Modelling of Interactions between Power System and Communication Systems for the Evaluation of Reliability

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***Abstract*— In the process of integrating further distributed generation units and optimizing current power systems intelligent applications such as generation side management represent a cost efficient alternative to conventional grid reinforcement and expansion. The functionality of those intelligent applications however is often dependent on an information and communication technology system (ICT-system). Therefore interactions between power system and ICT-system gain in importance with extensive installation of such applications, especially in the field of power system reliability. For the assessment of reliability in such power systems partly dependent on an ICT-System various additional aspects have to be considered. Therefore a new approach has been developed, which focuses especially on interactions with the ICT-system, intelligent applications and time dependencies of power demand and injection as well as failure rates for the calculation of power system reliability. The results emphasize its benefits for the evaluation of reliability in power systems depending on an ICT-system.**

***Index Terms*--cyber-physical interdependency, power system reliability.**

I. Introduction

In the course of the expanding deregulation of the electricity market, incentive [1] and quality regulation [2] have been introduced to increase the cost efficiency of the distribution grids and to prevent operators from reducing supply reliability. At the same time the long term goal of Europe to set up a system of electrical energy generation based on renewable resources has led to a widespread promotion of distributed generation (DG) units. The increasing penetration with DGs in distribution grids causes new technical challenges for voltage control, grid loading and reliability. Consequently network operators are on one hand bound to optimize their grids and thus reduce existing costs and on the other hand need to integrate large numbers of DG units. These constraints lead to a conflict within the grid optimization process. To handle this conflict, alternative methods for grid reinforcement in form of intelligent applications, such as generation side management, equipment monitoring and remote switching, are increasingly discussed and used. Moreover, these technologies are also promoted by upcoming control possibilities at customer side as well as their availability for decreasing prices. These applications are partly dependent on the information and communication technology system (ICT-system). If the operation of the distribution grid in between technical constraints becomes increasingly dependent on the proper functioning of these intelligent applications, the grid reliability also develops a dependency on the ICT-system. The frequency and duration, in which a power system is dependent on a specific intelligent application, arises from the power system design, the function of the intelligent application as well as the characteristics of power demand and power injection. In this context an enhancement of standard methods for the evaluation of the reliability, that generally focus on the failure mode of primary equipment at sectional static network load, has to be undertaken.

II. Overall System and Operating States

A. *Change in Overall System Structure*

Due to the introduction of intelligent applications for the support of system operation, the overall structure of the power system is changing. Some of those applications are already installed in power systems on a regular basis. Others are tested in pilot projects to determine their overall benefit and evaluate potential use cases. Most relevant intelligent applications are:

- Monitoring Systems
- Remote Control of Switch Gear
- Switching of Sectioning Point
- Transformer Tap Changer Control Based on Wide Area Measurements
- Demand Side Management (DSM)
- Generation Side Management (GSM)

Since further automation of the system requires additional information and communication, this trend will lead to an increased utilization of ICT and those before mentioned interdependencies, which have to be taken into account during common operating conditions and during contingencies. If this development advances further with the current dynamic, the overall system will soon be a combination of the following three parts: power system, intelligent applications and ICT-system. An overview of such an overall system is given in Fig. 1.

