PROFITABILITY OF UNDERGROUND CABLING IN THE FINNISH RURAL ELECTRICITY DISTRIBUTION IN THE FUTURE

Juha HAAKANA Jukka LASSILA Tero KAIPIA Jarmo PARTANEN
Lappeenranta University of Technology – Finland
juha.haakana@lut.fi

ABSTRACT

Tightening supply security requirements have induced a situation where a significant amount of the present overhead lines should be replaced by underground cables. This means a significant change in the annual amount of investments in both underground cabling and overhead lines. Thus, in principled way the amount of underground cable investments increases and amount of overhead line investments decreases. Former experiences of rural area cabling are minor, and thus the cabling process is not optimized that can be observed in the costs. Hence, there can be possibilities to cut the installation price of cabling.

This paper presents a comparison of network renovation with future investment prices in medium-voltage (10 kV or 20 kV) network in rural area conditions for underground cable and overhead line network. The study also takes into account operational and customer interruption costs peculiar to considered network types.

INTRODUCTION

Supply security requirements have tightened in the recent years. For instance, in 2013 the Finnish government set a new electricity market act [1], that defines limits for maximum allowed interruption duration, encouraged by Swedish electricity act from year 2006 [2], [3]. The limits in Finland are six hours for urban areas and 36 hours for rural areas while the Swedish electricity act defines only one interruption duration limit that is 24 hours. Even the limits seems to be quite equal in both countries, there is a big difference in the transition period when the limits come into effect. In Finland the last customers have to be included in the criteria at the end of 2028 while in Sweden all the customers have to be already included in the criteria from the year 2011.

The interruption duration limits are a challenge for most of the distribution system operators (DSOs). For instance, Finnish experiments in years 2010 and 2011 have shown that customer experienced interruptions have lasted even several hundreds of hours. Thus, to avoid this situation in the future in some cases the network will need significant changes where present overhead distribution lines are replaced by underground cables. Figure 1 illustrates present rates of major-disturbance-proof network (proportion of the network resilient to major disturbances) of Finnish distribution system operators DSOs in both medium-voltage and low-voltage networks. It shows three example supply security targets of DSOs from different operational environments. The supply security targets are based on the data of Finnish DSOs. It can observed that the most challenging target (CASE C) can initially be fulfilled by few DSO, the intermediate target (CASE B) is fulfilled by half of the DSOs and the easy target (CASE A) is fulfilled by most of the DSOs.

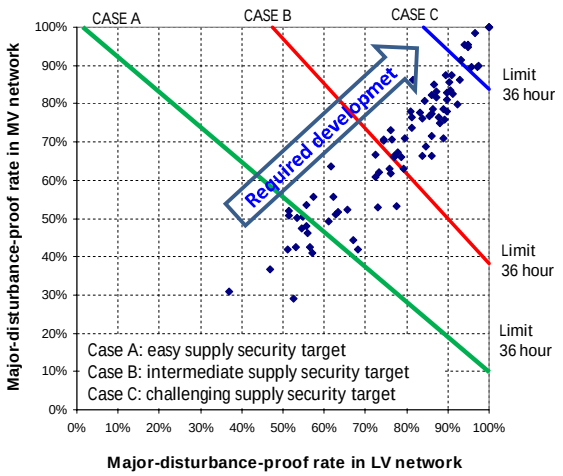

Figure 1. Rates of major-disturbance-proof networks of Finnish distribution system operators [4].

Underground cabling is a mature technology in city and town areas where it has mainly been utilised until the supply security reform. This is somewhat problematic for the long-term estimation of costs because the circumstances differ considerably between the operational environments. It is clear that city areas are most expensive to construct underground network because of other existing infrastructure, which is also the situation in town areas, but the rural area situation is completely different. Solutions of rural network can be totally different because of independence of other infrastructure and long distances enabling long unbroken cable pulling, low customer density and thus low delivered power. These provide a base for new ideas to be utilised in power delivery such as a cable plough and light substation cabin. These solutions may have a positive impact on price of cabling and thus to decrease the costs in the long run.

