RENEWAL PLANNING BASED ON ASSET HEALTH DATA USED IN COST-BENEFIT ANALYSES

Eivind SOLVANG
SINTEF Energy Research – Norway
Eivind.Solvang@sintef.no

Jørn FOROS
SINTEF Energy Research – Norway
Jorn.Foros@sintef.no

Lennart HEGGDAL
Istad Nett – Norway
Lennart.Heggdal@istad.no

ABSTRACT

The subject addressed is renewal planning of medium voltage (MV) distribution networks using asset health data as input to cost-benefit analyses of renewal alternatives. The paper presents results and experiences from the testing of a new method (REPLAN) for renewal planning. Two network companies have carried out extensive inspection and assessment of the technical condition of 11-22 kV overhead lines. The data acquisition includes taking pictures of components that are in poor technical condition. Cost-benefit analyses of relevant renewal alternatives are then performed based on the asset health of conductors, poles, cross arms, insulators, pole foundations and stay wires. Choosing the right alternative for renewal can result in great savings and a significant lifetime extension of overhead lines.

RENEWAL PLANNING CHALLENGES

The distribution network companies in Norway will experience an increasing need for renewal of the distribution network in the next decades. The renewal rate has been rather low in the last years, and together with an aging asset base, this may soon lead to an increased level of renewal. Hence, there is a need for methods and tools for efficiently identifying and evaluating appropriate renewal alternatives.

Component replacement can in some cases be a more economical alternative than complete replacement of the entire section of e.g. an overhead line. Similarly, it can be more economical to replace the entire substation than to carry out the renewal by replacing the components one by one. Replacing an overhead line with cable is an alternative that often should be evaluated.

The main challenges when analysing renewal needs in MV distribution networks are:

- The MV distribution network consists of many components spread over a large geographic area, which means that it is resource-demanding to carry out on-site condition monitoring and data acquisition
- Components are of very different age and design, which means that there are many variants to be analysed
- Renewal alternatives range from replacement of only single components (poles, insulators, etc.) to replacement of an entire overhead line or substation
- It is difficult to describe the condition of a component in such a way that the residual life and the failure probability can be estimated based on the information
- The calculation of total costs for failure, maintenance and replacement for each renewal alternative is demanding, and so requires simplifications to be done with reasonable use of resources

The REPLAN method is developed to meet these challenges.

INTRODUCTION TO REPLAN

REPLAN is a new method for automatic technical-economic analysis of renewal alternatives based on technical condition of power grid components. Relevant renewal alternatives are automatically identified, and the total cost of the alternatives calculated. This is based on condition assessments carried out through inspections, and then analysed by the REPLAN method. The method includes e.g. the following types of analysis:

- Analysis of component replacement
- Analysis of complete replacement of an installation

This paper deals primarily with component replacement analysis in 11-22 kV overhead lines. The method in REPLAN includes ten steps as shown in Figure 1. The first three steps (1-3) are manual in the sense that they are controlled by persons, but they may include the use of various tools. The remaining steps (4-10) are automatic and do not include user involvement. The results of the application of REPLAN are made available to decision makers in the last step (10). All steps are explained in more detail in the following, except step 3, which is selection of some calculation parameters by the user.

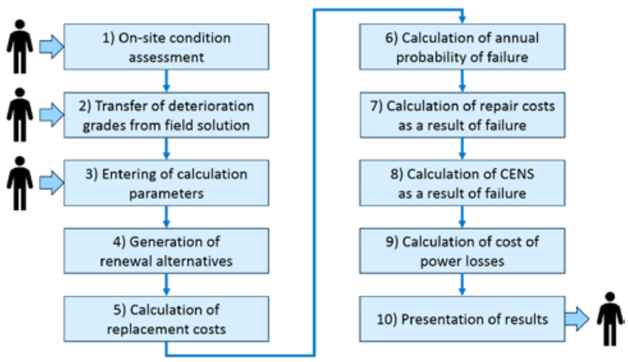

Figure 1: Steps in the REPLAN method

A low user threshold has been an important goal in the development of the REPLAN method. This is achieved e.g. by linking condition criteria to the expected residual life of components, and by using a selection of predefined renewal alternatives in the analyses. Thus, the analysis of relevant renewal alternatives can take place automatically upon a very limited number of user inputs. The overall goal of the development of the method has been to provide simplifications that enable asset health assessment and cost-benefit analysis of renewal alternatives with sufficient quality and reasonable use of time. The usefulness of the method is illustrated through real-life testing, showing that there is a significant potential to postpone renewal when this can be documented to have a tolerable risk level based on technical condition assessment and cost benefit analyses of renewal alternatives. The method, models, tool and three cases are described in more detail in [1]. The tool is Excel-based.

