing the performance and effectiveness of the same management.

For very critical loads, the designer has to configure the power system that can assume multiple sets and to plan guidelines and measures overcoming the fault event relevant for the loss service continuity, regardless of its probability. In the same way, the system manager has to know the admissible operational sets of switching configurations and the related procedures for the system recovery. The operational management has to complement the system design and requires separating the comprehensive design of the system for both the phases of designing and of executing and for both the phases of validating and perfecting the same system against the loss service continuity during the faults or maintenance exigencies.

The electrical structure can be analyzed and designed in a perfect analogy with a mechanical structure in relation to the internal forces characterizing the electrical behavior and to the external forces, as earthquake, fire, flood, extreme ambient conditions, lightning, electrical interferences. The design can apply a "Darwinian" approach in sizing the components and in drawing the layout that permits to optimize the electrical behavior of the system and also to minimize the external stresses during an hazardous event. This kind of approach has to aim at preventing and guaranteeing the best endurance more than protecting damages to systems operability. Different configurations can be arranged for a same functional structure, but he actual configuration of the power system has to consider also other aspects (e.g. constructive requirements, esthetical aspects, environmental conditions).

The thesis consists of two parts: the first part deals with the architecture impact on a complex system analyzing the system configuration and operational safety aspects; the second part refers to specific issues of mission critical power systems, data centers and hospitals especially.

The first part in particular is divided into seven chapters.

In the chapter 1.0 basic concepts of reliability theory are presented referring to the terminology, metric parameters and modes of failure. It's concisely discussed the techniques to enhance the system reliability. The system can be analyzed by decomposing it into smaller sub systems and estimating reliability of each subsystem to assess the total system reliability using, for instance, Reliability Block Diagrams model. Obviously for complex systems with multiple interconnections, direct analytical calculations are impractical. The reliability is calculated using a computer program that does random simulations.

In the chapter 1.1 it's highlighted the importance of a permanent and comprehensive design of a power supply system during the various stages of design and during the operational life cycle of the system. In fact during its life cycle, the electrical supply system would have to be switched to and from main sources, alternate sources, emergency generators, and/or uninterruptible power supplies (UPSs) so operational procedures are necessary for de-energizing the system (safety procedures) or for the transfer among sources (integrity procedures).

In the chapter 1.2 is suggested a syntax and semantics of a language to program operational procedures. This formal language is a unified suite of symbols, meanings and codes used on the basis of conventional rules. The programming language elements may be used in an interactive programming environment to allow to express concepts and procedures, to make analysis of formal connections and bonds between components of the electrical power system. It lets to provide information and give instructions for the execution of certain operations following correct procedures. A new methodology has been propounded to close the gap between the traditional system design integrity studies and their counterpart studies associated with system operational safety aspect.

The chapter 1.3 deals with the impact of the architecture on the comprehensive procedures for a complex system. It's defined the cut and tie rule, introducing ring configuration and floating nodes that the design could adopt to enhance the integrity of power system analysis and operation.

In the operation of electrical installations the risk assessment evaluates hazards and conflicts. In the chapter 1.4 it's presented a kinematics analogy between masses in spatial motion and electrical events in time (waves) that can offer a general way for studying conflicts in the intersections, preventing hazards. This analogy offers a new approach for operational procedures and allows the introduction of a "transitions" theory for intersections. The architecture of electrical installations can be designed in increasing complexity related to its exigencies, taking actions on multiple sources and on the configuration. Analogies between the operation of highway intersections of multiple traffic lanes and the operation of nodes of electrical power systems are proposed as offering an equivalent well-known way for examining constraints in the transitions, for facilitating the understanding of the mathematical description and advancing new approaches and new methodologies for solutions. Automatic transfer switches also assisted by engine generators and UPSs are available as basic equipment to support transitions. This part describes the special configuration of the node "double two", constituted by two automatic transfer switches connectible in parallel.

The architecture of a mission critical power system has to guarantee service continuity and so has to be designed with a multiple structures that permit the simultaneous operation of multiple sources. In the chapter 1.5 a practical case of multiple source systems is illustrated applying a specific logic to carry out the switching procedures: the micro-approach of the "flock" logic.

Strong earthquakes can cause serious problems to the dependability of supply of electrical power systems particularly in exposed and sensitive structures as strategic buildings. In the chapter 1.6 mechanical and electrical criteria are suggested for the design and installation of electrical power systems in buildings subject to seismic hazard.

Electrical equipment, which are non-structural building components, must be installed in compliance with the seismic requirements contained in current codes and standards. The failure of the building service may in fact depend on the fault of the electrical systems rather than structural collapses. A special power distribution, "brush-distribution", has an horizontal structure suitable for the strategic buildings as hospitals that are at risk for seismic event.

The second part of the thesis refers to specific issues of mission critical power systems, in particular data centers and hospitals. Several measurements were performed in laboratory and on field to analyze sneaky critical cases for the service continuity and the integrity of these strategic power systems.

This part is divided into four chapters.

The chapter 2.1 deals the data centers. For the reliability of data centers the electrical distribution architecture has a vital impact on performances throughout its lifecycle. In the first part of the chapter special standards are presented that establish tier classifications for the site infrastructures. Several distribution patterns are shown to highlight the improvement of the reliability with the increasing of the tier levels making actions on supply systems, on distributions (paths) and equipment.

It's presented analysis about equipment like electronic components (typical loads in data center) that exhibit excessive inrush currents at start up. Many tests were performed in laboratory feeding electronic equipment by main power supply and UPS. Considering the long service of all equipment in a data center after the fast start up it is a technical inadmissible inaccuracy to maintain a protection setting inadequate for the service also as long as many year, maintaining a rating current value I_n higher than the load current value and with a weak protection coordination permissive to a longer permanence of the short circuit current. Starting systems for equipment are suggested to solve the problem of inrush current and to allow an adequate protection coordination for the long service of the data center.

It's discussed, moreover, the importance in the switchboard design to plan the loads balancing, and the future expansion and it's proposed a synchronized transition by mobile UPS to change the feeding phase of a dual-corded equipment for optimizing the load balancing.

The chapter 2.2 concerns the hospitals as critical systems, where service continuity is essential. It's presented a short overview of distribution system types in accordance with the IEC standards and the variety of IT-systems applications. It's defined a complete system SSS & EUC (Safety Supply System and Equipment Under Control) with requirements such as to avoid shock hazard and not to occur power outage for fault both due to overcurrents and to overvoltages. In this system a functional safety is also based on the technical operation required to take action to restore the safe state with the shortest practicable delay, so the system performances are in relation to the competence of the operators. Doctors, surgeons, administrators, medical devices are rightly at the forefront, but electrical and technological systems and team of technicians are wrongly considered as ancillaries. So it's emphasized the importance that electrical operation must be organized (Business Continuity Management) and the need to have an emergency response team available at all times.

Several current absorptions measures and registrations were carried in some hospitals relating electromedical equipment, an example of a linear accelerator absorption is discussed.

The chapter 2.3 focuses on the existence of a global grounding system in city centers, urban and industrial areas with distributed low- and high-voltage grounding.

In any case, more electrodes coexisting with common portion of influence zone cause interferences among themselves during a fault event that can determine potential potholes and unexpected increases of touch and step voltages.

In the case of a ground fault in an electrical system that causes an injection of ground current by its ground system GS, the presence of another GS and, more in general, of other metal bodies buried in the area of influence of the first ground electrode, determines interfering effects that can be of impact for special power systems as data centers and hospitals.

New developments and methodologies are suggested in the study of the behavior of an aggregate of ground systems (zone of influence, effectiveness of meshing with the depth of the sink, and rolling sphere method for the analysis of the behavior of an aggregate of ground systems).

In the chapter 2.4 is discussed another special issue about as mechanical damages of the stranded bare conductors can degrade locally the effective sizing of the cross section and cause anomalous local conditions. The circuit protective devices can be unfit to detect the faults of cords that remain so energized and may cause overheating, arc-faults and fire ignition of nearby flammable materials and/or electric shock hazard.

Many events have demonstrated that fire ignitions are possible in cords. Generally and especially in strategic buildings as hospitals, prevent the ignition is better than extinguish the fire promptly.

An efficient protection is proposed by integration of active and passive techniques.

Part 1

Critical Systems as Complex Systems. Distribution Architecture of a Complex System. Theory of Complex Systems for Safety, Operation and Maintenance of the Power Systems

Chapter 1.0

Notes on Reliability Theory

Reliability terminology and metrics

There are many definitions for reliability engineering [42.p; 48.p], according to E.E.Lewis:
Reliability (R): Reliability is probability that a component, device, equipment or a system will perform its intended function adequately for a specific period of time under a given set of conditions.
According to the definition, the basic elements of reliability are probability, adequate performance, duration of adequate performance and operating conditions. The above definition covers all four aspects of product, unlike quality, which speaks only conformance to specifications. In other words reliability is quality over time, which is under the influence of time and environment unlike quality, which is a degree of confirmation alone not considering the time length and environment of operation. Another important difference between quality and reliability is that one can manufacture reliable systems using less reliable components by altering product configuration, whereas it is not possible to manufacture high quality systems with less quality components. Adding one or more similar components in parallel can increase the reliability of the system. Reliability can only be meaningful, if it is related to time.
Since reliability is a probability, it is expressed in decimals of 1,00 as given below.
Reliability = 1,00 means certain to work as intended. Reliability = 0,99 means 99% likely to work as intended.
Reliability at time "t" can be defined as:

$$R(t) = N(t) / N_0$$

where:

- $N(t)$ is equal to number of components surviving at instant "t";
- N_0 is equal to number of components at start (when t=0)

Availability (A): Availability is the long-term average fraction of time that a repairable component or system is in service and satisfactorily performing its intended function.
For example, if the electricity is off for 2 hours in a year, but the rest of the year the electricity is on, the availability of electrical power for that year is 8758 hours divided by 8760 hours, which is 0,999886.
An availability of 0,99999 could mean that the system was down for 5,3 minutes (or 315 seconds) per year. It would make no difference in the availability calculation if there was one 5,3 minute outage, or 315 one-second outages. It could also be one outage of 1,32 hours in 15 years. In all three cases, the availability is 0,99999.
There are two common measures of availability: *inherent availability* and *operational availability*.
The difference between the two is based on what all is included as "repair time".

For *inherent availability*, only the time it takes to fix the equipment is included. Inherent availability assumes that the technician is immediately available to work on the equipment the moment it fails, and that he has all the parts, etc. necessary to complete the repair.

For *operational availability*, all the delays for scheduling, travel time, parts, etc. are included.

Inherent availability and operational availability show different aspects of the system being analyzed. Operational availability would be the "real world;" how the system really operates. There are usually delays between the time a piece of equipment fails and when the repair begins. Spare parts inventories are also very significant and directly impact operational availability. Therefore, when determining spare parts inventories, on-site personnel and their level of training, etc. operational availability is a useful tool. Inherent availability is more useful tool in analyzing the system design. Since there are wide variations in the maintenance practices from facility to facility, operational availability could vary significantly between two facilities with identical infrastructures [9.p]. Eliminating all of the logistics involved with getting the parts and trained individual to the piece of equipment, and counting only the actual repair time provides a more accurate evaluation of the infrastructure design. It shows the availability that is "inherent" to the design, if the spare parts inventory and repair are perfect.

The *failure rate* (λ) is defined as the rate that a failure per unit time occurs in the interval, given that no failure has occurred prior to the beginning of the interval.

Mean time between failures (MTBF), as its name implies is the average time the equipment performed its intended function between failures.

Mean time to repair (MTTR) is the average time it takes to repair the failure and get the equipment back into service.

Mean time to failure (MTTF), is the average time that the equipment takes to fail.
In figure 1 it's shown the meanings of the parameters discussed above.
For the case of a constant failure rate:

$$MTTF = 1/\lambda$$

Electronic equipment, along with many other types of equipment, has a relatively constant failure rate over much of its useful life and follows an exponential statistical distribution. The common assumption for reliability analysis is that all the equipment in the system to be analyzed falls within this statistical distribution where the failures are random and the failure rate is constant. All of the calculations shown below assume a constant failure rate for the equipment.

Inherent Availability is mathematically defined as the mean time between failures divided by the mean time between failures plus the mean time to repair:

$$A = MTBF / (MTBF + MTTR)$$

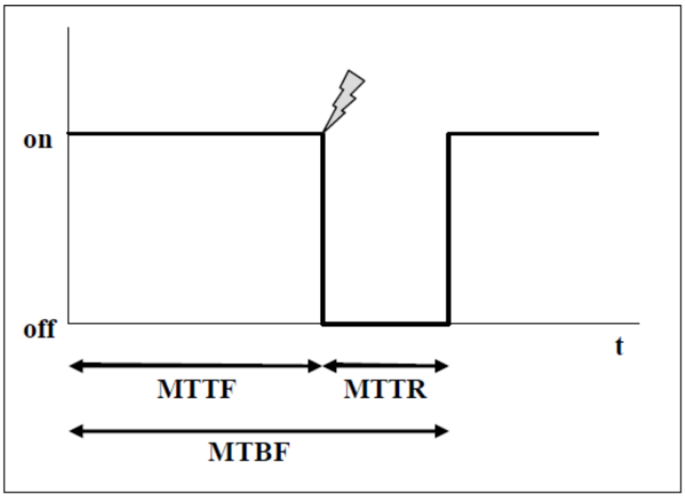


Figure 1. Meanings of the parameters MTTF, MTTR and MTBF

As already defined before, *Reliability* (R) is the probability that a product or service will operate properly for a specified period of time under design operating conditions without failure. Reliability is time dependent. The longer the time, the lower the reliability, regardless of what the system design is. The better the system design, the higher the probability of successful operation for a longer period of time. For a constant failure rate λ, reliability as a function of time R(t) is:

$$R(t) = e^{-\lambda t}$$

From the equations shown above, we see that there are five important factors to define the "reliability" of a system; MTBF, MTTR, availability, reliability and time. It can also be seen how these five factors are interrelated. What is not as obvious is that "availability" is time independent, since it is the combination of two terms that are themselves averages over long periods of time (mean time between failure and mean time to repair). Reliability, as we can see from the equation above, is very "time dependent." Reliability is the "probability of success" for a given period of time. Reliability is a metric directly related to how often (or how fast) the system fails. As shown in Table 1, the system that failed once in a year for 5,3 minutes would have a much better reliability than the system that failed 315 times for one second, but nowhere near as good as the system that failed once in 20 years for 1,77 hours, even though all have the same availability.

Table 1. MTBF of outages examples

Availability	**Number outages per year**	**Failure rate failure/hour**	**MTBF (hours)**	**MTBF (years)**	**Reliability (1 year)**
0,99999	315	3,60E-02	27,81	0,0032	0%
0,99999	1	1,14E-04	8760	1	36,78%
0,99999	0,067	7,61E-06	131400	15	93,55%

Modes of failure and causes

A *failure* is the partial or total loss or change in the properties of a device in such a way that its functioning is seriously affected or totally stopped.

The concept of failures and their details help in the evaluation of quantitative reliability of a device [6.p]. In general, some components have well defined failures; others do not. In the beginning, when the item or component is installed, the item fails with high frequency, which is known as initial failure or infant mortality. These are generally due to manufacturing defects. They are very high at initial stages and gradually decreases and stabilize over a longer period of time. Stable or constant failures due to chance can be observed on an item for a longer period. These types of failures are known as random failures and characterized by constant number of failures per unit of time. Due to wear and tear with the usage, the item gradually deteriorates and frequency of failures again increases. These types of failures are called as wear-out failures. At this stage failure rate seems to be very high due to deterioration. Therefore the whole pattern of failures could be depicted by a bathtub curve as shown in Figure 2.

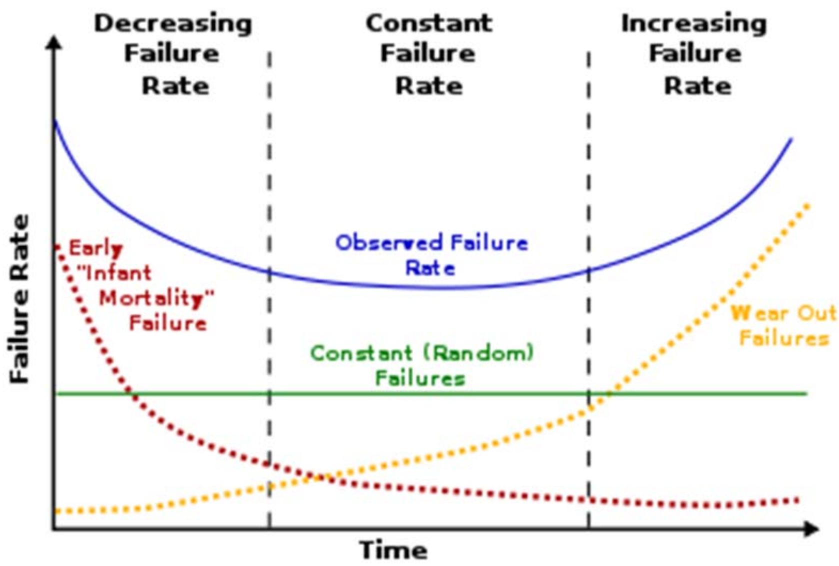


Figure 2. Failure Rate Curve (Bathtub curve)

Design for reliability

Reliability is now a well-recognized and rapidly developing branch of engineering. Manufacturing of a perfect component is almost impossible because of inherent variations and the cost for parts improvement is very high and the approach becomes unwieldy with large and complex systems. Since reliability study is considered essential for proper utilization and maintenance of engineering systems and equipment, it has gained much importance among the practicing engineers and manufacturers. The system designer is encountered with several problems while planning and designing the system for a reasonable level of reliability. Therefore a thorough reliability analysis needs to be attended at the design stage itself. The various means of increasing the system reliability and the constraints associated with them must be known. Reliability of a system can be improved by any one or combination of the following two methods namely:

- Improving the components
- By using redundancy technique

A number of techniques are available to enhance the system reliability. Some of the important techniques are shown in Table 2.
Combination of structured redundancy and maintenance and repair yield maximum reliability nearing to 1. In general it is not possible to produce components with high reliability due to number of constraints, such as cost, non-availability of production facilities etc., In such cases redundancy comes handy to the reliability engineer. In simple words, redundancy is the existence of more than one means for carrying out a given function. The following are the methods for introducing redundancy in to a system for improving reliability.

- Element redundancy
- Unit redundancy

Table 2. System Reliability Enhancement Techniques

	TECHINIQUE	REMARKS
1	Parts improvement method	Leads to higher cost
2	Effective and creative design	Failures cannot be completely eliminated
3	System simplification	Leads to poor quality
4	Use of over rated components	Leads to higher cost
5	Structural redundancy	Effective method for higher reliability
6	Maintenance and repair	Best for high reliability

Element Redundancy

Let C1 and C2 be the two elements with reliabilities R1(t) and R2(t) respectively connected in parallel as shown in the Figure 3. In this arrangement of elements, the reliability of the system will be much better due to the presence of redundant element and proper operation of one element is sufficient for the successful operation of the system.

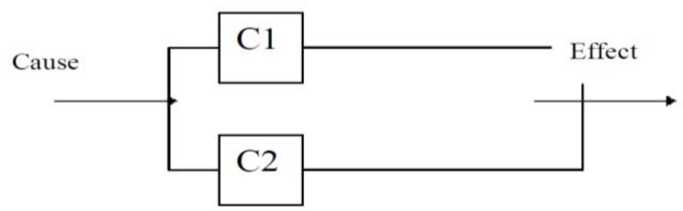


Figure 3. Element Redundancy

Unit Redundancy

To improve the reliability of the system, another similar system is connected either in series or parallel to the existing one is called the concept of unit redundancy. Consider a system with two elements C1 and C2 as shown below. For improving the reliability of the system, a similar system in parallel is added to the existing system, which is shown in Figure 4a.

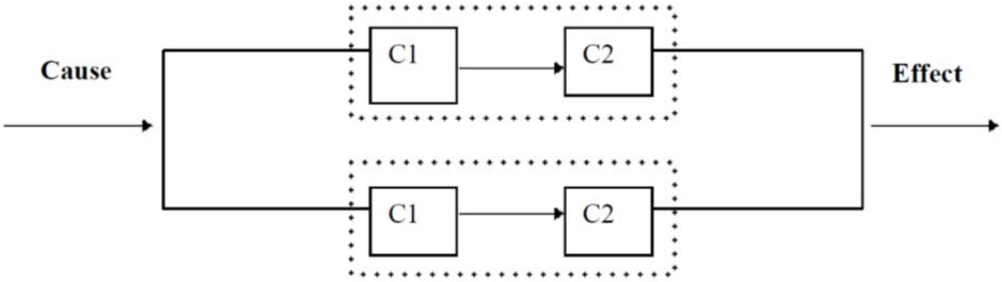


Figure 4a. Unit Redundancy

Unit redundancy is further classified into two types

- Active redundancy
- Stand by redundancy

Active Redundancy

Redundant system consisting of two or more components connected in parallel and both components were operating simultaneously is called active redundancy. In active redundancy all the redundant units are operated simultaneously instead of switching on only when need arises. The schematic diagram representing the active redundancy is shown in Figure 4b.

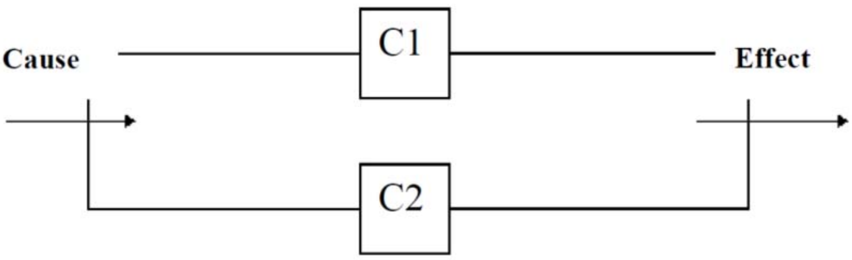


Figure 4b. Active Redundancy

Stand by Redundancy

In case of stand by redundancy the alternate means of performing the function is not operated until it is needed. The alternative means is switched on only when the primary means of performing the function fails. Standby redundancy is more appropriate for mechanical devices such as motors and pumps etc. The schematic diagram representing the standby redundancy is shown in the Figure 4c

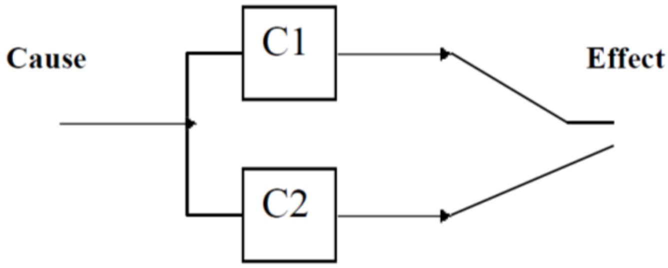


Figure 4c. Standby Redundancy

While designing the system the redundancy is highly appropriate in almost all the cases. The advantages of the redundancy approach are:

- Desired level of reliability can be achieved under the resource flexibility.
- Improvement in reliability per unit of resource is optimum when compared to any other approach.
- Redundancy requires less skill on the part of the design engineer.
- It is a quick method of solution.
- This method can be the best choice for improvement of reliability in case of failure of all other approaches.

Types of system reliability models

The objective of system engineer is to estimate various reliability parameters of the system. The system may vary from simple to complex. The system can be analyzed by decomposing it into smaller sub systems and estimating reliability of each subsystem to assess the total system reliability. The procedure to determine the system reliability is as follows.

- Identify the sub systems and elements of the given system.
- Identify corresponding individual reliabilities of the sub systems and elements.
- Draw a block diagram to represent the logical manner in which these units are connected.
- Determine the constraints for the successful operation of the system.
- Apply rules of probability theory to determine the system reliability.

To determine an appropriate reliability or reliability model for each component of the system by applying the rules of the probability according to the configuration of the components with-in the system is also known as system reliability. Several methods exist to improve the system reliability like using large safety factors, reducing the complexity of the system, increasing the reliability of the components etc. There are several types of configurations available, such as

- Series configuration
- Parallel configuration
- Mixed configuration
- Complex configuration
- Others

Reliability Block Diagrams (RBD) is a graphical representation of the components of the system and how they are connected [3.p; 51.p]. For electrical systems, the one-line diagram is used, and each major component, such as switchboard, generator, UPS module, transformer, etc. is represented as a block on the diagram. The failure and repair rates for each component are entered in the block that represents it in the RBD. The blocks are connected in the same manner as the flow of electrical power, including parallel paths where they exist. Calculations are then performed to determine the reliability, availability and, mean time between failures (MTBF) for the system modeled in RBD.

Series Configuration

In series configuration all components must be connected in series in order to make the system to perform continuously. In this system all components are considered critical in that sense that their function must be performed in order to make the system to operate successfully. Under this concept if any one component connected serially fails, the System will fail.
The reliability block diagram as shown in Figure 5 represents the series configuration.

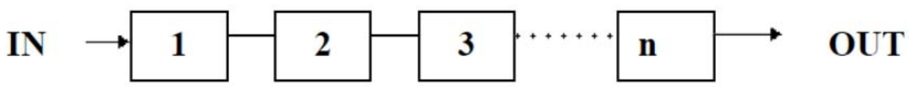


Figure 5. Series Configuration

The characteristics of series configuration are

- The components are interconnected in such a way that the entire System will work satisfactorily if all the components work without fail.
- The entire system will fail even if one of its components fails. System reliability ( ) can be determined by using component reliabilities.

If each component has a constant failure rate of then the system reliability is equal to

$$R_S(t) = \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} [exp(-\lambda_i .t)] = exp[-\sum_{i=1}^{n} \lambda_i .t] = exp[-\lambda_S .t] \qquad (1)$$

where:

$$\lambda_S = \sum_{i=1}^{n} \lambda_i$$

For a simple case of two blocks in series with failure rates of λ1 and λ2, the reliability as a function of time R(t) is:

$$R(t) = R(1) * R(2) = e^{-(\lambda 1 + \lambda 2) t}$$

Parallel Configuration

A system can have several components to perform the same operation and the satisfactory performance of any one of these components is sufficient to ensure the successful operation of the system. The elements for such a system are also said to be connected in parallel configuration as shown in Figure 6.

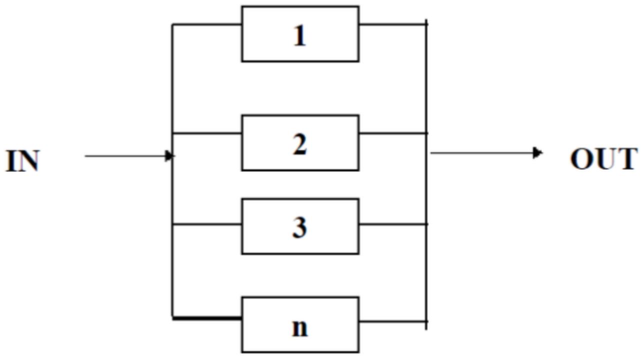


Figure 6. Parallel Configuration

The characteristics of a system with parallel configuration are

- The system will function satisfactorily even any one of the parallel units operates satisfactorily.
- The entire system will fail only when all the units in the system fails.

The system reliability is given by

$$R_S(t) - 1 - \prod_{i=1}^{m} [1 - R_i(t)] \quad (2)$$

If life times of the components follow exponential distribution then

$$R_S(t) = 1 - \prod_{i=1}^{m} [1 - exp(-\lambda_i . t)] \quad (3)$$

If all components are identical:

$$R_S(t) = 1 - [1 - exp(-\lambda . t)]^m \quad (4)$$

For a simple case of two blocks in parallel with redundancy, where 1 out of 2 is necessary for successful operation, the reliability as a function of time R(t) is:

$$R(t) = R(1) + R(2) - [R(1) * R(2)] = e^{-\lambda 1t} + e^{-\lambda 2t} - [e^{-(\lambda 1 + \lambda 2)\,t}]$$

Mixed Configuration

In mixed configuration, the elements are connected in series and parallel arrangement to perform a required system operation. In mixed configuration, to compute the system reliability, the network is broken into series or parallel subsystems. The reliability of each sub system is found and then the system reliability may be obtained on the basis of the relationship among the sub systems. The schematic diagram representing the mixed configuration is shown in the Figure 7.

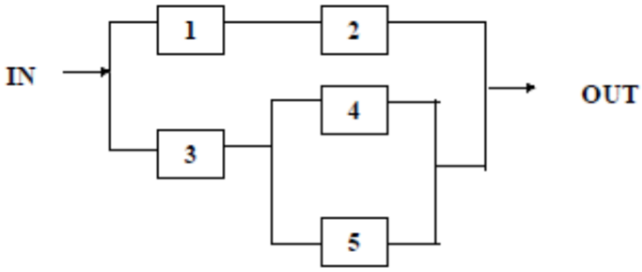


Figure 7. Mixed Configuration

Complex Configuration

For complex systems with multiple interconnections, where some of the components are neither in series nor in parallel but in a stand-by mode (such as a generator plant that is only active during a utility failure) direct analytical calculations are impractical. The reliability is calculated using a computer program that does random simulations. When performing a simulation, a random series of simulations are performed on the RBD. These simulations are test runs through the system (from the start node through the end node) in order to determine if the system completes its task or fails. During each iteration or test, the software uses the properties of each figure to decide whether that figure is operating or not and therefore determines if the system is operating.

Reliability optimization through redundancy

Redundancy makes it possible to achieve high reliable system using less reliable elements [43.p]. However redundancy increases product cost, weight and complexity of the system substantially. It is therefore, essential to optimize reliability of the system by keeping constraints like cost, weight, volume etc.

Redundant units may be operating actively in parallel and thus be subject to failure. Alternately they may be serving as spares to be used in succession for replacement of failed units. The first type of redundancy is sometimes referred to as parallel redundancy and the second type is referred as stand by redundancy.

Fixed specific constraints may exist on cost, weight, volume, etc., which cannot be violated and a redundancy allocation, which satisfies these constraints while maximizing reliability is desirable.

The reliability of a system can be maximized in two different ways.

1. The component reliabilities are known to determine the number of components in each stage and maximum system reliability for the given cost, weight and volume.
2. The number of components are known to determine the component reliabilities to maximize system reliability for the given cost, weight and volume.

Reliability cost models and their significance

There is always a cost associated with changing a design, use of high quality materials, retooling costs, administrative fees, or other factors. Before attempting at improving the reliability, the cost as a function of reliability for each component must be obtained. Otherwise, the design changes may result in a system that is needlessly expensive or over-designed. Development of the “cost of reliability” relationship offers to the engineer an understanding of which components or subsystems to improve. The first step is to obtain a relationship between the cost of improvement and reliability. The next step is to model the cost as a function of reliability. The preferred approach would be to formulate the cost function from actual cost data. This can be done taking the past data. However, there are many cases where no such information is available. For this reason, a general behavior model of the cost versus the component reliability can be developed for performing reliability optimization. The objective of cost functions is to model an overall cost behavior for all types of components. But, it is impossible to formulate a model that is precisely applicable to every situation. However, one of the reliability cost models available can be used depending on situation. All these models can be tried and one which is suitable to component or situation can be adopted.

Chapter 1.1

Comprehensive Design of Electrical Installations by Integrating System Configuration and Operational Safety Aspects

Introduction

Given the importance of electrical systems within the industrial and commercial installations, especially within the critical systems as hospitals, their complexity is increasing. The level of an electrical system's complexity may differ with the inclusion of main, alternate, stand-by and emergency sources, as well as with the applications of switch-able varying configurations [27.s];.

The high availability and integrity requirement of all the loads, or part of them, is satisfied by means of a system architecture that allows overcoming fault conditions [25.s]:

- adopting more power sources;
- modeling the system structure suitably for more configurations.

The level of complexity would affect the design efforts in a new system design stage, but also it would affect its commissioning, operating and maintenance procedures. During its life cycle, the electrical supply system would have to be switched to and from main sources, alternate sources, emergency generators, and/or uninterruptible power supplies (UPSs).

The switching over between configurations could be on:

- a *live-transfer* (make-before-break),
- *dead transfer* (make-after-break) or
- combinations of different types at different speeds (fast transfer, slow transfer).

During the maintenance periods of a system, parts of the system may have to be de-energized, Locked Out (LO) and Tagged Out (TO) to allow maintenance personnel a safe approach.

Regardless of the level of complexity, studies associated with establishing *operational procedures* for the industrial and commercial power systems have been addressing two general aspects:

- *Configuration Integrity Aspect*: which deals with ensuring that system integrity shall not be compromised under any permissible switching arrangements, and during the switch-over between configurations;
- *Operational Safety Aspect*: which deals with ensuring the safety of the personnel during system maintenance and includes the LO/TO procedures.

These two aspects are interconnected and both are necessary to ensure the design and execution of comprehensive system operation procedures.

In specific configurations, system integrity could be verified using system studies such as short circuit, load flow and motor starting for the subject configuration.
Such studies acquired advanced tools in both methodology and computer programs. Several good programs have been introduced for load flow, short circuit and motor starting and other system analysis associated with configuration requirements.
On the other hand, the methodology in developing and testing the configurations themselves and their associated procedures have not reached similar level of progress.
For example, the invention of the Kirk Key Interlock system in 1932 is still a major milestone in the operational safety until now. Similarly, until a few years ago, the operational safety aspects of an electrical system design were developed on a plant-by-plant basis mostly via consultations between engineers, system designers and assigned system operators as well as the interpretations of locally enforced electrical codes.
Although consultations between engineers and system operators are critical and should be always encouraged, some inconsistencies existed between the operational safety requirements for different plants in different regions of the World.
In recent years however, the operational safety aspects of the design were emphasized due to the realization of the importance of the operational safety aspects in the design in avoiding accidents and increasing system operational safety.

System configuration integrity

In a system, the supply continuity could be perfected by the configuration integrity to achieve upper system integrity.
Considering the two aspects of configuration, configuration integrity and operational safety, need to be translated into procedures for system operating purposes, the clear evaluation of all the sources and of all the possible sets of configurations is a basic foundation for a safe and secure operation of the electrical installation.

Figure 1 shows a sample case of a power system that has two normal sources and three emergency sources, none of them should be run in parallel, and only dead transfer is allowed.
This is a simplified case as in an actual industrial system where it could be an allowance for live transfer to achieve higher level of system reliability and availability. Figure 1 also shows the switches that in the normal status have to be locked in open (by padlocks).

To achieve continuity of supply on each bus, the first level of operational procedure is performed by the transfer via the own of the 3 automatic transfer switches designated as ATSs.
At such a level it is assumed that on each bus the main (normal) source has failed and a transfer is initiated to the alternated source.

A higher level of continuity is achieved via a more complex procedure where the tie switch T is operated for contingency, as the loss of U1 or U2, G1 or G2, and/or the emergency switch ES is operated to allow supply from the generator G3.
The several procedures need to be planned, designed in details, coordinated and tested.

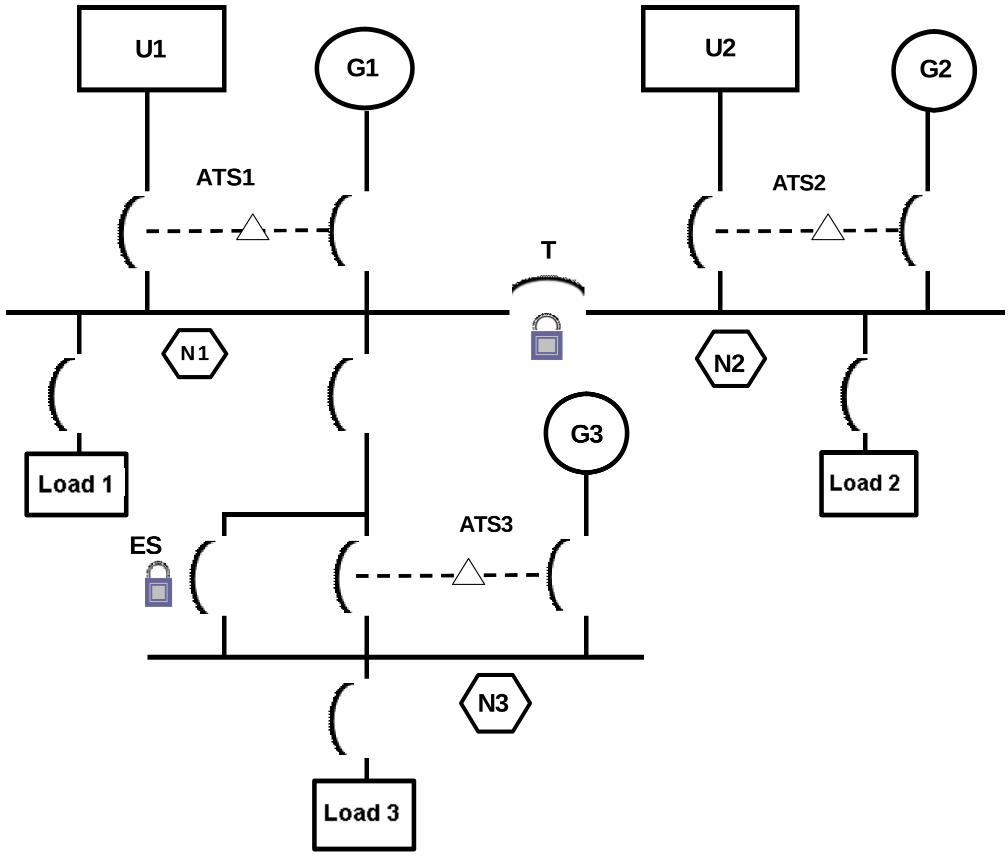


Figure 1. Sample case of power system with many sources and many sets to guarantee the service integrity with IEEE symbols

Load flow, short circuit analysis, source sets. The operational procedures

In the design stage of the electrical installations, the electrical system studies identify and avoid potential deficiencies and unacceptable conditions. Such studies are performed during the different stages of design prior to putting the system into operation.

All source configuration sets have to be studied, ensuring compliance to system load flow, short circuits and requirements by other applicable analysis.

The maintenance plan could be established as a core operation plan. In each maintenance plan, it would be identified which part of the system would be switched off, the maintenance zone, the duration of maintenance and the procedure to restore system to normal operation. In each maintenance/operation procedure all the sources and the main switching means (sources means) must be defined in each area or working zone. Working adjacent to an energized part of the system would require that arc flash requirements also be examined.

On the Integrity aspect for the above system, the integrity procedures would address source transfer under contingency. For each procedure, all admissible sources sets shall be defined, under different contingency conditions.

Contingency conditions could be identified as the eventual loss of:

- a generator,
- a transmission line,

- a transformer,
- a load.

Each case shall be analyzed to prevent the operation that may cause overcurrents, equipment overloads or down voltage levels.
As a minimum load flow and short circuit studies shall be performed for each configuration to determine the optimum size and location of components and the system optimum configuration. To identify the cases that a power system engineer/designer has to consider, the following two design steps shall be considered.
For the basic configuration of the power system, the design studies shall cover worst case scenarios. For the management and maintenance, the system operator needs the evaluation of all the admissible conditions, that the design studies have to cover and to define the procedures.

The operational procedures are of two kinds:

- *Safety LO/TO procedures*;

- *Integrity (configuration/transfer) procedures*.

The *safety or LO/TO procedures* involve several operating steps to isolate the safe working zone, which is the zone of operation (ZOS) that a maintenance operator (MO) has to make safe to touch.

The *integrity procedures* involve several operating steps to transfer a source from a circuit to an alternate one, to transfer the system or its portions from a source to another.

The best maintenance plan has to evaluate the merits of a redundant system and has to face the occasional out of service for maintenance by sources sets, avoiding the total shutdown or limiting it to portions.
In the safety procedures, the re-energizing operation could present some difficulties owing to the changed conditions of sources set. The power systems have different performances in relation to the operator competence.

Comprehensive design approach: a new methodology

A comprehensive approach is recommended in the design process to define and survey all its life cycle of the system. (figure 2).

The analysis and procedures have to follow: inspection, experience, intuition, regulations, codes, practices, laws, development of clearing procedures, evaluation, reiterative loop, independent review and confirmation.

These following steps allow closing the gap between the system configuration and its safe operation, reducing blackouts:

- Understand the system and its constraints,
- Identify switching scenarios,
- Consider site conditions,
- Use analysis and intuition to develop plans for the operational procedures,

- Critical review and confirmation by third party,
- Document the scenarios.

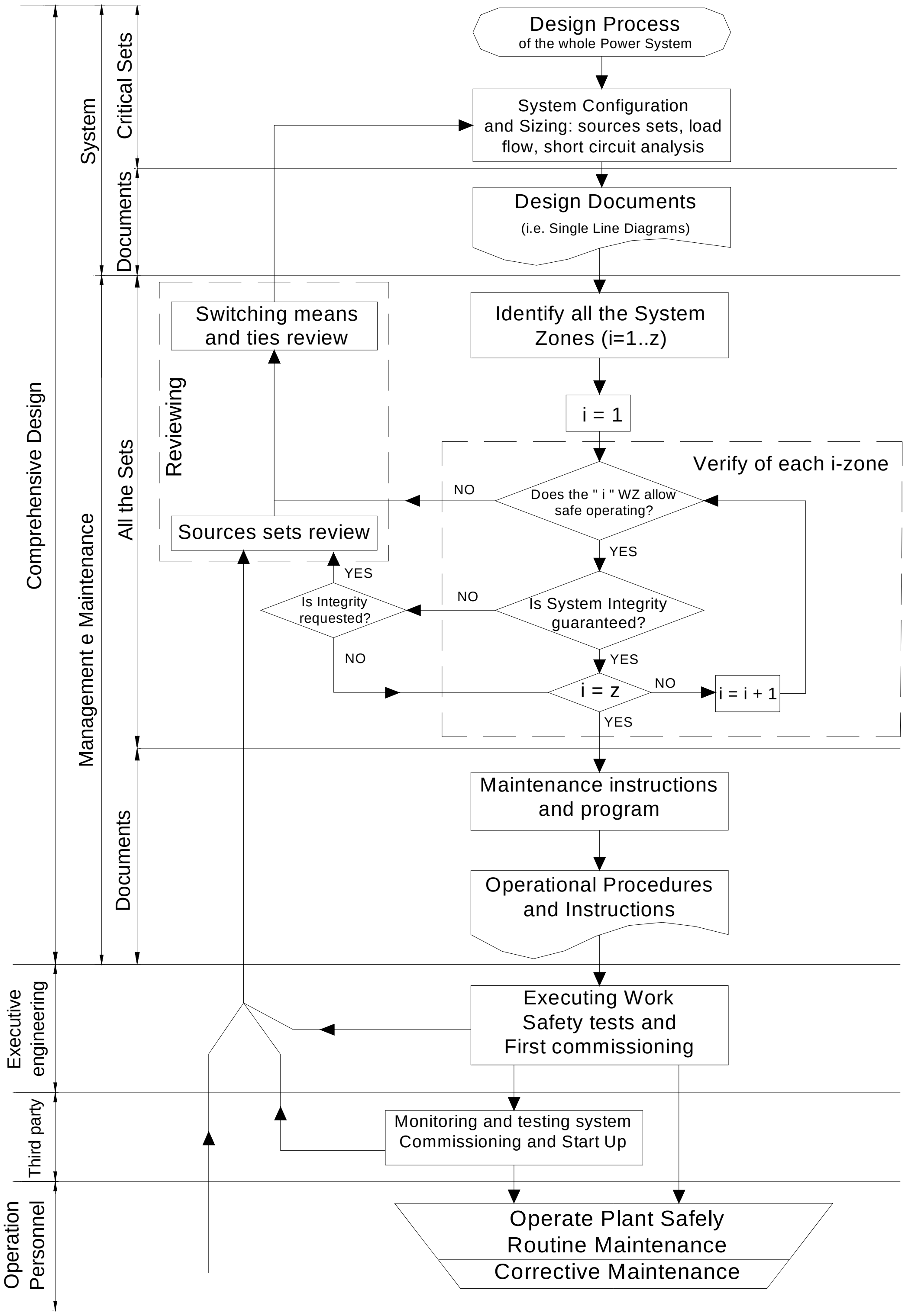


Figure 2. Comprehensive design and complete life cycle of a power system

To understand the system the design has to deal with:

- Single line and site diagrams,

- Performance characteristics,
- Short circuit, load flow, regulation, arc flash, etc.
- Equipment features,
- Ratings, physical configuration, etc.

Design documentation on the operation regards the management and maintenance. Operational procedures must be documented with:

- Manual methods frequently are slow to perform;
- Manual records are not always current, therefore misleading.

A new methodology overcomes these limitations. A mathematical model (discussed in chapter 1.2 and 1.3) has been suggested to define the procedures and it lends itself to solution by computer.
Basic rules of the statuses in the operational procedures are:

- the *exclusivity,*
- the *priority,*
- the *parity.*

Each system node for live service presents an intrinsic logic in relation to its constitution, described by the instructions founded on the three operating rules. Organize opportunely the architecture of the system and comply with the intrinsic logic gene of each node allows to facilitate and improve the operation of a complex system. Organize opportunely the architecture is to project its program and take actions on the sources and on the configuration, adopting the cut and tie rule, introducing ring configuration and floating nodes.
An articulate operation will be constituted by a sequence resultant of coordinated and coherent sets of the system nodes.

The Business Continuity Management (BCM)

The design of a power system requires a comprehensive and permanent design and highest consideration of competence of system operators. At this aim a business continuity management (BCM) is an essential component to be considered since the preliminary system design.

The BCM is as much effective as it recognizes the importance of analyzing its objectives and the organization's needs; implementing and operating controls, measures and procedures reducing the loss continuity risks; monitoring and reviewing the performance and effectiveness of the same management [33.s].
In the management of an electrical system it is necessary to outline guidelines for the implementation of activities with plans for the electrical operation and the setting up of a storage protocol and computerized data management resulting from maintenance practices.

The system operation requires continuous training and information to those involved, the ongoing evolution of structures and of the system sets, periodic monitoring of the MV and LV protection coordination, the control and protection of transformers, control of absorptions and energy consumptions of various system section with the support of the supervision system,

tests of engine generators, the inspections and testing of electrical equipment with the update of the mapping of the user areas of the various buildings, such as the presence of cuts and UPS.
The operation and management of the system thus engages in a planned maintenance of these systems.

For very critical loads, the designer has to configure the power system that can assume multiple sets and to plan guidelines and measures overcoming the fault event relevant for the loss service continuity, regardless of its probability. In the same way, the system manager has to know the admissible operational sets of switching configurations and the related procedures for the system recovery .
The design should have to be founded on the most complete information about the equipment behavior knowing steady and transient characteristic parameters.
The information level is crucial for the design definition of the functional requirements for each specific power system, the safety factors and the prospected tolerances.
Generally instead the information about the equipment parameters are generic and cautious.
During the life cycle of the system, the operational data offer essential information that allows perfecting and correcting the performances of the power system.

In conclusion, the operational management has to complement the system design and requires separating the comprehensive design of the system for both the phases of designing and of executing and for both the phases of validating and perfecting the same system against the loss service continuity during the faults or maintenance exigencies.

The standard ISO 22313 [33.s] applies the ‘Plan-Do-Check-Act’ (PDCA) cycle (Table 1) to planning, establishing, implementing, operating, monitoring, reviewing, maintaining and continually improving the effectiveness of a BCM.

Table 1. The comprehensive and permanent design**: e**xplanation of PDCA

Plan	Establish business continuity policy, objectives, targets, controls, processes and procedures relevant to improving business continuity in order to deliver results that align with the organization’s overall policies and objectives.
Do	Implement and operate the business continuity policy, controls, processes and procedures.
Check	Monitor and review performance against business continuity objectives and policy, report the results to management for review, and determine and authorize actions for remediation and improvement.
Act	Maintain and improve the BCMS by taking corrective actions, based on the results of management review and re-appraising the scope of the BCMS and business continuity policy and objectives.

Chapter 1.2

A Syntax and Semantics of a Language for Operational Procedures

Introduction: underlying theory and syntax for an operational language

Reliability and integrity of the power source guarantees continuity of the electrical system. During its life cycle an electrical power system and its parts will be switched by operational procedures for de-energizing the system (safety procedures) or for transfer among sources (integrity procedures) [3.s; 30.s]. Safety procedures involve several operating steps to isolate the safe working zone (SWZ), which is the zone of system (ZOS) that a maintenance operator (MO) has to make "safe to touch". Integrity procedures involve operating steps to transfer the system or its parts from one source to another. Switching transitions between configurations can be on a live-transfer (red) make-before-break or dead transfer (white) make-after-break, or combinations of different types at different speeds (fast transfer, slow transfer).

In fact, often additional power sources are necessary to improve reliability, sources that provide an alternative to the utility, sources such as local distributed generation. The electrical distribution architecture pertaining to power sources has a vital impact on power system integrity and operation throughout its lifecycle. The trend, toward distribution systems are evolving, is from the traditional vertically operated power systems into horizontally operated power systems.

Complete control of the system is necessary for all operating occurrences in an electrical power system, control based on a full understanding of system performance during such operations, particularly when they are complex. Probability theory shows that complexity increases the risk of chaotic phenomena and collisions ("collisions" draws a parallel with road traffic as described in the chapter 1.4) so complexity requires that the "safe sets" of operating procedures have to be identified out of all the probabilistic possibilities, selected and authorized. The distribution system needs to be active and intelligent: a language is needed for a natural micro approach.

The new approach offered is to structure a model of an operational language [22.p] based on genetic codes that generate and simulate the safe procedures for transitions, and only the safe procedures. Each system element has to be analyzed in its own characteristic behavior and the operation of each zone of the system ZOS has to be considered independently, one zone at a time. Finding practical methods to achieve the safety, however, is not always easy or obvious.

For a good design that addresses proper installation and operation, all the admissible sources sets and the related operating procedures must be identified, including contingency conditions. Studies of integrity procedures must consider the broad impact on the system, starting with load flow and short circuit analyses. Increased complexity of a system drives a need of semantics for clear definitions and of syntax for an operational language. This language must share the same base as that used for the underlying theory.

