Modular Probabilistic Approach for Modelling Distribution Grids and its Application

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Summary / Abstract

Due to the high increase in installed distributed renewable energy sources (DRES) new challenges in the planning and operation of distribution grids (DG) exist. This paper proposes an approach to generate models of present and future synthetic DG based on statistical data of existing networks and operational planning. Compared to the utilization of grid samples a probabilistic network generator offers significant advantages, which are demonstrated in this paper.
A modular design and a simple expandability is one of the most important requirements for its application in different issues. In this context four exemplary use cases are described – reactive power analysis, the identification of planning principles, analysing benefits of innovative network equipment and short circuit protection analysis.

1 Motivation and Overview

Due to the high increase in installed distributed renewable energy sources new challenges in planning and operation of DG exist. This trend will grow by the application of innovative equipment, e.g. on load tap changer (OLTC) in low voltage grids, electrical storages or information and communication technology (ICT).
In addition, due to the heterogeneous historical development of DG based on varying load and generation allocation, diverse characteristics of distribution grids exist in Germany. In general, grids are characterized by diverse parameters such as line/transformer characteristics, topology and connected consumer and producer. In several network calculations and analysing applications more specific parameters such as negative/zero sequences, failure rate of equipment or reactive power operating ranges of generators and control concepts are needed. All this data is affected by this heterogeneity of the DG.
However, for network studies addressing fundamental issues, using standardized grid samples or network topologies of single grid operators are not able to cover the huge diversity of distribution grids. For this reason the results of analyses based on sample grids may not representable for the whole solution space.
For this reason a probabilistic network generator is developed to tackle the issue of heterogeneity in DG. This network generator uses statistical data of a wide range of real networks to derive distribution functions and correlations of and between network topology and associated parameters. With the help of these functions the tool is able to create a variety of synthetic DG. A challenge is its utilisation for different analysis aspects with different requirements. Therefore a modular structure is used.
An overview of the approach with specific focus on its input data as well as design is given in this paper. The advantages of the approach are shown for certain use cases.

2 Probabilistic Modular Approach

2.1 General approach and modular design

For the generation of synthetic grid models an enhanced version of the generation tool described in [1] is used. The general concept of synthetic network generation is based on distribution functions for basic grid parameters, such as number of feeders in a substation, number of nodes in a feeder, line length between nodes, type of line and demand of single customers. These distribution functions are modelled with data from a statistical evaluation analysis of real networks. The statistical input parameters for different types of LV grids are derived from [2]. According to [2] LV grids can be classified in types and in groups such as: rural (2 types), suburban (4 types) and urban (3 types). The input parameters for types and diameters of cables and overhead lines are taken from publications regarding grid concessions, which in general contain specific data concerning the grid assets such as cable type and installation year [3].
At first, values are drawn from these functions to build the synthetic network. After that, the synthetic grid model is tested to identify violations of operating constraints such as current and voltage limits. Grid reinforcements

are being calculated to eliminate those violations. The result of this correction is a synthetic, load flow calculable grid model.

Furthermore, it is possible to specify maximum load and installed DG generation. Associated load and generation time series for every single network model will be generated using a developed time series model. A similar concept is described in [4].

Since not all features and parameters are necessary for each examination, the proposed method for modelling distribution networks is designed in a modular way. The basic network generator includes all essential functionalities and basic parameters. The optional modules contain additional data and methods, which are needed for the particular examinations (Figure 1).

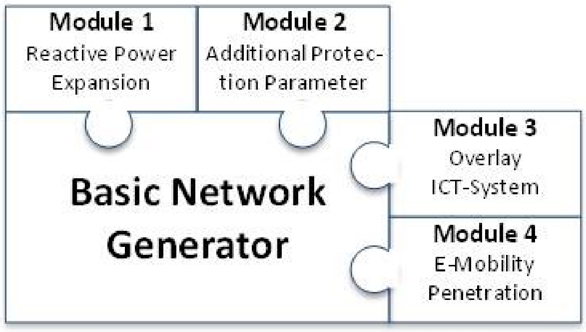

Figure 1 Overview

2.2 Detailed Modelling

The network generator determines the grid structure and dimensioning of equipment based on the operator's supply task.

