REPLACEMENT PLANNING STRATEGY TO OPTIMIZE LIFE CYCLE PROFIT

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SUMMARY

Replacement of old components in MV distribution networks should be based on risk assessment in order to optimise the life cycle profit. This strategy implies prioritising resources on the components that are important for the availability of supply and the safety of personnel. It is therefore convenient and cost-effective to concentrate the replacement analyses and planning on the potential most critical components. Low-risk components, however, are not subjects for planning, and should not be replaced before they fail and get damaged.

INTRODUCTION

This paper presents a model for replacement planning of components in MV distribution networks, and some results from case studies where the model is applied on a simple MV network example and two real cases; a 22 kV rural overhead network and a 11 kV urban cable network. The simple example is used to evaluate and compare four, in principle, different replacement strategies with regard to life cycle costs.

The paper is based on results from the work done by a Working Group financed by the Norwegian Electricity Federation (EnFO) and Norwegian utilities. The purpose of the Work Group was to test a decision support system (VefoNet) for maintenance and replacement planning developed in the Scandinavian project "Maintenance and Replacement Models for MV Distribution Network".

VefoNet is a prototype, which was developed in order to perform realistic tests of some decision support models developed in the project. VefoNet and the models are described in ref. [1]. The following six models are implemented in the prototype:

- *"Present value model"* where the optimal time for replacement is estimated based on life cycle costs.
- *"Age profile model"* where consequences of different replacement strategies are analysed.
- *"Budget model"* where economical consequences of certain decisions are analysed.
- *"Criticality model"* where components are ranked according to decreasing criticality.
- *"Replacement vs. repair model"* where the profitability of replacement instead of repair is analysed.
- *"Transformer replacement model"* where replacement of a transformer is analysed based on the cost of losses and cost of a new transformer.

Technical and economical analyses of replacement in MV distribution networks can be time-consuming, and require much data due to the large number of components in such networks. This is the main challenge regarding replacement analyses and planning in a distribution utility. It is neither convenient nor cost-effective to carry out e.g. annual analysis and assessment of all the MV components on individual basis. The utilities need an efficient planning model ('strategy') with well-defined criteria to be able to carry out systematic replacement planning on a reasonable level in terms of resources and quality. Key elements in such a model are:

- Focus on the most critical components.
- Simple replacement criteria regarding technical condition, availability of supply, safety of personnel, environment, etc.
- User-friendly tools for cost estimation.
- Good access to a network database, i.e. the planning functions should be integrated with the utility's network information system.

For a long time maintenance and replacement was a question of technical matters, but have now turned towards economy and profitability. This is due to the general trend in the electricity supply industry in Norway, as well as in other European countries. Governmental regulations and the owners increasing focus on profit now impose many Norwegian utilities to considerable cost reductions. Pressure is put on maintenance and replacement costs since these cost elements are, at least in the short run, the easiest to reduce.

Economical compensation for energy not supplied to end-users due to interruptions (> 3 minutes) is now coming up in Norway. This gives the utilities a clear economical incitement to replace worn-out components in networks where interruptions have large economical consequences. The VefoNet prototype and the planning model presented in this paper are tools, which are developed in order to meet this increasing focus on economy as described in this and the previous paragraph.

LIFE CYCLE ANALYSIS

Life Cycle Cost (LCC) is a well-known concept where all costs related to the entire lifetime of an item are considered. In addition to LCC, the life cycle analysis also includes an analysis of the system's potential life cycle income, i.e. the maximum possible income at 100% availability, and the Life Cycle Loss (LCL) due to unavailability. The LCL, which in the case of a power network is mainly due to interruption costs, is the difference between the potential and actual income. The Life Cycle Profit (LCP) can then be calculated as the difference between the actual income and the LCC.

Figure 1 is commonly used as an illustration of the fundamental relations between income and availability, losses and costs, and the profit.