To analyze the dynamic operation of a complex system, the approach must be to consider the "status quo" at each step of the step-by-step development of the operating procedure, through every one of the "safe sets" involved. To analyze a switching transition, the zones of the system (ZOS) must be considered in turn, one at a time. Applying the procedure for each separate ZOS, its set will be progressively opened and repacked in the new set.

Basic definitions for components, devices and units

Loads that require high availability and integrity, like medical equipment of hospitals and data centers, are satisfied by system architecture that overcomes fault conditions through adopting more power sources, introducing adequate components, and by suitable configuration of the distribution system.
At this aim it is essential to identify some meanings basilar to be shared, structured and symbolized.

Components and equipment of an electrical power system are power source generators, source distributors or "ways", and loads that have to be identified by basic aspects useful to the system operation and the service continuity.

Power sources can play different roles in emergency or in transitions:

- Utilities commonly are source generator leaders that are reference of the synchronism and the sequence for the power system as for all the other supplied power systems.
- Engine-generator sets, uninterruptible power systems UPSs and batteries are local source generators that are flexible to be synchronized.
- Capacitors and asynchronous generators are considered as source followers.

Source distributors or "ways" are cables and conductors, transformers, switching means and switchboards, nodes and bus systems, etc.

Loads are motors, equipment, lights, etc..

In reference to the service continuity, the loads are source dependent or of short autonomy with rechargeable batteries, single corded (feeder) or dual corded (feeders). A single power supply (single-corded) for essential loads as in data centers introduces a weakness avoidable by equipment capable of dual input power feeds (i.e. dual-corded) that can be connected to the outputs of two independent power sources.

The *Zone Of System, ZOS*, is a component or portion of the system limited by terminal points or poles P that are the interfaces with the system. Commonly, *sources* and *loads* are ZOS with one pole P; *distributors* have two poles P; *nodes* N, potential source of energy, constituted by switchboards are special ZOS that generally include three or more poles P.

The *Working Zone, WZ,* is the ZOS that a maintenance operator MO must make "safe to touch".

The *Perfect Unit, PU* is the complete combination of devices or units that allows the MO to guarantee or to perfect the system portion ZOS as SWZ. Generally, the PU consists of one unit for each pole of the same ZOS.

Sources of energy. In a complex system many sources converge on a node N or on a ZOS hence it is mandatory for safe operation a preliminary analysis of their characteristics of independency or their capability to run in parallel and so belong to the same "family". In this case the parameters p & m, defined in the following, have to be designed complying with load flow and short circuit studies. The ground connection has to be considered a source.

Sources need a logic identification for their operation

V_x symbol of an *x* supply (positive) source, logic value is +1 identified as V_x , it needs a verifying signal of its presence, and of its sequence and phase angle if multiphase. The sources x are generally independent ones that can't run in parallel.

G symbol of the ground, logic value is -1, also identified as "negative" source or anti-source; opposite to every V_x, $G = -V_x$. The ground is a common source; all ground connections run always in parallel.

It is suggested the following symbolism for characteristic parameters:

- n sources converging on N or ZOS ($n \geq 1$)
- p groups of sources (family) among the n sources, able to run in parallel on N or ZOS ($p \leq n$).
- m sources among a same family: $m \geq 1$ members connectible simultaneously in parallel on N or ZOS ($m \leq p$).
- n-p independent single sources among the n-ones
- g ground connections - common source $g \geq 1$ defined at every operation; they are autonomous by the number n of sources and can be also $g \geq n$.

Switching Means SM: Each pole of a Zone Of System consists of a Switching Means SM, which may be manual equipment or a device, one or group, located in a node. A device generally has a moving arm that, primarily, connects-disconnects the moving contact. It has two sides: the node side and the line side. The moving contact is connected to the buses on the node side.

The SM can be characterized on the basis of their performances, constitution, status, and by their interface referred to the node side.

Performances: The Switching Means SM can be identified on the basis of performance in the operation or normal service of the WZ and for its safety (figure 1) by the combination of the operational components VS, CS, GVS, GCS:

CS The Current Switch is capable of interrupting power system current, typically a breaker. It is located on the line side.

VS The Voltage Switch interrupts or isolates power system voltage, typically a disconnect switch. It is located on the node side. In Europe it is absent in LV SM or present as draw-out set of CB (Fig. 2 LVCB-DO).

GS The Grounding Switch identifies the combination of the two manual equipment GVS,GCS. In Europe can be a single MV device that allows the grounding of the WZ. It is applied on the line side.

GCS The Grounding Current Switch is the connecting pole on the line side of a manual equipment.

GVS The Grounding Voltage Switch is the connecting pole on the ground side of a manual equipment.

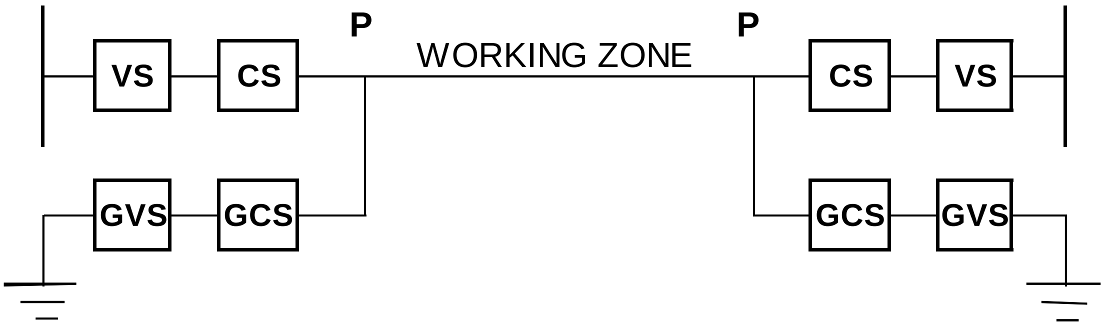


Figure 1. General case of the switching means, combination of VS,CS,GVS,GCS for each pole, that allow to energize, isolate and to ground the WZ

Constitution: The Switching Means SM can be identified on the basis of their constitution (an example is shown in figure 2):

IS Isolator Switch can have the combined duty of voltage-current switch (VS,CS) with or without a power fuse. In European practice it can also have integrated a grounding switch GS.

CB Circuit Breaker Unit capable of interrupting power system overcurrent

CB-BI Circuit Breaker Unit (CS) with a bus isolator (BI=VS) and a ground switch GS.

CB-DBI Circuit Breaker Unit with double bus isolator (Fig.2 doesn’t show the grounding switch that is present). This unit is a perfect unit PU for the CB as SWZ.

LVCB-DO Circuit Breaker in Draw-Out version.

BR The Bus Riser Unit is a complementary unit generally of CB-DBI. It is a direct connection between the line and the node buses. Carefully let’s note that it grounds the node if the line side is grounded

.

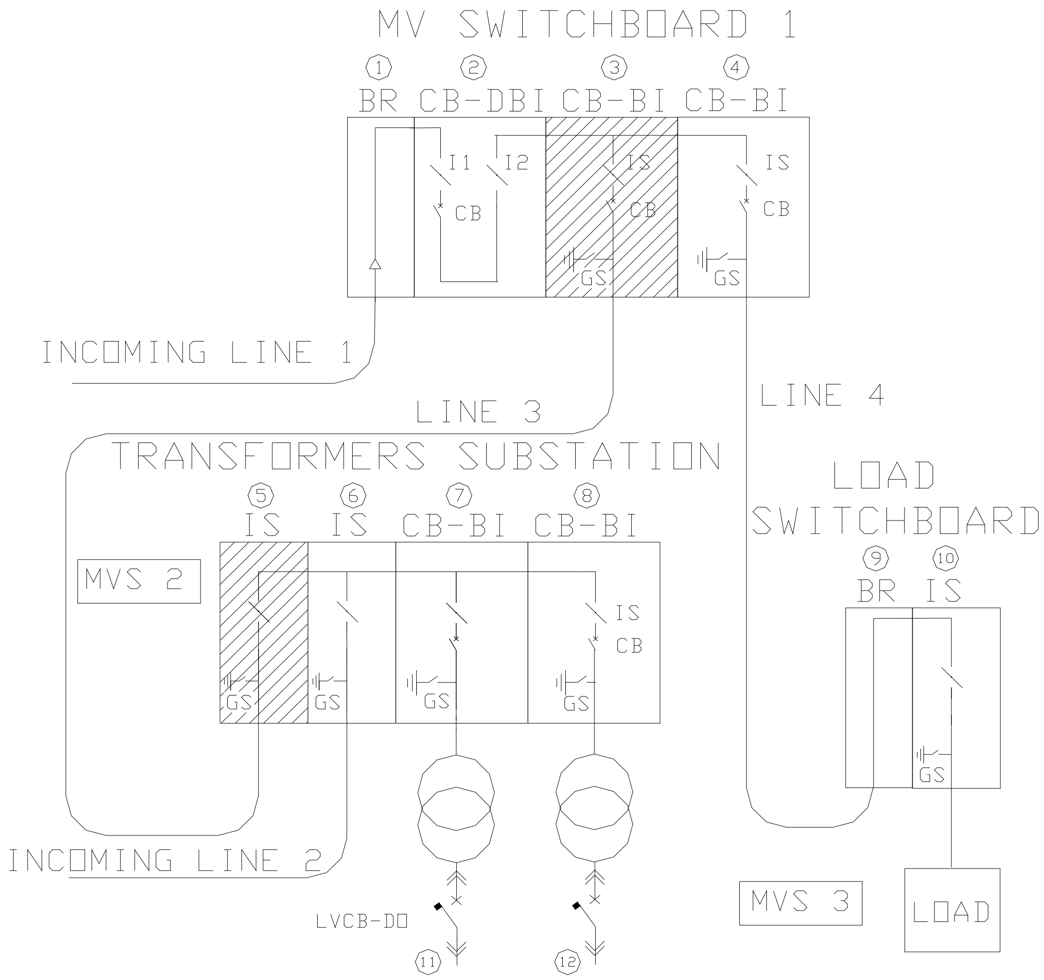


Figure 2. Electrical Substation: MV and LV Units with IEC/ EU/ symbols

Statuses: "Operational" mathematical symbols are introduced to define certain step-statuses in the procedures for energizing or de-energizing a node or a WZ of a system, operating on SM systems or SM combinations (i.e. IS-GS devices system of the load WZs in figure 2 and their procedure graphically presented in figure 3).

A "logic identification" can be attributed to the SMs statuses in their *wave-evolution* of operational transitions. The closed-ON/open-OFF/grounded-GON statuses SM[X], respectively for X=1, 0, -1 of the switching means SM, constitute the basic *three* signs/symbols in the language of the operational procedures (a *ternary code* with two binary reversible sequences, *wave-evolution*, 1 ↔ 0, 0 ↔ -1). Note that the ternary code 1, 0, -1 is necessary for safety procedures, the binary code 1, 0 is sufficient for integrity procedures.

The SM[X] statuses confirm the energized/open/ grounded statuses of the working zone WZ. For a simple WZ_i of one pole defined by a single device SM (IS) and supplied by a node N ($ID=V_x$), the logic ID that identifies the WZ_i statuses is obtained as product of the logic values:

$$logic\ (WZ_i) = SM_i\,[X]\ V_x \qquad (1)$$

For a WZ_i of two poles the logic ID WZ_i of the statuses is obtained as sum of logic contributes $SM_i \cdot V_x$ by all i-components of the SM system (VS,CS,GS for each pole) defining the WZ_i:

$$\text{logic}\ (WZ_i) = \Sigma_i\ SM_i[X]\ V_x \qquad (2)$$

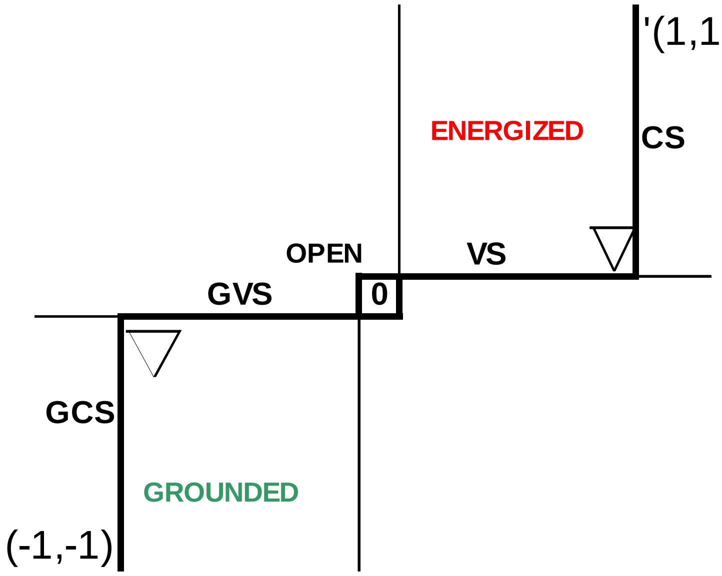


Figure 3. The electrical status space: the graphical representation of the operations on the combination of the switching means CS, VS, GVS and GCS

Commonly the WZs are vertically operated (supplied by a pole only) as well as the ring configurations are open.

The SM[X] statuses of its operational components (figure 4) can be defined by a logic identification ID, using logic values and colors:

+1 (R) "connected" condition, energized by a supplying source, "status one": logic value +1 (positive source); color Red. Plus (+) signifies energized.

+[1/m] "connected" condition, could be energized by a "m ≥1 connectible" sources: logic value +1/m for each connection ("can add m up to one"). It is essential to predetermine for source switches § because it is mandatory the authorization to the connection of m>1.

0(W) "open" condition or "status zero" or "reset status": logic value 0 of "neutral" sign; color White.

-1(G) "grounded" condition which is safe status, adverse to be energized: symbol G, logic value -1 (safety or negative source); color Green. Minus (-) signifies grounded.

-[1/g] "Grounded status" which could be provided by connections to ground-common source g ≥1 (and also g≥n): logic value -1/g for each connection. It is essential to know g : "must remove all g connections" to re-energize.

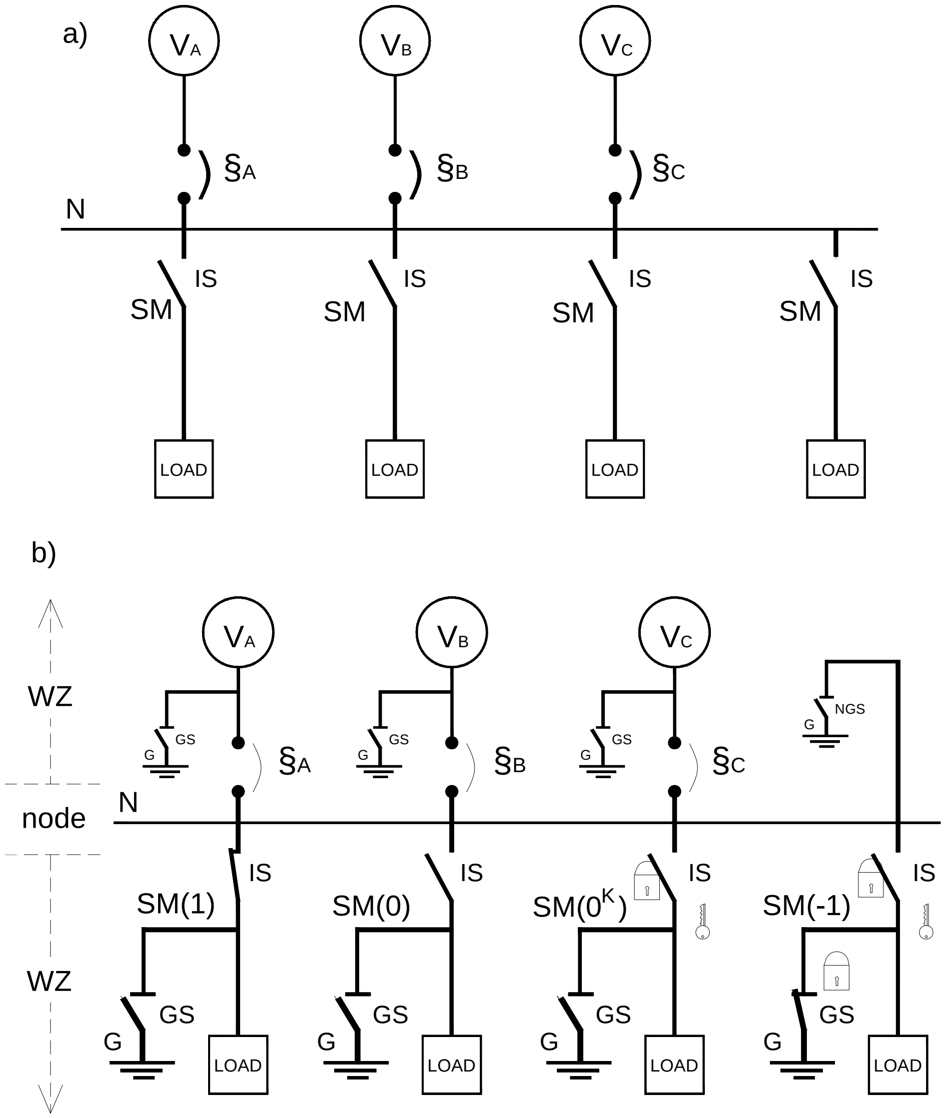


Figure 4. Basic electric node: the schemes adopt the IEEE symbol for the sources switch §, the IEC sources symbol for other switches; scheme a) shows a node N with three sources V_x; scheme b) shows the same node highlighting working zones WZs with switch means SM(X) in the statuses: connected 1, open 0, open locked ("packed") 0^k and grounded G having to be also locked

The operational language requires duplicating symbols for both the phases of executing and validating the same status X during a transition. It is essential to discriminate between the two aspects of the decision: a) selecting (or highlighting) a transition of a status, and b) the action of executing the change setting up a status comprising its verification.

For each status the syntax of the procedure requires a confirmation of the value from free to "packed" or locked.
So they can be introduced as operating logic values the X and X^a symbols:

X symbol X (=1,0,-1) shows a status free to be operated/changed;

X^a symbol X with a superscript shows a packed status, where “a” is the address-password of the transition step.

The X, without superscript, assumes a *local significance* and shows a status of a SM device, *free* and ready for activating its transition, like 1↔0 or 0↔-1.
A superscript ^{a} is a *pointer*, it highlights the status X in a *packed* condition of selected/tested status.

X^a is a *packed logic value*, dual of X, it has a *contextual significance* in a global procedure that is each step-status of a SM device has be *found* packed before operation and *left* packed after.
The superscript gives three levels of information about the packed value of the SM status as:

- “visually controlled”, symbol *a* = v, logic supervision confirmed by light signal or by the operator watching the SM contact directly;
- “instructions", symbol *a* = i, on the rule of operating step;
- “locked”, symbol *a* = k, shows the “key” that locks the status and could work as address instruction for next step. Note that $+1^a$ is a packed status where *a*=v or i: the *a*=k locked applies only for switch means like auxiliary voltage switches VS and tie switches T.

In conclusion, in the operational language the logic values of the statuses SM($+1^a$,+1,0,0^a;0,-1,-1^a) or SM($+1/m^a$,+1/m,0,0^a;0,-1/g,$-1/g^a$) constitute the *scale of sets* and the *declension* of the same SM or the SM combination, highlighting the active local transition on a SM device and the context of the entire *wave-evolution* of WZ operation (1↔0, 0↔-1) (Table 1).

Table 1. List of operations in the logic code for each pole of WZ of figure 1 represented graphically in figure 3. The superscript “a” addresses + to + (VS-CS) and – to – (GVS-GCS); 0Σ signifies all (Σ) means open (0); S is safe locked

Each pole of a working zone				
status	VS	CS	GVS	GCS
X^a	1^+		$0^{0\Sigma}$	0^-
X	1	1	0	0
	0	0	-1	-1
X^a	$0^{0\Sigma}$	0^+	-1^-	-1^S
a	+, Σ	+	Σ, -	-,S

Interface: The SM can be characterized on the basis of interface referred to the node side and the following symbols are suggested:

- SM a Switching Means of a node N or ZOS, is generically a load switch SM, if it energizes the load/line.and does not energize the node (SM←N) or ground the same node;
- § source switch of a node N or ZOS, is a switch means in which CS or IS provides or contributes energy to it (SM→N) (figure 4). Note that correctly, a proper source switch NGS has to provide or contribute to ground the node (NGS in figure 4).

- T tie switch operates a horizontal electrical connection between two nodes. It is a single switch or a pair linked by a connector, between two nodes or two sections of the same node, that could be alternatively a source switch § or a load switch SM for each of the connected nodes (SM↔N, cautiously §).
- Bond bond is an operational rule/link to avoid collisions/conflicts; it is expressed by a superscript in operational mathematical symbols. The bond is always logic for all means. For the devices, it could be a bond made by a mechanical locks.

Operation and safety bonds: a short summary

Both the operation of making "safe" a multiple-pole WZ and the operation on a complex node energized by multiple sources are worked by SM systems and by many source switches § respectively.

Considering the simple case of figure 4, for each load/pole of WZ_i, the logic ID that is of the scale of possible configurations (*sets wave*) of SM_i combinations is evaluated using equation (2):

$$logic(WZ_i)=VS_i[X]\cdot V_x+CS_i[X]\cdot V_x+GS[X]\cdot V_x \qquad (3)$$

Analogously for the node N of figure 4 with m>1, the logic ID of the *sets wave* of multiple $§_x$ is evaluated using equation (2) highlighting the connected statuses to be authorized 1/m

$$logic\ (N) = \Sigma_x\ §_x\ [+(1/m)^a,+(1/m),0,0^a]\cdot V_x \qquad (4)$$

Note that GS components don't operate on the node side. The evaluation of the two expressions (3) and (4) can be defined as products between matrixes of the switching means status values and the vector(s) of the ID V_x values.

Risk assessment evaluates hazards and conflicts in the operation of electrical installations. Procedures are needed to confirm that the operation is safe and functionally acceptable and to avoid collisions following all *waves of possible sets*. Some possible sets are destructive for the power system and dangerous for the operators, consequently, the sets waves for the operations on WZs and on nodes have to accept only *waves of safe sets* to guarantee the survival of operators and of the system [18.p].

Chapter 1.3

Architecture Impact on Integrity of Electrical Installations: Cut&Tie Rule, Ring Configuration, Floating Node

Symbols and definitions

The symbols in the figures and in the text are already discussed in the chapter 1.2 and proposed again below:

ZOS Zone Of System, component or portion of the system: *sources, loads*, *distributors* and *nodes* N

N Node

WZ Working Zone, ZOS that has to be made safe to touch for working on

SM Switching Means of a node N or ZOS, generically *load switch* SM, that does not energize (SM←N), or ground it

§ *Source switch* of a node N or ZOS, switch that provides or contributes to energize or to ground it (SM→N)

T *Tie switch,* single switch or couple linked by connector, between two nodes or two sections of the same node, that could be alternatively a source switch or a load switch for each one of the connected nodes (SM↔N, cautiously §)

n Sources converging on N or ZOS (n≥1)

p Sources group (family) among the n-ones, able to run in parallel on N or ZOS (p≤n)

m Sources among a same family connectible simultaneously in parallel on N or ZOS (m≤p)

n-p Independent single sources among the n-ones

Bond Operational link that is logic for all means: for the devices, it could be made a bond by mechanical lock

Introduction on the system architecture

System equipment and power sources

As has already been highlighted, the high availability and integrity requirement of all the loads, or part of them, is satisfied by means of a system architecture that allows overcoming fault conditions: adopting more power sources, introducing adequate components and modeling suitably the configuration of the distribution system. To face contingency conditions, such as the loss of a generator, a transmission line, a transformer, or a load, the level of complexity of an electrical system increases with the inclusion of more main sources, available for a simultaneous service, and/or alternate service, stand-by and emergency sources, as well as with the diverse applications of varying switch-able configurations [27.s].

The electrical system equipment, components of an electrical power system, are:

- *sources generators* (*leaders: general* as utilities, *local* as engine-generator sets, UPSs, batteries; *followers* as capacitors, asynchronous generators);
- *sources distributors or "ways"(*cables and conductors, transformers, nodes and busses systems, switchboards with "Loss of Service Continuity" classification in HV/MV systems and with different forms in LV systems, switching means fixed or in draw out version, etc.) [20.s; 11.s];
- loads (motors, equipment, lights, etc.; source-dependent-loads or source-independent-loads with rechargeable battery; equipment single or dual corded, available to a single or double supply respectively).

The sources can play different roles in emergency or in transitions:

- they can be common sources, as public electrical sources that have to maintain a coherence of behavior for all the supplied users (system voltage, phase angle and frequency in a.c.);
- they can be local sources, as engine generators EGs or UPSs that can have a flexible coherence of behavior to satisfy the local user, useful for the shuttle mission introduced in the following.

A single power supply (single-corded) for essential loads as in data centers introduces a weakness into an otherwise highly available installation. This shortcoming can be avoided by equipment capable of dual input power feeds (i.e. dual-corded) that can be connected to the outputs of two independent power sources. If one cord/supply fails, equipment operates automatically a transition, in fact the total load is instantly picked up by the other supply, provided it has the capacity to handle the total load. In the standard IEC 62271-200 [20.s] the classification LSC1,2a,2b of loss service continuity for HV switchgear and controlgear is based on the ability to maintain some level of service continuity with customer supply whilst a compartment is accessed. For the same purpose, the IEC 60439-1 [11.s] suggests different forms (1, 2a-b, 3a-b, 4a-b) of internal separation in LV switchboard assemblies by barriers or partitions.

All possible sources sets of a power system are related to its architecture and to the energized statuses of its nodes and its zones (ZOS).
The presence of generators can be decided to reduce the energy bill or due to the opportunity for co-generation. The presence of back-up generators is essential if the loads cannot be shed for a long duration (interruption are acceptable) and the utility network availability is low. The simultaneous presence of back-up generators and UPS units is used for permanently supply loads for which no failure is acceptable.
UPS units are also used to supply power to loads that are sensitive to disturbances (generating a "clean" voltage that is independent of the network).
Let's analyze the operability of the sources converging on a node.
Each source has to be identified by an ID logic symbol or letter: two or more sources are shown equal if they can be connected together.

Each source is characterized by:

- the voltage and frequency values,
- the sequence if multi-phase,
- the neutral status (TT-, TN-, IT- systems), if the neutral conductor is distributed,
- the control signal communicating outside the actual status.

Generally the sources switches have to disconnect the neutral conductor when it is distributed. The disconnection is opportune for operators of maintenance and it is necessary in the cases of more and independent sources.
Among the *n* sources converging on a node N or on a zone of the system ZOS, if *p*-sources ($2\leq p\leq n$) are able to parallel (*p-sources group of a same family ID*), generally *m-members* ($m\leq p$) are connectible simultaneously in parallel, provided that the power system is sized at these intersections to comply with load flow and short circuit studies. In other words, following the initial studies, all the prospective sources sets need the validation by the short circuits and the load flow analysis.

Classification of switching means and of system nodes

Let's analyze the rule played by switching means in the operation of a power system architecture.
The switching means of the nodes N or of the ZOSs are basically *source switches* §, *load switches and tie switches.*
For the statuses of each node N or ZOS, it is always essential to operate on its *source switches* §.
On the other hand, *load switch* of a node N or ZOS, generically SM, are the switches on that the operation does not alter the status of the node.
The *tie switch*, T can be alternatively a source switch or a load switch for each one of the connected nodes. It has to be cautiously considered a source switch.
To analyze the sources sets of a power system, the benchmark nodes are the *sources nodes* on which two or more sources converge by two or more sources switches, these have to be studied.
The other nodes are generally definable *loads nodes,* that switching only affects their energization.

A *floating node* (Figure 1) is a node supplied by two or more tie switches on dependence of the connected sources nodes. The floating node can reenergize each sources node when its source is in failure.

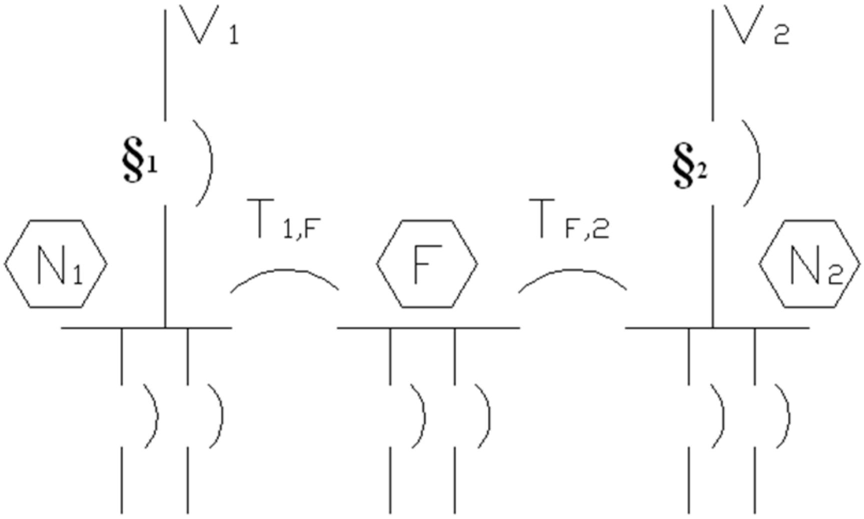


Figure 1. Floating node F: tie switches $T_{1,F}$ and $T_{F,2}$ between two sources nodes N_1 and N_2 (IEEE symbols)

System and operational system: free sets and authorized sets

The architecture of a power system can be configured in increasing complexity related to the exigencies of the power system, taking actions on the sources and on the configuration [49.p]. The architecture has to be designed and programmed evolving from *free sets* to *authorized sets* in consideration of the compatibility between the sources and the validation by the short circuits and the load flow analysis.
The architectural measures can be resumed in:

- Actions on the distribution levels from supply to the loads organizing a configuration of a *radial service* of load nodes (*free sets*)
- Actions on the redundancy of the supply adopting two or multiple ended configuration (like MV Switchboard shown in Figure 2), designing sources nodes energized by two or multiple sources, operating separately (exclusivity rule) [44.p],
- Actions on the redundancy of the distributors adopting *two or multiple poles configuration*, designing sources nodes energized by *two or multiple distributors-ways*, operating simultaneously (same family or same source) (as Main LV Switchboard shown in Figure 2) [44.p],
- Actions mixed on the *distributors and sources* adopting the criterion of partitioning and making redundant, *the cut & tie rule.* A sources node can be subdivided in more sections of the same distribution level, interconnected like a *ring/network* by tie switches. So the T switches generate an united system of more sources nodes and can add also floating nodes.

The redundancy can be:

- total: each element, source/distributor/transformer, being capable of supplying all of the installation,

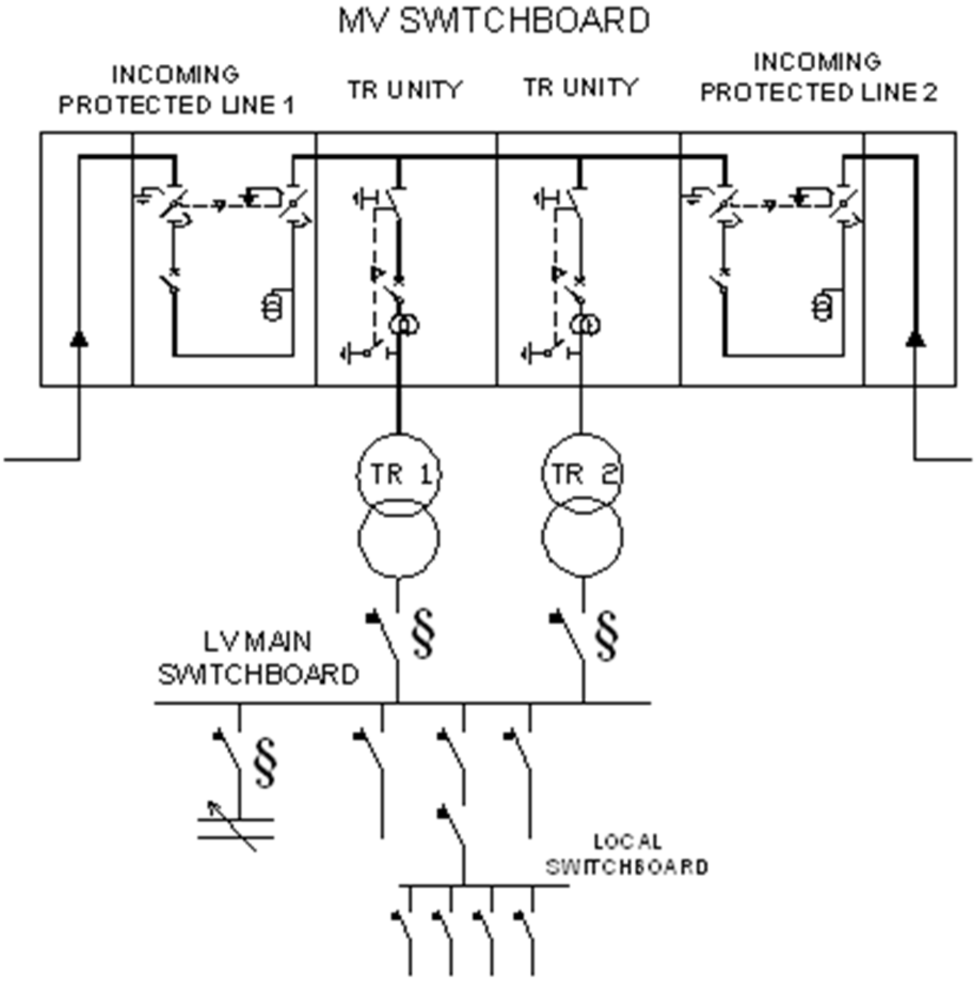


Figure 2. Actions on the redundancy: a MV Switchboard energized by two sources, operating separately (exclusivity rule), a Main LV Switchboard energized by two ways, operating simultaneously (same source)

- partial: each element only being able to supply part of the installation.

In the latter case, part of the loads must be disconnected (load-shedding) in the case of one of the elements failing.

An *automatic transfer switch* (ATS) is used to avoid the sources being parallel connected [27.s; 44.p].
For manual operation it is possible adopt two keys bonded by one ring or by one block. This configuration allows preventive and curative maintenance to be carried out on all of the electrical distribution system upstream without interrupting the power supply.

In conclusion, a complex architecture of a power system has to be programmed and it can be organized as rings/networks of nodes. In fact, the operation of the sources is not free, but requires authorization (*authorized sets*).
The operations are guided by constraints that interlink and interconnect themselves in a correct and structured sequence constituting each procedure.

Basic instructions of the statuses of a node or a ZOS in the operational procedures, as previously mentioned in chapter 1.1, are founded on the rules of:

- exclusivity,
- priority,
- parity.

that guide the step-statuses and define their constraints or bonds like logic "genes".
These instructions apply to the operation of each switch means of the node: they consider for the integrity the statuses of ON and OFF, both free and locked. Note that:

- the status locked ON in general doesn't apply, but it's possible for auxiliary switch means like voltage switches and tie switches;
- the statuses of connected to ground (GON), both free and locked, have to be considered in addition for safety.

The sources exclusivity defines a characteristic of a ZOS, node or WZ, with different admissible Energizing Statuses. Single source exclusivity or multiple sources family can determine the energized status of the node or the ZOS, from one-way or from multiple-ways (*m-members*) respectively.
The ground has to be considered as a source, so that the operation on a load node requires a safety procedure if it needs to be grounded.
The operation on a sources node requires integrity procedures also for transitions from a source to another. The switching over between configurations could be on a live-transfer (make-before-break) or dead transfer (make-after-break) or combinations of different types at different speeds (fast transfer, slow transfer).

A. Exclusivity rule and sources node: standby service and sources family.

In a *node of n- sources* in the general case of n-p single independent sources and a p group of a sources family, for live service the exclusivity rule imposes the *ExOR condition*:

- *one only of independent sources* among the n-p ones can be connected on the node and the other *n-1 sources* have to remain standby, not connected (*in a same node n-1 sources switches must remain open*).
- up to *m sources* among the p ones of the group can be connected on the node and at least the other *n-m sources* have to remain standby, not connected (*at least n-m sources switches must remain open*).

A.1 Dead transfer or white transfer. For changing service from a source to another of the n-p ones the priority requires to make the transition crossing before the NOR condition (*all n sources open*).

A.2 Live transfer or red transfer. For changing service the transition is free from a source to another of a group of p sources of a same family up to the m members, the priority requires before *at least n-m+1 sources open*. The logic connective is m-AND that is the possibility of adding from 2 sources up to m ones of the family.

Let's consider, as sample case, a node with n=4 sources of which a group of p=3 MV/LV transformers are able to the parallel, but only m=2 connectible simultaneously on the node. The fourth source is an independent engine generator-set.
A live transfer is always possible connecting a second transformer on the node; for turning the third transformer, it is mandatory disconnecting before one of the connected couple. For connecting the back-up generator, it is mandatory to make the transition crossing before the NOR condition of all n=4 sources disconnected.

B. Exclusivity rule and united sources nodes: simultaneous service in the power system

In a complex system with more sources, the introduction of tie switches allows system configurations of united sources nodes, like an unique sources node partitioned in sections of the same level, influencing the derived distribution level. These are the cases of interconnected nodes of main sources with or without addition of floating nodes (Fig.1).
In each section of a partitioned sources node, the connecting tie switches concur in the application of the exclusivity rule. The Figure 1 shows a node partitioned in three sections: $\S_1$-T_{1F},T_{1F} -T_{F2}, T_{F2} -$\S_2$. Let's note that each tie switch T appears and counts two times: section 1, if $\S_1$ is closed T_{1F} is open, section F, if T_{1F} is closed T_{F2} is open, section 2, if T_{F2} is open $\S_2$ is closed. Then, a ring of floating nodes, normally operated open between two sources nodes, requires that all ties switches or couples of ties switches T and the n=2 source switches can remain closed except one (*in a same ring of nodes, n+T-1 switches have to remain closed*).

A system of united nodes allows system sets with a simultaneous service of more sources in the power system. In fact, it allows maintaining connected simultaneously at least one source converging on each separated section, offering the advantages of this configuration.
About the influence on the derived distribution level, note that the closed status of a tie switch, connecting two node sections (MV N1 and N2 in Figure 3) in a same node, converts a double ended derived system in a two pole power supply of the same source or of the same family (LV N3 and N4 in Figure 3).

C. Exclusivity rule and sources node: logic link and mechanical bond for the operation

The logic condition ExOR of the exclusivity rule that imposes one source only connected on a node, can be applied like a mechanical bond of a single ring collecting together all the keys locking in open status the n source switches of the node, in the cases when the sources are independent single (not connectible in parallel).
In a case of n =3 sources (m = 1), the single keys ring (Figure 4) imposes in the transitions from a source to another the priority and parity rules. The single ring can be substituted by a portable locks block of captured keys, that are all the above mentioned keys (Figure 4).

For manual operation of an automatic transfer system (ATS) constituted by two source switches A, B and a tie switch T (as showed before in Fig. 3), it is possible to adopt two rings, one with the keys A and T and the other one with B and T keys (note: two keys are available for the same T switch).

In the cases when the sources of a family able to parallel are p and the sources connectible simultaneously in parallel are $m \leq p$, the p keys locking in open status the p source switches are needed to be simultaneously captured by a portable locks block to make free the ring of the n-p keys of independent sources.

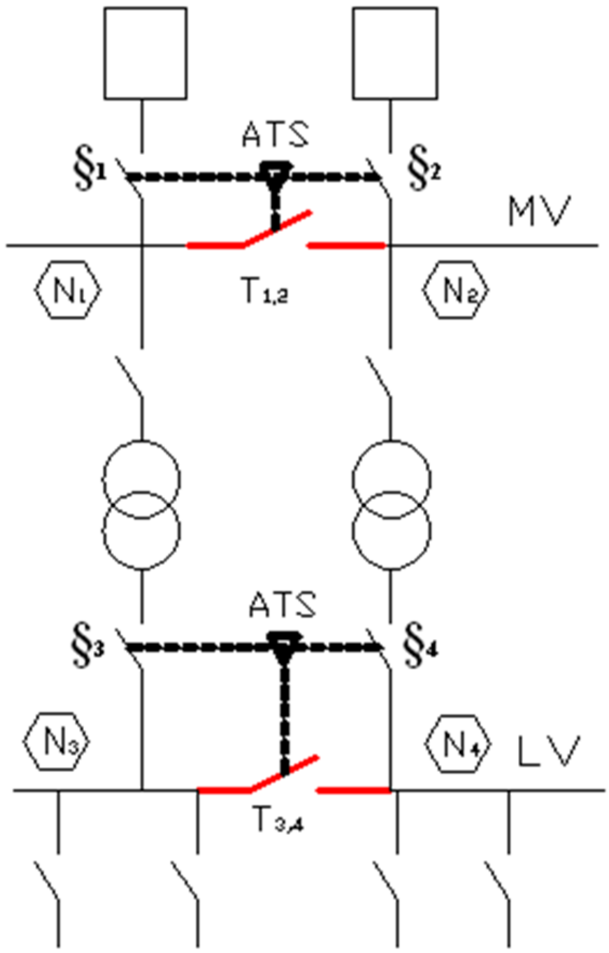


Figure 3. Tie switches and influence on the derived distribution level: the MV ATS converts the double ended system LV ATS in a two poles system and can get free the tie switch $T_{3,4}$

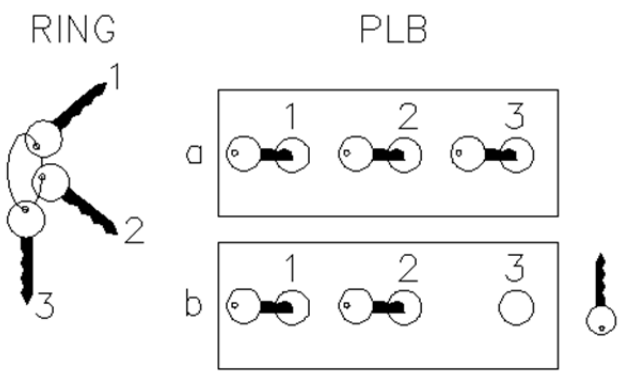


Figure 4. A ring of captured keys, i.e., m=1, for three poles, allows to use one key only. The equivalent Portable Locks Block PLB requires all the three keys captured (a) (all switches open = parity condition) before to release one (b)

To operate m switches of the p ones able to parallel adopting a portable locks block occurs at least p-m source switches have to be locked together with the ring of n-p keys. For changing a source of all active m-ones, p-m+1 switches are needed to be simultaneously captured to make free releasing only one of them. Also a solution adopting a unique portable locks block can be available.

For the logic link, the tie switches play a role equivalent to the source switches in the exclusivity bonds.
The closed status of a tie switch connecting two node sections in an unique node can influence the conversion of a double ended system at derived level in a two pole power supply. So, the locking key of the tie (MV $T_{1,2}$ of Figure 3) can contribute to authorize the same sources family for the distributors derived by the interconnected node sections (LV N_3 and N_4 getting free the tie switch $T_{3,4}$). Mechanically the locking key of the MV tie $T_{1,2}$ of Figure 3 can be ringed with a copy of the key locking open the LV $T_{3,4}$.

Operating factors and considerations

The design requirements and operational specifications have to be well defined and of major detail to "as built, as operated, as maintained", achieved at its commissioning and successively in design revisions, using the experimental operating data. The fitted architecture is often expressed in terms of seeking a compromise for the various performances at different phases in its lifecycle.
Take note that the designer needs to evaluate at least the worst cases; the operator has to study all admissible conditions of sources sets.
To verify the suitability of the power system components, each case must be analyzed by load flow and short circuit studies to prevent operation that could cause overcurrents, equipment overloads or poor voltage levels.
The design documentation has to provide in a whole way the most complete information about the decisions and choices, the general criteria complying with the standards and the functional requirements for the specific power system, the assumed safety factors and the prospected tolerances.
The information level is a crucial index of definition and accuracy that allows verifying the compliance with the prospected requirements. During the life cycle of the system, the operational data offer adequate information that allows improving and correcting the performance of the power system with iterative design revisions for rehabilitation, expansion and modernization.
The earlier we search for solutions, the more optimization possibilities exist.
All the admissible sources shall be defined, under different contingency conditions. In each maintenance/operation procedure all the sources and the main switching means must be defined in each area or working zone.
All the admissible sources sets and the related integrity procedures have to be defined, including contingency conditions, such as the loss of a generator, a transmission line, a transformer, or a load [36.s].

MV and LV configurations

The main configurations for possible connection are as follows [25.s; 27.s; 44.p]:

- for MV service: single-line service, ring-main service, duplicate supply service, duplicate supply service with double busbar;

- for MV/LV distribution sets: single feeder, one or several transformers; open ring, one MV incomer; open ring, two MV incomers.

Closed-ring set generally is not taken into account.

Let's analyze shortly some considerations on the main possible configurations.

- Radial single feeder configuration: this is the reference configuration and the most simple. The load is connected to only one single source.
- Two-pole configuration: the power supply is provided by two transformers, connected to the same MV line. When the transformers are close, they are generally connected in parallel to the same MLVS (Main Low Voltage Switchboard).
- Sheddable switchboard (simple disconnectable attachment): a series of sheddable circuits can be connected to a dedicated switchboard. The connection to the MLVS is interrupted when needed (overload, generator operation, etc)
- Interconnected switchboards: if transformers are physically distant from one another, they may be connected by a busbar trunking. A critical load can be supplied by one or other of the transformers.
- Ring configuration: this configuration can be considered as an extension of the configuration with interconnection between switchboards. This configuration requires special design of the protection plan in order to ensure discrimination in all of the fault circumstances. Normally the ring configuration is operated open.
- Double ended (sources A and B) power supply: this configuration is implemented in cases where maximum availability is required. The principle involves having two independent power sources, e.g.:
    - two transformers supplied by different MV lines,
    - one transformer and one generator,
    - one transformer and one UPS.
- Cut & tie rule: double ended with two ½ MLVS: it is possible to cut or split the MLVS into two parts, with a normally open link (T tie), in order to increase the availability in case of failure of the busbars or authorize maintenance on one of the transformers. This configuration can adopt an Automatic Transfer System, (ATS).
- Triple (or multiple) ended (sources A, B and C) power supply: for the triple ended power supply an automatic transfer system (ATS) with three switches is used to avoid the sources being parallel connected. For manual operation it is possible to adopt three keys bonded by one ring or by one block.

In conclusion, each installation is generally made up of a configurations combination that is of several sub-assemblies with different configurations, according to requirements for the availability of the different types of load (Figure 5).

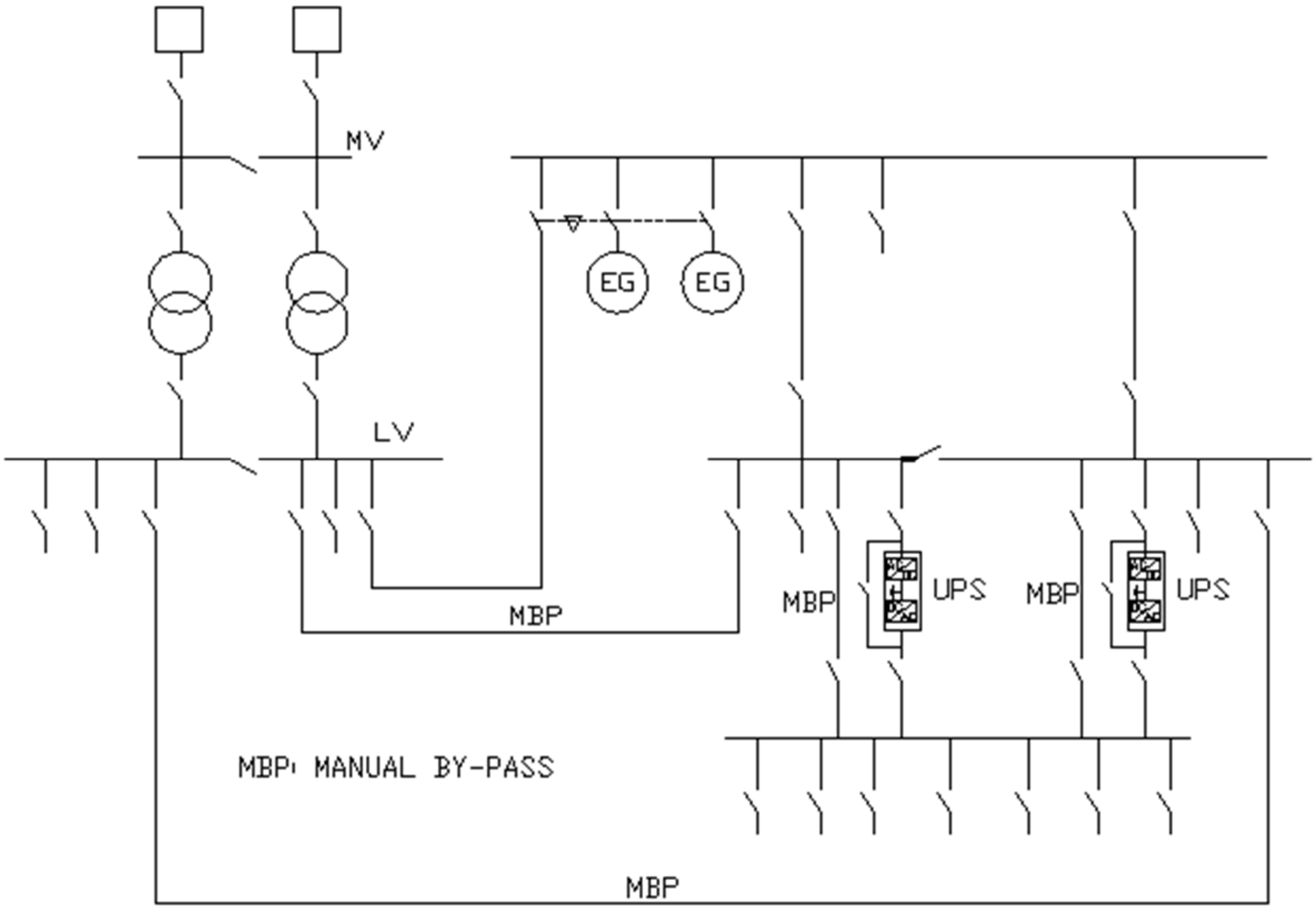


Figure 5. Configurations combination: all admissible sources sets and the related integrity procedures have to be defined (IEC symbols)

Chapter 1.4

Transitions Theory in Operation of Electrical Installations

Introduction: the micro-systemic approach

Requirements of high availability and integrity of mission critical loads, like medical equipment of hospitals and data centers, are satisfied by appropriate system architecture for the electrical distribution.
Architecture has a vital impact on installation performance throughout its lifecycle.
To survive contingency conditions such as the loss of a generator, a transmission line, a transformer, or a load, the level of an electrical system's complexity will be increased by the inclusion of more main supplies and alternate sources, by stand-by and emergency sources, as well as by the several applications of varying switchable configurations (see chapter 1.3). Business continuity and mission critical applications require evidently higher costs and lower efficiency.

