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Tiit HÕBEJÕGI[1], Kaija VILL[1], Juhan VALTIN[1]

Tallinn University of Technology (1)

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1 kV distribution system as a cost effective alternative to the medium voltage systems

***Abstract**. This article debates on the use of 1 kV system as a cost-effective investment solution in the rural areas and provides an approach for finding potential investment sites. This approach determines the maximum admissible 0.4 kV feeder length and through that, the potential sites where 1 kV system could benefit the network company. An example of the potential benefits and drawbacks of using 1 kV systems are also included. This approach was tested in Elektrilevi OÜ and the number of potential feeders was substantial. Therefore, Elektrilevi OÜ should consider using 1 kV systems.*

***Streszczenie.** W artykule analizowane jest zastosowanie rozsyłanie energii elektrycznej za pośrednictwem linii 1 kV. Analizę przedstawiono na przykładzie linii rozdzielczej w Estonii. **System rozsyłu energii 1 kV jako opłacalna alternatywa dla sieci średniego napięcia**.*

Keywords: 1 kV system, distribution network, investments, finding refurbishment projects.
Słowa kluczowe: system 1 kV, sieć rozdzielcza

Introduction

The lifespan of distribution networks' infrastructure is very long and investments extremely resource intensive. Therefore, it is essential to invest as efficiently as possible. However, distribution networks are created over a long period of time and the principles that govern these investments can change. Because of that, the original configuration of the distribution network will not always be the most optimal and may become inefficient in providing electricity for nowadays needs. If configuration cannot be optimized [1], large investments are needed. This article debates on the use of 1 kV system as a cost-effective investment solution in the rural areas and provides an approach for finding potential investment sites.

The authors created this approach for Elektrilevi OÜ (ELV), Estonia's largest distribution network, but it could also be used in other networks. ELV distributes power to about 500,000 customers with a total consumption of approximately 6.5 TWh as recorded in 2014. The company manages around 64,000 km of power lines and more than 24,000 substations. Although ELV has 15 1 kV substation areas that were built mostly in 2008, the use of the solution was discontinued in 2009 (Fig. 1).

We evaluate using 1 kV power lines to refurbish the low-voltage feeders of those customers, who currently have a 0.4 kV solution, but are situated too far from the substation, to provide power according to nowadays' standards. Currently, the standard solution in use in ELV is building a new medium voltage power line along with a MV/LV substation for these customers.

Firstly, we give an overview of some of the papers written on the subject of 1 kV distribution network. Secondly, we provide an approach for finding the number of potential customers, who could be refurbished using the 1 kV solution and how to evaluate the possible financial benefits it provides. Thirdly, we debate on the negative effects that using 1 kV solution has and why it was discontinued some years ago and provide a positive example of how it could provide a financial benefit. Finally, we test the approach presented in this paper in the ELV distribution network and give our expert opinion based on the results whether or not ELV should reconsider using the 1 kV solution according to the number of potential customers and its drawbacks.

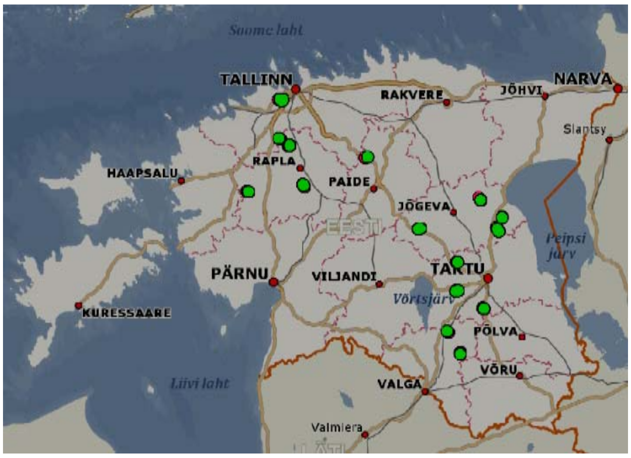

Fig. 1. Current 1 kV substation areas in ELV

Former studies on 1 kV systems

1 kV low-voltage systems became popular at the start of this century. The first 1 kV system known to the authors was built in 2001 by Suur-Savon Sähko OY, a Finnish distribution network [2]. Because of that, most of the research on the technical and economic evaluation of 1 kV systems in distribution networks were done in 2003-2007 by Lappeenranta University of Technology started. There are several master's thesis and at least one PhD thesis on this topic [2, 3, 4].

