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HEALTH INDEX

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ABSTRACT

The Health Index of an asset is a figure which reflects its condition.

This is a tool for asset management which makes it possible to define in unbiased way a policy for maintenance, refurbishing or replacement.

The design of an Health Index requires three steps :

- o *Finding the factors which affect links performance.*
- o *Grading the link characteristics for every factor.*
- o *Estimating the relative importance of the factors.*

The paper presents an example of Health Index, and deals with related topics.

KEYWORDS

Health Index, underground link, insulated cable, asset management.

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INTRODUCTION

Electric utilities, in France as in many countries, have to face an increasing demand for reliable electricity supply, whereas the electricity infrastructure involves a large amount of links which have been in service over many years.
In the same time, with restructuring the electricity market, the balance between capital investments, asset maintenance duties and grid operating costs becomes more and more a major concern.

That is the reason why the Health Index was designed, as a tool dedicated to risk and asset management.

This tool makes it possible to optimize maintenance policies, and helps comparing, in an unbiased way, the technical and financial efficiency of new investment versus refurbishment or uprating and upgrading of existing links.

Basically, the Health Index of a link is a figure which reflects its condition.

This paper presents the Health Index currently designed by EDF R&D:

- based on works in early nineties,
- updated according to the general frame by the Transmission Underground Cables Interest Group within CEA Technologies,
- together with a tool, using a similar approach, developed for RTE, to optimize the management of 225 kV oil pipe cables in the French grid.

REPLACEMENT CRITERIA

In early nineties, as a consequence of an increasing failure rate of synthetic cables wet designed i.e. without radial water barrier (copper tapes as metallic screen) in conjunction with end-of-life of some old mass impregnated paper cables and oil leakages on some oil-filled cables, EDF defined a replacement criterion to prioritize links to be replaced.

This criterion is based on a parameter V (the larger is V the higher is the replacement priority) which looks like an Health Index.

The design of V takes into account 3 influencing factors: the age of the link, its electrical and hydraulic behaviour in operation

V is expressed as:

$$V = A * Tv + Fr * Cc1 * Cc2 + Cf1 * Cf2$$

Where:

- o A is a function of the age of the link and Tv is for the influence of the technology on degradation rate (ranging from 0.5 for synthetic cables to 1.5 for mass impregnated cables)
- o Fr is normally 1; or 3 in case of identified unreliable manufactured design (e.g. synthetic cables without water radial barrier) or batch; Cc1 is a function of the number of breakdowns per km during last 5 years, and Cc2 is 3 in case of generic cause (water ingress, overheating, papers ageing...) or 1 for unidentified cause.
- o Cf1 and Cf2 deal with hydraulic history for oil-filled cables. Cf1 ranges from 0 to 5 as a function of the spill volume; Cf2 being 1 for local leakages, 3 for leakages due to global ageing.

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PIPE-TYPE CABLES RELIABILITY

More recently, the French Transmission System Operator RTE asked EDF R&D for a tool allowing prospects on 225 kV oil-pipe cables which were installed from 1957 to 1989, taking advantage of available diagnostic techniques.

This turned into a Performance Indicator dedicated to this type of cables, incorporating dissolved gas analyses (DGA).

This Performance Indicator (PI) uses available data recorded in operation databases: cable age, link load, number of cable breakdowns occurred on the link, link length.

It also calls for factors based on DGA, namely the mean value of various gas amounts at the measurement point on the link where these amounts are the highest, reported to the mean value for every links (excluding the 3 % lowest and highest values), referred to as GC in following formula. A coefficient FP is introduced for every gas as a function of the associated risk [1] (see table 1), depending on atoms recombining energy.

Table 1: Risk coefficient FP in DGA

FP	Gas
1	CH4 - C2H6 - C3H8
2	C2H4 - C3H6 - H2
3	C3H4 (double bond) - CO
4	C3H4 (triple bond) - C2H2

The same weight being given to general influencing factors and to DGA, the expression for the PI is as follows:

$$PI = ½ * [Zc/Zcav + Zd/Zdav]$$

Where:

$$Zc = A + B + C + D$$

$$Zd = \sum Fp_i * GC_i$$

Zcav and Zdav being for the average values of Zc and Zd respectively.

