THE IMPACT OF RESTRUCTURING URBAN AND SUBURBAN DISTRIBUTION GRIDS WITH SMART GRID APPROACHES ON SYSTEM RELIABILTY

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ABSTRACT

This paper presents a system reliability assessment method for distribution grids, which was used to evaluate how restructuring of urban and suburban distribution grids and the use of smart grid technologies impacts system reliability within the Austrian national founded research project "REstrukt-DEA". The method is based on system component availability values, load flow calculations and Monte Carlo simulations. The smart grid technology evaluated in this paper is the automative restoration scheme, which attempts to automatically restructure faulted sections of the grid using tie lines. As the system component availability values are often missing in real cases, the method uses availability scenarios, which enables the user to observe system reliability as a function of availability.

The results of the method are shown for a test urban distribution grid and three different investment scenarios, which are based on real grid investment cases.

INTRODUCTION

In deregulated electricity markets, regulatory authorities are adopting performance-based regulation for distribution system operators (DSOs). Performance-based regulation is based on incentives based on system reliability, customer service and operation costs. This provides the DSOs incentives for improving economic system operation and planning, and at the same time discourages them from sacrificing service reliability while pursuing financial benefits. As new investments in urban and suburban grid are limited by technical, financial, locational and environmental limitations, DSOs often resort to grid restructuring and smart grid technologies. In Austria the national founded project "REstrukt-DEA" focuses on the investigation of selective restructuring of networks in combination with intelligent and active network management approaches in urban grids in order to achieve secure energy supply.

To investigate the impact of new investments and grid changes, various techno-economic methods have been proposed. These most commonly evaluate system average interruption duration index (SAIDI) and expected energy not supplied (EENS) for different investment scenarios and the associated costs. This can be done using analytical or simulation techniques [1]-[5]. In the analytical approach the power system is represented by a mathematical model, and reliability is evaluated from the model using mathematical solutions. The problem with the analytical approach is the problem complexity, and a high number of assumptions are needed, which result in a loss of calculation accuracy [1], [2].

When the system is more comprehensively modelled, simulation techniques are required. In [3]-[6] the simulation techniques use Monte Carlo simulations to simulate random outages and conventional load flow calculations or linear programs to model the power system load flows. The results of the load flow analysis result in the estimated system reliability. As the system reliability and associated costs are calculated, different scenarios can be compared and the optimal scenario can be selected.

In this paper, the impact of grid restructuring and use of smart grid techniques on system reliability, i.e. SAIDI, is investigated. The smart grid approach used here is the automation restoration scheme. The scheme attempts to automatically reconfigure the grid during a fault state in an attempt to minimize the number of consumers affected [7]. To investigate both restructuring and smart grid technologies, i.e. automatic restoration scheme, for urban and suburban grids a universal simulation method is required.

Therefore, a Monte Carlo simulation technique is presented in this paper, which creates a random set of fault states for the grid, i.e. topology switching states. The fault states are defined by switching distribution lines off when a randomly generated value exceeds the line availability. The random states are defined for a longer time period in order to encompass all possible grid state scenarios. Using conventional load flow calculations for the generated grid states, system states are calculated. Furthermore, voltage violations and overcurrents are taken into account, as they can additionally cause the activation of system protection schemes which additionally change the state of the grid. Consequently, using the data from the calculated load flows the customers affected by the faults are discovered and SAIDI values calculated.

The presented method additionally uses an availability sensitivity analysis, where generic availability data is used and changed in order to estimate system reliability for different availability values. This is done due to the fact that line availabilities can often be difficult to assess or the data is missing, especially for new investments. The sensitivity analysis enables us to calculate different

reliability values as a function of line availability. By estimating line availability for existing lines where the data is not known, the user can see how the reliability changes for each investment scenario and for different expected availability values.
This paper is structured as follows. In the second section a brief description of distribution grid restructuring under the Austrian "REstrukt-DEA" project is described. In the third section the system reliability assessment method is described. In the fourth section a test case is given. Finally, in the last section the conclusions are given.

