COMPUTER-AIDED DISTRIBUTION NETWORK PLANNING USING EXPERT RULES

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ABSTRACT

This paper presents a computer-aided planning tool for the capacity planning of medium voltage distribution (MV-D) networks. Requirements originating from network planning practice are incorporated in an expert system. The proposed approach focusses on finding the locations and type of assets that satisfy topological, geographical, and operational constraints. The main principle of the approach is to start with all possible expansion options and then to reduce the number of these expansion options significantly by using expert rules based on established network planning practice. Practically feasible expansion options are modelled automatically to evaluate if they offer a solution to bottlenecks. Finally, a performance indicator is calculated to evaluate and select the expansion options. An example case is used to illustrate the planning tool. Goal of the tool is to support planning of MV-D networks in practice.

INTRODUCTION

Distribution Network Operators (DNOs) require more advanced planning tools to deal with the challenges of future network planning. New technologies, are often connected to the distribution part of the electricity network (e.g. distributed generators, electric vehicles, and heat pumps) as a result of the on-going energy transition. These technologies complicate the planning process and solutions become less straight-forward. Nevertheless, generation of alternative expansion plans is still done by hand [1]. This makes the process labour-intensive to assess various bottlenecks or scenarios and open to inconsistency and subjectivity. Automated generation and evaluation of expansion options can support the planning process [1],[2]. Therefore, this paper will focus on a computer-aided planning tool for the capacity planning of medium voltage distribution (MV-D) networks.

Requirements originating from network expansion planning practice are translated into if-then rules like in an expert system. An expert system is particularly useful for translating expert knowledge into a computer system. Additionally, an expert system increases the reliability of decisions, and offers an explicit explanation of how a decision was reached [3]. The proposed approach focusses on finding the locations and type of assets, in our case MV-cables, which satisfy topological, geographical, and operational constraints. The main principle of the approach is to start with all possible cable expansion options and then to reduce the number of these expansion options significantly by using expert rules based on established network planning practice.

The first section will present an overview of common bottlenecks found in the Dutch MV-D network resulting from interviews with DNOs. The second section will describe the tool. The third section will offer an example case. The fourth and final section contains a summary and conclusions.

COMMON BOTTLENECKS IN MEDIUM VOLTAGE DISTRIBUTION NETWORKS

Dutch MV-D network have a “European” distribution layout in which meshed networks are operated radially by Normally Open Points (NOPs) [4], like the example in Fig. 2. This means that the network can be reconfigured in situations of emergency or maintenance. Moreover, nearly all Dutch MV-D networks consist of underground cables.

From interviews with experts working in the field of MV-D network expansion planning, common bottlenecks and their solutions are gathered as they occur in practice. The main capacity and voltage bottlenecks in the MV-D networks are:

- *Overloaded cable*, where cables are loaded beyond their allowed level according to DNO design criteria or manufacturer specifications.
- *Lack of reconfiguration possibilities*, where MV-D network segments cannot be reconfigured due to capacity limitations or reconfiguration requires more than a specific number of steps.
- *Voltage level problems*, where node voltage levels are too high or too low as specified in DNO design criteria or manufacturer specifications.
- *Overloaded MV/LV transformer*, where transformers are loaded beyond their allowed level according to DNO design criteria or manufacturer specifications.

Each of these bottlenecks can be resolved in a number of ways. The ones most commonly applied in practice are listed in Table 1 (see Fig. 2 for terminology).

Table 1: Common capacity and voltage bottlenecks in MV-D networks and their solutions

Bottleneck	Solution
Overloaded MV cable	Add a new cable or replace an existing cable of small cross-section.
	Transfer MV/LV-transformer substations and/or MV-customer connections to a different feeder
	Moving normally open points
Lack of reconfiguration possibilities	Add a new cable or replace an existing cable of small cross-section.
	Connect an emergency generator in emergency situations (instead of reconfigured network operation).
Voltage level problems	Improve transformer control of HV/MV or MV/MV transformer
	Transfer MV-customer connections with distributed generators to different feeders
	Add a new cable or replace an existing cable of small cross-section.
Overloaded MV/LV transformer	Exchange the MV/LV-transformer
	Add an additional MV/LV-transformer substation

From Table 1 it can be concluded that most common bottlenecks in MV-D networks can be solved, or are at least influenced, by the addition or replacement of MV cables and MV/LV transformers. However, the expansion of MV/LV transformers is in practice a standardized and straightforward process [7]. Therefore, the proposed MV-D network planning approach in the next section will focus on cable additions.