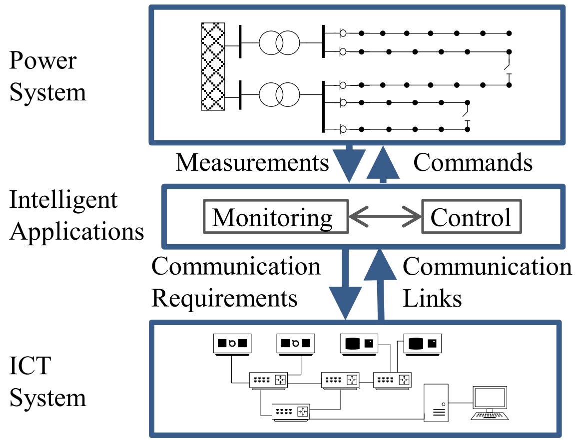


Figure 1. Parts of the Overall System

B. *Operating States of Grid Customers*

In an overall system featuring DSM and GSM the operating states of grid customers will change fundamentally. Currently it is usually distinguished between two operating states only: connected to the grid and disconnected from the grid, whereas the later operating state usually only occurs during contingencies. Besides those operating states defined by the grid connection, operating states based on the grid's ability to supply consumers and to redistribute feed-in have to be defined in systems featuring DSM and GSM. Since in future – partly already nowadays – both grid connection requirements and contracts between operator and customer additional may define status limits, operating states taking into account these before mentioned boundary conditions can be determined for every customer individually. Fig. 2 below shows exemplary operating states for DG unit featuring GSM.

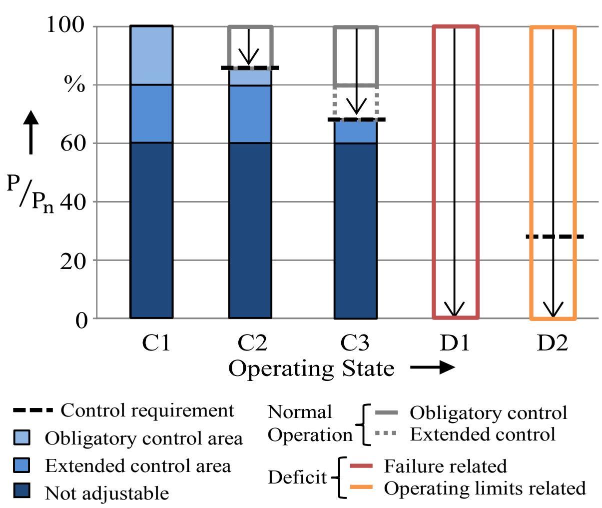


Figure 2. Operating States of a Generation Unit

Operating states labeled with the letter "C" are states where the unit is connected to the grid. Operating states labeled with the letter "D" are states where the unit is disconnected from the grid. Besides the operating state "C1" where the unit is able to feed-in all its power there are two operating states where it is connected to the grid but its feed-in is limited. In case "C2" it's feed-in is not limited for more than 10%, which is assumed to be a boundary condition defined in grid connection requirements (obligatory control area). In case "C3" there is an increased GSM, but the reduction of feed-in is not higher than a limit, which is assumed to be defined in a separate contract with the grid operator (extended control area). All these states can be classified as non-deficit states, since they are covered by agreements between network operator and customer. States where the unit is or has to be disconnected from the grid are classified as deficit, since the unit is no longer able to feed-in power independent from its capability to generate power. State "D1" describes a state where the unit is disconnected from the grid due to power system or ICT-system equipment failure. State "D2" defines a state where due to network constraints like equipment overloading, and over or under voltage the unit has to reduce it's feed-in more than its technical capabilities or the agreement with the network operator permit. This results also in a disconnection. In the assessment of reliability the different operating states of the customer need to the taken into account.

C. *Operating States of the Overall System*

The operating states of the overall system are defined by the operating states of its parts. Intelligent applications have a special status in this context because they are in general implemented on an intelligent electronic device (IED), which itself is part of the ICT-system. In case of an IED-failure all intelligent applications realized on this IED will also be in some sort of failure mode, at least in a defined fallback mode. Intelligent applications are therefore viewed as a part of the ICT-system. Consequently operating states of the overall system are influenced by the operating states of both subsystems ICT-system and power system as shown in table 1 and previously described in [3].

TABLE I. OPERATING STATES OF THE OVERALL SYSTEM [3]

States	Power System	ICT-System
1	Normal Operation	Normal Operation
2	Failure	Normal Operation
3	Normal Operation	Failure
4	Failure	Failure

Since a fault can occur in both of the subsystems, each one may enter a state of system failure independently from the other. The combination of the operating states of both subsystems leads to all possible operating states of the overall system. The reliability of the overall system can be derived from an analysis of all operating states encompassing faults. Besides the individual system states the interactions between power system and ICT-system need to be considered for the assessment of reliability as well.

