DECISION SUPPORT FOR LIFE TIME MANAGEMENT OF HV INFRASTRUCTURES

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ABSTRACT

Nowadays, power utilities have more or less the obligation to maintain their asset network. Regulators demand a reliable power supply of high quality. Furthermore, as the market will be open, failure can lead to a loss of image, with the effect of customers choosing other power companies to buy their energy from. Therefore, a well considered maintenance program is necessary to obtain a high quality network. The asset managers of the network owner are responsible for the reliability and availability of the high voltage components. Dependent on the maintenance strategy, which is applied by the asset manager, the maintenance program can be influenced. Strategies can be based on reliability management or more based on risk management. Furthermore, the availability of assets, which gives the possibility of maintenance activities, is influenced by the investment plan of asset management. This contribution discusses a systematic approach to come to a considered maintenance program for HV components. In particular, the authors look at it from different points of view. Figure below shows a diagram-based overview, concerning the different aspects of a life time decision support for HV infrastructures. These various aspects will be discussed point to point with main focus on power cable systems as power cables play an important role in the distribution of the electric energy to the utility’s customers.

INTRODUCTION

The asset managers of the network owner are responsible for the reliability and availability of the high voltage components. Dependent on the maintenance strategy, which is applied by the asset manager, the maintenance program can be influenced. Strategies can be based on reliability management or more based on risk management. Furthermore, the availability of assets for possible maintenance activities, is influenced by the investment plan of the asset manager. In the last years Reliability Centered Maintenance (RCM) is getting more and more attention as well. RCM is a policy for managing maintenance effort to keep system running and maximize up time. The safety and availability importance of the asset determines maintenance scheduling. At present in dependence of their business values several power utilities in the world are implementing the Risk Based Maintenance (RBM). In contrast with the RCM policy cost elements like penalty costs, constrain cost or other performance indicators are taken into account from the point of view of maximization of revenue.

ASSET MANAGEMENT APPROACH

Failure Statistics As no high voltage component has an endless lifetime, every component will be showing failure behaviour. Dependent on the type of components, the failure behaviour can be different. The main goal of applying maintenance is to prevent these failures. However, if certain components show an increasing number of failures, the maintenance program should be adjusted and be more pinpointed on these failing components. Hence, that it is necessary to frequently combine a large amount of practice and failure data, and deliberate the results in the maintenance program. In particular, the failure information of a particular network has to be verified on a large population as available e.g. in database of decision support systems, see figure 2.

Network Configuration Due to the fact that the construction and the operation of a HV asset are of importance for systematic condition assessment, the relevant elements have to be identified. For example, a distribution power cable is used to interconnect small substations. These cable sections may consist of three different types of components (figure 3). For practical reasons, a cable section may be constructed from multiple parts of cable, which are connected to each other with cable joints. At both ends of the cable, a termination is
mounted to connect the cable to HV installations. Due to repairs or changes in topology, cable sections often consist of various types of joints, cable parts and terminations. In addition, the age of components may vary due to repairs over the years. Moreover, the different topological and operational conditions of a particular cable system influence the service life of a cable system enormously.

For assessment of the insulation condition of power cables, some linkage between relevant information has to be obtained, then combined and used to generate knowledge adequate for decision making, see table 1.

<table>
<thead>
<tr>
<th>Database domains of power cables.</th>
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<tr>
<td>Component domain</td>
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<tr>
<td>consisting of specific insulation characteristics of the cable structure; e.g. cable insulation, accessories;</td>
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<tr>
<td>Diagnostic domain</td>
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<tr>
<td>consisting of the type of diagnostics applied; e.g. general condition assessment, assessment of weak spots;</td>
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<tr>
<td>Measuring data domain</td>
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<td>defining specific diagnostic quantities used during condition assessment;</td>
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Due to the fact that the configuration of the network is of significant importance for the maintenance and replacement strategy information elements regarding the configuration such as redundancy, type, service life and maintenance history have to be verified on a large population as available e.g. in database of decision support systems.