MEDIUM VOLTAGE DISTRIBUTION NETWORK PLANNING APPROACH

As future power flows are uncertain, DNOs are reluctant to act on long-term projected bottlenecks. However, short-term bottlenecks (that are already in place) will have to be dealt with. This causes network expansion planning problems in practice to be viewed as one-step (static) planning problems based on confirmed bottlenecks. The proposed planning approach will provide expansion options for these kind of planning problems.

An automated planning tool features three main steps: identification, evaluation and selection [2]. An approach is developed to implement these three steps as illustrated in Fig. 1. At the start, all possible cable additions (all connections between any two nodes) are identified. Identification of practically viable expansion options is done by using expert rules to discard as many non-practical expansion options as possible, based on established network planning principles. These expert rules are grouped by category: topological constraints, geographical constraints, and bottleneck-focused constraints. Next, evaluation of the remaining expansion options is automated. This includes finding new NOP locations and performing power flow calculations. Using these power flow calculations, cable loadings and node voltage levels are evaluated during normal operation and reconfigured operation. Finally, a performance indicator is calculated for all remaining expansion options to produce a sorted list of practically viable expansion options. The proposed approach is not an optimization method like in [5]. Solutions might differ from those from an optimisation method.

As the focus is on cable additions, the expansion options are saved as a matrix featuring all combinations of two nodes that can be connected by a cable. Only one half of the matrix is used as it is a symmetrical matrix.

The approach is implemented as an addition to Vision Network Analysis [6] and uses several evaluation

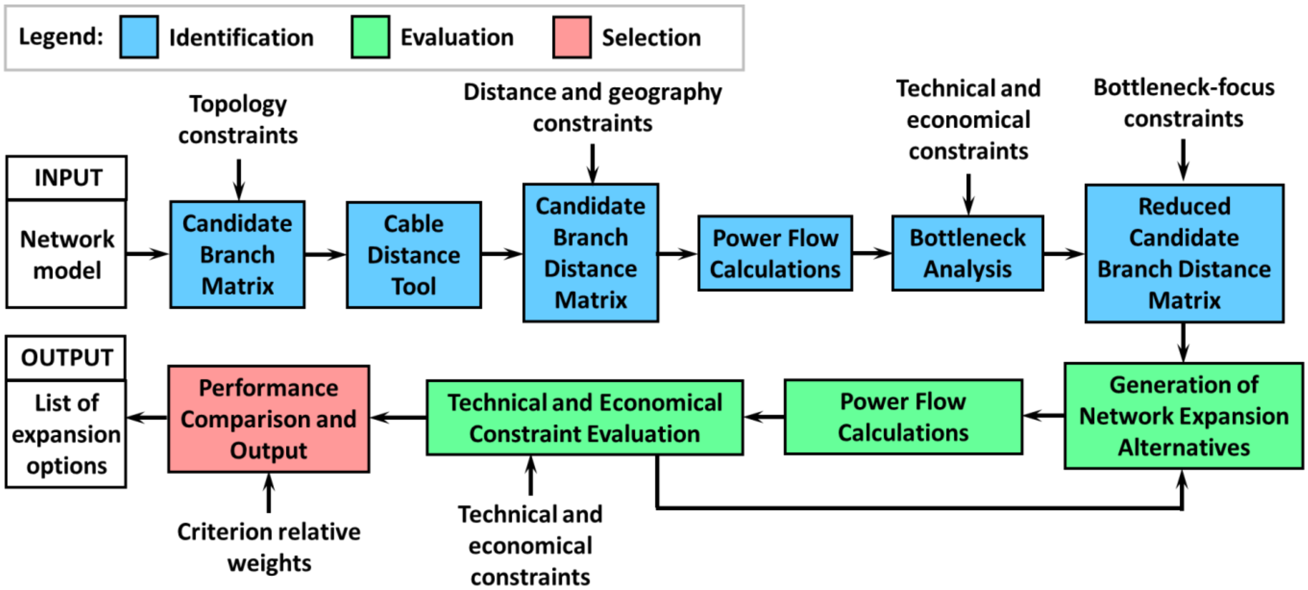

Fig. 1: Overview of an automated MV-D network planning approach using expert rules

routines available in this software. The consecutive steps are explained further in the following sections.

