A Life Cycle Cost study on the impact of the energy transition on the choice of voltage levels in the distribution grid

A LIFE CYCLE COST STUDY ON THE IMPACT OF THE ENERGY TRANSITION ON THE CHOICE OF VOLTAGE LEVELS IN THE DISTRIBUTION GRID

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ABSTRACT

This paper describes a methodology and results of a case study comparing the Life Cycle Costs (LCC) of four different operation voltage scenarios of a DSO, where large load increases are to be expected due to the Energy Transition in a period of 40 years. The methodology includes quantifying the conversion costs to another network structure, which makes the comparison much less straight-forward than a greenfield approach. Next to these costs, the investments for capacity extensions, maintenance of network components and costs related to Customer Minutes Lost are quantified. The result is a model for estimating the development costs as a function of load growth.

INTRODUCTION

The Energy Transition is expected to bring significant changes in the energy supply of many countries. The exact composition of the future energy mix is still very difficult to predict, as well as the growth of EV and PV use. There is a consensus that the burden on electricity distribution will grow significantly, but also that there is high uncertainty of the growth rate in the coming decades.

Large capacity increases raise the question of keeping or changing the existing network structure(s), as big investments open up a possibility for systematic changes, such as changing the voltage levels.

In the paper a methodology to compare the LCC based on scenarios with different voltage levels are presented. The data is based on the network of the Dutch DSO Liander N.V. The analysed period is 40 years, and with the load varying from 100 % to 300 % of the current level.

Costs involved in obtaining a certain capacity level within the designated time period can be divided into three categories:

- Investments to add additional capacity, and convert the network (or its parts) to another structure and / or voltage level (as needed)
- Maintenance and reconstructions due to initiatives of third parties,
- Costs related to Customer Minutes Lost (CML)

Different cases of LCC analysis are well documented in the literature, especially as analysis of individual substation (SubS) components or individual complete SubS [1, 2]. For a complete voltage level a LCC study can be found in [3].

The aim of this paper is to extend the study object to several voltage levels of a DSO, excluding the low voltage networks. For this reason also a large part of the focus is devoted to the costs needed to convert a part of the network from one voltage level to another, as a greenfield study can also lead to very different results.

The results are formulated as dependent on the load increase and not as a single solution for the most cost effective choice. The estimation of the load growth expected within the 40 year period is left outside of the scope of this study.

NETWORK STRUCTURES CONSIDERED

The four scenarios considered, given in Figure 1, are:

- A - Business as usual, with the transmission part operating at 50 kV and 10 kV levels. The 10 kV transmission is done with N-1 redundant links to switching stations (SS) or voltage control stations (VCS). In a VCS a 20 MVA 10/10 kV transformer is used for controlling the voltage. The distribution is operated at 10 kV,
- B - Complete 20 kV operation, both for transmission and distribution (complete conversion to this level). 20 kV transmission is done with N-1 redundant links to switching stations (SS) or voltage control stations (VCS). In a VCS a 20 MVA 20/20 kV transformer is used.
- C – “20/10 kV substations”, with partial 20 kV operation.
- D - “20 kV backbones”, with partial 20 kV operation: 20 kV transmission and partial 20 kV and 10 kV distribution (without converting the existing 10 kV distribution part, which is connected to the transmission via 20 kV backbones).

By 20/10 kV SubSs, 20 kV N-1 redundant parallel links are considered for connecting the primary SubS (with 20 kV on the MV side) to the 10 kV part of the distribution. Each of these links ends with a single 20 MVA or 40 MVA 20/10 kV SubS, from which multiple 10 kV feeders are branching. The average length of this link is assumed to be 8 km. These SubSs have two infeed versions:

- with a double 20 kV busbar system on the primary side, if partial 20 kV distribution is needed from this station,
- with a cable connection to the primary side, if all outgoing feeders are supplying only 10 kV feeders.

By backbone structures, 20 kV N-1 redundant transport links with a normally open point are considered, connecting the 20 kV transmission to the 10 kV part of the distribution. They contain cable links of 20 MVA, with an average length of 20 km, and on average four 20/10 kV 6 MVA stations per backbone.

