SELECTION OF RELEVANT FAILURE MODES AND SYSTEM STATES FOR THE EVALUATION OF RELIABILITY IN DISTRIBUTION GRIDS DEPENDING ON ICT

Daniel SCHACHT
FGH e.V. – Germany
daniel.schacht@fgh-ma.de

Sören PATZACK
FGH e.V. – Germany
soeren.patzack@fgh-ma.de

Hendrik VENNEGEERTS
FGH e.V. - Germany
hendrik.vennegeerts@fgh-ma.de

Simon KRAHL
FGH e.V. – Germany
simon.krahl@fgh-ma.de

Albert MOSER
FGH e.V. – Germany
albert.moser@fgh-ma.com

ABSTRACT

The increasing number of intelligent applications such as automation, monitoring and control functionalities in distribution grids often with high penetration by distributed energy resources may lead to a scenario, in which operation of distribution grids in between technical constraints becomes dependent on the ICT-system in common operating conditions. For the assessment of reliability in such scenarios tools for reliability calculations need to be enhanced by an emulation of intelligent applications and need to consider time dependencies of grid utilisation as well as equipment failure rates. These additions raise the computational effort necessary for reliability assessment. In order to cope with this challenge, algorithms for the selection of relevant failure modes and system states have been developed and are presented in this paper. Simulation results prove their benefit for the process of reliability calculation.

INTRODUCTION

The increasing penetration of distribution grids with distributed energy resources (DER) causes new technical challenges for voltage control, grid loading and reliability. At the same time operators are bound to optimize their grids according to incentive and quality regulation. These motivate network operators to reduce costs for the integration of DER by using intelligent applications such as automation, monitoring and control functionalities instead of conventional grid reinforcement. The aim for this trend is to utilize currently installed equipment more efficiently. However, intelligent applications are partly dependent on the information and communication technology system (ICT-system) and with the operation of the grid within its technical constrains becoming increasingly dependent on the proper functioning of these applications, the reliability of the grid to fulfill its distribution and transmission tasks gets depended on the ICT-system as well. For a reliability assessment of such a grid an overall system consisting of the three parts, power system, intelligent applications and ICT-system, as illustrated in Fig. 1, has to be considered.

The frequency and duration, in which the power system of such an overall system is dependent on a specific intelligent application is defined by the power systems topology, the functionality represented by the intelligent application, power demand and power injection. This effect leads to a time dependency of the failure's impact, since power demand and power injection vary significantly over time in distribution grids.

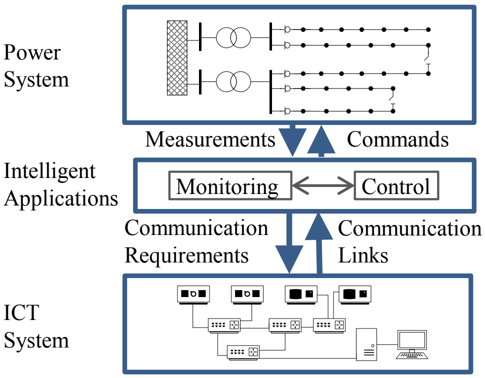

Figure 1 Parts of the overall system

In this context an enhancement of standard methods for the evaluation of the reliability has to be undertaken.

CALCULATION OF RELIABILITY IN DISTRIBUTION GRIDS DEPENDING ON ICT

For the assessment of reliability in distribution grids depending on an ICT-System the operating states of the overall system, which in this case consists of multiple parts, need to be taken into account. In this context intelligent applications can be treated as part of the ICT-system since they are implemented on ICT equipment (ICTE). Therefore the states of the overall system can be derived from possible operating states of the subsystems primary system and ICT-system as described in [1]. Since both of the system parts may enter a state of system failure independently from the other and have an influence on grid customers both systems need to be considered in a reliability assessment. Moreover, also combinations of failures in both systems have to be considered as is usually done in reliability assessment of the primary system. At the same time the impact of failures in such an overall system develops a time dependency, as already described in the introduction, due to the variation of power demand and injection over time. In addition to this the time dependency of failure rates, which has been described in [2], needs be taken into account as well since they have a direct influence on the probability of a failures impact.

In a new approach to assess the reliability of power systems depending on ICT systems all these effects and boundary conditions have been considered and have led to an enhanced algorithm shown in Fig. 2.

Overall the main enhancements of the new algorithm compared to currently used analytic calculation algorithms are the modelling of ICT-System and intelligent applications, their simulation in the resupply process as well as the detailed consideration of time dependency of network utilization by system states in order to cover a temporary need of intelligent application from network point of view and in the course of this the time dependency of equipment reliability.