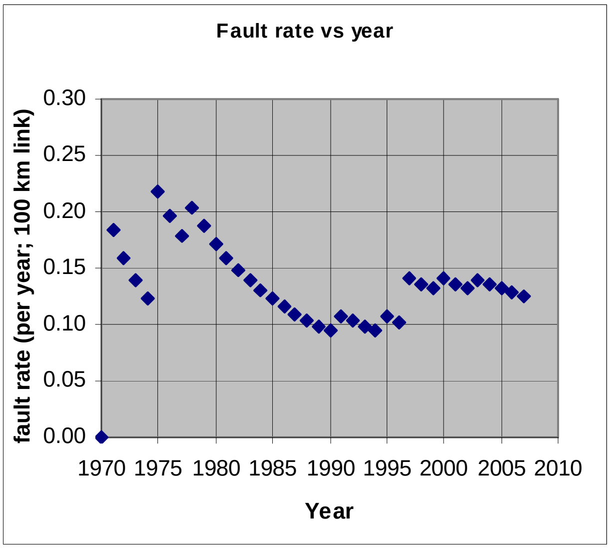
A is simply the link age reported to the average age (as it can be seen on figure 1, there is no evidence of increasing degradation rate due to ageing).

B is linked to the load (taken as 0.3 for weak loads; 1 for medium loads and 3 for heavy loads), directly in line with the paper depolymerisation rate (the rate at 40 °C being a reference, the rate is about 3 times higher at 55 °C and 10 times at 70 °C).

C ranges from 1 (no recorded breakdown) to 80 (5 previous breakdowns); being 5 for 1 fault ; 15 for 2 faults … as a consequence of the outcome of experience.

D is the link length reported to the average length.

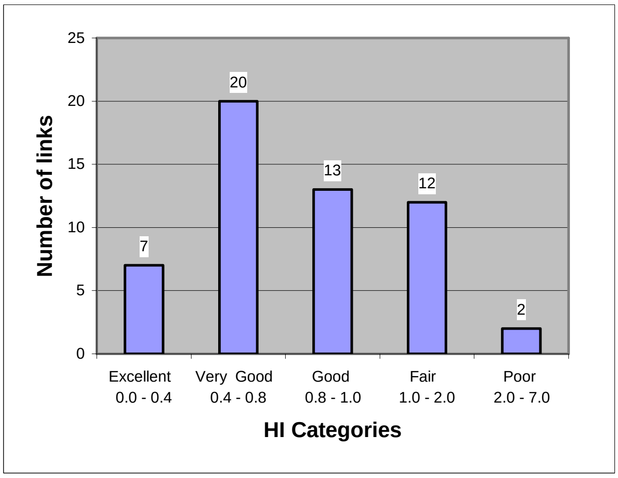
Figure 1: Fault rate of 225 kV oil-pipe cables



as the number of faults from 1970 to the considered year, reported to the product of the installed length by the average age, at considered year (no data 1957 to 1970).

The PI of the 54 links in operation in the 225 kV grid were determined and distributed in 5 categories (corresponding to a specific range) that can be assigned an appropriate ranking from “very good” to “very poor” (see figure 2).

Figure 2: Performance Indicator of 225 kV Oil-pipe links



It can be seen that the PI may be rewritten as:

$$PI = (A + Ts) /T_0$$

This suggests that the performances are depending on the actual age A, corrected by an extra-time Ts which expresses the effect of other influencing factors.

The Performance Indicator is used to focus on links which are likely to experience failure.

A failure probability is determined, without mathematical firm basis, as follows.

Assuming that the failure rate remains constant and that the operating conditions are not to change significantly, the expected number of breakdowns N during next 10 years, may be derived from fault records.
The probability of a failure Pfi occurring within next 10 years on a given link is linked to its PI by the following expression:

$$Pfi = N \times PI_i / \Sigma PI_i$$

It is worth noting that a breakdown recently occurred on one of the links with the highest PI.

Following up failure records and DGA, in coming years, and revisiting accordingly the various weighting coefficients, is expected to improve the efficiency of this Performance Indicator.