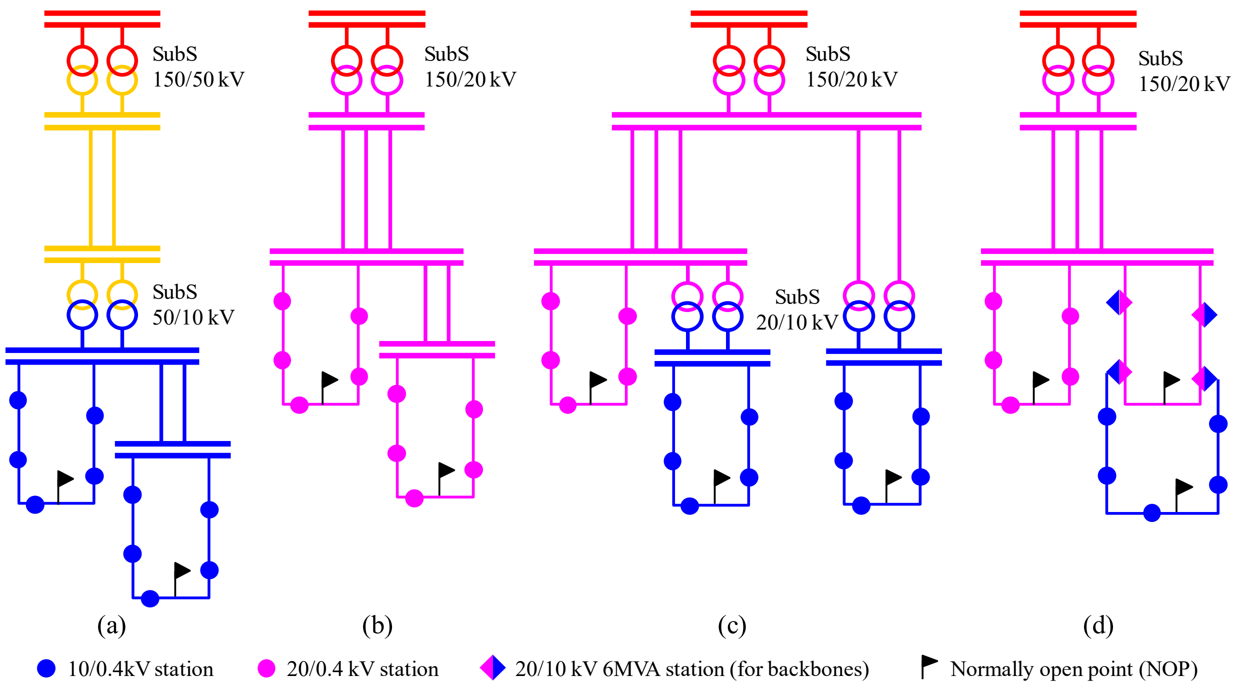

Figure 1. Considered scenarios of network development: a) Business as usual, b) Complete 20 kV operation, c) 20/10 kV substations, d) 20 kV backbones; voltage levels indicated with colors: Red – 150(110) kV, yellow – 50 kV, pink – 20 kV, blue – 10 kV

METHODOLOGY AND ASSUMPTIONS

The load growth consists of two parts: growth by existing clients (due to additional energy use) and growth by new clients (mostly due to new neighbourhoods). From the estimated population growth, and the estimated reduction of persons per household, it is assumed that the number of connections should increase by approximately 5 to 15 % in the analysed time period. This means that the load growth would be caused predominantly by increase of load per customer (at existing connections) instead of a very large amount of new neighbourhoods, where the infrastructure could be built from scratch.

