THE UNDERGROUND POWER NETWORKS OF THE FUTURE
WHAT DEGREE OF RELIABILITY IS APPROPRIATE?

Mireille Morazzani – Jean-Marc Boyer
ALSTOM T&D STC
1340 Rue de Pinville – La Pompignane
Tel: (+ 33) 467 02 95 70 – Fax: (+ 33) 467 02 95 72 – E-mail: jeanmarc.boyer@tde.alstom.com

ABSTRACT

The policy of the EDF (French electricity generating authority) on power distribution in rural areas has three main aims: reducing the number of power cuts, preserving the environment and maintaining safety standards. This policy has led to the use of new circuit interrupting equipment the reliability of which is particularly crucial due to the fact that it is located at key points in the underground network.
The high performance demands and the limited nature of the market combine to make the technical and economic challenge even more difficult to meet.
ALSTOM's solution consisted in using existing components drawing benefit from more than 10 years service experience and combining them in a configuration that is suitable to the new requirements.
We have used the following approach when calculating reliability:
-FMECA (failure modes effects and criticality analysis) was used to study the behaviour of components in their new context,
-Reliability was calculated on the basis of feedback from installed components,
-Predicting the behaviour of new equipment by carrying out a comparative analysis of specific identical functions in existing and new components.
The study confirms that in limited markets a solution should be sought that combines existing products and procedures the reliability of which can be quantified.

INTRODUCTION

Underground power networks

Secondary power distribution networks in rural and suburban areas have grown to meet an increasing demand. Faced with this demand, the EDF's policy has favoured underground networks for essentially environmental reasons. Environmental considerations are nowadays felt at every level of society, whether State, local authority, business or private individual [1], [2].

Moreover, underground power networks have the clear advantage of eliminating the type of power line disturbance to which overhead lines are subject by virtue of their outdoor location and exposure to contact with vegetation, the weather, etc.
In the early days of underground power networks, the major drawbacks were linked to the additional cost of burying the lines and the lack of suitable circuit interrupting equipment.
High-performance laying machines made it possible to lay Medium Voltage cables in rural areas at competitive prices. In order to control costs, suitable circuit interrupting equipment had to be designed and developed. Of particular importance were switch-disconnector equipments capable of interrupting the network, identifying the location of the fault and, if required, connecting a branch circuit.[3]

Quantities

Despite the significant growth of rural networks in France, the number of underground rural networks remains limited when compared with the urban system. Installing circuit interrupting equipment on these networks gives rise to small quantities.

Appearance

Operating needs in underground networks has led to switch-disconnector equipments being installed above ground. For this reason their impact on the environment, and particularly their appearance, must be taken into consideration.

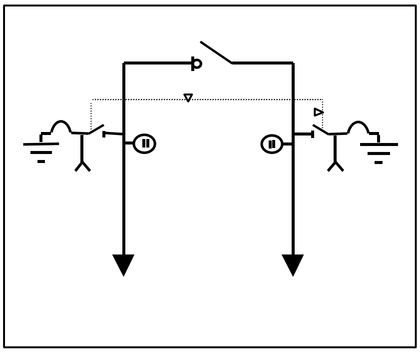
These two factors:
- Small quantities
- Appearance

have had a major influence on the choices taken in designing the Alstom solution.

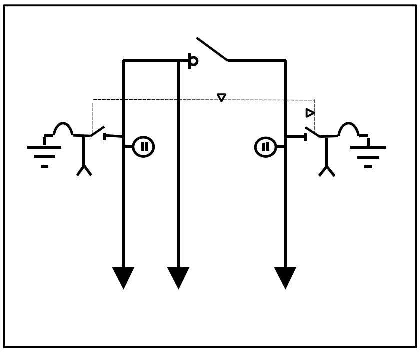
DESCRIPTION OF THE PRODUCT

The circuit interrupting equipment we have developed fits inside a small-size station.

To comply with the conditions and requirements outlined above, 2 versions of the circuit interrupting equipment have been designed:



- ACM: Manual switch-disconnector with upstream and downstream earthing,



- ACMD: Manual switch-disconnector with upstream and downstream earthing and branch circuit.

General information

The station specified by HN 64-S-49 consists of:

- Medium Voltage circuit interrupting equipment,
- One or two fault detectors,
- A prefabricated one-piece housing, the underground section of which is used for the evacuation of the cables.