HEALTH INDEX GENERAL DESIGN

There is no standard method for Health Index (HI) construction but the ways the various HI designers proceed are similar.

Finding the factors which affect links performances (Influencing Factors) is the first step in Health Index construction.

The second step (grading) involves the translation, for every influencing factor, of the link characteristics into a mark IF, a high value being representative of a poor condition regarding the concerned influencing factor.

In the third step (weighting), the relative importance of the influencing factors is estimated through a weighting factor WF.

The Health Index is then derived using the following simple formula:

$$HI = \Sigma [Wf_i \times If_i]$$

The selection of the influencing factors, the grading and the weighting are worked out by cable experts, based on the outcome of experience.

HEALTH INDEX BACKGROUND

Ideally, the Health Index should be the failure probability.

Following considerations illustrate the connection between HI and breakdown probability ... and, in the same time, highlight the differences.

The overall health depends on various influencing factors, such as design, age, load…

A breakdown probability may be associated to every assumed influencing factor (Bkd_Fi).

The sensitivity of the life expectancy to some factors is well established, whereas it is still questionable for some others.

So that estimating the overall breakdown probability (Bkd) as the result of elementary breakdown probabilities associated to the various influencing factors, needs introduction of confidence coefficients (Conf_Fi) which reflects the reliability of the assumed breakdown law (with low values where the effect is not clearly assessed, and high values, close to 1, where the reliance has been demonstrated)

The overall survival probability may be derived from survival probabilities associated to every factor, leading to a formula which is directly connected with HI design, where the influencing factors are supposed to be independent and the breakdown probabilities are assumed low:

$$1 - Bkd = \Pi [1 - Conf\_F_i \times Bkd\_F_i]$$

$$Bkd \approx \Sigma [Conf\_F_i \times Bkd\_F_i]$$

To get a significant HI, the grading factors, which reflect the failure probability as close as possible, the weighting factors, which may be identified to the confidence coefficients, should be reconsidered from studying the data on failure rates.

This approach is quite difficult due to the small data sets which are available from failure statistics, the insufficient knowledge on breakdowns mechanisms and the presence of various populations.

INFLUENCING FACTORS

The various influencing factors, recognized within the Transmission Underground Cable interest Group from CEATI were adopted by EDF R&D, as a valuable starting point, in the design of an Health Index for asset management purpose.

These factors are distributed in two main categories referred to as Electrical Issues and Maintenance.
A third category, which is not strictly speaking involved in HI design, is also of interest for the purpose of asset management, dealing with Risk issues.

Electrical issues

Electrical history
This factor is related to the failure history of the cable circuit, taking into account following considerations:

- Recent failures are given a higher rating as they could indicate a “wear out” condition.
- A cable insulation failure is rated higher than an accessory failure.
- If a failure can be attributed to poor workmanship during installation, the rating could be adjusted.

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Physical Age
This factor is the actual age of the cable circuit.
It does not take into account the loading, which is covered separately.

Outage records
This factor only takes into account outages caused by the cable system itself
Outages caused by other components may be ignored although they could impact the operating conditions of a cable circuit.

Loading history
This factor, which incorporates the effects of the load current, requires the keeping of good records of the typical loading patterns, as well as short term overloads (for instance exceeding rated current due to outages on other circuits) or any other unusual operating conditions that may affect the thermal conditions of the cable circuit.
For fluid-filled cables the life of the insulation is determined by thermal aging (maximum temperature at the conductor) i.e. the load current or hot spot temperature: if the cable is operated at only 70% of its maximum rating, the insulation life could be doubled.

Conversely, thermal aging appears as not being the limiting factor for XLPE transmission cables. Extreme thermal aging will cause hardening and cracking of the insulation shield but this should not occur in the expected lifetime of an XLPE cable, even with overload temperature up to 105 ℃ [2].

