PAPER-IMPREGNATED MV CABLES AGEING

Yves BRUMENT
EDF R&D LME - France
yves.brument@edf.fr

Valérie MURIN
EDF R&D LME - France
valerie.murin@edf.fr

Roger TAMBRUN
ERDF Direction Réseau - France
roger.tambrun@erdf-distribution.fr

ABSTRACT

Although paper impregnated cables represent only 13% of the medium voltage underground network (about 28,000 kms) in France, they are considered as sensitive cables because they are old and located in dense urban city.
The aim of the present work is to give to French DNO some key factors to evaluate the paper impregnated cables state and to define the priority of links replacement.
The study was based on a large spectrum of measurements and samples in order to make statistic calculations on different populations of cables:

- *Expertise of cables,*
- *Tan δ at 50 Hz vs temperature (from 23°C to 70°C),*
- *Relative humidity of paper,*
- *Tensile strength,*
- *Polymerization degree,*
- *Voltage breakdown on paper layer,*
- *…*

This study was led from 2006 to 2009.

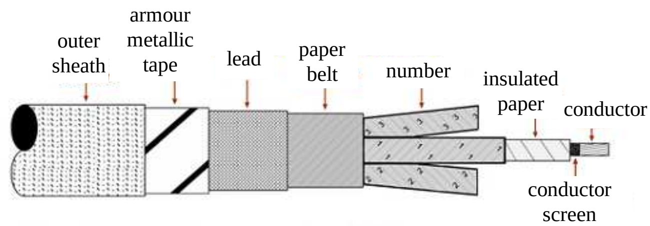
INTRODUCTION

On the French medium voltage network we still count about 28,000 kms of paper-impregnated cables. They are considered as aged but we are not able today to predict the end of life of this type of cables. 13% of cable faults are due to this kind of cables on the MV network.
The study was led to give some indications to French DNO on the paper impregnated MV cables state.
The first work made was to pick up from the grid cable samples in order to expertise them and carry out representative tests which could give information on the ageing key factors or degradation mode of paper and its impregnation.
The project contributors were chosen for their knowledge on PILC or paper such as INPG-PAGORA [1] or CTP [2] who are French paper experts or for their electric tests abilities such as LME [3].
After the hot sequence weather on 2003 and 2006 EDF R&D has determined that the behaviour of cable was directly linked to humidity content in paper.
The study had to confirm this observation and define criterion for paper impregnated cable end of life.

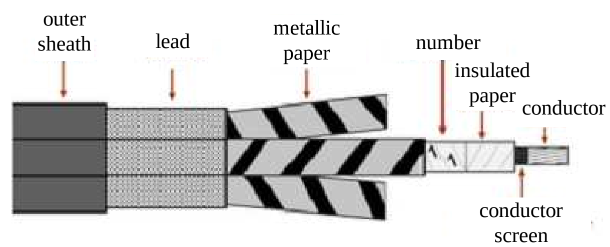
PAPER IMPREGNATED CABLES TECHNOLOGIES

Before all, a short reminder on paper-impregnated cables used on the French MV grid seems to be required.

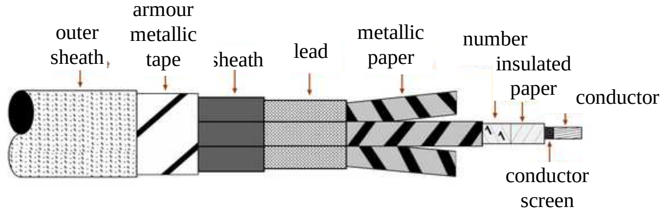
BELTED CABLES



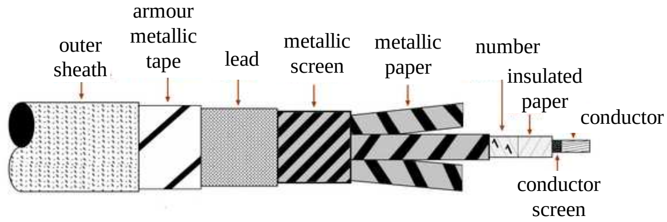
UNIPOLAR CABLES



TRIPOLAR BELTED CABLES



PAPER IMPREGNATED LEAD COVERED



The repartition of cable length laid on the French grid is the following:

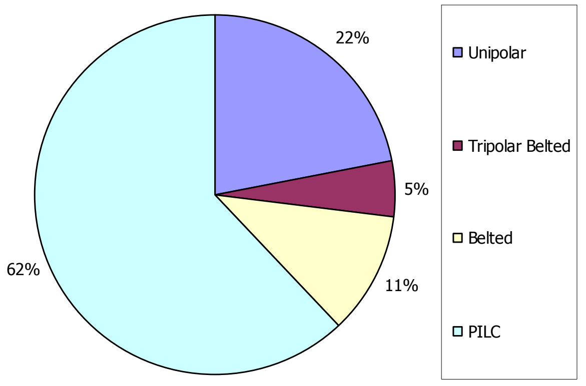


Figure 1: Laid paper impregnated cable distribution

Short reminder on impregnant

Different kinds of impregnant were used in paper insulation. The used oils are classified in 3 major categories in function of the main proportion of chemical groups:

- **paraffinic:**

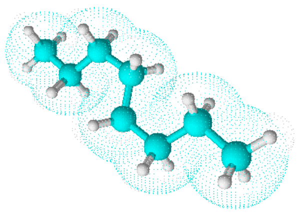


Figure 2: Example of paraffinic molecule - Octane

Crude oil origin: North America, Medium Asia;

- **naphtenic:**

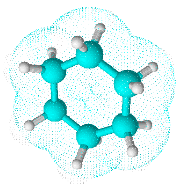


Figure 3: Example of naphtenic molecule - Hexane

Crude oil origin: California, Venezuela, Russia and Azerbaijan;

- **aromatic:**

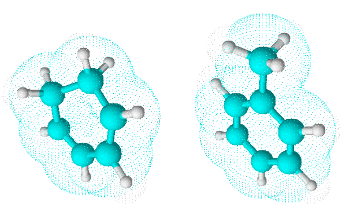


Figure 4: Example of aromatic molecules – Benzene (left) and Toluene (right)

Crude oil origin: Borneo, Indonesia.

Commercial impregnant are not pure chemical products but a mix of molecules belonging to one or another group. Additional products could be used to confer to imprégnants viscosity properties.

In France, the first used impregnants were called "**migrating**". The operating temperature of theses cables is fixed at **50°C**. These impregnant were used up until 1968. The second generation of impregnant were "**stabilized**" by incorporation of resin or wax. The operating cable temperature is **65°C**. These imprégnants were used from 1969. Attention has to paid on service conditions in order to not damage migrating paper-impregnated cables.

PAPER-IMPREGNATED CABLE AGEING RESULTS

From PI cables removed from the grid, a lot of tests was performed to evaluate the electric residual performances of insulation and their mechanical properties. Some tests were also carried out on paper to determine the ageing level and water content.

Polymerization degree of paper and water content

The paper ageing is measuring by the cellulose chain length. The monomer number that composes cellulose is called polymerization degree. It can be measured by viscosimetric method on paper sample.
When the cellulose chains divide into multiple one by environmental effects (temperature, moisture, acidity, etc.), the polymerization degree decreases like mechanical properties.

The figure 5 shows tensile strength versus polymerization degree for different PI cable technology.

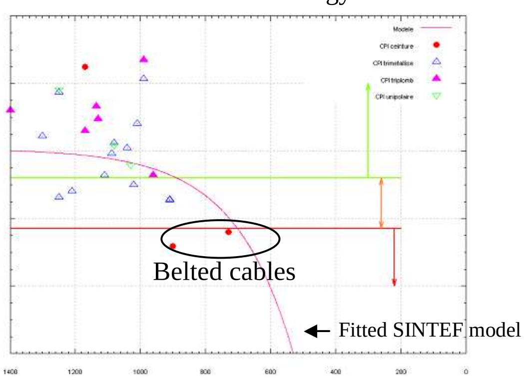


Figure 5: Tensile strength vs Polymerization degree

This figure shows that one cable technology is very sensible: belted cables. The measured polymerization degrees are really under the average value. **These belted cables were identified as mechanically weak**. This could be due to tangential field in insulation that has an effect on cellulose chains.