Most significant experiences of rural area underground cabling come from Sweden, where the supply security reform has established large scale underground cabling wave after the destructive storms in 2005 and 2007

causing preparation of new Electricity act.

COST FUNCTIONS

Comparison of different network technologies is approached by writing cost functions for both overhead line network and underground cable network. At first a general cost function for electricity distribution can be presented as follows:

$$C = \left(C_{\mathrm{CAP}}(t) + C_{\mathrm{OPEX}}(t) + C_{\mathrm{CIC}}(t)\right), \tag{1}$$

where C is total costs, C_{CAP} is capital costs, C_{OPEX} is operational costs and C_{CIC} is customer interruption costs in year t [5]. Capital costs typically contain investment costs and funding costs of investments. Operational costs contain annual network maintenance and fault repair costs, which can vary depending on the network type. Customer interruption costs are estimated costs of the harm that interruptions cause to customers. Interruption costs may consist, for instance, of unplanned interruptions, planned interruptions, momentary interruptions and voltage sags. The function of capital costs, operational and customer interruption costs are written

$$C_{\mathrm{CAP}} = C_{\mathrm{funding}} + C_{\mathrm{investment}}, \tag{2}$$

$$C_{\mathrm{OPEX}} = C_{\mathrm{maintenane}} + C_{\mathrm{faultrepair}} \tag{3}$$

$$C_{\mathrm{CIC}} = \frac{W}{8760}\begin{pmatrix} c_{\mathrm{u}} \cdot n_{\mathrm{u}} + c_{\mathrm{a}} \cdot n_{\mathrm{a}} + c_{\mathrm{ud}} \cdot d_{\mathrm{u}} + \\ c_{\mathrm{ad}} \cdot d_{\mathrm{a}} + c_{\mathrm{hsar}} \cdot n_{\mathrm{hsar}} + c_{\mathrm{dar}} \cdot n_{\mathrm{dar}} \end{pmatrix} \tag{4}$$

where

W	annual distributed energy of the DSO (kWh/a)
c_{u}	unit cost for unannounced interruption (€/kW)
c_{a}	unit cost for announced interruption (€/kW)
c_{ud}	unit cost for unannounced interruption duration (€/kWh)
c_{ad}	unit cost for announced interruption duration (€/kWh)
c_{hsar}	unit cost for high-speed autoreclosing (€/kW)
c_{dar}	unit cost for delayed autoreclosing (€/kW)
n_{u}	annual number of unannounced interruptions
n_{a}	annual number of announced interruptions
d_{u}	annual duration of unannounced interruptions (hour)
d_{a}	annual duration of announce interruptions (hour)
n_{hsar}	annual number of high-speed autoreclosings
n_{dar}	annual number of delayed autoreclosings

Investment costs of underground cables and overhead lines consist of partially different sections. In underground cable network the network construction includes in addition to cables excavation, cable joints, pad mounted substations, compensation and in some cases reserve power costs. Construction of overhead line network comprises less cost components, which are costs of conductors, poles and overhead line substations. The equation of the investment costs of both technologies underground cabling (UGC) and overhead line (OHL) can be written

$$C_{\mathrm{investment\ UGC}} = C_{\mathrm{conductor}} + C_{\mathrm{excavation}} + C_{\mathrm{substation}} + C_{\mathrm{joints}} + C_{\mathrm{compensation}} + C_{\mathrm{reservepower}}, \tag{5}$$

$$C_{\mathrm{investment\ OHL}} = C_{\mathrm{conductor}} + C_{\mathrm{poles}} + C_{\mathrm{substation}}. \tag{6}$$

Customer interruption costs

Customer interruption costs are estimated costs of the harm of interruption on customers. Even the interruption costs are an estimation of the harm of interruption, in Finland they constitute a real value for the DSOs. Customer interruption costs have important role in the Finnish electricity distribution regulation and they affect allowed regulatory return [8]. A simplified interpretation of the Finnish quality incentive in the regulatory model is that from the interruption history is calculated a reference level for CIC, which is compared with annual occurred CIC. If the annual CIC is lower than reference, the DSO gets reward that is a difference between reference and annual CIC multiplied by 50%. Similarly, if annual CIC is bigger than reference, the DSO gets sanction. Thus, the customer interruption costs are a real incentive to invest in fault reducing network technology.