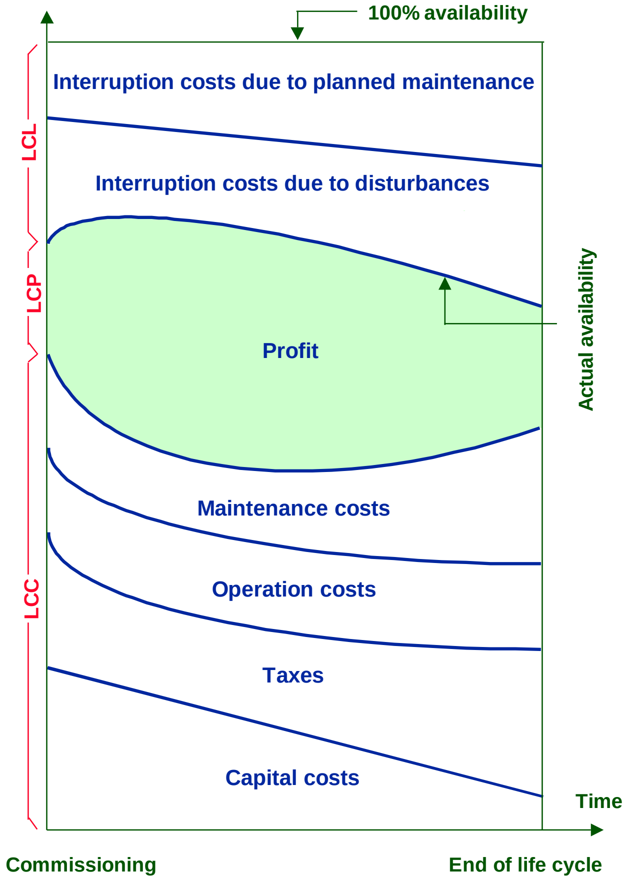

Figure 1 Life Cycle Profit

The life cycle profit can be increased by
- reducing the LCC, i.e. lowering the cost curve
- reducing the LCL by reducing the unavailability, i.e. raising the income curve

There is, of course, a close relationship between the cost elements. A reduction in the maintenance cost can reduce the availability, and therefore reduce the profit. An increase in the maintenance cost can also increase the availability and reduce the losses even more, so that the profit increases. The purpose of an optimisation is to determine the optimal cost level, and the induced loss level, to determine the maximum profit.

This can be accomplished in several ways, e.g.:
- Cut out unnecessary preventive maintenance, i.e. perform only cost-effective maintenance.
- Reduce maintenance on items planned to be replaced.
- Replacement in advance instead of repair.
- Establish procedures for condition monitoring as a basis for condition-based replacement.
- Partial replacement, e.g. replace only worn-out items and not all items of the same age, or replace only the wooden poles and not the entire line section.
- Extended lifetime by rehabilitation, e.g. re-impregnation of wooden poles.
- Reduce planning costs.
- Predefined criteria in case of unexpected failure.

This paper has extra focus on the last two elements.

It is almost impossible to estimate every cashflow related to an item over its life cycle. LCP is therefore best suited as a general model that illustrates the relationship between the cost elements.

PLANNING MODEL

Several models for calculation of optimal replacement time are developed. Common for these models is that they need detailed information on the item to be calculated.

Electrical networks usually consist of a large number of items, and it is a huge amount of work to obtain sufficient information on all these items. Therefore, it is a need for a strategy that can help focusing on those items for which such detailed information are most likely to be needed, and by this reducing the necessary data collection.

Figure 2 illustrates the main steps in the proposed planning model, and each step is summarised in the following.

Start

There is a clear distinction between the first time and consecutive times performing the steps in the model. The first time will require a little more work due to the need for obtaining basic information for all items. This is needed for the first determination of category (see later chapter). The planning process should later be repeated whenever needed, or at least every 5 year. The amount of work is however reduced to only updating the category for all items based on new information collected since last update.

Determine category

Coarse selection of all items into one out of five predefined categories. This is done to determine which items need closer technical and economical analysis in order to decide if they *actually* are due for replacement within the planning period. The overall strategy and general network information are important input to this step. This gives the first estimate on the total volume for replacement, i.e. how extensive the replacement should be.

