KNOWLEDGE PREPARATIONS FOR EXTENDING LIVES OF 10 KV PILC CABLES

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ABSTRACT

A massive number of 10 kV paper insulated lead covered cables in the Netherlands are outliving their design life. Nevertheless, the statistical life data analysis in this paper will prove that they have several decades of remaining lives. Our statistical method enables life data analysis to be applied to partly missing failure data. Additionally, we will discuss the limit of today's failure data and propose how to build a condition data system, through analyzing the stakeholders who acquire and use these data.

1. INTRODUCTION

Paper insulated lead covered (PILC) cable is a classic technology. In the Netherlands, it was firstly introduced to the distribution network in 1910's. In late 1990's, Dutch distribution network operators (DNO's) stopped using PILC to construct new connections below 50 kV. In our DNO, this population currently covers over 70% of the total length of 10kV networks. Until now, the installed PILC cables have not been replaced in a large scale. Within the existing PILC cables, over 15% have outlived their design life, typically 50 years. And this proportion will increase to 65% within 20 years. If this population needs to be replaced in the upcoming two decades, the DNO's will face extreme shortage of capitals, manpower, outage minutes and municipal permissions. [1]

In such a situation, we expect to apply life extension strategy on a significant number of cables. To support decisions to extend lives of such a large asset population, knowledge and information should be prepared in two aspects:

- Reliability analysis: It decides the general time span of life extension strategy. It is often realized through analyzing the failure data acquired from the entire asset population.
- Preparing condition data: Condition data describes the reliability and possible failure mode of individual assets.

Unfortunately, in our DNO, the availability of failure data and condition data has been limited by two organizational factors since 2000.

Firstly, major Dutch DNO's were merged from tens of municipal utility companies between 1998 and 2007. The failure data before 2003 were acquired in standards which vary significantly according to municipal companies. In other words, failure data before 2003 do not have the sufficient quality for statistical analysis.

In Section 2, we will perform statistical analysis on life data, in order to answer one question from asset management (AM) policy makers: what is the failure frequency in the cable population in the upcoming decades? In Section 2, we solved the problem of incomplete failure data, through developing a new statistical estimator according to the expectation-maximization (EM) theory [2].

Secondly, operation, maintenance and system planning departments in our DNO have digitalized their activity records separately in the 2000s. Electrical design of the grid, geographical information, load profiles, outage reports and maintenance records are isolated in different digital systems. Consequently, any search for life cycle activities on a given asset has to be finished manually. As a result, knowledge on cable conditions comes mostly from personal experience rather than standard data.

Section 3 will introduce our roadmap to develop a condition data system, as a necessary part of condition-based replacement of these cables. Within the roadmap, one intermediate step is critical: clarifying the root causes in the failure data. In our opinion, the evidences of failure causes should be collected from a wide range of personnel. Therefore, our discussion will focus on the stakeholders relevant in the data collection.

2. FAILURE AND LIFE DATA ANALYSIS

Statistical life data analysis was introduced to the asset management of Dutch DNO's in the last decade. Its common purpose is to predict the failure frequency in the analyzed asset population in the future. This section will follow a typical life data analysis procedure developed in [3] and [4], while our analysis will be different from [3] or [4] in two aspects:

(1) The failure frequency is predicted for several decades instead of several calendar years.
(2) The failure data missing before 2003 will be taken into consideration.

The Failure Data and Failure Mode Analysis

The failure records used in our analysis comes from the outage reports. In the Dutch distribution network, the 10 kV cables are operated in rings with regular open points. In such circuits, each short circuit failures on 10 kV cables will result in outages of clients. For each outage, the below content are typically recorded:

- its customer minute loss, which will be reported to the regulator,
- the communication records with the clients,
- the switching records from the control room,
- the work orders to the field mechanics, and

- the feedbacks from the field mechanics.

In addition, for identifying the unreliable components in the grid, the below contents are further added:

- the type of the failed component,
- an interval of the age of failed component, and
- a roughly classified failure mechanism.

Thanks to the additional information, a brief failure mode analysis is performed as below to exclude the failures which are not deciding the moment of replacement from the statistical analysis.

