Reliability Assessment of Distribution Systems including Microgrids

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Abstract— The electrical distribution system is moving toward a more decentralized, complex, and dynamic system. The system is experiencing a higher penetration of distributed energy resources, flexible resources, and active end-users, leading to an active distribution system. If these components are used actively, they can have a positive effect on the distribution system’s reliability. This paper aims to investigate how a microgrid with renewable energy sources and energy storage might influence the reliability of electricity supply in a radially operated distribution system. The reliability is investigated from both the distribution system perspective and the microgrid perspective with the application of different scenarios. A reliability assessment method for modern distribution systems based on Monte Carlo simulations is presented. The method includes load flow calculations to capture the behavior of the system and system components. The model is tested on the IEEE 33-bus network. The result is confirmed through statistical testing showing the statistical significance in providing support from the microgrid on the distribution system’s reliability.

Keywords—Active Distribution Systems, Distribution System Reliability, Microgrid, Monte Carlo.

I. INTRODUCTION

The electrical power system is under constant development, and in the upcoming years, a lot of changes will take place in the distribution system [1], [2]. The power system is moving from being somewhat hierarchical with the one-way transfer of energy to a more decentralized system where the system boundaries will be more invisible. The biggest changes can be seen in the distribution system, which will be more decentralized, complex, and dynamic with higher penetration of distributed energy resources and active end-users [3], [4], [5]. This will transform the distribution system into an active system with bidirectional power flows that will change the system behavior.

From a reliability perspective, this opens up new possible solutions. With more flexible resources in the system and integration of distributed generation (DG), there is a potential to increase the system reliability. Some research has been done to investigate the potential reliability improvement with these technologies integrated into distribution systems. Ref. [6] provides an overview of how flexible resources may impact the security of electricity supply (SoS) and includes a review of methods and indicators to quantify the impact. A review on power system flexibility is provided in [7]. In addition, flexibility is investigated concerning power system security. A survey of reliability assessment techniques for modern distribution systems is assessed in [8]. Here, multiple modeling techniques used for assessing distribution system reliability are investigated concerning active components in the system. The availability and impact of active components, such as DGs [9], [10], energy storage units [11], and systems with a combination of these [12], [13], have been investigated. The literature illustrates that DGs and flexible resources might have a positive impact on the reliability of distribution systems if administrated wisely.

Microgrids are an increasingly studied concept related to the improvement of system reliability [14]. The main attribute of microgrids is the possibility to operate in two different modes: 1) Grid-connected mode and 2) Islanded mode. This gives the opportunity of the microgrid to operate in an islanded mode during outages in the main system. If the microgrid and the distribution system work together, there is a potential of improved reliability related to unintentional outages in the system. By islanding parts of the distribution system with the microgrid, the microgrid could be the provider of these distribution system load points. Some studies have investigated the possibility of islanding parts of the distribution system during failure events. In [15] and [16], an analytical approach is used to find the contribution from the microgrid to the distribution system reliability. The contribution of the microgrid is determined by possible operating conditions of the microgrid and the DGs inside the microgrid, and is evaluated based on the ratio between demand and supply. A simulation-based approach with Monte Carlo techniques integrated into distribution systems. Ref. [17] has been used in [17] for intentional islanding of the distribution system. However, the paper does not consider the active participation of flexible resources and DGs to restore supply. Furthermore, a sequential Monte Carlo method is used in [18] to evaluate the impact from local and mobile generation units. Here,
parts of the system will be islanded, with some units operating as microgrids. In [19], the reliability of a distribution system with support from a microgrid including combined heat and power supply system is assessed. However, the microgrid does not include renewable energy resources (RES). In addition, some research related to the reliability of multi-microgrids has been assessed by [20], [21], and [22]. These papers do not consider the interaction between the microgrid and the distribution system, nor is the reliability of the microgrid investigated to any significant amount.

For microgrid support to be functioning, an interaction between the distribution system operator (DSO) and the microgrid owner must be in place. The type of interaction is dependent on who owns the microgrid. In [23], [24], and [25], this theme is discussed. In addition, regulatory frameworks related to the responsibility of islanded load points need to be in place. The regulatory interaction frameworks will not be considered in this paper, but are nevertheless important aspects to consider for the application of such support.

This paper will investigate the reliability of electricity supply from both the distribution system and microgrid perspective. The microgrid and the distribution system will therefore be distinguished based on system boundaries. This means that the distribution system and the microgrid will have clear and well-defined boundaries. The aim of the paper is to present a reliability assessment method applied on an interesting case study with results evaluated based on statistical testing. The presentation of the method focuses on the reliability analysis of a distribution system with the integration of a microgrid, and the method is presented in more detail in [26]. The contributions of this paper are:

- A simulation approach for calculating the reliability in a radially operated distribution system with the integration of an active microgrid.
- A case study where the reliability of both the distribution system and the microgrid is tested on the IEEE 33-bus network with different scenarios for microgrid support.
- The evaluation of results based on statistical testing with a sensitivity analysis.