Risk assessment for safety and service continuity evaluates the hazards and fosters adequate precautions in the operation of electrical installations. In electrical installations power supply interruptions and/or interruption of safety services are one of several hazards that may arise [7.s].
The fundamental rule for safe survival of the system is to avoid switching conflicts: software programs must follow safe transitions complying with instructions selected among all the probable options (authorized sets) [18.p; 22.p].
Each system intersection/node for live (energized) service presents an intrinsic logic in relation to the way it is constituted, described by the instructions founded on the three operating rules of *exclusivity, priority and parity* avoiding collisions (see chapter 1.3).
Equipment such as automatic transfer switches, also assisted by engine generators and UPSs, allow to apply the operational procedures in a micro-systemic approach founded on the coordination of the nodes/intersections.

A kinematics analogy between masses in spatial motion and electrical events in time (waves) can offer a general way for studying conflicts in the intersections, preventing hazards. A collision is an event in which two or more elements have the same intersection point at the same time (same action, space and time).
Considering the components of an electrical hazard as elements in motion, two kinds of "collisions" risk affect the events evolution in safety analysis and the programs for service continuity.
The colliding elements could be different sources of the electrical system convergent in a same node.
To enhance service continuity in a designed power system, the operation must be programmed and controlled and not random.

Integrity in electrical operations: analogy between multiple traffic lanes and multiple electrical sources

Intersections of multiple traffic lanes present an analogy with the operation of nodes of electrical power systems, offering an equivalent and familiar way for examining constraints in the transitions and facilitating the understanding of the mathematical description. Each flow direction may be designed with single or multiple traffic lanes that allow the simultaneous passage of single or multiple rows of vehicles.

To avoid interferences or collisions among the vehicles on the roads and analogously among multiple power sources available for a power system, the general criterion is authorizing *exclusively* single path or parallel paths of synchronized/equivalent status (*same sources family)*.

Electrical sources are of the same family by definition if they have the capability to run in parallel.

Architecture of road/electrical systems may be designed with a single or multiple structures that allow the simultaneous operation of single or multiple parallel vectors of a *same family*. Opportunely organized, the architecture will project its program and take actions on the sources.

Briefly, the architectural measures can be applied in actions:

- on the distribution levels,
- on total or partial redundancy of the distributors and of the supplies,
- adopting the criterion of partitioning and making redundant, *the cut & tie rule*, introducing ring configuration and floating nodes (*alternative independent ways*) (as already showed in chapter 1.3).

A sources node can be subdivided in more sections of the same distribution level, each one interconnected like a ring/network by a tie switch or better by a couple of tie switches (dashed lines). So that the T switches generate a united system of more sources nodes and can add also floating nodes, supplied by the same T switches.

The architecture of a mission critical power system has to guarantee service continuity. In case of failure, part of the loads must be disconnected (load-shedding) if necessary, and further, the time to repair the components has to be compatible to avoid the loss service continuity. At this aim, the switches are recommendable in a draw out version and in addition the tie switches in couples.

For data centers special standards [39.s; 50.p] establish four distinctive definitions of site infrastructure tier classifications (as will be argued better in the chapter 2.1):

- tier I, basic capacity;
- tier II, redundant capacity components;
- tier III, concurrently maintainable;
- tier IV, fault tolerant.

Tier I and tier II configurations are simple and direct with no redundancy or single distribution path with redundant components. Tier III and tier IV configurations are increasing complex with multiple distribution paths, concurrent maintainability and multiple active paths [47.p].

The complex architecture of a power system has to be designed and programmed, not left to chance. The operation of the sources switches (symbol § in the figures, as already defined in chapter 1.2) is not free, but requires authorization (*authorized sets*).
To allow vehicles to avoid conflicts while changing lanes or roads, various kinds of junctions are organized as common areas to the intersecting roads, such as grade or staggered intersections or cloverleaves.
A junction among more arms of roads is equivalent to a node among more convergent sources (figure 1).

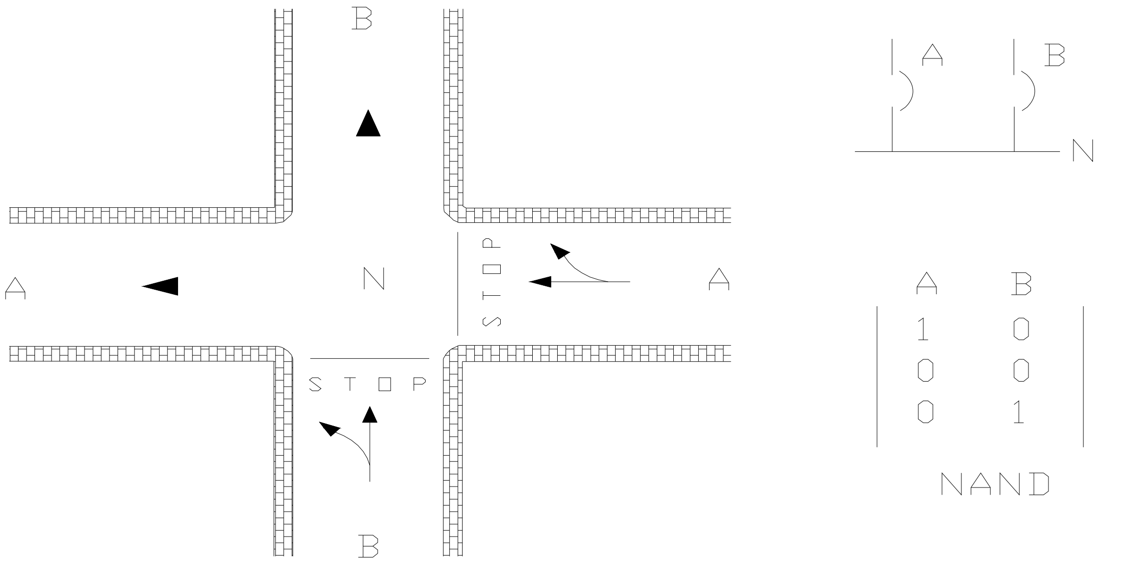


Figure 1. Crossing junction N and analogous electrical node N: a traffic light is equivalent to an ATS for an automatic operation of NAND

Grade intersections (junctions at road level) are organized with a traffic light procedure to allow vehicles entering it to continue their course or change road by a dead transfer or *white transition* with:

- the *priority* rule to decelerate, operated also by traffic lights and providing *deceleration* and acceleration lanes,
- imposing the parity condition of stopping to them and giving way.

Results of measures to avoid collisions always remain probabilistic, nevertheless the measures provide a basic criterion for impeding and diverting any collision into a safer space-time, sufficient to satisfy a *generalized parallelism*. The generalized parallelism is characterized by all the actions promoting and allowing a no-collision that could be:

- *time based (fast or slow stop)*: avoiding simultaneity of the crossing on the intersection as organizing a *traffic light procedure* or a longer time with an internal rotational motion (roundabout);

- *space based (additional element/shuttle)*: avoiding not parallel trajectories in the same space, that is, avoiding the conflict in the intersection point as organizing linear grade (height) separation of the crossing point, or as offering additional crossing trajectory with grade separation for an external rotational motion (*independence).*

The traffic control analogy, presented to facilitate the understanding of the logic and mathematical description, lends itself particularly well to single or multiple ATSs operations. In electrical power systems an *automatic transfer switch* (ATS), as a *traffic light*, based on the NAND logic (figure 1), is used as basic equipment to avoid the sources being connected in parallel, if it is not admissible (figure 2).

Really, there are two main types of transfer switches used as source selectors:

- electro-mechanical (ATS)
- static (STS).

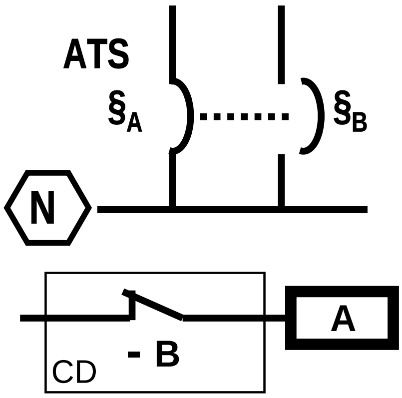


Figure 2. ATS conditioner CD: $§_A$, $§_B$ source switches have auxiliary contacts that are in inverse status (NOT) of the main ones; i.e. command signal to close $§_A$ is active only if $§_B$ is opened that is aux –B or NOT B is closed

To allow transitions needed for changing road/direction or electrical source in cases of maintenance, operation or fault, a junction or node of convergence has to be designed. The transition can be operated adopting an ATS from the main source to an alternative source:

- by a *live transfer* if the alternative source is coherent/parallel *(same family)*,

- by a *dead transfer* imposing the stop/black out (fast or slow) on the junction/node,

- by an *interchange live transfer* that is a live temporary transfer assisted by a local “shuttle” source (UPS, EG).

Interchange transfer

High availability installations use a power system architecture at least providing dual power paths to the critical loads. In this way the equipment can continue to operate with a failure at any point in either power path. To meet this goal the characteristics of the critical loads are relevant: source-dependent-loads or source-independent-loads, equipment single corded or dual corded.

Considering the kinematics analogy, a roundabout is a type of road junction where traffic enters as a one-way stream around a central island: following the general rule of a common direction each vehicle makes its individual choice by itself. All vehicles circulate around the central island in the same direction and *individually* choose their new direction/sense. For an analogy with a roundabout and the conflict for each vehicle among the four sense options of figure 3, an electrical equivalent intersection could be a node supplying a UPS by an ATS for the automatic transition between the two sources A and B.

The loads have guaranteed a supplying autonomy: the UPS, like a *shuttle,* guarantees a live temporary transfer (*interchange transfer*) for its loads sustaining the dead transfer operated by the ATS between the sources A and B.

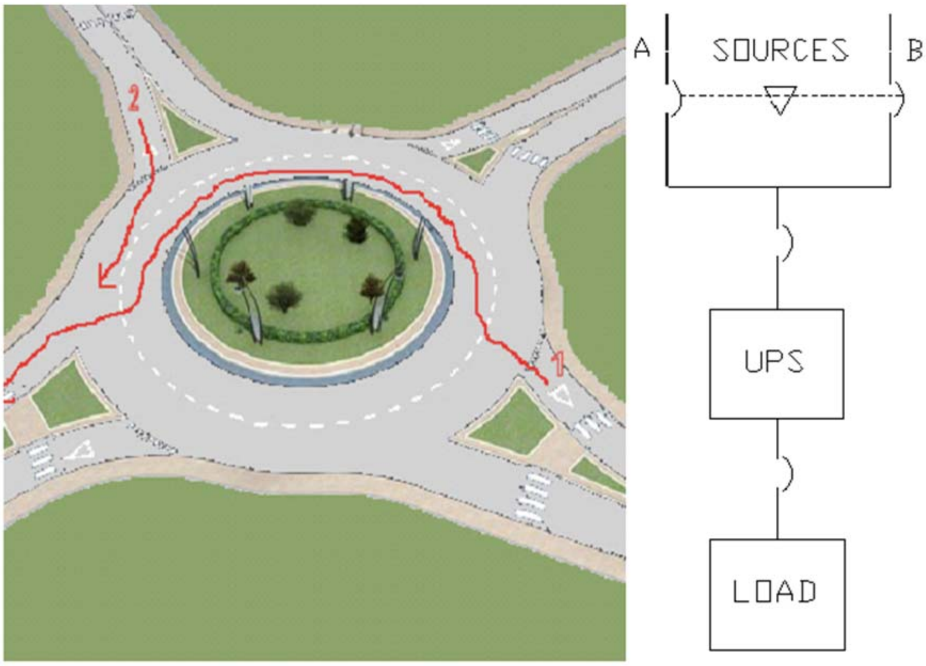


Figure 3. Roundabout and analogous electrical node

Cloverleaves and interchanges as junction systems of roads placed at overlapped levels are organized to facilitate transition from a road to another without imposing a stop but doing by a live transfer or *red transition.* For an analogy with a cloverleaf and the conflict for each vehicle (as shown in figure 4), an electrical equivalent intersection could be considered a node of loads, source-dependent (dead for blackout) supplied alternatively by two independent sources A, B, *common for other users,* like two public utilities, and by a local source *engine-generator* EG running in parallel for emergency or for cogeneration system.

A proper automatic transfer switch ATS can provide, in a shuttle mission, the transition between the two external sources A and B. In case of maintenance needs, the ATS, operating the dead transfer between the main sources A and B, can be properly assisted in a temporary live transfer (*interchange transfer*) for its loads by the "shuttle" EG. The EG runs in parallel or can be synchronized to A before A it is lost or the ATS disconnects it. EG like a shuttle can drive slowly the load toward the new synchronization with source B, guaranteeing as a live transition the following connection to B by the ATS.

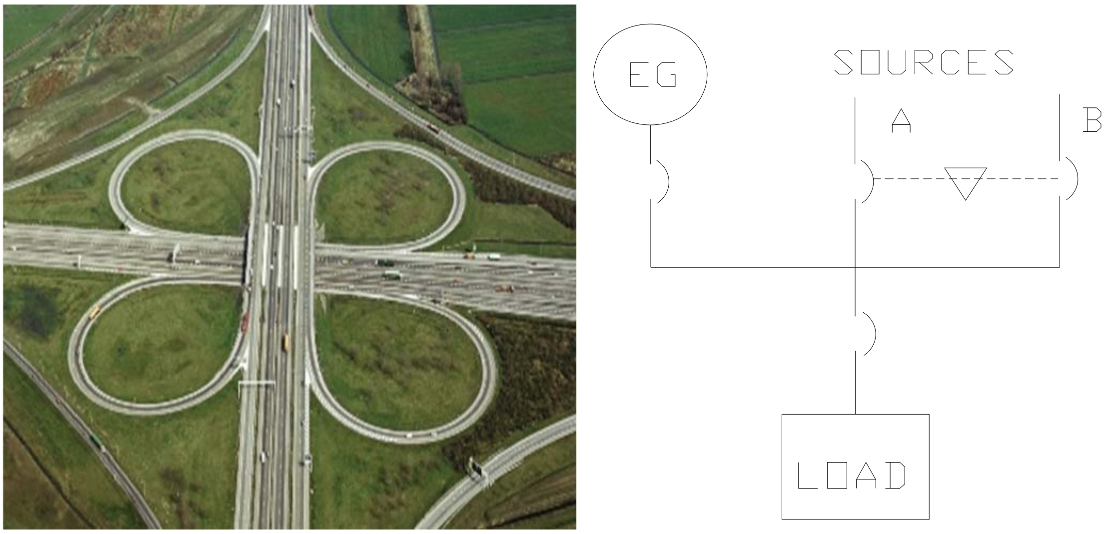


Figure 4. Cloverleaf and analogous electrical node

Let’s consider another way available in electrical power systems, the *Static Transfer Switch solution* STS provides an automatic seamless transfer between a business-critical load and the outputs of two independent UPS systems in a dual-bus power configuration.
A STS can be connected between the single corded critical load or a single corded loads group and the outputs of two independent power sources. The STS provides break-before-make switching between two independent AC power sources for uninterrupted power to sensitive electronic equipment. When used with redundant AC power sources, the switch permits maintenance without shutting down critical equipment, switching fast to guarantee the live transfer.

The node 22, double two

Electric power systems can offer different performances in relation to their architecture, to their automation and to the competence of the operators. In a complex system with multiple sources, the introduction of tie switches allows configurations of system of united sources nodes, like an unique sources node partitioned in sections of the same level: their operation influences the system, vertically and horizontally. The figure 5 shows a vertical case of influence.

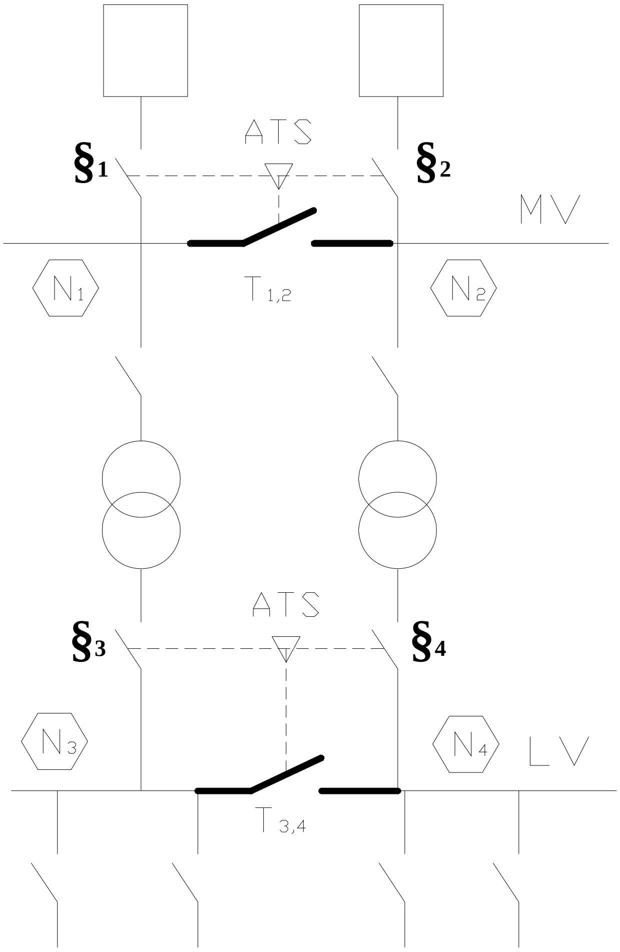


Figure 5. Tie switches and influence on the derived distribution level: the MV $T_{1,2}$, closed, converts the double ended system LV ATS in a two poles system and get free the tie switch $T_{3,4}$ if the transformers can run in parallel (IEC symbols)

It follows that in a complex system and so with increased risk, there is a need to develop methodologies of clearer definition and identification for all the system components, processes and operating procedures.

As already pointed, the operation of the sources switches is not free but requires authorization (authorized sets) in consideration of:

- the compatibility between the sources that is they could run in parallel (same family) or not;
- the validation by short circuits and load flow analyses that is they are actually connectible in parallel.

An installation can be made up of several sub-assemblies with different configurations, according to requirements for the availability of the different types of load.

Figures 6 and 7 show the special configuration of the node "double two", of two automatic transfer switches connectible in parallel, at same distribution level, constituted by two circuit breakers with automatic controllers and interlocks.

Figure 6 shows the case of a node with two sections (N1 and N2) connected by a tie switch $T_{1,2}$ (considered single to simplify). Each section is supplied by two alternate ways: *primary normal sources* A1, A2, and *secondary sources* B1, B2. The node sections could be also more than two.

The operation on the node requires adopting integrity procedures using manual operations and/or programmable logic controllers (PLC) and/or electromechanical releases. To close and operate tie switch T in the closed status, three components must operate correctly: a *tie shutter TS*, to authorize the closing of the tie if it is in a compatible status, a *synchronizer SY* of the automation supply of the ATS and a *tie conditioner TCD* to control the operation in the closed status. The applicable instructions can be related to the binary logic connectives/gates (like NAND, NOR, ExOR, AND) adopting Boolean notations.

In the general case, by closing the tie switch T, the node 22 allows energizing of the united node N1-N2 from the two alternate ways A1, A2 that are not of the same family and analogously from the pair B1 and B2. The two ATS are equivalent to a unique changeover constituted by four independent sources switches among which the logic connective/gate NAND(A1, A2, B1, B2) has to be operated. Its procedure can be compared to a traffic light for a crossing junction as in figure 2 but with the control of all the four directions. The two ATS can work also as a changeover constituted by two independent sources switches and a couple connectible in parallel.

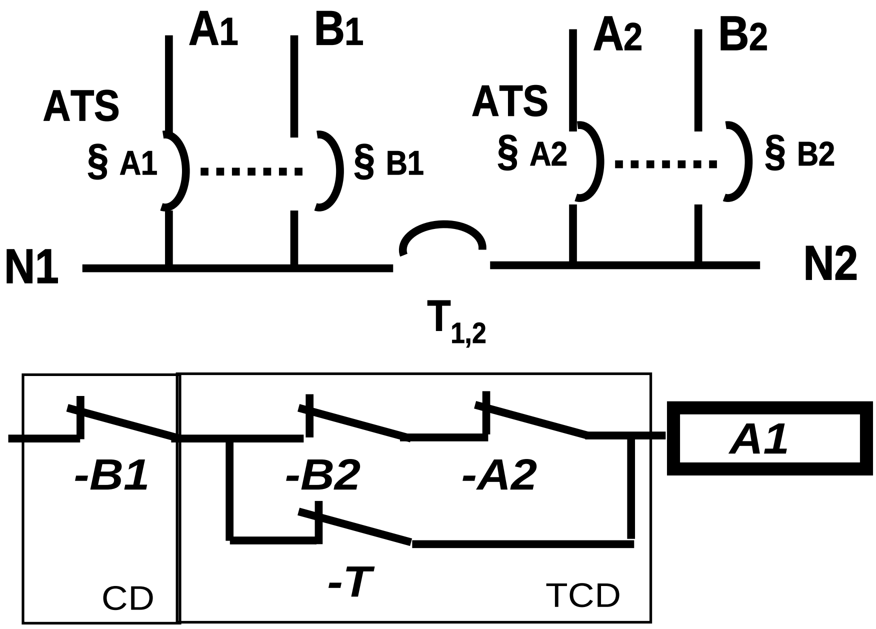


Figure 6. Configurations combination: the *node "double two"* for two sections (extensible to more sections). Let's consider that the two ATS have to be synchronized, i.e. by electrical interlock, to guarantee the condition of "all open" status for the transition: only if the sources switches $\S_{B1}$ $\S_{B2}$ $\S_{A2}$ are open, the live utility A1 will be connected (*conditioner* & *tie conditioner CD & TCD*)

Figure 7 shows the case of two normal sources A1, A2 that are of the same family and B1 and B2 are two distributors from the same engine-generator EG that is the emergency source. In this case, the tie T1,2 can be closed, if the two ATS are synchronized and conditioned to guarantee:

- white transition NOR(A1, A2, B1, B2 = 0000): avoiding the mixed conditions AND (A1, B1 or A2, B2 or A1, B2 or A2, B1), the general reset condition NOR is required for the transition from normal to emergency source,
- red transition: permitting the transitions on the node of the same kind or same family of sources, as connecting one or the couple of A1, A2 simultaneously OR(A1, A2) or one or the couple of ways B1, B2 simultaneously OR(B1, B2).

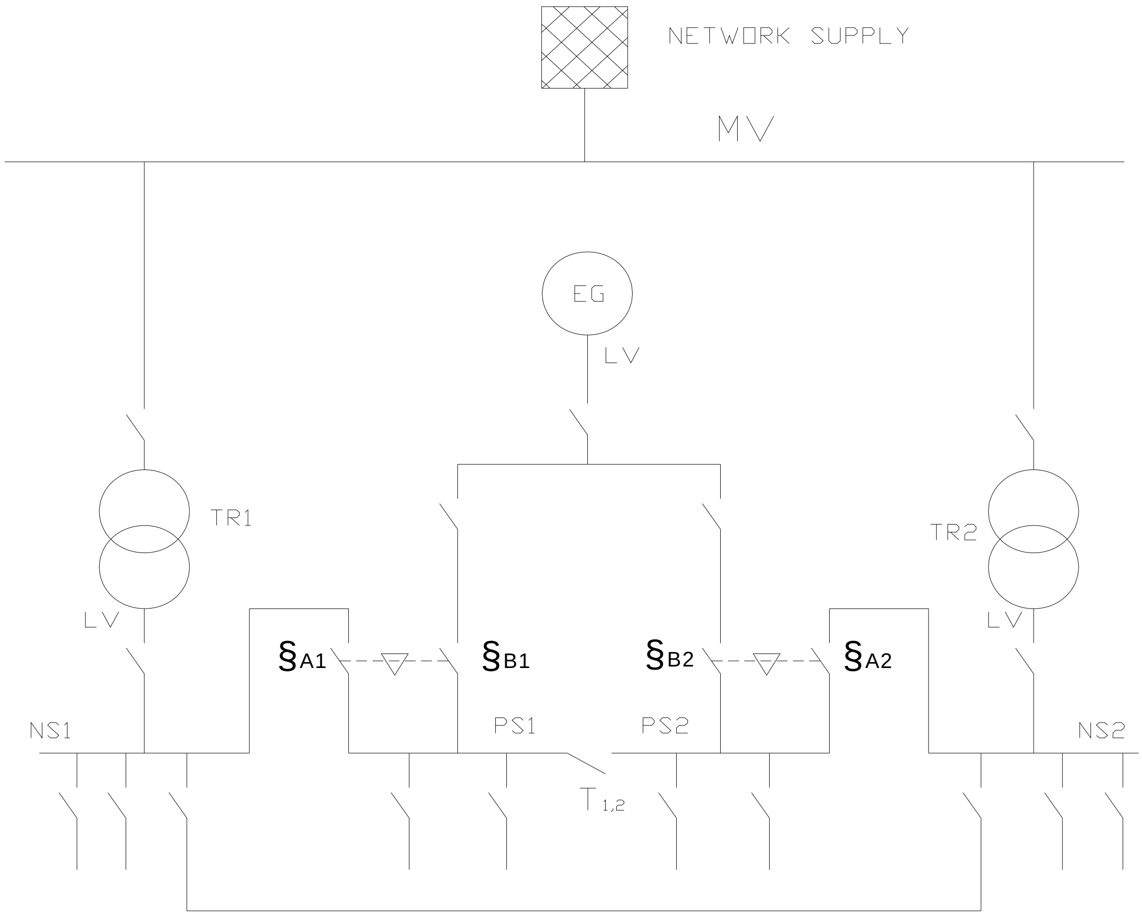


Figure 7. Double two node: the preferential loads of the sections PS1 and PS2 are energized by one or the couple transformers TR1,2 or one or the couple of the distributors by the EG; the couple of ATS needs of auxiliary components for synchronization (IEC symbols)

Figure 8 shows the same case as figure 7 but with the adoption of two ATS constituted by three circuit breakers with automatic controllers and interlocks: in this configuration the couple of ATS doesn't need of auxiliary components for synchronization.

The adjacent circuit breakers/tie switches T1 and T2 could be operated locked open or free of operating in coordination with the A1 and A2 circuit breakers respectively. In these ways the operation in parallel of the two ATS is self-synchronized by the two section ties T1 and T2 [20.p].

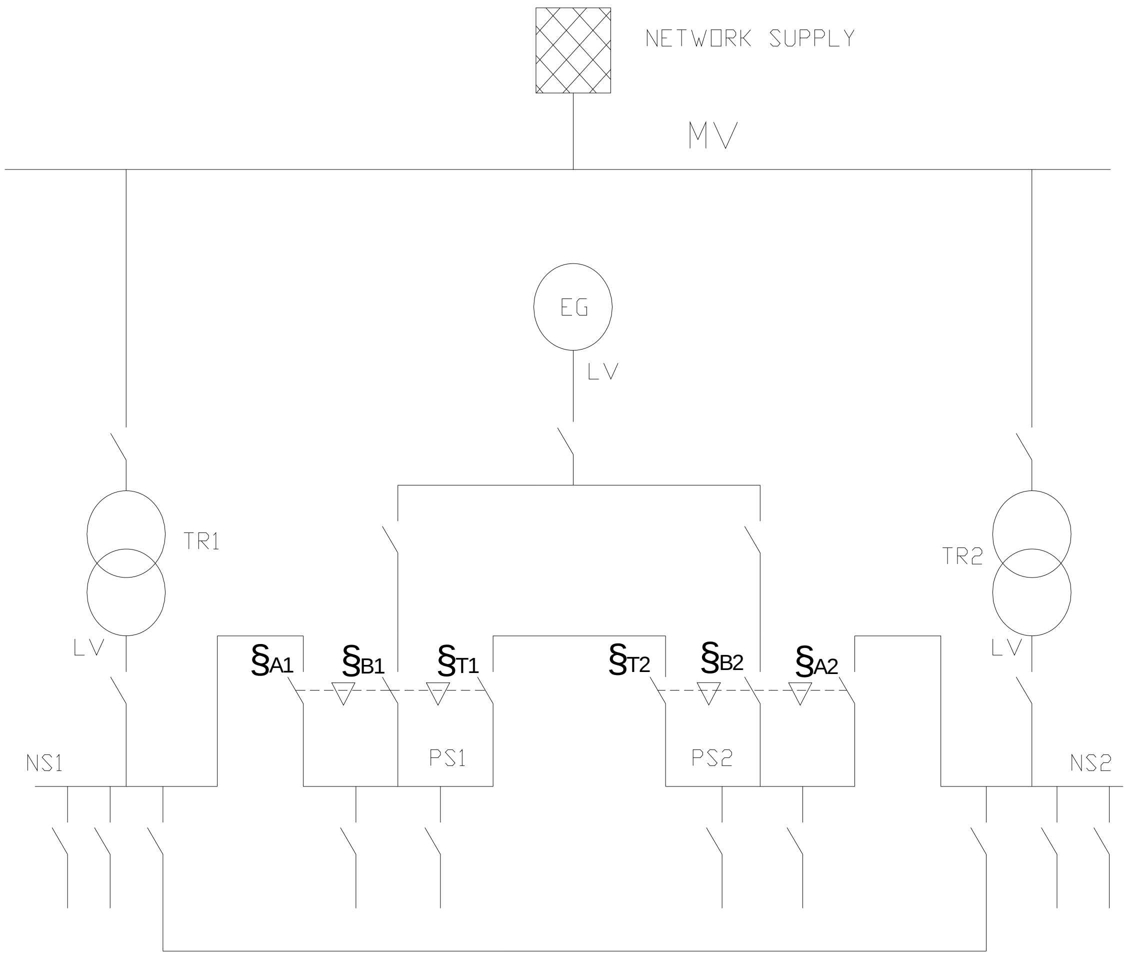


Figure 8. Double two node: the two ATS constituted by three circuit breakers make free their operation in parallel (IEC symbols)

Chapter 1.5

Switching Procedures In Multiple Source Systems: The Flock Logic Of Multi-Set Systems

Introduction

Risk assessment for safety and service continuity evaluates the hazards and fosters adequate precautions in the operation of electrical installations. In electrical installations power supply interruptions and/or interruption of safety services are one of several hazards that may arise.
Previous chapters prospect a mathematical and graphical approach to the assessment of risks inherent selected switching procedures.
The complex architecture of a power system has to be designed and programmed, not left to chance. The operation of the sources switches, that can provide to energize the system (symbol § in the figures) is not free, but requires authorization (*authorized sets*) [18.p; 20.p; 22.p].

The fundamental rule for safe survival of the system is to avoid switching conflicts: programs must follow safe transitions complying with instructions selected among all the probable options (authorized sets). Each system intersection/node for live (energized) service presents an intrinsic logic (genetic code) in relation to the way it is constituted, described by the pillar electronic gate NAND and in details by the instructions founded on the three operating rules of *exclusivity (ExOR), priority and parity (NOR), avoiding collisions.*

The figure 1 shows a sample case of a complex system with the three MV utility sources for the basic supply. The system has LV engine generators for the preferential loads in each transformer substation and local UPSs for the critical-vital loads.
The same figure only shows a block diagram of the MV essential components highlighting the sources switches. The MV power system shown in the figure is constituted by a main switchboard MSB subdivided in three sections interconnected by couple of tie switches T, a switchboard SBU of the utility U_1, seven MV SB switchboards of transformers substations, each one supplying two MV/LV transformers. The operation of the MV distribution to the MV/LV substations is radial (open loop).

The sources switches are in details Isolator Switch, Circuit Breaker Unit with a bus isolator (CB-BI) or with double bus isolator (CB-DBI). In European practice they have integrated a grounding switch. To complete the MV switchboards they are Bus Riser Units (BR) and Measurements Units (MU) (Figure 2) [45.p].

.

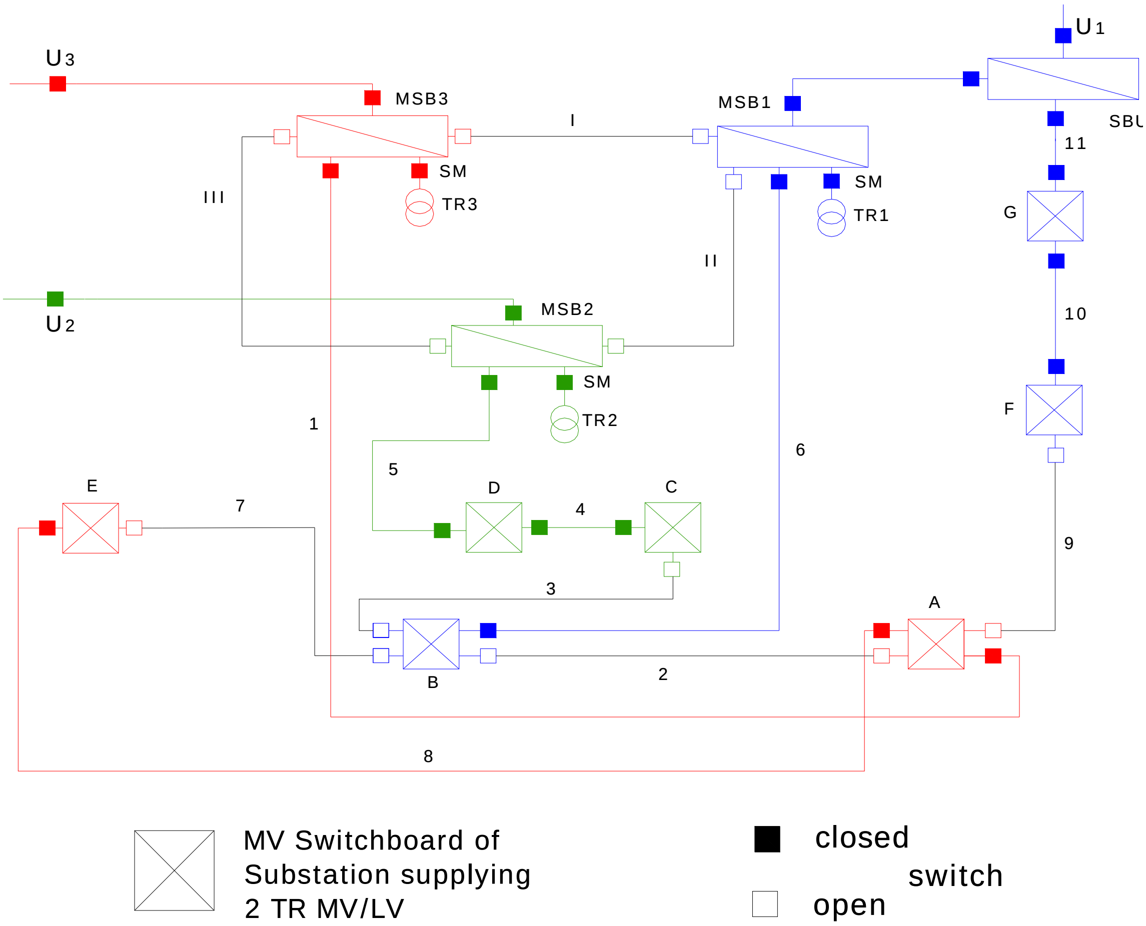


Figure 1. Sample case of a system with three independent MV sources by utility. The switches shown are all sources switches § excepted the switching means SM supplying the transformers TR1,2,3

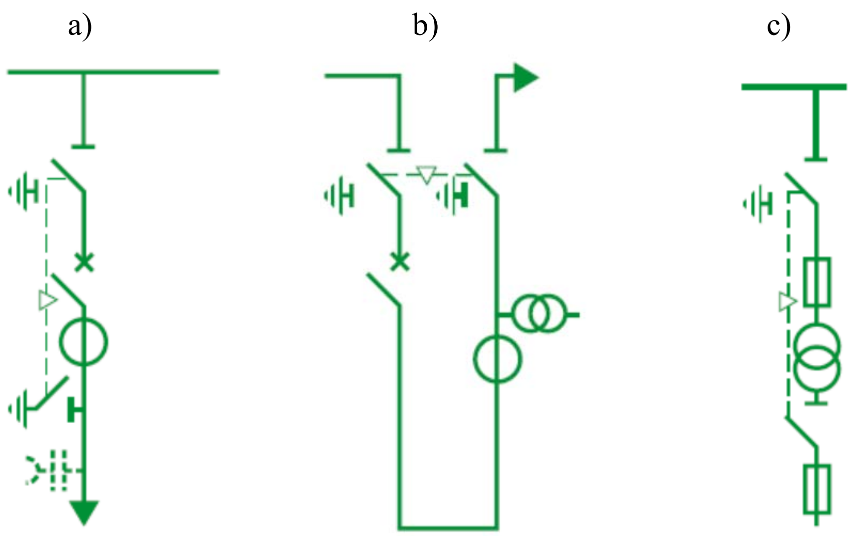


Figure 2. a) circuit Breaker Unit with a bus isolator (CB-BI) b) with double bus isolator (CB-DBI) c) measurements Unit (MU). All these MV units integrate a grounding switch

The architecture impact on the Service/Business Continuity

A sources node can be subdivided in more sections of the same distribution level, each one interconnected like a loop/network (figure 3) by couples of tie switches (dashed lines in the figure), as already discussed in chapter 1.3.

So that the T switches generate a united system of more sources nodes and can add also floating nodes, supplied by the same T switches (figure 3). The need for high availability and "integrity" of the loads is satisfied by a structure that allows overcoming fault situations and doing maintenance activities limiting and recovering the tier degradation. This case is generally referred to a case of emergency status with one of the elements in failure; the T switches support to recover partially the integrity of tier degradation.

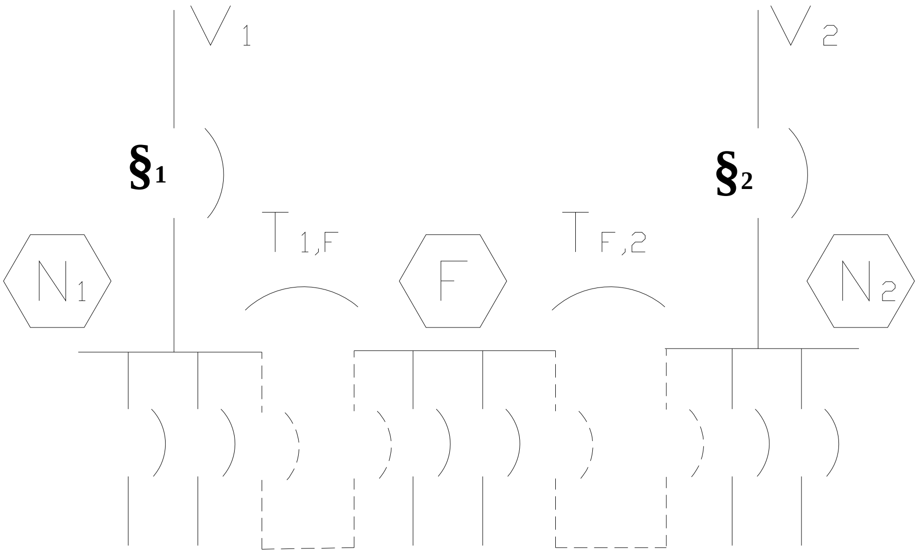


Figure 3. Floating node F: tie switches $T_{1,F}$ and $T_{F,2}$ between two sources nodes N_1 and N_2 (IEEE symbols) (T couples in dashed lines)

The architecture of a critical power system has to guarantee service continuity. The service continuity is a requirement that has to be guaranteed for time intervals from few hours to many years in relation to the loads characteristic as critical loads. So that the loads are classifiable in:

- normal/shedable (class >15s),
- preferential (class 15s),
- vital (class 0.5s)
- critical (class 0.15s – 0s).

In case of failure, part of the loads must be disconnected (load-shedding) if necessary, and further, the recovery time to repair the components has to be compatible with the tolerability of the reliability degradation or certainly to avoid the loss service continuity (Figure 4).

At this aim, the switches are recommendable in a draw out version and in addition the tie switches in couples. The electrical service continuity requests the distribution systems evolve from the traditional vertically operated power system into an horizontally operated power system and an effective business continuity management [33.s; 20.p].

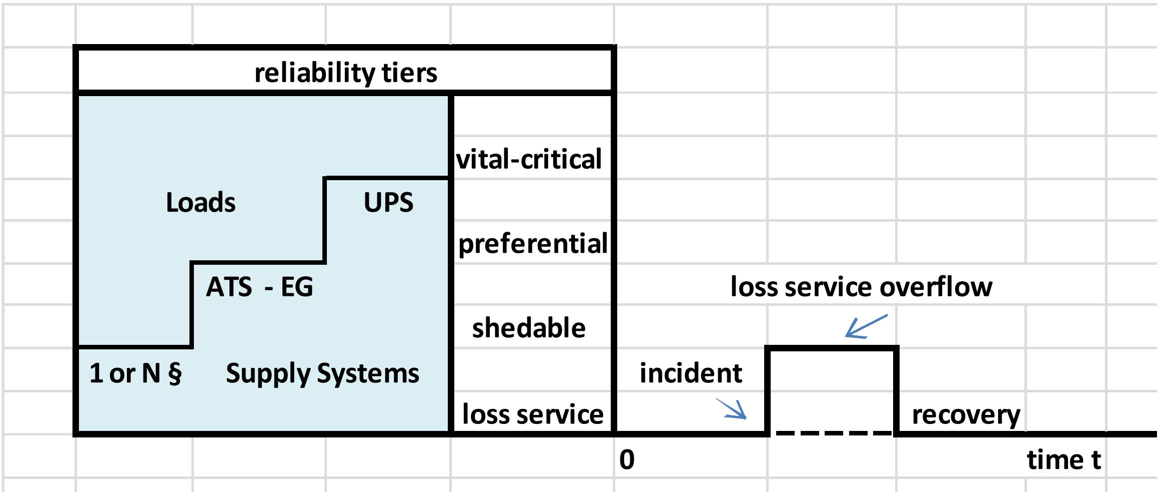


Figure 4. Reliability profile and mitigation after incident by BCM operating on the available sources (Supply systems: § source switch, ATS Automatic Transfer Switch, EG Engine Generator, UPS Uninterruptible Power System)

The micro-systemic approach of the switching procedures: the "flock" logic

As already discussed in the chapter 1.1, a business continuity management (BCM) is an essential component to be considered since the preliminary system design .
The BCM is as much effective as it recognizes the importance of analyzing its objectives and the organization's needs; implementing and operating controls, measures and procedures reducing the loss continuity risks; monitoring and reviewing the performance and effectiveness of the same management.
The BCM has to apply the switching/operational procedures in a micro-systemic approach founded on the coordination of the nodes/intersections complying with their genetic code.
The management of a complex system with multiple sources has to be planned with guidelines and strategies that consider the different reliability of the utilities sources, the actual system configuration in its parts and the loads exigencies of the buildings.

Instead the operation of the complex system must not be organized with a comprehensive approach (macro approach) that studies all the links among the system nodes in the transitions of the authorized statuses. It must be organized node by node with a local approach (micro approach). Each node must respect only the constraints with the adjacent nodes by applying a "flock logic". A lock moves without collisions because each component controls only the adjacent companions and follows the leading one in the chosen direction. So for electrical systems each node/switchboard must be managed considering only the adjacent nodes (by available direct connection) and has to be connected to the node supplied by the reference source, selected for the section of the system.

The condition NAND, pillar logic gate and wave of safe sets, represents the sum of:

- the ExOR condition, the exclusivity rule that imposes one source only connected on a node,
- the NOR condition, being disconnected at once all the sources.

The logic condition ExOR of the exclusivity rule that imposes one source only connected on a node, can be applied like a mechanical bond of a single ring collecting together all the keys locking in open status the n source switches of the node, in the cases when the sources are independent single (no connectible in parallel).

In a case of n = 3 sources (m = 1), the single keys ring, like a mechanical gene, (as shown in figure 5) imposes in the transitions from a source to another, for failure or maintenance, the priority and parity rules.
The single ring can be substituted by a portable locks block of captured keys, that are all the above mentioned keys (Figure 5).

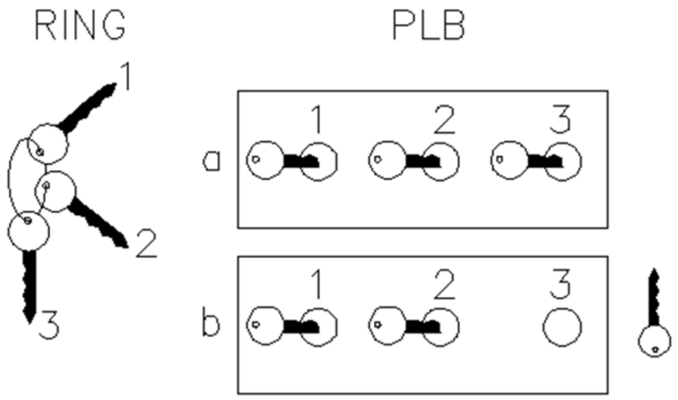


Figure 5. A ring of captured keys, i.e., m=1, for three poles, allows to use one key only. The equivalent schematic Portable Locks Block PLB requires all the three keys captured (all switches open (a) = parity condition) before to release one (b)

In the cases when the sources of a family able to parallel are p and the sources connectible simultaneously in parallel are m ≤ p, the p keys locking in open status the p source switches are needed to be simultaneously captured by a portable locks block to make free the ring of the n-p keys of independent sources.
To operate m switches of the p ones able to parallel adopting a portable locks block occurs at least p-m source switches have to be locked together with the ring of n-p keys. For changing a source of all active m-ones, p-m+1 switches are needed to be simultaneously captured to make free releasing only one of them. Also a solution adopting a portable locks block only can be available.

Let's analyze the sample case of figure 1. The power system has been designed with a multiple structures that has available three independent utilities sources. The system configuration has be planned considering the known different reliability of the utilities sources.
The normal set of the system is planned with the simultaneous activity of the three sources U1, U2, U3. So the system is practically subdivided in three independent sections.
The operation into three independent sections means that in the event of outage of an utility source, the black-out is limited to only one section.

In failure or maintenance conditions, it is possible to operate a transition to recovery the loss of the service for the normal/shedable loads[1] and to take over the service of LV EGs and local UPSs.

The figure 6 shows the diagram of the MSB in three sections MSB1, MSB2, MSB3.

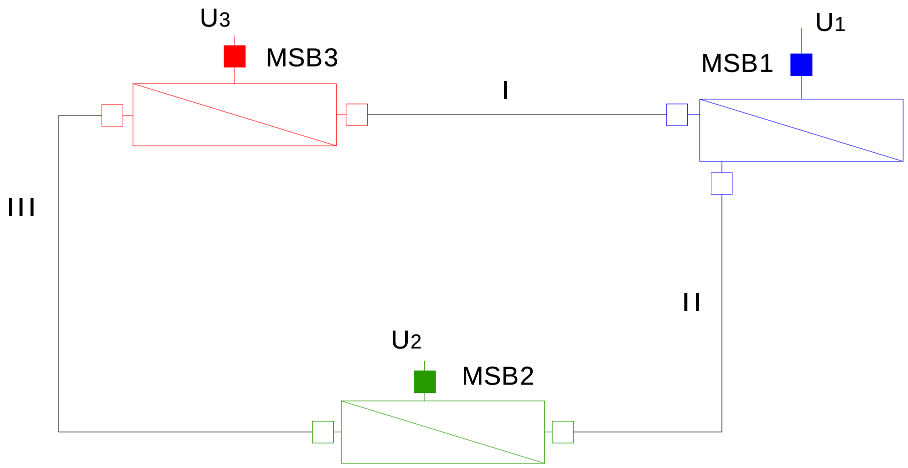


Figure 6. The diagram of the main switchboard in three sections MSB1, MSB2, MSB3

The figure 7 and 8 show the actual constitution of one section of the MSB and of a MVSB of a transformer substation.

Figure 7. A section of the MV MSB: it is constituted by 6 units in particular 1 BR unit, 1 CB-DBI (for incoming utility), 3 CB-BI and 1 MU

[1] Shedable loads are allowed to be shed if power supplies are insufficient, while non-sheddable loads must remain powered at all times.

Each switchboard has to be managed considering only the adjacent switchboards interconnected by couples of tie switches T (isolator switches or circuit breakers) and has to be energized through the ties couple supplied by the reference source, selected for the section of the system.
The switchboards MSB, A, B have 4 couples of § tie switches, the SBU has 3 § T couples and the switchboards C,D,E,F,G have 2 § T couples.

Figure 8. A MV SB of a transformer substation: a case of SB in two sections. The section is constituted by 3 CB-BI units, 1 MU and 1 IS unit as tie switch interconnected to the other SB section

The figure 9 shows a possible version of portable locks blocks PLB constituted by the combination of individual modules of three padlocks interlocked.
The “jolly” key (captive key) will be released if the two keys of the other two padlocks are inserted; these two keys are interlocked by rings with keys locking in open a couple of tie switches (T_{up} , T_{down}). It is used one only of the two keys if the operation has to be limited to the individual switch available on the switchboard for the incoming source.

The PLBs shown in the figure 9 allow to apply the operation of the MV switchboards characterized by 4,3,2 tie couples respectively. The “Jolly” key allows to apply the ExOR logic: this key permits to the PLB to release the keys of the tie couple authorized to supply the switchboard.