For this process the supply tasks are being determined based on the classification of LV grids and MV grids into types and groups. According to the grid type distribution functions for the number of feeders and the number of grid connection points in each feeder are being selected. For each grid connection point the type of customer is being defined based on distributions for household customers, business customers and industry customers, which are again specific for each grid type. After this generation of the supply task, network equipment for the supply of each connection point is chosen. This selection of equipment again is based on distributions even though this may lead to solutions, which are not ideal or not technically allowed. The latter problem is being addressed by checking operating constraints such as voltage variation and equipment loading in a power flow calculation. If operating constraints are violated, a simple form of network reinforcement is simulated. In this process equipment is replaced by higher rated equipment in those parts of the network which need reinforcement as long as constrains are being violated. Since the distributions for customers and equipment are closely matched on each other usually only small changes to the network equipment need to be performed. The main reason for the implementation of this approach was that it simulates to some degree the historical growth and reinforcement current grids have been subjected to over the past. Figure 2 shows a distribution of used cable types in real LV grids and a set of synthetic LV grids generated by the network generator.

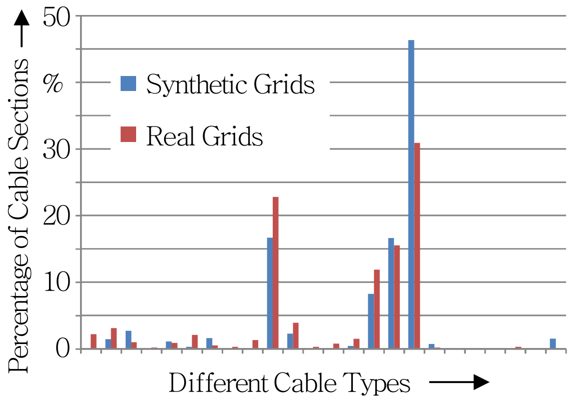

Figure 2 Distribution of Cable Type

As can be seen in Figure 2 the distribution of different cable types can be matched with a sufficient degree. Only for one cable type a significant difference between real and synthetic grids can be seen. A higher penetration of the synthetic grids with DRES compared to the real grid samples for example can lead to such a shift in cable type distribution. A difference of this degree can therefore be tolerated since load and generation in synthetic and real grids were not matched in this particular case.

2.3 Advantages of the probabilistic approach

Overall the described approach leads to a more accurate model of current grids than a number of sample grids, which is very important in the course of evaluating fundamental technical issues in distribution grids. For example the distribution of cable types this accuracy leads to significant benefit because a difference in cable type also leads to a difference in ampacity, zero sequence impedance and reactance which in turn influences the DG hosting capacity of the network, the maximum fault circuit current and the effect of reactive power management concepts. The definition of cable diameters for each cable section may lead to a different maximum ampacity of the feeder compared to a standard cable diameter, which is often used in the definition of sample grids. This approach might again affect DG hosting capacity, short circuit calculations and the effect of reactive power management concepts. For the selection of the rated power of distribution transformers similar arguments can be brought forward.

Currently different methods of distribution grid modelling are practised for research purposes. If the aim of a research project is to come up with specific solutions for a certain grid or for an area managed by a single network operator, the first choice for grid modelling is to use one or more models of real grids. Preferably the selection of these representative grids is being made by the network operator.

If the research project focuses on examining more general effects like changes in grid utilisation or new network planning concepts, the selection of grids used for this task needs to cover variations of basic grid parameters, which might have an influence on the research topic. Furthermore the representative status of these selected grids in comparison to other possible networks has to be known. To fulfil these requirements it is necessary to analyse a sufficient number of grids, which can also include networks that are not highly affected by the research topic. With a limited number of grid samples the minimal and maximal effects on DG are not necessarily covered and a statement concerning the occurrence of an examined issue over the variety of DG is also not possible. An example for this limitation of the use of grid samples compared to a probabilistic approach in this context is shown in Figure **3**.

