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**Management of risks due to load-flow increases in  
transmission OHL**

**Task Force  
B2.20**

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**TF B2.20**

# **Management of risks due to load-flow increases in transmission OHL**

## **Members**

J. PESTOURIE, TF convenor (FR), C. SPELLEMAN, Secretary (FR),  
R. STEPHEN (ZA), B. RISSE (BE)

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# 1. Context and objectives

## 1.1. Context of load-flow increases in OHL

The forecast for increased growth in demand for electricity over the next few years urgently requires Transmission System Operators (TSO) to take opportune action. Moreover, it is already difficult to build new overhead lines (OHL), because of environmental constraints and public opinion. In this context, increasing the load-flow in existing transmission lines is seen as a valid alternative.

Nevertheless, the current increase through OHL could not be realized without risk management (safety, components lifespan and exploitation, economical and environmental constraints), especially because the original design didn't take this aspect into account

However, even if the risks are likely to be increased with the load-flow, this increase needs to balance against a risk of non supply should the line not be updated. Indeed, the environmental and the financial consequences as well as the effects on health on non supply is often far in excess of the small effect of OHL rating increase.

## 1.2. Objectives of the Task Force

The objectives of the Task Force are to launch a reflexive approach regarding risks due to load-flow increases in transmission OHL, to discuss a risk management method and to give necessary tools for well-founded decision making [1],[2],[3].

We want to determine all of the risks (for equipment, safety, environment...), to assess risks due to upgrading in transmission equipment and to identify potential benefits in relation to acceptable risks.

In this way, we defined three questions :

- Which risks do we have if we increase average load on existing lines ?

This question corresponds to the following situation :

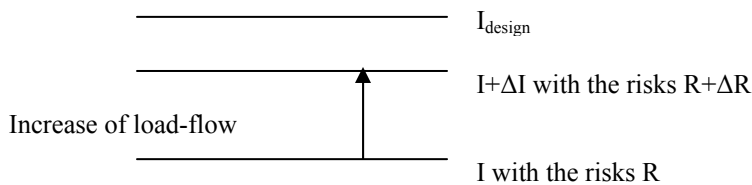


Figure 1 : risks due to average load increase on existing lines

It means that currently we have an inherent risk R and if we increase the current I (with  $I < I_{design}$ ), we will have a new risk  $R + \Delta R$ .

- Which risks do we have if we run existing lines short time at 100%, 120 %, ... ?

This question corresponds to the following situation :

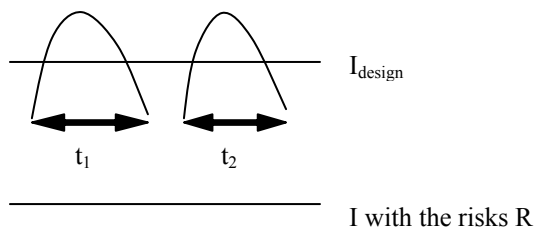


Figure 2 : risks due to short time increase at 100%, 120% on existing lines

It means that currently we have an inherent risk R and if we increase the current I (with  $I > I_{design}$  during a short time), we will have a new risk  $R + \Delta R$ .

- Which risks will occur by uprating lines to higher currents ?

This question corresponds to the following situation :

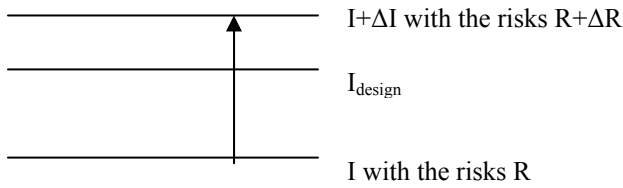


Figure 3 : risks due to uprating lines to higher currents

It means that currently we have an inherent risk  $R$  and if we increase the current  $I$  (with  $I > I_{design}$ ), we will have a new risk  $R + \Delta R$ .

We proposed for each situation to give a list of recommendations in order to determine the new value of risks. We can describe it with the following scheme :

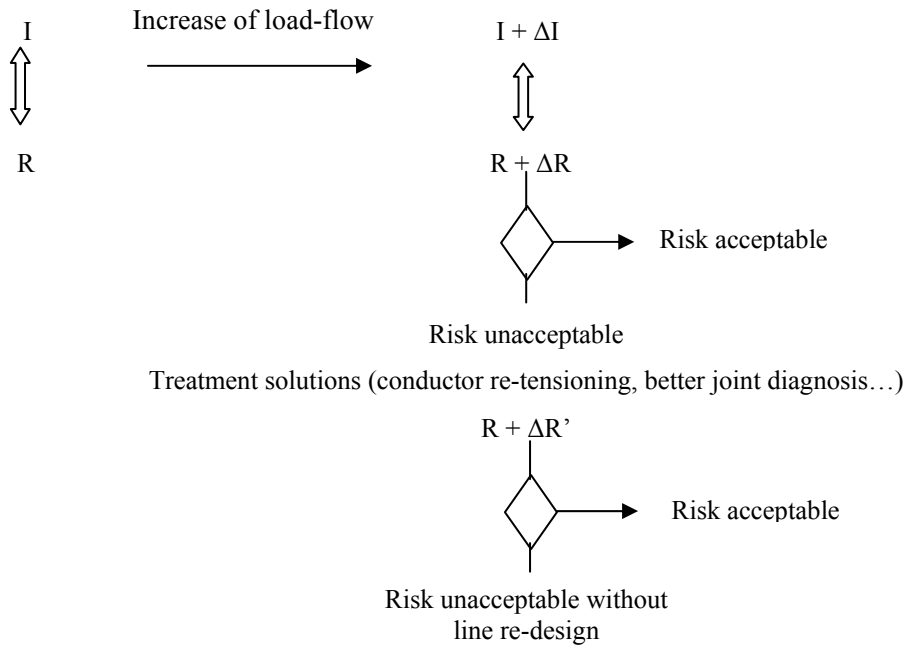


Figure 4 : scheme to define recommendations

In this way, the purpose is to estimate the evolution of risks with the increase of  $I$  and to determine all the data and information that could help engineers and managers in decision making to increase or not the load-flow in their existing lines.

## 2. Risk assessment of load-flow increases in OHL

### 2.1. Risk assessment method

Globally speaking, risk assessment is an efficient method to represent all dimensions of risks and to build a risk management process. More precisely, it is a process including survey, assessment, classification of risks related to an organization with the support of tools like risks maps, risks diagrams. These tools are powerful for analysis and communication. The typical product of risk mapping is a risk map. On this kind of map, major risks are represented as dots on a two axis diagram, each axis representing a risk attribute or risk dimension. The risk mapping method can also produce risk files and diagnosis tools useful for many purposes. Performing a risk map implies questioning, self assessment, knowledge management, internal communication activities, fruitful for the whole TSO organization.

In general, it is useful for managers, internal controllers as well as experts for technological risks assessment.

Risk assessment is an iterative process, organized on the basis of 5 main steps.

<u>Step 1</u> Establish the context	<u>Step 2</u> Identify risk scenarios	<u>Step 3</u> Model risks	<u>Step 4</u> Assess and prioritize risks	<u>Step 5</u> Risk Treatment
Definition of objectives and limits of risk management process	Identification of risk scenarios : cause/effect diagrams (descriptions, interactions, consequences)	Building of risk networks used as support for Step 4 (Bayesian network)	Evaluation of consequences and classification (assessment of likelihood and seriousness due to simulation, experience feedback, expert judgement)	Evaluation of solution impacts to treat the risks (re-tensioning the conductors, ...)

Table 1 : risk assessment method

The details of this methodology are given as follows :

- Establish the context : the purpose of this step is to set up the strategy and limits of risk mapping process. The main tasks concern the definition of : the physical boundaries, the “load-flow capacity increase”, the stakeholders and the types of risk taken into account,
- Identify risk scenarios : the objective is to list and identify as most as possible risks scenarios, with their descriptions and interactions. Bibliography , working groups, interview, experience feedback and surveys are used extensively. The n, each event of risk scenarios is described as an element of a cause/effect diagram,
- Assess risks : the goal is to describe, to analyze and to quantify the risks scenarios. This step facilitates the assessment as to the likelihood and the consequences of risk scenarios based on the simulation of physical phenomena, experience feedback, expert judgment and risk networks (Bayesian networks),
- Classify and prioritize risks : the aim is to prioritize risks and to establish which risks have to be treated as a priority. Risk map is the tool used as a support for decision making. Risks scenarios are represented in a two axis diagram, each axis representing one the dimension of risks (at least gravity, and probability),

## 2.2. Identification of risk scenarios

In our approach dealing with the management of risks due to load-flow increases, the components taken into account are :

- Conductors : homogenous (AAAC) and bi-metallic (ACSR or AACSR),
- Joints : compressed and tension conductor joints for homogenous and bi-metallic conductors,
- Earth wires : a priori only bi-metallic conductors. Moreover, for this type of equipment, we take both conductors and joints into account,
- Accessories such as clamps, jumpers, dampers, conductors spacers.

Towers and foundations are not taken into account because, a priori, upgrading has no direct effect on them. However, a tower or a foundation can intervene in a risk scenario and especially regarding the consequences. For instance, a conductor breakage can lead under certain circumstances to one or several tower drops.

Firstly, we proposed to build a global cause/effect diagram (as defined in step 2 of the risk assessment method) for each equipment of OHL, it means we link the initiator "increase of I" with the different risks for OHL.

However, after discussions with experts, joints are considered as the weakest point of the system in case of load-flow increases (more generally equipment with contacts as connections).