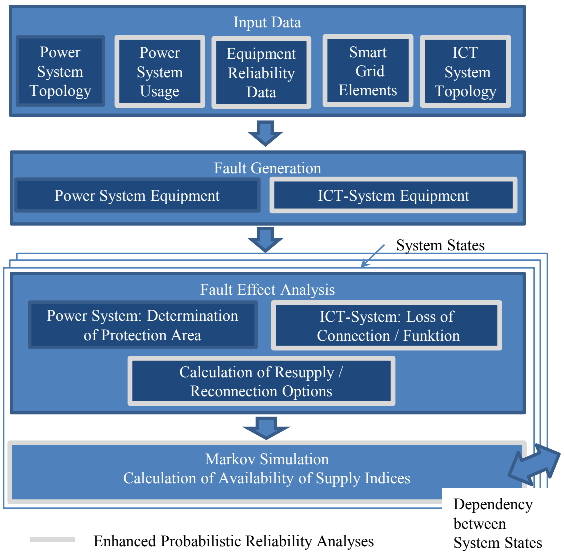

Figure 2 Enhanced algorithm for reliability assessment

SELECTION OF SYSTEM STATES

The different operating states of the primary system and the changing failure rates over time can be taken into account in the calculation process by using time series for the emulation of varying loads, feed-ins as well as failure rates and by performing reliability assessments for points in time called system states. This approach leads on one hand to very accurate results but on the other hand to a sharp increase in computational effort compared to currently used analytic calculation algorithms. Therefore it is necessary to expand the algorithm by a selection of system states, which enables the algorithm to generate similarly accurate results and at the same time reduces the computational effort significantly.

Analysis in [3] have shown, that power demand by customers and power injection by DER as well as failure rates of power system equipment (PSE) and ICTE may vary over hours of a day, days of a week and months of a year. These time dependencies are taken into account in the algorithm by selecting representative weeks for all four seasons of the year. For the selection of those representative weeks an evolutionary algorithm is set up and modified to cope with this specific problem. The time dependency of failures rates is already well taken into account by selecting four full weeks within a year, because they have typical seasonal, weekly and daily variations. Therefore the algorithm focuses on modelling power demand and power injection adequately. Since intelligent applications are most often used in situations with high power demand and high power injection those states need to be covered in the representative weeks with a high accuracy. Therefore the aim of the algorithm is to generate weeks from days within the season, which's load duration curves match with the overall load duration curve of the season, as shown in Fig. 3. Since the accurate representation of critical states with high power injection and low power demand as well as low power injection and high power demand is of much importance for the reliability assessment, the comparison of the load duration curves focus on quantiles, as illustrated in Fig. 3. The density of the quantiles, which are taken into account, increases as the focus area approaches those critical states, so that the critical states are well represented by the representative week.

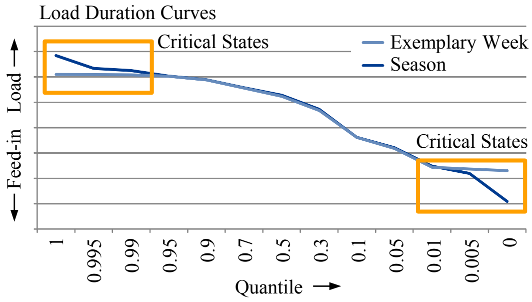

Figure 3 Load duration curves of an exemplary week and a season

In order to solve this problem of selecting a representative week a genetic algorithm is being used in the following ways. At first a number of weeks are generated by randomly selecting days of the season. Their fitness is being evaluated by comparing the weeks load duration curves with the load duration curve of the season they shall represent. Afterwards the genetic operators of mutation and crossover are being used to improve the fitness of the weeks in an iterative process as shown in Fig. 4.