Cable system design issues
This factor takes into account the experience acquired with particular cable and accessory designs, installations etc.
For example, 63 kV synthetic cables without radial moisture barrier are very sensitive to water-treeing (see figure 3). Similarly, if a specific type of accessories is prone to generate problems after a certain number of years in operation, the circuit would be given a higher rating, as would specific installations

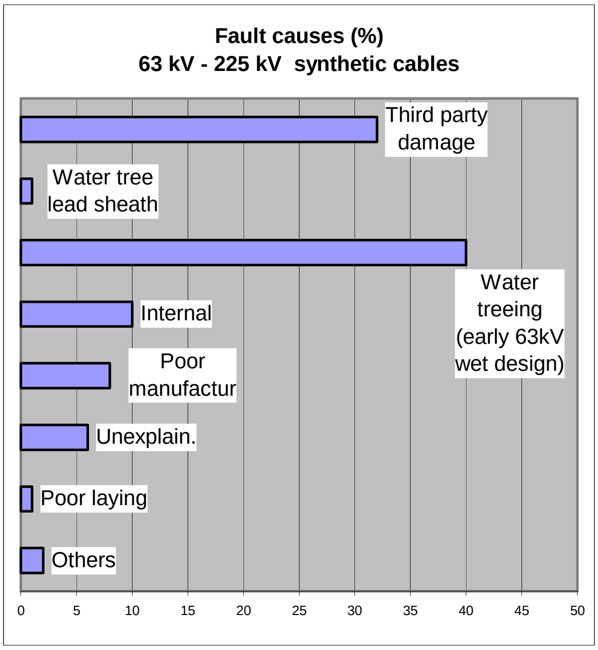
The maintaining of good records (details of circuit layout, installation environment, etc) is needed to know precisely what has been installed, when it was installed and when any replacements or modifications have been made.

Maintenance

System maintenance / inspection history
The factor integrates the number, recurrence and severity of defects from various origins (electrical, hydraulic, civil works) that may be recorded during maintenance operations.

Oil testing
Thermal and electrical aging of fluid impregnated paper will generate gases that dissolve in the fluid.
For example, the thermal decomposition of paper will generate carbon monoxide and carbon dioxide while hydrogen is one of the main gases evolved by partial discharges.

Figure 3: Fault causes - 63 kV to 225 kV synthetic cables
(from 1962 to 1999)



Dissolved gas analysis carried out at regular intervals are necessary as trends in the data are very important in assessing the health of the cable circuit.
IEEE Std 1406-1998 "Trial Use Guide to the use of Gas-in-Fluid Analysis for Electric Power Cable Systems" relates the gas concentrations and the ratios of different gases to the condition of the insulation system

Insulation condition
For paper cables, the paper tensile strength is a good condition indicator: where the tensile strength is low, the mechanical properties of the cable are poor, so that, although able to withstand the operating voltage, the cable would not be able to withstand mechanical vibration or short-circuit forces.
There is a good correlation between the tensile strength of paper and the degree of polymerization (DP), a DP of about 300) being considered as a minimum. Unfortunately, DP measurement is a destructive test.

Power factor (tan delta or dissipation factor) might be an alternative, since the power factor of the insulation begins to increase significantly when the tensile strength of the paper has decreased to about 10% of its original value.
It might be a useful indicator of the onset of end-of-life, but more data are still needed

Representing less than 15 % of the French MV underground network, Paper Insulated Lead Covered (PILC) cables, mainly installed 40 years ago, are still operated, particularly in French major cities. Even if most of PILC cables are still in good condition, presence of such cable leads to an increasing fault rate, specifically during hot summers.

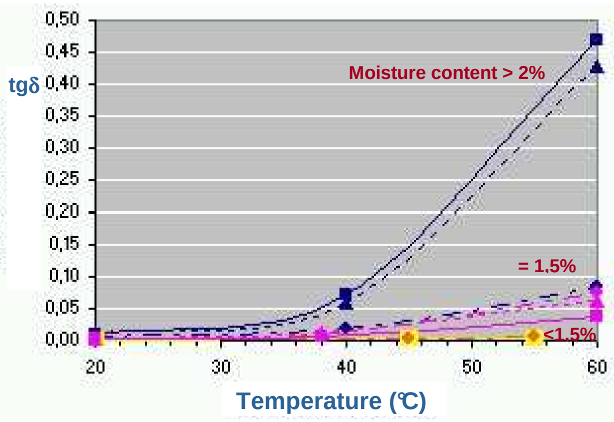
A diagnostic method, dedicated to these cables, combines on-site tan delta and partial discharges measurements. [3] Measured Tan δ is compared to a critical value S_C and variations between 18 kV and 6 kV are also taken into account.
Table 2 gives a synthetic presentation on tan δ measurements results used for recommendation.