The circuit interrupting equipment

This circuit interrupting equipment can operate on both 15 kV and 20 kV networks. It complies with specification HN 64-S-42. The equipment is housed in a compact metal enclosure. It consists of a gas tight metal tank that complies with specification IEC 298 filled under SF6 pressure (0.45 bar), containing:

- An MV switch-disconnector with a current rating of 400 A (complies with specification IEC 265-1),
- Two earthing switches (upstream and downstream of the switch-disconnector),
- A 400 A branch circuit in the ACMD version,
- A current injection system designed to detect cable insulation faults,
- 2 manual operating mechanisms,
- Two sets of 400 A pluggable bushings in the ACM version and 3 sets in the ACMD version.

In combining these components, the potential risks inherent in an MV switchboard are taken into consideration:

- Internal arc protection,
- Safety of position indicators,
- Ability to close earthing switches in the event of short circuit,
- Improved weather-resistance,
- Use of mechanical operating mechanisms that are simple, robust and maintenance-free,
- Elimination of oil as insulation medium.

Ratings

- Type of switchgear		Compact
- Rated voltage		24 kV
- Rated power-freq. withstand voltage		50 kV/50 Hz
- Rated lightning impulse withstand voltage		125 kV peak
- Operating voltages		20 & 15kV
- Rated current in continuous service		
Main circuit		400 A
Branch circuit		400 A
- Rated short circuit current		12.5kA/1s
- Internal fault current		8 kA/0.7s
- Zero sequence fault current		2 kA/0.7s
- Fault closing capacity		31.5kA peak
- Rated frequency		50 Hz
- Degree of protection	tank	IP 62
	housing	IP 2X

Reliability characteristics

The EDF has given commitments to ensure improved continuity of service. This will require improved control over the quality and reliability of electrical equipment.
It is vital to establish the role of each component of the network in the quality of the service provided to the consumer.
The service guarantee is ensured on the network in various ways to achieve the best compromise between the impact

on consumers of each power cut and the cost of the equipment installed.

In order to ensure continuity of service of its primary sub-stations, the EDF has chosen to back up protection, circuit interrupting and relay equipment. In the MV network downstream of primary sub-stations, the backups necessary to ensure the quality of service are provided by loop supply or double branch circuits. On the main sections of the network no backup is economically possible; this is why reliability is directly dependent on the circuit interrupting equipment itself. [2]

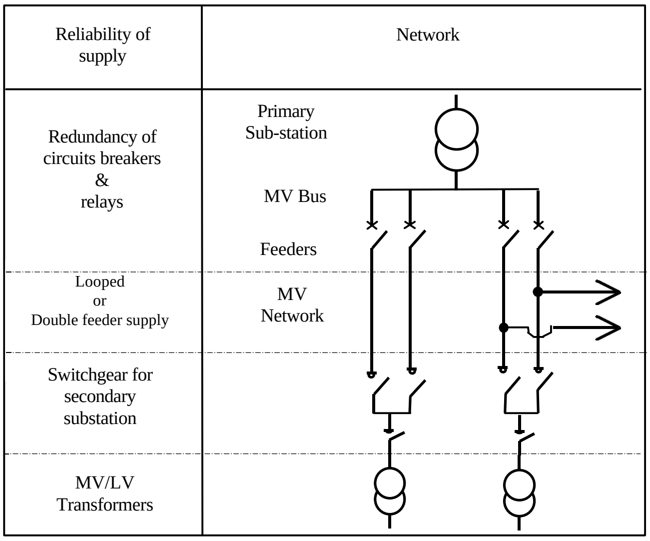


Diagram of distribution network

RELIABILITY ANALYSIS

Introduction.

The EDF requires suppliers to present a reliability study; these studies usually use the FMECA method. Alstom has undertaken its reliability study on the basis of the procedural guide of an FMECA carried out on MV equipment (HM2494065A). [4]

The first stage was to create a multidisciplinary working group including representatives from the technical, marketing, sales, quality, process, purchasing and production departments. A series of weekly working meetings was first arranged and an agenda drawn up of themes to be dealt with during the meetings. This study was scheduled to take place during the pre-industrialisation phase of the product which lasted over a period of 6 months. In order to keep the study pragmatic, each aspect of the product FMECA was extended by examining the production resources involved and the possible precautions to be taken when implementing the resources.