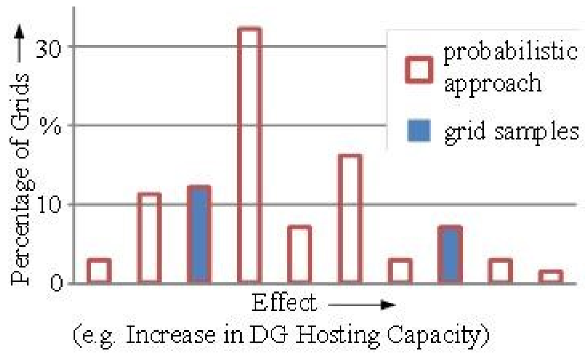

Figure 3 Difference between grid samples and probabilistic approach

In this example a new control concept for distribution grids is tested, which increases DG hosting capacity. An analysis based on sample grids shows that the effect can vary between two values. An alternative analysis based on a variety of synthetic grids however leads to the conclusion that in general a significant effect can be reached, which is often higher than the lowest value determined in the analysis based on sample grid, but a very high effect can be reached only in few networks. Such detailed results can be utilized by the network operator to define specific rules for the installation of this new control concept.

Therefore it can be concluded, that a detailed model, which features much of the diversity in current grids, should be used for the evaluation of current technical issues on the distribution level.

3 Exemplary Applications

3.1 Derivation of Planning Rules

Planning methods for LV- and MV-networks have to be updated caused by the high amount of DRES and the increased degrees of freedom in network planning. Whereas in the past the prevention of network constraint violation was only possible with reinforcement of conventional operating equipment, nowadays different solutions, such as MV-/LV-transformer with on load tab changer (OLTC), storages, Demand-Side-Management or STATCOMs must be considered.

The simulation of a wide range of different network structures, supply tasks and the identification of the most cost efficient solution for every network in particular is necessary to derive robust planning principles. Therefore, the proposed probabilistic approach is applied to derive robust new and innovative planning rules.

To achieve this goal, the network generator is used to create a great number of characteristic network structures without necessary reinforcements. In the next step, these networks are planned using an innovative planning method [5]. This developed planning method uses conventional and innovative network reinforcements to determine the most cost efficient solution for the network. By linking different parameters of the network (e.g. load density, generation density, length of lines) to investment decisions (e.g. usage of OLTC) conclusions about the influence of the parameters on the optimal solution can be derived. Based on the results of this analysis a method for solution generalization can be applied to determine new network planning rules for the day-by-day planning process. A simple example for the derivation is displayed in Figure 4.

For exemplary networks the most cost efficient network reinforcements were calculated. Each dot in Figure 4 illustrates one LV-network – a black dot represents a conventional transformer, a yellow dot represents an innovative transformer with OLTC. On the x-axis the *load-lever* (load multiplied with line length), on the y-axis the *generation-lever* (generation multiplied with line length) for each LV-network is displayed. As can be seen from the Figure 4, in networks with a generation-lever over 0.25

(red dotted line) an innovative solution is more cost efficient than a conventional method.
Therefore a new planning rule could be derived, that for LV-networks with a generation to line-length-ratio above a certain amount the innovative MV/LV-transformer should be considered in the day-by-day planning process.