DISTRIBUTION RESTRUCTURING AND AUTOMATIC RESTORATION SCHEME

Urban and suburban distribution network are most often designed as groups of interconnected radial networks. With radial topology, power is delivered from only one direction. If one line is disconnected, all downstream lines also lose power. Sectionalizing and tie switches are used in distribution networks for protection and configuration management. The first are normally closed and used to form radial network sections, while the second ones are normally open and are used for topology reconfiguration or reconnection of disconnected parts of the grid.
In Austria, the national founded project "REstrukt-DEA" focuses on the investigation of selective restructuring of radial networks and smart grid approaches in order to achieve improved security of supply [8].
The restructuring of radial networks in an urban and suburban environment in developed countries is limited due to the locational and environmental reasons and therefore the restructuring is limited to replacement of overhead lines with new underground cables, additional installation of new cables and topology changes at the main substations. These represent reshaping the radial sections in order to either reduce the number of customers connected to one radial section or reduce the total length of a section. The topology changes are typical examples of improving system reliability. The first topology restructuring change aims at lowering the number of customers downstream affected by a upstream fault, while the second restructuring change aims at improving component availability, i.e. line lengths have an effect on availability.
Among one of the smart grid approaches investigated in the project is the use of automatic restoration schemes. The idea behind the restoration scheme is the use of tie switches during fault states to restore power to the customers affected by the upstream fault, Figure 1. The automation restoration scheme works between the shortest possible segments between two adjacent distribution transformers. When a fault is detected, the faulted segment is disconnected (i). The automatic restoration device automatically attempts to reconnect the down-streamed non-faulted area that was affected by the upstream fault via tie switches (ii, iii) [7].

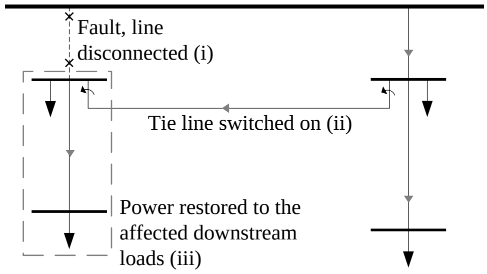

Figure 1. Automative restoration scheme for faulted radial sections.

SYSTEM RELIABILITY ASSESSMENT OF INVESTMENTS

To investigate the technical impact of selective network restructuring and automative restoration scheme, a universal comparative approach must be used. As distribution grids are complex systems, the approach or tool must be able to investigate any grid and any smart grid technology and be able to compare different measures in the same way. To assess the system reliability in this way, the presented method was used. The method can be divided into the data preparation and the Monte Carlo simulation step, Figure 2.

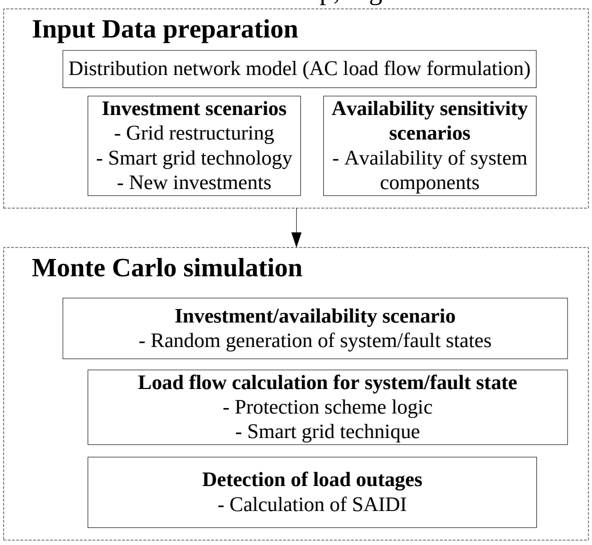

Figure 2. Scheme of the developed system reliability assessment method.

The presented method was developed in MATLAB® using PSS®SINCAL for AC load flow calculations.

Input data preparation

In the first step, the network investment scenarios are prepared, i.e. scenarios with various new investments, topology restructuring schemes and automatic restoration devices. In the input data preparation step, the system component availabilities, i.e. line availabilities are also defined. Here availability values are defined by scenarios, due to the fact that availability data is often missing in practice, either due to missing historical data for existing lines or no available data for new lines. If no data is available, generic data is used. The availability scenarios represent different values from low to extremely high availability in order to encompass different availability states. The generic availability data is based on the type of line (overhead or cable) and the line length. For each scenario, the availability of each line is shifted by a proportional value from the high shift factor s_h and low shift factor s_l around the generic value A(l), Figure 3.