In Finland, customer interruption unit costs are based on surveys where it has been asked the willingness to accept (WTA) and willingness to pay (WTP) for better reliability of electricity supply. In the Finnish model the interruption unit costs have been divided to four different types of interruptions, which are unannounced interruptions, announced interruptions, high-speed autoreclosings (HSAR) and delayed autoreclosings (DAR). Furthermore, unannounced and announced interruptions have been divided to two different costs: power based interruption cost that takes into account the magnitude of the load and energy based cost that takes into account the length of interruption. Finnish interruption unit costs are presented in Table 1.

Table 1. Interruption unit costs applied in Finnish distribution business regulatory model in the price of 2005 and 2014 [8].

Year	Unannounced interruptions		Announced interruptions		HSAR	DAR
	[€/kW]	[€/kWh]	[€/kW]	[€/kWh]	[€/kW]	[€/kW]
2005	1.1	11	0.5	6.8	0.55	1.1
2014	1.32	13.15	0.60	8.13	0.66	1.32

In the regulatory model the unit costs are multiplied by increase of consumer price index (CPI) that updates the value of interruption harm. The increase of CPI in Finland has been 2.00%/a between the years 2005–2013 [9]. This average increase has been used to estimate the future interruption costs in the calculation for the next 20 years (2014–2033). Interruption unit costs of year 2014 have been calculated using CPI.

Benefits of underground cabling

Underground cabling provides not only better supply

security but also stable reliability of supply in general. Thus, the customer experienced harm of interruptions is smaller compared with traditional overhead line networks that can be observed in the decreased customer interruption costs. Another cost group, where savings can typically be observed, when the overhead lines are replaced by underground cables, is operational costs including maintenance and fault repair costs. Cables require condition monitoring but the clearance of overhead line routes is not anymore required that typically causes more costs. Also decreased number of faults gains savings as decreased fault repair costs.

PRESENT AND FUTURE PRICES OF NETWORK TECHNOLOGIES

A typical situation is that underground cabling is considerably more expensive compared with overhead lines. The price difference is emphasized in urban environment because of the special expensive solutions in network construction such as crossing of roads. In rural areas the price difference is smaller because special solutions in underground installation can be minimized. Figure 2 presents statistics of distribution network component price development of in Finland [6]. The statistics shows that the trend of components related to underground cabling is decreasing and the trend of overhead line components is increasing.

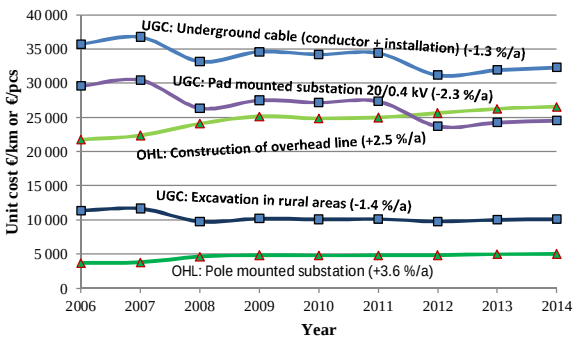

Figure 2. Unit cost statistics in Finland between years 2006 – 2014 [6].

Estimated rural area network average prices in year 2014 are presented in Table 2 and Table 3. The prices are based on unit price lists of Finnish Energy Authority [6] and Swedish Energy Association [7].

Table 2. Investment price of underground cable network at year 2014. Cost group other contains compensation, reserve power and cable joint costs. * means that these costs cannot be divided from the cost of cables + installation.