We focus on the example of Cause/effect diagram for bi-metallic conductor joints. The objective is to list and identify as most as possible risk scenarios due to the load-flow increase in joints, with their descriptions and interactions. The risk scenarios are defined with cause/effect diagrams, in which the various events and the logical links between them are represented.

By convention, the initiating event of all risk scenarios is the increase of load-flow and is on the left-hand side of the diagram.

The six following risks are studied :

- risks to life and property,
- risks to the environment,
- risks of breaking regulations,
- risks to transmission infrastructures (all the OHL equipment),
- financial risks,
- risks to transmission network management (maintenance, refurbishment, availability...).

We don't take the power system aspect into account in our approach.

These six risks are the final events and are on the right side of the diagram.

In the continuation, we distinguish the cause/effect diagram for :

- bi-metallic conductor joints,
- bi-metallic conductors,
- earth wires whose behavior is close to the combination of the bi-metallic conductors and bi-metallic joints behavior,
- accessories and other phenomena.

Obviously, interactions can occur between the different parts.

2.2.1. Cause/effect diagram for bi-metallic conductor joints

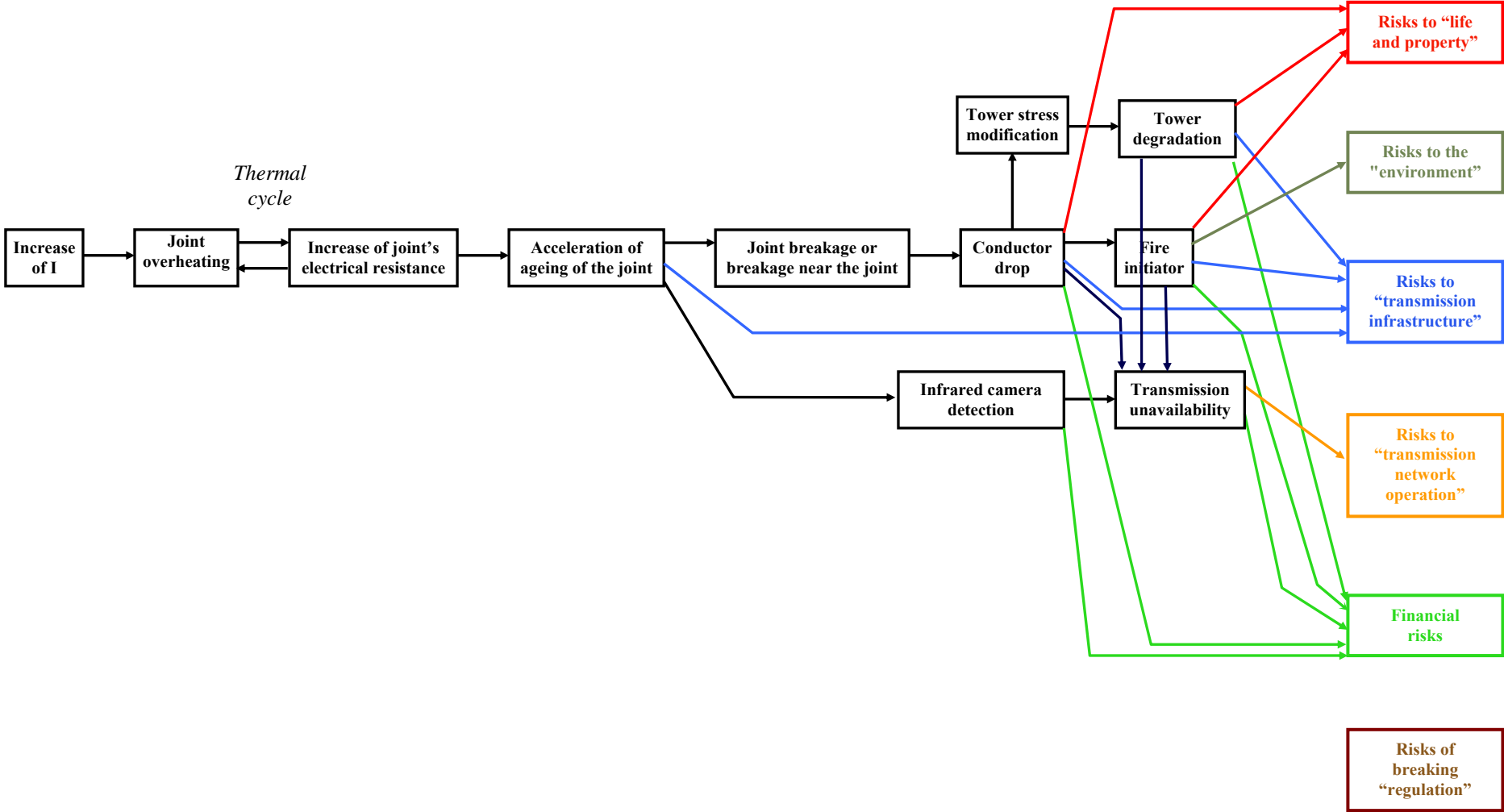


Figure 5 : cause effect diagram for bi-metallic conductor joints

The function of a conductor joint is to ensure the electrical and mechanical continuity of the conductor. The joints most often used for transmission OHL are of two types :

- expanded line joint composed of an annealed round metal tube of aluminium or aluminium alloy, expanded over the conductor through a joint former. This technology is rarely used anymore but many expanded joints are still in operation,
- compressed line joint obtained from a joint compression onto the conductor by a hydraulic press, in small successive pressure applications, or by explosion (not in France because of safety problems). This is the technique most widely used at present.

When not stipulated otherwise, the following description concerns every type of conductor joint. Furthermore, as seen previously, the load-flow increase is seen as the increase of the current transmission with the immediate consequence of heating in the conductor joints. This temperature increase results in increasing the joint electrical resistance, in turn causing an increase in temperature. The phenomenon is therefore cyclic. The electrical resistance increase represents the ageing of the joint, as evidenced by its temperature increase.

So, the increased joint temperature caused by the load-flow increase, can cause an acceleration of ageing. Naturally, this event has consequences in terms of assets (Risks to "Transmission Infrastructure") even if it does not go as far as breakage. The two underlying and correlated physical phenomena are :

- oxidation and corrosion : the electric contacts in the joints consist of aluminium or aluminium alloy elements containing silicon and magnesium. The corrosion rate of the electric contact depends essentially on the temperature, on the composition of the aluminium alloy and the surrounding environment in terms of pH, pollution, high current density...
- the relaxation of stresses : the decreasing force on the contact can trigger fretting corrosion associated with minor movements in the contact, making it more vulnerable to the effects of dynamic stress.

When new, the resistance per unit of length of a joint in operation is approximately one third that of the associated conductor, meaning that the joint temperature is well below than the one of the conductor.

In the course of time, contacts become oxidized, the joint resistance increases and the temperature may exceed that of the conductor. This overheating encourages the increasing degradation rate of the contacts, resulting in a thermal breakdown process, finally causing the joint breakage. We refer the breakage of the joint but this is not totally accurate because the conductor breakage is often in the immediate surroundings of the conductor joint. This damage process is almost systematically observed during failure analysis and very few cases are related to the direct degradation of the mechanical function of the joint. This type of degradation is valid for every type of conductor joints but concerns essentially conductor joints for bimetallic conductors. Finally, the influencing parameters, in addition to the current increase, are the defective installation of the conductor joint (in correct cleaning of conductor, problem of jointing, etc) and the operating environment (weather, pollution, etc.).

Subsequently, the joint breakage logically leads to the conductor drop, or at least of a sub-conductor drop for the multiple bundle line. In addition, starting from the conductor breakage, a number of different events may appear :

- The tower stress modification located near the breakage : the tension towers come under greater twisting stress and the suspension towers have to act as tension towers, although they are not designed for the task. In any case, the result is the towers degradation. This scenario therefore has an impact on the Transmission System Operator assets (Risks to "Transmission Infrastructure") that varies in its seriousness. In extreme cases, depending on the condition and type of towers, the result can be the breakage of one or several towers, which represent a risk to property and people (Risks to "Life and Property"), a risk of the transmission loss of the line and a financial risk because it would be necessary to repair the line to operational condition ("Financial" Risks).
- The initiation of a fire because of the conductor falling into an inflammable environment. At varying levels of severity, depending on the scale of the resultant fire, an event like this can have environmental risks, financial risks, risks to Transmission System Operator assets, affecting property and people (Risks to the "Environment", "Financial" Risks, Risks to "Transmission Infrastructure" and Risks to "Life and Property") and also operation, because of the possible loss of transmission.
- The loss of transmission and availability associated with the breakage and the repair time needed for re-establishing the line operation, as well as the possibility of transmission interruption on another line following a short circuit resulting from contact with the conductor of another line (for a double circuit OHL or HV line located under the transmission OHL). Under these conditions, the system operation is

affected to a varying degree depending on the strategic importance of the line (Risks to “Transmission Network Operation”) and has economic consequences because of the costs resulting from the loss of load-flow capacity, in particular for the interconnection lines (“Financial” Risks).

Furthermore, the conductor breakage has a direct impact on the Transmission System Operator as sets and a conductor drop can cause damage to the surrounding equipment (Risks to “Transmission Infrastructure”). Similarly, a conductor that falls (onto the ground or onto an obstacle) endangers property and people, without forgetting the case of a fall which is not followed by a definitive tripping. In a case like this, the live conductor will hang down at a more or less large distance from the ground, representing risks of electrocution (Risks to “Life and Property”). Finally, the breakage can also induce financial risks because it will require repairing (the costs will essentially come from manpower and supplies) (“Financial” Risks).

