OPTIMUM RESTRUCTURING OF LOW VOLTAGE DISTRIBUTION NETWORKS

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1 SUMMARY

This paper presents several re–configuration scenarios of rural low voltage distribution networks which are often constructed with overhead line systems. Mainly the optimised restructuring with new insulated overhead lines and cable systems are discussed. Several planning variants are compared on the basis of a detailed cost model. The analysis of the results gives important hints for the development of future planning strategies.

2 INTRODUCTION

The liberalisation of the European electric power industry is forcing the utilities to plan and operate their distribution networks more economically than in the past. One of the most important aspects for achieving this aim is not only to use existing cost saving potentials, but to make use of the capacity of both the lines and transformers to their load limits. Especially in the area of the network planning, the economical aspects of redundancies, which typically result from the usage of the (n-1)–principle, are being intensively and critically discussed. These aspects are gaining more and more importance with respect to the fact that huge parts of German low voltage distribution networks have to be renewed in the hear future because of their age.

This paper presents the results of a study on low voltage networks which tries to define rules for a new planning strategy for restructuring these networks. The new rules are derived from the analysis of several restructuring variants of a real low voltage distribution network which has a typical structure for rural distribution networks.

3 PLANNING SCENARIOS

The examined distribution network has a low load density which is typical for rural networks. While the largest part of the network consists of overhead lines a small number of customers in a newer residential area of the village is connected by cables. The total load of about 1 MVA is fed by 5 substations, which supply about 400 private customers. Some of the customers use night storage heating. There are also a few public and industrial consumers. Two of them have a total load of 100 kW.

First of all the target is to find out if there are cost saving potentials in this network and how to exploit them in short term. If this could be reached operational costs could be reduced and the reinforcement of the existing network could possibly be delayed or would not be necessary at all. If the network has to be reinforced the necessary investments and operational costs of the old and new resources have to be taken into account. Therefore in the next step new network structures with minimal operational costs are generated having a leaner construction with only the essential resources. These structures avoid redundancies as e.g. ring structures.

Since the reinforcement of the network is necessary anyway because of older resources having to be replaced by new ones in the next few years the question has to be answered whether the structure of the new network should use cables instead of overhead lines because of their lower operational costs or not. Besides this, the most economical way to route has to be determined.

The solutions to all the above questions can only be found on the basis of enough detailed models for the distribution network and the calculation of the costs. This should be focused in the next section.

3.1 Models

Network model The low voltage distribution network has been examined with the help of the network planning system IONN (interactive optimised planning of low voltage distribution networks) [1], which enables the planning engineer to analyse and optimise low voltage networks.

The correct modelling of the network data requires

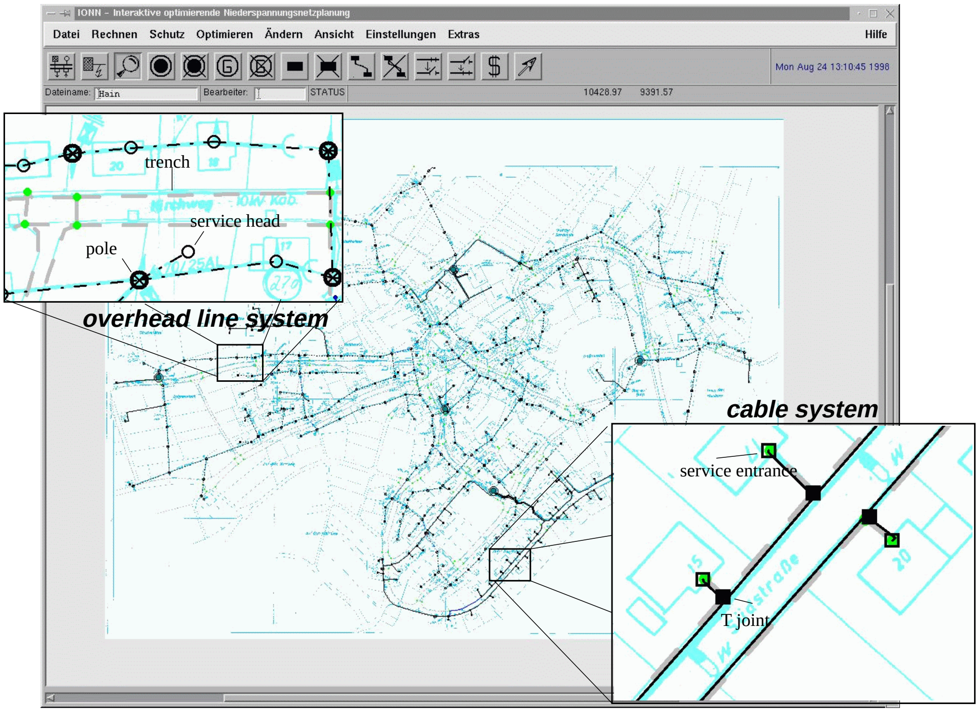

Figure 1: Digitised low voltage distribution network

a very detailed representation of the exact positions and routings of the lines and cables, so this has to be done with the help of the on–screen digitising capabilities of IONN. Figure 1 shows two sections of the network with overhead lines and cables in detail.