For the operation of the MV loop supplying by input-output units MV/LV substations, it is possible simplify and make compact special solutions of PLB.

In conclusion, appropriate PLBs or combinations of PLBs and keys ring can guide all operational procedures to comply with authorized safe sets.

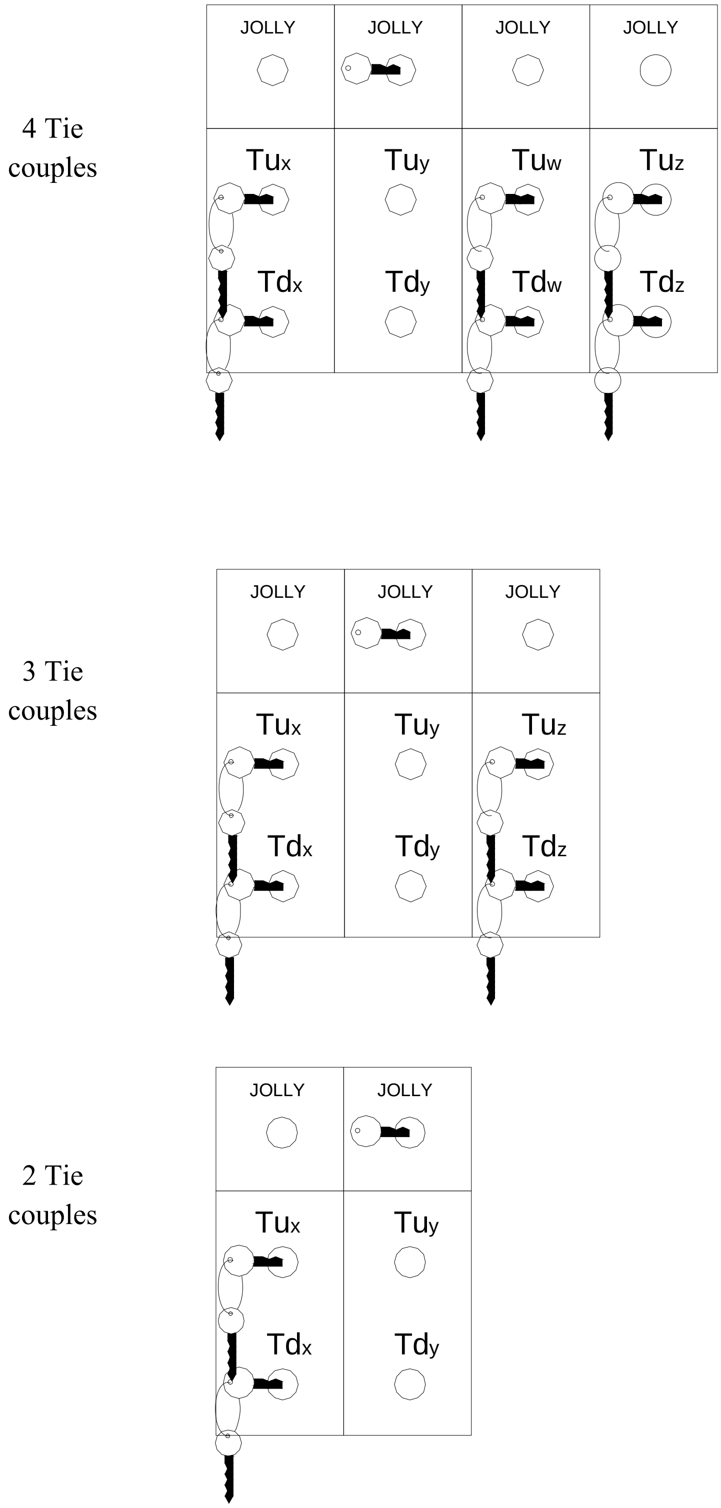


Figure 9. Portable locks blocks that allow to apply correctly the operation of the MV switchboards characterized by 4,3,2 tie couples respectively

A switching simulator of a remote control based on electronic gates can be constituted adopting for the command of each SM a double operating action (double click) based on the double value defining each status.
The double click simulates the double action of decision and execution that each operator has to do in manual operation on a SM, in open or closed status, before of unlocking it and then of operating it. Adopting the double click in the simulator, the first click will allow to control the correctness of the request by the automated supervision and control.
A simulator is very useful in BCM for verifying the effects of any set of switching operations and for assisting the training of the operators [21.p].

Chapter 1.6

Architecture Impact on Critical Power Systems Exposed to Seismic Hazard

Introduction

The earthquakes with a significant magnitude (usually more than 6 Richter scale) cause serious weaknesses in the functional reliability and continuity of supply of electrical power systems in the area, particularly in sensitive structures such as hospitals and strategic buildings. The failure of the building service may in fact depend on the fault on the electrical systems rather than structural collapses (Figures 1,2,3). Power systems that are "subject to seismic hazard" are installed in buildings located in seismic-hazard areas. Electrical equipment, which are non-structural building components, must be installed in compliance with the seismic requirements contained in current codes and standards.

These codes and standards have evolved over the years. Buildings that have a high occupancy level (cinemas, commercial buildings, schools, etc.), must retain their structural integrity to avoid human injury and in some cases also serve as shelter after the event. Some facilities such as railway stations, airports are really relevant to receive aid from neighboring areas not affected by the earthquake. Buildings that perform critical functions (hospitals, fire brigade buildings, community survey buildings, telecommunication systems) must be designed to withstand earthquakes and be able to retain their function so that immediate local aid can be furnished and coordinated [25.p; 26.p].

Figure 1. Batteries of an emergency generator set broken after an earthquake: the electrical service is not available because it is not possible

In strategic buildings as hospitals, with a high occupancy level, power systems are generally designed without taking into consideration specific anti-seismic protection, and the layout of

the rooms housing the strategic functions is only based upon logistic requirements. The equipment layout is entirely the result of the designer's experience and common sense.
Mechanical and electrical criteria for the design and the installation should become more stringent according to building occupancy categories (as hospitals, strategic buildings). An important goal is to coordinate the non-structural design criteria with a layout of the system architecture that avoids or intrinsically limits the seismic exposition to the extent limiting issues with installation.

Figure 2. Lighting system damaged after an earthquake

Figure 3. The support of a generator has collapsed after an earthquake. The emergency supply is not available

Dependability of electrical systems

The term dependability is typically used for computer systems and it is defined as the "ability to deliver service that can justifiably be trusted." The concept of dependability is explored by defining its *attributes*, its *means*, and its *threats*.
The *attributes* are the qualities that all contribute in some way to the achievement of dependability. The *means* are the ways on how dependability can be achieved (prevention, tolerance, removal, or forecasting of faults), and the *threats* are the impediments to dependability (faults, errors, and failures).

The remainder of this chapter will focus on the following attributes of dependability:

1) *availability*: readiness for correct service;
2) *reliability*: continuity of correct service;
3) *safety*: absence of catastrophic consequences on the users and the environment;
4) *security*: absence of consequences on the operation;
5) *integrity*: absence of improper system-state alterations;
6) *maintainability*: ability to undergo repairs/modifications.

The following objectives are identified for the electric operation of buildings with respect to the seismic phenomenon.

- to guarantee the *safety* of personnel during the earthquake and to mitigate the damages (*security*);
- to re-establish electric operation soon after the earthquake (*availability* and *maintainability*);
- to maintain electric operation during and after the earthquake (*reliability* and *integrity*).

Every building design should adhere to the first objective while the other two objectives are added on depending on the critical nature or importance of the building.

The three objectives named above lead us to define three classes of operation used in the design criteria, covering the operation of the system as a whole, its parts, and individual electrical components in relation to the installation requirements and mechanical and electrical characteristics required for the prospective seismic withstand capability.

First class of operation mitigates possible damages caused by the system components.

At the very least, components must be prevented from falling down during the earthquake which might entrap persons standing nearby and sustain injuries from being crushed by the weight of the equipment. Restraining equipment sway and preventing equipment from moving out of position avoids the stretching and straining of connecting conductors to the point of failure, which could then result in short circuits.

Second class of operation guarantees the mechanical operation of the system components.

The operation of electrical equipment (switchgears and panel boards, elevator motors, lighting fixtures, uninterruptible power supply) and of the electrical power system distribution (feeders, sub feeders, branch-circuits) is re-established soon after the earthquake. Service might be interrupted during the earthquake (the shaking may force electrical contacts to change status), but damage to equipment, if any, would be minimal and only minor repairs or adjustments needed to resume operation. The requirement for restraining equipment movement, as in the first class, still remains. For second-class systems, it will be necessary to use components characterized by "mechanical resistance to earthquakes", that is, certified for electrical operation after the earthquake.

Third class of operation guarantees the electrical operation of the system components.

No-break in the supply of vital services is allowed during and after the earthquake, i.e. they are characterized as uninterruptible power systems. Third-class systems should consist of components characterized by "electrical resistance to earthquakes", that is, guaranteed for electrical operation during and after the earthquake.

Design and installation: mechanical criteria

Building categories where special consideration to seismic hazards is required include buildings located in seismic-hazard areas and with one or more of the following characteristics of occupancy and activity importance:

1) *high occupancy level* (e.g., cinemas, commercial buildings, and schools);
2) *relevant importance* (e.g., railway stations and airports);
3) *strategic importance* (where service continuity is needed to support emergency services, e.g., hospitals, fire brigade buildings, community survey buildings, and telecommunication systems).

In these classifications of buildings (Tab.1), it is central that the electrical systems are designed to withstand the seismic forces to which they may be subjected.

Table 1. Categories, protective measures and performance

Building category	**Maximum protective measures required**	**Performance operation class**
High occupancy	Mitigate damage by system components	Safety of personnel during the earthquake
Relevant importance	Mitigate damage, mechanical integrity of system components	Re-establish electric operation soon after earthquake
Strategic importance	Mitigate damage, mechanical integrity & electrical operation	Maintain electric operation during and after earthquake

The electrical equipment are considered non-structural building components and they must be installed in compliance with the seismic requirements contained in current codes and standards [2.s; 29.s; 34.s; 37.s] (Fig.4a and Fig. 4b). These codes and standards have evolved over the years.

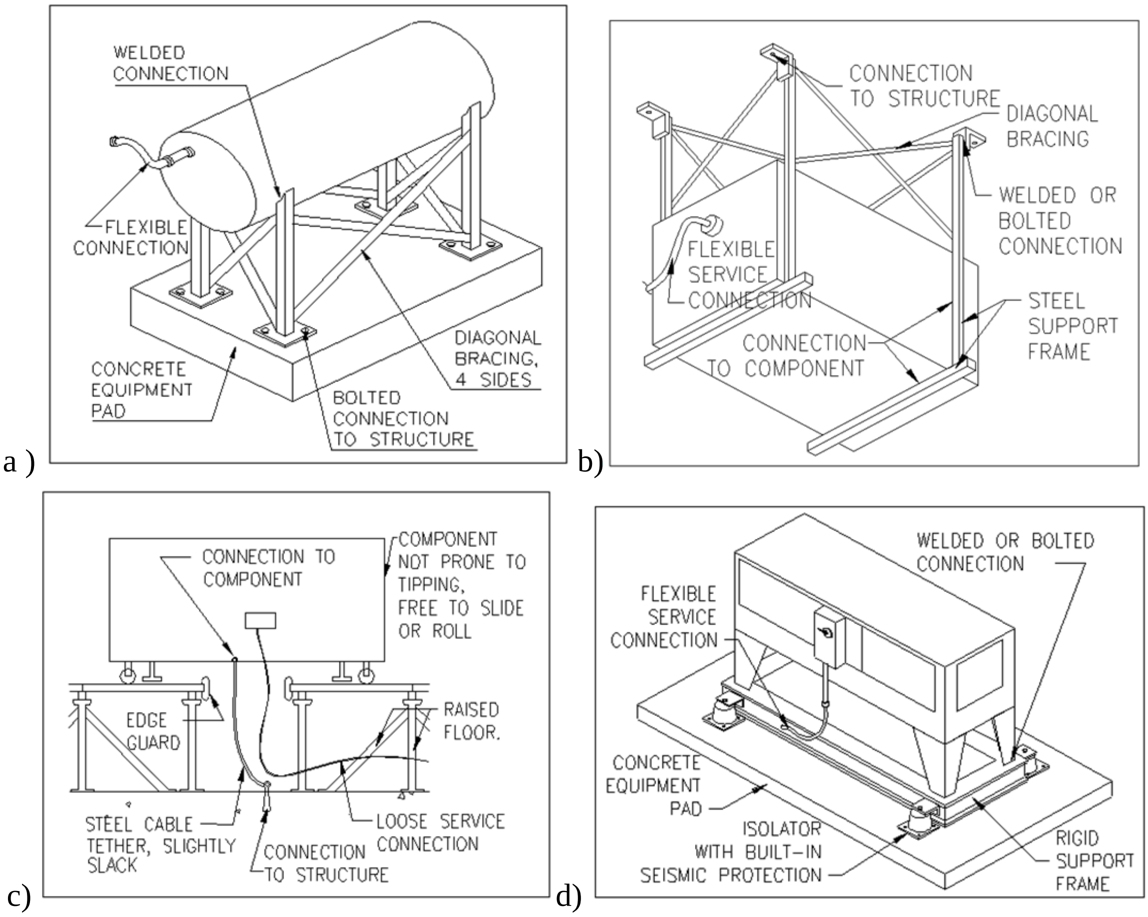


Figure 4a. Classification for components non-structural e installation characteristics: a) stationary components mounted on the floor; b) fixed components hanging from the ceiling or wall mounted; c) components fixed on upper floors; d) components isolated from vibration and mounted on the floor

As the mechanical designer has to arrange a structure looking to the weight moments, while considering optimal costs, practicality, reliability, etc., the electrical designer has to model the "weight," that is the electrical size of components and to arrange the correct "fulcrum point" for setting them. The design of the power systems "subject to external stresses hazard" has to consider the "weight/moment" in relation to the specific force, as the actual weight and moment of components in the seismic event.
The goal of the modeling "architecture" used for power systems located in seismically active areas is to achieve the objectives with respect to safety, maintenance, operation and reliability, while minimizing the use of special components and complex designs. The basic mechanical design criteria of the individual electrical components include the coordination of several tactics which complement each other toward achieving the same goals:

- *Minimize weight (Wp) of each component of the system (microsystem approach)[34.p];*

- *Minimize the Earthquake Force;*
- *Size and install components to tolerate or mechanically resist the expected seismic forces (Fp).*

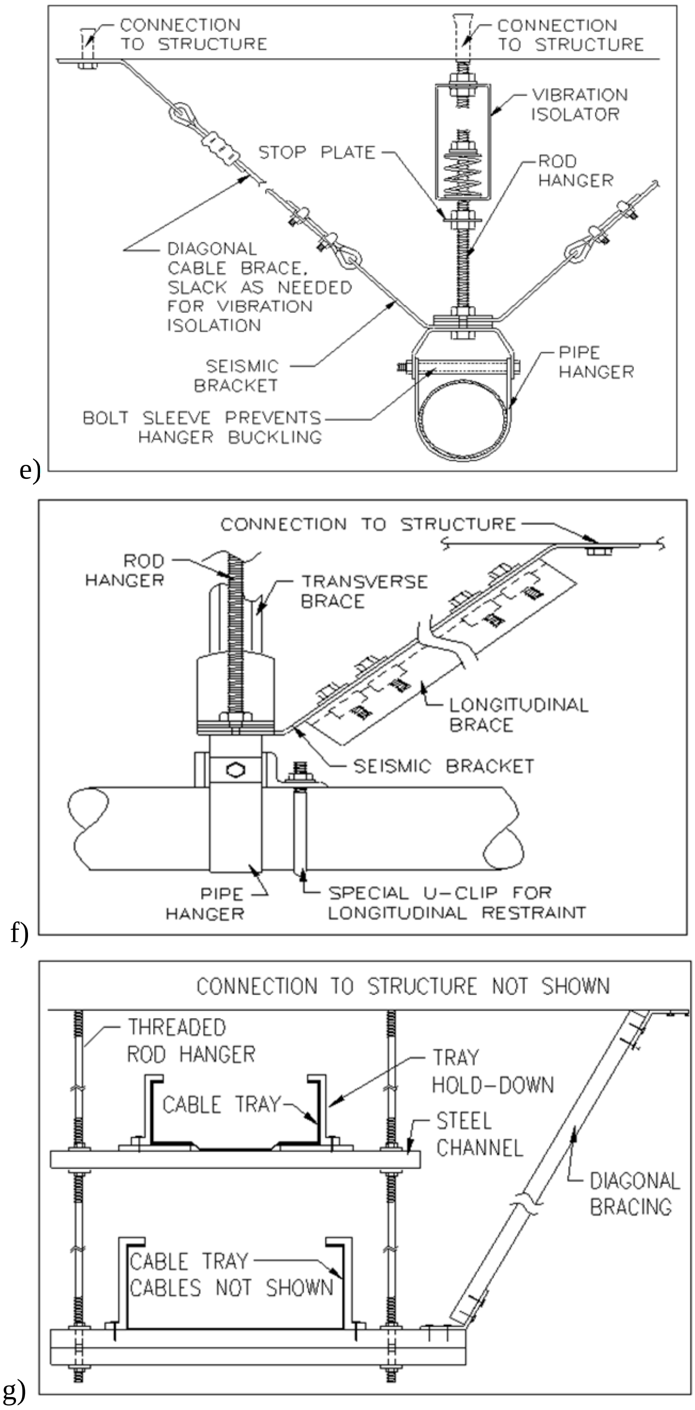


Figure 4b. Classification for components non-structural e installation characteristics: e) components isolated from vibration and suspended; f) piping systems; g) heating, ventilation, air conditioned systems

In 2002, the Italian Department of Civil Protection - Office of the National Seismological Service (SSN) has entered into a contract with the Applied Technology Council (ATC) of the

United States [38.s] drawing up the recommendations for bracing and anchoring components non-structural in Italian hospitals (as showed below in Figures 5 and 6).

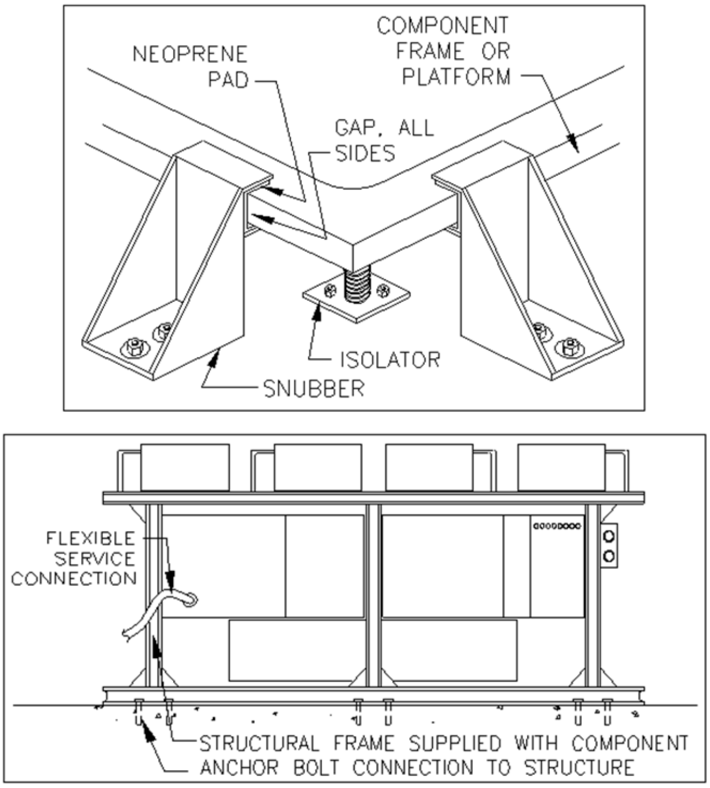


Figure 5. On the left: Spring isolators (snubbers) can be incorporated in the same unit of devices for limiting the displacements due to the earthquake. On the right: A point of high vulnerability is the connection of conduits to the fixed component

The specific non-structural components of the technical installations must be evaluated and classified from the point of view of the response to the earthquake on the basis of four considerations:

- Seismicity (identified as Seismic Zone by current regulations);
- The vulnerability of the component to earthquake damage (for a given level of seismicity);
- The importance of the component to the functionality of the hospital in the post-earthquake;
- The cost and the degree of disruption of hospital services need to adapt or anchor the component.

Design and installation: electrical criteria

The basic electrical design criteria of the electrical power system include:

1) Passive protection of the components and of the power system (locate components to minimize seismic forces);

2) Install components adequately to tolerate or resist the expected forces (Fp).

3) Adopt a specific power system distribution that has a seismically efficient structure.

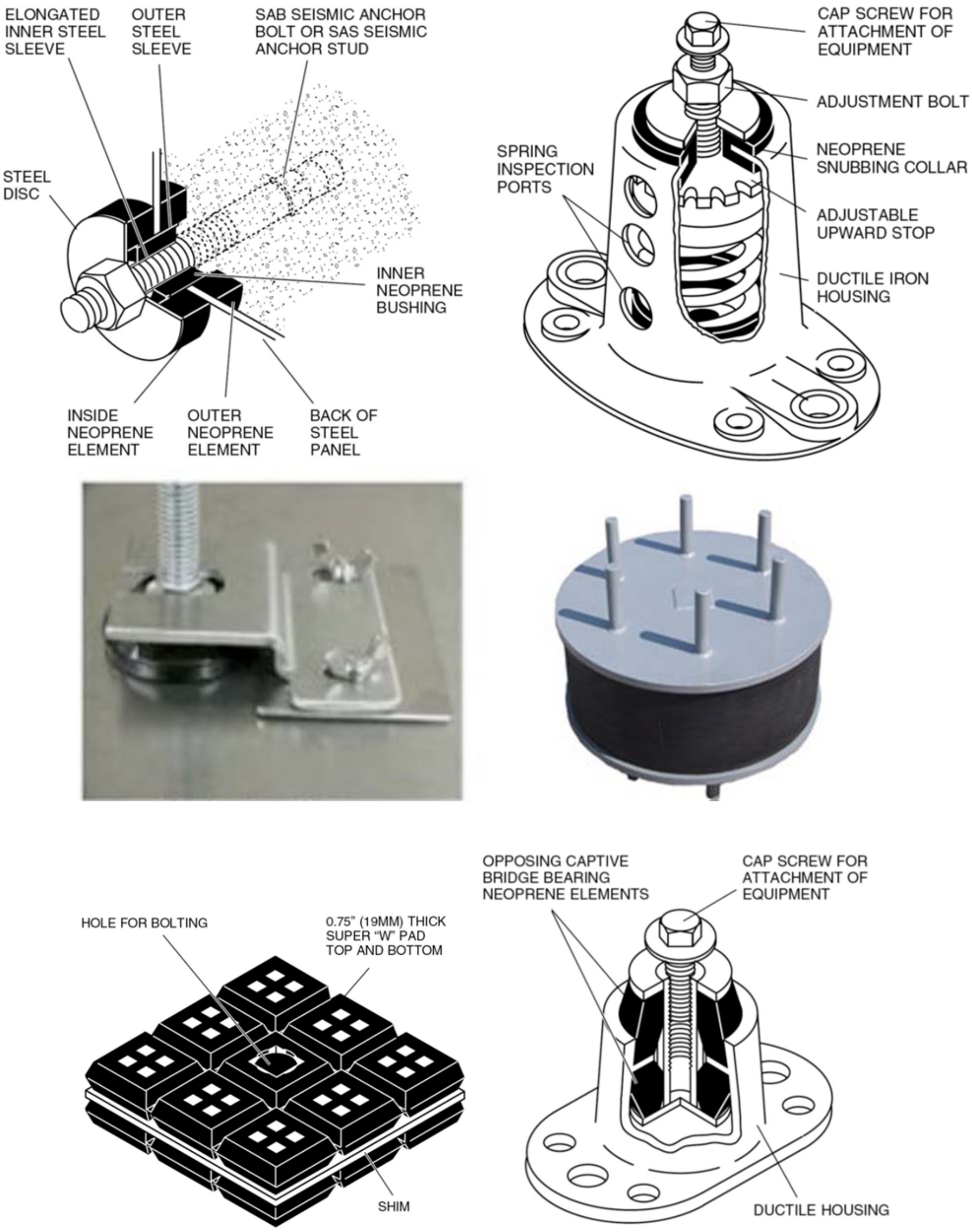


Figure 6. Special anchoring devices anti-seismic

Brush-distribution satisfies the mechanical criteria of locating large and heavy equipment in low exposure height and it exceeds this installation fee only with branch distribution equipment and low weight components (as shown previously in Fig. 3).

Electrical criteria should also include those factors that guarantee operation, safety and supply continuity of electric components.

Passive protection of the components and the power system has already been discussed. When the passive protection is not applied, components that have been qualified for their resistance and tolerance to seismic forces must be installed.

Microsystem approach in modeling architecture of electric power systems

A basic criterion in modeling the electrical system architecture is based on the micro system approach, adapting the system arrangement to set the effective component, (supplied load current) facilitating implementation of smaller sizes, energy and global costs saving, as adopting separate distributions and schemes for different categories of loads.
This solution allows the selection of circuit protective devices with a relatively low ratings, making up an efficient natural protection of minimal fault on the same circuits.
In fact, this protection is able to limit the possible consequences associated with the natural fault by equipment, that is the occurrence arcing and the local overheating, or the opposite occurrence in which the fault extinguishes itself without being detected and isolated. This kind of protection is particularly suitable for all power installations subject to seismic or fire hazards.

Arc fault protection

In electrical power systems, wiring exposed to mechanical damage and other insulation stresses (including wiring not fixed and connected by flexible cords and cables) may have failures characterized by arcing and burning. Protection must be provided to prevent the fault from extinguishing itself without being detected and remaining energized. Complete protection may be achieved by wiring the circuits, particularly extension cords, with special power cables. Ground-Fault-Forced Cables, GFFCs convert a line-to-line fault into a line to ground fault, that will be detected and protected by ordinary ground fault protective devices (GFPDs).

Brush-distribution

The criteria of minimizing weight and exposure to the earthquake hazard can be pursued by locating transformers, generator sets and main low voltage distribution as close to the load as possible and by applying the microsystem approach in configuring the electrical architecture.
A special power distribution type, “brush-distribution,” seeks to locate the heaviest equipment (transformers, generator sets, motors, panelboards) in ground or underground floors [30.p].
The electrical loads on upper floors (including lighting and appliances) must be subdivided in vertical sectors (or “towers”) rather than horizontally along the same level of each floor. So ground floors become the preferred location for transformer and local generator substations (one or more), main switchboards, horizontal feeder distribution, and distribution panelboards.
From these panel boards the vertical sub feeders supply the local panelboards of the loads in the vertical sectors above (brush-circuit arrangement).
The location of functional areas and services within the building has to comply with this approach (Fig.7). The design of electrical aspects must be organized by a close coordination with the architectural, mechanical, structural and civil aspects and should involve the building owner or operator.

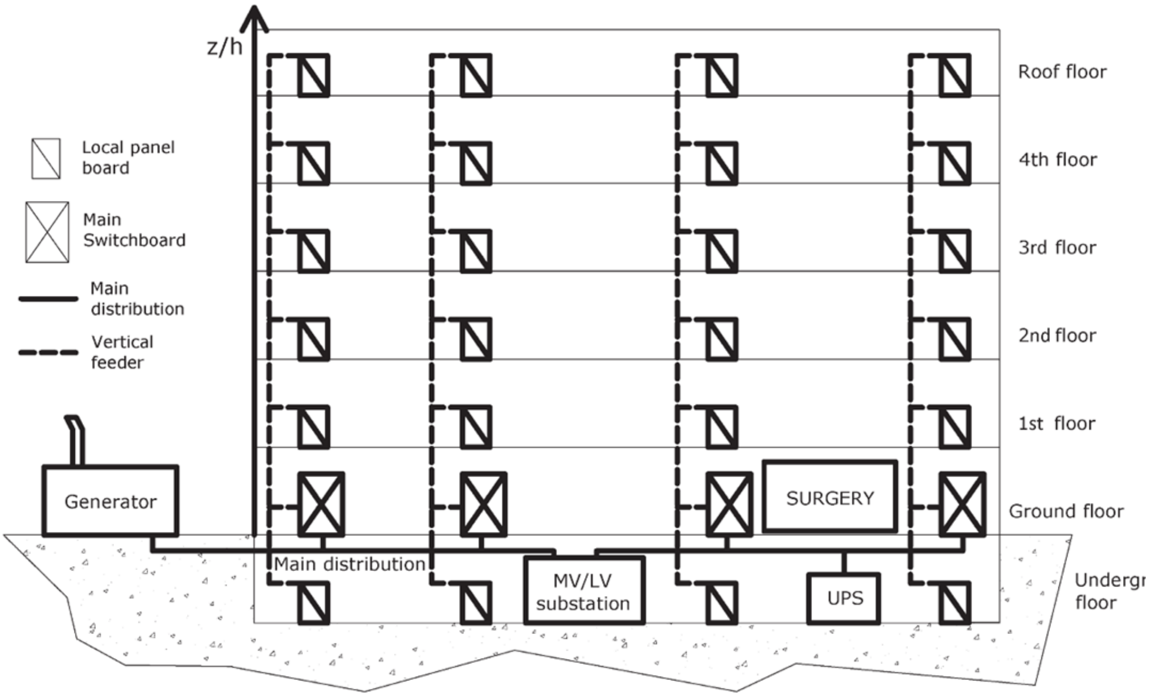


Figure 7. Special power "brush distribution system" layout for a hospital. The areas of the medical services dislocation planning has to be coordinated as much as possible with the criteria of the "brush distribution system"

In the figure 8 is shown the example of an hospital building subdivided in three areas/towers, two constituted by 6 levels, one by 7 levels. The main LV switchboard, the three distribution switchboards and the panelboards of the level 1, are all located in the ground floor [39.p].

In this specific case the main switchboard is formed by two section (indicated in the figure with two different colors), each one supplied by a MV/LV transformer. Every distribution SW are subdivided in two sections in turn. At level of floors for each area there are two separate panelboards, one fed by section I and the other by section II. In case of necessary (out of order or maintenance of a section) the separate panelboards are linked by a cable for the refeeding [14.p].

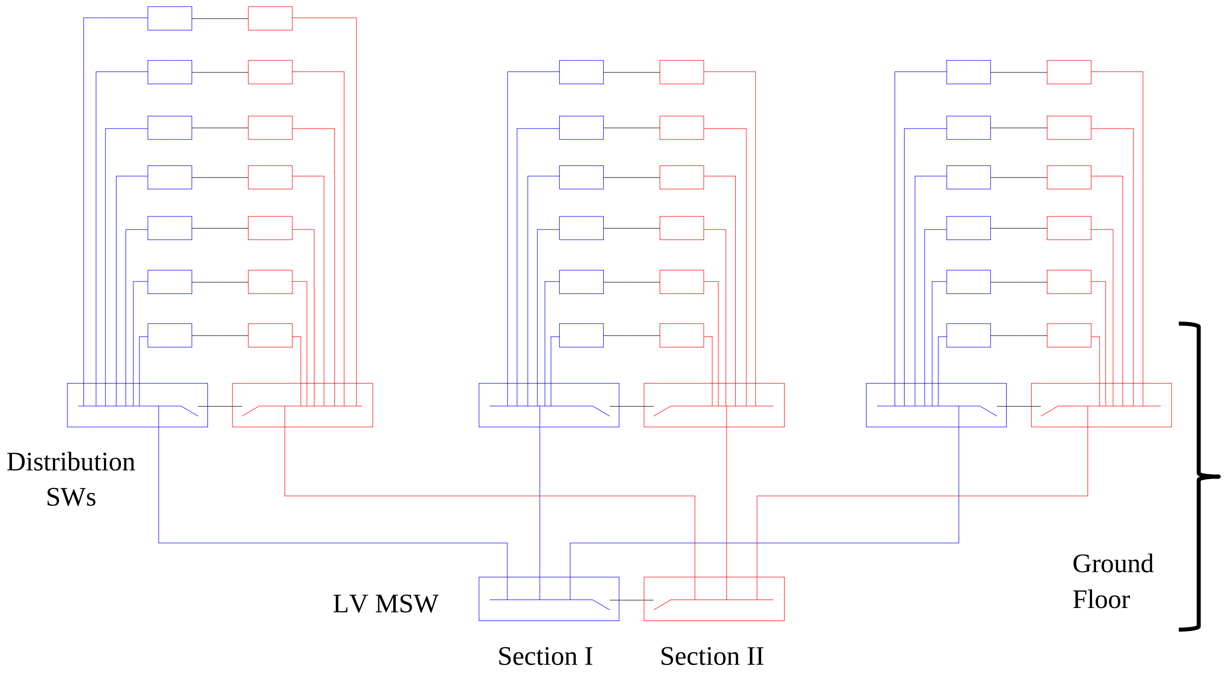


Figure 8. A case of an hospital building subdivided in three areas/towers, two constituted by 6 levels, one by 7 levels. The main LV switchboard, the three distribution switchboards and the panelboards of the level 1, are all located in the ground floor.

Part 2

Specific Issues of Mission Critical Power Systems

Chapter 2.1

Distribution Architecture in Data Centers: Inrush Currents of Electronic Equipment

Introduction

Requirements of high reliability of loads, like data centers, are satisfied by appropriate system architecture for the electrical distribution. To survive contingency conditions the tier of an electrical system's complexity will be increased by including more main supplies and alternate sources, by stand-by and emergency sources, and by modeling suitably the configuration of the distribution and its protection coordination that allows selecting and isolating fault conditions.

The service continuity of critical loads is a requirement that has to be guaranteed for time intervals from few hours to many years. The data centers after the start up request to maintain the service for many years if shutdown will be not necessary or caused by faults. So that the architecture of the power system has to guarantee operational performances preserving the global service continuity (figure 1) such as:

- *maintainability* of the system on its parts;
- *flexibility and expandability;*
- *selectivity of faults and immunity* to interferences among the system areas.

A single power supply for essential loads as in data centers introduces a weakness into an otherwise highly available installation. This shortcoming can be avoided by using complete or partial redundant systems and single equipment capable of dual input power feeds (i.e. dual-corded) that can be connected to the outputs of two independent power sources.

Briefly, the architectural measures can be applied in actions on the redundancy of (figure 1):

- the supplies system adopting *two or multiple ended configuration* designing system nodes energized by *two or multiple sources*, operating separately (exclusivity rule),
- the distributors adopting *two or multiple poles configuration* designing system nodes energized by *two or multiple distributors-ways*, operating simultaneously,
- the equipment supplies adopting *dual corded* equipment energized by *two ways*, operating simultaneously.

Actions mixed are practically applied on the *distributors and sources* adopting the criterion of partitioning and making redundant, *the cut & tie rule*, on a double system of sources-distributors with both supplies sharing the load on the supplying systems at all times. A sources node/switchboard can be subdivided in more sections of the same distribution level, interconnected by tie switches T. So the T switches can generate an united system of more system nodes (figure 2).

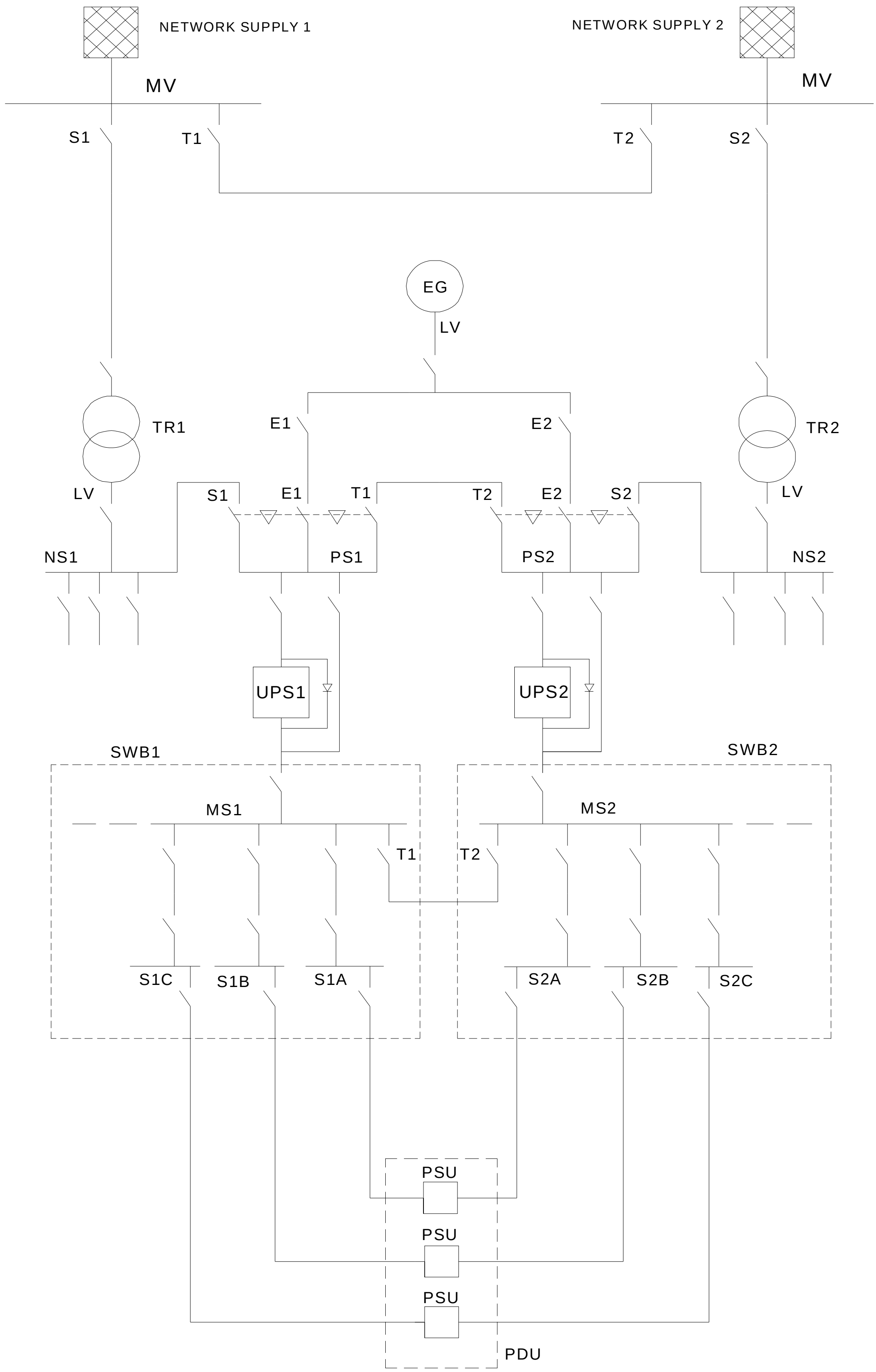


Figure 1. Architecture of the data center assumed as reference

Figure 2. A MV Switchboard constituted by 5 units: for network supply, transformer, reserve, measures and tie switch

The need for high availability of the loads is satisfied by a structure that allows overcoming fault situations and doing maintenance activities limiting and recovering the tier degradation. The redundancy can be:

- total for the system: each element, source/distributor/transformer, being capable and available of supplying all of the installation, is running in parallel at less of its capacity;

- partial for the system: some elements are in a steady or temporary condition of supplying actually the total installation power. This case is generally referred to a state of emergency with one of the elements in failure; the T switches support to recover partially the integrity of tier degradation.

If one source or distributor or cord fails, the system has to operate a transition, in fact the total load has to be picked up by the other dual component (source or distributor or cord).
When used with redundant power sources, the dual corded equipment permit maintenance without shutting down critical equipment, switching fast to guarantee an admissible transfer.
The electrical service continuity guaranteed by sources reliability and by power system integrity requests the distribution systems evolves from the traditional vertically operated power system into an horizontally operated power system.

Tier classification

The Telecommunications Industry Association is a trade association accredited by ANSI (American National Standards Institute). In 2005 it published ANSI/TIA-942 [39.s], Telecommunications Infrastructure Standard for Data Centers, which defined four levels, called tiers, of data centers in a thorough quantifiable manner. TIA-942 was amended in 2008 and again in 2010. TIA-942:Data Center Standards Overview describes the requirements for the data center infrastructure. The simplest is a Tier 1 data center, which is basically a server room, following basic guidelines for the installation of computer systems. The most stringent level is a Tier 4 data center, which is designed to host mission critical computer systems, with fully redundant.

The table 1 summarizes the tier level definitions for generators and UPSs.

Table 1. ANSI-TIA 942 Tier Level System - Generators and UPSs

	Tier I	Tier II	Tier III	Tier IV
Tier Definition	Basic Data Center – no redundancy	Single distribution path with redundant components	Concurrently maintainable – multiple distribution paths with only one active	Fault tolerant – multiple active distribution paths
Generator	N	N	N+1	N+1
Generator Sizing	Optional - if UPS has 8 minutes battery backup	Sized for computer & telecommunication system electrical and mechanical only	Sized for computer & telecommunication system electrical and mechanical only	Total Building load + 1 spare
UPS	N	N+1	N+1	2N
UPS Redundancy	Single Module of Parallel Non-Redundant modules	Parallel Redundant Modules or Distributed Redundant modules	Parallel Redundant Modules or Distributed Redundant Modules or Block Redundant System	Parallel Redundant Modules or Distributed Redundant Modules or Block Redundant System
N Number of components needed to support a load. Meets base requirement and has no redundancy. N+1 The number of components needed to support a load plus one additional unit. The failure or maintenance of any single unit, module, or path will not disrupt operations. 2N Two complete systems, each capable of supporting the load, with a fault tolerant dual path distribution. The failure or maintenance of any two single units, modules or paths will not disrupt operations.				

Independent from the ANSI/TIA-942 standard, the Uptime Institute, an american professional-services organization, has defined its own four levels.

A general overview of the Tier Classification system is shown in the table 2 as presented in a number of papers by the Uptime Institute [50.p].

The tier classifications provide some very useful guidelines to work from when trying to determine what is needed for a specific application.

Table 2. Tier Classification system defined by Uptime Institute

	Generator	UPS System	Mechanical	Maintanance
Tier I	Optional	N	N	Outage of maintanance
Tier II	N	N+1	N+1	Outage of maintanance
Tier III	N+1	N+1	N+1	Concurrently maintenable
Tier IV	2(N+1)	2(N+1)	2(N+1)	Fault tolerant

"N" means the number of generators, UPS modules, etc. needed to carry the load. If the load is 400 kW, one 400 kW UPS would be "N."

"N + 1" means there is one redundant component. In the case above of 400 kW load, "N + 1" would mean there were two 400 kW UPS modules; one to carry the load and one "redundant" UPS module.

"2N" means there are two complete systems in which either one can carry the load. There is not only a second UPS module, there is a complete second UPS system including the UPS

Input and Output switchboards, Automatic Transfer Switch (ATS), etc. “2(N+1)” means that in addition to the two complete systems, there are redundant components.

For the data center to be “concurrently maintainable” it must be designed so that all of the necessary maintenance can be performed while the critical IT load continues to operate. No maintenance outages are required that would remove power from the critical IT load for the data center to be properly maintained indefinitely.

For the data center to be “fault tolerant” it must be able to sustain one major failure within the electrical system, such as loss of one whole UPS system, while the critical IT load continues to operate without interruption. In the example of a 2N topology, because the UPS systems are completely independent of one another, a failure of one side would allow for the entire load to be transferred to the other automatically without any impact to the operations.

An important concept in reliability analysis is “single points of failure (SPOF). Single points of failure are all the places in the one-line from the utility entrance to the critical loads in which one component failing causes the system to fail. When the system is not as reliable as desired, to improve it the first step is to eliminate the single points of failure. In the tier examples that follow each step up in the tier classification eliminates some of the previous levels SPOF, until tier 4 which has eliminated all of the SPOF [26.s].

Reliability as a tool in comparison of design examples by tier classifications

Figure 3 shows a power system design that would most likely be considered Tier I. There is a single UPS module supplying power to the critical IT loads. In this example it’s included a generator and Automatic Transfer Switch (ATS), which Table 1 shows as “optional.”
For this system, loss of utility power or one of the Remote Power Panels (RPP) is about the only failure that would not impact the critical IT load. If the ATS or UPS Input switchboard fails, power is lost to the critical IT loads when the batteries run out of power.
If the Critical Output Distribution (COD) or one of the Power Distribution Units (PDU) fails, power is lost immediately to critical IT loads associated with the failed piece of equipment [3.p].

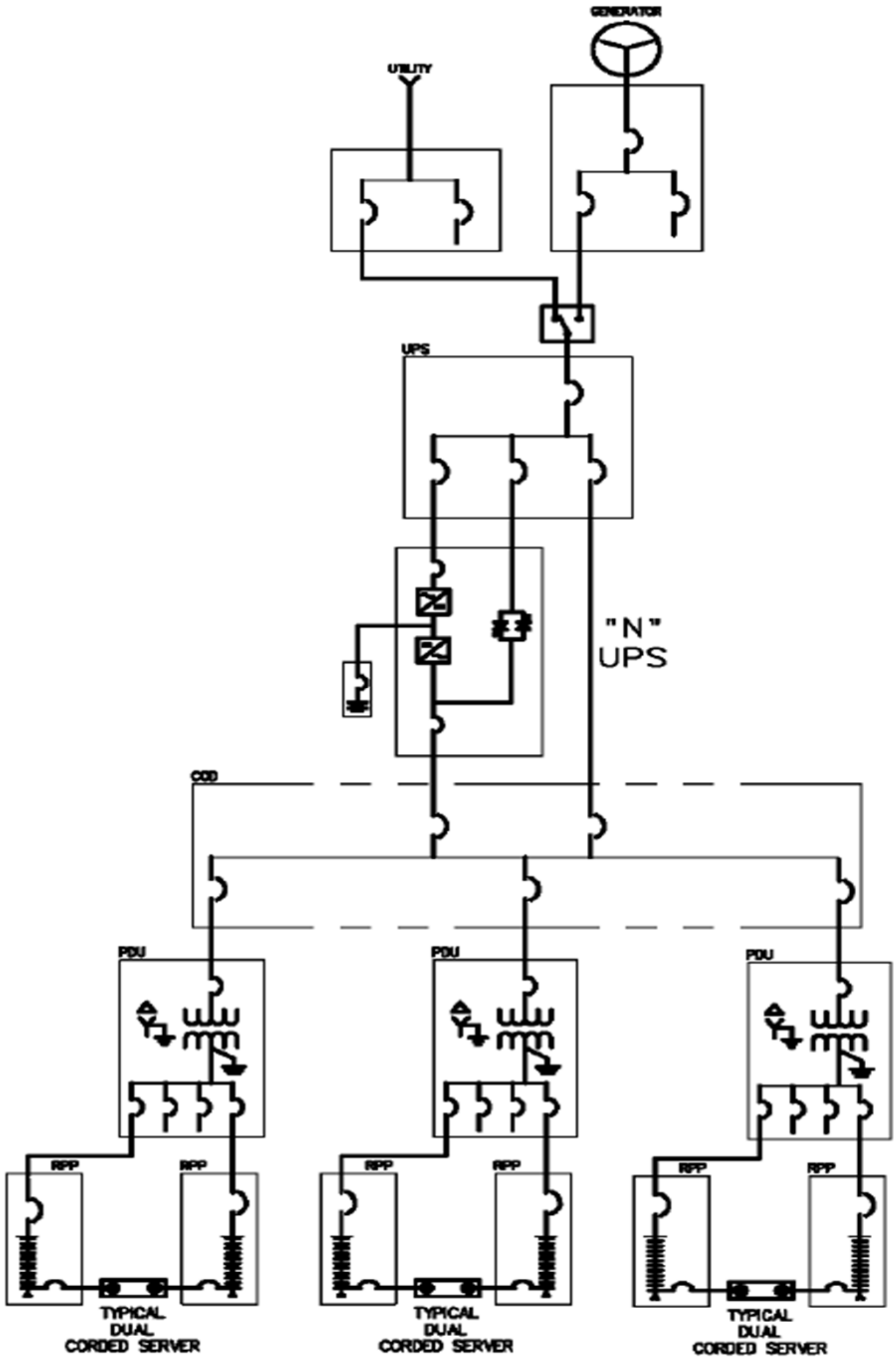


Figure 3. “N” UPS System and generator with IEEE symbols

Figure 4 shows the addition of a second path. In this design there are two ATSs and two sets of CODs and PDUs. The side with the UPS modules is the “active” source, as it is normally in service. The second ATS provides the “passive” source, which provides power to the other side of the dual cord loads. The system in Figure 4 is also *concurrently maintainable*, using one side to power both sets of PDUs during the maintenance.

