PROFITABILITY OF DIFFERENT LI-ION BATTERIES AS BACK-UP POWER IN LVDC DISTRIBUTION NETWORK

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ABSTRACT

This paper studies the profitability of different lithium-ion batteries as back-up power in low voltage direct current (LVDC) network. Battery energy storage can prevent part of interruptions in LVDC network that happen due to failures in medium voltage (MV) network. In the present Finnish regulation model avoiding customer interruptions directly affects distribution network operator's profits by decreasing quality of supply deductions that are used in reasonable return calculations.

LVDC technology provides a cost-efficient alternative for replacing low-loaded MV branches of the electricity distribution network. Benefits of LVDC are large power transfer capacity with low voltage, cost saving potential and improvements to reliability and voltage quality [1]. Elenia Oy has had pilot implementations already many years with promising results [2].

The key finding of the paper is that using battery energy storages to avoid customer interruption cost can be financially feasible in many medium voltage branches when the interruption frequency per branch is taken into account and the battery size is optimised based on the power requirement of the branch.

INTRODUCTION

Today's society is increasingly dependent on continuous availability of electrical energy. Power grid is also one of the largest national assets which great financial value. These two facts make the constantly available, affordable electrical power important.

During 2010-2011 Finnish power distribution system was struck by two large storms. As a result the Finnish Electricity Market Act [3] was revised and the requirements for uninterrupted supply of electric power were described. Distribution System Operators (DSO) were given strict requirements: urban areas are not allowed to face interruptions over 6 h and outside urban area the maximum interruption time is 36 h. This has quickly led to a decision of vast ground cabling which in return increases the cost of network infrastructure.

To address the cost and reliability issues both companies and authorities are searching for good solutions. One of the solution options is low voltage direct current (LVDC) networks.

Low voltage direct current (LVDC) network

LVDC is a fairly new alternative when considering replacement investments of medium voltage distribution networks. Direct current power transfer has not been used in the past decades except in high voltage DC links. The development of power electronics components has decreased the price of individual converters and thus made the direct current transfer worth considering again.

LVDC is defined here as systems where the maximum DC voltage is 1500 VDC and the higher voltage side is connected to 20 kV MV network. Maximum voltage requirements follow from European Union directive [4] and LVDC standardization [5], which in practice also steer the development of LVDC products, e.g. cable or switches. The basic structure of LVDC system with a battery included is presented in Fig 1.

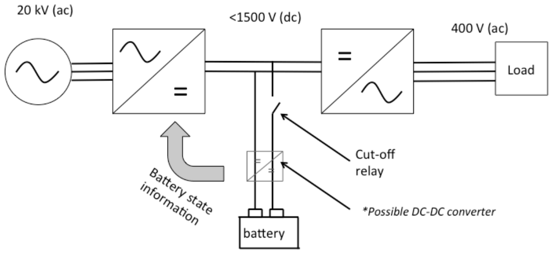

Figure 1. Components of example LVDC system with battery energy storage

There are two main advantages of LVDC system. The first one is cost saving potential when replacing the low-loaded MV branches. The second driver is additional benefits, that LVDC can offer to customers, e.g. shorter interruptions, voltage stability, and easier addition of flexible, bi-directional resources. Replacing MV branches by LVDC distribution can decrease customer interruption costs (CIC) because the LVDC network forms its own protection area whose faults do not cause interruptions in the entire MV feeder [1].

Regulation model of Finnish Energy Authority

The Finnish Energy Authority (EA) is the authoring body that monitors and regulates the energy market participants in Finland. EA operations are based on Electricity Market Act and the regulation model [6], which together formed the basis of the financial regulation of electricity distribution network operators (DSO) during the dataset used in this paper. Its foundation is in the present value of the distribution network, including all network components that are listed by EA, and based on the present value and fixed interest rate

$$R = \mathrm{WACC} \times (D + E), \text{ where}$$

R = reasonable rate of return after corporation tax, euros
WACC = real reasonable rate of return, per cent
D + E = adjusted capital invested (debt and equity) in the DSO's network, euros

Customer interruption costs decrease the quality bonus that is part of regulation model and thus reasonable return calculation. Quality bonus can be up to 20 % of DSO's accepted profit. CIC values are presented in table 1.