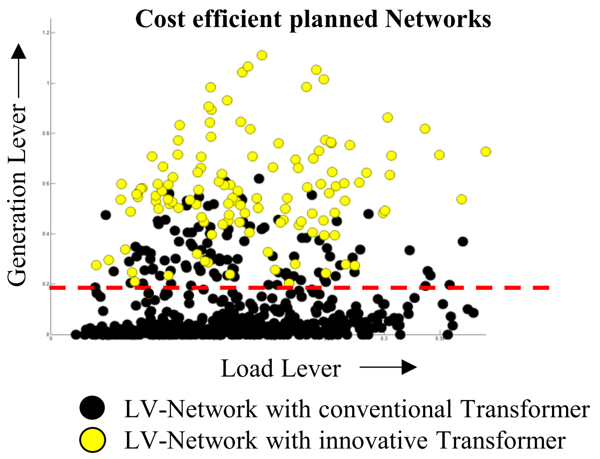

Figure 4 Usage of Innovative Operating Equipment in generated networks

3.2 Reactive Power Analysis

In the future electrical power grid, system services like reactive power (Q) have to be provided across several voltage levels. Studies are necessary to determine the flexibility potential of reactive power in distribution networks and the costs to provide it to higher voltage levels.
For this analysis a network model covering all affected voltage levels from extra high voltage to low voltage is required.
Although Q-transport in the extra-high voltage grid is technically limited to a distance of only a few nodes, the analysis necessitates a wide variety of underlying network models even for a small observation area. To reduce the complexity of data acquisition and to derive fundamental conclusions, only a probabilistic approach generating synthetic models of distribution networks can be used. The generation of these models has to consider local characteristics of the observation area in terms of network topologies and supply tasks.
The introduced enhanced generation tool is able to consider these characteristics as described in 2.1. Load and DG will be integrated under consideration of voltage limits regarding EN50160 [6] and ampacity limits of the network equipment. If limits are exceeded, the grid will be reinforced by using common distribution grid equipment. A further adjustment option is given by keeping free connection power for new DRES: The grid is expanded as far as a specified installed connection power of DRES can still be integrated.
With the help of this option it is possible to evaluate the existing conflict in objectives between distribution and transmission network which arises on the one hand due to the need of voltage support of the transmission network and on the other hand existing interests of a cost efficient and reliable system management of DG. In concrete terms, the distribution network operator is interested or obliged to connect further DRES on request which may lead to voltage stability problems in the distribution system itself. Next to cost-intensive network expansion, these problems can be solved by implementing voltage reactive power control at installed DRES. In many system states, there is on the one hand the need to provide capacitive reactive power by DRES (under-excited mode) to guarantee the voltage stability of the own network, on the other hand a requirement of inductive reactive power supply (over-excited mode) to improve the reactive power balance of the network and thus to support the overlaid network. By the mentioned measures for the distribution network the plant can no longer participate in an optimized strategy of reactive power management for the overlaid network, it acts on the contrary, depending on the network system state, even counterproductive. With the help of this option different degrees of utilization can be simulated and measured against costs for voltage stability in the transmission network.
Furthermore the reactive power expansion of the demonstrated generation tool offers the possibility to choose between different Q-control concepts for DRES and network components like transformer tap changers. For generation units it can be selected between a fixed cos(φ), a characteristic (cos(φ)(P) or Q(U)) or a centralized control of Q-provision. The transformer tap position can either be controlled by typical local concepts like voltage control or as well operated centrally. With the help of these options the future control concepts of distribution networks can be simulated and evaluated.
The provision of a variety of network models by the probabilistic approach allows determining the available Q-potential from distribution networks by an optimization approach. Hence, using the calculated Q-potential and information about power losses, a single distribution network can be represented as so-called *virtual prosumer*. Dependent on the control concept, their Q-behavior is adjustable similar to a conventional generator with use-case-dependent reactive power limits and information about power loss correlation as a function of the Q-balance.

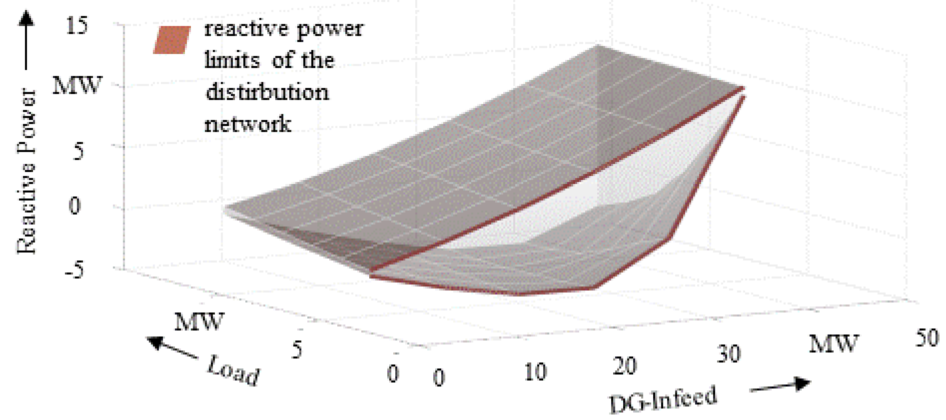

Figure 5 Reactive power limits of an exemplary rural distribution network

Figure 5 shows the determined Q-limits for a rural distribution network at the interface to the high voltage level with centralized control.

The upper shaded surface describes the distribution network's maximum under-excited limit and the lower surface its maximum over-excited limit. At low infeed of DRES there is only a small reactive power potential, since the grid codes in Germany define only active power dependent Q-limits of DRES without Q-provision at no infeed. The left Q-potential comes from DRES with a type of energy allowing a continuous operation mode (e.g. biomass energy) or by stepping of substation transformers without violating the voltage limits.