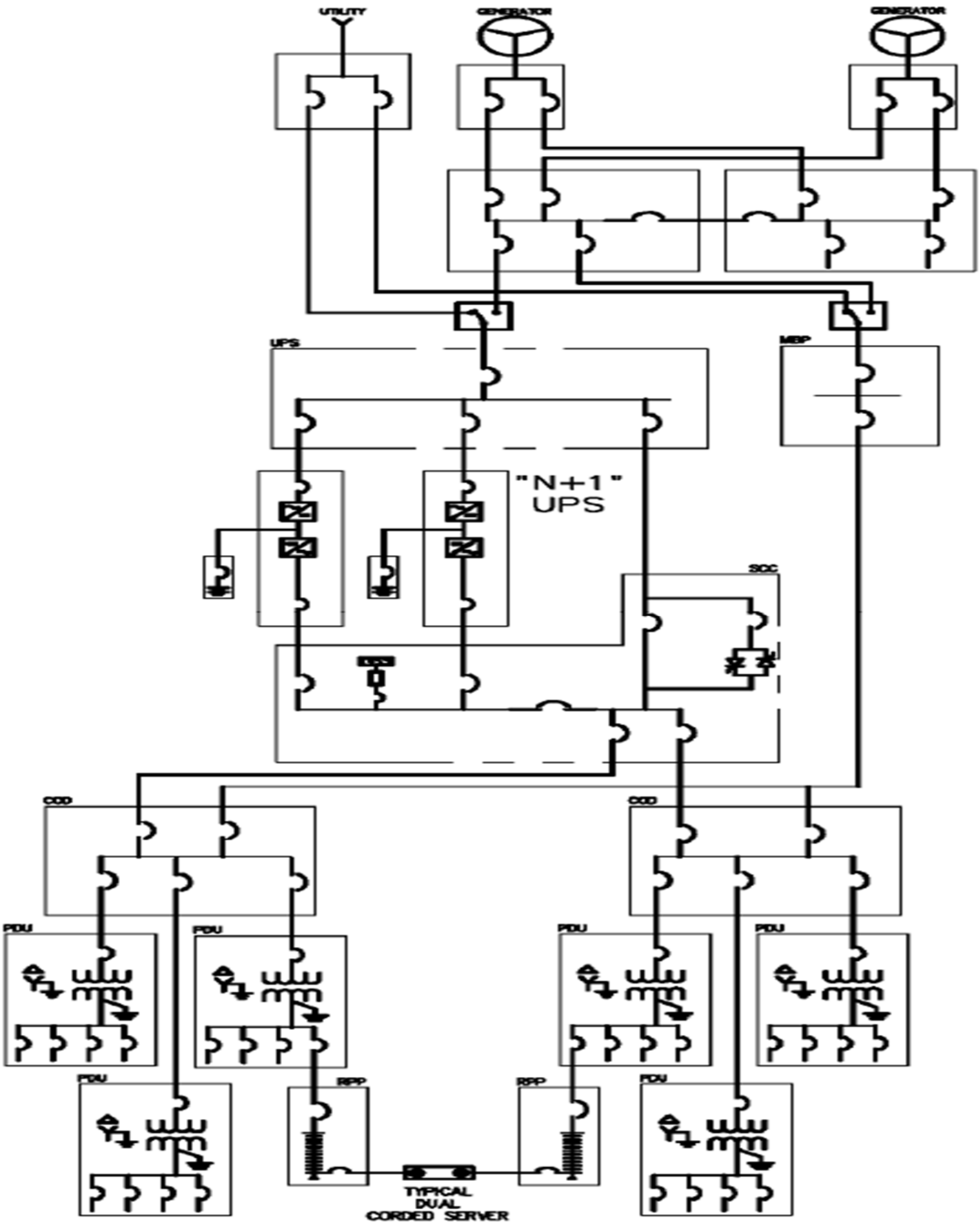


Figure 4. “N+1” UPS System and generator, 2 paths with IEEE symbols

Comparing the reliability calculations of the systems in table 3, the reliability is not very good until the system with the two paths one “active” and one “passive”.
A significant improvement is achieved by going to 2N, with two complete UPS systems.
For these examples, the difference in cost between N+1 and 2N is not as great if the system is small, since in both cases we have two UPS modules. With larger systems, the step between N+1 and 2N can be very great.

Table 3. Reliability calculations of the systems

Type of Power Systems	MTBF (years)	Availability	Probability of failure in 5 years
N shown in figure 3	8,56	0,99994632	40,76%
(N + 1)	10,80	0,99994945	35,97%
(N + 1) 2 paths shown in figure 4	46,55	0,99999751	10,26%
(N+1) with STS 2 paths shown in figure 6	65,64	0,99999748	7,40%
2N	65,98	0,99999752	7,37%
2(N+1) shown in figure 5	66,34	0,99999753	7,29%
2N with STS	67,39	0,99999768	7,07%

In the example shown in figure 5, there is a redundant UPS module and redundant generator in each of the two systems: 2(N+1) configuration.

Shown below in figure 6 is an example with reliability nearly as good as 2N. This one has Static Transfer Switches (STS) to switch the power from the active source to the passive source on failure of the active source. STSs are designed to transfer from one source to another so quickly that the IT equipment is not affected by the transfer.

For the example in figure 6, should the active source have a failure, the STS transfers the critical IT load to the alternate (passive) source (utility power). Since the utility power is available the vast majority of the time and the active source does not fail very often, the reliability is greatly improved with this configuration.
The big advantage of system shown in figure 6 over as in figure 4 is that normally both sides of the dual cord load are on UPS power and only when the UPS system fails (or one of the switchboards, etc. feeding it) are either side of the dual cord loads exposed to utility sags.

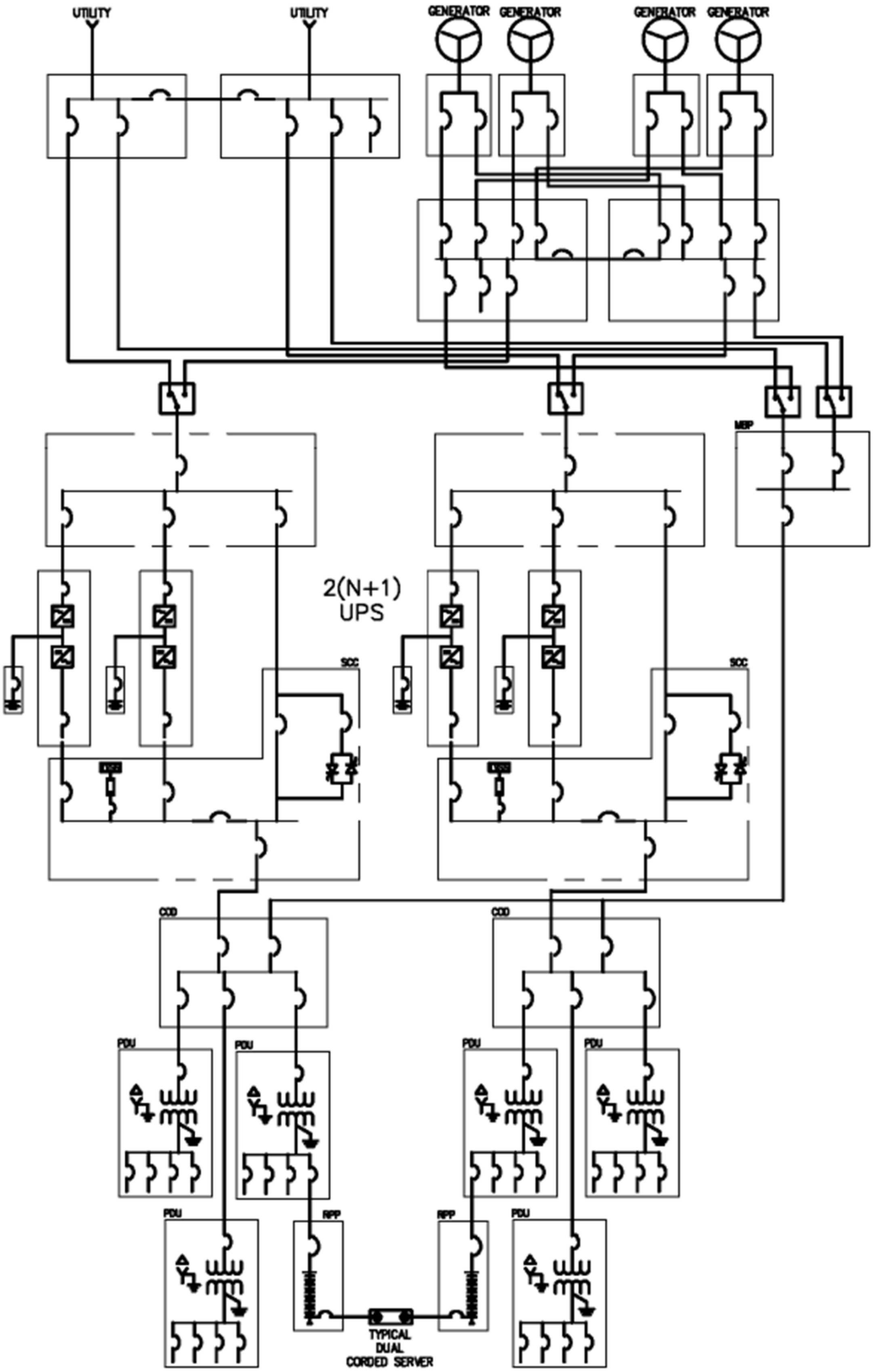


Figure 5. “2(N+1)” UPS power and generators with IEEE symbols

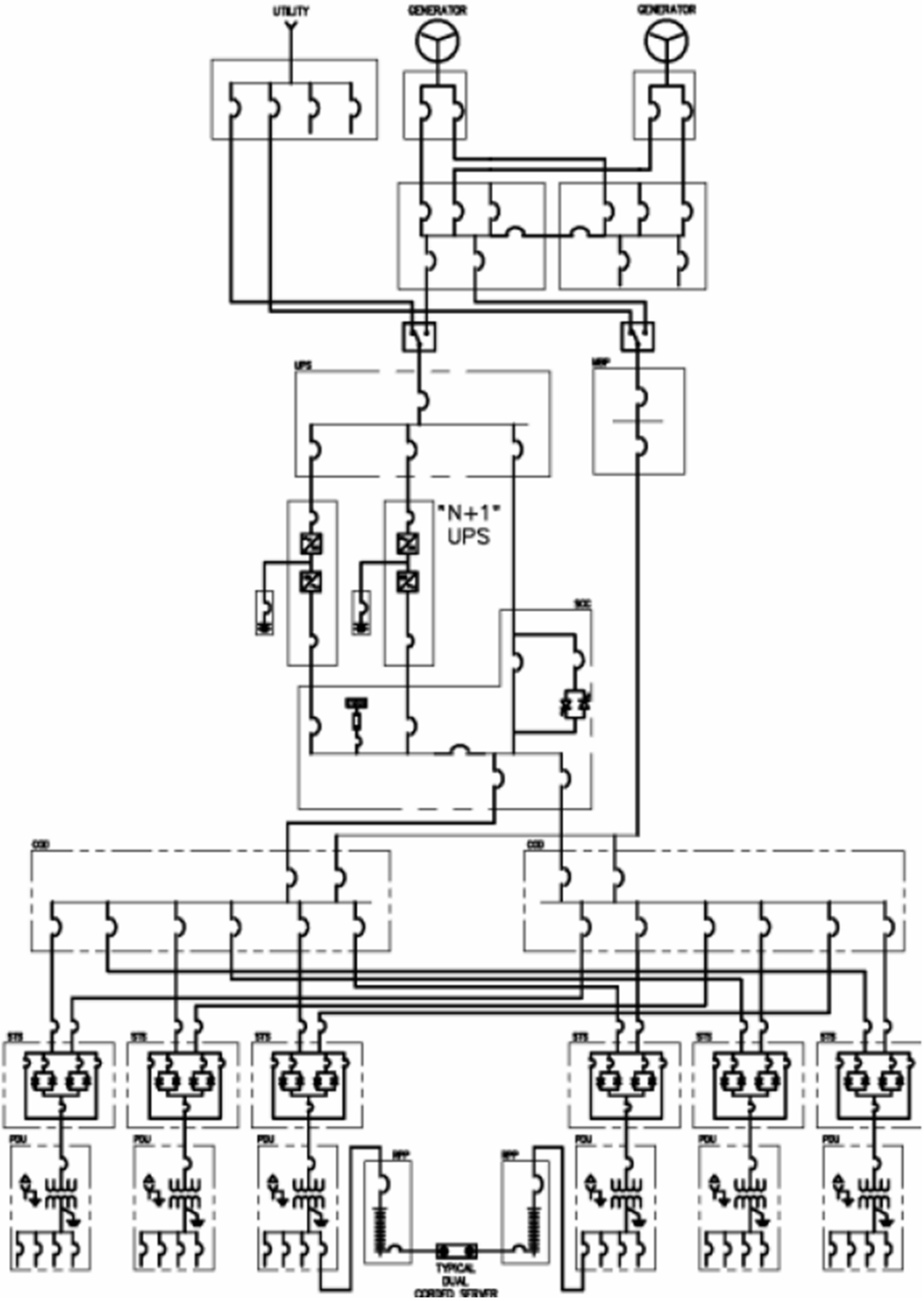


Figure 6. “(N+1)” UPS power and generators with STS with IEEE symbols

Distribution, maintainability, loads balancing

The recent server like blade server is a stripped down server computer with a modular design optimized to minimize the use of physical space and energy. Computers generally operate over a range of DC voltages, but utilities deliver AC power and at higher voltages than required within computers.

In these recent servers/power distribution units PDUs (figure 7), the AC/DC conversion is operated by power supply units (PSUs) that are available to a redundant power supply being dual corded or by a Static Transfer Switch STS, so that the failure of one power source does not affect the operation of the computer [4.p; 41.p; 46.p].

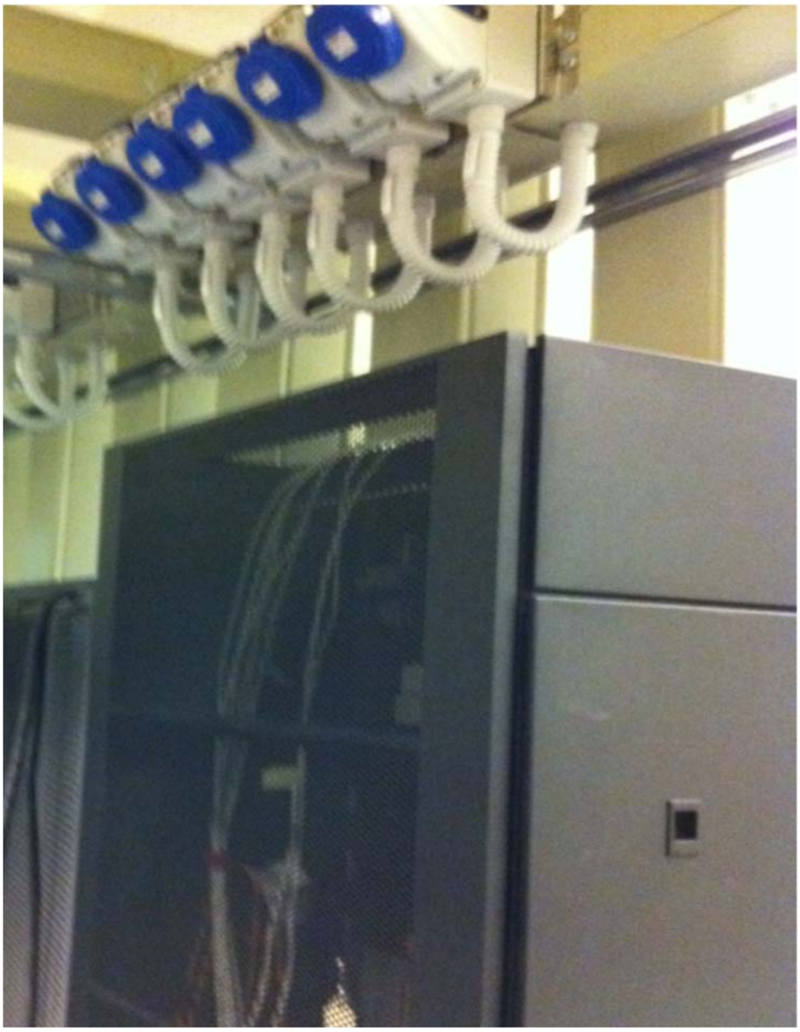


Figure 7. Three pairs of circuits/plugs available for a Dual Corded Equipment

The intent in "dual corded" equipment is that each power supply is drawing power from a different source, and running at less than 50% of its capacity, with both supplies sharing the load equally at all times. In this way, if power is shut down to one cord, or if one internal power supply fails, the total load is instantly picked up by the other supply, which still has the capacity to handle the total load.

With regard to the dual power supply equipment, it is noted that the double circuit applies to the single redundancy without doubling of the power absorbed.

In a data center with two independent UPS systems and dual-corded equipment, the service continuity is guaranteed even if one of two UPS systems breaks down. A STS can be connected between the single corded critical load or a single corded loads group and the outputs of two independent power sources.
The STS provides break-before-make switching between two independent AC power sources for uninterrupted power to sensitive electronic equipment.
Each UPS system supplies a general switchboard SWB that, in the data center architecture assumed as reference (figure 1), consists of a main section and more derived independent S sections on which are allowed periodic maintenances without loss service continuity since the dual-corded equipment. The switchboard design needs to plan the loads balancing, the future expansion and rehabilitation of the distribution (road map).
The protection must be coordinated for the selectivity of the fault on the final circuits to ensure the service continuity of the whole system.
The general design criterion of the distribution for the circuits supplying the power distribution units PDUs involves the use of circuits pairs from the two UPS systems. If multiple circuits pairs are adopted for the same PDU, each circuit will be derived from planned different sections to foster the loads balance on the UPS and the periodic maintenance of switchboards sections (Table 4).

Table 4. A road map example of balancing the circuit breakers CB on three sections of each one UPS for PDU with three pairs of inputs such as in figure 1

SWITCHBOARD OF UPS 1 &2 : PAIRS OF CIRCUIT BREAKERS FOR PDUs												
PDU	Load	C.B.	**SECTION A**			**SECTION B**			**SECTION C**			3 Pairs
name	watt	N°	**R**	**S**	**T**	**R**	**S**	**T**	**R**	**S**	**T**	Phases
		1	**1**				**1**				**1**	
		2		**1**				**1**	**1**			
		3			**1**	**1**				**1**		
		4	**1**				**1**				**1**	
		5		**1**				**1**	**1**			
		6			**1**	**1**				**1**		12 ABC
		7	**1**				**1**				**1**	= 36
		8		**1**				**1**	**1**			circuit
		9			**1**	**1**				**1**		breakers
		10	**1**				**1**				**1**	
		11		**1**				**1**	**1**			
		12			**1**		**1**		**1**			

The suggested architecture (figure 1) is alternative to the adoption of balancing the equipment loads by three phase distribution and PDU transformers (for the local distribution of the neutral conductor) [47.p; 3.p].
All circuits may be provided with a cable cross section as far as possible unified ensuring a defined voltage drop (generally no more than 2%).

The basic criteria of the road map for final circuits distribution in the data center are:

1 - single phase and three phase equipment with dual power supply (dual corded), must be supplied with a pair of circuits derived from the two general switchboards SWB and presenting the same phase (r or s or t) and, if three-phases, the same sequence (like r, s, t). If the pairs of circuits for a PDU are multiple (three pairs of circuits for the PDU as in figures 1

and 7), they have to be derived from different sections of each SWB to ensure the periodic maintenance of the same sections.
2 - single-corded equipment shall be distributed as regularly as possible over the three phases of each UPS system for the load balance. It must be examined from time to time the possibility to adopt STS or duplicate the equipment with the same function supplied by the other UPS.
3 - the switchboard sections design needs to plan and schedule the use of the available circuit breakers for load balancing and to guarantee a maintenance service (Table 4).

Inrush currents of electronic equipment: laboratory tests

An electronic equipment, when is switched on, causes a transient on the supplying source and an inrush current [11.p].

The UPSs have to ensure a capability in supporting the capacitive energy requirements and a low sensitivity to volt-time area decreases/increases. The loss of volt-time area is needed to refresh the capacitor storage energy that takes place by accumulating charges.
The current into a capacitor is known to be $I = C(dV/dT)$: the peak inrush current will depend upon the capacitance C, the voltage value at the insertion instant and the rate of change of the voltage (dV/dT). Note that sources with low dV/dT supply low inrush peak [17.p].

The response of the circuit to the equipment insertion has to be examined, assuming the capacitor is initially not charged and starts to accumulate charges by the voltage-time variation from the nominal steady state values. The inrush current will increase as these parameters increase: the capacitance value, the voltage instant value and the voltage-time change.

There have been several measurements of the inrush current of a laptop switching power supply by changing the power source and consequently the level of short circuit. Tests were performed with main power supply, UPS powered by main supply and UPS in a stand-alone condition [19.s].

The data sheet of the sources and devices used are:

- Main supply (grid): V_{RMS}= 230V; f=50 Hz; I_{kp}= 440A (prospective short circuit current at the socket)
- UPS: online double conversion type with an active power P = 3 kVA (figure 8a);
- UPS: online double conversion type with an active power P = 10 kVA (figure 8b).

a) b)

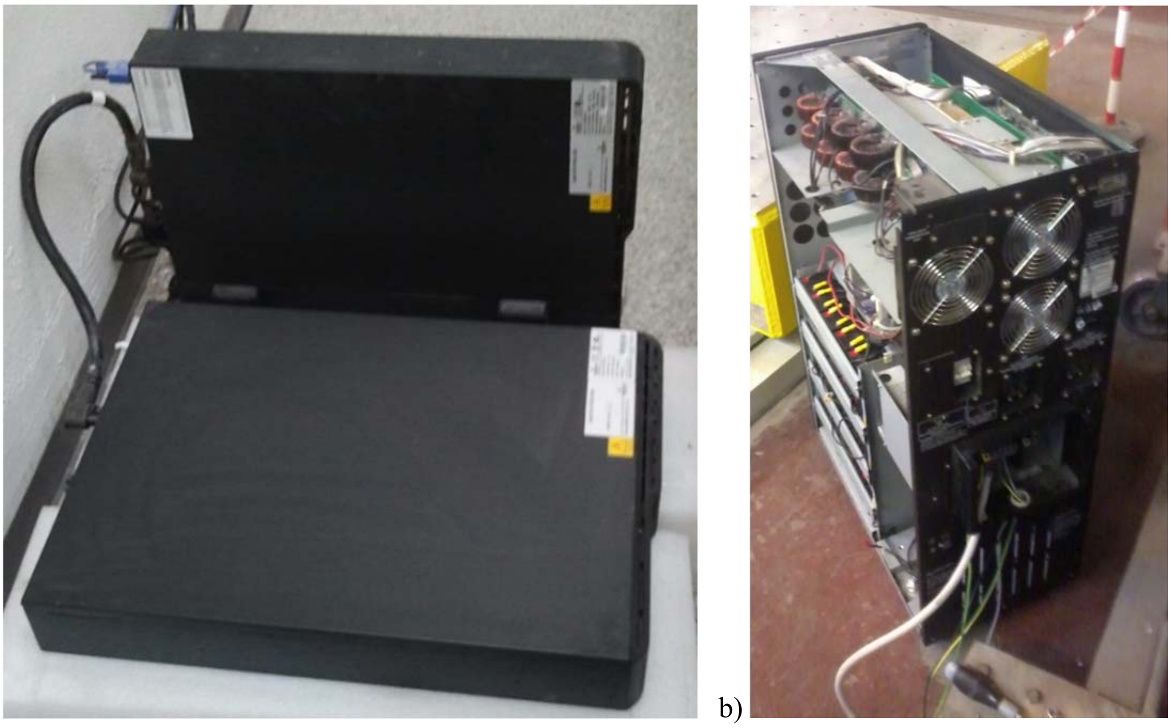


Figure 8. UPS - online double conversion type; a) P = 3 kVA; b) P = 10 kVA

The laptop switching power supply is characterized by a steady current equal to 80 mA (figure 9).

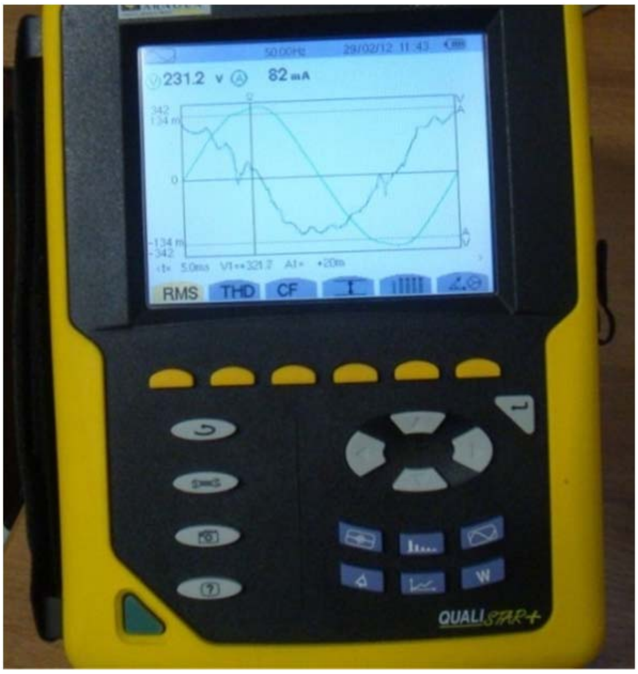


Figure 9. Steady current absorbed by the laptop switching power supply without load

All the next charts show the inrush current of the switching power supply in specific case: when the circuit breaker was closed, the supply voltage instantaneous value was equal to the peak value, approximately V=320V.

In the chart shown in Figure 10 the switching power supply is powered by the grid.
The I_{peak} is equal to 11A and the whole current transition persists for a time t= 1ms, in correspondence to the inrush current there is a voltage variation from the steady state value equal to ΔV=30%.
In this example of measurement there is also a second inrush current I_{peak2} =3,5A with a duration of t= 2,2ms.

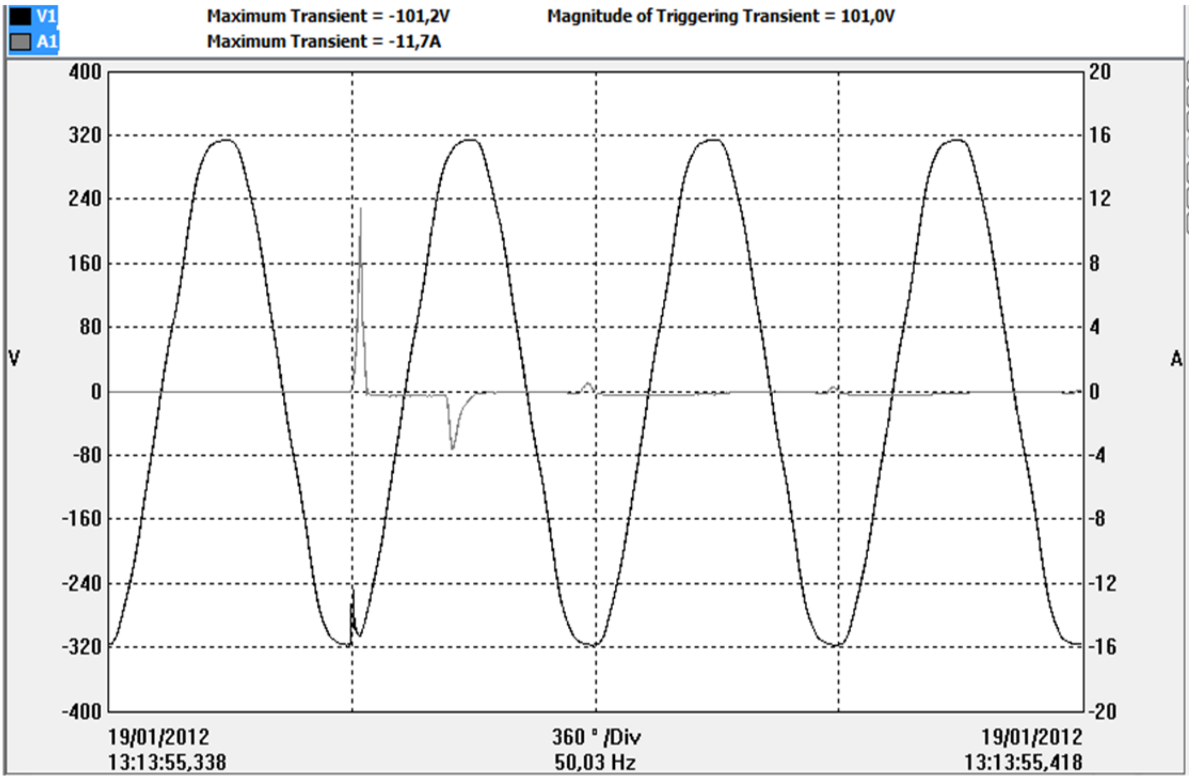


Figure 10. Switching power supply start-up powered by utility: I_{peak} = 11A t= 1ms, ΔV=30%. I_{peak2} =3,5A t= 2,2ms

In the chart below (Fig. 11) the switching power supply is powered by the UPS of 3 kVA.
The I_{peak} is equal to 26A and the whole current transition persists for a time t= 1,3 ms, in correspondence to the inrush current there is a voltage variation from the steady state value equal to ΔV=60%.
In this example of measurement there is also a second inrush current I_{peak2} = 6A with a duration of t= 2,4ms.

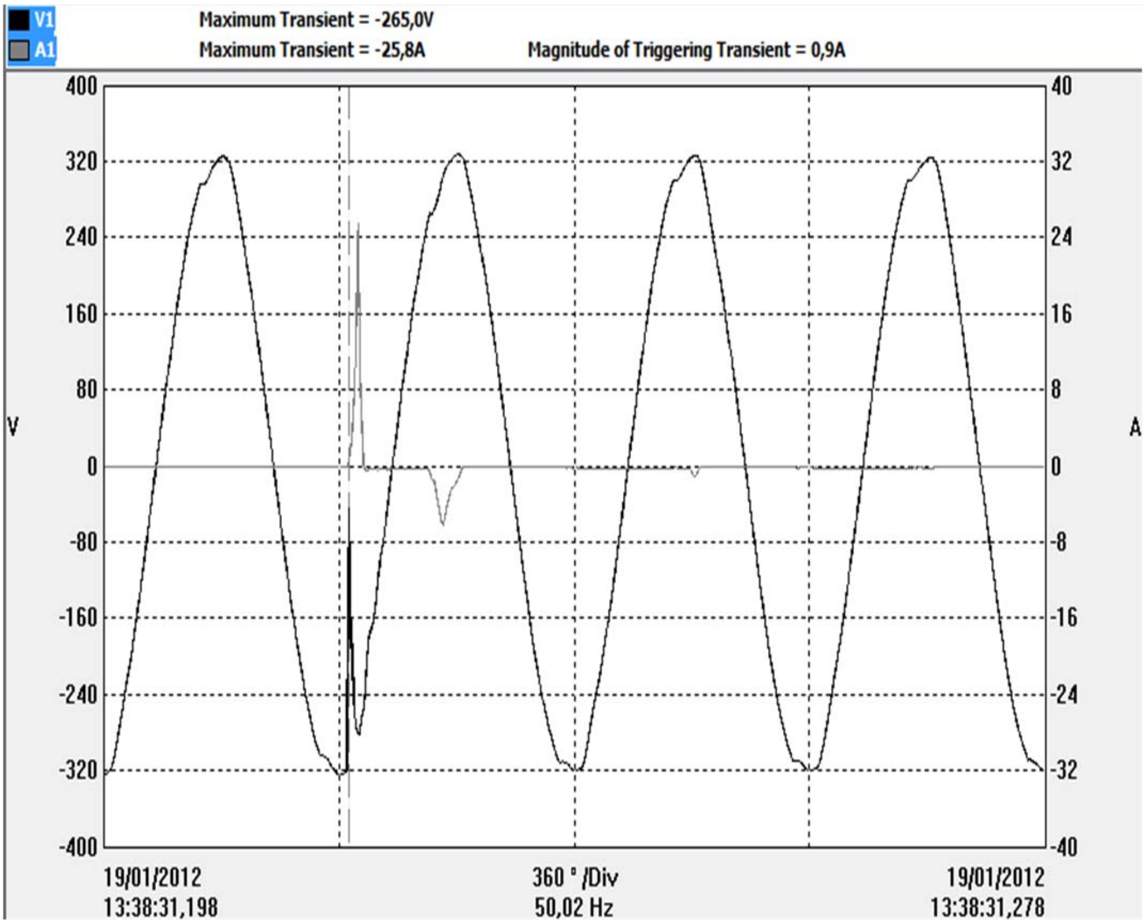


Figure 11. Switching power supply start-up powered by UPS of 3 kVA: I_{peak} = 26A t= 1,3 ms, ΔV=30%. I_{peak2} = 6A t= 2,4 ms

In the chart shown in figure 12 the switching power supply is powered by the UPS of 3 kVA in stand-alone condition.
The I_{peak} is equal to 28A and the whole current transition persists for a time t= 1,4 ms, in correspondence to the inrush current there is a voltage variation from the steady state value equal to ΔV=70%.
In this case the second inrush current is not significant.

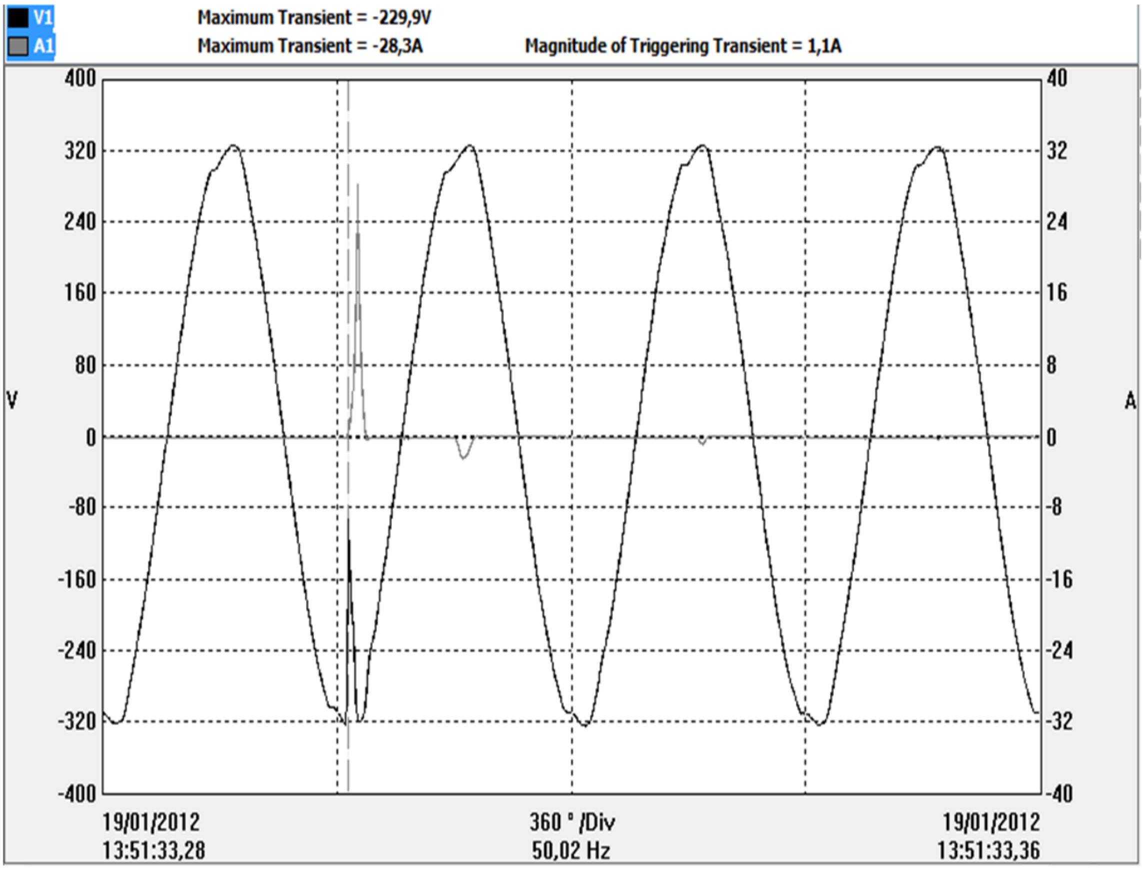


Figure 12. Switching power supply start-up powered by stand-alone UPS of 3 kVA: I_{peak}= 28A t= 1,4 ms, ΔV=70%

The table 5 points out a summary of the measurements carried out highlighting the range of values of the inrush currents, of the current transition duration and of the supply voltage variation detected.
How it's clear by the data showed in the table, the perturbation is lower when the source is the utility, while is greatest when the source is the UPS of low nominal power, independently if it's in stand-alone condition or powered by grid.

The utility is characterized by the highest level of short circuit current equal to 440A, the UPS of 10 kVA by about 100A (I_{kp}≈2*I_n) and the UPS of 3 kVA by about 30A,

Tests demonstrate that the UPS of 10 kVA has a lower dV/dT in comparison to the UPS of 3 kVA and consequently supplies a lower inrush peak.

Table 5. summary of the inrush currents measurements at the electronic equipment start up changing the type of the source

Source	ΔV [%]	I_{peak} [A]	t [ms]
Utility	20÷30	10÷17	1 ÷ 4,5
UPS 10 kVA	30÷60	8÷18	1÷ 5
Stand-alone UPS 10 kVA	35÷50	10÷16	1 ÷ 5
UPS 3 kVA	45÷80	13÷35	1,5 ÷ 5,5
Stand-alone UPS 3 kVA	45÷70	14÷34	1 ÷ 5

So about perturbation due to the inrush current, it's better to have a centralized UPS system of a large power respect to a distributed UPS system consisting in small units. Indeed even for this aspect it would be better supply the electronic loads at the start up by grid,

In the next paragraph it's proposed starting systems solutions to overcome the problem of inrush current and to allow an adequate protection coordination.

As already discussed in the TIER classification for Data Centers, a solution to improve the reliability of a power system is adopting STS (Static Transfer Switch). The STSs switch the power from a source to another source, in the case of TIER III from an active source (UPS) to a passive source (power utility), in the case of TIER IV from an active source to another active. STSs are designed to transfer from one source to another so quickly that the IT equipment is not affected by the transfer. So if the primary source (UPS) has a failure the STS transfers the critical IT load to the alternate (passive or active) source.

Tests were performed in laboratory adopting an STS [8.p] (as showed in fig. 13) with a nominal voltage of 230V, double inputs each one with by-pass and a single output to feed the laptop switching power supply used as reference load for the inrush currents measurements.

The control 'break before make' (BBM) switching feature provides high safety for loads. The transfer time switching is less than 5 ms.

Figure 13. Static Transfer Switch with a nominal voltage of 230V, double inputs with by-pass and a single output

In the figure 14 it’s showed the STS display. On the right side it’s possible to check which source is supplying the load and if the other is ready to supply. In this case the load is powered by the source S1 and the source S2 is ready to supply. On the left side it’s possible to see which is the priority source, in this case the source S1.

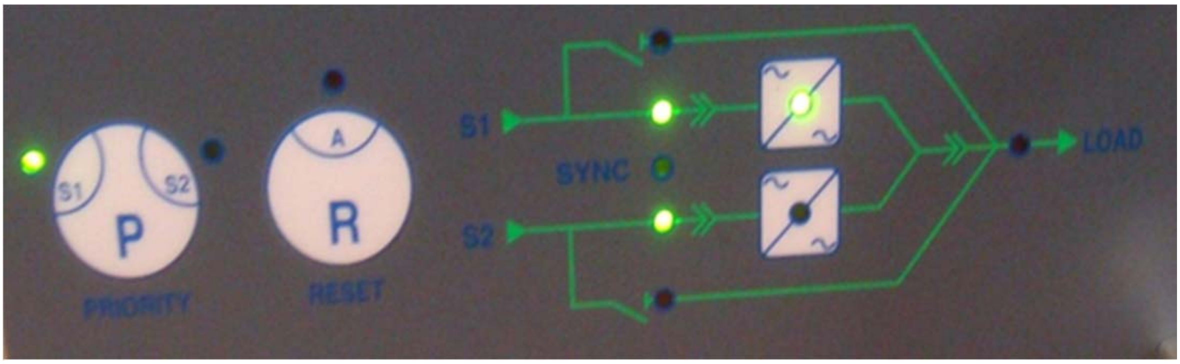


Figure 14. The STS display

In the tests it was realized a supply condition equivalent to the TIER III with STSs. The load is powered by an UPS (active source) and alternatively by the power utility (passive source). The UPS is an online double conversion type powered by the same utility of the other path, so the sources are synchronized.

Obviously at the start-up of the load the inrush current value depends from which source is adopted. As previously established the inrush current value is higher when the source is the UPS. After the start up transient the capacitor is charged, so if there is a failure to the primary source (in the laboratory it was open the circuit breaker of the primary path) and the STS switches the load to the alternative source, there is not relevant perturbation, in fact the power&quality analyzer doesn’t detect any transient.

For the same issue there is no perturbation when a manual switch (fig. 15) is operated to bypass the same STS, operation carried to make maintenance on the component.

Figure 15. The manual STS by-pass switch

Another test was performed changing the UPS power status opening the upstream circuit breaker. In this situation the stand alone UPS is not synchronized with the other source (the power utility). In this case the transfer time switching is higher respect to the previous condition with synchronized sources, however it's less then 10 ms. When a failure occurs to the primary source (in the laboratory it was turned off the UPS) the STS switches the load to the alternative source (power utility) and there is a voltage wave perturbation (fig.16) due to the STS time switching delay. The resulting current variation is not so relevant as the inrush current values detected at the start up, this happen because the capacitor time constant is much higher than the time switching delay.

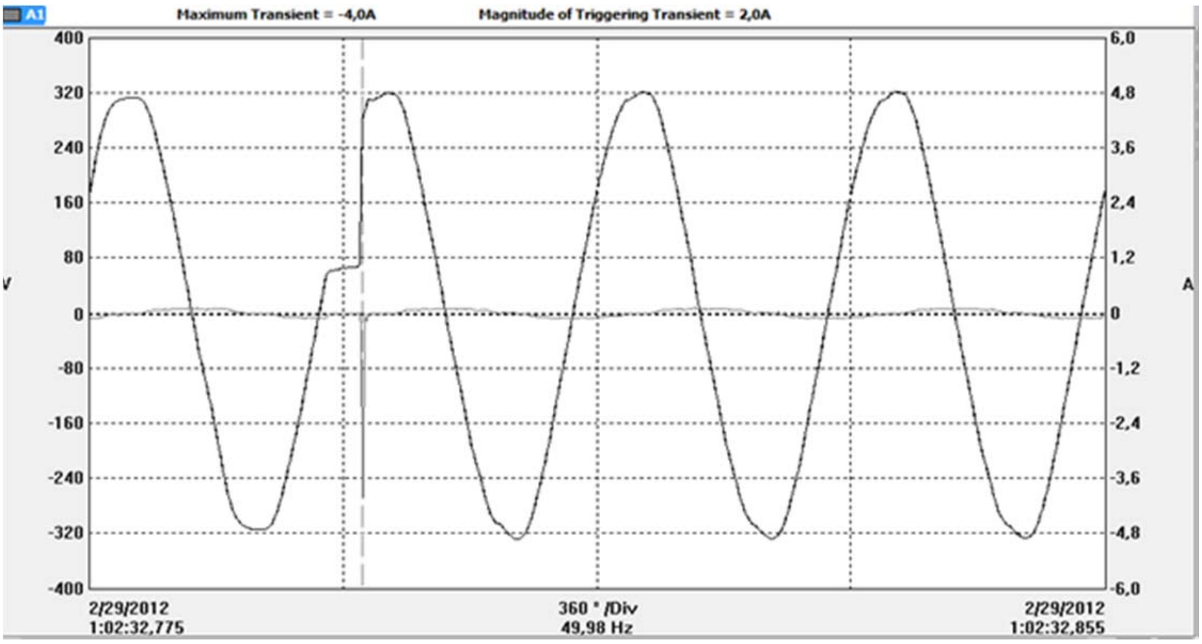


Figure 16. The voltage wave perturbation during the transfer by a source to another due to the time switching delay when the sources are not synchronized

The STS adopted makes the transfer only when the sources are synchronized or when are not synchronized but characterized by a low phase shift. So another test was to change the feeder of the UPS by grid choosing a phase opposite to the other source, this was realized reversing the upstream UPS socket.
In the case, showed in figure 17, the load is powered by S2 (utility power). Since the priority source is the S1 (the UPS) the STS should transfer the load when the S1 is not affected by failure. The transfer cannot be operated in fact as it's possible to see the STS display shows a warning signal due to the sources types that are not synchronized and characterized by a high phase shift (in this case ϕ=180°).

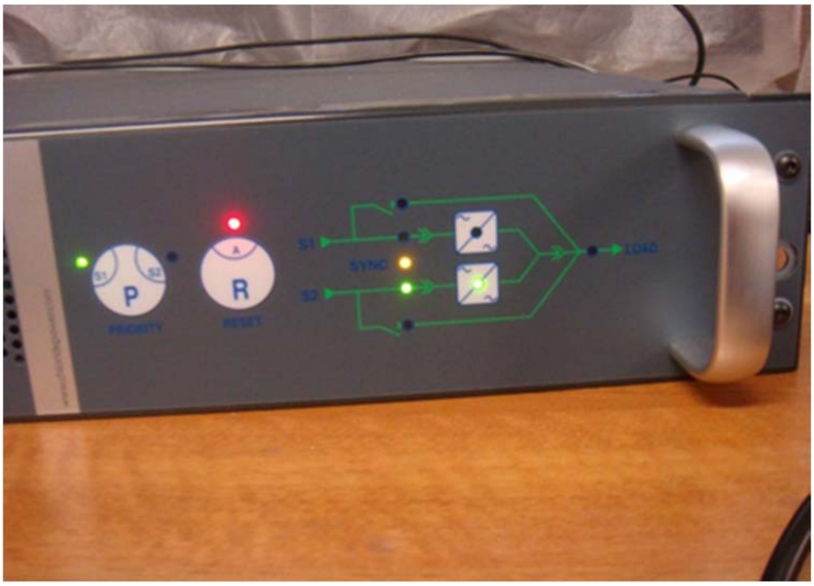


Figure 17. Warning signal given by the STS display: the transfer cannot be operated because the sources are not synchronized and characterized by a high phase shift

In conclusion it was established that the adoption of STSs to improve the reliability of the power system doesn't introduce relevant perturbations during the transfer from a source to another due to a possible failure, so regarding the protection systems there are not problems instead as at the start-up of the electronic equipment.

Protection coordination, transients mitigation and double protection system

The protective device (PD) needs to have settings that allow for the temporary condition of the equipment start up to persist without tripping. The selection of overcurrent protection devices is more difficult when high inrush currents must be tolerated. The overcurrent protection has to react quickly to overload or short circuit but not interrupt the circuit when the inrush current flows.
Considering the service time of all equipment in a data center, long also a lot of years, it is a technical inadmissible inaccuracy to maintain after the fast start up a PD setting inadequate.

Short-circuit tripping relays (instantaneous or slightly time-delayed) are intended to trip rapidly the circuit-breaker on the occurrence of a fault current. A selective discrimination is achieved by automatic protective devices if a fault condition, occurring at any point in the installation, is cleared by the protective device located immediately upstream of the fault, while all other protective devices remain unaffected and an insensitivity to local fault is guaranteed for the other parts of the system and for the supplying source especially if UPS.

For the modular circuit-breakers there is a wide variety of tripping devices which allow a user to adapt the protective performance of the circuit-breaker to the particular requirements of a load.
International Standard IEC/EN 60898-1 [21.s] defines the rated current I_n of a circuit breaker for low voltage distribution applications as the current that the breaker is designed to carry continuously (at an ambient air temperature of 30 °C). It classifies by the letters "B", "C" or "D" the instantaneous tripping current, that is the minimum value of current that causes the circuit-breaker to trip without intentional time delay (i.e., in less than 30 ms), expressed in terms of I_n:

- B above 3 I_n up to 5 I_n ;
- C above 5 I_n up to 10 I_n ;
- D above 10 I_n up to 20 I_n .

The PDU manufacturers recommend automatic protection devices for the equipment provided with a rating current value I_n higher than the load current value and a magneto-thermal protection curve of type C.
A protective device characterized by a rating current I_n higher than the load current and by a curve C presents a weak protection coordination permitting a long permanence of short circuit currents lower than the PD instantaneous tripping current.

For data centers a serious failure can be constituted by the loss of an essential PDU, so the failure of each supplying circuit not adequately selected and cleared can cause a more general perturbance/overload/failure with an impact equivalent to a “single point of failure” (SPOF) involving the switchboard section or all the UPS supply [1] [28.s; 3.p].

As already introduced, equipment like electronic components exhibit excessive inrush currents at start up that may cause the tripping of protective devices not adequately coordinated [26.s]. The philosophy of mitigation and/or control of switching transients can be accomplished through the following methods:

- by temporary insertion tolerant inrush currents,
- by resistance in series in the circuit,
- by proper switching sequences.

Starting systems for equipment should to solve the problem of inrush current and to allow an adequate protection coordination.
A starting system needs a configuration of a double switching at level of switchboard section or at the level of equipment input (figure 18).

[1] Structural single points of failure are all the places in the one-line from the utility entrance to the critical loads in which one component failing causes the system to fail. The reliability of data centers is improved eliminating the single points of failure. In the standard ANSI/TIA-942 each step up, in the tier classification, eliminates some of the previous levels SPOF until tier IV which eliminates all of the structural SPOF.

