A COMPARISON OF THE ELECTRICITY DISTRIBUTION INVESTMENT STRATEGIES

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ABSTRACT

The long-term development of the distribution networks and investment strategies is topical all over the world. Network owners and operators are facing the challenge of aging infrastructure and a need for massive reinvestments. Expectations for better reliability regardless of the state of operating (normal situation or a major event) have increased. From a business point of view, there are incentives for investments, by which the total network costs (investment costs, operational costs, and outage costs) can be minimized in the long run. Especially the role of outage costs has gained more weight on investment decisions than before. Different investments have different effects on distribution reliability. The new solutions such as low-cost primary substations, roadside building of networks, 1000 V network technology, pole-mounted switchgears etc. provide a variety of methods to increase reliability rapidly and by low costs. Nevertheless, full-scale underground cabling is only way to be prepared for major events (big storms). In this paper, different reinvestment strategies in rural area are studied.

INTRODUCTION

Key questions in distribution investment analysis are: in which way distribution networks should be renovated and what kind of strategies should be chosen? There is always the option to continue with the traditional technologies and practices as has been done up to the present; however, this way, the requirement for more reliable networks with lower expenses will not be met. There are several new and promising technologies available for distribution networks; these technologies are a part of strategy analysis carried out in co-operation with Finnish technical universities, network companies, and the Ministry of Trade and Industry. The aim of the research work was to find out how the electricity distribution reliability could be improved by different technologies and development strategies and what the benefits and costs (cent/kWh) would be for the end-customer.

The importance of continuous electricity distribution is growing in the modern society. Hence, the outage costs will have an increasing and more central role in the strategy analysis [1]. Traditional solutions are not reliable enough to meet the new requirements. In the survey, different strategies, such as removing lines from forest to roadsides, the implementation of 1000 V low voltage technology, underground cabling, network automation, and low-cost primary substations were analyzed. By long-term cost optimization, the optimal network development strategy can be found.

BACKGROUND AND CALCULATION

Techno-economical analyses are based on the optimization where investment costs, operational costs (maintenance, repairing and losses) and outage costs are taken into account as presented by Eq. (1). [2].

$$C_{\mathrm{tot}} = \int_{0}^{T} \left(C_{\mathrm{capex}}(t) + C_{opex}(t) + C_{\mathrm{outage}}(t) \right) dt \qquad (1)$$

Where

C_{tot} = Total costs
C_{capex} = Capital costs
C_{opex} = Operational costs (e.g. losses, maintenance)
C_{outage} = Outage costs
T = Life-time of network

Outage costs are defined by unit costs for power quality factors for different customer groups presented in Table 1 (CENS values).

Table 1. Unit costs for power quality factors for customer groups of DSO's in Finland. [3], [4]

Customer group and shares in Finland		**Unplanned interruption**		**Planned interruption**		**Auto-reclosings High-speed**	**Auto-reclosings Delayed**
		[€/kW]	[€/kWh]	[€/kW]	[€/kWh]	[€/kW]	[€/kW]
Residential	43 %	0.36	4.29	0.19	2.21	0.11	0.48
Agriculture	7 %	0.45	9.38	0.23	4.8	0.20	0.62
Industry	17 %	3.52	24.45	1.38	11.47	2.19	2.87
Public	12 %	1.89	15.08	1.33	7.35	1.49	2.34
Service	21 %	2.65	29.89	0.22	22.82	1.31	2.44

Investment costs of the alternative network technologies are presented in Table 2. In the same table also fault frequencies (long and short, planned and unplanned) are presented. Since there is uncertainty considering the costs of some techniques such as roadside building of networks, some variations have been made during the analysis. For instance, if a typical overhead line structure costs 19 600 €/km on the average, the cost for overhead lines next to road has been varied from 19 600 to 29 400 €/km (100–150 %).

Table 2. Investment costs, fault frequencies, repair and reconnection times, maintenance and repair costs. (OH=Overhead, UG=Underground)

Parameter	OH lines	OH lines next to road	Covered conductors	UG cables
Investment cost [€/km]	19 600	19 600 + 0…50 %	25 780	43 570 -10…-30 %
Interruptions [pcs./100 km, a]:				
- Unplanned	5…10	0…10	0…10	0…5
- Planned	2	2	2	2
- High-speed autoreclosings	50	25	10	0
- Delayed autoreclosings	20	10	4	0
Repair/reconnecting time [h]	1	1	1	1
Time for planned interruptions [h]	3	3	3	4
Maintenance and fault repair costs [€/100 km,a]	260	215	170	100

Structures of overhead (OH) lines both in a forest and in roadside and covered conductors are illustrated in Fig 1.