**Network Operation**  
During the service life of HV components the network operation will result in changing profiles of electrical, thermal and mechanical stresses, see figure 4.

In particular, a number of information elements is of importance to evaluate the service life reduction:
- the history and the future of annual load,
- maintenance aspect: poor workmanship, digging activities,
- short-circuit history.

Due to the fact that there is direct relationship between the insulation degradation and the thermal load, the availability of this knowledge may influence the estimation of the service life reduction of HV components. In particular, in case of power cables changes in thermal load may influence the axial and radial expansion and may result finally in additional degradation effects, e.g. local field enhancements, gas formation or treeing.

**Environmental Conditions**  
The environmental conditions may play under certain circumstances a relevant role in degradation processes. In particular the
- ground water level and pollution,
- weather /climate,
- mechanical stresses,
- wandering currents,

are important parameters and they have to be separately evaluated for particular networks. From statistics is known, that there is a relationship between the ground moisture content and insulation degradation of power cables. Also the wandering currents, from neighbourhood railway track may have negative influence on the electric degradation of a power cable section.

**Reliability & Availability**  
Nowadays, the possibilities of scheduling the maintenance activities become difficult as a result of the increasing 24/7 request of power and the optimized utilization of the power assets. The availability of power assets to maintain becomes more difficult. Large industry plants with continuous processes can often only maintain assets when there is a planned production stop. As a result of the low availability of these assets, the reliability of those assets can deteriorate, with the possibility of outages leading to unexpected production stops. Again, the consideration should be made between the technical aspects and the economical effects of applying maintenance.

E.g. in the case of power cable network the expected reliability and availability is strongly dependant on the acceptable risks. Finding a component with a low performance in vital situations will necessitate an action that will improve the performance dramatically. At the other hand, finding a component with a very high performance in a non-critical situation from the risk consequence point of view will give possibilities to decrease maintenance activities of redundancy strongly.

Practice based on a method to estimate the financial consequences of a failure given by the number of connections involved , the customer type(e.g. large industry, household) and the expected outage time.

The estimated failure probability is given by the asset construction, number of short-circuits, the insulation condition and operational load.
The financial consequences includes regulator penalties, loss of energy supplied and possible replacement costs, the failure probability is estimated on risk elements like age, environmental conditions and different weight factors of specific type of components. A utility even takes one interesting step further: the total asset group has been divided into three categories: critical, medium and non-critical, each with their own amount of percentage of the total population (see figure 5). The high-risk group is then submitted to the normal maintenance program, which can consist of inspections or preventive maintenance, while for the other two groups a representative sample is maintained.

**Legislation** Regular inspection of the electrical assets is nowadays legally determined, in order to find defect, which can lead to operation failures and possible dangerous situations. According to Dutch norms [NEN 3140], the inspections intervals can be determined on:

- Manufacturer’s advices;
- Inspection conclusions;
- Usage of the equipment;
- Effects of outages.

Juridical this means that the network owner should be able to prove that his electrical equipment is in a good and safe condition. Inspection intervals according to the norms have changed from every 5 years to condition dependent according the above-mentioned point. Moreover, with regard to safety and environmental aspects the regulatory requirements are becoming stronger. In particular, the Dutch norm NEN 350110 recommends that the responsible service provider has the obligation to collect in a systematic way the information about the over-all status of the infrastructure.

**Condition Assessment** The manufacturer maintenance advises are mostly based on expected asset life-time. As a result, with high safety margins the time-based maintenance is recommended. The fact that, in dependence on the type of insulating materials, defect induced degradation, service life, the assets may age in different ways which are not taken into consideration.

The major aspect for a considered maintenance program is based on the type of the used components and their present insulation status. To monitor the changes in an asset or its particular components, suitable diagnostics are necessary. For power cables, electrically based diagnostics are most convenient.