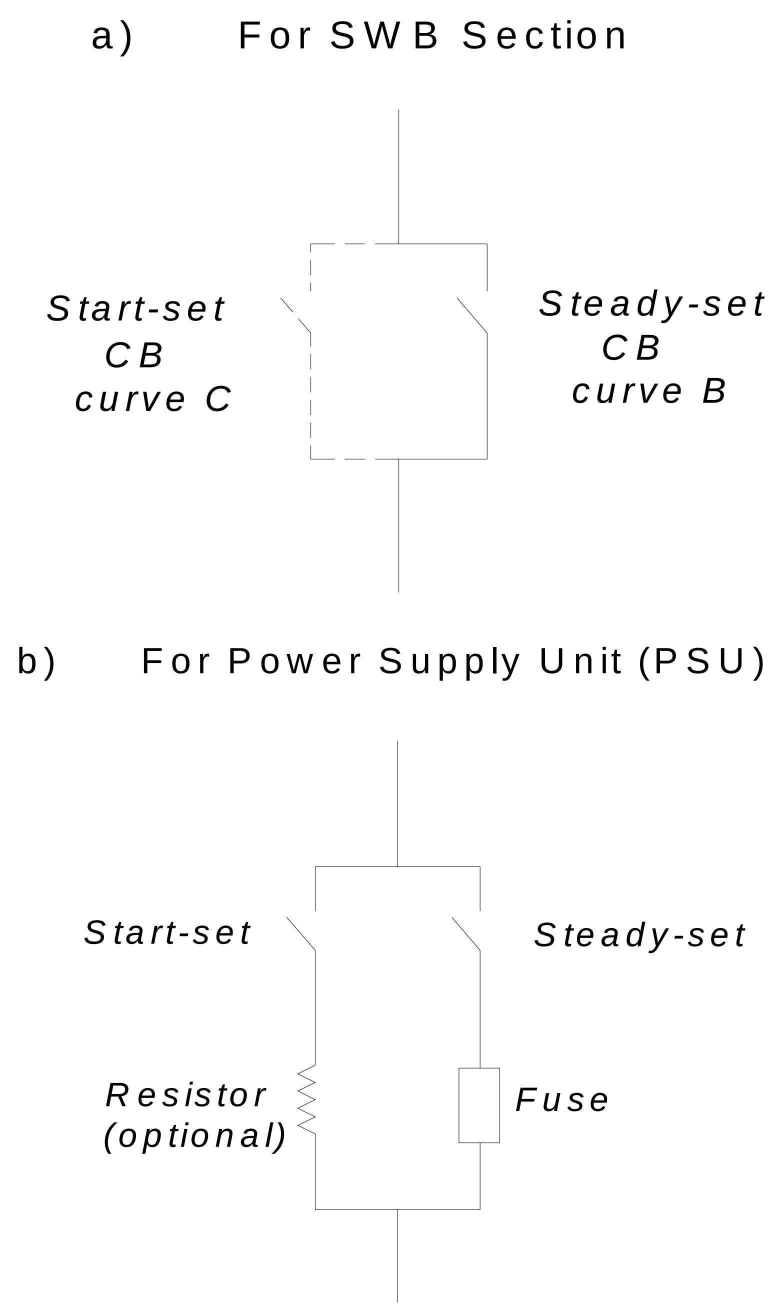


Figure 18. Starting systems for equipment: configuration of a double switching at level of switchboard section or at the level of equipment input

The double switching system is a parallel combination of a start-set and a steady-set systems that allows a double protection by the two conditions for a same derived circuit.

At level of switchboard section (S1-2A,B,C of figure 1), the start-set can be constituted by a circuit breaker with a time curve coordinated with the inrush current, while the steady-set by a circuit breaker coordinated with the equipment steady current. The circuit breaker of the start-set in withdrawable version can be multiuse for the insertion of more circuits.

At the level of equipment input (PSU input of figure 1), the double switching is needed for each input of a dual corded equipment.

The start-set can be constituted by:

- a switch for a direct insertion. In this case the equipment starts at inrush current so the upside protection of the same equipment has to be coordinated;
- a switch coupled to a current limiter as a resistance that reduces the starting current to a value compatible with a steady protection of the same equipment.

The steady set can be constituted by a switch coupled to a fuse coordinated with the equipment steady current.
The actual constitution of the double switching can be optimized in reduced versions or fitted devices.
The insertion of the circuit or of the equipment is operated by the start-set, being open the steady set. When the start-up is stabilized, it is necessary to operate the transition inserting the steady-set before breaking the start-set.
Considering the long service of all equipment in a data center the starting process does not need automation, but it is executed manually at initial start-up or after an accidental shutdown.

Synchronized transition by mobile UPS

During the life cycle of the system the load balancing is recommended to be monitored. In the data center evolution for optimizing the load balancing could be necessary to change the feeding phase (*s* in the example shown in the figure 19) of a pair of circuits of a dual-corded equipment.

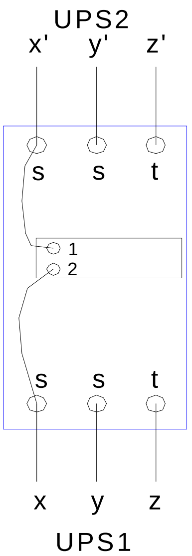


Figure 19. circuits pair of a dual-corded equipment without feeding phases balance

To ensure the synchronism during the phase transition in a cautious way, a local mobile online UPS can be used as a synchronizing “shuttle” as shown by 9 steps in figure 20.

The dual corded PDU supplied by three pairs of circuits can work also without a phase of a pair (figure 20, step III).

The UPS can be synchronized on the phase (s) of one of the supplying circuits pair in the starting situation (figure 20, step III) and after substitutes it (figure 20, step IV).

The dual-corded equipment can be only supplied by the UPS isolated (figure 20, step V).

Supplying the online UPS by new phase (r), the equipment can be transferred by a phase (s) to another (r) without fluctuations thanks to the double conversion (figure 20, step VI).

At the end the new pair of circuits, characterized by new phase (r), can supply the equipment (figure 20, step IX) and the PDU balancing is obtained [31.p].

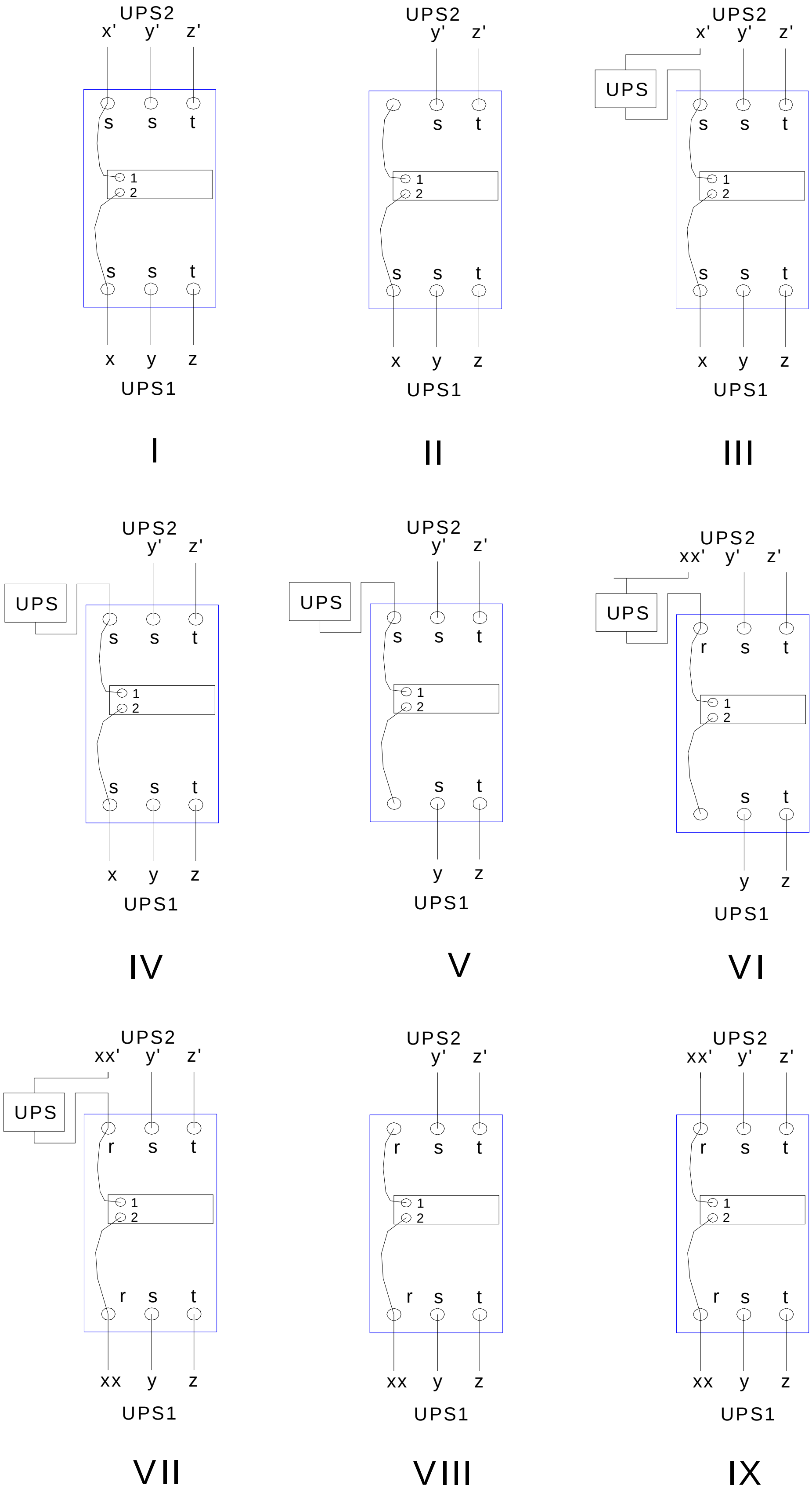


Figure 20. Synchronized transition by mobile UPS the feeding phase of a circuits pair of a dual-corded equipment

Chapter 2.2

Distribution Architecture in Hospitals: Complete & Medical IT-System

Introduction: protective measures for the safety in electrical installations

Standards provide protective measures for the safety of people, livestock and property against damage which may arise, where the following hazards may be featured:

- shock hazard by shock currents;
- fire hazard or excessive temperatures expected to cause burns and other injurious effects;
- ignition of a potentially explosive atmosphere;
- undervoltages, overvoltages and electromagnetic influences likely to cause or result in injury or damage;
- loss service continuity or power supply interruptions and/or interruption of safety services;
- arc flash hazard or arcing faults, likely to cause blinding effects, burns, excessive pressure, and/or toxic gases;
- mechanical movement of electrically activated equipment.

People and livestock shall be protected against injury and property shall be protected against damage as a consequence of the above mentioned hazards. The installation shall have an adequate level of immunity against electromagnetic disturbances. The sizing of components shall be determined for both normal operating conditions and for fault conditions according to:

- the admissible parameters, as design current, voltage drop, steady current capacity etc.;
- their admissible maximum temperature;
- the prospected electromechanical stresses due to short-circuit currents and ground faults;
- other mechanical stresses to which the components can be subjected;
- the method of installation.

For economic and reliable design of an installation within thermal and voltage drop limits, an assessment of maximum demand is essential. In estimating the maximum demand of an installation, or part thereof, diversity may be taken into account. Where the provision of safety services is required, the characteristics of the sources of supply for safety services and/or standby systems shall have adequate capacity, reliability and rating and appropriate change-over time for the operation specified.
The following characteristics should be considered:

- selection of the protective device in order to achieve fault discrimination
- selection of the protective device in order to achieve fault discrimination

- number of circuits,
- multiple power supplies,
- use of monitoring devices.

An automatic supply of a safety service is classified as follows according to change-over time of its availability (Table 1):

- no-break: an automatic supply which can ensure a continuous supply within specified conditions during the period of transition, for example as regards variations in voltage and frequency;
- very short break: 0,15 s;
- short break: 0,5 s;
- medium break: 15 s;
- long break: more than 15 s.

Table 1. changeover time availability of safety service automatic supply

Class 0 (no break)	**Automatic supply available at no-break**
Class 0,15 (very short break)	**Automatic supply available ≤ 0,15 s**
Class 0,5 (short break)	**Automatic supply available ≤ 0,5 s**
Class 5 (average break)	**Automatic supply available ≤ 5 s**
Class 15 (medium break)	**Automatic supply available ≤ 15 s**
Class > 15 (long break)	**Automatic supply available in more than 15 s**
NOTE1: Generally it's unnecessary to provide a no-break power supply for ME equipment. However certain microprocessor-controlled equipmentmay require such a supply.	
NOTE2: Safety services provided for location having differing classifications should meet that classification wich gives the highest security of supply.	

The IEC publication 60364-4-41 [8.s] "Electrical installations of buildings" fifth edition states that the fundamental rule of protection against electric shock is that hazardous-live-parts must not be accessible and accessible conductive parts must not be hazardous live, neither under normal conditions nor under single fault conditions.
Protection under normal conditions is provided by basic protective provisions (protection against the direct contact in the fourth edition) and protection under single fault conditions is provided by fault protective provisions (protection against the indirect contact).
The following protective measures are generally permitted:

- protection by automatic disconnection of supply,
- double or reinforced insulation (Class II equipment),
- electrical separation for the supply of one item of current-using equipment,

- extra-low-voltage (Safety and Protective Extra-Low Voltage SELV and PELV).

Protective measure by double or reinforced insulation is a protective measure in which basic protection is provided by basic insulation and fault protection is provided by supplementary insulation or equivalent measures of reinforced insulation. Where this protective measure is to be used as the sole protective measure and it consists entirely of equipment with double insulation (Class II equipment), it shall be verified that the installation will be under competent supervision in normal use so that no change is made that would prejudice the effectiveness of the protective measure.

Automatic disconnection of supply is a protective measure in which:

- basic protection is provided by basic insulation of live parts or by barriers or enclosures,
- fault protection is provided by protective grounding, equipotential bonding and automatic disconnection in case of a ground fault. Where this protective measure is applied, Class II equipment may also be used.

Exposed-conductive-parts shall be connected to a protective conductor under the specific conditions for each type of system grounding.
The types of system grounding are classified as: TN-system, TT-system and IT-system [7.s].
The first letter T (Terre =Ground) or I (Isolated) is the relationship of the power system to ground, respectively solidly grounded or ungrounded:

- T = direct connection of one point to ground;
- I = all live parts isolated from ground, or one point connected to ground through a high impedance.

The second letter N or T is in relationship of the exposed-conductive-parts of the installation to ground:

- T = direct electrical connection of exposed-conductive-parts to ground, independently of the grounding of any point of the power system;
- N = direct electrical connection of the exposed-conductive-parts to the grounded point of the power system (in a.c. systems, the grounded point of the power system is normally the neutral point or, if a neutral point is not available, a line conductor).

In other words, the second letter N or T is for the connection of the exposed conductive parts respectively to the same grounded point of the supplying power system (TN-system Figure 1a) or to an independent ground electrode (TT-system Figure 1b).
Subsequent letter(s) (if any) - Arrangement of neutral and protective conductors:

- S = protective function provided by a conductor separate from the neutral conductor or from the grounded line (or, in a.c. systems, grounded phase) conductor.
- C= neutral and protective functions combined in a single conductor (PEN conductor).

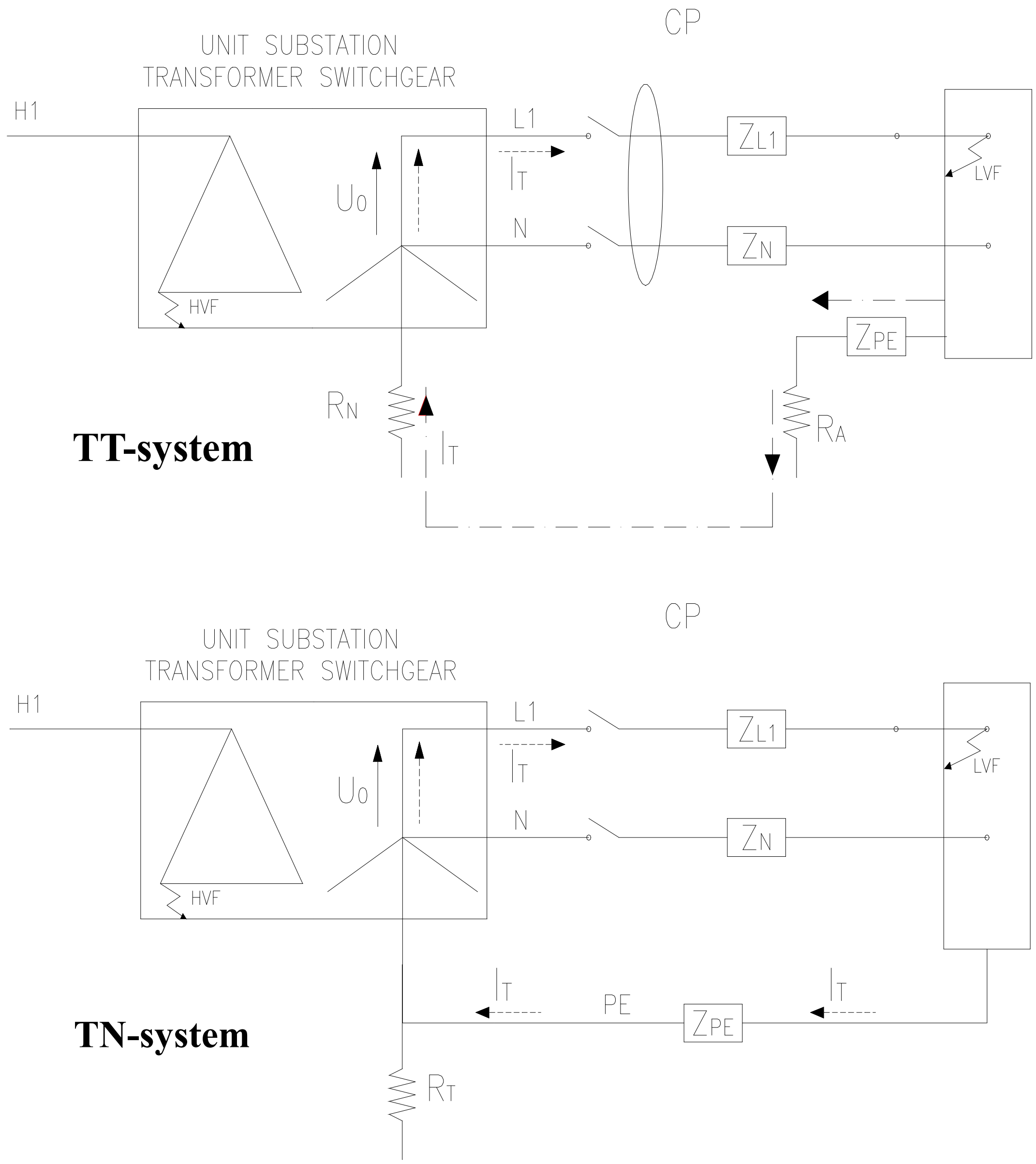


Figure 1. Types of system grounding a) TN-system; b) TT-system

TN-S system is the most general case of a TN-system and presents the neutral N and the protective ground fault conductor PE as being separated. Besides, the TN-C system provides in the same conductor (PEN) both the protective ground fault conductor PE and the function of the neutral N. For this system, it is not possible to use residual protective devices. Finally, the TN-C-S system is the combination of the TN-C system followed by the TN-S system.

TN-system and TT-system are erected to promote the circulation of ground-fault current and to favor automatic disconnection of supply.
On the contrary, *IT-system* is erected to prevent, limit and control the circulation of the leakage current [10.s].

IT- Systems and Business Continuity Management

In IT-systems, live parts are insulated from ground or connected to ground through sufficiently high impedance.

The fault current is then low in the event of a single fault to an exposed-conductive-part or to ground and automatic disconnection is not imperative.
Provisions shall be taken, however, to avoid risk of harmful pathophysiological effects on a person in contact with simultaneously accessible exposed conductive- parts in the event of two faults existing simultaneously [29.s].
It is recognized that there is a great variety of applications of IT-systems.
Examples of applications where functional safety can be requested depending on the risk analysis are:

- chemistry,
- mines,
- marine,
- hospital, operating theatre and intensive care unit in hospitals (group 2 medical locations),
- photovoltaic farms,
- railway signaling systems,
- control systems (e.g. in nuclear power plants).

Equipment under control EUC are defined by standard IEC 61557 [17.s] equipment, machinery, apparatus or plant, used for manufacturing, process, transportation, medical or other activities, whose power supply system is an IT system .

The supply source system for safety services and/or standby systems of a IT-system consists generally of a UPS, an insulation transformer and their connections that is a relevant Safety Supply System SSS (Figure 2).

Safety function is defined function to be implemented by a safety-related system or other risk reduction measures, that is intended to achieve or maintain a safe state for the EUC, in respect of a specific hazardous event.
Safety-related system SRS is designated system that both implements the required safety functions necessary to achieve or maintain a safe state for the EUC; and is intended to achieve, on its own or with other safety-related systems and other risk reduction measures, the necessary safety integrity for the required safety functions.

The IEC 61557-15 [17.s] defines basic safety functions as well as their related levels of functional safety (SIL) and defines feasible measures and principles to develop and validate the monitoring devices and systems under functional safety aspects.

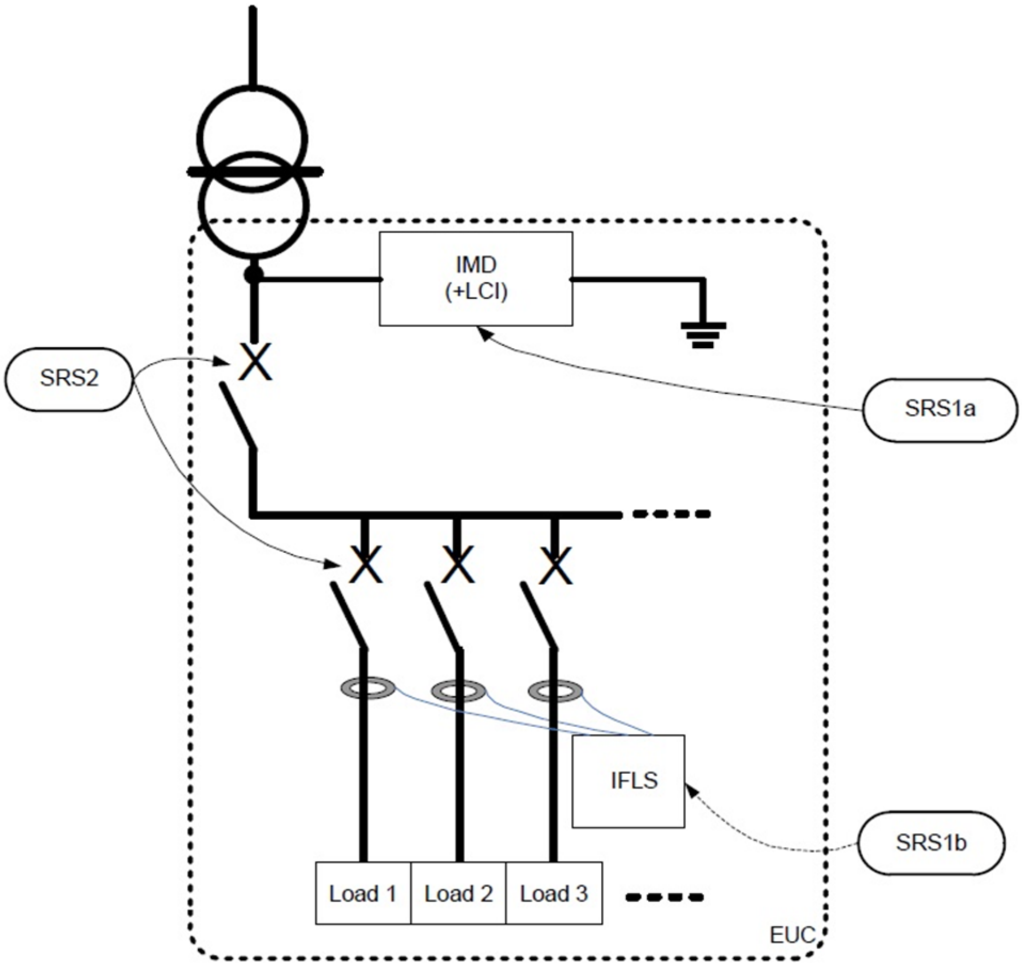


Figure 2. Safety Supply System SSS constituted by a UPS, an insulation transformer and their connections

Functional safety may be applicable to IT systems where safety is based on the following monitoring devices (a-c) and on additional safety related measures as protective devices (d-e) and competent people (f) [13.s]:

a. insulation monitoring devices (IMDs);
b. insulation fault location systems (IFLs);
c. residual current monitoring devices (RCMs)
d. overcurrent protective devices (OPDs);
e. residual current protective devices (RCDs)
f. human competent reaction of maintenance staff (HCR).

IMDs and IFLSs are not protective devices in general, but their function can be seen as safety functions which are part of the protective measures in an IT system involving human competent reaction (HCR).

Where a residual current operating device (RCD) is used, tripping of the RCD in event of a first fault cannot be excluded due to capacitive leakage currents.
The design of the IT-system as the EUC, the IMD or IFLS, the insulation transformer, has to select device capable of safe operation in all specified environments, for example temperature, humidity, vibration, EM phenomena, pollution degree, overvoltage category, altitude.

Human Competent Reaction HCR

In hospitals doctors, surgeons, administrators, medical devices are rightly at the forefront, but electrical and technological systems and team of technicians are wrongly considered as ancillaries. In fact a functional safety can be also based on the technical operation required to take action to restore the safe state with the shortest practicable delay of competent people (Human Competent Reaction HCR) that are supposed to be present when a monitoring alarm occurs.
The design of the safety-related systems shall take into account human capabilities and limitations and be suitable for the actions assigned to operators and maintenance staff.
The complexity of the work activity shall be assessed before the activity starts requiring the appropriate choice of skilled, instructed, or ordinary people for carrying out the work activity. Consequently, electric power systems can offer different performances in relation to the competence of the operators, considering that safety has to be the priority of the power system.

Requirements of high availability and integrity are satisfied by appropriate system integrated by an efficient business continuity management (BCM). The BCM is effective to the degree that it recognizes the importance of analyzing its objectives and the organization's needs.

The SRS (safety related system according to the IEC 61508 series [16.s]) corresponds to the protective measures related to the EUC. This SRS can be split into different levels of protection measures:

- SRS 1a: safety related system in charge of monitoring the IT system and in charge of warning in case of single fault. SRS 1a is based on safety functions provided by IMD.
- SRS 1b: safety related system in charge of monitoring feeders and in charge of locating a single fault, thus easing maintenance operations. SRS 1b is optional and based on safety functions provided by IFLS.
- SRS 2: safety related system in charge of tripping the complete IT system or a part of this IT system when a second insulation fault occurs before the single fault was repaired.

SRS 2 is based on safety functions provided by circuit-breakers.
If IT system is used in order to prevent circulation of hazardous currents or of arcs when a first insulation fault occurs, the SRS corresponds to the protective measures related to the EUC and the automatic disconnection is or should be imperative.
If IT system is used for continuity of supply reasons, the SRS corresponds to the protective measures related to the EUC and to the SSS, the automatic disconnection has to be avoided for the first fault and admitted only as emergency for the second fault.

In cases where an IT system is used for avoiding the loss of service continuity of supply, an insulation monitoring device shall be provided to indicate the occurrence of a first fault from a live part to exposed-conductive-parts or to ground on EUC. This device shall initiate an audible and/or visual signal which shall continue as long as the fault persists. If there are both audible and visible signals, it is permissible for the audible signal to be silenced. It is recommended that a first fault be eliminated with the shortest practicable delay and so the HCR becomes essential (Table 2).
When a fault occurs during a surgical operation, the protection system shall include a count-down time so that emergency response team must solve the problem before the system collapses and it's necessary to change the operating room.

Table 2. IT-System types, functional safety requirements

IT-System			
Functional Safety	**IT**	**IT-M**	***Safety Related System SRS***
	protective reaction		
	Automatic Disconnection	**HCR**	
avoid arc /shock currents	**Requested**	**Accepted**	**equipment under control EUC**
Service Continuity	**In Emergency**	**Requested**	**complete system (source&equipment)**

Coherently, the design of the complete IT-system that is of the EUC, the IMD or IFLS, the insulation transformer, the upper SSS has to select device capable of the special safe operation. The SSS has to be adequate to its functional safety and apply the protection of double or reinforced insulation guaranteeing an inherent safety.

It is well known that a complete risk assessment has to consider not only the probability of occurrence of the loss of service continuity, but also its potential consequences, at this aim the SSS characteristics can allow to compensate the importance of consequence.

In this manner the components has to be of high quality, adequately installed and oversized especially against all the causes of prospected supply disconnection or out of the service, as over-currents, ground faults and over-voltages.

IT-M Systems: complete system SSS & EUC

General requirements for IT-M

In group 2 medical locations, the medical IT system shall be used for final circuits supplying, as EUC, ME equipment and ME systems intended for life support, surgical applications and other electrical equipment located in the "patient environment" or that may be moved into the "patient environment".

The medical IT system shall be equipped with an insulation monitoring device (IMD) (Figure 3).

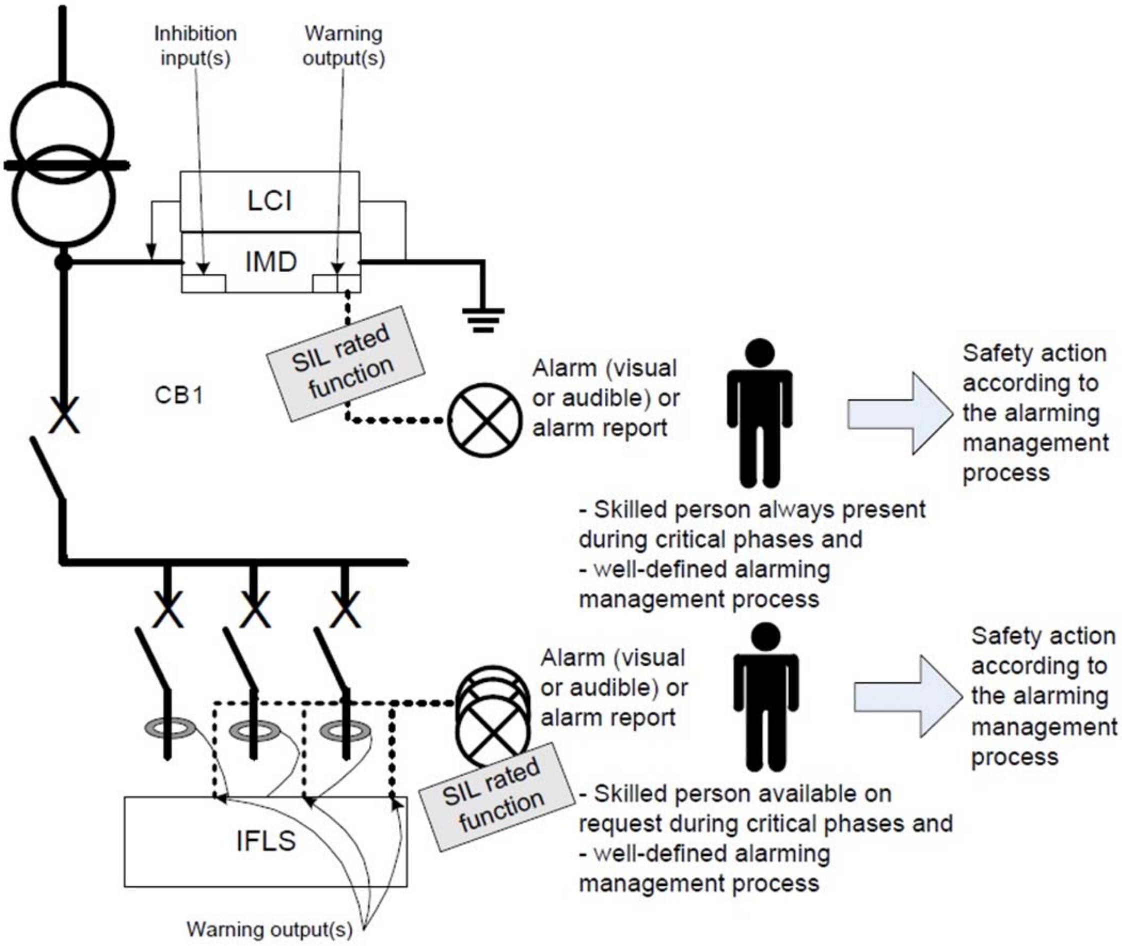


Figure 3. Medical IT system equipped with an insulation monitoring device (IMD) and insulation fault location systems (IFLS)

For each medical IT system, an acoustic and visual alarm system incorporating the following components shall be arranged at a suitable place so that it can be permanently monitored (audible and visual signals) by the medical staff and the technical staff (Fig. 4):

- a green signal lamp to indicate normal operation;
- a yellow signal lamp which lights when the minimum value set for the insulation resistance is reached. It shall not be possible for this light to be cancelled or disconnected;
- a specific signal for overload and high temperature for transformers;
- an audible alarm which sounds when the minimum value set for the insulation resistance is reached.

This audible alarm may be silenced;
the yellow signal shall go out on removal of the fault and when the normal condition is restored.

a) 

b) 

Figure 4. an acoustic and visual alarm system a) in an operating room; b) incorporated in the operating room switchboard next to the operating room

At least one single-phase transformer for medical location or functional group of medical locations shall be used to form the medical IT systems for portable and fixed equipment. The rated output shall not be less than 0,5 kVA and shall not exceed 10 kVA (Fig. 5a). The transformer shall be installed in close proximity to the medical location, for example at a maximum distance of 25 m between the output terminals of the transformer and current using equipment (Fig. 5b).

The leakage current of the output winding to ground and the leakage current of the enclosure, when measured in no-load condition and the transformer supplied at rated voltage and rated frequency, shall not exceed 0,5 mA.

Local alarming and local transformer monitoring warning IEC 61557-15 will take into account safety functions involving human reaction, on the conditions that:

- at least one person is supposed to be present when the alarm occurs, e.g. in the operating theatre of a hospital (both surgeon and nurse are supposed to be present);
- the reaction of a human person facing an alarm is part of a well-defined alarming management process, e.g. a facility manager is supposed to be available on request.

a) 

b) 

c) 

Figure 5. a) one single-phase transformer for medical location with a rated power of 7,5 kVA. b) with a rated power of 5 kVA; c) the single-phase transformers are installed next outside the operating rooms (about 10m between the output terminals of the transformer and current using equipment)

Typical configuration of design, overvoltages on the safety supply system

In a group 2 medical location the SSS has to be adequate to its functional safety; in case of a single fault of supply, a total loss of power shall be prevented by the total selectivity of the protection devices and by effective technical measures to ensure the continuity of mains power as the provision of two supply independent or the main net-supply and a local additional power supply unit or the provision of a ring-structure, capable to back up the mains supply.

In a group 2 medical location, a safety power supply is required, which will energize the installations needed for continuous operation in case of failure of the general power system, for a defined period within a pre-set switch-over time.
In particular, it is recommended to consider for the SSS (UPS + Insulation Transformer) components and configurations capable to guarantee an inherent safety, to apply the protection of double or reinforced insulation, an accurate installation of the components guaranteeing for them the pollution severity grade 3 (conductive pollution or non-conductive pollution that becomes conductive due to condensation), an overvoltage category III (complying with the requirements of availability and security special) [13.p] and so avoiding the implementation of surge protective devices SPDs at the input of the insulation transformer [15.p; 16.p] or inside the SSS (Table 3).

Table 3. Required impulse withstand voltage for equipment with different nominal voltages of the installations

Nominal voltage of the installation [V] *		**Required impulse withstand voltage for [kV] *****			
Three-phase systems **	**Single-phase systems with middle point**	**Equipment at the origin of the installation (overvoltage category IV)**	**Equipment of distribution and final circuits (overvoltage category III)**	**Appliances and current-using equipment (overvoltage category II)**	**Specially protected equipment (overvoltage category I)**
-	120-240	4	2,5	1,5	0,8
230/400 ** 277/480 **	.	6	4	2,5	1.5
400/690	-	8	6	4	2.5
1000	-	12	8	6	4

*According to IEC 60038.
** In canada and USA for voltages to earth higher than 300 V, the impulse withstand voltage corresponding to the next highest voltage in column one applies.
*** This impulse withstand voltage is applied between live conductors and PE.

These electric sources and the electrical supply system for safety services should be arranged in such a way that periodic verification and necessary maintenance can be achieved without neither decreasing the availability of the electric power supply for the safety services nor prejudicing the same electric power supply (Figure 6).

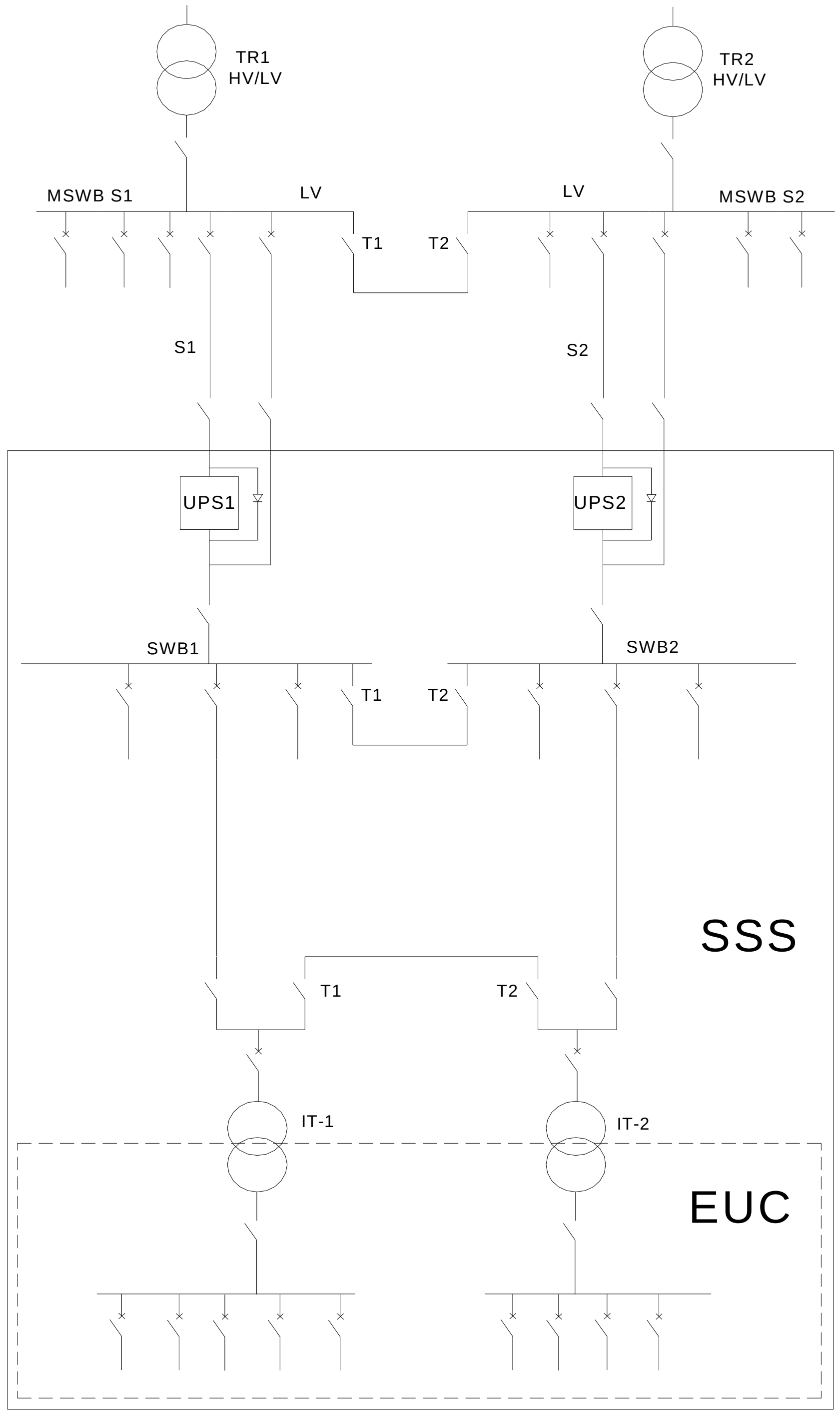


Figure 6. An example of a system that allows periodic verification and necessary maintenance without decreasing the availability of the electric power supply and not prejudicing the same supply

Inrush currents of electro-medical equipment: field measurements

There were carried several measures and registrations of current absorptions relating electro-medical equipment supplied by UPSs working in actual hospitals in Rome, Italy.

It's reported below, as example, a registration of current absorption relative to two equal linear accelerators (LINAC) supplied by a three-phase online UPS of 120 kVA.
The UPS, as shown in the scheme (Fig.7), is fed by LV Main Switchboard located in the electrical enclosure with the cable feeds "UPS" and "UPS by-pass" protected by four pole magneto-thermal automatic circuit breakers with a rated current I_n equal to 250A and a breaker capacity I_k equal to 36 kA.

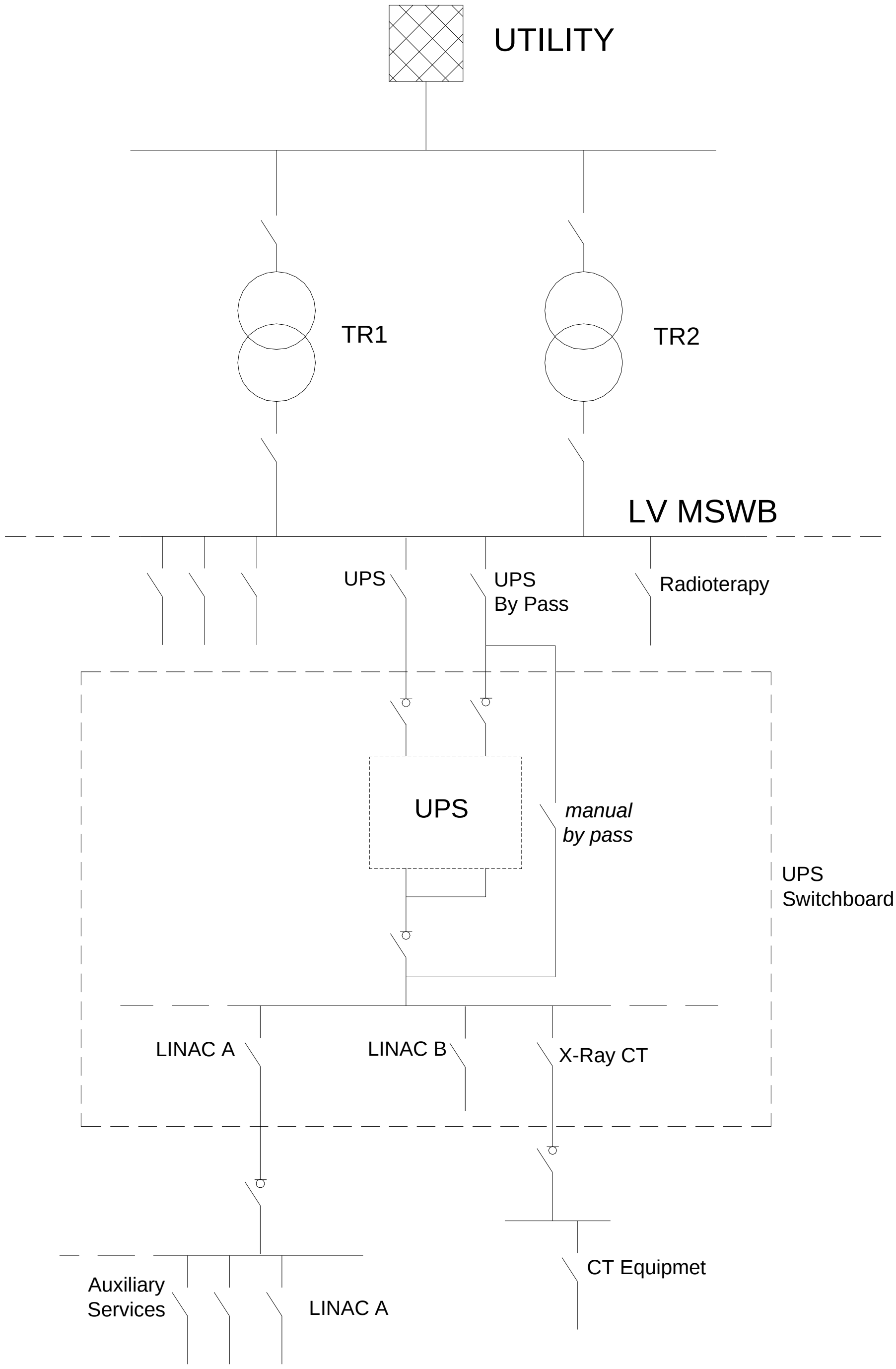


Figure 7. The single-line diagram of an hospital in Rome, showing in particular the supply of three electro-medical equipment by an Uninterruptible Power Supply UPS

Downstream the UPS Switchboard (Fig.7), there are three medical equipment: two linear accelerators (LINAC) and one X-ray computed tomography (CT) [13.s]. As automatic circuit

breakers for the three medical devices were adopted four pole magneto-thermal breakers with a rated current I_n equal to 100 A and a breaker capacity I_k equal to 25 kA.
In contrast to the CT, the LINAC circuit breakers fed not only the medical device but also all the auxiliary service of the relative medical room.

Electrical data sheet of the LINAC, shown in the Fig. 8:

- Voltage supply: 400V ±5% (3LNPE)
- Frequency: 50 Hz ±1%
- Line cable resistance : ≤ 150 mΩ
- Apparent power with cosφ shown in the table below:

Operating mode	Pa [kVA]	P [kW]	I [A]
Stand-by	3	2,7	4
Ready	20	18,0	26
Bearn on	45	40,5	58

Figure 8. Linear accelerator equipment used for radiation therapy

A collection of current absorption registrations was carried out by a network analyzer using current clamps with full scale of 150 A. It's shown below (Fig. 9) a registration achieved on the UPS Switchboard when the two LINAC were working and CT was not. The absorption due to ancillary services is constant and of negligible intensity compared to the electro-medical equipment.

The sampling period was set to 1 s, which is the minimum time sampling of the instrument adopted. The graph shows three different trends of RMS current, I_{RMS}, referring to the minimum, average and maximum value recorded in the sampling period. As can be seen the peak value recorded I_{RMSMAX} is equal to 146 A with a duration of less than one second in fact in the same sampling period was recorded I_{RMSMED} equal to 105 A and a I_{RMSMIN} equal to 82A.

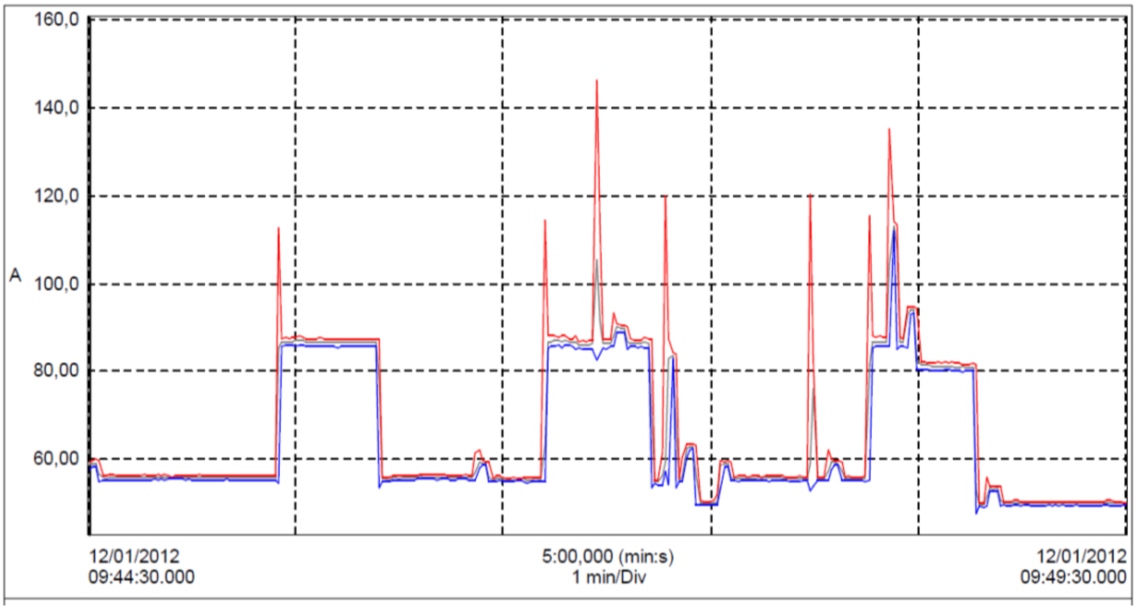


Figure 9. Current absorption due to 2 linear accelerators equipment (LINAC A and B) working simultaneously

In the Figure 10 it's shown a registration achieved on the LINAC A Switchboard, the absorption due to ancillary services is constant and of negligible intensity compared to the electro-medical equipment. The sampling period was set to 1 s, as the registration discussed before. As it's possible to see in the graph, the peak value recorded I_{RMSMAX} is equal to 102 A with a duration of less than one second in fact in the same sampling period was recorded I_{RMSMED} equal to 40 A and a I_{RMSMIN} equal to 28A.

From the graph it can be understood as the inrush current is due to the start of production of the electron beam; once the transient is completed the absorption is reduced remaining constant for few seconds, in this case persisted for about 20 seconds, with an absorption of about 47 A.

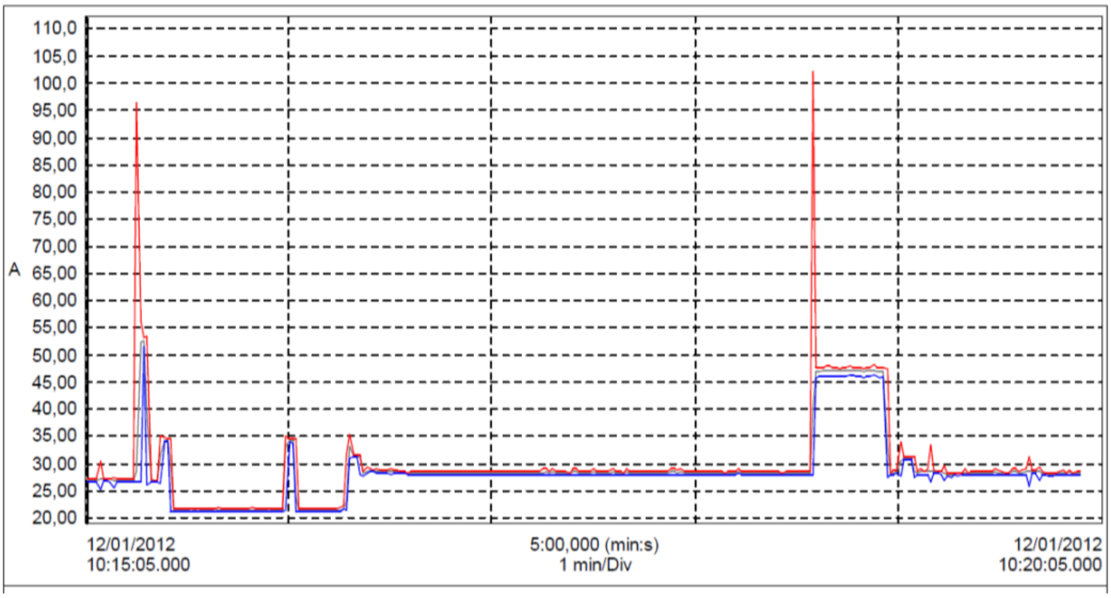


Figure 10. Current absorption due to 1 linear accelerator equipment (LINAC A)

Comparing the measured values in this recording with the data sheet of the device reported in the previous table, it can be deduced has never occurred the full power operation (58 A), while for most of the time the device was in *ready mode* (about 28 A including the modest absorption due to other services).