Based on this input, the growth of loading per MV feeder can be calculated, for the 10 kV and 20 kV levels (A – only 10 kV feeders, B – only 20 kV feeders, C and D – both 10 kV and 20 kV feeders used). Due to the increased loading per customer, there is a need to reconfigure the MV feeders for a shorter length to meet the requirements regarding the quality of the supply. This requires additional feeders which can take over a part of the load of the existing ones, and this need is different for 10 kV and 20 kV feeders when comparing for the same cable cross-section – assuming the same standard cable size.

Starting from the current average length of 7.7 km for 10 kV distribution feeders, the average feeder lengths as a function of network loading are calculated, with the results as shown in Figure 2 (min and max from the number of new connections assumed).

For both primary (HV/MV) and secondary (MV/LV) SubSs, it is assumed that the average loading per SubS stays constant and equal to the current average loading. The reason for this is that the risk assessment stays the same for the investment decisions, regardless of the chosen voltage level.

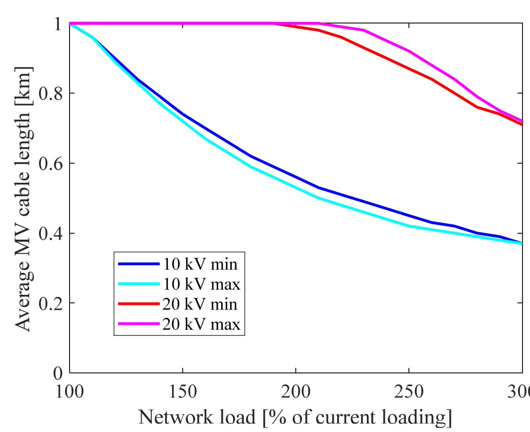

Figure 2. Average feeder length as a function of network loading (and loading per customer)

For distribution cables, in scenario B, the conversion to 20 kV operation is needed for the 10 kV cable network. For this reason, the 10 kV GPLK insulated cables need to be replaced, as they cannot safely operate at 20 kV. The 10 kV XLPE insulated cables can be reused (proven by laboratory testing), but their joints need to be replaced as the 10 kV ones are not appropriate. On the other hand, scenarios which continue using 10 kV cables can also obtain some additional capacity from interventions for maintenance and reconstructions, where a certain amount of cables is replaced every year – in most cases with a higher capacity on those sections. It is also important to notice that for a large load increase it is not possible to make all voltage level conversions before the capacity bottlenecks appear anywhere. This means that even a cable network partly converted to 20 kV (with additional capacity on a part of it) still gets some temporary expansions while on the 10 kV level. This is accounted for with a coefficient of "delayed" conversions, as 10 kV level reinforcements in scenario B.

For scenarios C and D, the existing 10 kV distribution is kept, and the expansions are done with both 10 kV and 20 kV feeders (depending on the local circumstances). It is assumed that at lower rates of load growth it is mostly easier to adapt the existing 10 kV feeders. In case of a very large load growth there would be a need for many more feeders, so the advantage of 20 kV capacity would need to be utilized more often. The relation between the load growth and the share of 10 kV and 20 kV expansions is assumed to be linear, with a starting point at 95 % 10 kV expansions (with almost no load growth) and the end point at 40 % 10 kV expansions (with 300 % of the current loading).

Investments needed for additional capacity and conversion of existing infrastructure

Capacity increase is separated into three categories:

- secondary (MV/LV) SubSs
- distribution MV cables
- transport, including primary (HV/MV) SubSs and transmission MV connections

For secondary SubSs, the capacity increase can be divided into newly built SubSs (additional locations), upgrading of existing ones and conversion of existing ones to the 20 kV level. Out of these options, the cheapest one is upgrading existing 10 kV SubSs with a bigger transformer. This is however possible only in a limited number of stations where the MV switchgear, LV switchgear and space available can support a larger transformer. Replacing existing 10 kV stations with 20 kV stations is the most expensive option, as it requires removing the existing ones. This is necessary to convert the complete or a part of the distribution network to 20 kV, but at the same time creates spare capacity at the given location (which may or may not be utilized dependent on the local load growth).