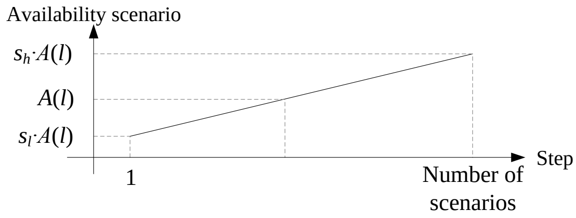

Figure 3. Availability scenarios.

Monte Carlo simulation

In the second step the Monte Carlo simulation is performed for each investment scenario and availability scenario, Figure 4. At each Monte Carlo simulation step random topology states are generated according to the availability scenario. This is done by generating a random number between 0 and 1 for each line. For each line the number is compared to its availability value and if the randomly generated value is higher, the line is considered to experience a fault; otherwise the line is operating normally. The topology states can represent faulted system states, which result in disconnection of faulted lines (protection schemes) and therefore faulted sections of the grid. AC load flow calculation is used to recalculate the voltages and load flows for the new system state. Overloaded elements or nodes with under- or over-voltages are additionally discovered, which may lead to additional disconnects of elements.

The protection schemes work by firstly checking for faulted states, generated at the beginning of the Monte Carlo simulation step. The lines are disconnected if the fault exists. Additionally, after each AC load flow calculation, node voltages and line currents are checked. If the voltages are violated, the lines connecting to the node are disconnected. If the line currents exceed the thermal rating, the line is also disconnected.

If the investment scenario includes automative restoration schemes tie switches can be used to restore power to some parts the affected sections. The AC load flow calculation is repeated until the system returns to a steady operation (automation restoration schemes were successful and protection schemes do not continue disconnecting elements) or a total blackout (protection schemes cause cascaded disconnects). After the AC load flow calculation, the load outages are calculated and the resulting SAIDI stored. Here the time affected by the faulted state is assumed to be equal to one step time within the observed time period.

The Monte Carlo simulation steps are repeated for a longer time period, e.g. year, to encapsulate the majority of all possible occurrences in the grid. The sum of all SAIDI values of all Monte Carlo iterations is the final reliability index for the observed investment/availability scenario. This allows us to compare different investment scenarios.

The SAIDI value for the i-th faulted event is calculated using (1), where t_i is the duration of the i-th interruption, N_i is the number of affected customers, while N is the number of all customers in the observed area. If the automative restoration scheme is active, the equation is expanded with the last term of the equation. $N_{i,ar}$ is the number of outaged customers that the automative restoration scheme restored. $t_{i,ar}$ is the restoration time, which includes the scheme logic processing and tie-line switching.

$$\mathrm{SAIDI}_i = \left(N_i \cdot t_i\right)/N + \left(N_{i,\mathrm{ar}} \cdot t_{i,ar}\right)/N \qquad (1)$$