We decide to perform life data analysis only on the failures of the cable (excl. accessories), because it is the most expensive part in a cable system. According to our experience, laying a new 10kV cable typically costs €100,000 per kilometer. In contrast, the joints on each km of cable cost less than €5,000 to replace. Moreover, poor quality of joints does not lead to the decision to replace the complete cable. Joint failures depend heavily on the type of joints. In the last few years, the replacement of a certain type of joint has reduced the frequency of joint failures in our network significantly.

Failures on cable (excl. accessories) are completely recorded from Jan 1, 2003. Until Jun 30, 2013, over 3500 failures are available for our analysis. Figure 1 shows the contribution of different causes to the final failures according to our database.

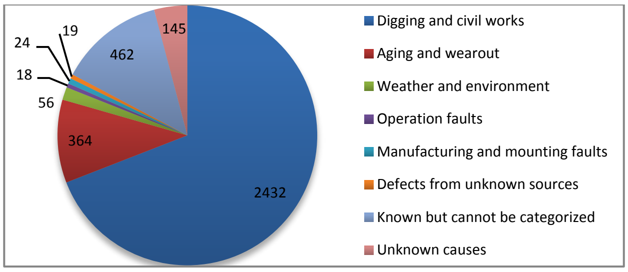

Fig. 1. Numbers of failures of different causes on the 10 kV PILC cables (excluding accessories)

Not all eight causes in Fig. 1 are relevant to the replacement of PILC cable system. In our opinion, the relevance of a failure cause to our study needs to be examined in three aspects. Firstly, the failure cause should result from defects which distribute over a complete cable. For local defects, repairs such as replacing several meter cable with a long joint are much cheaper than complete replacements. Secondly, replacements should effectively eliminate the hazards of failures. As a counter example, replacement is unlikely to be a solution to digging failures. Thirdly, the failure cause should belong to the aging phase, rather than the infant mortality phase of the asset life cycle. Otherwise, it is not relevant to our old PILC cable population. Therefore, we identify "aging and wear-out" as the failure cause relevant to our study and only include aging failures in our life data.

The Life Data

Our long-term prediction of failure frequency is realized through life data analysis. A sample of lifetime typically records time-to-failure (TTF) in one of the three ways below [5]:

(1) Exact TTF: It is available when both the moment of installation and the moment of failure are recorded.
(2) Suspended lifetime: Only the minimum possible TTF can be observed. Typically, the moment of installation is known, but the failure has not occurred yet.
(3) Interval TTF: The TTF is only known to be in an interval. Interval TTF can be acquired when either the moment of installation or the moment of failure has not been precisely recorded.

Exact TTF's are calculated from two datasheets. The first datasheet records when each component was installed. The second datasheet records when and which component has failed. In laboratory life tests, exact TTF's are often available.

However, for assets in the field, these datasheets are often incomplete for Dutch DNO's. The asset tags of our 10 kV cables are not known to the asset manager until early 2000s due to the merging of Dutch DNO's. Consequently, only the following two sets of data are available.

Firstly, the municipal managers know the total length of cables installed in their municipality in each calendar year. After summarizing these data, the distribution of age of all 10 kV cables at 2013 can is known (see Fig. 2).

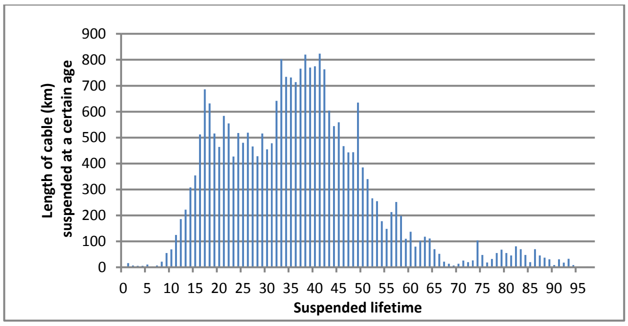

Fig. 2. Distribution of lifetime of 10 kV PILC cables which remain in service at 2013

Secondly, the field mechanics reports the rough interval of TTF after each failure occurred since 2003. Fig. 3 has shown these interval TTF data. They are estimated in intervals because the installation year is not labeled on the cables. Instead, the field mechanics judges the installation years according to historical drawings, or even their personal memories in many cases.