Although it may not go as far as to cause the breakage of a conductor joint, accelerated ageing can cause the degradation of the conductor joint which, as we have seen, will appear as an abnormal temperature rise. Under these circumstances, following a thermographic inspection to detect the “hot points” liable to cause an eventual failure, the conductor joint is usually shunted or replaced, depending on its condition, causing the line to become unavailable (unless the work is carried out live) with consequences in financial terms (“Financial” Risks) and in terms of system operation (Risks to “Transmission Network Operation”). The lines in question are generally strategic for the system and this type of operation is performed as quickly as possible. However, for lines under great stress, it is acceptable to let the conductor joint age before replacing it. In this case, corrections must be set up almost immediately and associated with thermographic inspection on an almost monthly basis. Limiting the Permanent Maximum Permissible Loading of a line, even temporarily, following the discovery of conductor joints in a thermal acceleration phase, is not used in practice.

2.2.2. Cause/effect diagram for bi-metallic conductors

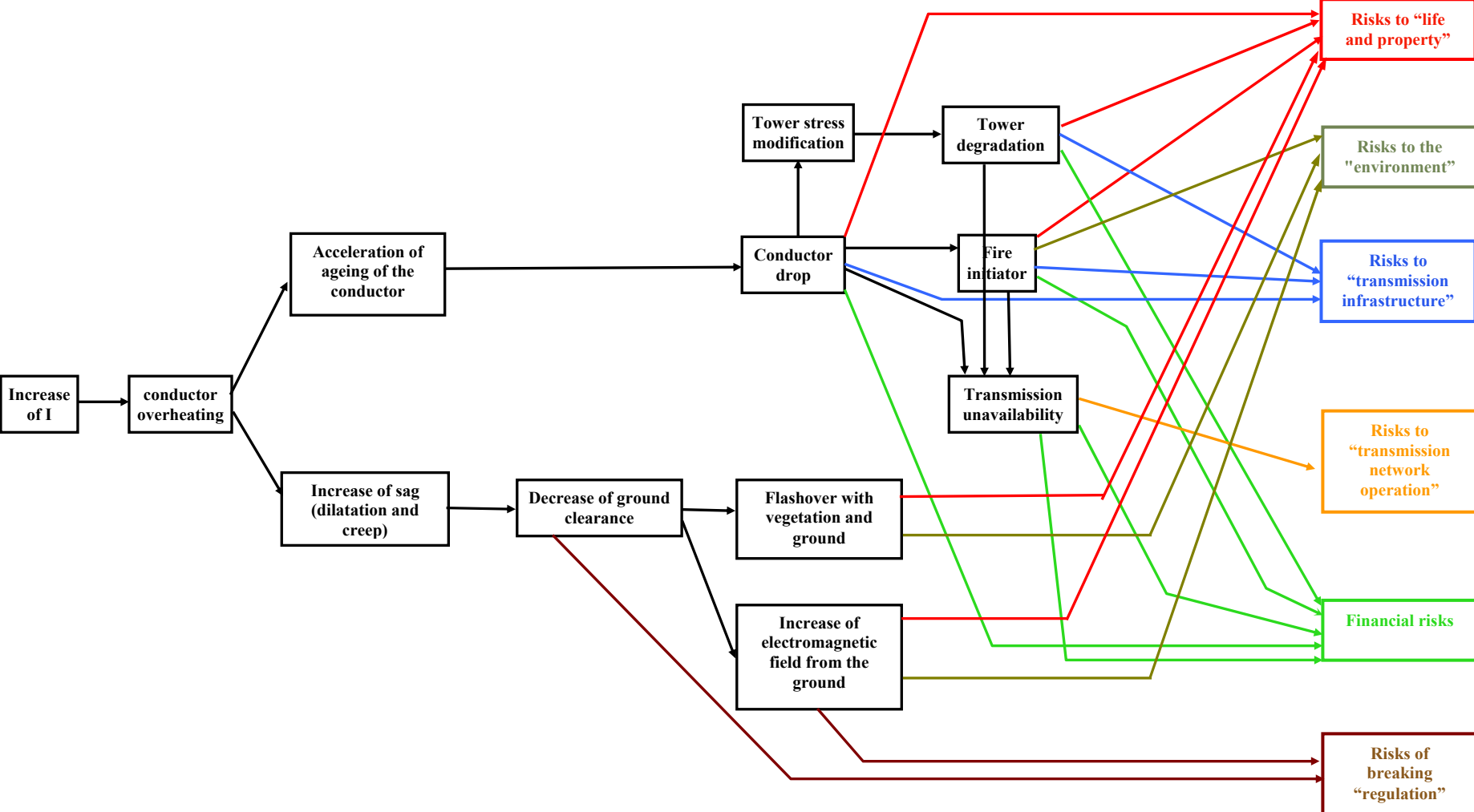


Figure 6 : cause effect diagram for bi-metallic conductors

In the same way as for the joints, the direct consequence of increasing the current through the conductors is their heating which causes two different types of elongation : elastic elongation called dilatation and permanent elongation called creep. We differentiate these two phenomena in order to take the consequences of the creep on the TSO's infrastructure into account which may require a re-tension operation (Risks to "transmission infrastructure"). However at a given moment, the consequences of the dilatation are superimposed on those of creep.

We should bear in mind, reading the subsequent analysis, that the OHL is initially designed and built in order to satisfy its function and comply with the regulation all along its life. For example, the sag due to creep is estimated and taken into account to define the initial augmented clearance of the line. Moreover, the line is designed to work properly with a maximum operation temperature of the conductors. The operation of the line inside its "design operating range", even with increased current is a standard and common situation which does not create a risky situation. The risk analysis is obviously more relevant for old and very loaded lines in order to define the needed maintenance works and finally to decide to stop the operation of the line.

The points in common between dilatation and creep are the increased sag, transient in the one case and permanent in the other. Consequently :

- In both cases, the ground clearance (or the distance with respect to obstacles) decreases. Under these conditions :
  - ✓ it is absolutely essential to respect, at least, the template defined by the law (Risks of breaking "regulation"),
  - ✓ this induces an increased probability of arcing which may have an impact on life and property (Risks to "life and property"), initiate a fire and cause transmission losses,
  - ✓ there is an increased electromagnetic fields at ground level because of the fact that the conductors are nearer. This possibly having an influence :
    - as far as the regulations are concerned if the limits defined by the law are exceeded (Risks of breaking "regulation"),
    - on the acceptance of the line by nearby people (Risks to "life and property") even if all the epidemiological studies carried out do not show any kind of direct link between the pathology and the presence of fields close to the thresholds defined by the law,
    - on the environment in the broadest sense of the word (Risks to "environment") even if, in theory at present, there is no scientifically identified significant phenomenon.

However, even if the consequences of these phenomena are almost insignificant, or improbable to say the least, they can have a potential degrading effect on the TSO's image.
- The increased sagging of conductors caused by creep and dilatation also leads to an increased probability of phase to phase arcing in the same circuit, if the increased sag differs according to the phase (for instance: differing cable technologies), or of a nearby circuit (for instance, a HV circuit near a 400 kV OHL). This type of arcing results in a loss of transmission availability in the line, or in a nearby line, with the consequences explained previously (see joints paragraph), as well as the possible breakage of the external wires (wires of aluminium alloy).
- Finally, the permanent decrease (due to creep) of the ground clearance beyond a given level, can cause a modification in the operation of the line (Risks to "transmission network operation") resulting in the limiting of the Permanently Permissible Maximal Loading and economic losses caused by using the line below its load capacity (Financial risks).

The heating of the conductors following increased current also causes degradation among the conductor themselves. Indeed, for bimetallic conductors, increased temperature causes the migration of the grease in the conductor encouraging the loss of steel galvanization and therefore the corrosion of the steel and aluminium (or Almelec) wires in the internal layers (in contact with the strands of steel), even leading to their breakage in the extreme cases. Indeed, when the corrosion of the layer of aluminium (or Almelec) in contact with the galvanised steel is considerable, the resistivity of the aluminium increases. Subsequently, the current passes partially through the steel, causing the temperature increase of the conductor until the aluminium (or Almelec) melting temperature, and in the worst cases, can lead to the breakage of the conductor in a full span. In parallel to this gradual corrosion of the aluminium, the steel strands degrade as soon as the layer of zinc disappears. In this case, the loss of the mechanical strength of the steel can also cause premature breakage of the conductor. As a general rule, the first phenomenon is the faster of the two. In the same way as for the breakage of a joint, the breakage of

a conductor because of the breakage of steel wires (or of aluminium/Almelec wires) in the internal layers, can cause a change in the forces working on the towers, a fire starting, the loss of transmission availability on the line as well as direct consequences on life and property (Risks to "life and property"), on the TSO's assets (Risks to "transmission infrastructure") and on the financial level (Financial risks).

To inspect this type of degradation, it is possible to measure the residual galvanisation of the steel wires in the core of the conductor on the basis of Foucault currents principle. Various criteria are generated to justify the starting of investigations: conductors that have suffered from degradation and/or repair, age of the conductor and situation of the line in a corrosive area. In the event of severe galvanisation losses being detected, investigation continues with destructive testing on a cable sample to confirm and quantify the residual life duration accurately. If aluminium losses are detected over more than 10% of a span, it becomes imperative to replace a part of the span or to reinforce it. Accordingly, the detection of severe degradation is a way of forestalling latent breakage but does mean changing entire conductors or just portions of conductors that generate transmission losses for the line in question but also the momentary limiting of the Permanently Permissible Maximal Loading in some cases, with the consequences already discussed (Risks to "transmission network operation" and Financial risks). Of course, intervention after detection also generates substantial costs (Financial risks).

