1 KV LOW VOLTAGE SYSTEM AS A PART OF A DISTRIBUTION NETWORK REINVESTMENT STRATEGY

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ABSTRACT

As the importance of reliable and secure electricity distribution is increasing, many utilities have made strategic decisions to develop their network on the basis of reliability. However, the cost efficiency of the solutions should not be forgotten. In cost optimisation the reliability of the system can be taken into account by including outage costs as one input parameter into the planning calculations. This enables determining long-term cost effective reinvestment strategies that also have remarkable impact to the reliability of the network.

The focus of this paper is the challenges in evaluating and selecting distribution network reinvestment strategies based on the application of different network techniques. Common to the considered reinvestment strategies is the utilisation of the 1 kV low voltage (LV) system and so one of the main objectives in this paper is to illustrate how the 1 kV system is dealt in the strategic network planning. On this basis the effects of large-scale utilization of the 1 kV system to the structure and costs of distribution system are analysed. One approach is obtaining the changes in the network arrangements due to the application of the 1 kV system.

Presented conclusions are based on actual network reinvestment strategy studies. The studied network consists of 1000 km of medium voltage (MV) and 2100 km of low voltage (LV) lines and is a part of the network of a Finnish distribution company Suur-Savon Sähkö Ltd. (SSS Ltd.)

INTRODUCTION

The age-structure of distribution networks and the increasing demands for better power quality are a real challenge in network development. For the development of the reliability of electricity distribution, especially in rural areas, the MV-network has a major role. However, as major part of the total system is LV-lines, it is reasonable to consider also the LV-network in the strategic planning.

The application of the 1 kV low voltage network in electricity distribution has been studied and results have already been reported in various publications [1]. The application of the 1 kV LV level between the medium voltage and the 0.4 kV LV-network increases the reliability of distribution as it increases the number of protection areas in the network. The 1 kV solution also has lower investment costs than the 20 kV solution both in overhead (OH) line and underground cable (UGC) networks. In its present form, the 1 kV distribution system is ready for large-scale use.

The techno-economic lifetimes of primary components are long and the networks built today will still be in use after several decades. Long lifetimes emphasize the importance of long-term network planning. The development plan provides basis and background information, main principles and initial data for detailed network planning.

PRINCIPLES OF STRATEGIC PLANNING

In the long-term development planning, the target is to define the guidelines for the development of the network during the planning period, that is, what large and far-reaching investments are required in different years in order for the network to comply with the set requirements during the entire planning period. The network planning tasks are based on the optimisation where investment costs, operational costs (maintenance, repairing and losses) and outage costs are taken into account over the lifetime as presented by (1) [2].

$$C_{tot} = \int_0^T \left(C_{capex}(t) + C_{opex}(t) + C_{out}(t) \right) dt \qquad (1)$$

in which

C_{tot} = Total costs
C_{capex} = Capital costs
C_{opex} = Operational costs (losses, maintenance, etc)
C_{out} = Outage costs
T = Life-time of network

The objective is total cost minimization in long run without violating the technical conditions of the planning assignment. Typical boundaries come from voltage drop limits, fault currents and electrical safety regulations. In network planning, not only the construction and loss costs, but also the outage costs have to be financially measurable. The expected value of outage costs plays a significant role in the profitability analysis of network cabling, backup connections, and automation level.

The 1 kV system

To achieve the maximum benefit from the utilization of the 1 kV system the MV level and both LV levels (1 kV and 0.4 kV) have to be calculated together [1]. However, in the evaluation of long-term investment strategies the 1 kV system can be calculated as a part of the MV-network. The economical range of application of the 1 kV system as replacement of a MV-line can be determined as a function of costs, transmission power, -distance and transmission capacity of the 1 kV system. A 1 kV line is economical option as long as its total costs are smaller than the total costs of the MV line to be replaced, as represented by (2), and when the technical limits are satisfied.

$$c_{\mathrm{MV}} \cdot x + C_{\mathrm{T1}} + c_{\mathrm{LV2}} \cdot y \geq C_{\mathrm{T1'}} + c_{\mathrm{LV1}} \cdot x' + C_{\mathrm{T2}} + c_{\mathrm{LV2}} \cdot y' \quad (2)$$

in which

c_{MV} = total costs/km of MV line
c_{LV1} = total costs/km of 1 kV LV line
c_{LV2} = total costs/km of 0.4 kV LV line
C_{T1} = total costs of MV/0.4 kV substations
$C_{\mathrm{T1'}}$ = total costs of MV/1 kV substations
C_{T2} = total costs of 1/0.4 kV substations
x = length of MV line
x' = length of 1 kV line
y = length of 0.4 kV network in MV/0.4 kV system
y' = length of 0.4 kV network in MV/1/0.4 kV system

The equation (2) can be simplified to represent the minimum economical length of a 1 kV line as a replacement of a MV-line. An example of the economical application range of the 1 kV system is presented in figure 1.