Most of the research done on 1 kV systems studies the benefits of refurbishing short low-loaded 20 kV overhead power lines that are underutilized, with 1 kV systems. Some studies also evaluate the financial feasibility of the 1 kV systems compared to other alternatives for increasing network reliability [5, 6, 7, 8].

Few articles on the topic have been published after 2009. However, some interest has resurfaced in the Swedish network company Vattenfall Eldistribution AB. An article by D. Söderberg and H. Engdahl studies the possibility of using 1 kV systems for providing power for electric vehicle charging stations and households in the rural areas. This topic is important because the growing use of electrical cars and the ever higher quality standards for household applications increases the pressure on the distribution networks [9]. In his 2013 article [10], D. Söderberg analyses the necessary parameters for transformers operating in the 1 kV system.

Description of calculation method

Because 1 kV solutions are not standard in ELV, building a completely new power line will most likely be just as if not more expensive than building a medium voltage power line. Therefore, only those feeders, where the existing poles can be used will be under evaluation. In order to calculate the maximum length of these feeders, AMKA-type aerial bundled cable will be used. The standard dimensions and resistances for AMKA are presented in [11]. Increasing the cross-section of the cable, the weight increases also, meaning that the existing poles may also need replacement, increasing the investment costs.

One of the restricting factors of the length of the feeder is the tripping time of a fuse situated on the start of the feeder. In ELV distribution networks, usually gG-type fuses are used for feeder overcurrent and short-circuit protection in MV/LV substations. According to the standard IEC 60364-4-41, the maximum allowable tripping time during one-phase fault is 5 seconds. Minimum one-phase short-circuit current (in temperature 40^0 C and a coefficient for voltage 0.95 as stated in the standard IEC 60909-0) can be calculated according to eqn. 1:

$$(1) \qquad I_k^{(1)} = \frac{0{,}95U_n}{\sqrt{3}\left(2{,}16z_f + z_{tk}^{(1)}\right)}$$

where: U_n – nominal line-to-line voltage of the network (V), z_f – feeder total impedance on the temperature 20^0 (Ω), $z_{tk}^{(1)}$ – transformer impedance during one-phase fault (Ω).

As the standard IEC 60269 states minimum short-circuit current for gG-type fuses and cable impedances per kilometer are known, the maximum length l of the feeder in km-s can be calculated according to eqn. 2:

$$(2) \qquad l = \frac{1}{2{,}16z_j}\left(\frac{U_n}{\sqrt{3}I_{kmax}^{(1)}} - z_{tk}^{(1)}\right)$$

where: z_j – cable impedance per kilometer, Ω/km

Transformer impedances during one-phase fault for Yzn vector group transformers mostly used in ELV network are presented in [12]. Another important restriction is the maximum allowable voltage drop along the feeder at nominal load. In ELV, the maximum admissible voltage drop used for designing and construction of new power lines is 5%.

In practical calculations, eqn. 3 is used for estimating the maximum voltage drop $\Delta u_{\%}$ of a feeder:

$$(3) \qquad \Delta u_{\%} = \frac{\sqrt{3}I_l z_j l}{10U_n}$$

where: I_l – load current of the feeder (A), z_j– cable impedance per kilometer (Ω/km), l – feeder length (km), U_n – nominal line-to-line voltage of the system (kV).

As the maximum admissible voltage drop 5% is known, the length of the feeder can be calculated using eqn. 4:

$$(4) \qquad l = \frac{50U_n}{\sqrt{3}I_l z_j}$$

Maximum admissible feeder length is determined by stricter criterion of both as described above. Using this method, it is possible to calculate the maximum length of the feeder (Fig. 2).