Table 1. Customer Interruption Cost parameters (i.e. unit prices) for 2015 in Finland [6]

Unexpected interruption		Planned interruption		Delayed Automatic Reclosing	High-speed automatic reclosing
€/kWh	€/kW	€/kWh	€/kW	€/kW	€/kW
13,13	1,31	8,12	0,60	1,31	0,66

LITHIUM-ION BATTERIES

Lithium-ion battery chemistries differ from each other substantially - one chemistry has higher energy density, and the other one may last longer in use. That is why choosing the correct battery with correct characteristics for the application is important. The key characteristics when analyzing battery energy storages (BES) for interruption avoidance are:

1. Price (€/Wh , €/W)
2. Power (or current) rating (C-rate = A / Ah)
3. Energy capacity (Wh)
4. Expected lifetime (calendar life, cycle life)

Power rating: C-rate is the value describing how quickly a battery can be discharged. 1 A output power from 1 Ah battery cell equals 1 C (battery empty in 1 hour). Doubling discharge current to 2 A equals 2 C-rate (battery empty in 0.5 hours). In this study kW/kWh was used for C-rate value.
Calendar life: time before battery reaches end-of-life
Cycle life: amount of full charge-discharge cycles battery can provide before reaching end-of-life
Expected lifetime: In this paper lithium-ion battery is considered to have reached its end of life when 20 % of the original capacity has been permanently lost. Battery "end-of-life" is loosely defined but the capacity loss indication needs to be taken seriously as lithium-ion batteries may expose a safety risk if mishandled or used after significant capacity loss [7].

Battery cell has minimum and maximum voltage, maximum charge and discharge current and operating temperature requirements. It is important to understand that li-ion batteries should never be operated outside given limits (i.e. safe operating area).
Three different lithium-ion battery types were chosen for the comparison in this study.
LFP: Lithium Iron Phosphate [Sinopoli]
LTO: Lithium Titanate [Altairnano]
NCA: Lithium Nickel Cobalt Aluminum Oxide [Tesla]

The battery properties are presented in table 2.

Table 2. Battery characteristics comparison [Sinopoli, Altairnano, Tesla]

	LFP	LTO	NCA
Price (€/kWh)	500	1300	250
Power rating	1 C	6 C	0.33 C
Cycle life	2500	15 000	500
Calendar life	15	25	15

Notice: The battery characteristics always leave room for discussion whether the expected lifetime and price is chosen correctly. LFP and LTO values have been taken from datasheets, NCA values from Tesla datasheet.

BATTERY UTILIZATION CYCLE

The battery utilization cycle was created from real interruption and network data from Elenia Oy's network.
Elenia Oy is the second largest DSO in Finland with some 418,000 customers in a 50 000 km2 geographical area. The market share of Elenia Oy is 12% and it has a distribution network of altogether over 65,000 km. It consists of 23,200 km of 20 kV MV lines and 40,600 km of 0.4 kV LV lines. There are also 22,732 pieces of 20/0.4 kV secondary substations. Elenia Oy's distribution network consists mainly of sparsely populated areas, so the development of distribution technology is especially important in the rural area networks [1].
The mass computation was done with the Network Information System for the entire distribution network of Elenia Oy in order to get the dataset for this study. The dataset represented 6320 individual network branches from time period 2013-2015 including exact interruption data and measured power consumptions. Branch maximum load was used to calculate BES power output requirement. Branch average load was estimated to be half of the branch maximum load.
Table 3 presents the average values of the interruptions and the their duration to give the reader an idea of values. It is important to notice that the interruption times and costs were calculated for every branch individually and not using average values.

Table 3. Distribution network branch average values

Average load	32,9 kVA
High-Speed Automatic reclosing	13,0 pc
Delayed automatic reclosing	8,0 pc
Amount of longer interruptions per year	7,0 pc
Average duration of longer interruptions	2,05 h

High-speed automatic reclosing (HSAR): interruption time less than 1 second, automatic reclosing
Delayed Automatic Reclosing (DAR): interruption that lasts less than three-minutes, automatic reclosing
Longer interruptions: interruption over 3 minutes

Figure 2 sums up the proportional size of different interruption types and their effect to customer interruption costs in Elenia's network. Interruptions lasting less than 20 minutes create over one third of all customer interruption costs and less than 2 hours about two thirds of the costs.

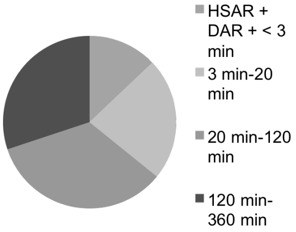

Fig 2. Total CIC per different interruption durations

BES power requirement and battery C-rate value determine the minimum battery size (kWh). Later the battery size directly affects the battery cost (see figure 2). Battery size was chosen for every branch separately based on power requirements of a branch and the battery maximum output power. Minimizing the battery size gives the highest value because most of the time only a fraction of battery energy is used and in the rare cases of long interruptions the battery is unable to supply power for extensive periods. Table 4 presents the duration of BES power output during interruptions. LTO battery provides only 20 minutes of energy because it has higher C-rate than the others and therefore battery size can be smaller.