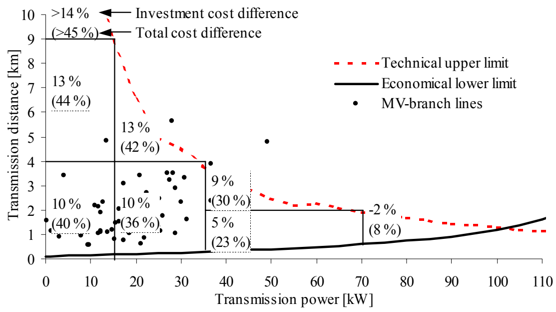

Figure 1. The economical application range of a 1 kV aerial bundled cable and investment and total cost difference compared to a 20 kV overhead line on a rural MV-feeder. The dots in the figure represent the branch lines of the feeder.

Analysing economical application ranges in different conditions has enabled determination of simplified guidelines for categorising the branch lines of the MV-network to the possible 1 kV targets and other branch lines. The 1 kV system is an economical replacement of MV-branch lines of which power and length is less than 50 kW and 3 km or 30 kW and 5 km. If the strategic analysis result that the 1 kV system is worth consideration, it can be taken into account in the detailed planning.

The structure of the network under renewal studies affects to the number and economical impact of the 1 kV system. As the figure 1 show the cost benefit of the 1 kV system increase along with transmission distance. Although the network has a lot of possible 1 kV targets according to the guidelines, the economical impact can be small if the branches replaceable with the 1 kV are mainly very short. However, the economical benefit of the 1 kV system can increase after utilization other technical solutions to the network.

The core principle in detailed designing of the MV/1/0.4 kV network is to minimize the length of the required MV-network within the technical boundary conditions and to find a balanced techno-economic solution between the line lengths of the 1 kV and 0.4 kV networks in each 1/0.4 kV transforming district. The main optimisation tasks are locating the MV/1 kV substations and determination of the most profitable number and locations of 1/0.4 kV substations. Constructing long 0.4 kV networks reduces the transmission capacity and economical benefit of the 1 kV system. Thus, finding local optimum separately for each voltage level on the traditional way does not lead to the optimum of the whole MV/1/0.4 kV system [1].

CASE STUDY OF STRATEGIC PLANNING

The studied area is in the network of the Finnish distribution company Suur-Savon Sähkö Ltd. The network consists of seven 110/20 kV primary substations and supplies 165 GWh energy to approximately 14 000 customers. The structure of the MV-network is mostly radial and 70 % of the lines are located to forests. Only interconnections between primary substations and few long feeders have backup connections. The studied network is a good representative of an average rural area network of SSS Ltd. and large enough to estimate overall effects of implementing the strategies in company-wide. Key figures of the network are presented in Table 1.

Table 1. Key figures of the study area.

	LV-network (2 114 km)	MV-network (988 km)
Overhead lines	1.60 %	95.60 %
Underground cables	14.50 %	2.60 %
Aerial cables/ABC lines	82.00 %	0.40 %
Underwater cable	2.00 %	-
Covered conductor lines	-	1.40 %

Medium voltage network is divided to three parts in order to find effects of different investment strategies to the reliability. About 40 % of the MV-lines are so called main or interconnection lines between primary substations or other feeders. 29 % of the MV-lines are low-loaded branches (<50 kW) replaceable with the 1 kV technique and the rest are high-loaded (>50 kW) branch lines.

Parameters

In this study, investments costs of different strategies based on the component cost list of the Finnish electricity market authority. The capital costs are divided into MV and LV investment costs and to financial costs. Financial costs are due to the cost of capital needed for the network investments and depict the paid interest. The financial costs are based on the yearly net present value of the network. Operational costs include the costs of losses, maintenance and fault repairing. Outage costs are formed using outage cost parameters for different electricity consumer groups and interruptions (Table 2). The study period (*T*) is 40 years and the interest rate (*p*) is 5 %. Load growth is not taken into account ($r = 0$ %). The costs of network losses are 35 €/MWh.

Table 2. Unit costs for power quality factors [2].