The additional capacity of secondary SubSs for each scenario is:

- A: $L_{inc}/AL_{sec} = N_{upg} \cdot C_{upg} + N_{new10A} \cdot C_{new}$
- B: $L_{inc}/AL_{sec} = (N_{conv} + N_{newB}) \cdot C_{new}$
- C: $L_{inc}/AL_{sec} = N_{upg} \cdot C_{upg} + (N_{newC10} + N_{newC20}) \cdot C_{new}$
- D: equal to scenario C.

where L_{inc} is the load increase, AL_{sec} is the average loading of a secondary SubS, N_{upg} is the number of SubSs which can be upgreaded, C_{upg} is the average capacity gain of an upgrade, N_{new} is the number of new SubSs needed (different for each scenario and has the 10 kV and 20 kV part for scenarios C and D), C_{new} – is the capacity of a new SubS, which is considered the same for the 10 kV and 20 kV options, N_{conv} is the number of SubSs which need to be converted from 10 kV to 20 kV in scenario B (the current number of 10 kV stations).

For distribution MV cables, the additional cable length is calculated based on the needed capacity, average loading of a feeder and average feeder length. For 10 kV and 20 kV feeders the average length is already discussed at the beginning of this chapter and in Figure 2.

The capacity calculation for distribution cables can be summarized as:

- A: $L_{inc}/AL_{MVcab} = (L_{addA} + L_{M\&R}) \cdot C_{MV10}$
- B: $L_{inc}/AL_{MVcab} = (L_{addB} + L_{pres10}) \cdot C_{MV20}$
- C: $L_{inc}/AL_{MVcab} = (L_{add10C} + L_{M\&R}) \cdot C_{MV10} + L_{add20C} \cdot C_{MV20}$
- D: equal to scenario C.

where AL_{MVcab} is the average loading of MV cables, L_{add} is the additional cable length needed, $L_{M\&R}$ is the total length of cables which are replaced due to maintenance and reconstructions (within 40 years), C_{MV} is the capacity of a MV cable used for expansions (and maintenance) – where the same cross-section is used for 10 kV and 20 kV and L_{pres10} is the present length of 10 kV cables which can also be reused with 20 kV.

For the transport part of the network, there are several parts which need to be considered: the primary SubSs, existing 50 kV cables and N-1 redundant 10 kV cables with switching stations (SSs)/voltage control substations (VCSs).

For the primary SubSs the situation is analogue to the secondary SubSs for scenarios A and B: in scenario A there is a need to expand the existing stations and build new stations as required by the additional loading; in scenario B there is a need to adapt the existing SubSs to obtain the 20 kV level on the MV side and to build new SubSs as needed for the remaining capacity growth (again with the capacity increase due to conversion to 20 kV). Scenarios C and D have the same requirements as scenario B in this part.

A very important aspect of the conversion of 150(110)/10 kV SubSs to 150(110)/20 kV SubSs is the costs additional to the newly built SubSs. This process requires a temporary working condition where both 10 kV and 20 kV are operating, with N-1 redundancy for each of the voltage levels. This involves (in most cases) an additional 150(110) kV bay, temporary 20/10 kV transformer(s) (where the transformers - but not the transformer cells -

can be reused for following SubS conversions), and in many cases a new switchgear building (temporary constructions are also a possibility but mostly avoided in practice). As one example, a short version of the conversion process for a 53 MVA 150/10 kV SubS into an 80 MVA 150/20 kV SubS, including one attached MV ring, is shown in Figure 3. The figure also shows the gradual movement of an additional normally open point (NOP), as the secondary SubSs are converted from 10/0.4 kV into 20/0.4 kV (blue and pink circles in the figure). Scenarios C and D use the same principle as scenario B here.