CONDITION ASSESSMENT (STEP 1-2)

Deterioration grades

The REPLAN method starts by assessing the condition of the components in question. The condition assessment determines a deterioration grade (DG) according to condition models for all components. For overhead lines, condition models exist for pole, stay wire, pole foundation, cross arm, insulator and conductor attachment.

In general, the deterioration grades are specified according to Table 1. Here, the condition criteria have for ease-of-use been linked to a time for replacement. This simplification should work well for components of relatively similar expected lifetimes and with relatively similar aging speed. The latest time for replacement is the expected year at which replacement at the latest can be done while keeping the probability for failure at a tolerable level. A tolerable level is user specific and may be e.g. a 10% probability of failure before replacement (see the failure probability model below). In the REPLAN method, all failures are events that lead to power outage.

Table 1: Deterioration grades (DG)

DG=1	No sign of deterioration
DG=2	Some sign of deterioration, but replacement is not expected to be necessary within the renewal period of analysis (20 years)
DG=3	Extensive signs of deterioration. Replacement is relevant in year 6 and is expected to be necessary at the latest in year 11
DG=4	Critical condition. Replacement is relevant in year 1 and is expected to be necessary at the latest in year 6
DG=5	The component cannot carry out its required function (i.e., it is in a state of fault). Replacement must be done in year 1

All components have several failure causes and failure modes. These depend on the component type and possibly also other factors such as component brand, design, environment factors, etc. Some examples of failure causes/modes are rot, corrosion and partial discharges. The deterioration grade should be assessed for each failure mode for each component, and then aggregated to an overall level (e.g. conservatively taking the worst grade as the overall grade).

To aid the condition grading when components are inspected, some condition criteria more specific than those in Table 1 have been established per component. This is based on the handbooks from Energy Norway [2], as well as pictures of relevant conditions collected from distribution network companies in Norway. This is ongoing work for both overhead lines and MV/LV substations and will be further developed. In the project, a number of pictures have been collected showing the extent of deterioration to components. Deterioration grades have been evaluated for the component and failure cause/mode shown in each of these pictures, such that these pictures can be used as condition criteria. Currently, these images are stored in a file structure that will eventually be transferred to a database that should become available as part of the REPLAN method.

Figure 2 shows an example of an image showing rot in a pole that has been assessed as DG=4. Of course, such an assessment should be based on more observations than what the picture can convey (i.e., the internal condition of the pole).

Figure 2: Rot in a pole (DG=4)

Condition assessment tools

Good tools for use in the field are important for the quality of the condition assessment. For example, the residual strength of poles with rot, woodpecker holes and/or other damage is difficult to assess. Some tools exist today, but further improvement is needed. Images and videos from inspection of overhead lines using helicopters and drones are useful. There is currently promising development of machine learning algorithms for automatic identification of damage to overhead lines based on images and video.

Data acquisition

Data acquisition for condition assessment happens through inspections. Registration of observations should be as simple as possible, e.g. through a portable device connected to the system containing grid and component data. This way all relevant grid and component data is available for the inspector, and all observations can be uploaded to the system for further evaluation and analysis.

RENEWAL ALTERNATIVES (STEP 4)

Relevant renewal alternatives are identified based on the above condition assessment. For components with DG=1 or DG=2, replacement is not relevant. For components with DG=3, DG=4 or DG=5, the points in time at which replacement is relevant are shown in Figure 3. This is replacement in the present year (denoted R1), replacement in year 6 from now (R6), replacement in year 11 (R11) or replacement in year 16 (R16). The period of analysis for the REPLAN method is 20 years, meaning that replacement later than this is not considered.

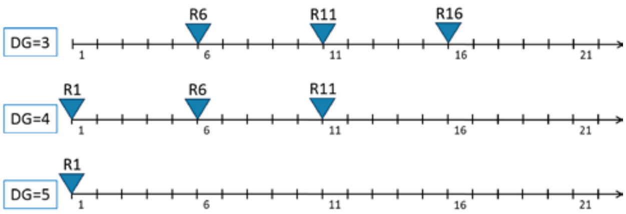

Figure 3: Points in time at which replacement is relevant, depending on the deterioration grade

For the alternatives R16 for DG=3 and R11 for DG=4, the probability for failure before replacement is expected to become higher than acceptable. These alternatives are still included in order to assess the cost of such high-risk alternatives.