Since the two accelerators are of the same type, it can be understood as the maximum peak (146 A), detected in the registration of the absorptions of the two devices simultaneously (Fig. 9), is due to the sum of the inrush of one (about 100 A) and the processing activities of the other (about 50 A).

For most of the time, it can be noted that an accelerator is in operation while the other is in the ready mode. It's not occurred instead the overlap condition of beginning treatment of both accelerators that would cause the absorption of a current equal to about 200 A or greater in case of full power operation of one or both accelerators.

By these measurements, it's possible to affirm that electro-medical equipment exhibit high peak currents at start up. Unlike the electronic equipment in data centers, discussed in the chapter 2.1, the medical equipment service is not long but intermittent (as shown in the example of the linear accelerator) and so starting systems suggested for the PDU loads are not suitable.

In case too medical equipment are simultaneously supplied by an UPS, the excessive current value occurs the UPS bypass operation. To avoid a frequent bypass operation, it's necessary oversize the UPS power to guarantee the start-up of the multiple loads.

To use properly multiple loads simultaneously, the operation manager needs a complete knowledge of the electrical behavior of the medical equipment used in the structure, by monitoring the absorptions in all the different modes of use of the medical equipment [7.p; 7bis.p].

This data knowledge greatly helps to understand if it’s possible to add, in case of need (for example for an extension of the structure), another equipment on the same UPS system or it’s necessary to increase the power of the system or realize a new one [28.p].

Chapter 2.3

Interference of Ground Systems near Critical Power Systems

Introduction. Global grounding system

The standard IEC 61936-1:2010-11 [18.s] "Power installations exceeding 1 kV a.c. Part 1: Common rules" defines the Global Grounding System GGS as an "equivalent grounding system created by the interconnection of Local Grounding Systems LGSs that ensures, by the proximity of the Grounding Systems GSs that there are no dangerous touch voltages".
Such systems permit the division of the ground fault current in a way that results in a reduction of the ground potential rise at the LGS. So that it could be said to form a quasi-equipotential surface. The existence of a GGS may be determined by sample measurements or calculation for typical systems. Typical examples of GGSs are in city centers, urban and industrial areas with distributed low- and high-voltage grounding.
The GGS defined by the IEC Standard appears to include only "intentionally" connected individual GSs. The GGS actually existing in an area (i.e. due to the above listed interaction factors) may coincide or be more invasively extended than the GGS as defined by the standard. In a common area of influence the existing GSs naturally interact with different level of "globality".

The mutual influence between the GSs in a same industrial or/and urban area can be due to:

- *intentional* (direct) connection: the individual GSs are connected by means of MV cable sheaths, buried ground conductors, counterpoises, etc.
- *non intentional* connection: the GSs are connected by common buried metal structures with different primary function, e.g. armor of concrete structures steel pipes, other extraneous conductive parts ExCPs, etc.
- *conductive* coupling: "nearby" GSs interfering with each other when they are dispersing fault currents.

So, other GSs interacting with the main one via actual connections or by proximity effect, could be included in the GGS since they not only increase its efficacy under normal condition, but also share the risk ensuing from malfunction of the global system.

A ground fault current that is dispersed by a GS can transfer abnormal touch voltages on a GS that exists closely in the same area (*transferred potential*) [12.s].

Simplified design criteria of individual grounding systems

A Global Grounding System should therefore include also those GSs that, though not directly connected to it, are actually tightly coupled via unintentional connections or conductive coupling. This is often the case of urban or industrial areas, where the GGS actually has a bigger extension than the one defined according to the IEC standard, due to the other GSs and buried conductors that may be present in the area.

At this aim it is possible to define the “globality” level of GSs that share a portion of zone of influence (Figure 1):

- *Isolated;*
- *Interfering;*
- *Interconnected;*
- *Integrated.*

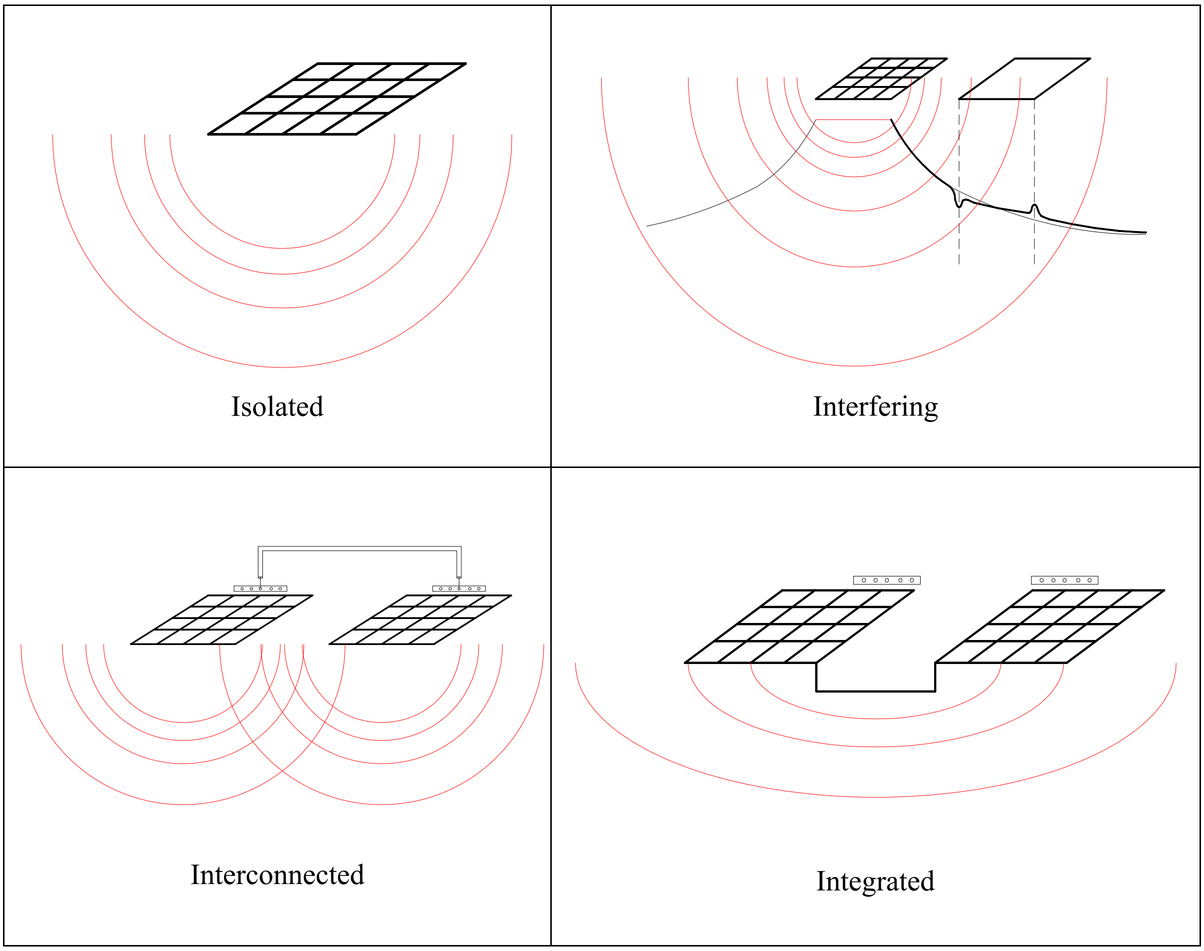


Figure 1. Globality levels of GSs in their zone of influence

Special consideration should be given to HV GS common to the LV if this common system is not part of a GGS [4.s]. In this case it is necessary to verify the efficiency of GSs; the measurements of touch and step voltages and of ground resistance present some operational difficulties.
The greatest difficulty regards the location of the auxiliary electrode; in particular, it has to be placed at a distance outside the area of influence of the GS.
The design of the GS and a preliminary determination of the ground resistance and the ground potential rise can be accomplished as follows:

a) collect design data communicated by the supply network operator of ground fault current I_T for evaluating the ground potential rise GPR and the fault duration t_d that defines the permissible touch voltage;

b) determine the current discharged into soil from GS, based on ground fault current and on appropriate reduction factors;

c) determine the overall impedance to ground, based on the layout, soil characteristics, and parallel GSs, generally the ground resistance R_T [23.s; 24.s];

d) determine the GPR U_G;

e) if the ground potential rise is below the permissible touch voltage and prescribed requirements are met the design is complete;

f) if not, determine if touch voltages inside and in the vicinity of the GS are below the tolerable limits.

If *transferred potentials* cause inadmissible touch and step voltages outside or inside the electrical power installation or interfering GSs have an unbalanced impact on the other ones, it is necessary to proceed with mitigation at exposed location.

Simulation programs allow to analyze, under specific simplifying assumptions of the models used, the behavior of GSs according to their globality level. They can assist the choice of the type and the characteristics of the GS with an analysis of its critical points where it is necessary to mitigate the ground potentials, to improve its behavior in the design phase. In the phase of verification, the programs allow to identify where taking measurements of touch and step voltages prospected critical inside or outside the power installation.

It has been adopted a computer program based on the Maxwell method or partitioned electrode method [23.p]. This method is based on the consideration that the various constituent parts of the electrode assume the same potential, and therefore are divided into parts so elementary such as to assume that in each of them there is a constant current density. Higher the number of parts are and more true is the assumption. The program models a two-layer soil resistivity model.

The interference of Ground Systems GS near Critical Power Systems

The interferences create significant modifications in the surface potentials both on areas relatively large and especially on limited areas. Thus it results unexpected touch and step voltages because the superficial potential presents bumps and potholes.

Analysis of the behavior of two GSs: the floating behavior

In the case of a ground fault in an electrical system that causes an injection of ground current by its GS (active ground electrode), the presence of another GS and, more in general, of other metal bodies buried in the area of influence of the first ground electrode, determines interfering effects that can be of impact and particularly sensitive for special power systems as data centers and hospitals [22.s; 31.s]; (Figure 2) (*interference by buried extraneous conductive part BExCP).*

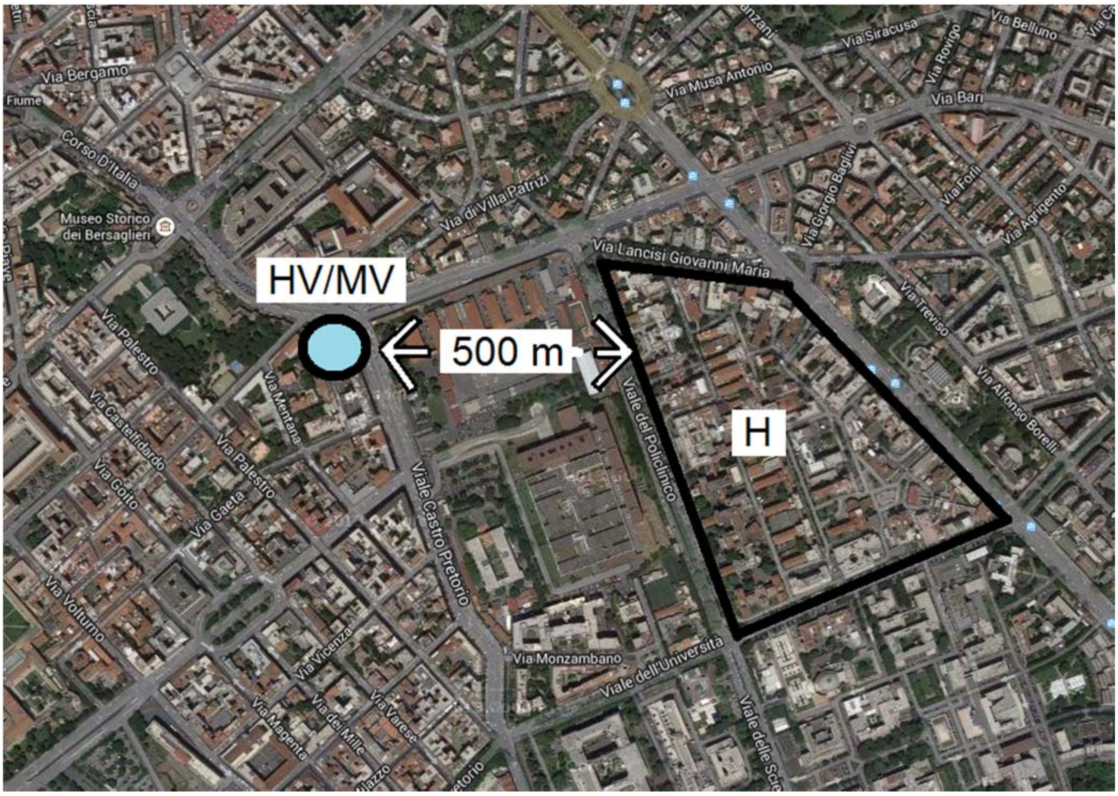


Figure 2. The Polyclinic Umberto I – Sapienza Hosptital is at a sufficient distance of 500 m from one of its feeding substations HV/MV

The most significant interfering effects are:

- the alteration of the distribution of the current dispersed from the various parts of the active electrode, compared to that which occurs in the absence of interfering bodies;
- the distortion of the electric field distribution in the ground, especially in the vicinity of the ground electrodes;
- interfering ground electrode/metal body has a floating behavior, as inert; in fact, it drains currents next to the active electrode and returns these currents in distant areas, establishing local electric fields in the ground;
- the assumption by interfering electrode of potential that gives rise to touch and step voltages and ground potential shifts.

Figure 3 is related to an interfering electrode constituted by a meshed square, being active another square electrode showing the superficial potential variations as local bumps and potholes. Generally, when the electrodes are comparable, the transferred potential on the inert electrode is practically equal to the weighted average of the potentials on the ground in the absence of interfering electrode and from it intercepted.

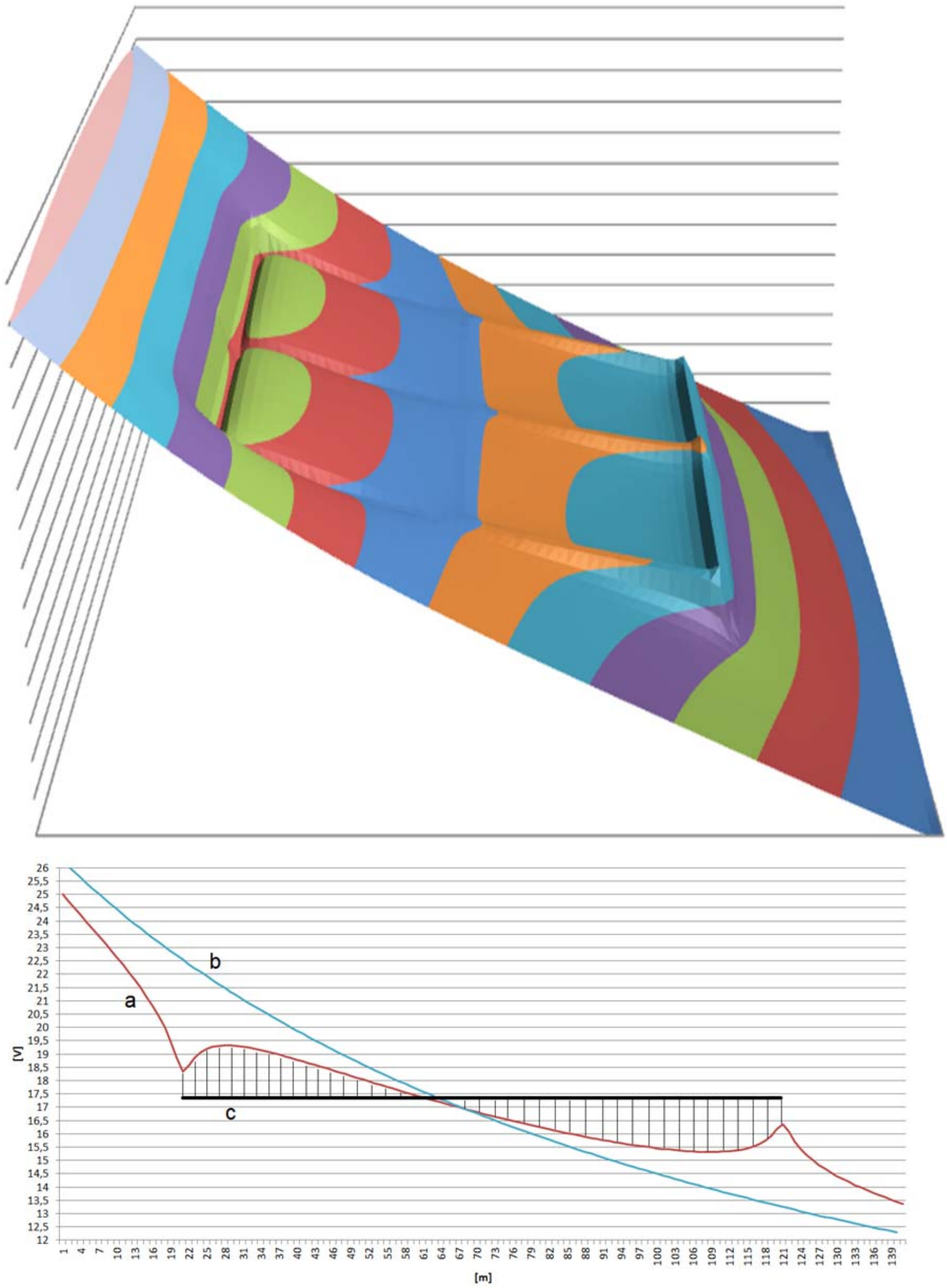


Figure 3. The 3D representation of the surface potentials of an interfering meshed square electrode in influence zone of a bigger square electrode during a ground fault (up).
The down graph represents: the interfering behavior of the surface potential (line a) compared with the isolated behavior (line b) and with the electrode potential (line c)

An effect on the active electrode is the reduction of its ground resistance and ground potential rise. This reduction is negligible if the ground resistances of the electrodes are comparable (the electrodes are comparable if R_A / R_B ranges between about 10 and 0,1).
Worth instead of being considered the reduction which may lead an inert electrode-GGS constituted by more electrodes integrated and/or interconnected with an incomparable interfering electrode system. In particular, a GGS or equivalent electrode present a high "inertia" to the transfer effect and stick a very low potential, close to zero, assumed in the

proximity of the active electrode, where the ground surface potentials maintains non-zero values (*interference by BExCP-GGS*).

The amount of the effects described mainly depends on the following parameters:

- Size, shape, relative positions of the electrodes of the electrode active and inert;
- Degree of the soil homogeneity;
- Structure of the inert system. Typical cases are:
  - a single GS;
  - an aggregate of GSs with some components at considerable distance out of the influence zone of the active electrode;
  - a long electrode capable of exchanging currents with the soil surrounding it.

In conclusion, the Grounding System GS must be designed taking into account also the effects caused by interference.

Active electrode A and inert electrode B.

Let's consider a simplified system of two electrodes A and B, of which the first, active (symbol ^), disperses the current I and assumes the potential U_A^, the second, inert (symbol °) in the area of influence of A, assumes the transferred potential U_B° (Figure 4).
Table 1 shows the results of the study of some simple structures of electrodes buried in a soil with homogeneous resistivity subject to mutual influence during a ground fault or current injection I, particularly in order to show the applicability of the methods and fields of the calculation program adopted [23.s; 24.s].
External electrodes are assumed buried 0,5 m of depth with different square structures: simple, with rods (5m) or with meshes. The active electrode is A and the floating electrode is B. The resistance R_B of the simple square (side = 10 m) can be assumed equal to R_A^ D = 30m of the first case.

The global behavior of B electrode, when assumed as inert-floating, can be defined by the overlap of two opposite and simultaneous behaviors:

- Passive asymmetrical behavior at zero potential. The electrode B behaves as current recipient by its individual elements in which it can be divided, the sum of the currents entering in the b elements Σ-$I°_j$ = -μ_B I is a share (μ_B) of the ground current I from A. Each element reacts locally in order to make zero the potential induced on itself, the global electrode B so behaves asymmetrical;
- Active symmetrical behavior at the induced potential U_B°. Simultaneously, the electrode B behaves as a current dispersing the share μ_B I of the ground current from A, the sum of the current outgoing ΣI_j^= μ_B I is equal to the current recopied in the passive behavior.

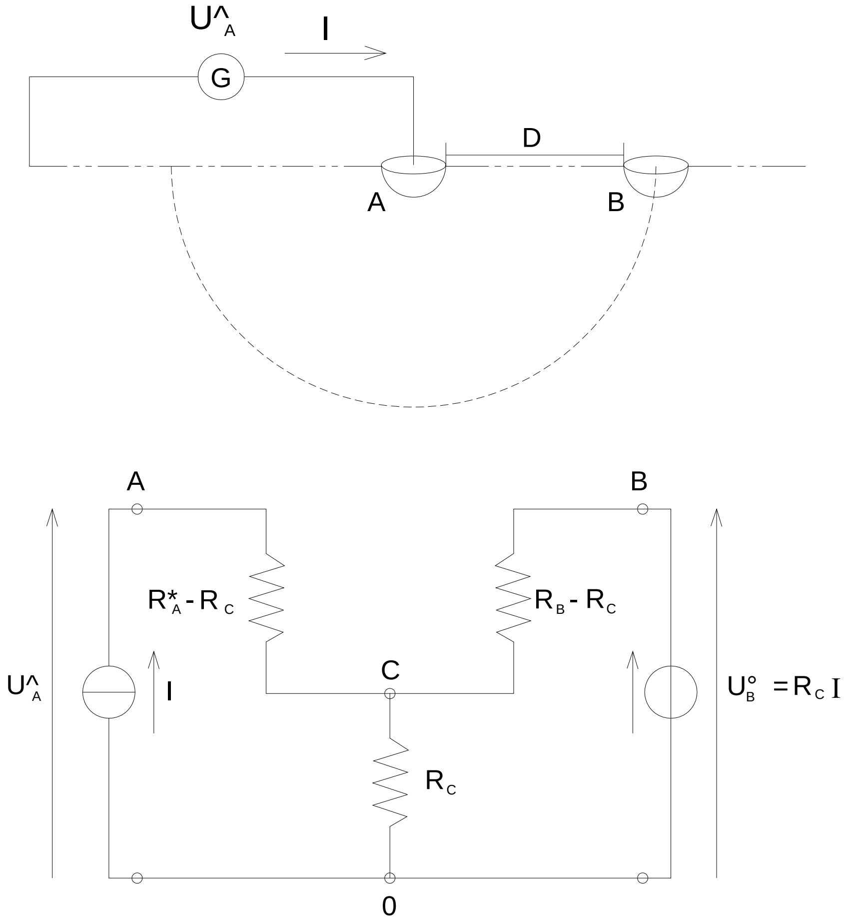


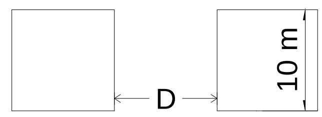
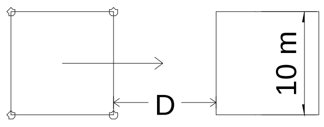
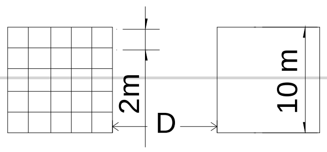
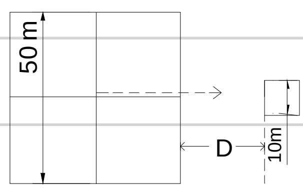
Figure 4. Scheme of equivalent circuit of the two interfering electrodes at the mutual distance D

The two electrodes are characterized by the ground resistance R_A and R_B in their behavior of isolated electrodes (one in the absence of the other in the area of influence). They can be calculated by specialized software programs.
For the A-B electrodes system can be defined some global parameters:

- the equivalent resistance of the A-B system view from active A is R_A^ = U_A^ / I , of different value compared to R_A. Let's note that the reduction of the ground resistance R_A^ can be neglected especially if it is bigger than the inert electrode (see Table 1), and so it can be assumed approximately R_A= R_A^.

- the mutual transfer resistance R_C of the A-B system $R_C = U_B° / I$.

Table 1. Ground resistance (R_A^) and transfer resistance (R_C) values for 4 configurations of active A and inert B electrodes for some values of the distance D. It is assumed for the soil a resistivity ρ = 100 Ω m. The ground resistance (R_B) of inert B isolated is equal to 5,44 Ω.

	A B	D (m)	5	10	15	20	25	30
I		R_{A*} (Ω)	5.410	5.430	5.440	5.440	5.440	5.440
		R_C (Ω)	1.150	0.830	0.650	0.540	0.460	0.400
II		R_{A*} (Ω)	3.860	3.880	3.890	3.890	3.890	3.890
		R_C (Ω)	1.130	0.825	0.652	0.539	0.460	0.402
III		R_{A*} (Ω)	4.280	4.300	4.310	4.310	4.310	4.310
		R_C (Ω)	1.139	0.826	0.652	0.539	0.460	0.400
IV		D (m)	10	15	25	35		
		R_{A*} (Ω)	0.905	0.905	0.905	0.905		
		R_C (Ω)	0.431	0.377	0.303	0.253		

The circuit diagram of Figure 4 allows interpreting its operation.
Similarly the functions between A and B can be reversed. Let's note analogously that for B active, it can be assumed approximately $R_B = R_B$^.

Therefore, given two (or more) interfering electrodes and calling the active one A and the inert one B, it can be established that:

- They constitute a system characterized by the ratio R_A/R_B the two own resistance "isolated"; the electrodes are comparable if R_A/R_B ranges between about 10 and 0,1.
- The mutual transfer resistance $R_C = U_B°/I = U_A°/I$ is common to the A-B system and the transferred voltage U° is the same when at equal distance D and equal ground current I, one of the electrodes is active and the other is inert ($U_B° = U_A°$).
- The share μ_B I = (R_C / R_B) I of the ground current I dispersed by the active electrode and intercepted by the inert B is inversely proportional to the resistance isolated R_B. Analogously the intercepted current share μ_A I = (R_C / R_A) I in the reversed function.

In order to exemplify the approach, let's consider the sample case IV of Table 1 in a homogeneous ground with a distance D = 35m between the electrodes. By Table 1 it is possible to estimate:

$$R_A = 0{,}905\ \Omega,\ R_B = 5{,}440\ \Omega,\ R_C = 0{,}253\ \Omega$$

$$\mu_A = R_C / R_A = 0{,}28 \text{ p.u.},\ \mu_B = R_C / R_B = 0{,}05 \text{ p.u.}$$

Considering an injection of current in A of 1000 A, $U°_B = R_C I = 253$ V; $U°_A$ is prospected equal to $U°_B$. In a practical way, with electrodes A and B of any structure, the suggested allows to measure the $U^\wedge_A$ and $U°_B$ values by injecting a current I in the active electrode A. By reversing the test, using electrode B as active, it is possible to evaluate $U^\wedge_B$ and $U°_A$ that is prospected equal to $U°_B$. The shares ($\mu \leq 1$) of intercepted current by inert electrode respectively are

$$\mu_A = U°_A / U_A,\ \mu_B = U°_B / U_B$$

assuming that $U_A \approx U_A^\wedge$, $U_B \approx U_B^\wedge$.

In conclusion, two or more ground systems in a common zone of influence, are interfering, in other words they constitute a global system of "interfering level". In conditions of homogeneous soil, the presented analysis highlights that in the system A-B, the voltage U° transferred on B with A active is the same transferred on A with B active (*rule of the mutual transfer*). If inadmissible touch and step voltages appear outside or inside the electrical power installation, it is necessary to proceed with mitigation and provide eventually the "bonding" of the A-B system, upgrading it to interconnected or integrated globality level.

In the case of two incomparable electrodes with R_A/R_B of value out of the normal range, because one only is a global or near global ground system (BExCP-GGS), the prospected value of its potential U is in comparison to the other electrode in the lower value of R_A/R_B and so the mutual transferred potential will be $U° \leq U \approx$lower value. In this case, in consideration of various influencing parameters as mainly the distance between the two electrodes, it is necessary to evaluate the superficial potentials and proceed with special mitigation that can be more exacting than a simple interconnection or integration.

Approximate methods for calculating the behavior of the system of two electrodes.

The potential $U_B°$ transferred on the inert electrode B can be calculated using approximated procedures.

When the electrode B is buried at a low depth, it can be assumed that the transferred potential coincides with the potential produced by the electrode A, undisturbed, on the ground surface corresponding to the central area and in particular in central point if the electrode B is of very modest dimensions.

In general, the potential $U_B°$ can be calculated according to the knowledge of the potential distribution determined by the electrode A undisturbed, performing the arithmetic average of the values in a sufficiently large number of ground points in the positions occupied by the elements of the inert electrode B.

This method of approximate calculation of $U_B°$ can be more easily used when one of the two comparable electrodes is of simple structure and small dimension related to those of the other which will be considered active. Considering the rule of the mutual transfer, certainly in an approximated evaluation it is convenient to choose as inert the electrode of smaller dimension for evaluate U° that remains the same also reversing the activity.

A sample case of test

It was made a ground test in a simple case of transformer substation MV/LV with an open land around (Figure 5). It was so possible make measurements of the potentials assumed by the soil in reference to a remote electrode, during the dispersion of a test current (I = 5A) from the ground electrode of the substation (R_A = 6 Ω) (active electrode A). Four rods (a, b, c, d) were been located in the soil, as indicated in the Figure 5. It had been carried out the measurement of the potentials assumed by the four electrodes individually, the potentials assumed by the systems, as inert electrodes B, of the interconnected three electrodes a, b, c, and then of all the four rods a, b, c, d.

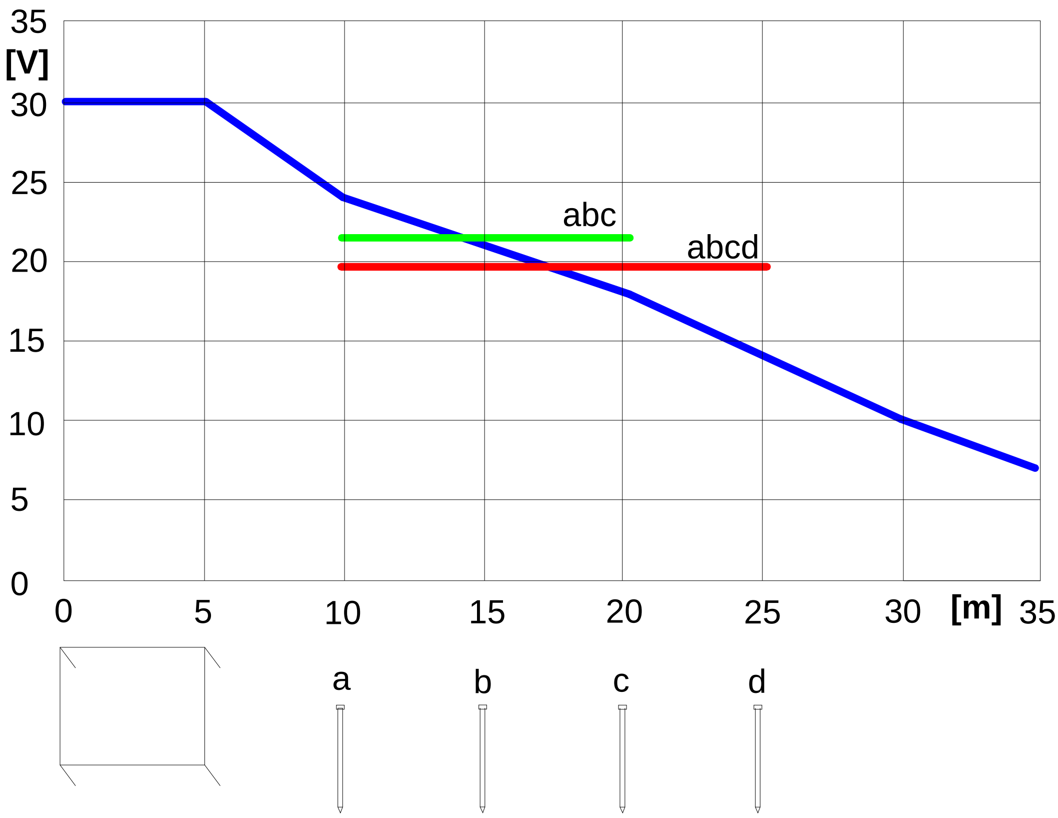


Figure 5. Ground test in a case of isolated MV/LV substation with 3 or 4 interfering rods at short distance

In conclusion, an interfering electrodes system on an active electrode A can stick low potential assumed by the buried electrode BExCP in the proximity of the active electrode, where the ground surface potentials maintains higher values (Figure 6).

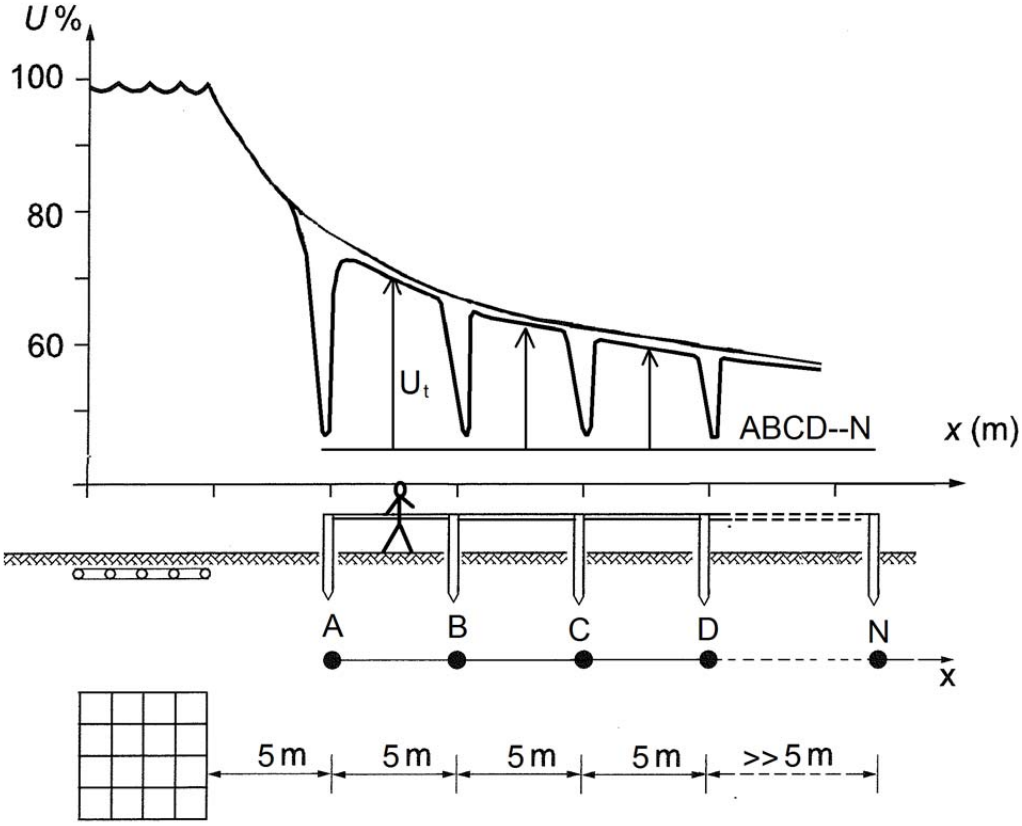


Figure 6. Sample case of an interference between an active electrode and a long fence (BExCP-GGS). During a fault unexpected Ut voltages may occur on the fence

The bonding actions: interconnection and integration of grounding systems

The adopted simulation program has allowed a sensitivity analysis of various parameters of GSs, in relation to their constitution and globality level.

Through the study of interferences, which occur in groups of GSs coexisting in a common influence area, it is possible to identify the need to correct the asymmetries by bonding them with the interconnecting wiring distribution system overall electrodes.

The analysis has been developed assuming as reference two ground electrodes constituted by bare rope buried at 0,5 m with a rectangular shape (40x80m) and the other a square shape (40x40m). The two electrodes are both meshed with meshing of 20 m and are adjacent at a distance of 30 m as shown in the Figure 7 (configuration 1).

The first case considers the two electrodes only interconnected by an external conductor. The analysis proceeds to analyze 4 different modes of integration.

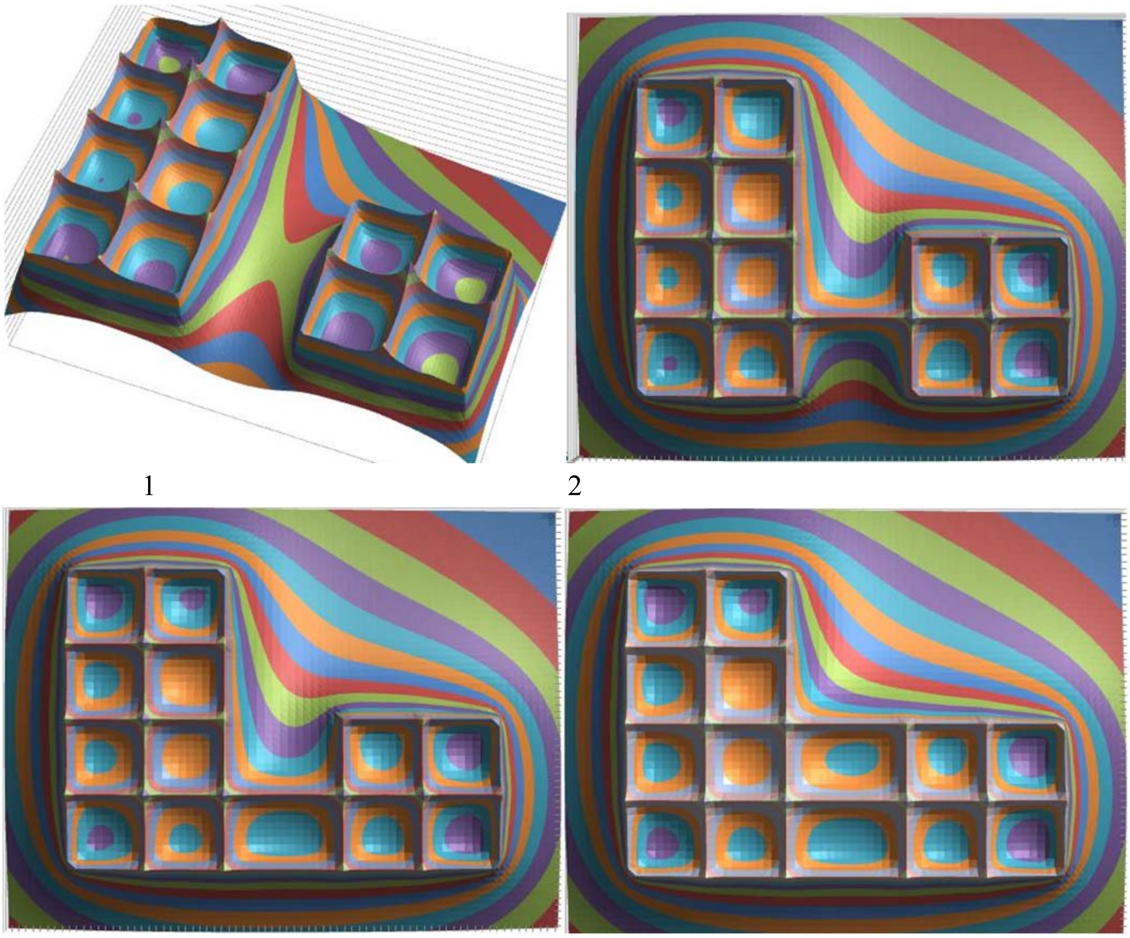
To allow the qualitative reading of the 3D trend, the ground surface potentials have been associated with a color variation (Figure 7).

Therefore, to identify the most critical points of the ground, i.e. those in which the surface potential deviates the most, or with greater gradient, by the GPR, it has to observe fast color changes.

The maximum values occur at the points overlying the intersections between the conductors that constitute the mesh and the edges of the electrode system, making evident the position

and conformation. These values are then observed a progressive decrease towards lower values at the points of the inner mesh.
Observing the figures it is known that in any single mesh presents a "pothole" of decreasing values from the edge toward the center. The minimum value is not always in the exact center of the mesh but is much more decentralized as more decentralized the mesh is respect to the ground electrode as a whole.
A ground potential lower value at a surface point respect to another implies touch voltage greater in the first than in the second point.
The integrations, performed through the interconnecting bare conductors buried in the ground, modify the asymmetry with different results depending on the number of conductors used to integrate the electrodes system and their position.

The situation is more skewed with a sole trunk of integration, centrally placed (configuration 2 Figure 7), while the more symmetric is the one with 3 wires electrodes (configuration 4) buried in the ground and therefore themselves a constituent part of the sink.
In the Figure 7 it can be observed a significant reduction of the minimum value of touch voltage by perfecting the integration between the electrodes.



1 2 3 4

Figure 7. Two ground electrodes with a rectangular shape A (40x80m) and a square shape B (40x40m): in the first case A and B are interconnected only, the following cases show different integrations through the interconnecting bare conductors buried in the ground

In conclusion the integration makes the two electrodes a single ground system more efficient because it has a lower ground resistance and touch voltages significantly reduced in the area adjacent to the two electrodes, avoiding unexpected potential potholes.

The rolling sphere method for graphical tests

A criterion to improve the integration of an aggregate of GSs in mitigating potential gradients or potential potholes is to increase the similarity between the set of electrodes and the hemispherical electrode.
A hemispherical electrode buried in a soil with homogeneous resistivity presents in fact absolute symmetry and uniformity of the current distribution in the ground in every direction.
These characteristics can be graphically tested using a sphere that rolls around a hemispherical electrode without interference over the entire surface. In particular, the radius of the rolling sphere represents the maximum distance of the prospected transferred potential in a hemispherical field of reference.

A sphere that rolls along the perimeter of a square or rectangular electrode, at the vertices suffers a sharp change in direction. Having two (or more) adjacent electrodes, in origin at a mutual distance D, the sphere with a diameter less than or equal to D that rolls along the edge of the electrodes set undergoes changes of direction.
The better integration between the electrodes will be achieved when the direction change can be made more moderate and the rolling sphere cannot penetrate inside of the circumcircle to the electrodes set to be integrated.

The Figure 8 shows how the integration between the two electrodes shown in a) is the worst while that in d) is the best [27.p].

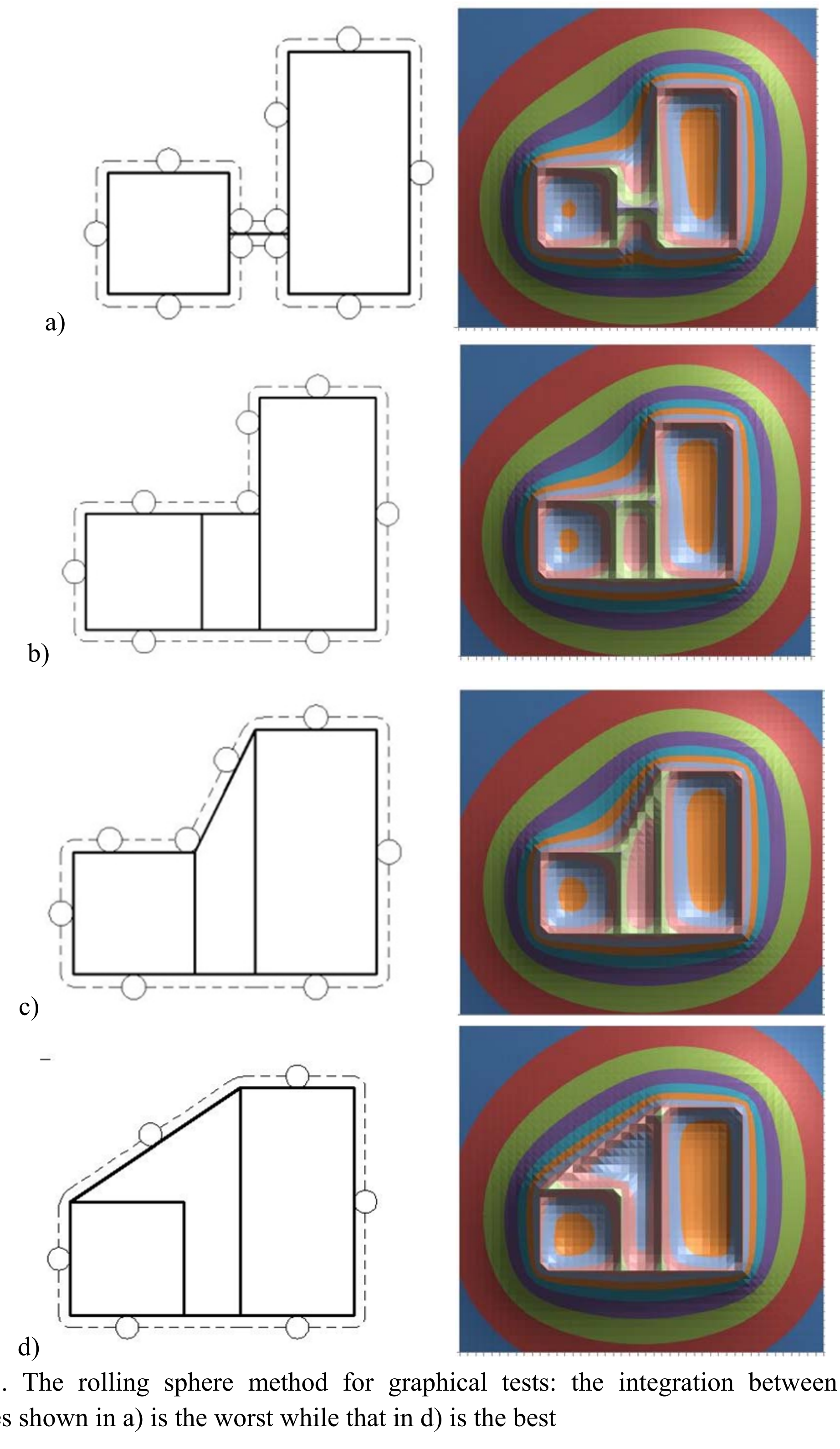


Figure 8. The rolling sphere method for graphical tests: the integration between the two electrodes shown in a) is the worst while that in d) is the best

Chapter 2.4

Unprotected Faults of Electrical Cords and Extension Cords

Symbols

The symbols used in the figures and in the text are:

S, S_F, — cable cross-sectional area, conductor size S and local fault size S_F in mm^2

$DEG = S_F/S$ — conductor area degradation

I_m, t — instantaneous tripping current [A] and total fault clearing time [s] of the selected protection device (PD)

I_Z — cable current-carrying capacity or ampacity: its values are tabulated or calculated by the empirical formula (simplification of the Cenelcom method [6.s]) $I_Z(S)=\alpha I_Z(1)\, S^b$, where: $I_Z(1)$ is the current-carrying capacity of 1 mm^2 cross-sectional area, dependent on the kind of cable, corrected by appropriate derating factors α; *b* is a parameter equal to 0.625

I_B, I_{BF} — circuit load current in normal conditions and for a series fault in a point respectively; usually $I_{BF} \le I_B \le i_B\, I_Z$

LO_p — prospected local overload by DEG, $LO_p = =I_Z(S)/I_Z(S_F) = (S/S_F)^b$

$CUF=i_B$ — cable utilization factor, ratio of the maximum load current on the cable to its ampacity; $i_B \le 0.8$ NEC [35.s] and $i_B \le 1$ IEC [9.s].

LO — actual local overload by DEG, $LO= I_B/I_Z(S_F)= CUF\cdot LO_p$

$\delta_Z(S)$,$\delta_B(S)$ — admissible and actual values of cable *steady current S-density* [A/mm^2] related to I_Z/S and to I_B/S respectively.

$\delta_Z(S_F)$,$\delta_B(S_F)$ — admissible I_Z/S_F and actual I_B/S_F values of *S-density* [A/mm^2] related to a degraded S_F

K — IEC constant value [$As^{1/2}/ mm^2$], dependent on the kind of cable and on its operating temperature T_Z; it takes account of the resistivity, temperature coefficient and heat capacity of the conductor material and the appropriate initial T_i and final T_f temperatures (respectively prior and after to a current change). For copper conductors, the conventional value is K=115, if insulated by Polyvinyl Chloride (PVC) T_f =160°C, T_i=T_z=70°C; it is K=143, if insulated by Ethylene–Propylene EPR T_f=250°C, T_i=T_z=90°C.

K^2S^2 — admissible let-through energy for the cable.

I_k — prospective short circuit current, reference value of a transient anomalous current in the fault point.

I_F — parallel fault current

I_{GF} — ground fault current or local fault involving the ground

$\delta_F(S,S_F)$ — cable *transient current T-density*: actual transient fault current density $\delta_F(S)=I_F/S$ or I_k/S in the circuit section S and $\delta_F(S_F)=I_F/S_F$ or I_k/S_F in the degraded S_F [A/mm^2]

δ_K admissible *adiabatic or T-density* value $\delta_K = K/\sqrt{t}$ [A/mm^2] dependent on the assigned kind of cable and on the tripping time t of the protective device (PD) (IEC Standard admits 5 s as limit value for adiabatic events).

Introduction. Accidental faults in wiring systems: fault types, fire and electric shock hazards

The common electrical equipment as computers, table lights, televisions, refrigerators etc., are supplied by electrical power cables, cords, extension cords generally flexible and of low cross section, constituted by stranded bare conductors.
A lot of events have demonstrated that fire ignitions are possible in cords and can present the following characteristics:

a) a slow evolution, because they can follow to a low overheating process,

b) an absence of electrical stresses in the supplying circuit, because anomalous conditions can remain localized at the fault point,

c) of special unprotected faults because the faulted circuit and its coordinated protective device remain in compliance with the standards in force.