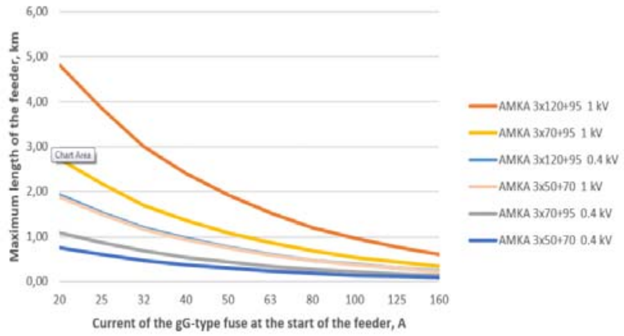

Fig. 2. Maximum length of the feeder depending on nominal current of the fuse and dimensions of the aerial cable

It appears that using AMKA 3x120+95 on 0.4 kV has approximately the same restrictions as using AMKA 3x50+70 on 1 kV. Therefore, only AMKA 3x70+95 on 1 kV and AMKA 3x120+95 on 1 kV will be used in the evaluation.

To calculate the financial benefits of using 1 kV systems, we use the net present value (NPV) method, which is used in capital budgeting to analyze the profitability of an investment or project. NPV can be calculated by using eqn. 5:

$$(5) \qquad NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

where: NPV – Net present value (€), C_t – Net cash flow during the period (€), C_0 – initial investment (€), r – discount rate, t - period number, T – number of time periods.

The initial investment can be calculated using eqn. 6:

$$(6) \; C_0 = C_{mv} \times L_{mv} + C_{lv} \times L_{lv} + C_S \times n_S + C_{Sw}$$

where: C_{mv} – unit cost of building a medium-voltage line (€/km), L_{mv} – length of the medium-voltage line (km), C_{lv} – unit cost of building a low-voltage line (€/km), L_{lv} – length of the low-voltage line (km), C_S – unit cost of the substation (€), n_S – number of substations, C_{Sw} – cost of the switching to connect to an existing network or substation (€).

Net income does not differ regardless of the solution provided to the customer. Therefore, net cash flows equal net expense that can be calculated using eqn. 7.

$$(7) \; C_t = \left((E_{MOHL} + E_{IOHL}) \times L_{lv} + (E_{MS} + +E_{IS}) \times n_s + E_D \times L_D + E_{EL} \times W_{EL}\right) \times (1 + CPI)^t$$

where: E_{MOHL} – base unit cost for the overhead power line maintenance (€/km), E_{IOHL} – base unit cost for the overhead power line inspection (€/km), E_{MS} – base unit cost for substation maintenance (€), E_{IS} – base unit cost for substation inspection (€), E_D – base unit cost for deforestation (€/km), E_{EL} – unit cost for energy loss (€/kWh), L_D – length of deforestation area for period t (km), W_{EL} – average energy loss for period t (kWh), CPI – average change in the consumer price index.

The alternative that provides the higher NPV is financially more feasible.

Obstacles and challenges in using 1 kV systems

1 kV low voltage system has been under evaluation in Finland and Sweden for some time and has proven its viability. The system is also in use in Norway and Latvia. Nevertheless, distribution networks form over a long period of time and no two systems are alike. Therefore, not all benefits and drawbacks that the 1 kV system presents exist in ELV network.

For example, in Finland over 90% of the network failures happen in the medium voltage network [2][6], while in ELV about 75% of the network failures take place in low voltage network. Finnish practice shows, that replacing a faulty underutilised middle voltage overhead lines with 1 kV aerial bundled cable, it is possible to decrease the total length of medium voltage lines in that area by 10-30% while at the same time increasing network reliability. In ELV, the effect would be much smaller, as most failures take place in low voltage network.

An important risk factor is the absence of a long-term experience with 1 kV systems. The first 1 kV system in Finland was built in 2001. Therefore, these systems have not yet proven, that they are reliable on a long term basis. Because 1 kV systems usually use components designed for 0.4 kV systems, it is unclear how it could affect the isolation. Finnish experience [2] shows that partial discharges can appear in AMKA type aerial overhead cables when ambient humidity is high. In underground cables, electrical treeing has been observed.