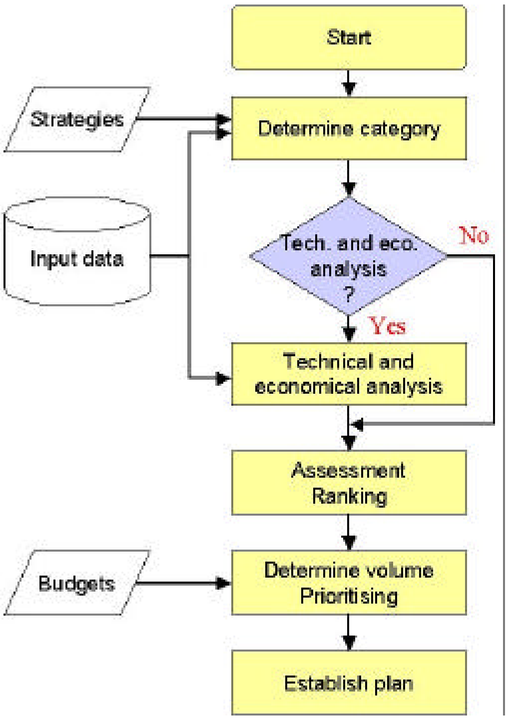

Figure 2 Planning model

Technical and economical analysis
Detailed technical and economical analysis of pre-selected items resulting in decision indicators. There is a need for collection of additional required data, but this depends on how detailed the analysis should be. This step can be omitted if there is no need for further analysis, or if such analysis is not relevant.

Assessment and ranking
If the results from the previous analysis show that an item is either better or worse than expected, the category for that item may be changed. The utility's overall strategy and objectives, together with the decision indicators and other relevant information, lead to a ranking of all items as regards the time for replacement. The *actual* need for replacement is now determined, together with a new estimate on the total volume for replacement.

Determine volume and prioritising
The actual replacement may be restricted due to budget limitations. There may therefore be a need for prioritising, based on e.g. expected technical lifetime and age profile.

Establish plan
The final step is to establish the replacement plan to be implemented based on the previous steps.

Input data
There is always a need for relevant, sufficient and updated information, and the most important sources are
- Network database, including manufacturing data and information on technical condition
- Fault statistics
- Cost catalogues

The main steps *Determine category* and *Technical and economical analysis* are further explained in later chapters.

PLANNING PERIOD

Items in electrical network usually have long expected technical lifetime, e.g. 30-50 years. The period of analysis for replacements should therefore also be long, e.g. 20-30 years. Due to uncertainties, however, it is more adequate to prepare a replacement plan with a shorter horizon, e.g. 10 years.

The replacement plan should include an action plan, i.e. a detailed plan describing which items should be replaced, and when, for the first 5 years, where as the plan should only give a rough outline of the replacement for the next 5 years. The plan should therefore be updated every 5 year, including a 5-year detailed plan and a 5-year rough outline.

Figure 3 Planning period

DETERMINE CATEGORIES

The basic idea is to use a few simple but well-defined criteria based on e.g. performance indicators to sort all items into one out of five predefined categories. The criteria should take into account the utility's philosophy as well as technical, economical and environmental aspects.

The categories are defined in such a way that only the items in two of the five categories need closer investigation to decide whether the items *actually* need replacement during the planning period, or if the items residual lifetime can be extended, e.g. by intensified maintenance.

By using a strategy based on such categories, the time and effort used in data collection and analysis can be significantly reduced, i.e. it helps in the selection of items that should be given priority on condition monitoring.

- *Category I* comprises items that obviously should be replaced as soon as possible. There is no need for further analysis.

- *Category II* comprises items that are expected to be replaced within the next five years. The final decision of time for replacement should be based on technical and economical analysis.
- *Category III* comprises items that are expected to be replaced within the next ten years. The final decision of time for replacement should be based on technical and economical analysis.
- *Category IV* comprises items that are not expected to be replaced within the next ten years. There should be no need for technical and economical analysis.
- *Category V* comprises low-risk items, i.e. where the consequence of a failure is below an acceptable limit (failure-based replacement).

Since the replacement plan should be separated in two 5-year periods, the items are also divided into Category II (1-5 years) and III (6-10 years) in order to focus even more on the items most likely to need replacement.