For every type of conductor, heating can cause the corrosion of the outer wires in contact with the environment. The consequences of this type of phenomenon are the degradation of the wires and their increased resistivity, causing increased electrical losses and therefore financial losses (Financial risks). In the more extreme cases, it can result in the breakage of the wires, having a direct impact on the TSO assets (Risks to "transmission infrastructure"). This type of degradation then generates hot points that can be detected by infrared camera operations, including for the inner wires, but to a lesser extent. Thermography campaigns are a way of preventing conductors from falling by working on the hot points through the use of "twisted armour rods" for instance. However, all these detection and repair processes generate costs that cannot be discounted (Financial risks) associated with a loss of transmission in the event of action, or even limiting of the Permanently Permissible Maximal Loading in the more serious cases.

Finally, increased transmission causes an increase in electrical losses eventually generating an economic cost (Financial risks).

### 2.2.3. Cause/effect diagram relative to earth wires

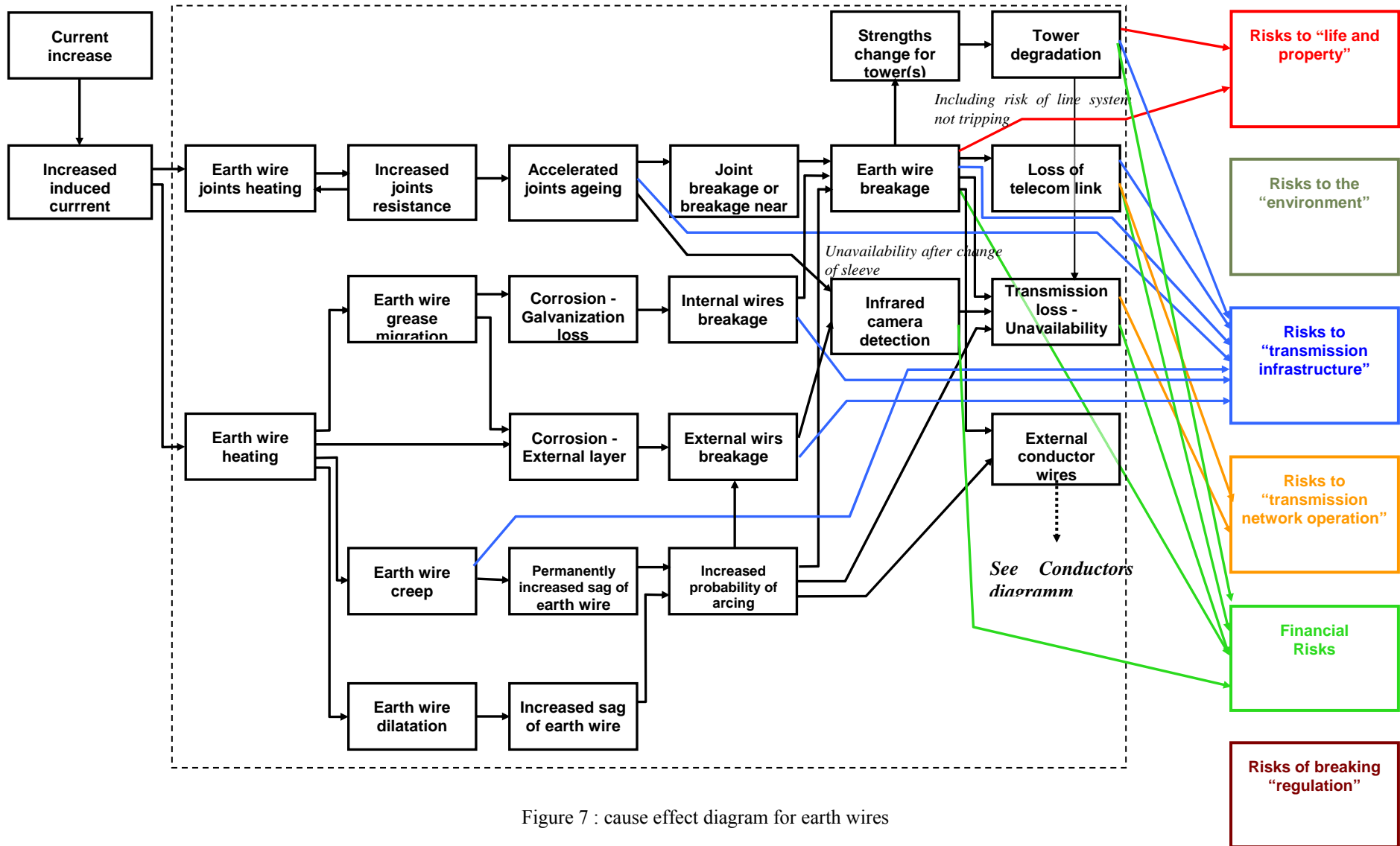


Figure 7 : cause effect diagram for earth wires

The earth wires in a transmission network are almost exclusively of the bimetallic type. This means that scenarios concerning earth wires cover most of the scenarios explained for bimetallic conductors and bimetallic conductor joints, bearing in mind that the only difference is the fact that the permanent transmission is unknown because degradation is caused by induced currents and generally not measured by TSOs.

The earth wires are not designed to transmit permanent current and accordingly, even if the induced current is less than the transmission current on the line, the consequences will not necessarily be lower.

Therefore, we have the same event with the possibility of earth wire breakage following the joint breakage, resulting from their heating. Conversely, for the earth wire, there is a specific risk because the breakage of the conductor can cause the breakage of the telecom link (more and more optical fibres into earth wires) associated with a risk in terms of the assets (Risks to "transmission infrastructure"). Telecom links are used for the operation of the transmission network (Risks to "transmission network operation") but can also generally be used by the local communities in the case of optical fibres (the high-voltage electricity transmission network is used as an optical fibre infrastructural support). In the event of the optical fibres becoming unavailable because of the breakage of the earth wire, TSO have to pay penalties on a contractual basis which is combined with the cost of repair work and represent financial risks (Financial risks).

Moreover, full span earth wire breakages result from the degradation of steel wires as soon as the layer of zinc disappears, unlike the conductor breaks which result from the wires melting of aluminium caused by an increase in the conductor temperature.

Earth wire falls may be particularly dangerous to third parties if the protection devices do not trip. Indeed, in such a case, the earth wire could come into contact with a phase and cause an arcing (Risks to "life and property").

Lastly, if an earth wire fell onto a conductor phase, it could cause the breakage of the outer wires of the phase (link with the cause/effect diagram for conductors). Under these conditions, after an earth wire breakage, the conductors located underneath are generally compromised.



The increase of transmission current causes, of course, overheating in contacts. Hot points may then appear at the interfaces between equipment and cause breakage in the more extreme cases. The concerned equipment are essentially :

- dampers,
- jumpers.

This type of break represents degradation of the TSO assets (Risks to “transmission infrastructure”) but can also cause damages in the event of a jumper or a damper falling onto nearby conductors, or generating a phase to phase fault with a risk of the outer wire breakages (link with the cause/effect diagram for conductors). The consequence of this type of event also concerns property and people (Risks to “life and property”) because after the breakage of a jumper or a damper, it may hang down in empty space (without contact with the phases) with a risk of arcing, touching the tower and increasing the “tension step” on the ground or be accompanied by falling equipment.

In addition, the breakage of a jumper or a damper causes a loss of transmission for a time depending on the repair time needed. The possibility of interrupting transmission on another line (after a short-circuit resulting from contact between a jumper or a damper and the conductor of another line) should not be left out of consideration. This event can concern more particularly double circuit OHL and HV or MV lines located under the VHV lines. Under these conditions, the operation of the system is affected to a varying degree depending on the strategic importance of the line (Risks “to transmission network operation”) and has economic consequences because of the cost of work to re-establish the transmission capacity, in particular for interconnection OHL (Financial risks).

The equipment sensitive to high temperatures, like conductors spacers that may comprise to some extent elastomers, in theory are not impacted by the load-flow capacity increase because the temperature ranges corresponding to operation are in theory below the temperatures liable to cause their degradation, even for heavy overloads (to be investigated in greater detail). But this type of scenario should not be left totally out of account because it has a potential impact on third parties in the event of equipment falling, for instance if an aircraft daily warning device falls (Risks to “life and property”), as well as on the TSO assets (Risks to “transmission infrastructure”). Moreover, in the event of an aircraft daily warning device catching fire (temperature from 300 to 400°C), Almelec loses its mechanical properties, meaning that a conductor could fall, having consequences on assets and on third parties. On this point, following falls (with catching fire), plastic daily warning devices are no longer used on the conductors and are now replaced (or are in the process of being replaced) by aluminium devices. Plastic devices are only tolerated on the earth wires.

In addition, contact parts are closely monitored by infrared camera. Therefore, in case of detection, the identified equipment is replaced, generating costs related to the work (Financial risks) with transmission unavailability if live work is not possible (Risks to “transmission network operation”).

Other phenomena can be listed, even if their occurrence and/or consequences are negligible in relation to the scenarios identified above. Thus, increased current transmission can cause an increase in electromagnetic coupling (for instance, with motorway barrier is located near the lines) or an increased probability of overload protections being tripped.