Another risk in using 1 kV systems is the possibility of confusing these lines with 0.4 kV lines, as the material in use is the same. Therefore, it could increase the time of fault localization. Labelling becomes even more important.

The overall use of 1 kV solution in ELV network depends whether or not the potential financial and non-financial benefits justify the drawbacks listed above. Therefore, it is necessary to find the number of potential customers or feeders, where 1 kV solution should be considered.

The potential benefit of using 1 kV solution

In order to show the possible benefits of using the 1 kV solution, the refurbishment of Holdre substation feeder 1 (Fig. 3) will be evaluated.

Fig. 3. Holdre substation feeder 1.

In all figures in this paper, green represents existing 0.4 kV power lines, red existing 15 kV power lines or substations, blue represents new 1 kV lines and substations, purple represents new 15 kV lines and substations and black represents all dismounted lines and substations.

According to ELV network standards, new medium voltage underground power lines have to be built next to the roads. New medium voltage overhead power lines are not used as the total lifecycle costs are equal or greater than those of the underground cable lines. 1 kV overhead lines have the potential benefit of using existing poles, which cannot be used in medium voltage systems (they are too short).

The first alternative is to change the existing 0.4 kV power lines with an aerial bundled cable. However, because the distance from Holdre substation is 2335 m, this solution would not meet current network standards.

The second alternative is to change the existing 0.4 kV power lines with an aerial bundled cable and use it on 1 kV, then add a new substation at the end of the feeder (Fig. 4). Almost all existing poles have to be changed. In total, 2240 m of aerial bundled cable, one new substation and two transformers (15/1/0.4 kV and 1/0.4 kV) are needed. A total of 1460 m runs through a forested area. The initial investment cost for this solution is 52 263 €. In addition, the present value of the total lifetime expenses for this alternative is 22 645 €. Large expenses are mostly due to the deforestation costs. Therefore the total cost for the company is 74 908 €.

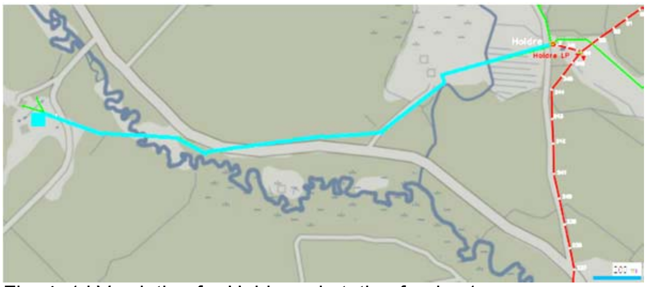

Fig. 4. 1 kV solution for Holdre substation feeder 1.

The third alternative is to build a new medium voltage underground power line and a new substation area for the customers (Fig. 5).

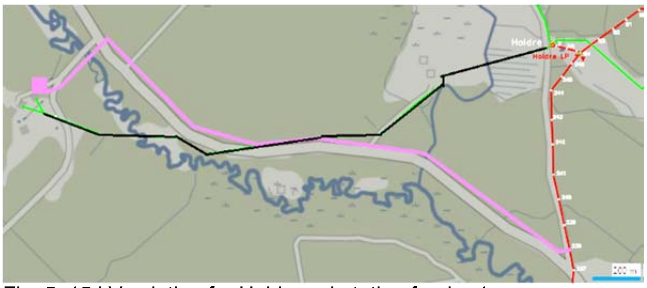

Fig. 5. 15 kV solution for Holdre substation feeder 1.

The total length of a new medium voltage power line is 2624 m. In addition to the underground cable, medium voltage switching, one new substation and a transformer (15/0.4 kV) are needed. 0.4 kV power lines (except for the connection between customers) is dismounted. The initial investment cost for this alternative is 79 582 € and the present value of the lifetime costs for the company 4 576 €. Therefore the total cost for the company is 84 158 €.