III. TIME DEPENDENCIES

Interactions between power system and ICT-system usually occur in times of extensive network usage by consumers or generators and during faults. Therefore time dependencies of network usage and failures rates need to be taken into account.

A. Network Usage by Grid Customers

Since intelligent applications are used to keep grids within their operational constrains, especially in times of high load and low generation as well as low load and high generation their availability is of much importance. Depending on aggregation level and fluctuation of primary energy sources network usage by load and generation can be very stochastic during typical equipment down times, as Fig. 3 shows. This fact leads to the necessity of using time series of load and generation in process of reliability assessment.

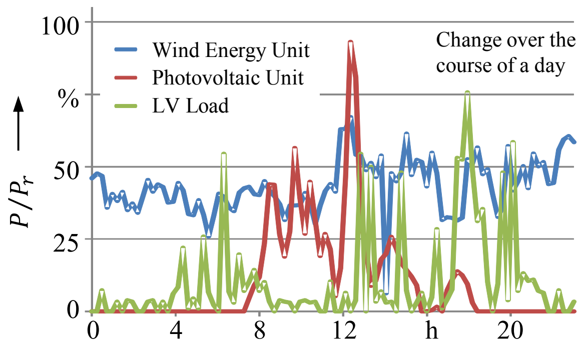


Figure 3. Stochastic Network Usages

B. Failure Rates of Equipment

Moreover, the time dependency of failure rates has to be considered. Since the network dependency on intelligent applications varies with time due to changes in load and generation a simultaneous increase or decrease in failure rate will also influence the grid reliability. Since failures of power system equipment (PSE) are often induced by external effects such as construction work or storms, which tend to vary in occurrence probability over time [4], the failure rate of power system equipment is in most cases time dependent. A detailed analysis of the disturbance and availability statistic [5] confirms this assumption. In Fig. 4 the time dependency of the failure rates for a medium voltage (MV) cable with XLPE (cross-linked polyethylene) isolation, a MV overhead line and a high voltage overhead line are shown.

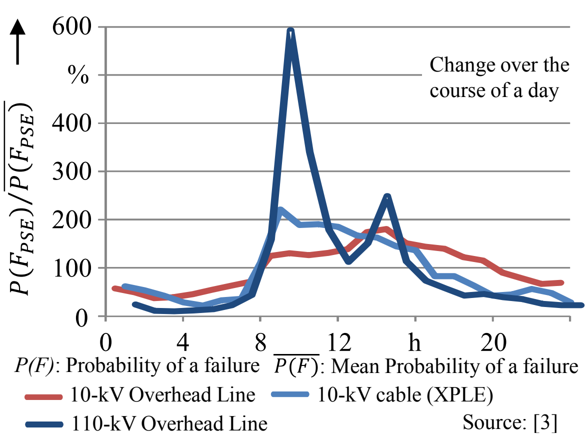


Figure 4. Time Dependency of Failure Rate of PSE

Failures on XLPE cables are in circa 40% of all cases caused by excavation during construction work. This leads to a significant correlation between cable failures and working hours of construction workers. Similarly significant correlation can be determined between storms and overhead lines. In both cases there is strong correlation with PV- and wind power infeed respectively. Other power system equipment is effected by more diverse failure causes and therefore shows a less prominent time dependency of its failure rate. Overall time dependency of PSE failure rates can be most accurately modelled with time series for each equipment type and voltage level.

For ICT-equipment (ICTE) in electrical networks due to lack of statistical data no analogue analysis is possible, but some manufacturers [6] and institutions [7] have carried out analyses of failure causes or already determined the time dependency of failure rates of ICTE for other purposes. Fig. 5 shows time dependencies of failure rates for processors and for optical fiber cables as well as time dependencies of interruptions caused by failures in the SCADA system. It can be concluded from the available data that a time dependency of ICTE failure rates is very likely and should be considered with models similar to those for PSE.