## 2.3. Model of risks

The evaluation of risks scenarios consequences is the most critical part and the most difficult. First of all, it is necessary to have a good idea of physical phenomena. After that, this step permits to assess the likelihood and gravities of each risk.

In this part, the methodology proposes to use physical phenomena model (conductor creep model, electrical resistance evolution, corrosion model...). For instance, an assessment of all the surveys of joints for the two last decades indicates that they constitute a weak point in OHL. Internal corrosion or a defective realization is the original cause, which leads, later on, to the increase of the contact resistance and therefore of the temperature of the joints. Then, two approaches are considered:

- Analytic approach: then the first step is to examine how the joints are made and what phenomena occur in their ageing. This analysis leads us to retain the most influential factors and propose a modeling of the joint and of the evolution of its degradation in the past. The objective of the model is to predict joint

ageing in several selected situations close to situations in operation. These simulations have to make it possible to extract the strong tendencies and from them draw conclusions about the service life of joints. They have impacts on initial quality and in situ inspection of the joints and maintenance of OHL. The goal is to try to build this sort of model but there are some problems : too many factors are difficult to assess, the creep breakage phenomenon doesn't take into account with an analytical approach, the validation of the model is difficult because of the lot of parameters, ...

- Finite elements approach : it makes it possible to study for instance mechanical constraints and breakage risks of steel strands for bi-metallic joints with numerical modeling :
  - ✓ analysis of electromagnetic phenomena,
  - ✓ analysis of mechanical and thermal phenomena.

## 2.4. Risk mapping

### 2.4.1. What is a risk mapping?

We propose to build a risk map. The goal is to describe, to analyze and to quantify the risks scenarios. This step permits to assess especially the likelihood and the consequences of risk scenarios. Moreover, we decide to use a qualitative approach in order to assess all the risks. Indeed, this TF B2.20 is not the place to develop and deal with models and physical phenomena simulations.

On this kind of risk map, major risks are represented as dots on a two axis diagram, each axis representing a risk attribute or risk dimension.

The following picture gives an example a risk map with control limit and acceptability limit :

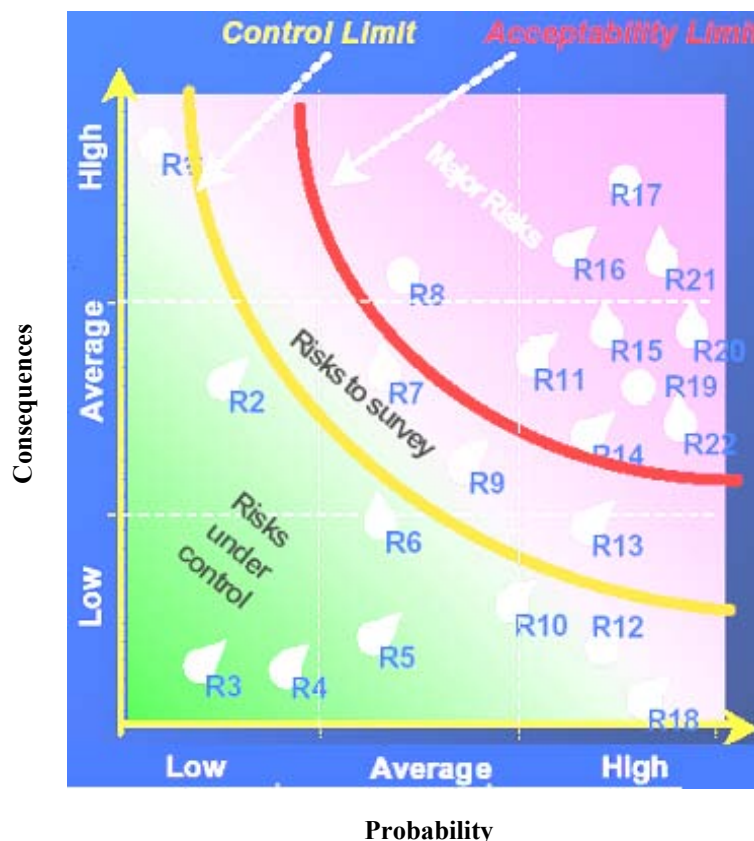


Figure 9 : example of risk map

In the cause/effect diagrams of conductors and joints, we have defined six risks (risks to life and property, risks to environment...) and events which lead to those risks.

The events identified (or event combinations) are to be combined into the risk map similar to the example of a

risk map already produced. Once this was done the mitigating factors would be analyzed. Thus work on treatment of risk would occur after the risk map is completed.

It makes it possible to classify and prioritize risks and to establish which risks have to be treated as a priority. Risk map is the tool used as a support for decision making. One stake is to precisely define the different limits between unacceptable risks, risks to survey (acceptable but more efficient control) and risks under control.

## 2.4.2. Evaluation of consequences and classification

Based on cause/effect diagram for joints and conductors, we define the following events or event combinations which lead to final risks (knowing that the initiator event is the increase of I) :

- acceleration of ageing of the joint,
- conductor drop due to joint breakage,
- fire due to conductor drop after joint breakage,
- tower degradation due to conductor drop after joint breakage,
- acceleration of ageing of the conductor,
- conductor drop due to strand breakage,
- fire due to conductor drop after strand breakage,
- tower degradation due to conductor drop after strand breakage,
- decrease of ground clearance (increase of sag),
- flashover with vegetation and ground (increase of sag),
- increase of electromagnetic field from the ground (increase of sag).

Regarding the earth wires, the load-flow increase leads to higher induced current (even if it is difficult to evaluate the value) and consequently we note in the same way the acceleration of ageing and a higher probability of breakage. We don't detail this case in this document.

Dealing with accessories (clamps, jumpers, dampers, conductor spacers, ...), the load-flow increase will certainly accelerate ageing and consequently failures.

The methodology makes it possible to define the type of risks and to evaluate their consequences. The following table gives an example of it.

Type of risks	Scale of consequences 1 (low) to 4 (high)	Comments
Risks to life and property	1 Low impact 2 Damage property and/ or medium impact towards people 3 Damage property and/or high impact towards people 4 Fire, explosion... and/or dramatic impact towards people (death ...)	
Risks to environment	1 Low impact 2 Medium impact (electromagnetic field...) 3 High impact (fire...) 4 Catastrophic impact (large fire...)	
Risks to transmission infrastructure	1 Low impact 2 Medium acceleration of ageing	

	3 High reduction of lifespan 4 Component damages at short time	
Risks to transmission network operation	1 No impact (no unavailability) 2 Low impact 3 Medium impact (N-1) 4 High impact (N-2)	We don't detail the risks to transmission network operation
Financial risks	1 Low impact 2 Medium impact 3 High impact 4 catastrophic impact	We don't detail the financial risks but all risks are converted into financial risks.
Risks of breaking regulations	1 No impact 2 Low impact 3 Medium impact 4 High impact	We don't detail the risks of breaking regulations

Table 2 : type of risks and evaluation of their consequences

The methodology makes it possible to find out all the events (or event combinations) and to evaluate their likelihood and their consequences. The following table gives an example of it.

<b>Events or event combinations</b>	<b>Probability Scale 1 to 4</b>	<b>Consequences Scale 1 to 4</b>	<b>Comments</b>
Acceleration of ageing of the joint	1 Low impact 2 Medium acceleration of ageing 3 High reduction of lifespan 4 Component damages at short time	Risks to transmission infrastructure	
Acceleration of ageing of the conductor	1 Low impact 2 Medium acceleration of ageing 3 High reduction of lifespan 4 Component damages at short time	Risks to transmission infrastructure	
Acceleration of ageing of the accessories	1 Low impact 2 Medium acceleration of ageing 3 High reduction of lifespan 4 Component damages at short time	Risks to transmission infrastructure	
Conductor drop due to : joint breakage strand breakage	2 Low impact 3 Medium impact 4 High impact 5 Unacceptable impact	Risks to transmission infrastructure Risks to life and property Risks to environment	
Fire due to conductor drop :	2 Low impact	Risks to transmission infrastructure	

after joint breakage	3 Medium impact	Risks to life and property	
after strand breakage	4 High impact	Risks to environment	
	5 Unacceptable impact		
Tower degradation due to conductor drop :	2 Low impact	Risks to transmission infrastructure	
after joint breakage	3 Medium impact	Risks to life and property	
after strand breakage	4 High impact	Risks to environment	
	5 Unacceptable impact		
Flashover with vegetation and ground (increase of sag)	1 No impact	Risks to life and property	
	2 Low impact	Risks to environment	
	3 Medium impact		
	4 High impact		
Increase of electromagnetic field from the ground (increase of sag)	1 No impact	Risks to life and property	
	2 Low impact	Risks to environment	
	3 Medium impact		
	4 High impact		

Table 3 : events and evaluation of their likelihood and consequences

One way to build risk map is to translate cause/effect diagrams into Bayesian networks in order to quantify risks. Use of Bayesian belief network is especially efficient:

- to analyze global risk and domino effects,
- to find optimal decisions and create probabilistic expert systems.

The main advantages are to use all the skills necessary for risk analysis and to make it possible to merge physical phenomena quantification (conductor creep model, increase of sag...), experience feedback and expert judgment. It is suitable for applications in the areas of diagnosis, prediction, decision analysis, sensor fusion, expert system building, reliability analysis and probabilistic modelling.

A Bayesian network (or belief network) captures believed relations (which may be uncertain, stochastic, or imprecise) between a set of variables which are relevant to some problems. In this type of network, one node is used for each scalar variable, which may be discrete, continuous, or propositional (true/false).