The above alternatives apply to each of the components in an installation. For an installation (e.g. overhead line or substation), these must be combined to arrive at renewal alternatives covering all components. The current version of the REPLAN method includes the following renewal alternatives for installations:

Alt. 1 DG=5 (R1), DG=4 (R1), DG=3 (R1)
Alt. 2 DG=5 (R1), DG=4 (R1), DG=3 (R6)
Alt. 3 DG=5 (R1), DG=4 (R1), DG=3 (R11)
Alt. 4 DG=5 (R1), DG=4 (R6), DG=3 (R6)
Alt. 5 DG=5 (R1), DG=4 (R6), DG=3 (R11)
Alt. 6 DG=5 (R1), DG=4 (R11), DG=3 (R16)
Alt. 7 DG=5 (R1), DG=4 (R1)
Alt. 8 DG=5 (R1), DG=4 (R6)
Alt. 9 DG=5 (R1), complete replacement (R6)
Alt. 10 Complete replacement (R1)

The alternatives should be understood as follows. For example, alternative 1 means that all components with DG=5, DG=4 and DG=3 are replaced in year 1. Alternative 9 and 10 means complete replacement of the whole installation. The alternatives represent both early replacement, replacement according to the condition criteria and late replacement. Based on this, the decision maker can assess profitability against current risk.

Finally, the replacement time for components are adjusted if it is beneficial to replace some components simultaneously, even though their conditions may differ. Specifically, for overhead lines, this means the following:

- The pole foundation and stay wire are replaced if the pole is replaced
- The insulator and conductor attachment are replaced if the cross arm is replaced
- The conductor attachment is replaced if the insulator is replaced.

FAILURE AND COST MODEL (STEP 5-9)

To enable cost-benefit analysis of relevant renewal alternatives, a failure model is introduced per component. This model enables calculation of failure probability as a function of component condition, which is input to cost calculations. The failure model includes:

- Probability distributions for calculating annual probability of failure. The parameters of the probability distributions are governed by the component deterioration grade, as well as external stresses to the component.
- Outage times due to failure. The outage times are specified per component type and are dependent on the component's location in the network.

Figure 4 shows an example of a probability distribution, in this case for a component that has been evaluated to have DG=3. The distribution is generated from two parameters: The mean residual life and the 10-percentile. The mean residual life for this distribution is 20 years. The 10-percentile, i.e. the period in which the failure probability sums up to 10%, is 10 years.

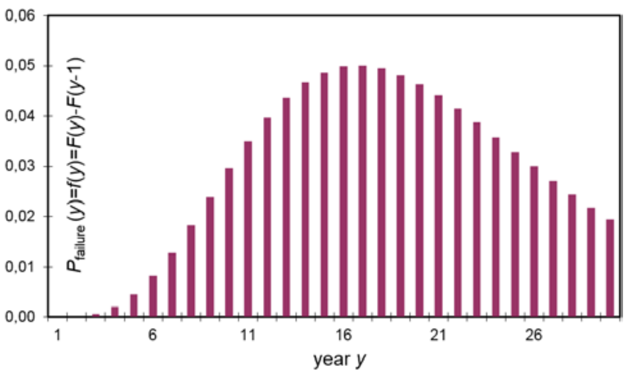

Figure 4: Example of probability distribution, in this case for a component that has been evaluated to have DG=3

The corresponding cumulative probability distribution is shown in Figure 5. Note that as Figure 4 shows, this failure model assumes zero failure probability at time zero, even if the component is in poor condition already at this time. However, the probability of failure is not equal to zero in the first year even though it is very small for this distribution. The distribution represents the annual probability of failure from the time the condition assessment was made.

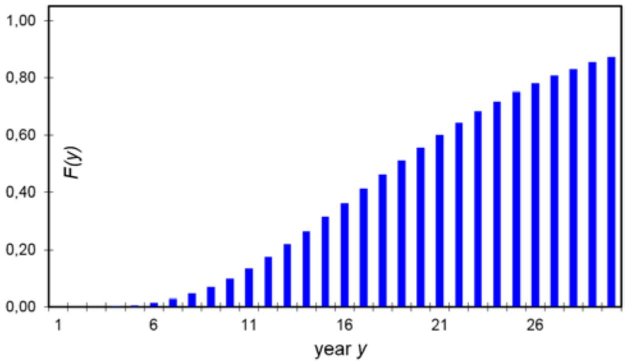

Figure 5: The cumulative version of the probability distribution shown in Figure 4

After replacing a component, the deterioration grade is set to DG=1, and the probability distribution is updated. This enables proper calculation of the failure probability and failure cost both before and after replacement is carried out.