	Total [€/km]	Cables + installation (95 mm^2) [€/km]	Excavation [€/km]	Other [€/km]	Substation [€/km]
Finland	60 000	25 000	10 000	10 000	15 000
Sweden	50 000	38 000	*	*	12 000

Total investment cost of underground cabling in Finland is estimated to 60 000 €/km, where the proportion of cables and installation is 25 000 €/km. Excavation costs (10 000 €/km) are average cost for rural areas that is classified to easy circumstances. Other costs of underground cabling consist of cable joints, compensation and reserve power costs. Substation costs in case of underground cabling are a combination of present prices of light pad-mounted substation (50%) and pad-mounted substation (50%). In Sweden the similar cost of underground cabling is estimated to 50 000 €/km that is considerably lower than the Finnish cost. A reason for the lower cabling cost can be, for instance, more efficient work practices because of experience in cabling process in rural areas and also lower voltage (10 kV instead of 20 kV) level in MV network. The utilities in Sweden have already applied underground cabling in rural area distribution networks for almost a decade. From this perspective it is reasonable to expect that the cost of cabling reduces in the coming years in Finland.

Table 3. Investment price of overhead line network at year 2014.

	Total [€/km]	Conductors + installation (99 mm^2) [€/km]	Substation [€/km]
Finland	32 000	27 000	5 000
Sweden	39 000	34 000	5 000

In Finland total costs of bare overhead lines (99 mm^2) are 32 000 €/km, where the proportion of conductors and installation is 27 000 €/km including also the cost of poles. Cost of substation is 5 000 €/km. The substation is bare 1-pole substation used in overhead line network. The costs are collected from unit cost list of Finnish Energy Authority [6]. Similar unit costs in Sweden can be found from the cost catalogue of Swedish Energy Association [7]. In Sweden the cost of similar overhead line with 1-pole substation is 39 000 €/km that is considerably more than the Finnish cost. Higher safety requirements and perhaps lower construction volumes in Sweden may explain higher costs in overhead line construction. The comparison shows that in Sweden the difference between the costs of underground cables and overhead lines is quite small, only approximately 10 000 €/km while in Finland the difference between the network techniques is almost 30 000 €/km.

Future prices

Use of underground cables in rural area conditions has not been common until these days. Thus, it can be assumed that the components and installation methods are not completely mature that may decrease the price in future. For instance, the excavation methods are not completely investigated and compensation solutions are not optimized for rural area cabling process. Also, the ploughing technologies can still be developed and perhaps the cable technology is not fully developed. At

least in Finland the process can be improved. In rural areas the requirements of substation cabins are different than in town areas that may indicate an opportunity to reduce the costs. Figure 3 presents the investment costs of underground cabling and overhead lines for next 20 years. The price of cabling is estimated to decrease by 2% each year that is similar value that is presented in Figure 2. When the Finnish initial price is 60 000 €/km, the price after 20 years is 40 100 €/km. Thus, with this estimate of underground cabling, the price difference between the techniques reaches the Swedish level.

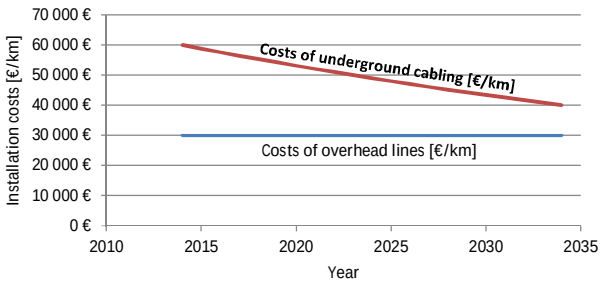

Figure 3. Finnish unit costs of underground cabling and overhead lines in 20 year period. Price of underground cabling decreases by 2 % each year.