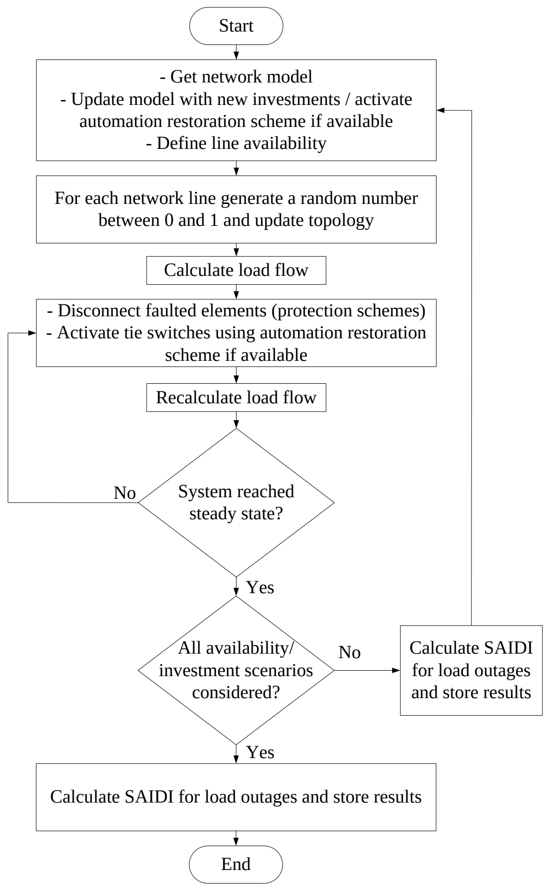

Figure 4. Monte Carlo simulation scheme.

CASE STUDY AND RESULTS

The presented method is shown on an urban/sub-urban test distribution grid based on one of the Austrian distribution grid sections [8].

The method was used to present the impact of a restructuring investment scenarios and the use of automative restoration scheme on system reliability. Grid investment scenarios are given in Table I.

The first grid scenario G1 represents the replacement of the overhead lines at the beginning of each radial section with equally long underground cables. These overhead lines represent long lines and have low availability. The replacement of the lines with cables would improve their availability due to the fact that underground cables are not exposed to external weather influences [9]. This scenario would however represent high costs if the overhead lines would be replaced with equally long underground cables. Grid investment scenario G2 represents the replacement of the long overhead lines at the beginning of the section with short underground cables. To enable this, restructuring of the grid is needed. This is done by changing the radial section structure, where some sections are grouped with other sections that are geographically close. Grid variant G3 represents grid variant G2 with the additional implementation of the automative restoration scheme logic that controls automatic tie line switching during fault states. The base grid and investment scenario G1 is given in Figure 5, while the restructured grid given in investment scenario G2 and G3 is given in Figure 6. The areas shaded with light and dark grey in Figure 5 and 6 represent how the last radial section in the base grid was merged with part of the third radial section.

Table I. Grid investment scenarios.

ID	Investment scenario
G1	Replacement of overhead lines at the beginning of each radial section with equal length underground cables
G2	Replacement of overhead lines at the beginning of each radial section with shorter underground cables
	Reconstruction of grid - permanent topology change (grouping two or more radial sections into one to adjust to shorter cable lengths)
G3	Investment scenario G2 + activation of automation restoration scheme

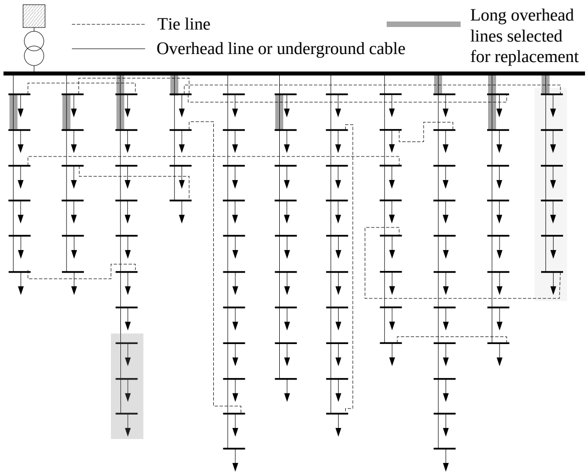

Figure 5. Distribution grid topology for base grid and investment scenario G1.

The load and renewable energy generation at the load points is defined for high winter load and low renewable energy generation. To present how grid investments affect the grid, the load is assumed to be the same throughout the Monte Carlo simulation in order to equally compare the different investment scenarios. The number of Monte Carlo simulations is equal to 105120, which represents a one year observation period on a 5 minute interval basis.

The number of customers at each load point was defined randomly in accordance with the approximately known number of customers in the area. The average number of customers per load point is 109, ranging from 15 to 213 customers per load point, with an average load of 225 kW.