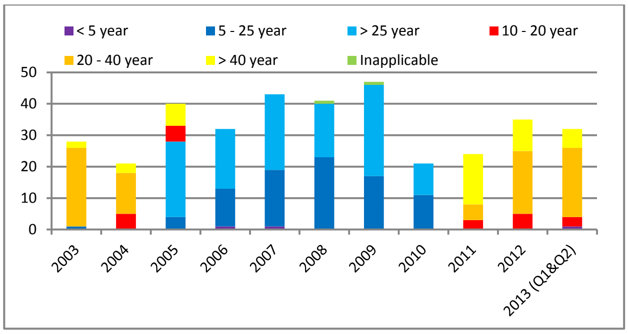

Fig. 3. Distribution of lifetime of 10 kV PILC cables which remain in service at 2013

The Method to Estimate Weibull Parameters

In life data analysis, we assume that **the time-to-first-failure in each km of cable follows a 2-parameter Weibull distribution**. Our life data analysis will firstly fit the TTF data in Fig. 2 and 3 to a probability distribution. Then, the failure frequency will be derived from the best-fit Weibull distribution. This is a typical process of life data analysis.

There are two widely-accepted methods which can estimate the Weibull parameters: the rank regression and the maximum likelihood [3]. Unfortunately neither can deal with our problem that the failure data before 2003 is missing. In [1], we have shown that the missing data will lead to bias in statistical estimations on Weibull parameters and failure frequencies. Thus, we have developed our own solution: an algorithm based on expectation-maximization (EM) theory. Details of the EM theory can be found in [2].

In our algorithm, the life data are noted as below:

- $\mathbf{T}_{exact}$ is a 364 by 1 array in which list the (expected) TTF's of failures occurred between Jan 1, 2003 and Jun 30, 2013 from Fig. 3.
- $\mathbf{T}_{sus}$ is a 25753 by 1 array in which list the suspended life time of each km of cable surviving at Jun 30, 2013. It is converted from the distribution of service life in Fig. 2.
- $\mathbf{T}_{mis}$ as an array of unknown length in which list the expected values of TTF's of missing failures occurred before Jan 1, 2003. It will be estimated in the E-1 step.

And the scale parameter and shape parameter of Weibull distribution are respectively noted as η and β.

Our EM algorithm iterates a loop which consists of E-1 step, E-2 step and M-step. The loop is generally described below. Details of each step are described in [1].

Firstly, before the iteration,

- Initialize η and β as a random value. For example, $\eta(1)=170$, $\beta(1)=3$.

Then, in each iteration,

- In E-1 step: Given $\eta(i)$ and $\beta(i)$, the expected number of the failure occurring before 2003 and the expected values of these TTF's, noted as $\mathbf{T}_{mis}$, are calculated.
- In E-2 step: Given $\eta(i)$ and $\beta(i)$, the expected values of the interval TTF's, noted as $\mathbf{T}_{exact}$, are calculated.
- Merge $\mathbf{T}_{mis}$, $\mathbf{T}_{exact}$ with the suspended data $\mathbf{T}_{sus}$.
- In M-step: Perform maximum likelihood estimation (MLE) on the complete data array $[\mathbf{T}_{mis}, \mathbf{T}_{exact}, \mathbf{T}_{sus}]$. The MLE of η and β will be used in the next iteration, therefore noted as $\eta(i+1)$ and $\beta(i+1)$.

Finally, the iteration ends when $\eta(i)$ and $\beta(i)$ converge. The converged values will be used as the final EM estimation.

The Failure Frequency Prediction

The Weibull parameters have been estimated with two methods, firstly with our EM algorithm, then with the normal MLE which neglects the missing data. In the our EM iterations, $\eta(i)$ and $\beta(i)$ converged respectively to 185.9 and 2.3286. From the MLE method, we got η=185.9 and β=3.0232.