Criteria

Each utility must establish their own set of unique predefined criteria for *each* category based on the utility's own long-term goals and strategies.

Technical criteria
- Technical limitations
- Technical solution/construction
- Technical condition
- Expected technical lifetime
- Electrical losses
- Availability

Economical criteria
- Annual budgets
- O&M costs
- Repair costs
- Interruption costs

Environmental/Safety criteria
- Geographic and climatic conditions
- Demographic development
- Health, environment and safety of personnel
- Regulations

Replacement vs. repair

The categories can also give an indication on whether to replace or repair in case of a failure.

If there is a failure on an item in Category I, there is no need to assess corrective maintenance. Immediate replacement is the only solution.

If there is a failure on an item in Category II, then corrective maintenance is the best solution if the costs are below a certain value, e.g. 10% of the replacement cost, else immediate replacement should be considered.

If there is a failure on an item in Category III, then corrective maintenance is the best solution if the costs are below a certain value, e.g. 25% of the replacement cost, else immediate replacement should be considered.

TECHNICAL AND ECONOMICAL ANALYSIS

Technical analysis comprise:
- *Analysis of mechanical condition* to reveal worn-out items.
- *Loadflow analysis* to reveal heavily loaded items and sections.
- *Short-circuit analysis* to reveal items with nominal short-circuit capacity below the highest possible.
- *Reliability analysis* to reveal high-risk items, i.e. items that supplies customers that require a high quality of supply.

In the case studies (see next chapter) the network information system Netbas has been used to perform loadflow and short-circuit analysis.

Several decision support models for maintenance and replacement are implemented in the VefoNet prototype, and the following are used in the case studies:

- The present value model has been used to estimate the expected economical lifetime.
- The criticality model has been used in the analysis and ranking of items based on age, condition and importance in the network.
- The replacement vs. repair model has been used to analyse how expensive a repair in case of a failure can be before replacement in advance is recommended.
- The transformer replacement model has been used to estimate economical lifetime for transformers.
- The age profile model has been used to analyse the resulting age profile and total cost for the alternative replacement strategies.

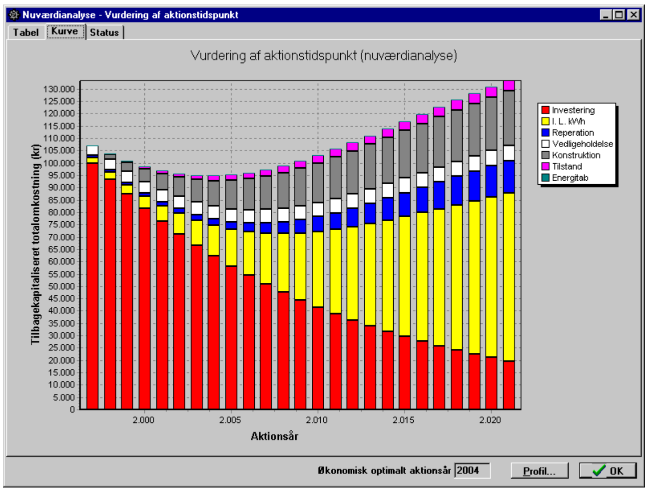

Figure 4 Results from the present value model presenting how the cost elements varies according to different possible replacement years. Optimal replacement year is calculated to be 2004.

CASE STUDIES

Simplified case network

The purpose of these case studies is not to give a comprehensive description on how to implement the proposed planning model, but rather to highlight important elements in the model.

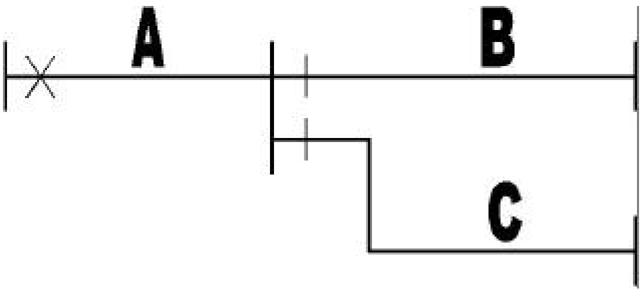

Figure 5 Single line diagram of the simplified case network

- *Section A* is commissioned in 1960, and comprises 10 km overhead lines, 7 pole-mounted substations and 3 kiosks. Peak load is 2 MW (1 MW industry).
- *Section B* is commissioned in 1960, and comprises 10 km overhead lines and 10 pole-mounted substations. Peak load is 1 MW.
- *Section C* is commissioned in 1970, and comprises 10 km overhead lines, 7 pole-mounted substations and 3 kiosks. Peak load is 2 MW (1 MW industry).