Table 2: Diagnostic criteria

	tan δ < Sc/2	Sc/2<tan δ <Sc	tan δ > Sc
Δtanδ/ΔU%<3%	Healthy	Follow evolution	Critical
Δtanδ/ΔU%>3%	Follow evolution	Follow evolution	Very critical

It is worth noting that power factor values are sensitive to temperature and moisture in the insulation

Figure 4: Power factor as a function of temperature and moisture



As regards synthetic cables, recent cable ageing tests confirmed conclusions from CIGRE [1] that, for the time being, extruded polymeric insulants used in high voltage cables do not appear to exhibit property changes that can be said to be significant in terms of cable life reduction when contamination from external sources, e.g. water, oils, sulphur are avoided.

There is increasing interest in PD measurements [4], as improvements in measuring systems to reject external noise have increased the sensitivity of such measurements.

PD may be useful for fluid-filled cable systems to detect localized defects.
With XLPE cables, the situation is different since, in case of PD within the insulation, the time to failure would be relatively short and it is unlikely a PD test would have been performed before failure occurred. But PD might be useful to identify defects at accessories

Corrosion Protection Issues
Defects recorded during maintenance operations, on the corrosion protection system (pipe coating or outersheath, cathodic protection) should be integrated, with a higher weight if stray currents are known to be large, for example, due to neighbouring transportation systems.

Accessory condition

Monitoring equipment condition
(such as gauges, DTS)

Civil structure condition
(termination support structure; joint racks..)

These 3 parameters may be evaluated through visual inspection (structures damaged, weakened, rusted, showing signs of weathering …) or testing.

Installation conditions
Any excavation or new installations which may cause third party damages or detrimental changes in the thermal resistivity of the soil or backfill in contact with the cable circuit should be recorded

Hydraulic history

Table 3 gives an example of the way hydraulic history may be managed.

Table 3: Hydraulic history issues

Influencing Factor: Hydraulic History – Weight 4				
HPFF	**LPFF**	**XLPE**	**Grading**	Condition
Pumping plant condition and performance		n.a.	**10**	oil being added regularly
Oil being added regularly			**8**	2 or more major leaks outside station
Number of oil leaks			**5**	1 leak outside sation
Forced cooling control unit condition			**3**	1 leak inside station
Brine chiller system			**1**	minor leak inside station

Environmental, Safety, and other Risk Issues

Risk issues weighting depends on utilities priorities and local or national safety rules and regulations.

3 parameters are of interest for LPFF and HPFF which may be the origin of ground and water pollution, in case of oil spilling.

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Environmental impact
Grading should take into account containment (low mark) vicinity or crossing (high mark) of water

Potential oil spill
This factor is directly linked to the oil spill volume.

Regulatory requirements
This item is based on the history of oil environmental incidents due to oil.

Three other parameters deal with public and workers (in substations or manholes) safety.

Level of exposure
This level depends on protective measures and operating rules.

Short-circuit level magnitude
The environmental consequences in case of cable breakdown or arcing in an accessory are strongly dependent on the short-circuit magnitude.

Sheath grounding
Surge voltage limiters involved in single-point bonded and cross-bonded links may explode in case of internal fault.

Finally, a parameter is introduced to take into account the consequences of a failure.

Importance of circuit
This feature assesses the financial impact of a fault, taking into account the importance of the customers or the criticality of the supplied zone, and the expected outage time.

CONCLUSION

An asset Health Index is a powerful tool for representing the overall health of an asset.

Taking advantage of existing outcome of experience and diagnostic techniques, it provides a way for capturing operating observations and field inspections or testing into a figure which images asset condition.

This makes it possible to optimise maintenance procedures and replacement policies.

But, work has still to be done to link firmly the Health Index to a failure probability … and get any evidence of service degradation for synthetic cables with radial moisture barrier.

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