The failure model is the basis for calculating the cost of energy not supplied (CENS) in the cost-benefit analysis. In addition, cost of repair after failure, costs of power losses and the costs of replacement are included in the cost model. All costs are calculated for a 20-year period of analysis. This is illustrated in the case study in the next section.

For the cost calculations, also outage times due to failure is needed, and these depend on the network in question. Suggested outage times per component type are shown in Table 2 for the three cases/networks to be discussed in the next section. The long outage times for case 2 are due to extra travel time because the overhead line is on an island without a bridge connection.

Table 2: Outage times (in hours) per component type due to failure for the three cases to be discussed in the next section

	Case 1 and 3	Case 2
Pole	3.0	7.0
Pole foundation	2.0	6.0
Stay wire	1.0	5.0
Cross arm	2.5	6.5
Insulator	2.0	6.0
Conductor attachment	1.0	5.0

CASE STUDY

On-site condition assessment

The case study has included on-site condition assessment and technical-economic analysis of the following three MV overhead lines:

- Case 1: 136 pylons with wood poles along a 10.4 km 11 kV overhead line built in 1954 and 1955. Peak load is 170 kW.
- Case 2: 41 pylons with wood poles along a 4.2 km 22 kV overhead line built in 1953. Peak load is 150 kW.
- Case 3: 92 pylons with wood poles along a 5.6 km 11 kV overhead line built in 1949, 1963 and 1975. Peak load is 300 kW.

Table 3 shows the results from the on-site condition assessment for poles and cross arms with degradation grade (DG) equal to 3, 4 and 5.

Table 3: Number of poles and cross arms with DG=3, 4 and 5

	Poles			Cross arms		
DG =	3	4	5	3	4	5
Case 1	61	8	0	3	9	0
Case 2	1	0	0	16	16	0
Case 3	11	0	1	31	30	8

The experiences of both companies that carried out the on-site condition assessment were positive. Smartphone registration was easier than using paper, especially in bad weather. The work was done by teams of two people. It was important that the crew could switch between inspection and other tasks in order to avoid the work becoming monotonous. The quality of the condition assessment improved when both people on the team were experienced. The discussion then became more valuable.

It was advantageous to use an all-terrain vehicle (ATV) since one had to carry some equipment, including for climbing the wood poles. Good training and exchange of experience between teams was important. The criteria for the condition assessment were generally understandable. Most difficult was the assessment of interior rot in the wood poles. It was important to limit the climbing to poles where you could see potential damage to cross arms and insulators from the ground.

Summary of results for case 3

Figure 6 shows the summary of the results of the on-site condition assessment and the cost calculation for case 3. The figure is an excerpt from the main screen picture of the Excel-based tool in REPLAN. Corresponding summaries are not included for case 1 and case 2 for space reasons. The results of the on-site condition assessment include all components and not just poles and cross arms as in Table 3.

Total costs are calculated for the ten predefined renewal alternatives. All amounts (NOK) are current values. The column labeled "PM" includes on-site condition assessment during the period of analysis. The cost of scheduled replacement is divided into "R1", "R6", "R11" and "R16". "CENSn" is the cost of notified interruptions related to scheduled replacement. In this analysis it is assumed that the replacement will be carried out without interruption (CENSn = 0 NOK). "Repair" is the cost of repair after failure. "CENS" is the cost of energy not supplied due to failure. "Power losses" is costs of power losses. The rightmost column shows the percentage value of the total cost where the total cost for the alternative with the lowest total cost is set to 100%.

CENS is calculated according to [3]. The regulation is in Norwegian, but [4] gives a description of the calculation methodology in English.

Best renewal alternative

Alt. 5 and alt. 8 have the lowest total cost. It is not profitable with even earlier replacement due to relatively low CENS due to failure. This is also the reason why the total cost for alt. 8 is only 2% higher than for alt. 5, although no components with DG=3 in alt. 8 are replaced during the period of analysis. Alt. 5 is best since alt. 8 results in significantly higher probability of failure. Low CENS is due to the overhead line supplying households and the peak load is only 300 kW. Alt. 9 and alt. 10 with larger cross-section reduce the losses in peak load by 0.6 kW. This is not enough for complete renewal to be profitable.