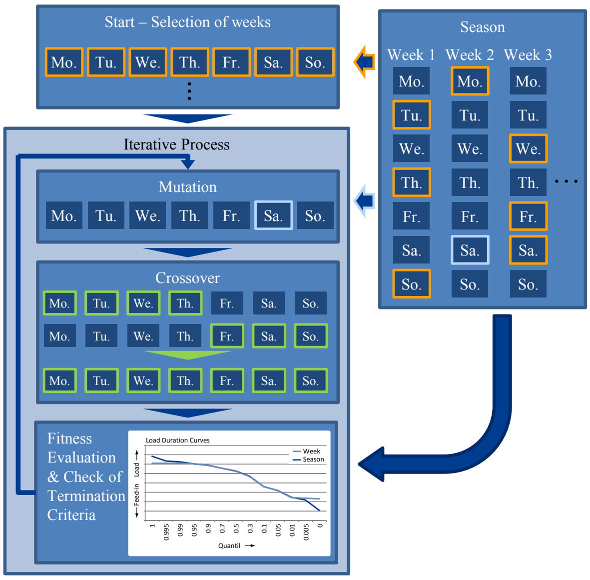

Figure 4 Algorithm for selecting representative weeks

The days of the previously generated weeks are being mutated by selecting a random day of the week and replacing it with another day of the season. Hereby the weekday of the new day has to match the weekday, which is being replaced. After a predefined number of iterations a crossover between two randomly selected weeks is preformed, whereby a number of days are exchanged between weeks. After each iteration fitness values of all weeks are being evaluated. The algorithm terminates if the load duration curves of a week and of the season perfectly match or a predefined number of iterations is exceeded.

SELECTION OF FAILURE MODES

In the assessment of reliability the number of overlapping single failure combinations increases rapidly with the size of the system under consideration, if every single failure is combined with every other single failure. Especially in distribution grids depending on ICT-systems this fact represents a challenge since ICTE is also being considered in the reliability calculation. A complete enumeration of all failures is still possible but would lead to a significant increase in computation time and would not be effective, since many failure combinations do not lead to a worse failure impact on customers than the independent single failures themselves. For these reasons a new algorithm for selecting failure modes in a distribution grid depending on an ICT-system has been developed. It is based on three evaluation steps as shown in Fig. 5.

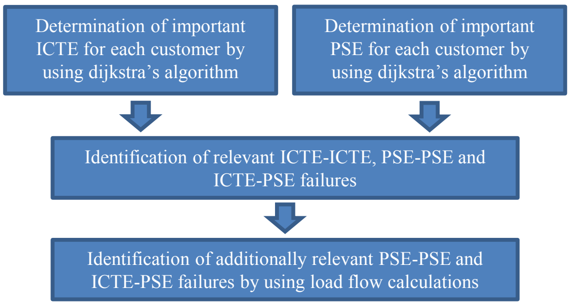

Figure 5 Algorithm for selecting relevant failure modes

In the first step important PSE and ICTE for each customer is determined by using the Dijkstra's algorithm to identify primary and secondary paths from each customer to important other ICTE and the power system's main injection. Fig. 6a illustrates this concept.
From the perspective of customer 1 the primary path to the substation is represented by line 1. If line 1 fails, the secondary path to the substation leads over line 2 and other parts of the power system. Since the part of the secondary path after line 2 can be realized over multiple alternative paths, the elements of these paths are not relevant for the identification of overlapping single failures because their function in the resupply process can be taken over by each other. Moreover, randomly overlapping failures of more than 2 components can often be neglected due to their low probability. Therefore only overlapping failures of line 1 and line 2 are relevant for the reliability assessment of customer 1.
For the identification of relevant ICTE-ICTE failures this concept of identifying critical equipment in the primary and secondary path to other ICTE (e.g. the control centre) is also being used.

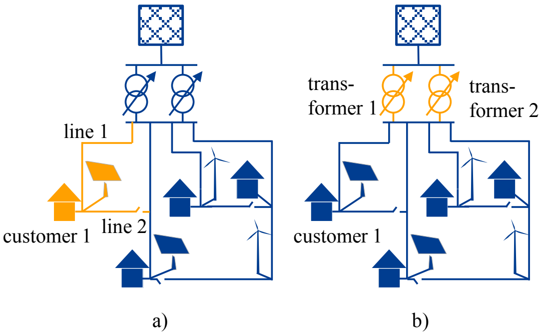

Figure 6 Relevant failure modes identified by Dijkstra's algorithm (a) and load flow calculation (b)

To determine relevant ICTE-PSE failures the results of the evaluation of primary and secondary path in power system and ICT-system are being considered. For ICTE-PSE failures elements of the primary path in the power system are combined with ICTE connected to PSE of the secondary path in the power system. All single failures in the ICT-system, which affect the performance of these ICTE, represent relevant failures, which need to be considered. From the perspective of customer 1 in Fig.6a such a failure combination could be a failure of line 1 and a failure of the remote control of the switch on line 2.
Since not all relevant failure combinations in the system can be identified by using Dijkstra's algorithm and effective combination, an additional step is needed. By performing a load flow calculation after a PSE is disconnected from the grid, it is possible to determine the additional loading this failure would cause on other PSE. If the change of loading exceeds a predefined threshold, the disconnected PSE and the PSE with additional loading represent a relevant combination, which needs to be considered. In Fig. 6b such a relevant combination is illustrated. The loading of transformer 1 increases significantly, if transformer 2 is being disconnected from the grid due to failure. In addition to those combinations, the PSE, which is disconnected in the load flow calculation, is being combined with ICTE failures which may lead to a further increase of loading of other already critically loaded PSE. These ICTE can be identified by evaluating power demand and power injection controlled by ICTE as well as the paths these loads and feed-ins take within the power system. If an ICTE controls load or feed-in above a certain level and this load or feed-in has a direct influence on the critically loaded PSE the combination of these elements is taken into account as well.