In the further process of this study routing problems to find the minimum spanning cable trees have to be resolved. So in addition to the existing cables, potential new routes of new lines of cables, i.e. new trenches, have to be constructed too. All consumers are handled as network–nodes. Their load characteristics can be modelled with the help of *typical consumer classes* having typical load profiles [1]. The necessary information for this model can be accessed through a consumer–data base which contains the energy–consumption and in a few cases the peak–power of the consumers.

Cost model To evaluate the economics of a planning variant both the investment costs and the yearly costs have to be taken into account. To do so the total cash value B for a certain planning horizon of n years has to be calculated. With the rate of interest p and $q = (1 + \frac{p}{100})^n$ the total cash value is given by

$$B = \sum_{i=0}^{n} A_i \cdot q^{-i} - R_n \cdot q^{-n} \tag{1}$$

A_i are the yearly costs caused by the investments and operational costs.

The cash value $R_n \cdot q^{-n}$ of the remaining value R_n allows us to evaluate the remaining value of the network at the end of the planning horizon.

So the following five cash values have to be taken into account to find the total cash value of the network:

B_I	investment costs for new resources
B_D	cash value of the costs for dismantling existing resources
B_R	cash value of the remaining value of the network
B_PV	cash value of the costs of losses
B_B	cash value of the maintenance costs

The yearly costs are split into two parts: the costs of losses and the costs for the maintenance of the resources.

The calculation of the costs of losses can be done using the well–known approach in [2] by calculating both the costs of power and energy losses. On the basis of long–term studies there exists a detailed data base on the maintenance costs of each type of resource like lines, substations and transformers as well as cabinets, service heads and the poles. Because of the importance of the maintenance costs of the two concurring systems, overhead lines and cables, the corresponding values of maintenance costs are explicitly listed in table 1. All cash values are evaluated on the basis of a planning horizon of 20 years.

Table 1: Relative maintenance costs of several types of lines

type of line	rel. maintenance costs in %
overhead line	300
insul. overhead line	210
cable	100

3.2 Restructuring the current network

To find the short–term cost saving potentials an analysis of the current state of the network has to be done with the help of a load flow calculation. This allows us to calculate the minimum voltages of the nodes and the daily load profiles of the lines. The network is divided into several distribution areas with one substation each, which are separated by separation points. The costs of this network which are listed in table 2 are used as a reference for all further planning scenarios in this paper. The total length of all lines in the net is 11455 m. Since this is the current state of the network there are no costs for new investments and dismantling of resources assumed. One typical property of rural networks is the dominance of the maintenance costs in comparison to the costs of losses, which are only about half of the maintenance costs. The total cash value of the current network is set to 100 % and all costs which are calulated in the further process of the paper refer to this value.

Table 2: Percentage costs of the current network

B_I	B_D	B_R	B_B	B_PV	B
0	0	-16	73.6	42.4	100

Because of the low load density the results of the load flow calculation show no overload on transformers and lines but the maximum allowable voltage drop $\Delta U_{max} = 10$ % is reached in the outer regions of the network.

3.2.1 Optimum separation points

The current network will be called S in the further process of this paper. The first possibility to save costs is the optimisation of the borders of the various distribution areas, the so–called *optimisation of separation points*. These points are shifted in such a manner that a given objective – in this case the costs of losses – can be minimised. The resulting network variant is V1.

Obviously the cost savings especially for the costs of losses $\Delta B\_PV = 6.7\%$ are lower as one can expect in urban distribution networks [1]. Nevertheless a huge cost saving potential can be expected through this sort of optimisation, which is shown by the diagrams of loads and voltages of lines, transformers and nodes. Figure 3 shows the gain in load reserve g, which results especially from the increase in the reserve of transformers and node voltages. The diagrams contain the gain for the most significant resources, in the case of the lines those with the highest load. The maximum load of the transformers can be decreased by about 15 % because of the more homogeneous distribution of the load on the various transformers. Most of the transmission lines only have a maximum load of about 50 %. So small increases of the load of some lines which can be seen in the diagram have no significant negative influence on the available capacity in the network.