Qualitative study

Implementation. ALSTOM's solution consisted in using existing components drawing benefit from more than 10 years service experience and combining them in a configuration that is suitable to the new requirements.

Functional analysis of the future product enabled us to provide all the functions required using existing components, while adding functions particular to this application:

- Ensuring that power is carried by the main distribution cables and the branch circuit
- Establishing the service current
- Establishing the connection to ground
- Interrupting the main distribution cable
- Allowing for fault detection
- Indicating the presence of voltage
- Ensuring safety of the operator and the surroundings once the switchgear installed in the concrete housing
- Ensuring an acceptable appearance

These major functions required the following main components:

- Bushings	Existing components
- Busbars	Modified components
- Switch-disconnector	Existing component
- Operating mechanism	Existing components
- Earthing switch	Existing and modified components
- Injection bushings	Existing components
- Voltage presence indicator	Existing component

As soon as these functions had been defined, we listed the potential failure risks associated with the functions; these risks are known as hazards:

- Unwanted power interruption
- Failed interruption
- Unwanted power connection
- Failure to connect power downstream
- Risks for operators
- Downstream unusable
- Risk of total destruction of the panel
- Panel inoperative
- Earthing of live cables
- Impossibility of accessing cables
- Operation of external protective devices
- Unwanted earthing

The study continued with drafting of Table 1, showing all the possible manoeuvres: Combination of all “open” and “closed” positions of the switch-disconnector, the 2 ground connections and acknowledgement of the associated interlocks preventing the occurrence of hazards.

Table 1 : Possible manoeuvres

Man.	SWD			ESW 1			ESW 2		
a	O	→	C	C		O	C		O
b	C	→	O	C		O	C		O
c	C		O	O	→	C	C		O
d	C		O	O	←	C	C		O
e	C		O	O	→	C	C		O
f	C		O	O	←	C	C		O
g	C		O	C		O	O	→	C
h	C		O	C		O	O	←	C
i	C		O	O		O	O	→	C
j	C		O	O		O	O	←	C

Man. : Manœuvre, →: manœuvre in action, C :closed ,O :open, C : Locked
SWD : Switch-disconnector , ESW : Earthing switch

Each manoeuvre leads to a static state. Table 2 shows all the static states of the active component: Switch-disconnector, the two ground connections and the two injection bars.

Tableau 2 : Static states of switch-disconnector and earthing switch

State		Pos. 0=inactive, 1=active						Position 0:open 1:closed		Secondary State Possible	
		SWD		ESW 1		ESW 2					
		C	O	C	O	C	O	bar1	bar2	Sign.	Inj.
A	1	1	0	0	1	0	1	1	1	X	
	2							0	1		
	3							1	0		
	4							0	0		
B	1	0	1	1	0	1	0	1	1	X	
	2							0	1	X	X
	3							1	0	X	X
	4							0	0	X	X
C	1	0	1	1	0	0	1	1	1		
	2							0	1	X	X
	3							1	0		
	4							0	0	X	X
D	1	0	1	0	1	1	0	1	1		
	2							0	1		
	3							1	0	X	X
	4							0	0	X	X
E	1	0	1	0	1	0	1	1	1	X	
	2							0	1		
	3							1	0		
	4							0	0		

SWD :Switch-disconnector ; ESW : Earthing switch
Sign. :Significant Inj. :Injection
bar. :injection bar

The two tables enabled us to specify for each constitutive component of the product, in each function, the possible manoeuvres and the states attained. We then linked them to the hazards.
This in-depth analysis allowed each member of the working group to have information on each component and to define a common frame of reference. This preliminary step to drawing up the FMECA table is necessary to give a uniform, consensual approach that can subsequently be applied to each component of the product.

The FMECA table. The FMECA table uses the columns imposed by the EDF guide. In particular, it uses the lists of “failure modes” and “causes of failure” to be in line with the customer and also because experience has shown these lists to be relevant and thorough for the MV equipment in question.
Without going into details of the FMECA method, we now give a few words, column by column, about one of the constituent parts of the grounding terminal, the bearing:
- Function: Guiding and/or maintaining components used for circuit interrupting, insulating, connecting and/or transmission. This function is fulfilled during the manoeuvre of a→j (See table 1).
- Failure mode: “Does not operate when required (failure to meet demand)”
- Cause of failure: Vibrations
- Local effect: loosening of bolted connection
- Final effect: Internal arc (caused by rotor falling)
- Preventive maintenance: Not applicable
- Reliability uncertainty factor: Procedure tested
- Occurrence of the failure: 3 (rare)
- Level of gravity of the failure: 7 (catastrophic)
- Criticality of the failure: 21 (3X7)
- Hazard: Internal arc.