CONCLUSIONS

The testing shows that systematic technical-economic analysis of renewal alternatives can be automated when the condition assessment is based on criteria for technical condition related to predefined residual lives and associated renewal times. Automation here means the minimum use of time to carry out the actual analysis. The technical-economic analysis of predefined renewal alternatives shows that there can be large cost differences between different renewal alternatives. Choosing the right alternative can therefore result in great savings. The analysis shows that condition-based replacement of individual components can provide a significant lifetime extension to the main components and the overhead line as a whole.

REFERENCES

[1] E. Solvang, J. Foros, 2018, "*Renewal planning of MV distribution networks*" (in Norwegian), SINTEF Energy Research, 2018:01350.

[2] Energy Norway, 2013, "*Handbooks for condition monitoring: Overhead lines, XLPE cables, Mass impregnated cables*" (in Norwegian), Publication no. 358-2013.

[3] NVE, *Regulations governing financial and technical reporting, income caps for network operations and transmission tariffs* (in Norwegians), www.nve.no.

[4] G. Kjølle, H. M. Vefsnmo, 2015, "Customer interruption costs in quality of supply regulation: methods for cost estimation and data challenges", *Proceedings CIRED Conference, Lyon, 2015.*

Project	Renewal of 22 kV overhead line (Case 3)
First year in the period of analysis (20 yr)	2020
Discount rate (% p.a.)	4,5

Results from the on-site condition assessment (number of)

	Poles	Pole foundat.	Stay wires	Cross arms	Insu-lators	Conduc. attachm.	Con-ductors	Earth wires
DG=5	1	2	0	8	4	3	0	0
DG=4	0	3	0	30	1	1	0	0
DG=3	11	0	2	31	0	0	0	0
DG=2	66	3	2	2	1	0	1	0
DG=1	14	84	18	21	86	88	91	0
No DG	0	0	0	0	0	0	0	0
Sum	92	92	22	92	92	92	92	0

	Number of
E-pylon in soil	25
E-pylon on rock ground	44
H-pylon in soil	12
H-pylon on rock ground	11
Dual A-pylon in soil	0
Dual A-pylon on rock ground	0
Length of overhead line (km)	5,6
Length of earth cable (km)	0,0

Costs, present values (NOK)		Preventive maintenance (PM) / replacements (R)						Failures		Power	Total	
		PM	R1	R6	R11	R16	CENSn	Repair	CENS	losses	cost	%
Alt. 1	DG=5 (R1), DG=4 (R1), DG=3 (R1)	14 681	1 022 143	0	0	0	0	85 308	32 363	172 514	1 327 010	132
Alt. 2	DG=5 (R1), DG=4 (R1), DG=3 (R6)	17 507	521 358	338 157	0	0	0	86 586	32 771	172 514	1 168 892	116
Alt. 3	DG=5 (R1), DG=4 (R1), DG=3 (R11)	20 878	521 358	0	199 929	0	0	126 307	51 651	172 514	1 092 636	108
Alt. 4	DG=5 (R1), DG=4 (R6), DG=3 (R6)	17 507	133 335	591 344	0	0	0	118 454	50 263	172 514	1 083 417	108
Alt. 5	DG=5 (R1), DG=4 (R6), DG=3 (R11)	20 878	133 335	253 103	199 929	0	0	158 175	69 143	172 514	1 007 077	100
Alt. 6	DG=5 (R1), DG=4 (R11), DG=3 (R16)	20 878	133 335	0	149 643	61 555	0	364 324	177 343	172 514	1 079 591	107
Alt. 7	DG=5 (R1), DG=4 (R1)	20 878	521 358	0	0	0	0	273 934	122 070	172 514	1 110 752	110
Alt. 8	DG=5 (R1), DG=4 (R6)	20 878	133 335	253 103	0	0	0	305 802	139 562	172 514	1 025 193	102
Alt. 9	DG=5 (R1), complete replacement (R6)	0	133 335	1 756 399	0	0	0	40 508	21 984	165 824	2 118 050	210
Alt. 10	Complete replacement (R1)	0	2 651 106	0	0	0	0	15 054	7 398	162 656	2 836 213	282

Figure 6: Summary of results from the on-site condition assessment and the cost calculation