The actual age of sub-stations varies for all sections.

In addition, the following assumptions are made:

- Specific interruption cost is assumed to be 4 euro per kWh for commercial and 0,25 euro per kWh for domestic customers in case of unplanned interruptions, and 70% of these figures in case of planned interruptions.
- Costs of preventive, corrective and condition-based maintenance are according to average values in Norway.
- Failure rates are based on average values from Norwegian statistics.

Selected replacement strategies

This simple example network is used to evaluate and compare four, in principle, different replacement strategies with regard to life cycle costs.

Failure-based replacement (Planned corrective) - RS1
No preventive maintenance is carried out, and items are replaced only after a failure. By following RS1 one does not perform *any* of the steps in Figure 2. It *can* however be a well-founded strategy if non of the items are of any importance. In the calculations it is assumed that the items on average fail when they reach their expected technical lifetime. The present value of RS1 is estimated to be 2.029.000 euro.

Category-based replacement - RS2
Replacement is based on the predefined categories. Assuming the criteria for determining the categories are sufficient, there is no need for more detailed analysis, i.e. *Tech. and eco. analysis* in Figure 2 is not performed. The present value of RS2 is estimated to be 1.449.000 euro.

Condition-based replacement - RS3
Replacement is based on measured and estimated condition. RS3 includes all steps in Figure 2, including technical analysis of the *items in Category II and III*. The present value of RS3 is estimated to be 1.334.000 euro.

Economy-based replacement - RS4
Replacement is based on optimal economical lifetime calculated in VefoNet. The calculations are based on results from both technical and economical analysis of the *items in Category II and III*. The present value of RS4 is estimated to be 1.344.000 euro.

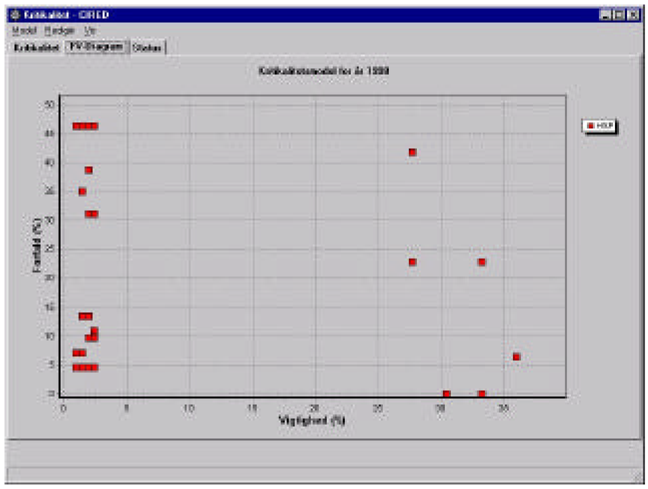

Figure 6 Results from the criticality model presenting each items relative technical condition and importance

The six dots to the right in Figure 6 represents the 6 kiosks in the network. The three upper ones are the most critical ones since they are old and supply industrial customers. Some of the pole-mounted substations are also critical due to age and wear.

Table 1 Summary of costs related to the selected strategies [1000 euro]

Cost elements	RS1	RS2	RS3	RS4
Investment cost	487	628	565	683
Prev. maint. cost	0	127	140	127
Corr. maint. cost	116	58	52	44
Interruption cost	1426	636	577	490
Total	**2029**	**1449**	**1334**	**1344**

The investment cost for RS1 is the lowest since all replacement is postponed as long as possible. Due to no preventive maintenance and therefore increasing failure rates, and only unplanned replacement, the corrective maintenance and interruption costs however, are very high. RS2, RS3 and RS4 include preventive maintenance and planned replacement that reduces the interruption cost. The increased preventive maintenance in RS3 result in a postponed replacement, and therefore a reduced investment cost.