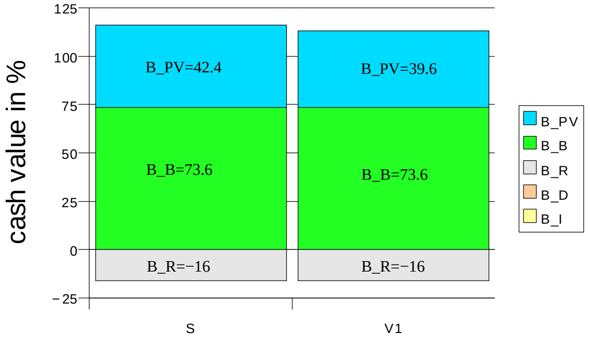

Figure 2: Costs after the optimisation of the separation points

The most important aspect in rural networks is to operate the net with allowable voltage drops. The diagram with the changes in the voltage drops shows that a general decrease in the maximum voltage drop of about 3 % can be reached with the help of the optimisation of the separation points. So a potential raise of 25 % of the loads of all private consumers can be handled without exceeding the allowable voltage limits. Future investments which are often needed to keep the correct voltage drops can be avoided or at least delayed. Another positive aspect is the higher robustness of the network against load changes.

The maintenance costs are independent from the location of the separation points. But now the reserves of the resources can be used to get a leaner network by dismantling those resources which are only built to get rings for higher nodal voltages. In addition to this, maintenance costs can be saved by reducing the redundancies in the network.

To construct a leaner network the following approach has been taken for the overhead lines as well as for cables:

- removal of currentless lines
- removal of poles and cabinets which are not used

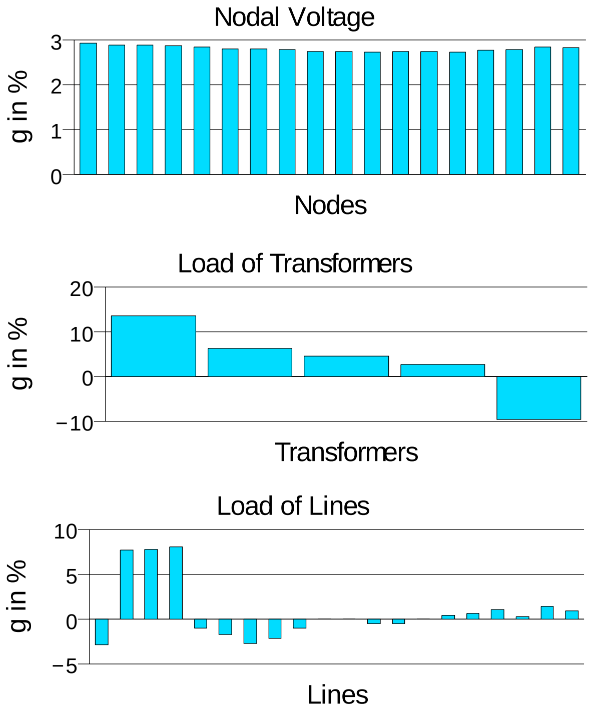

Figure 3: Gain in reserve for the resources

for distribution purposes

- fitting the routing of the overhead lines to the new topology
- removal of rings

The costs of losses for the resulting leaner planning variant are about the same as the costs of V1. But because of the leaner structure the total length of the network can be reduced by 7.3 % and the resulting maintenance costs can be reduced by about 8 %. So the range of cost savings is significantly higher than the additional costs for the dismantling.

Apart from this possibility to save costs by reducing the network, huge parts of the overhead lines have to be replaced in the near future because of the age of these resources. So every utility has to decide the principle question whether the most efficient way is to reinforce the network with new overhead lines or cables.