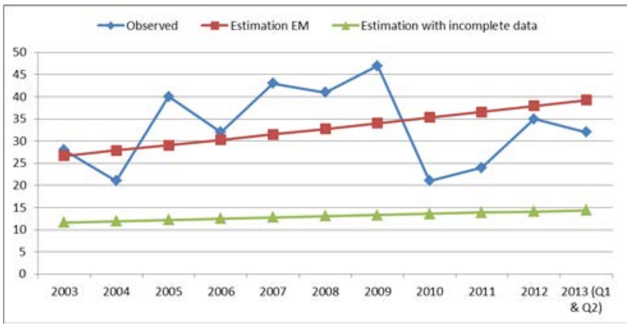

Fig. 4. The failure frequencies calculated from our EM estimation match the observation from 2003 to 2013 better than those calculated from maximum likelihood estimations

The Weibull estimations are verified in Fig. 4. It shows the failure frequencies between 2003 and 2013 calculated from EM and MLE estimations. The EM estimations in Fig. 4 match the observed failure frequencies better than the MLE. This fact implies that EM can reduce the biases of failure frequencies caused incomplete failure data.

Considering that our EM estimation is valid, we infer that that our 10 kV PILC cables can be operated reliably for the upcoming two decades. In Fig. 5, the failure frequency is calculated for the upcoming decades. Though the growth of failure frequency appears to be significant, it will not exceed 100 per year at 2050. Since 250 failures per year are currently caused by digging, the existing resources are likely to be sufficient to maintain the additional failures correctively.

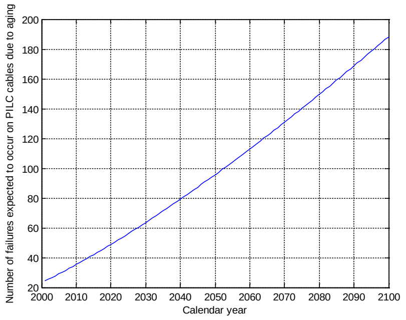

Fig. 5. . The failure frequencies predicted from our EM estimation on Weibull will not exceed 250 per year before 2050

Statistical Conclusions

From the predicted failure frequencies in Fig. 5, we form the two conclusions as follows:

(1) In our 10 kV PILC cable population, failures due to aging are unlikely to outnumber those due to digging before 2050. This ensures us of the maintainability of these cables, and encourages us to further explore solutions to extend their lives.

(2) The standard deviation of time-to-first-failure on each km of cable is several decades. It implies that the replacement wave (probably occurring after 2050) should be condition-based.

3. BUILDING CONDITION DATA SYSTEM FOR ASSET ANALYTSTS

Our life data analysis has concluded that: we should start to replace our 10 kV PILC cable condition-based after 2050. This implies that condition data on individual 10 kV cables should be available at 2050. In contrast, 10 kV cables are currently maintained correctly. Few of these cables are measured regularly either online or offline.

Currently, it is difficult to decide the right type and amount of condition diagnosis, which is the main obstacle to achieve condition-based replacement. Physically, the large number and high reliability of cables, as well as the short lifetime and high cost of diagnostic equipment lead to the low efficiency. Cognitively, knowledge on when, where and how to diagnose our 10 kV cables is in shortage.

In our opinion, the knowledge should be established in three steps:

- the static information of assets,
- the failure information, and
- the condition data system.

The three subsections below will briefly discuss how the three steps have been and/or should be realized.

Separate Sources of Static Information of Assets

The static information of an asset is unlikely to change in its life cycle. The static information of cables can be generally divided into three parts: (1) connections, (2) routes, and (3) high voltage constructions and specifications. Historically, the three parts were collected respectively by (1) system planner, (2) network operator and (3) logistic manager. Nowadays, the three data collections have become (1) the network models, (2) the geographical information system (GIS) and (3) the asset logistic data model (ALDM).

Currently, each information system has covered the vast majority of medium voltage network and components. However, asset analysts need to manually couple data from different system.