The water content in the complex paper/impregnant can,

under temperature conditions, leads to free water presence. A study led with INP-PAGORA at Grenoble shows that during daily load cycle, at the decreasing load i.e. decrement temperature, the water could be present under droplets form (radius R) and then arranged under electric field effect that leads to breakdown.
The critical electric field equation is:

$$E_{crit} = 1.542\sqrt{\frac{t}{2R}} \qquad (0.1)$$

So, the paper has to be considered as a water tank, while impregnant behaves as a water barrier more or less permeable in function of temperature. The impregnant seems to be more sensible at a temperature over 50°C. With the temperature, the impregnant absorbs the water and the paper desorbs the water. With time the paper absorption ability decreases due to probably paper capillaries reduction. The time constant for the paper to absorb water is about ten times more important than to desorb water.
All these studies show that an aceeptable water content level is about **3% RH** (relative humidity). In case of **very warm weather**, this level is reduced to **2% RH**.
The measurement levels of water content for all cable technologies removed from the grid are the following:

- Average: 0.87% RH,
- Median: 0.56% RH.

70% of the samples were measured under 1% RH and 95% of them were under 3% RH.

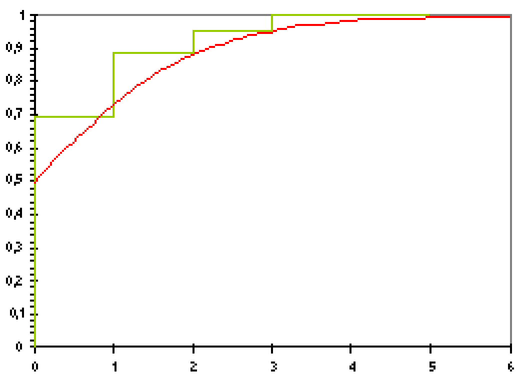


Figure 6: Cumulative density versus RH% Distribution

From measurement results we determined a relation between relative humidity and cable age:

$$RH(\%) = 0.02.age + 0.2 \qquad (0.2)$$

From this equation, we could estimate a paper-impregnated cable lifetime at 100 years to reach 2.2% of relative humidity. This value is considered as a limit. After 140 years, the value is around 3% which is the critical value above a cable is considered as weak.

As the water content in the case of a cable is due to load (temperature), a thermal effect ageing has to be considered. The cable operating temperature is including from 35-40°C to 65°C at the most.

Let us consider the equation of Kraft paper lifetime vs operating temperature:

$$\frac{1}{DP_{initial}} - \frac{1}{DP_{final}} = A\,e^{\frac{-E}{kT}} \qquad (0.3)$$

with $DP_{initial}$ = 1200,
DP_{final} =530,
A = Adjust coefficient,
E = Activation energy (in relation with relative humidity),
k = Boltzmann constant,
T = Operating temperature.

I allows to obtain curves network of paper lifetime in function of relative humidity.

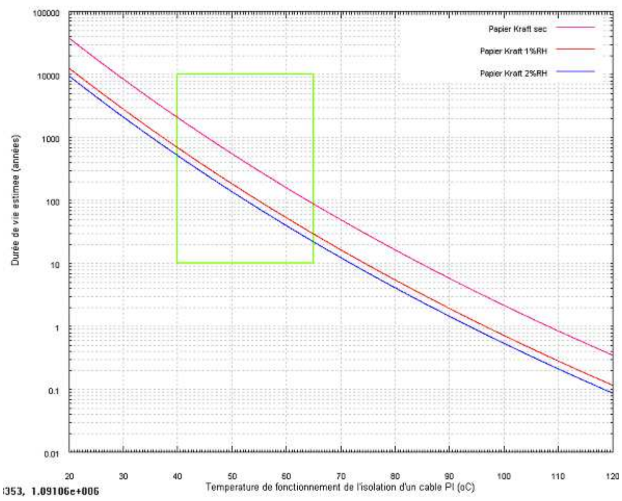


Figure 7: Expected paper lifetime versus operating temperature

For a 2% water content in paper the predicted lifetime at 50°C is 140 years that confirm the previous equation (1.2).