In condition assessment of power cables of a particular network the particular cable section can be categorized in to 3 groups based on diagnostic measurements:

- Category 9; the insulation condition code 9 means that the component is in a perfect condition and the next inspection can be scheduled in the next 5 years.
- Category 6 means that the component is in an aged stage and the next inspection is required in the next 3 years.
- Category 1 means that the cable section is in bad condition and requires soon maintenance e.g. weak spot in the cable section should be replaced.

The information about the actual condition status is of importance for the estimation of the insulation degradation ratio e.g. annual insulation defect degradation ratio $\text{DR}_{\text{DD}}$, see figure 6a.

Moreover, this information can be combined with operational conditions and the degradation ration in function of thermal aging $\text{DR}_{\text{OL}}$, see figure 6b.

**Figure 6:** A) Annual insulation degradation ratio as determined for three different insulation condition categories. B) Annual operational load degradation ratio as determined for paper/oil insulation. C) Schematic presentation of influences of operational and degradation effects on asset service life.

Combining both degradation ratio’s may result in the assessment of total remaining life $RL_{\text{tot}}$. In particular using this parameter the influence of actual condition and the operational condition can be combined with the expected service life of an asset. Based on this information for particular HV component proper maintenance strategy can be selected. Figure 6c shows a schematic influence of both effects on the total asset condition in function of asset service life.
AM ORGANISATION AND INFORMATION ASPECTS

For a successful AM decision process it is necessary to translate the necessary information aspects into usable data sources. These data types influence the identification/separation, type and complexity of data sources and the decision systems they support. The subdivision of the decision process as described below emphasizes that to facilitate AM different disciplines are involved in gathering and processing all necessary information. For example, when supporting the AM decision process from the point of view of an organisation, most information about technical aspects might be easily available and gathered amongst (service) engineers, while the economic data will be more easily available and processed amongst financial staff-members. The corporate level benefits from a team with experience in legal issues, risk assessment, risk management and network planning. When the AM decision process is supported with automated tools, all these roles will still be necessary. At the end the stakeholders expectations will be taken into account at the corporate level, thus from the above can be learned that to facilitate the AM decision process correctly, one has to include all the different disciplines and cover all aspects of all the three levels.

The aspects of information needed to support AM decisions can be divided in three main categories being technical, economical and societal aspects.

Technical Aspects Relevant information needed for AM decision support is dependent on several asset-related parameters, such as the insulation ageing of a component and the probability of an over-voltage across a component, e.g. as a result of switching activities. The component ageing is related to the absolute age, the type, the history and the operating conditions of a network (sub) component. In order to decrease the probability to a failure, condition assessment can be used. A combination of diagnostic tools for condition assessment is chosen and applied, depending on the different types and locations of insulation defects induced degradation sites. The technical aspects cover amongst others condition assessment, aging models, and failure probability, but also information on the equipment inventory, the network topology, the available spare parts, the current maintenance procedures, the history of maintenance actions and the history of failures.

Economical Aspects As every technical aspect will have its financial counter-part, economical aspects are for example the costs of maintenance, repairs and failures, but also the costs of condition assessment and the investment costs for equipment and spare parts. Here these costs will be called the economical information on assets. The costs related to a failure are dependent on the outage-related expenditure. Failures mostly result in major damages to network components and their environment, which will lead to high maintenance and repair costs. In case of major critical damages, provisional solutions are needed to restore the energy supply as quickly as possible, eventuating in higher expenditures. Outages can result in customers’ compensation and responsibility claims in the form of penalties. The need for economical information finds its origin in the fact of driving a business, e.g. penalty costs from customer contracts, possible claims from customers and the costs of undelivered energy. Here these aspects will be called the economical information on business.