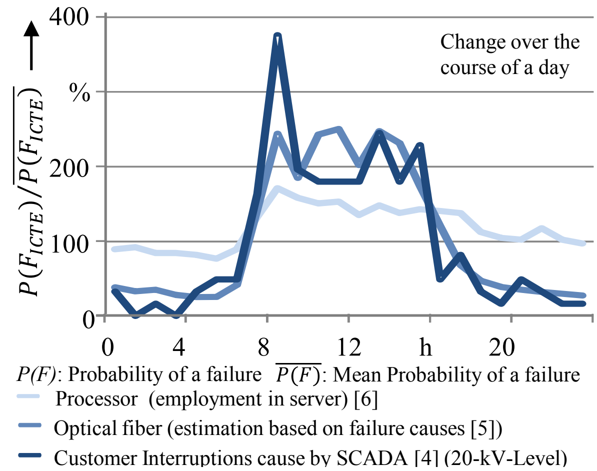


Figure 5. Time Dependency of Failure Rate of ICTE

IV. MODELLING OF ICT-SYSTEM

The ICT-system can be realized in different topologies which vary especially with the transmitting medium. The reliability of communication in an ICT-system is further influenced by switching state of the system, redundancy of communication paths and equipment failure rates. Therefore an explicit modelling of the ICT-system is necessary to simulate all possible interactions between ICT-system and power system. Fig. 6 shows a basic concept for an ICT-system in different degrees of detail as well as its connection points with the power system.

A communication system usually is defined by network layer, station layer and field layer, whereas the station layer may be omitted in modern architectures. Overall the communication system can be modelled as network consisting of nodes and branches as shown in the Fig. 6.

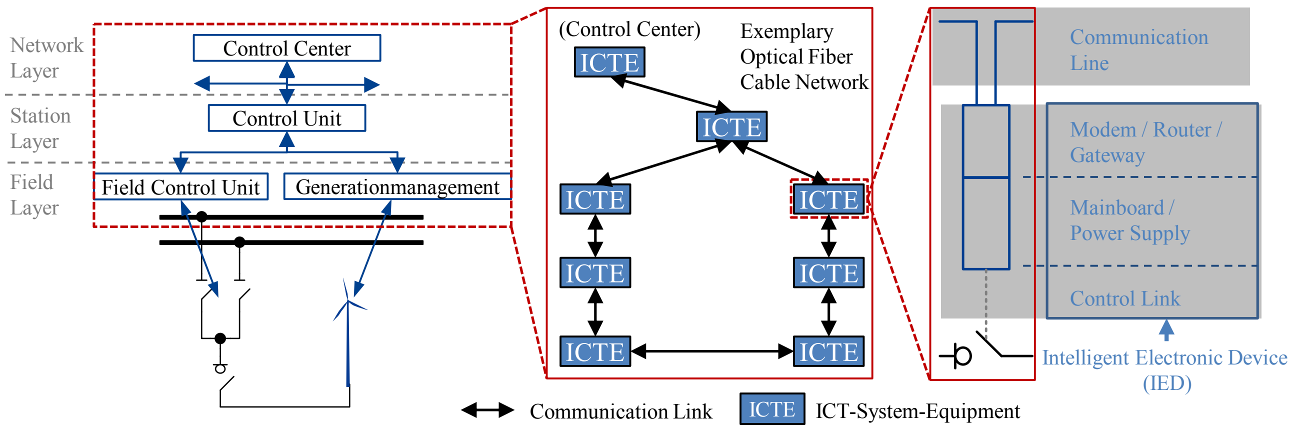


Figure 6. Modelling of ICT-System

Thereby each node of the network can be described as intelligent electronic device (IED). By using this approach each IED includes a communication unit, which may be a modem or router and may contain a network gateway, a functional unit, which represents the IEDs main functionality as well as the IEDs power source, and a connection to the power system equipment.