The nodes are then connected up with directed links. If there is a link from node A to node B, then node A is sometimes called the parent, and node B the child. Probabilistic relations are provided for each node, which express the probabilities of that node taking on each of its values, conditioned on the values of its parent nodes. Some nodes may have a deterministic relation, which means that the value of the node is given as a direct function of the parent node values.

The following picture (figure 10) gives an example of Bayesian network for conductor joints, in which it is possible to merge :

- physical phenomena quantification (joint ageing acceleration),
- experience feedback (scheduled unavailability, fortuitous unavailability, ...),
- expert judgment (impact on towers, fire initiator...).

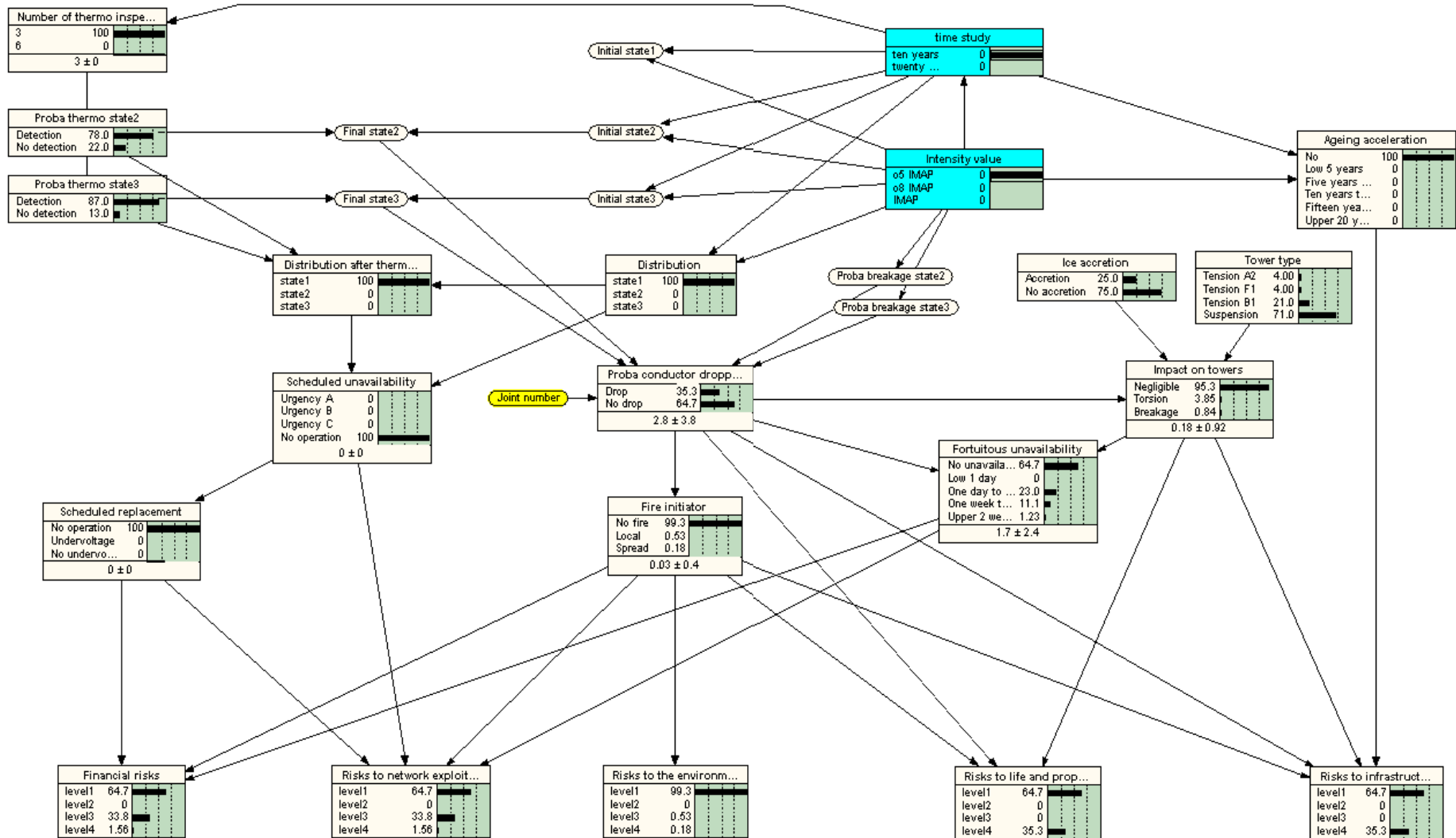
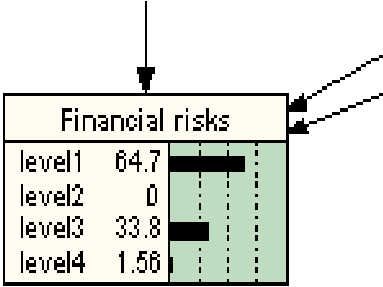


Figure 10 : example of Bayesian network for conductor joints

Once the Bayesian network is done, it will calculate the likelihood and the gravity of the six following risks (risks to life and property, risks to the environment, risks of breaking regulations, risks to transmission infrastructures, financial risks, risks to transmission network exploitation), sorted with scale of consequences from level 1 (low) to level 4 (high).

For instance, the considered situation leads to a “financial risks” with the following features :

- level 1 (low impact) : probability of 64.7 %,
- level 3 (high impact) : probability of 33.8 %,
- level 4 (catastrophic impact) : probability of 1.5 %.



Taking into account all the situations, it is possible to build risk map in order to help in decision making regarding load-flow increases in transmission OHL equipment.

### 3. Practical case of joints: risk due to load-flow increases

#### 3.1. Impact of joint life expectancy [1] to [8]

An assessment of all the surveys of joints for fifteen years indicates that they constitute a weak point in overhead lines. Internal corrosion or a defective installation is the original cause, which leads, later on, to the increase of the contact resistance and therefore of the temperature of the joint.

The factors that affect the ageing of the joints are numerous and varied. To make the presentation clear, those that are connected to corrosion can be differentiated from those that belong more to the mechanical domain.

- the speed of corrosion of electric contacts depends mainly on the temperature, the composition of the aluminium alloy and the surrounding environment: pH and pollution by chlorine, sulphate, copper ions, etc.
- the relaxation of stresses in the contact units has an effect on the durability of the contact. Reduction of the force on the contact by relaxation of the stresses can result in manifestations of fretting corrosion associated with small movements in the contact and make it more vulnerable to the effects of dynamic pulls.

The relative importance of each factor in contact degradation inevitably depends on the environment and on the stress to each joint. In addition, the different causes of the degradations interact with each other. It is thus unrealistic to want to deduce the behaviour of a joint in the past from theories -still very disputable- of the evolution of the elementary phenomena that are in play. The approach taken for simulation of the ageing of joints is global: the evolution of joint degradation is characterised by an increase in its electric resistance.

The evolution of joint electrical resistance in function of time is as follows :

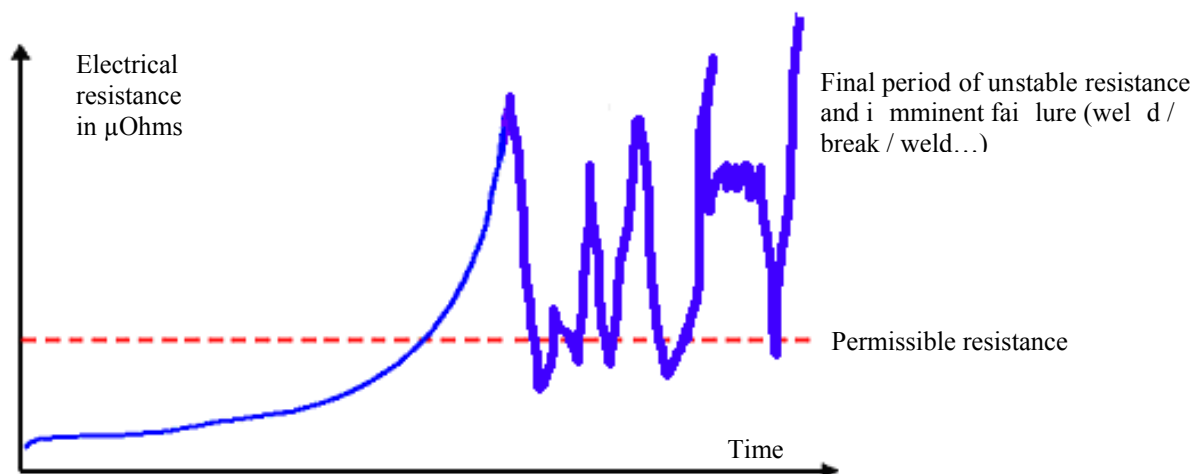
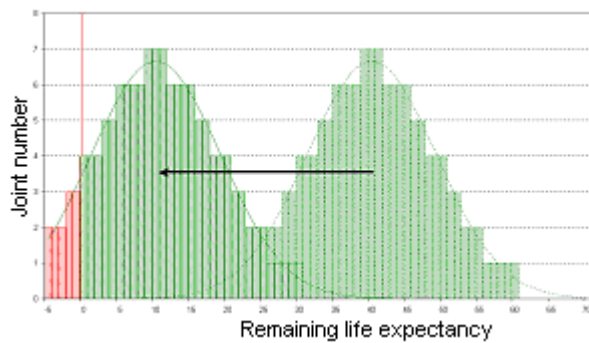


Figure 11 : evolution of joint electrical resistance in function of time

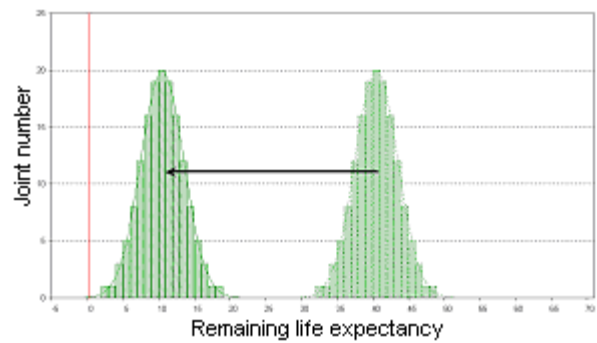
The ageing model of this type of equipment is not reliable, because of the large number of parameters (environmental constraints, defective installation,...). In this way, a lot of Transmission System Operators in the world use diagnosis method, based on temperature measures or electrical resistance measures, rather than parametric model.