The rest of this paper is organized as follows: section II introduces the concept of SoS along with the definitions, the four aspects of SoS, and the new network configuration. In section III, the method for how to calculate reliability in a distribution system with a microgrid is introduced and illustrated. The case study conducted on the IEEE 33-bus network is discussed in section IV. The results of the case study are illustrated and discussed in section V before the paper is concluded and future work discussed in section VI.

II. SECURITY OF ELECTRICITY SUPPLY IN THE FUTURE DISTRIBUTION SYSTEM

The European Commission defines the SoS as the ability of an electricity system to supply final customers with electricity [27], while the Norwegian Water Resources and Energy Directorate (NVE) defines it as the ability of an electricity system to continuously deliver electric power of a given quality to the end-user [28]. In this matter, the SoS can be seen as a property belonging to the power system where the outcome is measured based on the delivered power to the customers both regarding the quality of the power and the amount of delivered power. In [29], a framework to assess SoS in power systems is developed. Furthermore, the paper presents twelve dimensions that are critical for SoS in power systems. SoS can further be divided into four important aspects. NVE [28] and the Norwegian regulation of the quality of supply [30] defines the four SoS aspects as follows:

1) Power capacity—The power systems’ ability to cover the instantaneous load in the system. Power capacity is characterized by the available capacity of installed power production in the grid.

2) Energy availability—The power systems’ ability to cover the electricity demand in the power system. There is an energy shortage in the system if the generation units in the system generate less energy than the electricity demand in the system.

3) Power quality—The power systems’ ability to deliver power of a given voltage quality.

4) Reliability of supply—The power systems’ ability to deliver electric power to the end-user. The reliability of supply is measured in frequency and duration of outages in the electrical power delivery.

In a traditional power system, the transmission system operator (TSO) is responsibility for the power capacity and energy availability, whereas the power quality and the reliability of supply are regulated by the distribution system operator (DSO). However, in a modernized power system, the boundaries of the responsibility for the different SoS aspects will be changed. With more generation in the distribution system, and the distribution system becoming more similar to the transmission system, more responsibility might fall on the DSO. It will therefore be necessary to investigate the SoS differently in future power systems. However, in this paper, the emphasis will be on the reliability of supply.

A. The reliability evaluation of the future distribution systems with microgrids

In a traditional radially operated distribution system with one-way transfer of power as seen in Fig. 1 a
failure of, for example, a line in the network will result in all the downstream load points being isolated from the main power source unless there is an alternative supply route in the network. In Fig. 2, a failure has occurred on a line in the distribution system and been isolated. This results in the load points, highlighted in the red dotted box, downstream of the failed line to be isolated from the rest of the distribution system. Since there is no alternative supply route or any generation unit in this area, these load points will not be supplied until the failure is repaired and the line connected.

In this operation, the microgrid must be able to withhold the balance in the system along with the frequency and the voltage levels in the isolated part of the network. This means that the microgrid is in charge of regulating all the SoS aspects during the isolated operation.

Figure 1: Traditional radially operated distribution system

Figure 2: Traditional radially operated distribution system with failure

However, if there is a flexible resource such as a microgrid present in the network, the situation might be changed. The aim is to use the flexibility in the system to restore or to help the network during periods with, e.g., low supply, failures in the network, and capacity problems. A microgrid can support the system in two different modes: 1) isolated operation and 2) grid-connected operation or supportive operation.

1) Isolated operation: If a failure occurs on, for example, a line in the distribution system as seen in Fig. 3, the downstream load points will be isolated from the overlaying network and traditionally these load points will not be supplied. However, if a microgrid or another flexible resource is present in this isolated part of the network, at least parts of the supply can be restored. The microgrid will then operate in an island mode during the outage time of the faulty component. When the failure is repaired, the isolated part can be disconnected from the overlying grid again.

In this operation, the microgrid must be able to withhold the balance in the system along with the frequency and the voltage levels in the isolated part of the network. This means that the microgrid is in charge of regulating all the SoS aspects during the isolated operation.