Identification step

Identification of viable expansion options is done by starting with all possible expansion options and eliminating as many as possible based on expert rules derived from established planning practices.

The elimination steps are divided into three categories: topological constraints, geographical constraints and bottleneck-focus constraints. This saves calculation time as not all elimination rules have to be evaluated on the full set of expansion options. Expansion options eliminated in previous steps do not have to be tested again. The division into three categories can be done as the categories offer constraints that can be grouped together and can be tested independently from each other. Additionally, some calculation steps are required before the constraints can be evaluated. For example, before geographical constraints are tested, cable routes have to be estimated. Between each elimination step, a calculation step is done on the remaining expansion options, respectively the cable distance tool step and the power flow calculation step. Additionally the matrix used to store the expansion options is saved after each constraint evaluation and is named respectively the Candidate Branch Matrix (CBM), the Candidate Branch Distance Matrix (CBDM) and the Reduced Candidate Branch Distance Matrix (RCBDM), see Fig 1.

Topological constraints

Topological constraints focus on the topology of the network. Certain topological connections are not allowed by design guidelines and criteria. In this method the constraints are translated into the following rules:

- *If* the nodes of an expansion option are in the same feeder group, *then* remove the expansion option from the set.
- *If* the nodes of an expansion option already has a cable in between, *then* remove the expansion option from the set, unless the cross-section is below the threshold for replacement.
- *If* one of the nodes of an expansion already has the maximum allowed number of connections, *then* remove the expansion option from the set.
- *If* the expansion options connect two MV-T substations, *then* remove the expansion option from the set.

The resulting expansion options are stored in the CBM.

Cable estimation

Before geographical constraints can be tested, the cable routes of the remaining expansion options have to be estimated. The cable length is important to determine the impedance of a new cable, the corresponding investment costs, and to discard expansion options based on distance. The cable-length estimation is done using a route planner. The route is estimated using public roads and a pedestrian mode of transportation. This is a valid approximation as cables are often placed along public roads to ensure accessibility for repairs.

Geographical constraints

If the cable routes are estimated, geographical constraints are tested. In this method these are translated into the following rules:

- *If* route estimation of a cable expansion option fails (for example due to missing geographical data), *then* remove the cable expansion option from the set.
- *If* the distance of a cable route is longer than D_{max} (case dependent) *then* remove the cable expansion option from the set.
- *If* the nodes of an expansion option are a MV/LV transformer substation and an MV-T station respectively, and a shorter connection between the MV/LV transformer substation and another MV-T station is possible, *then* remove the cable expansion options from the set.
- *If* the nodes of an expansion option are both MV/LV transformer substations and both have a possible connection to an MV-T substation that is shorter, *then* remove the cable expansion option from the set.

The resulting expansion options are stored in the CBDM.

Power flow calculations

Power flow calculations are performed to determine cable loadings and node voltage levels. This is done for both normal operation and multiple reconfigured states. In reconfigured operation a cable (section) is isolated and all substations are fed via the closing of NOPs. In our routine only one switching action is allowed for reconfiguration (i.e. one NOP is closed), which is the most conservative criteria. The most extreme current level in each cable, and the most extreme node voltage levels (high and low), are determined for all reconfiguration states. Additionally, for cases with distributed generation, this is done for both the load-only and generation-only situations, where respectively all generators and all loads are disconnected for the analysis. The DNO's goal is to find the highest (worst-case) possible loadings of MV-D cables. The power flow calculations use deterministic peak load values, as is common for MV-D network modelling.

Network analysis

The results of the power flow calculations are compared with the (user configurable) design criteria in Table 2. This is done to find the bottleneck, or the greatest bottleneck, if there is more than one. The location of the bottleneck in a network is important to find appropriate expansion options.

Bottleneck focus constraints

Expansion options are limited to nodes within the feeder group of the bottleneck, meaning all nodes in the feeders connected to the bottleneck without traversing an MV-T substation. This is done as expansions outside this region will have relatively little effect on the bottleneck. This is done with the following rule:

- *If* none of the nodes of a cable expansion option is within the feeder group of the greatest bottleneck, *then* remove the cable expansion option from the set.