A mayor difference between the power system and the ICT-system is the fact that the ICT-system not only consists of a physical layer, which realizes communication, but also of different functions concerning information transport. Those functions are being realized within communication protocols, which are implemented on IEDs. Protocols designed for substations are defined in IEC 60870-5-104 [8] and IEC 61850 [9] for example. When analyzing reliability in an ICT-system this fact leads to the necessity to distinguish between failure categories: functional failure and network failure. For this purpose IED components are combined in classes with respect to their influence on overall functionality of the IED.

In case of a functional failure the IED is no longer able to support communication routing and functionalities defined by intelligent applications. A software error will lead to a similar effect and therefore is included into the same model. Signal dropouts and signal errors on the connection between IED and power system equipment can be detected by the IED as described in [10], cause the same effect and therefore are included as well. A power outage at the IED also will cause a functional failure but has to be modelled separately because it may be influenced by various factors such as a power system which is not part of the overall system or a back-up power source.

A network failure only affects the communication unit of the IED. The IEDs functionalities defined by intelligent applications are still in operation, able to detect this state and define a new operating mode. Signal dropouts and signal errors are detected by error detection, which is a standard feature of TCP/IP based protocols IEC 60870-5-104 and IEC 61850. Therefore signal dropouts and signal errors lead to the same effect and are therefore included in the network failure model. Fig. 7 shows the resulting model for an IED for a reliability assessment of the ICT-system.

Besides failures which may affect a single IED and its availability, system aspects of the ICT-system need to be considered in the process of reliability assessment. Especially the activation of available redundant communication paths and the evaluation of communication network utilization rate need to be considered.

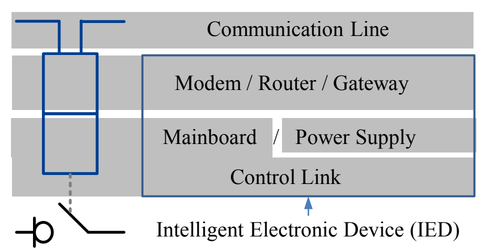


Figure 7. Modelling of an IED for Reliability Assessment

Routers and switches feature a functionality called dynamic routing, which enables those elements to automatically determine alternative communication paths in case of an equipment failure. Dynamic routing techniques, as defined in Routing Information Protocol Version 2 [11], are considered state of the art. A single failure of equipment therefore does not necessarily lead to an interruption of communication if an alternative path can be found.

Transmission rates of ICT communication links vary with the form of physical realization. Since state of the art substation protocols provide functionalities such as GOOSE [9] (Generic Object Oriented Substation Events), which realize an event based prioritization of information, transmission rates in failure modes can be configured by the system engineer in such a way that there will be no ICT-system overloading. Moreover, bandwidth needs for smart grid elements like GSM or DSM in a single distribution network with approximately 600 nodes and in part redundant communication paths are quite low. Transmission rates of communication links are therefore not further considered.

The ICT-system operation in fault situations is usually limited to repair and replacement. Other actions such as dynamic routing and change of operating modes of intelligent applications are usually performed automatically by protocols and software, but have to be taken into account in the simulation of the ICT-system. However, it can be concluded, that for the simulation of information exchange path searching algorithms are sufficient.

V. Modelling of Intelligent Applications

Based on their primary communication directions intelligent applications can be categorized into two groups: application with primarily unidirectional information exchange and application with primarily bidirectional information exchange. For a reliability assessment a mayor difference between these groups is the fallback position in case of network or functional failure. Applications with primarily unidirectional information exchange need to receive a command or send measurements for proper functioning. If the communication path is disrupted the functionality provided by these applications is no longer available. Therefore a network failure at IED level has the same effect as a functional failure. Applications with control and monitoring tasks such as remote switching, switching of sectioning points and monitoring systems can be associated with this group of applications. Fig. 8a shows an illustration of the effect.