Fig. 1. OH-lines in the forest and in the roadside, covered conductors.

To able compare different strategies, costs have to be calculated for the whole life-time of the network. Annual and continuous costs such as operational costs and outage costs have to be discounted before they are comparable with the investment costs. For this operation, economical parameters have to applied (Table 3).

Table 3. Calculation parameters.

Parameter	
Interest rate, p	5 %
Load growth, r	1 %/a
Life-time, t	40 a
→ Discounting factor for…	
- loss costs (~ r^2)	23.37
- outage costs (~ r)	19.91
- maintenance costs (no depence r)	17.16
Time of peak load	3500 h

The target area of the analysis lies in the Finnish distribution company Suur-Savon Sähkö Ltd. The area is located in a lake district area in central Finland. The target area network consists of five 110/20 kV primary substations and over 1000 km of 20 kV medium voltage networks. This is 15 % of Suur-Savon Sähkö Ltd.'s whole distribution network. The network is built with overhead line technology and the cabling rate is 2 %. There are about 14 000 customers in the target area within 900 distribution substations (20/0.4 kV).

TECHNO-ECONOMIC ANALYSIS

In this chapter, some technologies are described and economical limits for use are defined.

Underground cabling (UG)

Compared to overhead lines, improved reliability can be achieved by applying underground cabling. Especially during big storms, the benefits of underground cable networks come from. There are some challenges in cable networks considering fault location and repair, a lower adaptability compared to OH line networks, and higher investment costs. The new branch lines require specific component; at medium voltage, the so-called RMUs (ring main units) or branching from the distribution substation, and in the low-voltage network, a distribution cabinet. These challenges are emphasized if cabling is increased in a rural area. The Fig. 2 illustrates the optimal limit for cabling in the medium-voltage network in Finland. The curves indicate the optimal limits of cabling based on the CENS values in Table1. Because the exact improvement in fault frequency is not always easily definable and it also depends on the area where the cable is to be installed, fault frequency is varied in calculations. In the figure, a change in fault frequency (x-axis) indicates the decrease in the fault rate of permanent faults, if the OH network is replaced with a UG cable network.

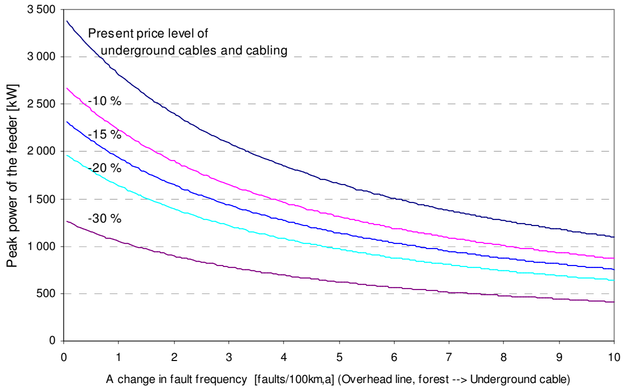

Fig. 2. Economical limits (kW) for underground cabling depending of the fault frequency development and the price of cabling. A change in fault frequency indices estimated improvement in reliability when OH lines are replaced with UG cables. For instance 0 indices that there are as many permanent faults in the UG cable as in the OH line network, whereas 10 means that all the 10 faults can be avoided in the UG cable network. Reconnection time is 1 h.

It can be seen from the Fig. 2 that for instance if the estimated improvement (change) in reliability is 6 faults/100km,a when an OH line is replaced with a UG cable, the economical limit for UG cabling is for a feeder in which the peak power is at least 1500 kW. This is the limit when the analysis is based on present investment prices. It can be seen that if the prices of cabling (and cables) decrease for instance by 15 %, the economical limit for cabling decreases from 1500 kW to 1000 kW.

Overhead (OH) lines along the roadsides

In rural areas, most of the lines and line paths are located in forests. The solution dates back to several decades, when the target was to minimize the material costs in network construction investments. The reliability of supply was not among the central issues. Now, several decades later, the reliability of supply has become a focal boundary condition in the network planning. Fig. 3 illustrates the optimal limit for roadside building in the medium-voltage network. The investment cost of roadside building depends greatly on the road structure in question. If there are plenty of angles, the total length of the feeder will be longer, and expensive pole structures have to be used. Because of this uncertainty considering the building costs, variations have been made during the analysis. When a typical OH line structure costs 19 600 €/km, the cost for OH lines next to a road has been varied from 19 600 to 29 400 €/km (100-150 %).