Table 2: Maximum allowable loadings and voltage limits

Criteria	Operation mode	Set limit
Cable current load level	Normal operation	$I < 1{*}I_{nom}$
	Reconfigured operation	$I < 1.3{*}I_{nom}$
Node voltage level	Normal operation	$0.9{*}U_{nom} < U < 1.1{*}U_{nom}$
	Reconfigured operation	$0.9{*}U_{nom} < U < 1.1{*}U_{nom}$

Evaluation step

Evaluation of the remaining expansion options is done by modelling them one by one. This includes adding the cable, the circuit breakers and NOPs (to ensure radial normal operation). NOPs are placed where they minimize peak losses.

Power flow calculations are done to assess if the network expansion satisfies the design criteria as shown in Table 2. If a network expansion does not satisfy these criteria it is removed from the set at this point. Of the accepted expansion options several performance values are calculated to assess how well the network expansion performs. These performance values are:

- Maximum current load level in all cables, normal operation.
- Maximum current load level in all cables, reconfigured operation.
- Maximum node voltage margin, normal operation.
- Maximum node voltage margin, reconfigured operation.
- Combined peak losses in all cables during normal operation.
- Investment costs as determined by the cost of the added cable (including digging costs), the added circuit breakers, and the cost of moving NOPs.

Selection step

The remaining expansion options are sorted by a performance indicator. This indicator is calculated using the weighted product model [7] as shown in (1). This model is suitable since all performance values have to be good to achieve a good performance indicator. A bad performance value in one category is not compensated by a good performance value in another category. Each performance value of each expansion option is first divided by the worst case of the relevant performance value in the remaining set. This makes the resulting value dimensionless which enables the comparison of values with different dimensions. The assigned weights can be altered depending on their importance on a case by case basis.

$$P(A_k) = \prod_{j=1}^{n} \left(\frac{a_{k,j}}{a_{worst,j}} \right)^{w_j} \qquad (1)$$

where,

$P(A_k)$ is the performance of alternative k,
$a_{k,j}$ is the value of alternative k for criterion j,
w_j is the assigned weight for criterion j.

EXAMPLE CASE

To illustrate the method described in the previous section, an example case is presented. Fig. 2 shows a simple MV-D network consisting of three feeders and one MV-T substation (node 1). The blue and red circles are distributed generators and loads respectively; their size is an indication of their power. Orange cables contain the NOPs. The greatest bottleneck in this network is the cable between node 1 and 16 in the reconfiguration state where the cable between nodes 1 and 31 is isolated. The feeder on the right is in that case connected to the middle feeder by closing the NOP. Additionally, node voltages are too high (in several cases of reconfiguration) near the generators located on the middle and right feeder. This situation could occur, for example, if MV customers install new distributed generators (e.g. Combined Heat and Power units). Table 3 Table 3demonstrates the possible results of the tool by showing the top 5 expansion options for the example case. The best ranked expansion option is shown to have the lowest investment costs as this is also the performance value with the greatest weight.

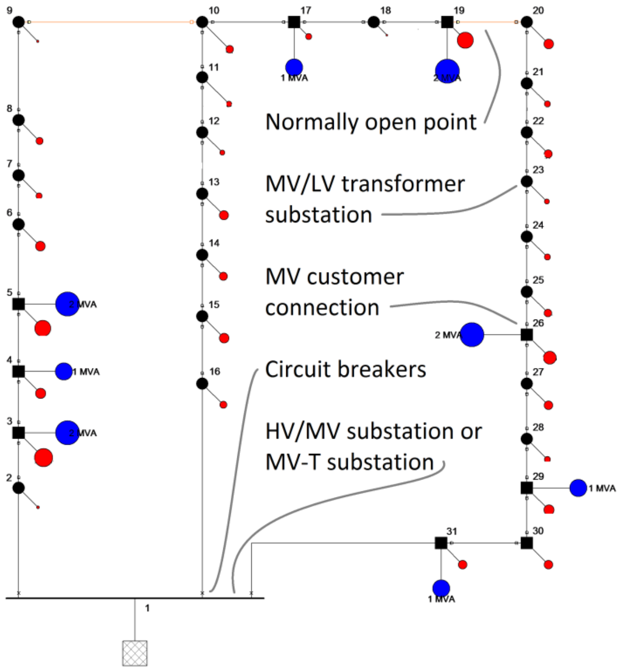

Fig. 2: MV-D network consisting of one feeder group

Many non-practical options are eliminated in the search for feasible expansion options. Fig. 3 shows on a