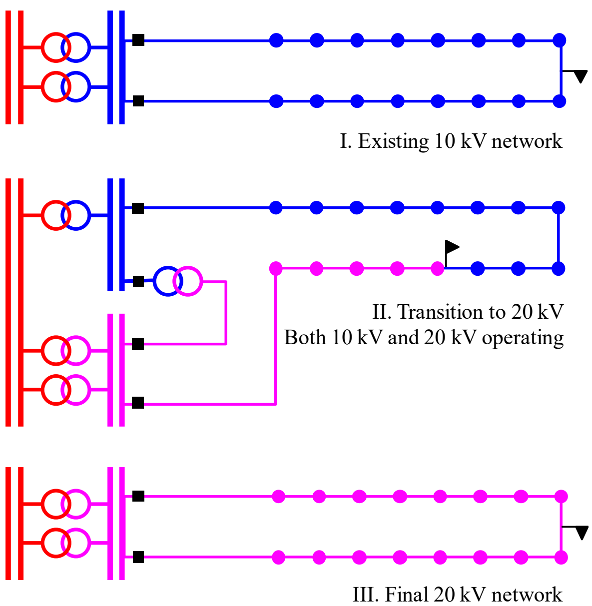

Figure 3. Schematic overview of the conversion of one 53 MVA 150/10 kV SubS into a 80 MVA 150/20 SubS in four steps, including one of the attached MV rings

The existing 50 kV cable network, is included as a future component only in scenario A. Here the expansions are calculated similarly as for the MV cable network, using the required additional power and the current average loading, and a fixed average circuit length. In scenarios B – D, the 50 kV cables are calculated as reused as much as possible at the 20 kV voltage level as N-1 redundant links. Here this includes the XLPE insulated population of the 50 kV cables.

The existing 10 kV redundant links with SSs/VCSs is considered with the largest variety. In scenario A, the percentage of transport done via such links is maintained constant including all network expansions. For scenario B, the same principle is used, but the conversion of such existing links to 20 kV is also needed, and also the existing 50 kV cable network into the redundant 20 kV circuits with VCSs instead of 50/10 kV SubSs. Scenarios C and D have in this case different requirements than B, as conversion from 20 kV to 10 kV is needed for the part of distribution which still needs to operate with the 10 kV voltage level.

Scenario C converts 20 kV into 10 kV via N-1 redundant 20 kV cable links and 20/10 kV SubSs (also explained in the second chapter). These structures are gained from converting similar 10 kV structures and the 50 kV part of the transport, with additional structures required to cover the complete current 10 kV distribution. Their expansions are calculated based on the load increase and a fixed average loading level.

Scenario D converts 20 kV into 10 kV via backbone structures, explained in the second chapter. Laying these structures is required for the entire current MV distribution. Their expansions are calculated based on the load increase and a fixed average loading level.

Costs related to maintenance and reconstructions

The costs of maintenance are calculated per category of network components based on the estimated population aging and planned replacement cycles. This is calculated for secondary SubSs, MV cables, 50 kV cables and primary SubSs. For new equipment, both added as expansions and conversion of existing assets, it is assumed that no significant costs due to aging appears within the 40 year period. In this respect large network changes, in scenarios B – D, have much lower costs.

Reconstructions, like initiatives of third parties, are also calculated based on the current experience – mainly affecting the 10 kV and 50 kV cables (e.g. moving cables due to construction of highways, canals, etc.) and can be expressed as km of cables/year which need to be replaced. These costs appear in all scenarios.

Costs due to customer minutes lost

The current practice of quantifying costs due to CML is based on an average amount per customer per minute (presently one euro). The average amount of minutes lost per customer is approximately 20 minutes per year for this DSO. Out of this amount, the impact of the transport network is very limited in most years, the impact of distribution is 12-13 minutes/year and the impact of LV distribution contains the rest but is out of scope here as the LV structure can be equivalent in all four scenarios.
To compare the scenarios in this respect, the change of average MV feeder length and number of customers per feeder is compared (due to the dependency from the loading level) as a source of relative change of the current number of CML. Additionally, in scenario D, the impact of automated 20/10 kV 6MVA stations is assessed as a way to limit the reparation time of faults within 20 kV backbones (the 20 kV backbone does not contain redundancy by parallel cables, but automatic switching allows very quick network reconfiguration).