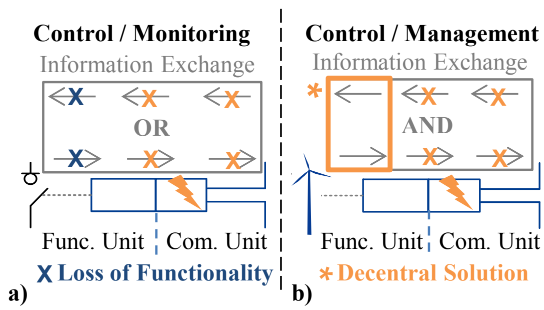


Figure 8. Intelligent Applications during Network Failure

Applications with primarily bidirectional information exchange receive commands as well as send measurements. A control of the application based only on local measurements is therefore in most cases still possible. If the communication path is disrupted the functionality of these application can be realized up to a limited extend by a decentral solution. Therefore a network failure at IED level does not lead to total loss of functionality. Applications with control functionalities based on algorithms or management tasks such as online tap changer control, DSM and GSM can be associated with this group of applications. For example for an online tap changer control based on wide area measurements a fallback position in case of network failure, which is based on local measurements only, can be defined. Fig. 8b shows the effect.

In the assessment of reliability these fallback positions of the applications have to be considered for a correct modelling of their functionalities.

VI. Necessary Changes to Current Algorithms for Reliability Assessment

As already described in chapter II.C the reliability in grids depending on ICT-system is no longer determined by the power system alone but also by the ICT-system. However a fault in the ICT-system only causes a deficit in time spans, in which the power system is dependent on intelligent applications. Therefore the probability of a deficit is influenced by the following factors: ICT-System reliability, intelligent applications, load and generation as well as power system reliability. The impact of a deficit is being influenced by power system topology, ICT-system topology and power system utilization. Load and generation as well as failure rates of power system equipment and ICT-system equipment are time dependent. Overall this leads to the following necessary enhancements to the probabilistic calculation process.

First of all the input data of the algorithm is being extended by the ICT-system topology, ICT-equipment reliability, a definition of intelligent applications and discrete but fixed scenarios for power system usage by load and generation are replaced by time series for load and generation. In the following the individual calculation steps, which are being modified, are described.

In the fault generation process ICT equipment failures as well as failure combinations of ICT and power system equipment failures are being integrated.

In the failure mode effect analysis, for every fault scenario the fault impact is determined with consideration of the time series for load and generation. This requires repeating the fault impact analysis for every point in time of those time series. Furthermore the resupply process is being enhanced by the consideration of intelligent applications and a detailed evaluation of current and voltage values, which requires load flow calculations.

In the procedure of calculating availability of supply indices the time dependencies of failure rates have to be considered. This is done by adjusting the input data of the Markov process in every iteration step of the procedure. The resulting calculation algorithm is shown in Fig. 9.

The concept of the determination of availability of supply indices in the new approach can be described as follows. Single points in time with a very short duration (e.g. 1 minute) are extracted from time series of customers and can be linked to specific failure rates by their time stamp. For these single points in time the effect of faults occurring at this point in time and faults, which occurred in the past but still have an effect on customers at this point in time, have been evaluated in the failure mode effect analysis. By taking into account faults, which occurred in the past by matching results of the Markov process for previous points in time with results of the failure mode effect analysis for the point in time under consideration, an overall assessment of the probability of a deficit at a single point in time is possible. Furthermore it can be distinguished between operating states of curtailment of power demand (DSM) and injection (GSM) as well as complete grid disconnection. The sum of the results of all single points in time leads to the probability of a deficit in a year. The calculation of single points in time also allows the determination of deficit energy and the number of minutes involved in deficits over a year. The frequency of faults and the frequency of the caused deficits can be determined by taking into account the probability of a fault at a single point in time and its duration.