For instance, we consider a overhead line with about fifty joints on each phase with the similar operation constraints (load, environmental constraints,...). This case leads to homogenous ageing of the joint population.

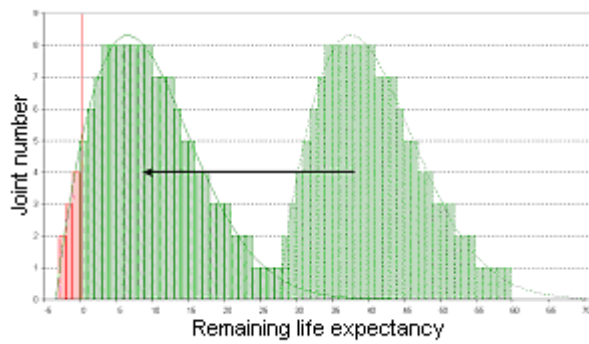
The ageing, without load-flow increases, is described as follows with a translating movement of probabilistic density. The red line shows the joint breakage.



Case n°1 : normal law  $\lambda = 40, \sigma = 9$



Cas n°2 : normal law  $\lambda = 40, \sigma = 3$



Cas n°3 : Weibull law  $\alpha = 15, \beta = 1.9, \theta = 27$

Figure 12 : distributions of remaining life expectancy

A simple graphical analysis highlights density features :

- the dispersal : a narrow density must be anticipated. Indeed, all the joints will reach the life expectancy during a short period (case n°2),
- the maximal value : it defines the maximal number of replacements without preventive maintenance. In the case n°1, this maximal value is low and the distribution is wide : this case of ageing is the most favorable,
- the increase slope : the case n°3 with a steep slope represents the situation for which the number of breakage increase highly.

So, the stake is to determine correctly the distribution of the joint state and its evolution in function of time. The idea is to try to anticipate the most as possible the consequences of large degradation (large unavailability, corrective maintenance costs...).

The previous graphs (with electrical resistances translated in remaining life expectancy) are interesting in order to forecast maintenance.

However, load-flow increases will influence the evolution of distribution. Indeed, the theoretical study shows that the more the contact will be degraded the larger will be the ageing acceleration due to load-flow increases.

We consider the following theoretical evolution of joint electrical resistance when we apply several different load-flow increases after 25 years (from 0,4 up to 0,8 maximal permanent current).

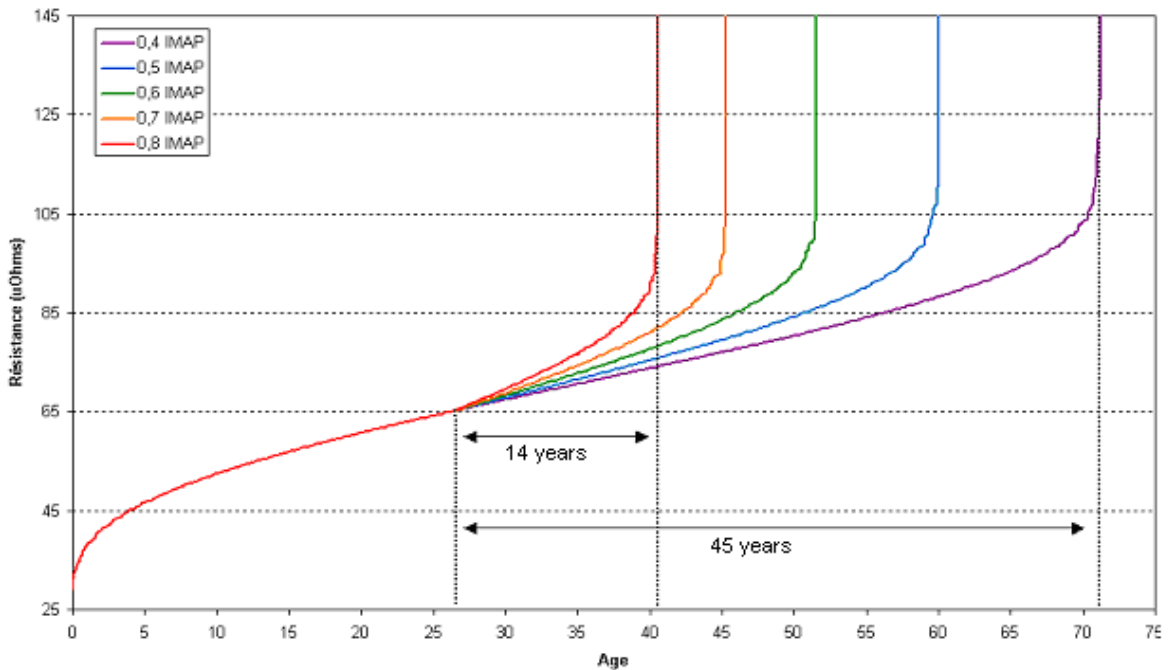
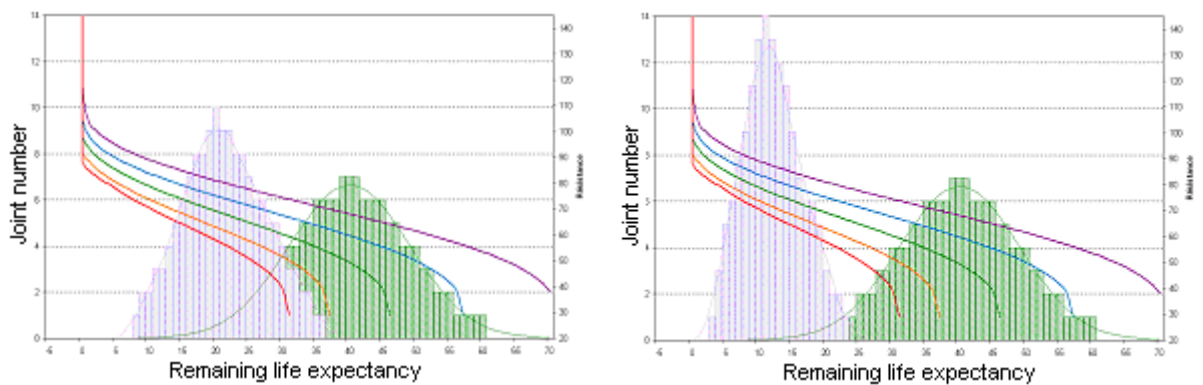


Figure 13 : theoretical evolution of joint electrical resistance with several different load-flow increases

In this example, the increase from 0,4 up to 0,8 maximal permanent current would reduce the remaining life expectancy from 45 to only 14 years. The results must only be considered as global behaviour of the joints and can't be applied for a real study.

For each previous distributions (normal and Weibull laws), we apply this method and we obtain new distribution, with lower life expectancy.



Increase from 0.4 up to 0.6 IMAP

Increase from 0.4 up to 0.8 IMAP

Figure 14 : distributions of remaining life expectancy - Case n°1 : normal law  $\lambda = 40, \sigma = 9$

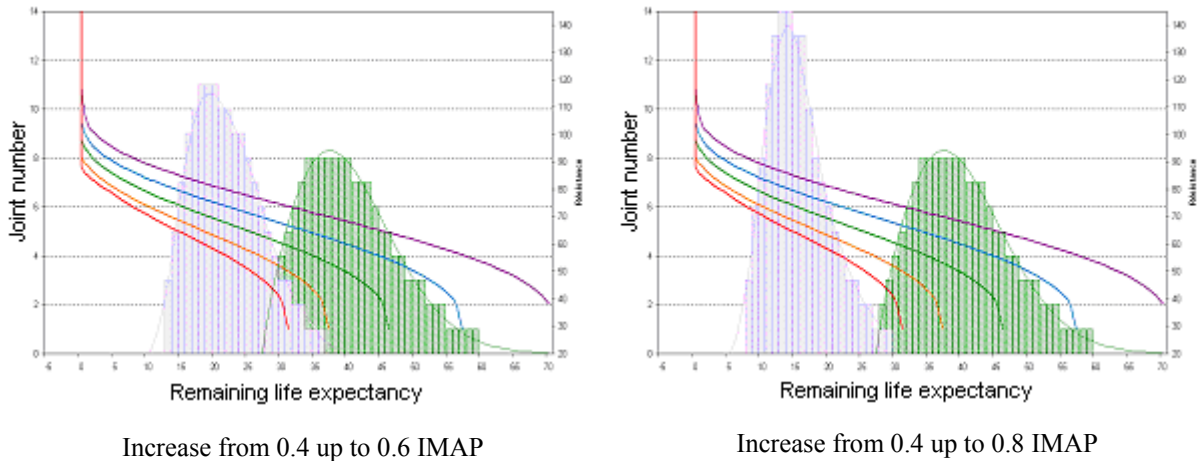


Figure 15 : distributions of remaining life expectancy - Case n°2 : Weibull law  $\alpha = 15, \beta = 1.9, \theta = 27$

The green columns represent the initial distribution. The purple distribution is the one which will describe the some joint population at the same time but with different operation constraints (it is not only the ageing impact, showed by a translation).