ANALYSES AND RESULTS

Profitability of underground cabling depends highly on environmental circumstances such faulting sensitivity and power density of the distribution network. Faulting sensitivity of the network depends mainly on the network structure and location of the network (forest, roadside, field). Present valuation of customer interruptions means that already relatively low power density makes it profitable to construct underground cable networks if faulting sensitivity of overhead lines is high. In Nordic countries electricity distribution network contains typically two kinds of feeders: short urban feeders and relatively long rural area feeders. Urban area feeders are often already cabled underground but the rural area feeders consist typically of overhead lines which are often vulnerable to faults. Analyses and results of this study are mainly focused on rural area networks.

Case network and calculation parameters

Case network in the analyses is 30 km long overhead line network, where the average frequency of permanent faults is 7 faults per 100 km in a year and customer experienced duration of interruption averagely 3 h/fault. The number of high-speed autoreclosings (HSAR) is 20 and delayed autoreclosings (DAR) 5 per 100 km per year. If the overhead line is replaced by underground cables, number of permanent faults is estimated to be 1 fault per 100 km in a year, customer experienced duration of interruption averagely 5 h/fault and number of momentary interruptions is zero because reclosings are not used in fully cabled networks. The fault rates and durations of interruptions are presented in Table 4.

Table 4. Fault rates and interruption durations applied in the case network. The statistics are typical in Finnish distribution system.

Network type	Permanent faults [pcs/100 km,a]	Duration of interruption per permanent fault [h/fault]	HSAR [pcs/100 km,a]	DAR [pcs/100 km,a]
Overhead line	7	3	20	5
Underground cable	1	5	-	-

Maintenance of underground cable networks is not required to be as intensive as overhead line networks. The annual maintenance of underground cables are related to proactive condition monitoring, but in the overhead line networks in addition to condition monitoring of the poles the clearing of the vegetation in the line paths and next to line paths require significant annual effort. In addition, fault repair costs are lower in underground cable networks compared with overhead line networks that reduce the total costs of underground cables. This is a consequence of higher fault number of overhead lines.

Table 5. Operational costs applied in the case network.

	Maintence cost [€/km,a]	Fault repair cost [€/km,a]
Overhead line	130	120
Underground cable	40	40

Results of calculation

In Finland, today's investment price of underground cables is considerably higher than overhead lines. This denotes that underground cabling has to reduce other costs so that the total costs of cabling could be lower than overhead lines. Figure 4 illustrates the total costs of both underground cable and overhead line strategies as a function of installation year, when the average power of network is 400 kW, rate of interest is 5%, investigation period is 40 years (assumed lifetime of the network) and investment price of underground cables decreases 2% per year next 20 years. The initial price of underground cable construction is 60 000 €/km and the price after 20 years in 2034 is 40 100 €/km. Construction price of overhead line is 32 000 €/km. The cost comparison shows that with the present cost parameters, in the case network, it is not profitable to apply underground cables. However, the situation changes if the network can be renovated in year 2024 or after. Total cost of network during the 40 years lifetime, renovated for instance in 2014, are 1 900 000 € for underground cable renovation and 1 600 000 € for overhead line renovation. Respectively if the renovation year of the network is 2025, the total costs are 1 080 000 € for underground cable renovation and 1 100 000 € for overhead line renovation that makes it profitable to invest in underground cables.

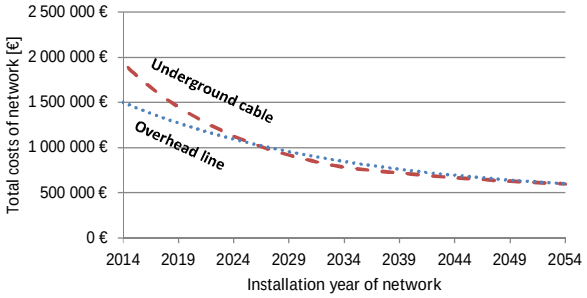

Figure 4. Total costs of underground cable and overhead line network as function of renovation year. Average power is 400 kW, Investment price of underground cabling decreases 2% each year next 20 years. Rate of interest is 5%.