Societal Aspects However, within the asset management decision process, technical and economical aspects are not the only aspects to keep in mind. As an example, risks are not only determined by the economics. There are also some societal aspects that have to be considered, such as the impact on society of outage and failures. Failure acceptability can be reflected as the degree in which a failure is acceptable from the social point of view. The failure impact is depending on the criticality and number of connections, which are affected with a failure and the time to restore the particular failure. Even so, frequent energy interruptions in a short period of time will not be acceptable from a social point of view. Furthermore, the social impact of utility’s policy is determined among others by two factors: the imago to the public and the feeling of safety.

Decision process

When pursuing optimal economical performance decisions have to be made about which of all the possible maintenance or investment actions are the correct ones. Simply put, this can be seen as decision process, where decisions are made on technical, economical and societal information. However, this is a continuous process, as decisions influence the system, and therefore influences at least the technical and economical information on which the decision is based.

Looking in more detail, this decision process can be seen as build of three separate levels, as illustrated in Figure 7. The first level deals with the technical information; the second level uses the results of the first level and the economical information on assets, while the third level combines this with the economical information on business and societal information.

A way to approach this separation is to think of the first level, which consists of technical information and is mainly focussed at components, as the component level. The second level, which combines the economic information on assets with the results of the first level, has more focus on the level of the network (the reliability and operational performance), while the third level uses the economic information on business combined with the societal information, to make decisions about risk which have mainly a corporate focus. From a technical point of view, multiple scenarios can be found to influence the performance of assets. For example, scenarios could be in- or decreasing maintenance and inspection intervals, replacement or refurbishment, but also about changing the maintenance strategy from corrective maintenance to time based or condition based maintenance. The scenarios are found by analysis and combination of the equipment inventory, the maintenance actions already performed on the equipment, the current rules that exist for
maintenance, and condition assessment, that results from
diagnostics, in combination with statistical evaluation of
practical failure cases, reliability evaluation and ageing
models result.
All these scenarios will have a different effect on the technical
performance (in terms of reliability and availability) of the
asset. At this stage, scenarios should not be excluded based on
their effect on technical performance, because in the next
levels, the scenarios will be combined with other relevant
data, which even may cause a scenario with a negative effect
on technical performance to be the most economic while
having the smallest risk. The stakeholders’ expectations for
example will be taken into account at the third level.
Combination of the technical information of the scenarios
with relevant economic data from underlying economic
systems will result in a quantification of benefits and costs of
each scenario. These benefits and costs are not exclusively
expressed in economic terms, but could also be expressed in
other terms such as reliability or expected lifetime. For
example, enlarging an inspection interval may cause a benefit
in decreased expenditures, but could have costs in terms of
decreased reliability.
On the other hand, shortening the interval might have costs in
increased expenditures, but could lead to benefits in increased
reliability.

![Figure 7: Asset maintenance management decision process on three levels](image)

[5] To avoid complexity this continuous aspect of the decision process is
not reflected in the figure.

Useful decision support tools should address all the categories
information and different levels in the decision process. The
tool should support the asset manager in his decision process,
aiding the asset manager to take his decision supported by the
tool. Figure 8 shows the output of such a decision support tool
giving credit to the different categories of data.

**CONCLUDING REMARKS**

Life-time decision support is a systematic approach to come
to a considered maintenance program.
Life-time decision support for HV-infrastructures comprises
the following aspects: Failure statistics, network
configuration, network operation, environmental conditions,
reliability & availability, legislation and condition assessment.
The information aspects of AM decision process can be
divided into the three categories: technical, economical and
societal.
The decision process itself can be regarded as consisting of
three separate levels: component, network and corporate.
When an implementation of an AM decision process (or the
supporting decision support tools) does not cover the all
aspect categories of information and all of the three levels, the
main goal of AM, finding the best balance between
component performance and stakeholders’ expectations, will
not be reached, which probably will not lead to the highest
efficiency possible.

![Figure 8: Example of output of a decision support tool addressing the three
categories of information technical, economical and societal.](image)

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