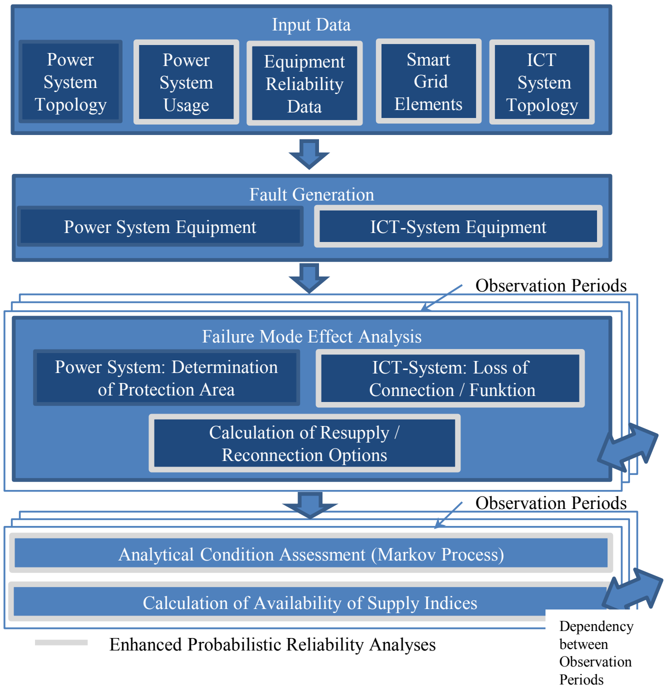
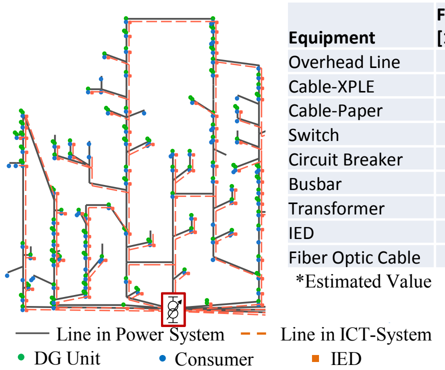


Figure 9. New Reliability Calculation Algorithm

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 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.

VII. Exemplary Results

A. *Exemplary grid*



Equipment	Failure Rate [1/a, 1/(a*km)]	Time to Repair [h]
Overhead Line	0.0197	2.4
Cable-XPLE	0.0013	3.8
Cable-Paper	0.0027	2.8
Switch	0.0001	1.4
Circuit Breaker	0.0020	6.0
Busbar	0.0001	2.0
Transformer	0.0044	2.3
IED	0.0104	2.0*
Fiber Optic Cable	0.0025	8.0

*Estimated Value

Figure 10. Part of Exemplary MV Grid and Reliability Parameters [6,12,13]

Calculations with the new approach were carried out for an exemplary MV distribution grid with a mainly open loop ring topology. In the grid GSM was used to integrate further DG units. Furthermore it was assumed that all switch gear in the grid could be remotely controlled. In common operating conditions during periods of maximum power injection and very low demand GSM is used to prevent cable and overhead line overloading. After faults during times of resupply GSM is need, to prevent equipment overloading, since the grid's ampacity is reduced significantly. If the necessary reduction in feed-in exceeds the controllable amount provided by GSM, DG units need to be disconnected, which leads to additional deficits besides the deficits caused by grid disconnection based on PSE failure. Besides the power system an independent ICT-system was modelled. As communication medium fiber optic cables were chosen and the ICT-system was emulated in parallel to the power system. Fig. 10 shows power system and ICT-system topology of the exemplary MV grid. For a first assessment of reliability only independent single faults were considered of equipment in the power system as well as in the ICT-system. Overlapping independent single faults also have an effect on overall reliability but have a much lower appearance rate.

B. *Scenarios*

1) *Operation with Intelligent Applications*

In the first scenario a grid operation with utilization of intelligent applications was considered. Therefore both power system and ICT-system failures have been determined in the reliability assessment. Besides the consideration of possible additional failures the utilization of GSM and remote switching capabilities during the resupply process was taken into account as well.

2) *Reinforced Power System*

For comparison reasons an additional calculation with a reinforced power system has been carried out. The reinforcement needs and optimal installation place of additional equipment has been determined with the algorithm presented in [14]. Since the age of the current infrastructure is unknown only additional equipment was installed, which leads to a significant number of double lines. From a reliability assessment point of view this kind of reinforcement represents a worst case scenario. The reinforced power system no longer requires the use of GSM during common operating conditions. If line overloading should still occur during contingencies DG units are being disconnected from the grid instantly.