Calculation results show that at present average power of the feeder has to be around 800 kW to provide economic profitability for underground cable network from the perspective of total costs. With the scenario of decreasing installation costs of underground cables and increasing interruption unit costs the break-even power to provide economic profitability decreases. This means that incentives to invest in underground cable network increase in the future. This has been illustrated in Figure 5 that presents break-even surface of profitability of underground cable network. For instance, if cabling price decreases 1% per year the break-even point is achieved in the network renovated after 2034 with power of 380 kW.

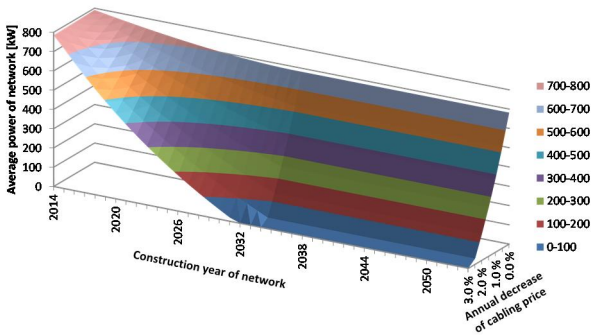

Figure 5. Break-even surface as function of feeder load and decrease percentage of underground cabling price to provide lower total with underground cable network compared with bare overhead line network. Total costs of underground cable network are lower than costs of overhead line network with higher power.

CONCLUSIONS

Underground cable networks are rare outside town areas. There are several reasons why cable networks are uncommon such as high investment costs of underground cables and relatively low sanction as a consequence of power distribution interruption. However, the situation is changing because of tightening supply security requirements that inevitably increase the cabling volume and also raise the valuation of customer experienced interruption costs. The increased cabling volumes mean that cabling methods and components can be developed from rural area perspectives, and thus, the new methods and components decrease the unit costs of cabling compared with overhead line construction. Thus, economic profitability of underground cabling increases in the future.

A scenario, where the cost of underground cabling decreases 1% per year next 20 years, halves the break-even power of the network, when underground cable and overhead line networks are compared. At present, in the case network between these network types, the break-even is around 800 kW and after 20 years the break-even power is 380 kW.

ACKNOWLEDGEMENTS

This work was supported in part by Smart Grids and Energy Markets (SGEM) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, TEKES.

REFERENCES

[1] Finnish Electricity Market Act 588/2013.

[2] J. Setréus, C. J. Wallnerström, and L. Bertling, 2007. “A comparative study of regulation policies for interruption of supply of electrical distribution systems in Sweden and UK.” *Proceedings of the CIRED 2007, 19th International Conference and Exhibition on Electricity Distribution.*

[3] Swedish Electricity Act 1997:857

[4] J. Haakana. J. Lassila. T. Kaipia and J. Partanen, 2014. “Influence of Supply Security Requirements on Underground Cabling Rates in Finland.” *Proceedings of the ISGT Europe 2014, 5th IEEE PES Innovative Smart Grid Technologies European Conference.*

[5] E. Lakervi, and E. J. Holmes, *Electricity distribution network design*, 2nd Edition. IEE Power Engineering Series 21. England, 1995

[6] Finnish Energy Authority. 2014. *Unit prices of electricity distribution components 2006–2014.* Available at http://www.energiavirasto.fi/

[7] Swedish Energy, *Cost Catalog, Lokalnät 0.4-24 kV and optical network - KLG 1:14*

[8] Energy Authority of Finland (EA). 2011. Sähkön jakeluverkkotoiminnan ja suurjännitteisen jakeluverkkotoiminnan hinnoittelun kohtuullisuuden valvontamenetelmien suuntaviivat vuosille 2012–2015 [Guidelines for assessing reasonableness in pricing of electricity distribution network and high voltage distribution network operations for 2012–2015], (in Finnish), www.energiavirasto.fi, accessed 7 November 2014.

[9] Statistics Finland, 2014. http://www.stat.fi/til/khi/2014/03/khi_2014_03_2014-04-14_tau_003_fi.html