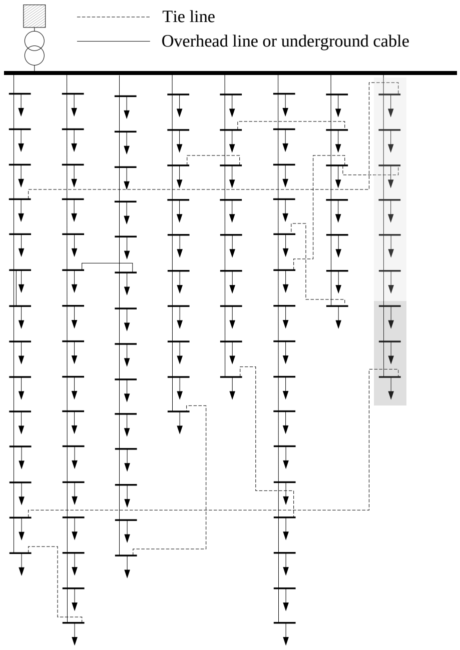

Figure 6. Distribution grid topology for investment scenario G2 and G3.

Where data was available, line availability was calculated based on historical events of outages of lines and cables in the last two years for a real distribution grid. The lines and cables were of various lengths and from the data calculated, generic availability of lines and underground cables was calculated as a function of their length. The data was extrapolated for the lines where line availability was not known and for new investments.

As these availabilities represent approximated values, availability scenarios were defined. For the purpose of this paper the line availability for elements without known values was shifted around the generic availability values from 0.98× to 1.02× generic values with 50 interval steps. For the observed grid the lines at the start of radial sections and new investment elements did not have known values. This enables the user to observe how system reliability behaves when line availability changes

or what the exact value is if the user considers generic values either too high or too low. This enables the user to observe system reliability as a function of line availability.
The results of the system reliability analysis are shown in Figure 7, where the SAIDI value is given for the base grid and investment scenario G1, G2 and G3. The SAIDI results are normalized based on the base grid SAIDI value for non-scaled line availability values, i.e. for 0 % line availability scenario. The SAIDI values for the base grid, G1, G2 and G3 are 1, 0.95, 0.91, 1.02 and 0.44. The results for the base grid and G1 show how replacing the long overhead lines with underground cables improve SAIDI in accordance with their higher availability. Although the scenario G1 improves on the reliability at 0 % shift, this investment represents a high cost investment, as replacing long overhead lines with equally long underground cables is extremely costly [5], [9].
For the restructuring scenario G2, SAIDI values improve with line availability values above 0% scaling compared to the base grid and G1. At scaled availabilities below 0 % SAIDI values are lower than the base grid and G1. This is due to the fact that with the restructuring, fewer radial sections exist with more load points compared to the base scenario and G1. Therefore when line availabilities are relatively low, an outage at the start of the longer radial section at G2 scenario impacts more customers. The presented restructuring must include the replacement of lines with low availability. By implementing the automative restoration scheme (G3), SAIDI is greatly lowered, as the automated switching of tie lines reduces the time and number of outages.

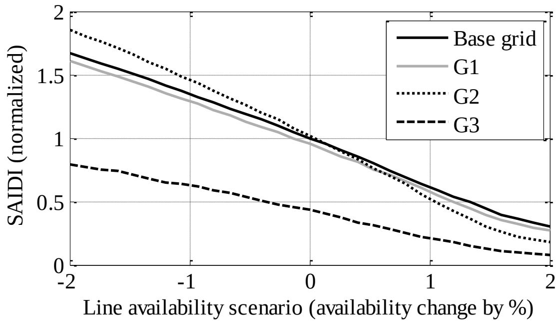

Figure 7. Calculated SAIDI values for observed investment/availability scenarios.

CONCLUSIONS

With the new performance-based regulation distribution grid operators are implementing, grids are being restructured, new investments are being planned and smart grid technologies implemented in order to maintain or improve system reliability. In order to investigate different strategies and investment scenarios, reliability assessment methods are required. In this paper, a universal comparative method is presented. The method is a Monte Carlo based method, where different system and fault states are created. Based on these states, load flow calculations are performed and system reliability is calculated. The presented method can take into account various smart grid technologies and their impact on the grid, such as the automative restoration scheme. This enables a uniform approach of comparing different grid investment scenarios. Additionally, the method enables the use of system component availability scenarios. This is used in cases where availability data is not known and the result is system reliability as a function of availability. The method was tested on a test urban distribution grid for three different investment and availability scenarios.

Acknowledgments

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