Table 4. Battery powered supply time of power

	LFP	LTO	NCA
Calculated coverage time	120 min	20 min	360 min

Branches undergo on average 7 longer interruptions per year and 105 longer interruptions during 15 years. This means that the battery calendar life limits the BES usage and cycle life does not. The lifecycle cost calculation is therefore straightforward – cost is the purchase cost of battery and later removing the battery (very small compared to purchase).

There are two factors that can be controlled in DSO application that affect the battery calendar life directly – the biggest factor is storage temperature and second factor is cell voltage during rest. Storing the battery in cool location (below 30 °C) all year around is single most important factor for battery lifetime management.

COST AND BENEFIT CALCULATION OF ENERGY STORAGES

The method for estimating BES cost and benefit is presented in figure 3. First the branch maximum load was retrieved from Elenia's data and that gave the power requirement for BES. Battery C-rate was used to derive minimum battery size that would be able to output the required power for the branch. After knowing the battery size the price of BES was calculated. This cost calculation was made for every network branch.

Minimizing the battery size is the most economical choice, because then the energy stored in the battery is utilized the most in various interruption times.

Battery cost was compared to interruption data and the interruption costs that occur per branch that was also calculated from Elenia's data. Based on interruption durations and available battery energy it was possible to see which interruptions could be covered fully or partially in the branch. This led to avoided interruption cost value.

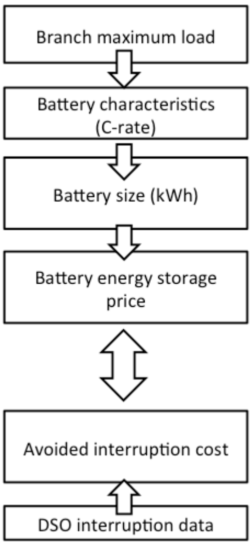

Figure 3. Interruption cost versus battery investment

In the comparison LTO battery gave the best cost-benefit result from the three battery options. Figure 3 presents the payback period for BESs in all the 6320 branches using the sizing and avoided cost method described above.

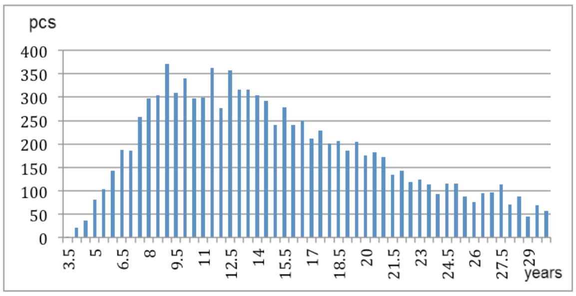

Figure 3. LTO battery payback time per branch

The expected lifetime for the batteries (see table 2) is 15-25 years, which is considerably less, then the payback period. In essence it means that in the branches where payback period is shorter then the battery lifetime, the investment would be profitable. From the picture we can notice that roughly half of the branches fall on the positive side (payback shorter than BES lifetime).

CONCLUSION

Batteries, as a part of LVDC system, that have high power output compared to energy storage total cost can help distribution network companies to avoid interruption costs in financially feasible way. The battery usable lifetime (15-20 years) clearly exceeds the payback period (average 13 years, minimum 3.5 years) in significant number of cases. In several hundreds of branches were batteries identified as being financially profitable as a part of LVDC. Finding the branches that suffer most interruptions because of network faults is a key factor when calculating wide scale financial feasibility and considering locating the battery systems.

It is important to notice that the lowest kWh-price does not necessarily provide financially best solution – battery energy storages must be chosen especially for the application with good knowledge of utilization cycle. In this study lithium titanate battery has clearly highest kWh-price but due high power output characteristics it provides highest value for investment.

In interruption avoidance the value is in avoiding the short interruptions as they can be served with small battery (smaller investment) and short interruptions occur more often.

DISCUSSION

It is important to notice that this paper has introduced battery energy storages as part of LVDC network – in reality LVDC networks are still rare and thus the extra power electronics for AC network was not in the calculations.

One of the important issues which delays the use of BESs by DSOs is the regulation model that doesn't encourage investing in energy storages. Also the possible use of BES to disturb the electricity sales market needs to be taken into account in the future. Some propose third party involvement as a service provider to DSOs but that creates higher operating costs for DSO and thus is against DSO's business interests.

One interesting suggestion is also the voluntary participation of customers for lowering their electricity consumption during battery supply. This would increase the usable time of the battery.

In general, BES solutions still lack the long period experience, before we will see the true benefits that they deliver. The feasibility study shows that BES should be given a proper environment for testings as they have all the potential for both cost savings and improvement of supply quality.

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