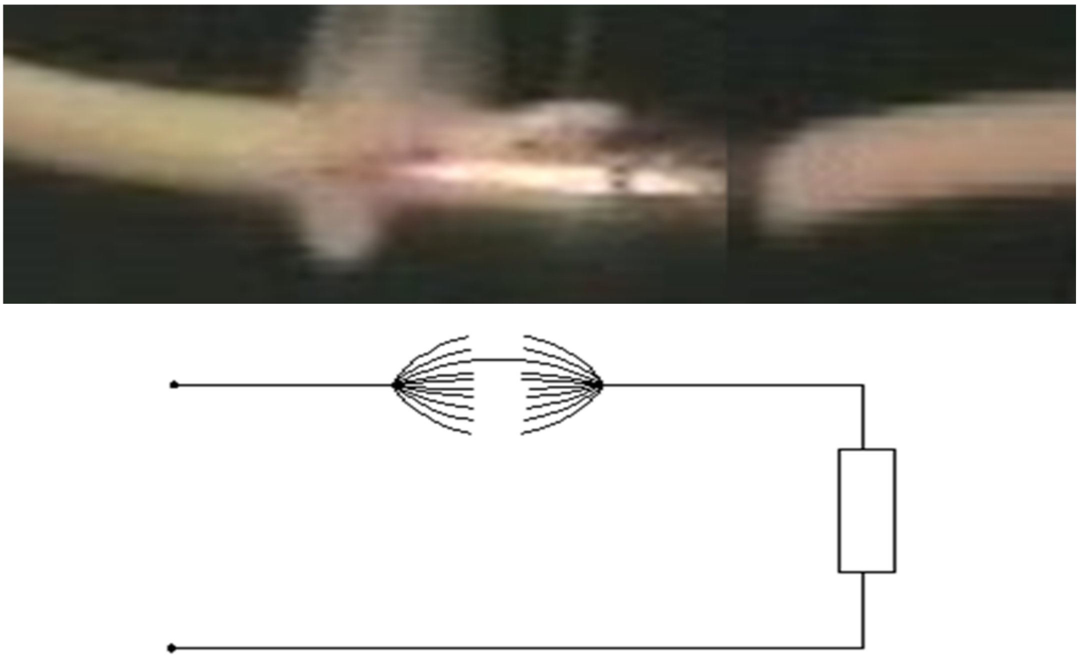


Figure 1. shows a circuit supplying a load with a damaged conductor ($I_{BF} \cong I_B$): the photo (extracted by a video) shows the faulted point during a simulating test where, as displayed in the scheme, many filaments are broken and the few continuous filaments are incandescent and igniting the cable insulation

The mechanical damage of the stranded bare conductors can locally break many filaments and degrade the effective cross section, causing anomalous local conditions [37.p].
The continuous residual filaments of the conductors let flow the circuit current I_{BF} that can have a value up to the load current I_B. The filaments work as a “fuse”. In the faulted circuit point where the original cross section area S is reduced to the value S_F, the fault current

practically remains $I_{BF} \cong I_B$ and the load current I_B can operate locally as an overcurrent with an uncontrolled overheating (fig. 1).
In a different way, the broken filaments can originate bolted short circuit I_k, series arc faults ($I_{BF} \leq I_B$) or parallel arc faults ($I_F \leq I_k$) that make easy the fire ignition, especially if following to a localized overheating process. In fact the heat from such faults could be significant enough to cause ignition of nearby flammable materials as wood, sawdust, textile material (*fire hazard*).
Similarly, false contacts, loose terminal connections and other maintenance inaccuracies can create critical conditions of local increased resistance to the current, with consequent local overheating.

In short, in reference to the branch circuits, cords and extension cords, there are three basic-types of conductors faults:

a) in line or series I_{BF} up to the load current I_B value,

b) line-to-line/neutral or parallel I_F up to the short circuit value I_k,

c) line-to-ground up to the ground fault value I_{GF} (figure 2).

Obviously, there are also faults of mixed types.

Within each electric system, the problems associated with the faults detection can present different levels of difficulty.
While the ground faults I_{GF} and all the faults that involve the ground in AC systems can be detected by adopting residual current devices (RCDs or GFPDs), the series and parallel faults/short-circuits in cords and extension cords can make ineffective the circuit protection coordination.
The series faults I_{BF} by mechanical damages, of value up to the load current I_B, request special techniques for their detection [12.p]. Furthermore providing protection for increased contact resistance when arcing does not occur is difficult.

Being the cords tapped by final circuits, the parallel faults/short-circuits could be not sufficient to cause the trip of the overcurrent protective device (OPD) either for a magnitude lower than the instantaneous tripping current I_m or for a too short duration.
The self-extinguishing arc can leave the circuit energized with local damage to the cord insulation (*electric shock hazard*).
The arc fault is an intrinsically random phenomenon. It is characterized by a sputtering behavior that is made easier by the flexibility of cords and in AC systems by its switching off at the zero crossing, considering that the power factor is near to the unity in final circuits.

Admissible steady and transient current densities

The circuit conductors have to be adequate to the currents soliciting the circuit in normal conditions I_B and in transient events such as overcurrents I_k in coordination with the protective device.

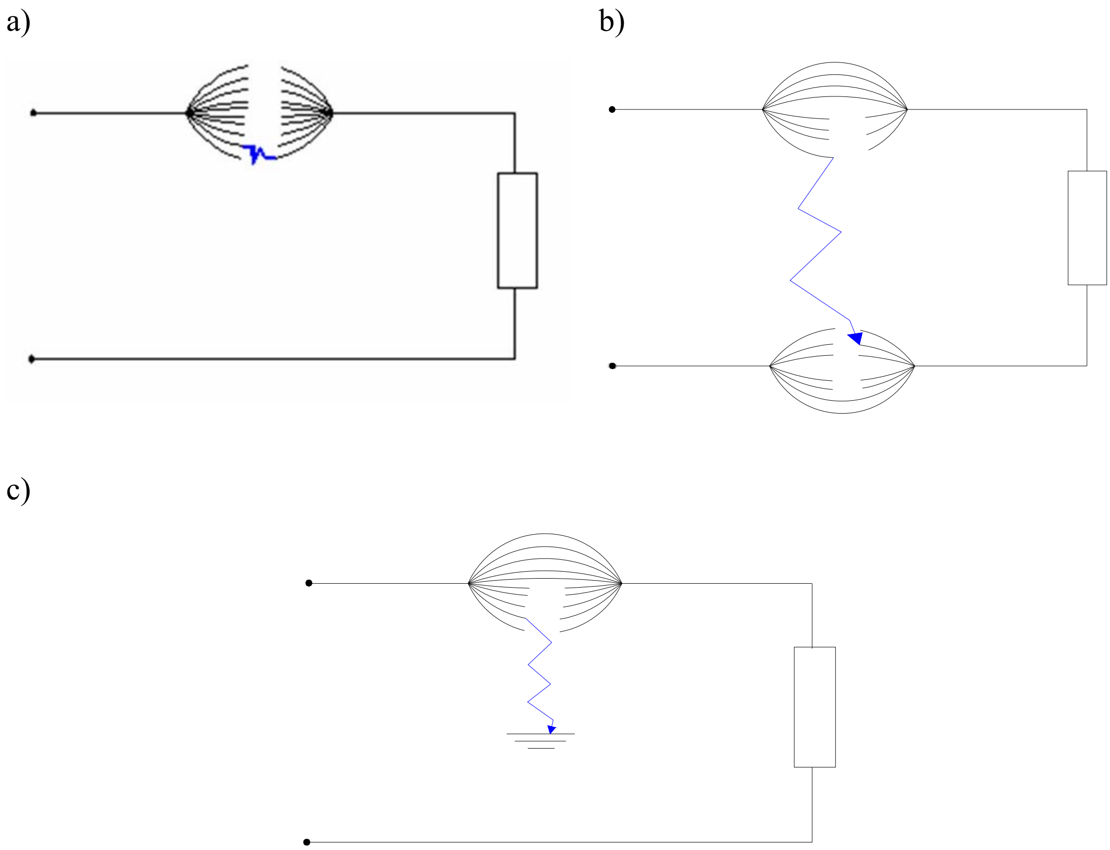


Figure 2. Faults can reduce the conductors section causing overheating and can evolve in arcing among broken filaments; the arcing basic-types are: in line or series $I_{BF} \leq I_B$; line-to-line/neutral or parallel $I_F \leq I_k$; line-to-ground I_{GF}

Operational parameters such as the steady and transient current densities δ_Z and δ_K are introduced to analyze the influence of the variation of the conductor cross-section S area in a faulted point [32.p].

The fault current, for local series faults $I_{BF} \leq I_B$, for local parallel faults $I_F \leq I_k$, flows in the circuit with a density in the faulted section increased by the ratio $S/S_F = 1/DEG$ in comparison to the density in other sections of the circuit. These increment is not tolerable by the conductors also if their behavior is different for the series or parallel faults.

The selection of the commercial series area S for the circuit conductors has to satisfy both the steady and transient conditions, to be adequate at its proper capacity [19.p].

Steady Condition (Series Faults)

It is well known that each commercial series area S of the circuit conductors guarantees a proper ampacity $I_Z(S)$.
The thermal withstand capability of continuously carrying the current $I_Z(S)$ depends on many parameters, including conductor material, coating, insulation temperature rating, installation, ability to dissipate heat, ambient temperature, etc. The admissible steady current S-density of the cross section area S remains defined as the $\delta_Z(S) = I_Z(S) / S$.

The ampacity $I_Z(S)$ for conductors of S size is determined by proper tables and by calculations under engineering supervision [35.s].
The admissible ampacity $I_Z(S_F)$ in the fault point of reduced cross section S_F can be estimated in a simplified way using the empirical formula derived by the Cenelcom method. In fact this formula can assist the definition of the ampacity $I_Z(S_F)$ for size of conductors, out of the commercial series. This formula is applicable to the conditions of steady-state operation of cables not buried at voltages up to 1.2 kV.
A mechanical damage can degrade the cross section area of a cord to the value S_F from the original S; in this case its load current $I_{BF} = I_B$ becomes a local overcurrent if its value results higher than the admissible $I_Z(S_F)$ in the fault point. The local overcurrent (LO) can be valued as the ratio:

$$LO= I_B / I_Z(S_F)= i_B\, I_Z(S) / I_Z(S_F) = i_B\, (S/S_F)^b = CUF\cdot LO_p \quad (1)$$

being b =0.625, i_B the utilization factor (CUF) and $I_Z(S) / I_Z(S_F) = (S/S_F)^b = (1/DEG)^b$ the prospected local overload (LO_p) for an area degradation, while even a DEG of up to 0,1.

Table 1. Influence of the DEG on the values of LO_p, CUF, densities δ_B and δ_F

DEG S_F / S	**LO_p $I_Z(S) / I_Z(S_F)$**	**LO* $I_B / I_Z(S_F)$**	**S-density* $\delta_B(S) / \delta_z(S_F)$**	**T-density $\delta_F(S_F) / \delta_F(S)$**
1,00	**1,00**	**0,80**	**0,80**	**1,00**
0,9	**1,07**	**0,85**	**0,77**	**1,11**
0,7	**1,25**	**1,00**	**0,70**	**1,43**
0,5	**1,54**	**1,23**	**0,62**	**2,00**
0,3	**2,12**	**1,70**	**0,51**	**3,33**
0,1	**4,22**	**3,37**	**0,34**	**10,00**

(*) The values are referred to a CUF=0,8

The second column of table 1 shows the LO_p that is the prospected local overcurrents in p.u. of the original ampacity $I_Z(S)$ for a cross sectional area reduction S_F/S.
The expression (1) shows how the actual LO is mitigated by the utilization factor i_B up to that its value $I_B / I_Z(S_F)$ remains not greater than 1.

The third column of table 1 shows the actual LO in reference to a DEG = S_F / S and to an actual load I_B=0,8 $I_Z(S)$ (CUF=0,8). Let's note that an actual overload is reached if the DEG assumes values lower than 0,7.
Then for a DEG=0,1, the load current in the fault point becomes a LO equal to $0{,}8\cdot 10^{0.625}=0{,}8\cdot 4{,}22= 3{,}37$ times than the admissible value.

The steady behavior of the conductors is characterized by the capability to heat transfer that justify a slow evolution of several fire ignitions, because they can follow to a low overheating process.

The steady heat transfer depends on cable geometry and its surroundings and it is proportional to the superficial longitudinal area of the conductor. Therefore the *admissible steady current density (S-density)* $\delta_Z(S)=I_Z/S$, ratio between the ampacity I_Z and the related cross section area S, highlights the characteristic that its value increases with the decreasing of the cross section S.

It is well known that the steady heat transfer is proportional to the superficial longitudinal area A of the conductor (if cylindrical with r radius, A is equal to $A=2\pi r$ per meter of length), therefore the density $\delta_Z(S)$, ratio between the ampacity I_Z and the related cross section area ($S=\pi r^2$), increases with the decreasing of the cross section S.

A useful expression to highlight the influence of the variation of the conductor cross-section area in a faulted point from the value S to S_F, can be formulated by the (1) as the ratio between the actual density $\delta_B(S)$ that is assumed admissible for the circuit cross section S and the admissible density $\delta_Z(S_F)$ for the degraded S_F:

$$\delta_B(S) / \delta_Z(S_F) = i_B (S/S_F)^b S_F / S = CUF \cdot LO_P \cdot DEG \quad (2)$$

In conclusion, in a faulted area S_F, with a reduced ampacity $I_Z(S_F)$ the actual load current $I_{BF} \leq I_B$ becomes a local overcurrent as much as the actual CUF is higher. It obviously cannot be detected by the overcurrent protective device (OPD) coordinated with the global circuit characteristics.

The fourth column of table 1 shows the relative values $\delta_B(S)/\delta_Z(S_F)$ of the actual admissible density $\delta_B(S)$ in reference to $DEG=S_F/S$ values and a CUF=0,8. Let's note that for a DEG=0.7, $\delta_B(S)/\delta_Z(S_F)$ assumes the same value 0,7.

Transient Condition (Parallel Faults)

The general rule for the distribution circuits is that the circuit conductors must have a cross section area S adequate to guarantee the let-through energy (I_k^2t) on its derivation point in the system

$$I_k^2 t \leq K^2 S^2 \quad (3)$$

that can be expressed in relation to the parallel fault $I_F \leq I_k$ as

$$I_F \leq I_k \leq (K/\sqrt{t}) S = \delta_K S \quad (4)$$

where

t is the trip duration of the PD, in seconds;

S is the cross-sectional area [mm^2];

I_F, I_k are the effective parallel fault and short-circuit currents in the conductor, [A] r.m.s. value;

K is an IEC factor [$As^{1/2}/mm^2$] taking account of the resistivity, temperature coefficient and heat capacity of the conductor material and the appropriate initial and final temperatures.

δ_K the term $K/\sqrt{t}$ defines the admissible transient or adiabatic T-density [A/mm^2].

$\delta_K S$ is the admissible short-circuit current for the conductor of cross sectional area S related to the

t time, [A] r.m.s. value.

Let's note that they remain defined also $\delta_F(S) = I_F / S$ or I_k / S and $\delta_F(S_F) = I_F / S_F$ or I_k / S_F that are the actual value of the fault current density in the circuit and the faulted section respectively.

Hereafter $\delta_K S_F$ is the admissible short-circuit current for the conductor in the faulted point of the degraded cross sectional area S_F related to the t time.

The circuit conductor ensures a *thermal withstand capability of carrying a short-circuit current* $\delta_K S$ for the transient time t of the trip of the protective device PD.

Differently than the steady heat transfer, the *admissible transient current T-density δ_K* of the conductor, defined as ratio between the maximum overcurrent admissible for the conductor and its cross section area S in coordination with a timely PD tripping time, has a value invariant with the cross-section area S , being related to a transient adiabatic heating.

If the PD tripping time is equal to t=1s, it results $\delta_k = K$ that is the δ_k value is coincident with the K value. In reference to t=1s, for Ethylene–Propylene (EPR) insulated cables, δ_k is equal to 143 A/mm^2, for Polyvinyl Chloride (PVC) insulated cables δ_k is equal to 115 A/mm^2.

Considering that the time t = 5 s is the IEC limit value for considering adiabatic the heating events, the maximum δ_K that can persist for 5 s, is equal to $\delta_K = K/\sqrt{5} \cong 0,45$ K (for EPR, ≅64 A/mm^2, for PVC, ≅52 A/mm^2).

The admissible short-circuit current of the intact conductor $\delta_K S$ must not be lower than the actual value I_k of the circuit, but also the admissible short-circuit current $\delta_K S_F$ of the conductor in the degraded section must satisfy the same condition and so the faulted section can become a critical weak point.

For a parallel fault $I_F \leq I_k$, the prospected admissible short circuit current $\delta_K S_F$ of the conductor (in p.u.) in the faulted point of the reduced S_F compared to the value $\delta_K S$ in the other circuit sections of area S shall be estimated proportional to the ratio DEG=S_F/S and can cause dangerous overheating.

The fifth column of table 1 shows the values of the ratio $\delta_K S$ / $\delta_K S_F$ in reference to DEG values; the admissible short circuit current $\delta_K S$ in the intact section is higher than the admissible value $\delta_K S_F$ in the degraded section.

In other words the same column shows that for each DEG the ratio $\delta_F(S_F) / \delta_F(S)$ assumes the inverse value $S / S_F = 1 /$ DEG.

For instance in reference to a DEG= S_F / S =0,1, the admissible $\delta_K S_F$ is only 0,1 of the admitted value $\delta_K S$ for the circuit and so the actual T-density $\delta_F(S_F)$ in the fault point assumes a value 10 times the T-density in the other intact points.

The protective device PD is coordinated in relation to the $\delta_K S$ of the intact cross section of the circuit and so the unprotected fault can locally develop an high value of incident energy in comparison to the actual admissible value $\delta_k S_F$ in the faulted section S_F.

In conclusion, series faults can cause slow phenomena of fire ignitions. Parallel faults as short circuits limited in value by arcs, can lead to faster fire ignitions, especially if they do not cause the tripping of the PD.

Circuits protection criteria against arcing-faults

A complete design of final circuits should include the connections of portable equipment and of extension cords (as requested by NFPA 70 [35.s]) that are exposed to arc faults and may cause fire and/or electric shock hazards. In the contrary, IEC Standard 60364 [7.s] stops the design of power systems at the outlets of branch circuits or at the fixed equipment.

Since cords supplying Class II equipment are without a grounding protection conductor, the failure of the double insulation, caused by external damage, is unlikely to be detected as a ground fault. The IEC standard asserts that conductive parts enclosed in the insulating enclosure shall not be connected to a protective conductor.
Protection must be provided to prevent the fault from extinguishing itself without being detected and so remaining energized and accessible to a direct contact, because in this case it presents an electric shock hazard.

An efficient protection of local faults can be achieved by integration of active and passive techniques:

- adopting the special device Arc-fault Circuit Interrupter (AFCI) or Detection Device (AFDD) that recognize arcing faults [12.p];
- wiring the circuits, cords and extension cords particularly, with a grounding protection conductor also supplying Class II equipment, that could involve the ground in all the faults.

Active protection by AFCI

An Arc Fault Circuit Interrupter (AFCI) is a circuit breaker designed to prevent fires by detecting an unintended electrical arc and disconnecting the power before the arc starts a fire. An AFCI must distinguish between a harmless arc that occurs incidental to normal operation of switches, plugs and brushed motors and an undesirable arc that can occur, for example, in a lamp cord that has a broken conductor in the cord.
Conventional circuit breakers only respond to overloads and short circuits; so they do not protect against arcing conditions that produce erratic, and often reduced current. An AFCI is selective so that normal arcs do not cause it to trip.
The AFCI circuitry continuously monitors the current and discriminates between normal and unwanted arcing conditions. Once an unwanted arcing condition is detected, the AFCI opens its internal contacts, thus de-energizing the circuit and reducing the potential for a fire to occur.
An AFCI should not trip during normal arcing conditions, which can occur when a switch is opened or a plug is pulled from a receptacle.
AFCIs resemble a GFCI/RCD (Ground-Fault Circuit Interrupt/Residual-Current Device) breaker in that they both have a test button although each has a different function.

GFCIs and RCDs are designed to protect against electrical shock of a person, while AFCIs are primarily designed to protect against electrical fires caused by arcing.
Some outlets must be protected by both a GFCI and an AFCI, such as an outlet near a wet bar in a family room.

Passive protection by GFFC

In these cases it is recommendable the use of Ground-Fault-Forced Cables, GFFCs that convert a line-to-line fault into a line to ground fault or into a mixed type case. By adopting these special power cables, the fault, if remains forced to ground, can be easily detected by RCDs in AC circuits or by the insulation monitoring devices, according to the selected grounding system (IEC TN-, TT- or IT-systems).
The adoption of a CUF low value in the cords guarantees a higher endurance to mechanical damages, but it makes heavier and less easy to handle the cords and in case of not detected fault can present the shock hazard.

The residual current device RCD type A ensures that its tripping is triggered, as the normal type AC (alternating current) and also by residual pulsating direct current, as the arc fault presents generally a sputtering behavior, reduced to trains of a half cycle duration.
The standard IEC 60755 [14.s] defines the types AC, A and B of RCDs depending on the characteristics of the fault current.
The RCDs type AC guarantee the tripping for residual sinusoidal alternating currents, while the RCDs type A ensure the tripping as for type AC and for residual pulsating direct currents also if superimposed by a smooth direct current.
The RCDs type B ensure the tripping as for type A, for residual currents sinusoidal up to 1 kHz or sinusoidal superimposed by a pure direct current or which may result from rectifying circuits, for pulsating direct currents superimposed by a pure direct current [5.s].

The special design for single-core or multi-core power cables is that each insulated core has a concentric conductor shield (figure 3) that will probably force to ground all of faults caused by mechanical stresses.
The shields have to be grounded and so sized to allow the use as grounding conductor for both the cable and the supplied equipment.
The shields are interested by currents in ground fault conditions only and so, as a *sentinel*, ensure that all the faults are rapidly detected in AC circuits by RCDs [36.p; 37.p].

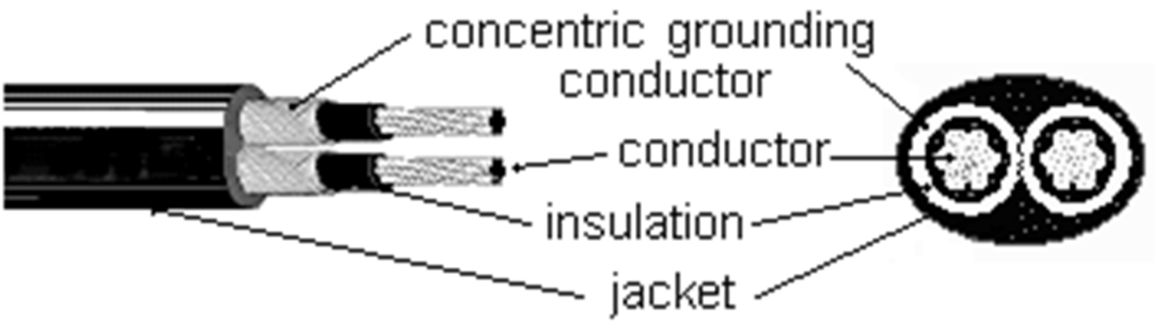


Figure 3. shows a Ground-Fault-Forced Cables (GFFC) type, double-core cable with concentric conductor shield (grounding conductor) on each core (or at least on n-1

Laboratory tests

Some tests were realized in laboratory making simulations of ground faults. It was realized a double-core cable with conductor shield (grounding conductor) on each core (Fig.4).

Figure 4. shows a Ground-Fault-Forced Cables (GFFC) type, double-core cable with conductor shield (grounding conductor) on each core realized in laboratory for tests

It was prepared an outlet protected by an automatic circuit breaker with a rated current equal to 16 A and a residual current device RCD of 0,03 A[1]. As test load it was chosen an halogen lamp.

Feeding the test load by a faulted cable, where the insulation of a single core was intentionally damaged, at the begging the lamp lights up, moving the cable there is the ignition of the arc fault and the RCD immediately trips (Figure 5).

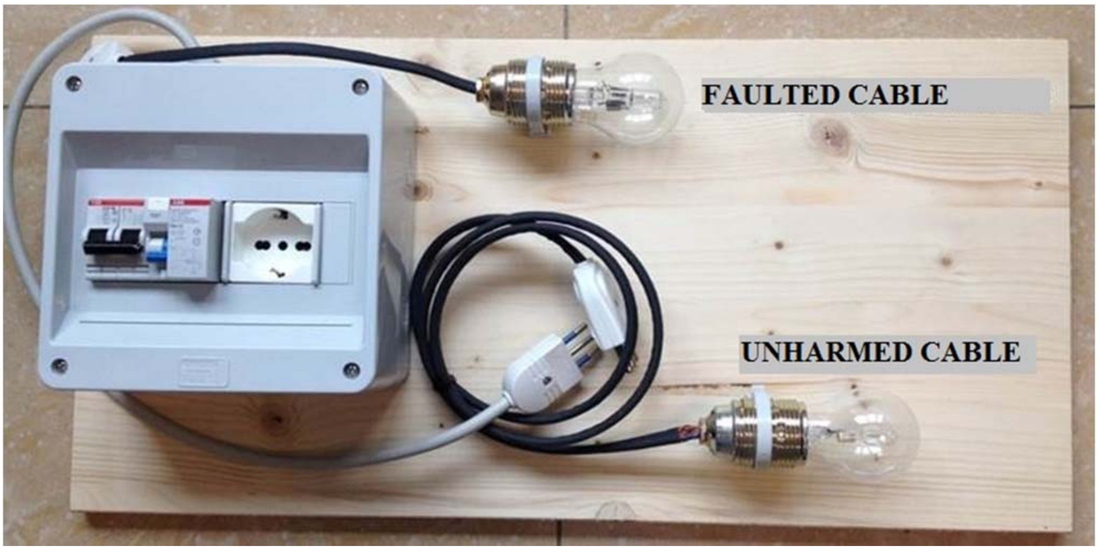


Figure 5. shows a Ground-Fault-Forced Cables (GFFC) type, double-core cable with conductor shield (grounding conductor) on each core realized in laboratory for tests

[1]An additional measure of protection against the hazards of direct contact is provided by the use of Residual Current Devices rated at 30 mA or less, referred to as high sensitivity RCDs. According to IEC 60364-4-41, additional protection by means of high sensitivity RCDs ($I\Delta n \leq 30$ mA) must be provided for circuits supplying sockets with a rated current ≤ 20 A in all locations and for circuits supplying mobile equipment with a rated current ≤ 32 A for use outdoors. This additional protection is required in certain countries for circuits supplying sockets rated up to 32 A and even higher if the location is wet and/or temporary.

A fast trip of protection devices is very important:

- to prevent the re-ignition of the sputtering arc;
- to limit the let-through energy value and reducing the fire hazard;
- to limit the shock hazard exposure time related with touching an energized conductor where the fault has deteriorated the insulation.

An additional way of protection of local parallel faults could be achieved operating on the overcurrent protective device OPD. The OPD has to be set adopting an instantaneous tripping current I_m [A] as follows

$$I_m = 0{,}7\ I_k \qquad (5)$$

where

I_k is the bolted fault at the end of the circuit,

0,7 is a recommendable empirical factor: it has been observed that the arc-fault has a 50% probability to reach a peak value not less than 70% of bolted short circuit value I_k.

Conclusions

In the first part of the thesis, new developments and methodologies are presented in the study of critical systems, such as data centers and hospitals, considered as complex systems. A theory of complex systems for safety, operation and maintenance aspects is defined that enables to assist the management of the system throughout its whole life cycle and allows an implementation of programming languages.

It was established that the design of a power system requires a comprehensive and permanent design and a business continuity management (BCM) is an essential component for its operation (Chapter 1.1).

It has introduced a program language (Chapters 1.2-1.3) for analyzing and transcribing the instructions of safety procedures for each working zone WZ and of integrity procedures for each sources node versus the loss of service continuity. Each node presents a kit of instructions as a l*ogic gene* describing a complete and reversible evolution of the component switching means from an opening status to a closing one.

The suggested advanced approach assists in the elaboration of the procedures for switching from one set or configuration of a power system to another and will help the training of operators in defining the instructions to be used in the development and the operating of each power system.

It's suggested a kinematic analogy (Chapter 1.4) among the operation of highway intersections of multiple traffic lanes and the operation of nodes of electrical power systems that lets the introduction of a transitions theory for intersections suggesting new ways for a better understanding and new methodologies for solutions such as the micro-system approach. An automatic transfer switch (ATS), as a traffic light, avoids the sources being connected in parallel, if it is not admissible. Roundabouts, cloverleaves and interchanges as junction systems of roads suggest interchange live transfers by UPSs or EGs combined with ATSs. In a complex system with multiple sources, the introduction of tie switches allows flexible configurations and concurrent maintainability, but deeply influences the operational procedures of the distribution system, at all the levels, horizontally and vertically. A special configuration is introduced, called node "double two", constituted by two ATS connectible in parallel by tie switches, that needs auxiliary components for its synchronization unless it's adopted two ATS constituted by three circuit breakers with automatic controllers and interlocks.

Complete control of the system is necessary for all operating occurrences in an electrical power system, control based on a full understanding of system performance during such operations, particularly when they are complex. Complexity requires that the "safe sets" of operating procedures have to be identified out of all the probabilistic possibilities, selected and authorized adopting the suggested new language program. By a case of a system with multiple sources (Chapter 1.5) is applied the micro approach of the "flock" logic. Instead, the operation of the complex system must not be organized with a comprehensive approach (macro approach) that studies all the links among the system nodes in the transitions of the authorized statuses. It must be organized node by node with a local approach (micro approach). Each node must only respect the constraints with the adjacent nodes by applying a “flock logic”. A lock moves without collisions because each component only controls the adjacent companions and follows the leading one in the chosen direction. So for electrical systems each node/switchboard must be managed only considering the adjacent nodes (by available direct connection) and has to be connected to the node supplied by the reference source, selected for the section of the system.

The strategic electrical power systems are an example of structures at greater risk in the event of lightning, earthquake, fire. In strategic buildings it becomes essential to prevent the causes of hazards/accident rather than provide interventions to limit the consequences. The design and installation of electrical power systems in buildings subject to seismic hazard (Chapter 1.6) must consider several mechanical and electrical criteria. At least three levels of performance are identified for equipment including the resistance to the seismic stress, the re-establishment of service after the earthquake, and the guarantee of duty during and after the earthquake. System planning is the most important phase in the design of an electrical power distribution system for strategic buildings located in earthquake hazard areas. In seismically active areas the applying electrical power systems problems are significantly limited by adopting the microsystem approach and the “brush-distribution” in modeling the electrical system architecture.

In the second part of the thesis specific issues of mission critical power systems, in particular data centers and hospitals, have been discussed. Several measurements were performed in laboratory and on field to analyze sneaky critical cases for the service continuity and the integrity of these strategic power systems.

In data centers (Chapter 2.1) equipment like electronic components exhibit excessive inrush currents at start up that request a rating current value I_n higher than the load current value and with a protection coordination tolerant the inrush current. Considering the long service of all equipment in a data center after the fast start up it is a technical inadmissible inaccuracy to maintain a protection setting inadequate for the service also as long as many years, maintaining a rating current value I_n higher than the load current value and with a weak protection coordination permissive to a longer permanence of the short circuit current.

A serious failure can be constituted by the loss of a PDU that would impact the overall mission of the facility by its operational essentiality and so the failure of each supplying circuit not adequately selected and cleared can cause an impact equivalent to a “single point of failure” involving the switchboard section or all the UPS supply.

Starting systems for equipment should be adopted to solve the problem of inrush current and to allow an adequate protection coordination for the long service of the data center. Two kind of starting system have been suggested: a configuration of a double switching at level of switchboard section and another one at the level of equipment input. The double switching is constituted by a start-set and a steady set. The insertion of the circuit or of the equipment is operated by the start-set, being open the steady set. When the start-up is stabilized, it is necessary to operate the transition inserting the steady-set before breaking the start-set.

Moreover it’s highlighted how is particularly important the switchboard design in data centers to plan the loads balancing and the possibility of future expansion. It’s proposed a synchronized transition by mobile UPS, a specific solution to change the feeding phase of a dual-corded equipment for optimizing the load balancing.

In the hospitals, where service continuity is essential, the electrical operation must be organized and it is necessary to have an emergency response team available at all times (Chapter 2.2). It’s defined a complete system SSS & EUC (Safety Supply System and Equipment Under Control) with requirements such as to avoid shock hazard and not to occur power outage for fault both due to overcurrent and to overvoltage.

Several measurements have been carried out in actual hospitals of current absorptions of medical equipment supplied by UPSs. It was found electro-medical equipment exhibit high peak currents at start up, but unlike the data centers equipment, the service is intermittent and so starting systems are not suitable. Therefore, particular attention must be given to the UPS system sizing. In fact, to avoid a frequent UPS bypass operation due to an excessive current, it’s necessary oversize the UPS power.

A complete knowledge of the electrical behavior of the medical equipment used in the structure, by monitoring the absorptions, greatly helps the operation manager to properly use multiple loads simultaneously and to understand if it’s possible to add new ones in case of need or it’s necessary to increase the power of the existing UPS system or realize a new one.

The existence of a global grounding system is a reality in city centers, urban and industrial areas with distributed low- and high-voltage grounding (Chapter 2.3).

In any case, more electrodes coexisting with common portion of influence zone cause interferences among themselves during a fault event that can determine potential potholes and unexpected increases of touch and step voltages. Interfering effects can cause damages to special power systems as data centers and hospitals.

The most significant interfering effects were defined in the zone of influence of an aggregate of ground systems GSs (active electrode and inert electrode). An approximate method for calculating the behavior of the system of two electrodes was suggested, the method has been validated by tests on the field. Using a simulator program, the benefits of bonding actions on two adjacent GSs by interconnection and integration have been presented. Finally, a new method called “rolling sphere method” is proposed for graphical test to improve the integration of an aggregate of GSs in mitigating potential gradients or potential potholes.

Cords and extension cords are exposed to accidental faults that may cause overheating, arc-faults and fire ignition of nearby flammable materials and/or electric shock hazard (Chapter 2.4). Several events have demonstrated that fire ignitions are possible in cords.

Generally and especially in strategic buildings as hospitals, prevent the ignition is better than extinguish the fire promptly.

A contribution to make efficient the protection is achieved by wiring the circuits, extension cords particularly, with new special power cables Ground-Fault-Forced Cables GFFCs that convert each kind of fault, series or parallel, into a line to ground fault easily protected in AC circuits by residual current devices RCDs or GFPDs.

References

Standards

1.s CEI 64-8, *Impianti elettrici utilizzatori a tensione nominale non superiore a 1 000 V in corrente alternata e a 1 500 V in corrente continua*. Edition 7, 07-2012

2.s EN 1998, Eurocode 8: *Design of structures for earthquake resistance – Part. 1: General rules, seismic actions and rules for buildings*. European Committee for Standardization (CEN), Brussels, 2004

3.s EN 50110-1, *Operation of electrical installations - Part 1: General requirements*. 03-2013

4.s EN 50522, *Earthing of power installations exceeding 1 kV a.c.*. July 2012

5.s EN 62423, *Type F and type B residual current operated circuit-breakers with and without integral overcurrent protection for household and similar uses*. 04-2013

6.s IEC 60287, *Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses*. 12-2006

7.s IEC 60364-1 *Low-voltage electrical installations - Part 1: Fundamental principles, assessment of general characteristics, definitions*. Edition 5, 11-2005

8.s IEC 60364-4-41, *Low-voltage electrical installations – Part 4-41: Protection for safety – Protection against electric shock*. Edition 5, 12-2005

9.s IEC 60364-5, *Low-voltage electrical installations Electrical Installations Of Buildings - Part 5: Selection and erection of electrical equipment*. 2002

10.s IEC 60364-7 *Electrical installations of buildings - Part 7-710: Requirements for special installations or locations - Medical locations*. Edition 1, 11-2002

11.s IEC 60439-1, *Low-voltage switchgear and controlgear assemblies - Part 1: Type-tested and partially type-tested assemblies*. Edition 4.1b, 2004

12.s IEC 60479-*1, Effects of current on human beings and livestock - Part 1: General aspects*. Edition 4, 07-2005

13.s IEC 60601-2-7, *Medical electrical equipment - Part 2-7: Particular requirements for the safety of high-voltage generators of diagnostic X-ray generators*. Edition 2, 02-1998

14.s IEC 60755, *General requirements for residual current operated protective devices*. Edition 2, 01-2008

15.s IEC 61010-1, *Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use - Part 1: General requirements*. 06-2010

16.s IEC 61508, *Functional safety of electrical/electronic/programmable electronic safety-related systems*. Edition 2.0, 04-2010

17.s IEC 61557-15, *Electrical safety in low voltage distribution systems up to 1000V AC and 1500 V DC – Equipment for testing, measuring or monitoring of protective measures – Part 15: functional safety requirements for insulation monitoring devices in IT systems and equipment for insulation fault location in IT systems*. Ed.1.0, 02-2014

18.s IEC 61936-1, *Power installations exceeding 1 kV a.c. Part 1: Common rules*. Edition 2 , 08-2010

19.s IEC 62040-3, *Uninterruptible power systems (UPS) - Part 3: Method of specifying the performance and test requirements*. Edition 2, 03-2011

20.s IEC 62271-200, *High-voltage switchgear and controlgear – Part 200:AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*. First edition 11-2003

21.s IEC 60898-1, *Electrical accessories Circuit-breakers for overcurrent protection for household and similar installations Part 1: Circuit-breakers for a.c. operation*. Edition 1.2, 07-2003

22.s IEEE Std. 80, Guide for Safety in AC Substation Grounding, 1986

23.s IEEE Std. 81, Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground system, 1983

24.s IEEE Std. 81.2, Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems, 1991

25.s IEEE Std. 141 (Red Book), *Electric Power Distribution for Industrial Plants - Chapter 2 System planning*. 12-1993

26.s IEEE Std. 399 (Brown Book), *Recommended Practice for Industrial and Commercial Power Systems Analysis*. 09-1997

27.s IEEE Std. 446 (Orange Book), *Emergency and Standby Power Systems for Industrial and Commercial Applications*. 06-2000

28.s IEEE Std. 493 (Gold Book), *Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*. 02-2007

29.s IEEE Std. 602 (White Book), *Recommended Practice for Electric Systems in Health Care Facilities*. 03-2007

30.s IEEE Std. 902 (Yellow Book), *Guide for Maintenance, Operation and Safety of Industrial and Commercial Power Systems*. 10-1998

31.s IEEE Std. 1100 (Emerald Book), Recommended Practice for Powering and Grounding Sensitive Electronic Equipment. 12-2005

32.s IEEE Std. 1159, *Recommended Practice for Monitoring Electric Power Quality*. 06-2009

33.s ISO 22313, *Societal security - Business continuity management systems – Guidance*. Edition 2012

34.s FEMA no. 450, NEHRP *Recommended Provisions and Commentary for Seismic Regulations for New Buildings and Other Structures, prepared by the Building Seismic Safety Council*. Federal Emergency Management Agency (FEMA), Washington, DC, 2003

35.s NFPA 70, S*afe electrical design, installation, and inspection to protect people and property from electrical* hazards. National Electrical Code Edition 2014

36.s NFPA 70E, *Standard for Electrical Safety Requirements for Employee Workplaces*. Edition 2012

37.s NZS Std. 4219, *Seismic performance of engineering systems in buildings*. Standard Council of New Zealand, 2009

38.s Rapporto ATC 51-2, *Raccomandazioni congiunte Stati Uniti-Italia per il Controventamento e l'Ancoraggio dei Componenti Non Strutturali negli Ospedali Italiani*. Applied technology council, 2003, www.ATCouncil.org

39.s TIA-942, *Telecommunications Infrastructure Standard for Data Centers*. April 2005

Papers and technical texts

1.p ABB, *Distribution systems and protection against indirect contact and earth fault*. ABB SACE, May 2008

2.p Anthony M., Arno R., Saba P.S., Schuerger R., Beirne M., *Reliability engineering applied to Critical Operations Power Systems (COPS)*. IEEE/I&CPS Tech. Conf., Tallhassee, Florida, USA, May 9-13, 2010

3.p Arno R., Friedl A., Gross P., Schuerger R., *Reliability Data Centers by Tier classification*. Industry Applications IEEE Transactions on, Volume 48, Issue: 2, page(s): 777- 783. Publication Year: 2012

4.p Avelar V., *Powering Single-Corded Equipment in a Dual Path Environment*. APC by Schneider Electric, White Paper 62, 2004

5.p Baran M., Mahajan N. R, *DC Distribution for Industrial Systems Opportunities and Challenges*. Industry Applications IEEE Transactions on, vol. 39, issue: 6, page(s): 1596 – 1601, November-December 2003

6.p Campagno L., Trapani N., *Principi fondamentali della teoria dell'affidabilità in campo manutentivo*. Rivista Manutenzione, Tecnica e Management, giugno 2003

7.p Prudenzi A., Caracciolo V., Silvestri A., *Identification of electrical load, typical patterns in hospital for supporting energy management strategies*. 20th Congress of the IFHE - Barcelona Spain October 20-22 2008

7bis.p Prudenzi A., Caracciolo V., Silvestri A., *Electrical load analysis in hospital complex*. IEEE PowerTech, Bucharest romania, June 28-July 2 2009

8.p Chloride - Emerson Network Power, *Vademecum sulla progettazione di un Data Center. Stato dell'arte e sviluppi per una maggiore efficienza energetica*. Chloride Products&Services - Emerson Network Power (Italia), 07-2011

9.p Dhillon, B.S., *Maintainability, Maintenance, and Reliability for Engineers*. CRC Press, march 2006

10.p ENEL, *Qualità dell'alimentazione elettrica negli impianti industriali*. Direzione Comunicazione Enel SpA, www.enel.it/infrastruttureretì, February 2006

11.p EPCOS *Damping of Inrush Current in Low-Voltage PFC Equipment. Application note*. 2001

12.p Gregory D., Scott G. W., *The arc-fault circuit interrupter, an emerging product*. Industry Applications IEEE Transactions on, vol. 34, pp. 928–935, September-October 1998

13.p Hasse P., *Overvoltage Protection of Low-Voltage Systems*. Institution of Engineering and Technology, Revised edition, 01-2000

14.p Martirano L., Parise L., *Dependability in Electrical Power Systems Exposed to Seismic Hazard*. 12th International Conference on Environment and Electrical Engineering, EEEIC 2013 Wroclaw Poland, May 5-8 2013

15.p Mazzetti di Pietralata C., Fiamingo F., Flisowski Z., Lo Piparo G.B., Amicucci G.L., *Surge protective devices for low voltage systems: practical approach for the protection distance evaluation*. IEEE Power Tech, Lausanne, Switzerland. Page(s): 778- 782, July 2007

16.p Mazzetti di Pietralata C., Fiamingo F., Lo Piparo G.B., Roussea A., *A method to determine the need of SPD for the protection against lightning overvoltages of electrical and electronic installation supplied by power lines.* 29th International conference on lightning protection ICLP, Uppsala Sweden, June 23-26 2008

17.p Mohan N., Undeland T. M.,. Robbins W. P, *Power Electronics: Converters, Applications and Design*. John Wiley & Sons Inc, Edition 3, 10-2002

18.p Parise G., Hesla E., Parise L., *A Syntax And Semantics Of A Language For Operational Procedures*. Industry Applications IEEE Transactions on, Volume: 49, Issue: 1, page(s): 250–255. Publication Year: 2013

19.p Parise, G., Hesla E., Parise L., *AC DC Power Circuits Design By Microsystem Criteria*. IEEE-IAS I&CPS Tech. Conf. Stone Mountain, Georgia, USA, April 30 - May 3, 2013

20.p Parise G., Hesla E., Parise L., *Transitions theory in operation of electrical installations*. Industry Applications IEEE Transactions on, Volume: 49, Issue: 3, page(s): 1056–1061. Publication Year: 2013

21.p Parise G., Hesla E., Parise L., *Switching Procedures in Multiple Source Systems: The Flock Logic of Multi-Set Systems*." IEEE-IAS I&CPS Tech. Conf. Fort Worth, Texas USA May 20-23, 2014

22.p Parise G., Hesla E., *A Programmable Language For Clearing Procedures*. IEEE-IAS I&CPS Tech. Conf. Saratoga Springs, NY USA May 8-11, 2005

23.p Parise G., Lucheroni M., *Measurements of Touch and Step Voltages Adopting Current Auxiliary Electrodes at Reduced Distance*. Industry Applications IEEE Transactions on, vol. 44 n.6, November-December. Publication Year: 2008

24.p Parise G., Martirano L., Parise L. *Ecodesign Of Ever Net-Load Microgrids*. Industry Applications IEEE Transactions on, Publication Year: 2013

25.p Parise G., Martirano L., Parise L., De Angelis M., Perno S., Reggio A., *Seismic Qualification Categories (EQC) of Electrical Equipment*. IEEE IAS Annual Meeting, Orlando Florida USA October 6-11, 2013

26.p Parise G., Martirano L., Parise L., De Angelis M., Reggio A., Weber J., *Seismic Qualification Of Electrical Equipment In Critical Facilities*. IEEE-IAS I&CPS Tech. Conf. Stone Mountain GA USA, April 30 – May 3, 2013

27.p Parise G., Martirano L., Parise L., *Globality Levels of Grounding Systems*. IEEE-IAS ICPS Tech. Conf., Fort Worth, Texas USA, May 20-23, 2014

28.p Parise G., Mazzetti C., Parise L., Fiamingo F., *Safety system with harmless first fault: Complete & Medical IT-System*, IEEE IAS Annual Meeting, Vancouver BC Canada October 5-9, 2014

29.p Parise G., Parise L., Martirano L., *An example of a commercial/residential common microgrid integrating cogeneration and electrical local users*. Cigrè Symposyum, the electric power system of the future-integrating supergrids and microgrids Bologna, Italy, September 13-15, 2011

30.p Parise G., Parise L., Martirano L., De Marco A. *Electrical Service Continuity In Hospitals Exposed To Seismic Hazard.* 4 European Conference On Healthcare Engineering 51 Journées D'études Et De Formation IHF Palais des Congrès de Paris May 30 – June 1 2011

31.p Parise G., Parise L., *Electrical Distribution For A Reliable Data Center.* Industry Applications IEEE Transactions on, Volume: 49, Issue: 4, page(s): 1697 – 1702. Publication year: 2013

32.p Parise G., Parise L., *Microsystem criteria in electrical installations ecodesign*. IEEE/I&CPS Tech. Conf., Tallhassee, Florida, USA, May 9-13, 2010

33.p Parise G., Parise L., *Branch Circuits Ecodesign*. IEEE-IAS I&CPS Tech. Conf. New Port Beach,California USA, May 1-5, 2011

34.p Parise G., Parise L., *Microsystem Criteria In Branch Circuits Design*. IEEE-IAS I&CPS Tech. Conf. New Port Beach,California USA, May 1-5, 2011

35.p Parise G., Parise L., *La continuità del servizio elettrico nelle infrastrutture critiche*. Convegno Nazionale AEIT "Prospettive Economiche e Strategie Industriali" Milano Italy, June 27-29, 2011

36.p Parise G., Parise L., *Unprotected Faults of Electrical Cords and Extension Cords in AC and DC Systems*. Industry Applications IEEE Transactions on, Volume 50, page(s): 4-9. Publication Year: 2013

37.p Parise G., Parise L., Nicolucci P., *Localized Fire Ignition Hazard In Branch Circuits, Cords And Connected Equipment*. IEEE-IAS Annual Meeting, Orlando Florida USA, October 9 -13, 2011

38.p Parise G., Parise L., Pedrini D. *Electrical Service Continuity In Hospitals*. 21st Congress of International Federation of Hospital Engineering (IFHE) "Healthcare Engineering against Cultural Background" Tokyo Japan, November 17-19, 2010

39.p Parise L., *Ospedale Madonna delle Grazie di Matera: criteri di miglioramento sismico degli impianti elettrici*. 9° Congresso Nazionale “Tecnologia e Sanità” Rieti Italy, May 29-31, 2014

40.p Rasmussen N., *Data Center Projects: System Planning*. APC by Schneider Electric, White Paper 142, Rev.2, 2013

41.p Rasmussen N. Torell W., *Comparing Data Center PowerDistribution Architectures*. APC by Schneider Electric, White Paper 123, Rev.3, 2013

42.p Rausand M., Høyland. A., *System Reliability Theory: Models, Statistical Methods, and Applications*. John Wiley & Sons, 2004

43.p Sankaraiah, G., *Optimal reliability design of integrated reliability models for Redundant systems with multiple constraints*. 2010

44.p Schneider Electric Groupe, *Electrical Installation Guide - MV & LV architecture selection – Chapter 6 and 7*. Edition 2007

45.p Schneider Electric Groupe, *Modular units - Air insulated switchgear up to 36 kV*. Medium Voltage Distribution Catalogue 2012

46.p Seymour J., Horsley T. *The Seven Types of Power Problems*. APC by Schneider Electric, White Paper 18, 2009

47.p Siu S.K., Lopopolo J., *Compatibility, Sizing, and Design Considerations for Generators and UPSs in Tiers I, II, III, and IV Topologies*. Industry Applications IEEE Transactions on Volume: 47 , Issue: 6, page(s): 2324 – 2329. Publication Year: 2011

48.p Stapelberg R. F., *Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design*. Springer-Verlag. Edition 1, april 2009

49.p Tajali R., *Switchgear Design Impacts Reliability Of Backup Power Systems*. Electrical Line Magazine Vol. 14/1 2008

50.p Uptime Institute, Data Center Site Infrastructure Tier Standard: Topology. June 2010

51.p Wang W., Loman J. M., Arno R. G., Vassiliou P., Furlong E. R., and Ogden D., *Reliability Block Diagram Simulation Techniques Applied to the IEEE Std. 493 Standard Network*. Industry Applications IEEE Transactions on, vol. 40, no. 3, May/June 2004

Index Tables and Figures

Part 1
Critical Systems as Complex Systems. Distribution Architecture of a Complex System. Theory of Complex Systems for Safety, Operation and Maintenance of the Power Systems