3.2.2 Reinforcement with Overhead Lines

Firstly a new planning variant with insulated overhead lines will be examined. All resources of the existing conventional overhead line system are replaced by insulated overhead lines which have lower maintenance costs. There are two basic ways to do this:

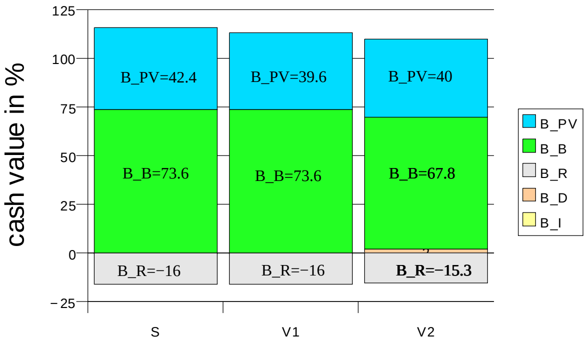

Figure 4: Costs of the leaner network structure

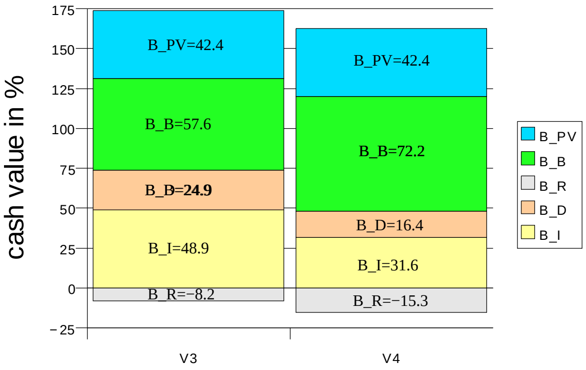

Figure 5: Static and dynamic reinforcement by insulated overhead lines

1. The static approach V3 where all lines are replaced at once.
2. The dynamic approach V4 where each overhead line is replaced by a newer one after its service life is over.

The diameters of the old and new lines are the same.

Figure 5 shows the costs of the variants V3 and V4. The premature replacement of the existing lines in variant V3 leads to a 13.1 % loss of the remaining cash value of the network V3. In the diagram this is included in the low remaining cash value of variant V3.

The results show that in spite of the lower maintenance costs the premature replacement is not the most efficient way of the reinforcement. This is due to the higher investment and dismantling costs as well as to the lower remaining value. So it is recommended to do the reinforcement as the equipment reaches its maximum service life dynamically.

Secondly it is possible to do the reinforcement by building a cable network rather than on overhead line network. The efficiency of this approach will be discussed in the next section.

3.2.3 Reinforcement with new cables

In comparison to overhead line systems cable networks have lower maintenance costs, higher reliability and higher capacities. Another reason to install cable systems is the poor optical appearance of overhead lines. Nevertheless the investment costs for cables are enormous so the decision should be taken carefully. In this paper the economy of cable networks as a long–term alternative variant to overhead line systems is examined by using an optimisation approach, which will be presented in the next paragraph.

Optimisation approach On the basis of a given topology of trenches, which represents routing possibilities for new lines between two connection points, the set of the load nodes Ω_L has to be connected in the most cost–efficient way. Ω_L is only a partial set of the set Ω_K of all nodes to be constructed because additional distribution nodes as cabinets and T joints are taken into account. So not only the optimum routing of an unknown number of cables but also the set of necessary distribution nodes for connecting these lines has to be determined.

This optimisation problem can be simplified by using an objective function which exclusively represents the total sum of investment costs of new resources. So the result of such an optimisation approach is a minimum spanning cable tree with a minimum length, i.e. with a minimum amount of underground construction and material costs.

Today such optimisation tasks are handled with the help of global optimisation methods. Their biggest advantages against other heuristic approaches are their high robustness, the ease of implementation and their flexibility. The most important members are the *genetic algorithms*, *simulated annealing* and *tabu search*.

In this paper the simulated annealing [3] method is used because of its success in other areas of optimisation which are treated with IONN [1].

The principle process of simulated annealing is given by algorithm 3.1.

Starting from an initial solution i_0, which represents the set of all nodes $\in \Omega_K$, new configurations are generated stepwise by "small" changes $m_{i,j}$ for a temporarily fixed control parameter. In this application the removal or addition of a randomised selected node — which is not a load node — corresponds to such a small change. The objective function O describes the investment costs which have to be paid to build the minimum spanning network between all nodes $\in \Omega_K$. The acceptance probability has a value of 1 if the new configuration has a better objective value than its successor. Worse configurations are accepted with a probability of $e^{\frac{-\Delta O}{c}}$. After a certain number of migrations the stationary distribution is reached and the acceptance threshold can be decreased. This process will be repeated until no allowable new states can be generated.