For example, given two feeders, none of our software system can acquire the total length of all PILC cable in the ring between them. The feeder name comes from the network model; the length comes from the GIS; the cable type comes from the ALDM. But these data records are not linked to each other. Since the failure probability of a cable relates to its length, today's asset analyst cannot make a quick scan of the reliability of large number of cables. In sum, the compliance problem among different parts of static data should be solved the joint effort from system planner, network operator.

From Outage Reports to Failure Data

As Section 2 mentioned, the failure data is the most complete data source for reliability analysis. As a result of corrective maintenance, in our DNO, failure records are de facto outage reports which focus on client service quality rather than lifetime/reliability estimation. When failures are treated as risks, these outage reports describe mainly the consequences rather than the causes.

Today's failure data should be reveal more details about failure causes, so that it support decisions to invest on condition diagnosis. Specifically, the evidences of failure causes of a failed 10 kV PILC cable is available in several manners below, according to our experience.

- Experienced mechanics can understand thermal aging of paper. They can identify traces left by overheating of cables.
- With proper training, mechanics can recognize soil type and humidity during digging. These are possible triggers for hot spot and chemical aging.
- Cable specialist can measure the cables segments removed during the failures in laboratory, especially regarding the degree of thermal deterioration of paper.
- Accepting tests (typically tan δ and partial discharge tests) are frequently performed on newly installed cables together with some old segments. These tests provide useful evidence for thermal and electrical aging of the old segments.
- Thermal-mechanical aging and consequent contaminant in oil insulation are likely to be

detected in online partial discharge measurements.

The collection of information above should follow two principles: (1) quality better than quantity, and (2) multiple witnesses on the same scene. The first principle means that only a proportion of failure causes need to be described. If 10 out of the 300 failures occurred per year are sufficiently studied regarding their root causes, within 10 years, the sample pool will be sufficient to support in-depth failure mode analysis. This will further generate knowledge rules for application condition diagnosis. The second principle means that the software system managing failure data should allow different personnel to describe his/her viewpoint on the failures. To include extensive descriptions, external link to documents, pictures and views need to be possible.

Additionally, a failure data sample should be linked to three parts static information, since the static information can help to identify failure causes in the ways below.

- The historical load profiles can be traced through the id of cables in network model.
- The thermal limit of cables depends on the soil type. Ground traffic can lead to mechanical stress to the cables beneath. Both soil type and traffic load can be acquired through giving GIS coordinates.
- The failure modes depend heavily on the high voltage constructions and specifications, which are mainly included in ALDM.

Therefore, when the failure assets are searchable in network models, GIS or ALDM, decision makers can trace life cycle activities on the cable through digital system rather than personnel experience. This brings benefits to acquire and to preserve the knowledge on failure modes.

In sum, the management of failure data will concentrate on acquiring evidences of failure causes from large number of personnel of different technical background, while make the collected information available in long term through connecting them to static information in network models, GIS and ALDM.

From Failure Data to Condition Data

In the last subsection, we explained that the content and preparation method of failure data are different from those of outage reports.

In short term, failure data will still be managed in the same software system with outage reports. Meanwhile, the evidences on failure causes collected from personnel mentioned in the last subsection will form the first collection of condition data. But they will still be attached to failure data, since the preventive maintenance, inspection and diagnostic activities to collect these condition data are not common in today's 10 kV cable systems.

In long term, however, failure data and condition data should be separated from outage data, because their concerns are different. On one hand, outage data should continue to be managed by the client service and the control center, so that the consequences of failures can be studied according to their occurring time, location, etc. On the other hand, a condition data system should include the results from preventive maintenance and diagnostic activities, so that asset analysts can find out the probability of a certain failure mode, or the remaining life of a certain asset system.

4. CONCLUSIONS

Through applying our expectation-maximization algorithm on incomplete failure data, we conclude statistically that: the growing number of aging failures on our 10 kV PILC cable population is maintainable before 2050. Condition data on these cables should be available to support decisions on replacements. Before building the condition data system, two preparations are necessary. Firstly, the asset static information in different digital systems should comply and connect with each other. Secondly, a collection of failure data should be acquired through adding evidence of failure causes to outage reports.

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