Customer group and energy shares		Unplanned interruption		Planned interruption		Auto-reclosures	
						High-speed	Delayed
		[€/kW]	[€/kWh]	[€/kW]	[€/kWh]	[€/kW]	[€/kW]
Residential	51 %	0.36	4.29	0.19	2.21	0.11	0.48
Agriculture	10 %	0.45	9.38	0.23	4.8	0.20	0.62
Industry	11 %	3.52	24.45	1.38	11.47	2.19	2.87
Public	10 %	1.89	15.08	1.33	7.35	1.49	2.34
Service	18 %	2.65	29.89	0.22	22.82	1.31	2.44

Evaluation of investment strategies

The common factor to the network reinvestment strategies presented, is the large-scale utilisation of the 1 kV technique. The considered network development strategies for network renewal are:

1) Reconstruction of existing network with old techniques and line routes, no changes in LV-network (ABC-lines)
2) Moving MV lines next to roads and 1 kV at branches, no changes in 0.4 kV LV-network (ABC-lines)
3) Moving MV lines next to roads and 1 kV at branches. UGC LV-network in conditions suitable for cable ploughing, rest ABC lines
4) Totally underground cabled network: MV-lines underground cabled next to roads to dug cable ditches, 1 kV at branches. LV-UGC ploughed where possible rest installed by digging. 85 % of distribution substations are pad-mounted satellite substations and the rest typical pad-mounted cabin substations.

Covered conductor (CC) OH-lines are only applied if the economical benefit achieved in outage costs is high enough to pay back the CC-line's higher investment costs compared to typical OH-line. Figure 2 illustrates an example of the changes on a medium voltage feeder in strategy 3) and 4). The figure shows the effect to the network topology of both the 1 kV system and moving lines next to roads.

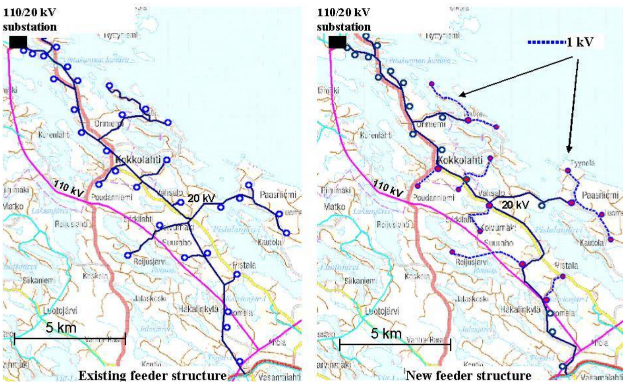

Figure 2. Cost optimisation based changes on a medium voltage feeder after rerouting and application of the 1 kV system.

According to the geological survey approximately 80 % of the LV cables can be ploughed at the study area. At current price level in Finland the ploughed UGC brings average 50 % lower investment costs than utilization of same cross section ABC lines and even 70 % lower investment costs than installing the cable to ordinary dug cable ditch. Moving the MV-lines beside the roads does not affect to the length of the network at the study area. Numerous customers (loads) are located near today's roads but the MV lines go mainly through the forests. Moving the lines next to the roads increases the length of main lines but also reduces the number of branches, decreases the number of faults and eases the maintenance work. Exact improvement of reliability depends on the area, but according company-specific statistics, improvement has been round 40-50 %.

The total costs of the development strategies are presented in figure 3. In this figure the costs are yearly-based costs discounted over the study period in the case that the networks corresponding each strategy are complete already at the beginning of the study period and require only replacement investments (static state). The figure 4 shows the discounted yearly-based total costs over the study period in the case that the reconstruction of the network towards each strategy is started at the beginning of study period and finalised during the last year of the study period. This analysis takes account that the transition from present network to the target network does not happen immediately. For instance if the full-scale UG-cable network is the target, the full benefit of reliability improvement can be achieved only after the network is fully rebuilt from present network to UG-cable network.

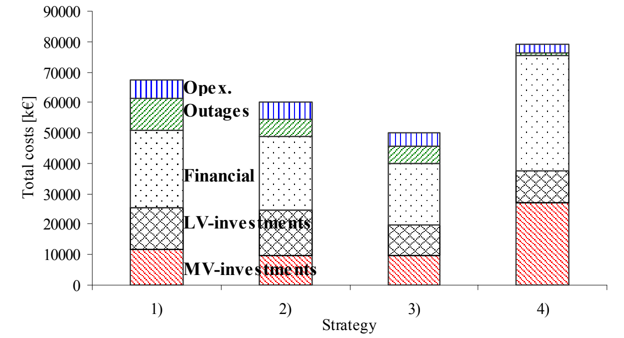

Figure 4. Total costs of considered reinvestment strategies over the study period.