Other important elements that should be included in a real analysis are:

- Replacement of the whole substation if either the transformer or the breakers must be replaced.
- Replacement of old substations if the line is replaced.
- Construction of new lines to reduce losses and as backup to reduce interruption costs.

TESTING OF THE VEFONET PROTOTYPE

The proposed planning model is developed to improve the planning process in large networks, and has therefore less relevance for a small network as in the previous case studies. The model is therefore also tested on one larger rural and one larger urban network. The Working Group has also used these two networks for the testing of VefoNet. Necessary technical data was imported from the network information system Netbas. Figure 7 presents an example from VefoNet.

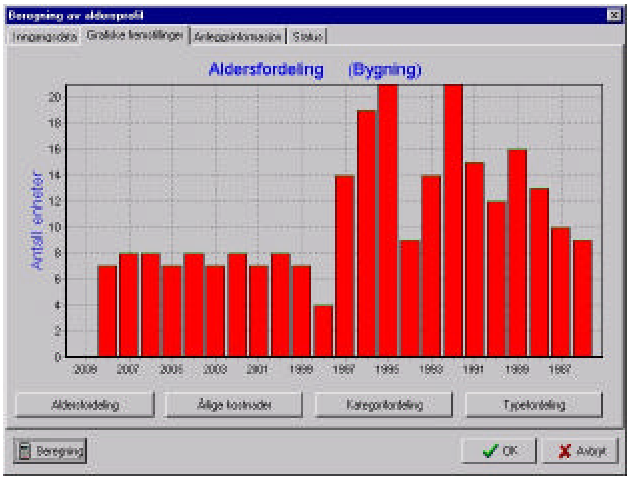

Figure 7 Results from the age profile model presenting the age profile after 10 years with the selected strategy

The most important conclusion from these tests is the necessity of a close integration between the NIS and the maintenance system to ensure available and updated information on all items.

WORK METHODS AND TECHNICAL SOLUTIONS

A replacement planning strategy should include predefined alternatives ('company standards') regarding work methods and technical solutions. The technical and economical analyses (Figure 2) are in general limited to these alternatives. In many cases, the planner may have only one main alternative to consider, e.g. the utility has decided that in certain areas earth cables should be used when overhead lines are replaced.

The use of hot-line work and mobile generator/cable are two important *work methods* in the case that the utility wants to avoid interruption during the replacement of components. Choice of work method is often also a question of safety of personnel.

Choice of *technical solution* is a question of component and system design. Covered conductors and gas-insulated switchgear are two examples regarding component design, while upgrading of the voltage level and modification of the network and switchgear configuration are matters of system design. It is very important to assess the system design in the replacement planning, and not only analyse like for like substitutions.

Simplification of the system design is in some cases the most profitable element in a replacement project. Considerable cost savings can be achieved if components should be removed on permanent basis instead of being replaced. Analyses have shown [2] that the total equipment and interruption costs can be reduced in cable networks with high reliability and complex configuration by disconnecting unnecessary redundant MV cables (N-2 connections) and leaving out the MV cable switches in some of the substations where the switchgear is replaced. The simpler solutions will reduce the interruption rate, and in some cases also reduce the total annual interruption time.

CONCLUSIONS

By following the strategy described in this paper the focus is on just the items most probable for replacement. Planning and replacement costs, but also total life cycle costs in the network, are reduced when the resources are focused on the potential most critical items.

The final results from systematic replacement planning based on the described strategy, or model, are well-founded and documented replacement plans. The documentation of costs and other consequences related to alternative replacement strategies is important decision support information.

Replacement of MV networks and MV/LV substations should not only be based on a like for like substitution. There can be considerable cost savings in changing the existing configuration and design, especially in complex cable networks with a large number of redundant cables and cable switchgear.

REFERENCES

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[2] Solvang, E. et al: Reliability and cost evaluation of MV distribution network and switchgear configurations in urban areas, CIRED'95.