Impregnation rate – IR spectrum

The impregnation rate was measured on paper and the average value is around 40%, the impregnation rate waited for this kind of cables. We don't note any waxing, cracking or wrinkles on paper.

The IR spectrum of an ageing impregnant and of a new one didn't show any chemical ageing or change.

Tan δ at 50 Hz and various temperature

To evaluate the electric behaviour of insulation, a lot of tan δ measurements were performed on paper. The used method is a measurement at 50 Hz and under increasing temperature from 23°C to 70°C. By this method, we would show that the behaviour of tan δ is linked with the water content in paper.

Figures 8 and 9 show the tan δ versus the temperature for dry and wet papers.

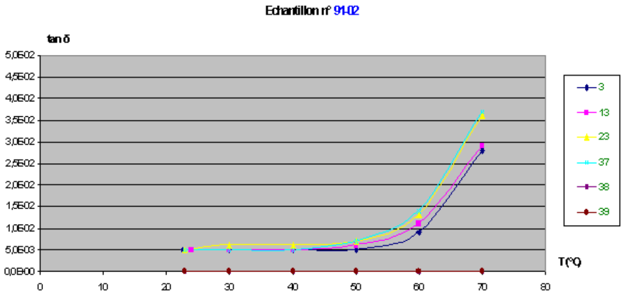


Figure 8: tan δ evolution versus temperature for dry paper

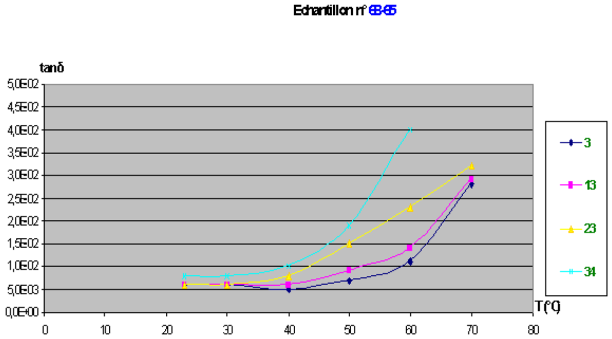


Figure 9: tan δ evolution versus temperature for wet paper

From the experiments , an empiric calculation of tan δ level as a function of the operating temperature (T_f) and the cable age (age) has been established.
The current value for tan δ of a paper impregnated reference cable (new) is postulated around 5 to 6.10^{-3}. [4]

CONCLUSION

Thanks to this study, EDF R&D has determined a critical level for accessible parameters such as:

End of life criteria

Parameter	Critical level	Observation(s)
Polymerization degree	500	New = from 1,200 to 1,400
Relative humidity	3% HR	In case of warm weather: Reduced to 2%

These criteria give indications for the renewal of old paper-impregnated cables. The main conclusions on the state of MV paper impregnated cables laid on French Distribution grid are the following:

- The belted cables were identified as very poor and to be replaced as soon as possible. They represent only 3,000 kms of cables but installed in dense urban areas so difficult to be changed.
- The other paper impregnated cable technologies didn't show weakness and can be considered as in a good state. Their remaining lifetime is about 40 years, theoretical lifetime for a cable.

EDF R&D with INP-PAGORA are now working on a tool to evaluate paper condition based on residual mechanical properties. This work is on progress and should be ready during 2011.
This tool has to be easy-to-use and particularly robust because of on the field conditions.
But it's an other study … story!

REFERENCES

[1] INP PAGORA: French High School on Paper, Grenoble, France
[2] CTP: Paper Technical Centre, Grenoble, France
[3] Laboratoire de Matériels Electriques – EDF R&D *Electrical Equipments Laboratory – EDF R&D*
[4] Diagnostic for cable system asset management and preventive maintenance at EDF – Thierry ESPILIT & al – CIRED 2007, paper 457