At a low consumption and an increasing infeed of DRES the Q-potential expands proportionally caused by the linear correlation between active and reactive power defined by a fixed cos(φ)-limit. In the exemplary network at an infeed of about 20 MW this relation in the minimum Q-balance (over-excited mode) is interrupted. The reason is given by the necessity of voltage maintenance in the distribution system. At high infeed of DRES the voltage at the grid connection nodes of the plant rises especially for DRES which are electrically far from the regulated substation. To avoid violation of voltage limits, DRES has to provide capacitive reactive power (under-excited mode). The result is an operating range limited to an under-excited Q-balance during high feed-in and low demand in the distribution network. For the shown network, the whole DRES connection capacity is used from the perspective of voltage maintenance due to the merging of upper and lower limit at maximum infeed of DRES.

For every use case it is possible to calculate an individual power loss curve of the distribution grid which describes the losses depending on the Q-balance. The figure shows a parabolic relationship. A power loss curve will be determined for every use case and every virtual prosumer to allow representing the conflict of potentially increasing power losses when supporting the transmission network with reactive power.

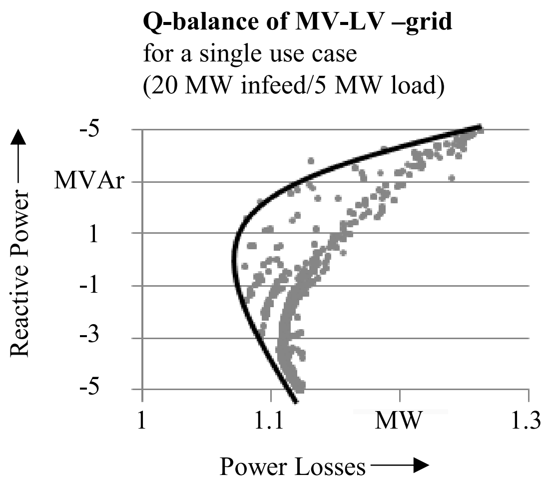

Figure 6 Power losses against Q-Balance for a single use case

The demonstrated generation tool enables to calculate the Q-potential for all distribution networks in the observation area. Using this information together with a network model of high and extra-high-voltage level allows deriving basic recommendations for the organization of the future reactive power exchange at the interface between distribution and transmission networks and the contents of corresponding contracts. Exemplary results of this analysis can be found in [7].

3.3 Short circuit and protection analysis

For protection design the reliable differentiation between normal operation and fault case is necessary. Therefor the minimal short circuit current must be known. In general a fault simulation is used based on IEC standard to determine the minimal short circuit current [8].

In general, practical assumptions (e.g. about short-circuit power of overlay networks and generators) are needed for a simulation. This leads to inaccurate results, which have to be considered in network protection planning by using safety factors.

For minimal current fault simulation it is unalterable to consider unsymmetrical faults as well as negative and zero sequence parameters for all network equipment.

As Figure 7 shows the Z_0/Z_1-ratio (angles constant) has an impact on the choice of the relevant minimal short current situation for protection analysis. If the ratio is lower than 1.23 the bipolar short circuit determines the minimal fault current. However, the current in the conductor in case of a phase to earth fault is much higher than the current I''_{kE2E} to earth. Therefore, if the ratio is higher than 1.46 in case of neutral grounding short circuits with earth connection are the most relevant for short circuit protection parametrization. Otherwise the bipolar short current stays relevant for this purpose..

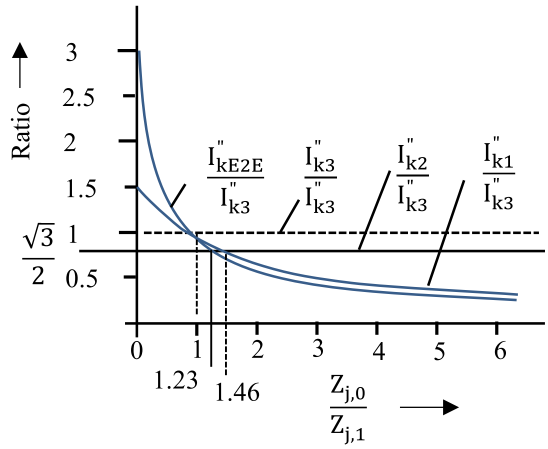

Figure 7 Influence of Z_0/Z_1-ratio on short circuit current level at fault location [9]

Especially for zero sequence parameters a high variation is observed in reality, mostly dependent on the geography e.g. ground conductance and the type of installation as shown in Figure 8 exemplary for different wire sizes of a 10 kV N2XSY cable.