C. *Results*

Fig. 11 shows the deficit probability and deficit frequency for the entire grid by the system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI) as defined in [15]. Since only DG units are equipped with GSM and connected to the ICT-system, the evaluation distinguishes between consumers and DG units.

In scenario 1 deficit frequency and deficit probability for consumers is lower than in scenario 2 because less equipment is used in the power system to supply consumers. Deficit frequency increases more than deficit probability in scenario 2 because additional equipment in general only causes failures of short duration in a power system equipped with remotely controlled switchgear. However for industrial consumers an increase of the SAIFI value by ~25% can be critical.

For DG units the deficit frequency remains roughly the same in both scenarios. In the first scenario ICT-system failures contribute significantly to the overall deficit frequency for DG units because the fallback position of the GSM in case of a functional failure of the IED is to disconnect the DG unit from the grid to prevent overload conditions. Those failures also lead to a significant rise in deficit probability because DG units are disconnected until the IED is replaced or repaired, which was assumed to take 2 hours. A switching operation in the primary system equipped with remote switching capabilities on the contrary only takes 5 minutes. Therefore a single failure in the primary system has in general less effect on the DG unit than the failure of its control IED. Deficits due to disconnection from power system because of overloading amount only to ~1% of the deficit probability in the exemplary MV grid in scenario 1. In scenario 2 deficits caused by disconnection due to power system overloading can almost entirely be prevented as well.

Deficit frequency and deficit probability are lower for DG units than for consumers because DG units are in this particular exemplary grid less frequently installed in single branches without alternative supply paths and DG units are only susceptible to failures during hours of feed-in.

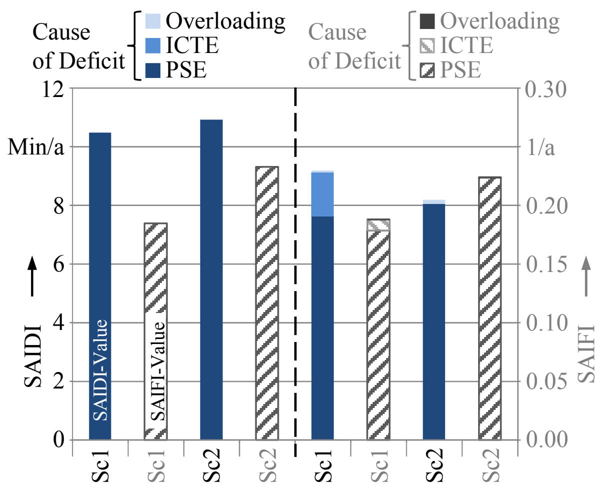


Figure 11. Deficit Frequency and Probability for Exemplary MV Grid

In general it has to be stated, that in the exemplary calculations the reliability for the IEDs was set to a high level compared with the reliability data of ICT equipment stated in [13]. The use of less reliable equipment or another ICT-system design may lead to an increase of the ICT-system's impact. In contrast to this development the network operator may change the fallback position of the GSM or the DG unit operator may install a backup IED for GSM. In these two cases the impact of the ICT-system would decrease significantly. Therefore it can be concluded that the impact of the ICT-system on reliability may differ significantly between different solutions.

VIII. Conclusion

The analysis of potential interactions between power system and ICT-system show, that if intelligent applications are used to control and monitor a power system, it can in some points in time be dependent on the ICT-system. This dependency in turn can have a significant impact on power system reliability. Therefore a new approach for the calculation of power system reliability has been developed. Results using the new algorithm show, that the use of intelligent applications may be advantageous for some customers because otherwise necessary extensive reinforcement of the power system also can have negative effects on reliability. Moreover the new approach enables operators, to evaluate grids featuring intelligent applications, and hence leads to more security in the process of planning future distribution grids.

Acknowledgements

The abstract contains results from a study, within the evolvDSO project, which describes potential future DSO roles, related services and their requirements for the development of novel tools. This work received funding from the European Union Seventh Framework Programme under grant agreement n° 608732.

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