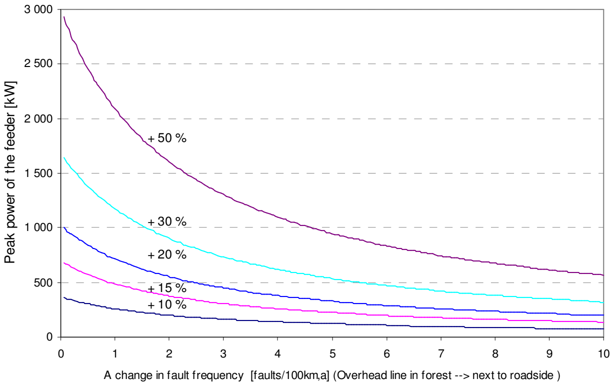

Fig. 3. Economical limits (kW) for roadside building of OH lines depending of the fault frequency development and price of roadside building.

It can be seen from Fig. 3 that for instance if the estimated building costs are 30 % higher compared to a typical OH line and the improvement in reliability is 5 faults/100km,a when the OH line in forest is replaced with an OH line in the roadside, the economical limit for roadside building is for a feeder on which the peak power is at least 500 kW.

Building the lines along the roadsides instead of in the forests is most often economically reasonable in Finland, since the peak power on a medium voltage (MV) feeder is about 1500 kW on the average. On the other hand, placing the lines along the roadsides is still somewhat problematic due to the opposition of road providers against electricity distribution lines along roadsides; a line built too close to the road may be an obstacle to the road maintenance.

Covered conductors (CC)

In the MV network, plastic-covered conductors (CC) are used to some extent. Their insulation structure is simple and inexpensive. The reliability of this conductor structure is better than that of an OH line, since the tree limbs or birds on the line do not cause an outage. The present investment costs of covered conductors are 30 % higher than the costs of corresponding OH lines. Because there are no reliable and extensive statistics of short interruptions in a CC network structure, it is reasonable to perform sensitivity analysis. In Fig. 4 economic limits for CC networks are calculated by varying the number of short interruptions.

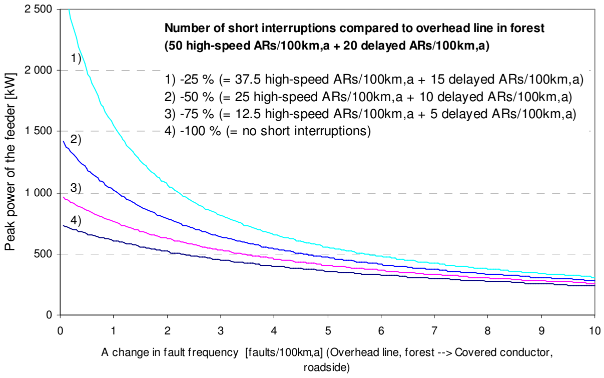

Fig. 4. Economical limits (kW) for use of covered conductors depending of the fault frequency development and the development of short interruptions.

It can be seen for instance that if permanent faults can be decreased by 2 faults/100 km,a by installing covered conductors and it is estimated that there are only a half of short interruptions compared to typical OH lines, the economical limit for CC installation is app. 750 kW.

RESULTS OF THE ANALYSES

As the demands for reliable electricity distribution have increased, also other cost components have entered the process of selecting the network structure. The role of outage costs in particular and the acceptable duration of interruptions in delivery are now the core design parameters, as the modern society is highly dependent on reliable supply of electricity. The previous figures show that there are numerous of economical incentives for more reliable network structures. The above-presented technologies constitute only a part of the designers' toolbox of the methods to build reliable distribution networks in a cost-effective way, for instance, also low-cost 110/20 kV primary substations, light 110 kV lines, 1000 V low voltage technology, pole-mounted switchgears, network automation are among the alternative solutions available. In the following studies above technologies are taken into account. One of the main results is presented in Fig. 5, where the total costs of different investment strategies are illustrated. Strategies are explained in the Table 4.