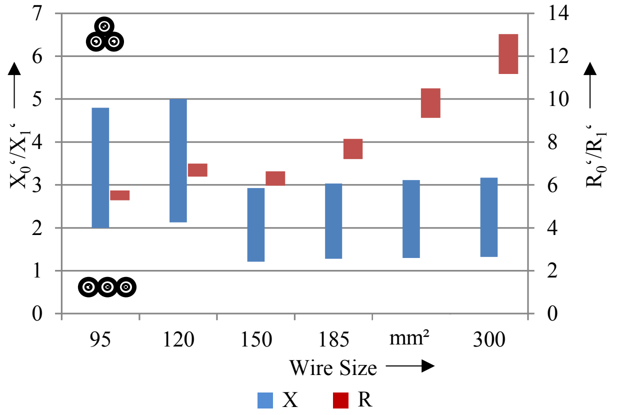

Figure 8 Range of possible R_0'/R_1' and X_0'/X_1'ratios of different wire sizes, exemplary for N2XSY Cable [8]

An equivalent parameter variation in reality can be observed regarding all other power lines.

To tackle this issue, the network generator can be used for specifying the influence of parameter uncertainties. Therefore grids can be provided with different parameter settings. The simulation of the protection design shows influences on relevant parameter settings e.g. threshold setting value or tripping time. Figure **9** illustrates an example: In three MV branches the influences of a different overlay network short-circuit power on the threshold setting value is shown. As can be seen in the figure, different equipment in the single branches leads to a high variation of influence of the short circuit power.

The influence of different parameters on network protection can be determined via sensitivity analyses in the generated networks. Also an evaluation is possible to determine these kinds of influence factors in a high amount of diverse grids.

With the additional view on required decentralized generation behaviour in fault situations, different grids can be used to simulate and to proof protection concepts in prospective distribution grids.

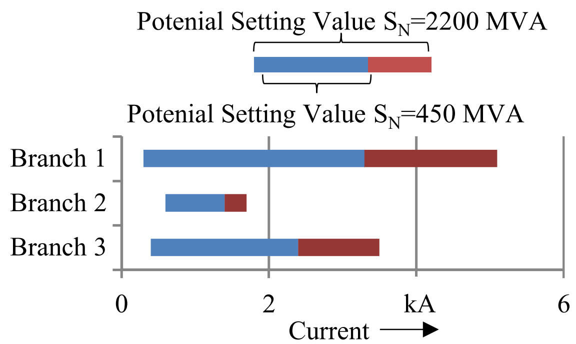

Figure 9 Exemplary potential setting value in three MV branches dependence on overlay network short-circuit power

4 Summary

This paper gives an overview about the opportunities of a probabilistic approach to generate synthetic models for distribution grids. The general approach is described as well as its modular extensions for specific applications.

The main reason for the usage of a great number of synthetic networks compared to a few grid samples is to cover the huge diversity of distribution grids, which is exemplarily illustrated in the distribution of cable types.

Exemplary applications of the network generator are presented. One of them involves the derivation of planning principles. In a simple example the benefit of the probabilistic approach analysing the usage of innovative operating equipment in generated networks is determined. Another presented use case is the analysis of reactive power control concepts in distribution grids. By means of the network generator it is possible to simulate reactive power potentials in a huge number of different grids, over several voltage levels and for various penetrations with distributed generation. The results can be used to define the flexible reactive power potential for system services in both distribution and transmission grids.

A last a use case is shown for the short circuit simulation. In comparison to the other applications more parameters of the electrical equipment are needed, e.g. the short circuit power of overlay networks or negative and zero sequence parameters. In practice, the precise values are often not known, therefore secure factors are used. By the aim of the probabilistic approach diverse grids can be generated and the sensitivity of different parameters can be analysed, which is applicable to find correct parameter settings for network protection systems. In addition to that, the illustrated applications ICT and E-Mobility in Figure 1 can also be treated by using the network generator.

Overall, it can be concluded that the probabilistic approach is well suited for a high range of different network planning analysis und is a useful tool for the evaluation of diverse applications.

5 References

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