The final results for either alternative are presented in Table 1.

Table 1 Initial investment and lifetime expenses of either alternative

Solution	Initial investment, €	Lifetime expenses, €	Total expenses, €
1 kV solution	52 263	22 645	74 908
15 kV solution	79 582	4 576	84 158
Difference	- 27 319	18 069	- 9 250

Therefore, using 1 kV solution would save ELV 9 250 € on the total lifetime expenses of this system. That is a significant 11 % of the total cost of the 15 kV solution that would currently be used.

There are also other possible benefits. One of the first 1000 V distribution systems that was built in Estonia in 2007, is situated in North-Estonia near Tallinn in Harku parish. 1 kV system was chosen because distances were too long for standard 0.4 kV system and required voltage quality could not be guaranteed. Also, a new medium voltage overhead line could not be built, as Estonian Law of Electrical Safety stated that mass gathering events (for example sports competitions) are prohibited in the protection area of high-voltage (>1 kV line-to-line) overhead lines.

Final evaluation for 1 kV systems in Elektrilevi OÜ

Using the approach provided in this paper, all potential customers whose connection could be refurbished using 1 kV systems were located. Only customers who are located farther than 1 km from the substation were under evaluation. The total number of these customers is 7185. The energy consumption of 861 of those customers has been zero during the past year and are therefore excluded from sample. From the remaining 6324 customers, only 461 can be refurbished using a 0.4 kV solution. 1877 customers are situated either too far from the substation or the nominal current of their feeder circuit breaker is too high even for 1 kV solution. The remaining 3986 (Table 2) is the total number of potential customers, whose power supply could be refurbished using 1 kV solution.

Table 2 Number of potential customers by cable type suitable for refurbishing

Type	No. of customers
AMKA 3x70+95 1 kV	1193
AMKA 3x120+95 1 kV	2793
TOTAL	3986

As there are often more than one customer on each feeder, the number of potential feeders should also be analyzed. Using the same criteria as for the customers, the resulting number of potential feeders suitable for refurbish using 1 kV system, is 2474 (Table 3).

Table 3 Number of potential feeders by cable type.

Type	No. of feeders
AMKA 3x70+95 1 kV	922
AMKA 3x120+95 1 kV	1552
TOTAL	2474

There are a large number of potential customers and feeders, where using 1 kV solution could benefit the distribution network company and therefore in the authors' opinion ELV would benefit from using this system.

Summary and outlooks

To conclude, this paper provides an approach to evaluate the potential use of 1 kV solution as a cost effective alternative. The maximum length of a 0.4 kV feeder depends on the current of the fuse at the start of the feeder and the dimensions of the power line. Two restrictive factors were considered in finding the maximum length of 0.4 kV feeders: minimum one-phase short-circuit current and the maximum admissible voltage drop (5% in Elektrilevi OÜ).

This approach was used in Elektrilevi OÜ, where a total of 3986 customers and 2474 feeders were found to be potentially suitable for 1 kV system. As the example provided in this paper showed a significant saving on the total lifetime costs, the authors recommend using 1 kV solution in Elektrilevi OÜ.

There are two important topics that need future study. Firstly, before starting to implement a new voltage level, the distribution network needs to find the exact breaking point or the number of substation areas using the new voltage level needed, to overcome the drawbacks of 1 kV systems. Secondly, as 1 kV solutions and off-grid systems target the same customers, further study is needed to determine which system the distribution network should concentrate on.

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***Authors**: Tiit Hõbejõgi, Head of Network Development, Elektrilevi OÜ, Kadaka Str. 63, 12915 Tallinn, E-mail: tiit.hobejogi@gmail.com; Kaija Vill, Network Analyst, Elektrilevi OÜ, Kadaka Str. 63, 12915 Tallinn, Email: kaijavill@gmail.com; Prof Juhan Valtin, Tallinn University of Technology, Department of Electrical Power Engineering, Ehitajate tee 5, 19086, Tallinn, E-mail: juhan.valtin@ttu.ee.*

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