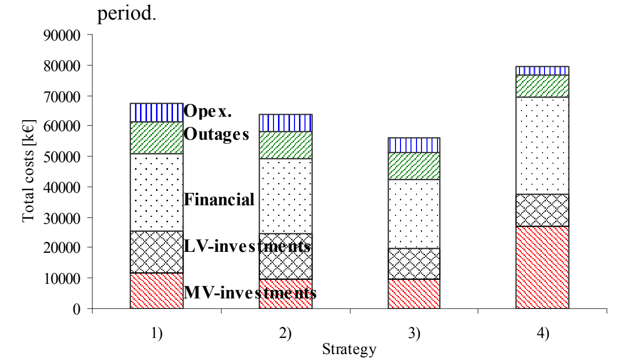

Figure 4. Total costs of considered reinvestment strategies over the time, during which the network is reconstructed (the first 40 years).

Comparison of the development strategies is presented in table 3. In the table the values of MV- and 1 kV networks are proportioned to the sum their lengths 997 km.

Table 3. Comparison of the development strategies.

Line type / parameter	1)	2)	3)	4)
Proportion of OH-lines	94.7 %	65.8%	65.8 %	0 %
Proportion of CC-lines	1.4 %	1.4 %	1.4 %	0 %
Proportion of MV UGC	2.9 %	2.9 %	2.7 %	70.1 %
Proportion of 1 kV	1 %	29.9 %	29.9 %	29.9 %
Amount of LV UGC	14.6 %	22.8 %	82.6 %	100 %
SAIFI [1/a]	1.69	0.61	0.61	0.25
Max. outage time/a [h/a]	10.6	7.5	7.5	7
Replacement value [M€]*	59	57	46	88
Yearly outage costs [k€/a]	611	323	323	60

*Sum of the product of component prices and number of components

The impact of the 1 kV system can be seen at the capital costs and outage costs. At development strategy 2), in which the only change in the LV-network is the addition of the 1 kV system, the sum of MV and LV investment costs are 4 % lower than in strategy 1). In strategy 3) the capital costs of the network are reduced even more due to the cost savings achieved with ploughed LV-underground cables. The total cost optimum is reached in strategy 3). The UGC-strategy 4) is not a cost effective solution at the area even if it is combined with the 1 kV technique. The capital costs of the UGC-strategy are about 1,5 times as high as in the present network and nearly 2 times higher than in the optimal development strategy 3).

The lowest operational and outage costs are in the UGC-alternative. Due to the higher transmission capacity and lesser need for maintenance the operational costs of the UGC-network are lower than in the OH-line network. Although the 1 kV system increases the losses at the branches it has been used, the losses of the development strategies 2), 3) and 4) are smaller or equal compared to the existing network. This is due to the replacement of the old small cross section MV with modern line types. The differences in operational costs are so small that other cost components (capital and outage costs) are in dominant role when final strategy is chosen.

An important incentive and boundary to this investment strategy analysis has been the need for more reliable distribution system compared to present one. The differences in outage costs of UGC- and OH-line strategies are remarkable. Eventually the outage costs in the UGC-network are about 10 times lower than in the present network. In the cost optimum strategy 3) the outage costs in complete network are about 40 % lower than in the present network. However, if the capability to survive any major disturbance is a prime criterion, a full-scale underground cabling in both low and medium voltage networks is only workable method. In this case the role of the 1 kV system is to cut down the capital costs.

Results of the detailed planing of the 1 kV system

In the strategic part of the planning it was assumed that the length of the network remains the same than in present network although the low loaded MV-branch lines were replaced with 1 kV. According to the results of the detailed planning of several 1 kV transforming districts on a feeder the length of 0.4 kV network reduced average 24 % and the total length of lines at the transforming districts reduced average 5 %. The application of the 1 kV system leads typically to a complete rerouting of the lines. In some cases the optimum is reached by combining the customers of two near by low loaded MV-branch line to one large 1 kV district. As a conclusion it is evident that the assumptions made for the strategic planning do not at least lead into too optimistic situation. In overall, from the level of the strategic planning, the amount of targets and cost savings achieved with the 1 kV system are likely to increase during the detailed design work.

CONCLUSIONS

As the importance of long-term strategic planning increases, methods to include new technical solutions to the profitability analyses are needed. The cost optimum solution is reached by investing in technologies that are cost effective compared to the traditional solutions. At the same time, the effects on reliability can be remarkable.

In strategic network analysis the 1 kV system can be taken into account by mapping out the MV-branch lines replaceable with the 1 kV lines and assuming that the total length of the network does not change. The 1 kV system is an effective tool for improving the reliability and decreasing the capital costs of the distribution system. The detailed designs have revealed that the assumptions made for the strategic planning do not lead into too optimistic results, but just the opposite. However the presented method of mapping out the 1 kV targets is able to give accurate enough results for further conclusions during strategic planning and decision-making. The amount of the 1 kV targets and so achieved cost savings are likely to increase during the detailed network design from the results of the strategic network planning.

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