Table 3: Results of example case: top 5 of feasible expansion options for given weights

Ranked expansion options		Nr. 1	Nr. 2	Nr. 3	Nr. 4	Nr. 5
Cable between nodes		1-29	1-28	1-27	1-22	1-25
Max load normal operation [%]	(weight: 2/16)	93.27	93.27	93.27	93.27	93.27
Max load rescheduled operation [%]	(weight: 1/16)	111.83	111.83	111.83	111.83	111.83
Voltage margin normal operation [p.u.]	(weight: 2/16)	0.04	0.04	0.04	0.01	0.04
Voltage margin rescheduled operation [p.u.]	(weight: 1/16)	0.1	0.1	0.09	0.09	0.09
Combined cable peak power losses [kW]	(weight: 2/16)	10.67	10.5	9.89	10.89	9.95
Investment costs [€]	(weight: 8/16)	41,974.00	49,848.00	55,800.00	70,432.00	58,900.00
Performance indicator		0.56	0.61	0.64	0.65	0.65

logarithmic scale the (remaining) number of expansion options at different stages for the example case (blue line), and in addition, for a 241-node real-world case with a similar kind of bottleneck (green line). The starting set of expansion options is reduced significantly and shows that the method is effective for both cases. Notice that the small example case ‘loses’ many expansion options due to topological constraints, while the bigger case (with multiple feeder groups) shows greater expansion options reductions from the consecutive geographical and operational constraints. Additionally, there is also a significant decrease in expansion options during the evaluation step (coming after the RCBDM) of the tool.

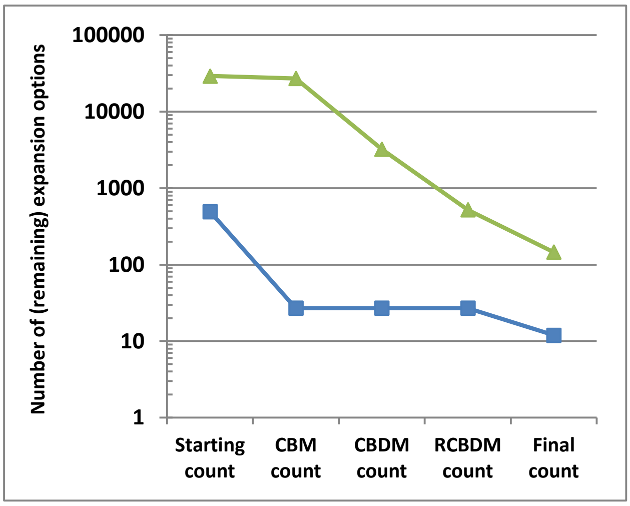

Fig. 3: Number of (remaining) expansion options at different stages for a MV-D case with 31 nodes (blue) and a case with 241 (green) nodes.

CONCLUSIONS

This paper presented a computer-aided planning approach for the capacity planning of medium voltage distribution (MV-D) networks. A rule-based approach identifies practically-relevant expansion options out of all possible expansion options. If-then rules are implemented to include design principles of DNOs. In addition, expansion options are modelled automatically to evaluate if they offer a solution to bottlenecks. Finally, a performance indicator is calculated to compare the expansion options.

The main advantages of the proposed approach are the fully automated testing of topological and geographical constraints, and the automated evaluation of relevant expansion options. The starting set of expansion options is reduced significantly by this approach, making it possible to tackle one-step planning problems. Future research could consider long-term planning problems and the inclusion of additional constraints and/or evaluations (e.g. the evaluation of short-circuit criteria).

Nevertheless, the proposed approach can support network planners by performing many functions automatically currently done by hand. Moreover, the tool is applicable for routine network planning problems in MV-D networks. Automatic evaluation, and a multi-criteria analysis, produce a (top) list of feasible solutions for the decision maker. These properties improve consistency and reduce subjective decision making.

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