The last column of the FMECA table is reserved for noting steps that be taken to reduce the criticality of failures.
In the present case, the bolted connection was replaced with a riveted connection that changed the situation as follows:
- Occurrence of the failure: 1 (exceptional)
- Level of gravity of the failure: 7 (catastrophic)
- Criticality of failure: 7 (1X7)
- Hazard: Internal arc.

The hazard remains the internal arc but criticality is considerably reduced.

Quantitative study

Introduction. The goal is not to quantify all the potential risks. Only risks having an effect on quality of service and personal safety are considered.
We therefore did not attempt to determine the failure rate of the finished product on the basis of the following general definition of a failure: “An event that prevents a device from normal performance of the functions for which it was designed”. Instead we evaluated the failure rate of the complete equipment relative to the different types of failure contained in the EDF specification:

Table of reliability characteristics

Characteristic or function	**Values of reference reliability levels (Failure rate)**
Faults inside a panel	$1X10^{-7}$ per operating hour (for each panel)
Leak in a sealed, pressurised system	$0.3X10^{-7}$ per operating hour (for each panel housing)
Failure by a disconnecting switch or earthing switch to open or close	$0.6\ X10^{-7}$ per operating hour (for each panel)
Voltage presence indicator	$0.5X10^{-8}$ per operating hour (for each complete equipment)

It may be noted that the reliability requirements for a switch-disconnector equipment are particularly important since the position of the equipment in the network means that there is no protective backup.

The MV cables and cable terminals were not included in these criteria since the criteria only concern the equipment itself. But the system was designed so that connections could be established without deteriorating the cables: the cables were ensured a large radius of curvature and operators were ensured sufficient room to work inside the housing.

Methodology. For each evaluation, we considered that the faulty component would cause the failure of the complete equipment, i.e. that the various components making up the equipment are connected in series. ($\lambda=\Sigma_i \lambda_i$).
We carried out this study using the failure records over a period of 4 years of similar products using identical

components to ours: A compact type equipment composed of three functional units (Fluokit C). This basis was representative since it related to 12,650 equipments, i.e. approximately 38,000 functional units.

Where no specific commissioning date was available, we assumed an average operating life of 2 years for each equipment. This operating life, combined with the number of equipments and the number of functional units allowed to estimate the total number of operating hours for each equipment and each functional unit.

The faults recorded were classified by category of failure and then totalled. The number of incidents per type of failure relative to the total number of service hours gives the failure rate of the category.

Once we had obtained the failure rates for installed equipment, we established the figures for our equipment for each category of failure. We checked what the impact of modifications would be on failures.

Because the functions present on the installed equipment were identical to those present in our equipment, and because modification did not alter the operating context, the influencing factors are the same. We therefore consider that these failure rates can be applied to our equipment.

This holds good for all criteria except gas tightness since the tank of our equipment has some differences from those of the installed equipment:

- The shape, weld length, weld path and weld procedure itself,
- The number of components feeding into the equipment, the length of the seals.

We checked that the length of the seals (welds or seals) was less in our equipment. Moreover, the industrial welding procedure used in our equipment gives improved weld quality.

Therefore the differences do not have a negative effect on the results obtained for the tightness criterion.

CONCLUSION

In conclusion we would to highlight 5 points:

- The lack of function backup associated with the overall aim of zero faults leads to a specification of low ?.
- Calculating forecast reliability is always a difficult process; results are most credible when they are based on existing data and/or feedback from a representative population of large quantities and identical components.
- The forecast reliability applied to network equipment is nowadays quantifiable using simple, effective tools such as FMECA, data bases, feedback and a few hypotheses designed to simplify the exercise. However, progress remains to be made in order to account for dormant systems.
- Only this practical exercise can make use of preconceived ideas or intuitions. The use of the FMECA method by a multidisciplinary group gives an exhaustive picture of all the functions to be fulfilled together with the associated risks and weighted notation eliminates any trace of subjectivity or unquestioned assumptions.
- The use of this method is an effective tool for learning about a product, giving participants technical training and ensuring their mutual enrichment. It is the more useful in that subsequent production difficulties may be solved by referring to the results of the study.

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