Algorithm 3.1 Simulated annealing

```
given:
  initial configuration $i_0$
  Start control parameter $c_0$
  objective function $O$
  random generator Rand(0,1) produces values in range [0,1]
begin
  $i := i_0$
  $c := c_0$
  repeat
    repeat
      generate randomly $j = i \oplus m_{i,j}$
      $\Delta O := O(j) - O(i)$
      if ($\Delta O < 0$) or ($e^{\frac{-\Delta O}{c}} >$ Rand(0,1)) then
        $i := j$
      end if
    until stationary distribution is reached
    decrease $c$
  until stop criterion
end
```

The underground construction costs for the minimum cable network can be calculated on the basis of the topology of trenches where the branches — the trenches — are weighted with the costs of each trench. Such a minimum spanning tree can be generated with the help of Kruskal's algorithm [5]. The weights depend on different costs for several sorts of trenches. For example street crossings are about twice as expensive as normal trenches in the sidewalk.

Apart from this the investments for the additional cabinets and T joints have to be taken into account, so the best solution represents a compromise between the minimum number of nodes and minimum investment costs for new lines. Figure 6 shows the costs of both the cable variant V5 and the already discussed variant V4 with new overhead lines. The routing of the new cables has a big influence on the topology of the existing network. So only a static approach can be used to determine the investment costs. But this flaw does not affect the most important message of figure 6.

First of all it can be noticed that the ideal cable network reduces the total length of lines by about 5 %. As expected the maintenance costs can be reduced, too, and the costs of losses decrease because of the larger diameter of the used cable type (150 mm^2). But these cost savings and the higher remaining cash value cannot compensate the high investment costs for underground construction.

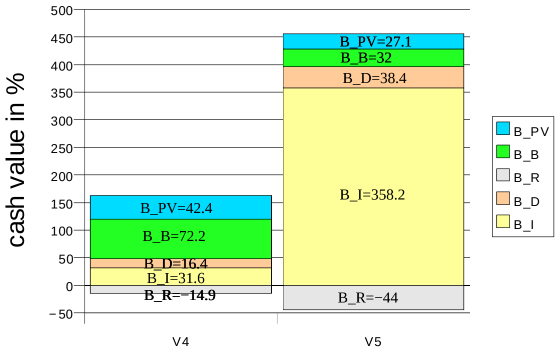

Figure 6: Costs of the new cable network

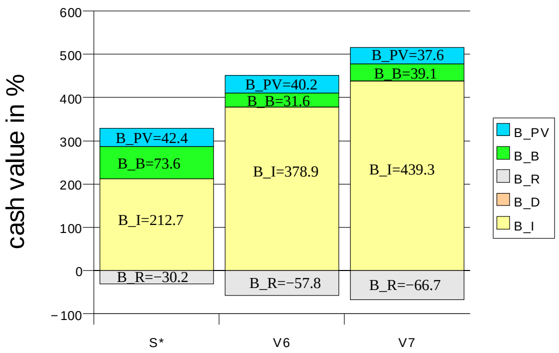

Figure 7: Costs of new cable networks with one and two–sided cable trenches

These results raise the question about the terms under which the cable network could be the most efficient structure. So a new cable network which feeds all the loads including the consumers who are connected to the existing cables will be generated to achieve the theoretically reachable optimum as a lower limit for all possible planning variants. This solution can be found with the above presented algorithm 3.1. On the basis of the resulting cable network, the optimum locations of the new substations are generated with an approach described in [4]. The resulting variant V6 is compared with the costs of the current network for the hypothetical case that this net will be rebuilt today in the same manner and with the same resources.

First there are two remarkable aspects: the total length of the network can now be reduced by about 13 % with the effect that the cash value of the costs of losses remains at the same level as the current state in spite of the larger diameter of lines.

Although the cable variant has a better initial situation with its optimised station locations it remains about 30 % more expensive because of its costs for underground construction. So it can be stated that the cable network can only be an economic alternative to overhead line systems in the case of significantly lower investment costs or co–laying possibilities.

The routing of cable networks on both sides of the street is another way to build cable networks which can be often found in practice. The variant V7 of figure 7 represents the optimum way to realise this strategy. This variant is generated by penalising the trenches of street crossings with very high underground construction costs. The total cable length of this variant increases by about 22 % in comparison to the current state so the investment costs increase too. Therefore the building of cables on both sides of the street cannot be recommended for distribution networks with this low load density.

4 CONCLUSION

In this paper several planning alternatives for restructuring an existing low voltage distribution network with overhead line systems are investigated. This has been done based on a detailed model for both the network and the costs. It can be shown that an optimisation of the separation points lifts the nodal voltages by about 3 % so the building of new resources can be avoided or at least delayed. It is recommended that future reinforcements should be carried out in a dynamic way with clear topologies without redundancies. Cable networks are economical alternatives to systems with insulated overhead lines only for those cases where the costs for underground construction can be reduced significantly. In such cases routing in one trench per street represents the most economical process.

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