The consequences of load-flow increases are :

- a narrowed standard deviation,
- an increase of maximum values,
- a stiff slope (more joints to replace in a shorter time).

Consequently, those models clearly show that load-flow increases will reduce joint life expectancy and the stake is to determine very accurately when we have to replace the joints. In this way, we have to consider the reliability of the diagnosis method.

## 3.2. Diagnosis method to identify defective joints

Two methods are presently being used for diagnostic testing of conductor joints of overhead lines. These are infrared (IR) imaging systems (“thermography”) and resistance measurements. The latter method requires measuring cables to be connected directly to the conductor, and the associated practical difficulties have severely limited its use. Infrared imaging surveys, on the other hand, can be carried out quickly and easily by using a helicopter, and are widely applied.

### 3.2.1. Thermographic inspection

Infrared photography detects heat radiated in the infrared spectrum. Detected temperatures at the joint are compared with detected temperatures at the conductor. It can be performed from the ground or from a helicopter.

However, the shortcomings of the infrared imaging technique have gradually become more evident. The results are dependent of load and weather conditions, reflections can give erroneous readings, the emissivity factor must be correctly set, the sensitivity for discovering even substantial increases in electrical resistance is poor, certain contact flaws that lead to a fluctuating resistance can easily be overseen, etc...[9], [11] Cases where conductor joints have failed completely just weeks or months after infrared imaging inspections have found them to be in good condition, have caused an increasing number of utilities to question the suitability and reliability of infrared imaging as a method for detecting developing electrical failures on conductor joints. Some have even stopped doing thermography on overhead lines.

The joint's electrical condition is evaluated by its overheating in relation to the conductor (infrared camera). According to the extrapolated value of joint's temperature as well as the stake associated with the line, 3 possible replacement decisions :

- Joint replacement as soon as possible
- Joint replacement within a few months (3 max)
- Joint replacement within the year

But the infrared camera inspection's results are not completely satisfactory :

- the detection of a « hot point » occurs at a late stage in the degradation process (when the mechanical properties of the joints have already decreased),
- the necessary conditions for efficient detection by infrared camera are rarely present : sufficient load-flow ( $I > 0,4 \cdot I_{MAP}$ ) and sufficient low wind speed ( $V_{measured} < 10$  m/s).

Infrared imaging surveys are widely applied by TSOs because it can be carried out quickly and easily. Regarding joint ageing, the drawbacks are from load-flow increase point of view :

- thermographic inspections don't make it possible to forecast replacement at long date : indeed, we can only detect very bad joints with hot points (high temperature due to degraded contacts),
- the method is not reliable due environmental constraints (wind, emissivity...),
- we are not able to determine the evolution of joint ageing between two inspections, so it is impossible to define a trend for a given joint population.

Dealing with IR inspection, it makes it possible to detect hot points, but in some specific cases it can lead to false diagnosis.

### 3.2.2. Conventional joint electrical resistance DC measurements

Within the scientific community it has for long been a consensus that the parameter best describing the electrical performance of an electric contact such as a conductor joint, is its electrical resistance. Interpretation of resistance measurements for making decisions about whether and/or when to replace a joint can be somewhat difficult and a matter of different views, although the assessments in general are much more trustworthy than those based on infrared imaging. Typically the interpretation is done with basis on  $k$ -values, i.e., the ratio between the measured resistance across the joint and the resistance of an equal length of the conductor. The criterion for recommending immediate replacement differs; in a survey among different experts it was found to vary as much as from  $k > 1$  to  $k > 3$  [10].

Recommendations based on estimates of what conductor joint temperature the resistance causes have also been given [12]. It is important to realize that these interpretations of resistance measurements are based on some kind of practical experience, and only to a very little extent on an understanding of the physical conditions at the interfaces between the joint and the conductor. As is well known from the theory for electrical contacts [13], [14], the current crosses the contact interface through a number of minute contact spots (sometimes referred to as "a-spots") and aging and resistance increase of a connector or a joint are directly related to processes and phenomena occurring in these very small areas.

To derive a reliable value of the voltage drop, at least four different DC currents should be applied in sequence. The current-feeding contacts should be installed on the conductor at the distance of least half a meter from the end of the joint in order to have the current distribution equalized in all strands.

From load-flow increase point of view, it is impossible with this method to compare resistance values measured at two different periods : we can't determine the evolution of joint resistance between two inspections, so it is impossible to define a trend for a given joint population.

### 3.2.3. Pulse current measurements for condition assessment of conductor joints of overhead lines [15]

The contact spot temperature is a good indicator for how severely a connecting device such as a conductor joint is electrically stressed. Nearly all conceivable processes that may contribute to the degradation of the contact spots, such as oxidation, corrosion, diffusion, mechanical creep etc. proceed at a much higher rate at elevated temperatures. Moreover, mechanical stresses induced by thermal expansion and contraction of the contact spot region under thermal cycling may also have an impact [16] [17] [17].

The proposed diagnostic method relies on this correlation between contact spot temperature and the condition of the joint. The test procedure is to pass currents of increasing magnitudes up to and above the maximum rated load current of the conductor joint and accurately determine the resistance each time. The condition of the joint is then assessed with basis in to what extent different current magnitudes  $I$  cause the contact spots to heat up and thereby change the contact resistance  $R$ . Three regions exist :

- $R(I) = \text{constant}$ . The current is sufficiently low and/or the joint is sufficiently good so that no notable contact spot heating occurs.
- $R(I)$  increases with increasing current in a reversible manner. The contact spots are substantially heated and the joint is deteriorated / carries more current than it can do in a safe way.
- $R(I)$  changes significantly and in a irreversible manner between subsequent measurements. The contact spots are so heated that local melting occurs. The joint is severely deteriorated / overstressed.

From the above it follows that that the current rating of the line must be taken into account when interpreting the measurements. For example, reversible contact spot heating starting at 1000 A does not indicate deterioration in the conductor joint of a 70 mm<sup>2</sup> earth wire, but does so in a 1200 mm<sup>2</sup> phase conductor joint.

This following graph shows  $R(I)$  for side A (left) and side B (right) of one joint. This joint conductor typically has a current carrying capacity of 700 - 800 A.

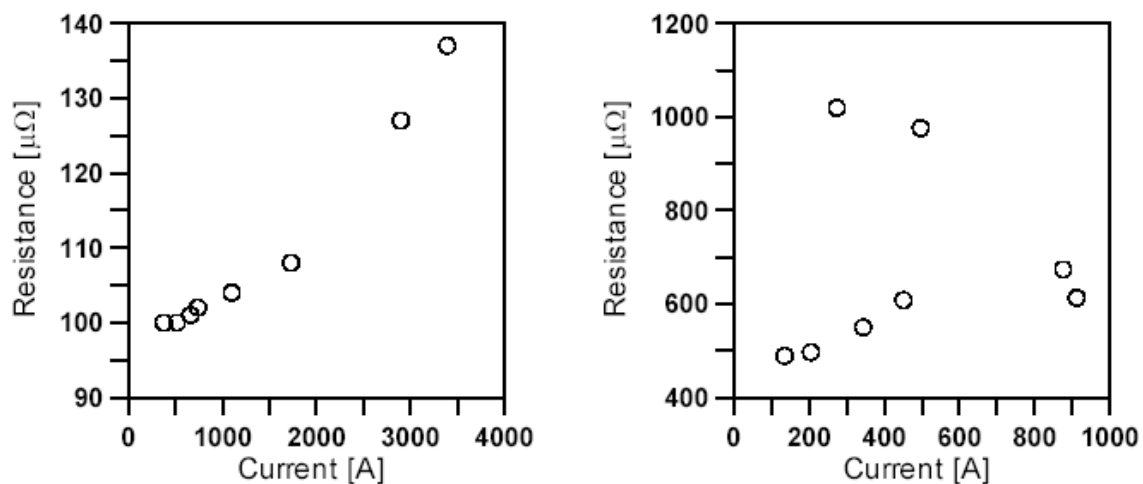


Figure 16 :  $R(I)$  for side A (left) and side B (right) of one joint

Besides from the ability to detect degrading joints at a very early stage, a major advantage with this method is that no reference values are required. The interpretation is solely based on comparing resistances obtained with low and high currents, not on earlier measurements, manufacturer specifications or other data that may not be at hand.

## 4. Conclusion

The current increase through OHL could not be realized without risk management (safety, components lifespan and exploitation, economical and environmental constraints), especially when the design operation range is exceeded.

Risk assessment is organized on the basis of 5 main steps :

- Establish the context,
- Identify risk scenarios (with expert judgment),
- Model risks,
- Assess and prioritize risks,
- Treat risk.

So this document highlights the risk scenarios through the cause-effect diagrams, in order to list all the physical phenomena. Then, it gives examples of several tables that help to classify the risks described previously. However, once this information is treated, it appears that the stake is to determine the life expectancy of contacts.

In the studied case, joints are considered as the weakest point of OHL in the case of load-flow increases but the ageing model of this type of equipment is not reliable, because of the large number of parameters (environmental constraints, defective installation,...). So the solution appears to be a management process based on accurate diagnosis method to define the maintenance policy to minimize risks.

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