Table 4. Development strategies (MV=medium voltage, LV=low voltage)

	Development Strategy
1	**Traditional strategy** (continuing with old solutions) - Reconstruction of existing network with old techniques and line routes, no changes in LV network: aerial bundled cables (ABC)
2	**Optimized MV network** (incl. 1 kV technology) - Moving MV lines next to roads and 1 kV at branches, no changes in 0.4 kV LV network (ABC-lines)
3	**Optimized MV and LV networks** - Moving MV lines next to roads, 1 kV at branch lines, UG cabling in LV network in conditions suitable for cable ploughing (about 80 %), the rest with ABC-lines
4	**Target: Decreasing average number of faults (SAIFI) by 50 %**
5	**Target: Decreasing maximum number of faults by 50 %**
6	**Full-scale underground cabling** (MV and LV networks) - MV lines underground cabled next to roads to cable ditches, 1 kV at branches, LV-UG-cable ploughed where possible, the rest installed in ditch. 85 % of distribution substations are pad-mounted satellite substations and the rest traditional pad-mounted cabin substations

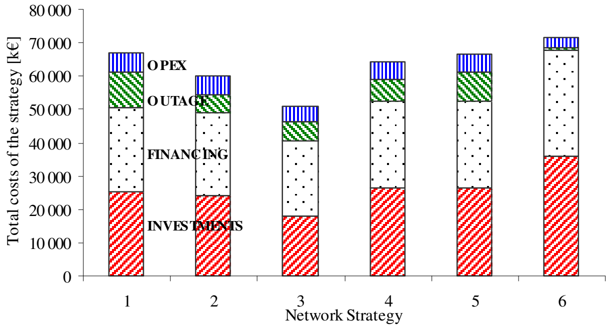

Fig. 5. Total long-term costs of different investment strategies in the studied distribution network.

In optimized solution, presented technologies are utilized. Outage costs are about 50 % in optimized solution and 10 % in full-scale UG cable solution compared to traditional strategy. Investments costs of the strategies are based on the component cost list of 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 they reflect the paid interest. The financial costs are based on the yearly net present value of the network. It is assumed that present network value is 50 % of replacement value. Operational costs include the costs of losses, maintenance and fault repair.

In the analysis, it has also been taken into account that the transition from the present network does not happen immediately; for instance, if the full-scale UG cable network is the target, the full benefit of the reliability improvement can be achieved only after the network is fully rebuilt from the present network to a UG cable network. The effects on the distribution fee of end-customers at the end of the study period are presented in Table 5.

Table 5. The effects on distribution fees.

Strategy	A change in distribution fee [cent/kwh] if the strategy is carried out during…			
	10 years	20 years	30 years	40 years
1	0.00	0.00	0.00	0.00
2	0.05	-0.08	-0.08	-0.08
3	0.60	-0.08	-0.43	-0.44
4	0.09	0.08	0.07	0.06
5	0.10	0.09	0.08	0.07
6	2.52	1.68	1.04	0.75

It can be seen that the costs of different strategies for end-customers depend greatly on the time scale of the renovation. For instance if the full-scale UG cable network is the target, an addition in the distribution fee varies from 0.75 cent/kWh to 2.52 cent/kWh depending on the implementation schedule (from 10 to 40 years). This is due to the higher financing costs in the faster schedule.

It has to be notice that this study has been done to the rural area distribution network where loads are small and customer density (customers/km) is very low. This affects especially on the costs of cabling strategy. Remarkable part of cabling costs comes from pad-mounted distribution substations.

CONCLUSIONS

The outage costs play a significant role in the determination of the profitability of different technologies. In the optimal solution costs can be reduced by investing in technologies that are cost effective compared to the traditional solutions. At the same time, the effects on reliability (SAIFI and SAIDI) are remarkable. Optimized solution is a case-specific combination of the presented technologies. However, optimized solution contains a risk of big storms. If the capability to manage severe storms in any situation is a prime criterion, a full-scale underground cabling in both low and medium voltage networks is only workable method. In rural area full-scale underground cabling would increase the distribution tariffs by 30–50 %. The costs of different strategies for end-customers depend greatly on the time scale of the renovation

The tightening environmental requirements, demands for preparing against big storms, the development in cable production and ploughing methods, and the increasing role of the life-cycle cost consideration will lead to an increased use of underground cables also in the rural areas in Finland. This tendency can already be seen in several other Western European countries; in Sweden, the process has already started.

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