EXEMPLARY RESULTS

The selection of system states and the selection of failure modes have been tested using the exemplary grid shown in Fig. 6. For each line a length of 5 km was assumed. Each customer had a peak demand of 2.5 MW and each DER a peak injection of 7 MW. Both customers and DER were modelled using synthetic time series generated according to the description in [3]. In parallel to the power system an ICT-system based on UMTS communication was modelled. In the reliability analysis only failures of overhead lines, transformers and ICTE for generation side management at each DER was considered. The failure rates and times to repair are given in table 1.

Table 1 Failure rates and times to repair [4, 5]

Equipment	Failure Rate	Time to repair
Overhead Line	0.0197 1/(a*km)	2.4 h
Transformer	0.0044 1/a	2.3 h
ICTE	0.0104 1/a	2 h*

*Estimated value

Fig. 7 shows the results of the calculations. In the first test shown in Fig. 7a, two reliability assessments were carried out. In the first one the time series of a whole year were considered. In the second one only four representative weeks identified with the described algorithm were taken into account. The average system interruption duration index (ASIDI) and average system frequency index (ASIFI), which were calculated for DER in the grid according to [6], show that there is some degree of difference in the results. For the ASIDI value a difference of 0.34 min./a occurs, which is compared to the overall value of 8.89 min./a comparatively small. For the ASIFI value an even better result can be achieved. The small disparity in the ASIDI values is caused by a difference in the total number of feed-in hours, which cause a raise of the PSE value, and by deficits, which are induced by overloading of PSE equipment after initial PSE failure. These deficit states occur with a very small probability and therefore affect the ASIFI value very little but may cause a significant difference in the ASIDI value because they may affect a grid customer for a time span much larger than the average switching time.

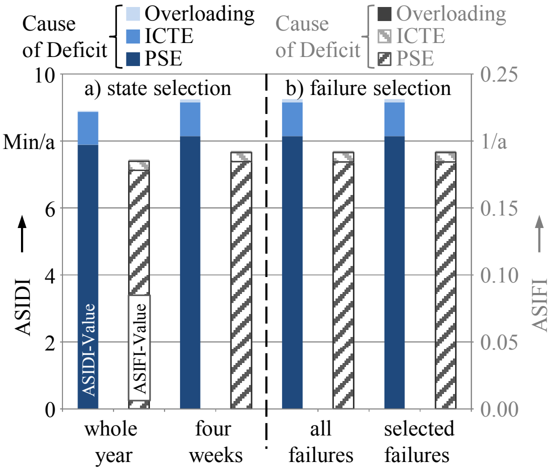

Figure 7 Exemplary results for selection of relevant system states (a) and failure modes (b)

The accuracy, with which these events can be considered, is limited by the resolution of the assessment, which is directly influenced by the time series for loads, feed-ins and failure rates. If a more accurate evaluation of these events is necessary, more than one week per season should be selected to give a more precise view of these events.

In the second test shown in Fig. 7b again to reliability assessments were carried out. In the first calculation all possible overlapping single failures were considered. In the second calculation only those overlapping single failures were taken into account, which have been identified as relevant by the selection algorithm for failure modes. The comparison between the ASIDI and ASIFI values shows, that there is no difference between the results even though the number of considered failures for this small exemplary grid could already be reduced by ~25%. The algorithm is therefore very well suited to determine the number of failure modes, which have to be considered in the reliability assessment.

CONCLUSION

The assessment of reliability for distribution grids depending on an ICT-system requires significant enhancements to to currently used analytic calculation algorithms. Besides the power system, the ICT-system as well as time series for power demand, power injection and failure rates need to be considered. This leads to a significant increase in necessary computational effort. In order to reduce this computational effort an algorithm for the selection of relevant system states and an algorithm for the selection of relevant failure modes were introduced. The tests of the algorithms show that they are both capable to effectively reduce computational effort and at the same time have little influence on the accuracy of results.

The new approach enhanced by the introduced algorithms enables operators, to evaluate new grid structures featuring equipment dependent on the ICT-system and hence lead to more security in the planning process of future grids.

ACKNOWLEDGEMENTS

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