RESULTS

The costs for all four scenarios, given as a minimum and maximum value to account for uncertainty, are shown in Figure 4 - Figure 6 for the transport, MV cables and for the secondary SubSs The total costs of all network parts are shown in Figure 7.

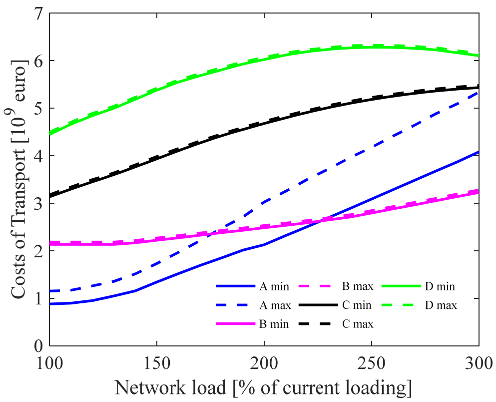

Figure 4. Costs of the transport

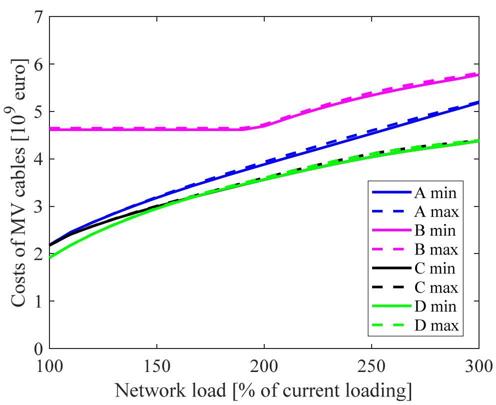

Figure 5. Costs of distribution - MV cables

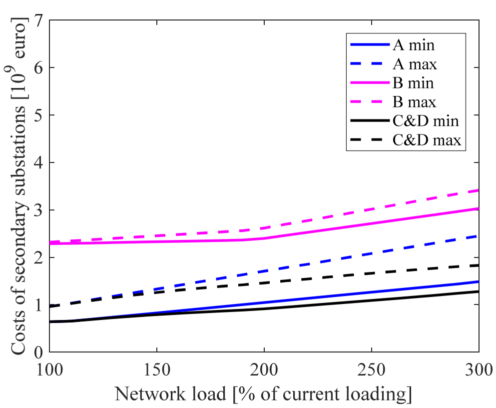

Figure 6. Costs of distribution - secondary SubSs

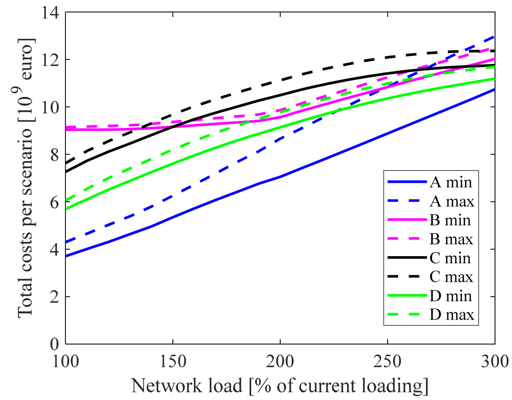

Figure 7. Total costs (minimum and maximum) of the four considered scenarios

CONCLUSIONS

This paper describes a methodology and results of a case study comparing the Life Cycle Costs of four different development scenarios of the Dutch DSO Liander N.V., for the period of coming 40 years. The results show the costs to maintain or convert the existing network structures for the loading between 100 % and 300 % of the current level.

The results are quantified as dependent on the loading level, and there is no scenario which is most efficient for any value of the loading. It can be seen that the current structure is competitive even at high levels of load increase. This is due to the very large share of costs related to MV distribution, where a very significant amount of investments in needed to convert to 20 kV operation. With transport, conversion to other types of structures becomes competitive even at slightly lower levels of load increase. At very high levels of load increase other structures start gaining advantage over the current one, due to the higher capacity per substation and MV link. It is however out of the scope of this study to estimate the loading level after 40 years, and the tempo at which this increase would occur.

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