Figure 3: Supply restored with microgrid in island mode with isolated part of the distribution system

2) Supportive operation: Usually, in distribution systems, some alternative supply chains might exist that can be used in case of redirection of power or failure in the network. Then the line can be connected and help supply loads in the system in areas that would have been isolated during the faulty period. However, some of these lines have lower capacity limits and might end up being congested, or they might end up creating bottlenecks in the network. Local production in the distribution network will prevent congestion and bottlenecks. Fig. 4 illustrates how a microgrid can support the system during a fault in the system. The load points could have been restored with only the connection of the alternative line, but the microgrid is now able to support the system with local production.

Figure 4: Supply restored with alternative supply chain and microgrid support

III. RELIABILITY ANALYSIS

A. Reliability evaluation in traditional distribution systems

In general, there are two ways of analyzing the reliability in the distribution system, namely through analytical approaches or Monte Carlo simulation. The analytical approaches use simplified models with averaged quantities to estimate the reliability indices. Monte Carlo simulations, however, allow for a more
detailed representation of the reliability indices by generating reliability indices through numerous independent instances with stochastic variations. The numerous instances result in a detailed distribution of reliability indices. Analytical models are more generic and are often, therefore, more applicable for many different cases, whereas Monte Carlo simulation models will give a more detailed analysis of the system to be modeled.

RELSAD is an example of an analytical approach developed for calculating the reliability in a radial operated distribution system [22]. The RELRAD methodology calculates the individual load point reliability indices analytically based on the fault contribution from all the network components and their consequence on a given load point. However, such an approach does not consider the active components in the network, such as microgrids, DGs, and batteries, and since it uses average values for load and generation, the electrical consequence and the behavior of the network are not considered. Therefore, simulation is a more suitable method to calculate the reliability in an active distribution system including microgrids, flexible resources, and DG.

B. Reliability evaluation in modern distribution systems

To calculate the reliability in future smart and flexible distribution systems, an appropriate method is needed. The traditional approaches will not be able to utilize the full potential of the active components in the distribution system and a form of simulation approach will be more advantageous. Since the active components interact with the distribution system based on multiple independent factors, such as failures and weather conditions, the simulation of their impact on the distribution system must cover all possible scenarios. A Monte Carlo simulation approach, which makes use of random sampling of input, is well suited for this type of problem.

In this relation, RELSAD, a reliability assessment tool for modern distribution systems was developed. RELSAD is a sequential Monte Carlo simulation model. The method is built on object-oriented programming as a Python package. A description of RELSAD is given in [26].

In RELSAD, a power system - $P_s$ is first created before distribution systems - $D_s$ and microgrids - $M_s$ are created inside the $P_s$. After this, the electrical system components can be created and added to associated network layers. The electrical components are lines - $l$, buses - $b$, disconnectors - $d$, circuit breakers - $cb$, generation units - $p_u$, and batteries - $p_b$. In addition, a load - $p_d$ can be assigned to each bus.

The incremental procedure of the model is illustrated in Algorithm 1. After a $P_s$ is created with associated systems and components, the incremental procedure will set the load and generation at the system buses for the current time increment. Then the failure status of each component is drawn based on random sampling and the failure rate of the different components. If any component is in a failed state, the $D_s$ and/or $M_s$ with the failed components will be divided into sub-systems, and a load flow and optimization problem will be solved for each subsystem. When this is performed, the history variables of the components are updated. The history variables can then further be used to evaluate the reliability of the $P_s$, the different subnetworks (the $D_s$ and $M_s$), and the individual load points. The rest of this section aims to describe the different procedures of the reliability evaluation in greater detail.

| Algorithm 1: Increment procedure |
|----------------------------------|
| 1 Set bus $p_d$ and $p_u$ for the current time increment; |
| 2 Draw component fail status; |
| 3 if Failure in $P_s$ (in the systems, $D_s$ and $M_s$) then |
| 4 Find sub-systems; |
| 5 foreach sub-system do |
| 6 Update $p_d$ demand (charge or discharge rate); |
| 7 Run load flow; |
| 8 Run optimization problem; |
| 9 end |
| 10 Update history variables; |
| 11 end |

C. Microgrid reliability

The reliability evaluation of a microgrid is dependent on the operation mode of the microgrid. If the microgrid is in island mode, the microgrid will function as an independent system. Whereas, if the microgrid is connected to the overlying distribution system during the outage period, the microgrid will be a part of the distribution system and the systems need to interact. In [33], new metrics for the reliability of microgrids in island mode are proposed.

In this study, the aim is to investigate the impact of the microgrid as well as the reliability of both systems. Since the microgrid primarily will be connected to the distribution system, island mode is only achieved during outages in one of the systems. This will then make the regular reliability indices well suited for evaluating the reliability in the microgrid.

Algorithm 2 illustrates the controller procedure for the microgrid. First, the sectioning time of the $cb$ is updated if needed. This is done in case the system was in a sectioning time in the previous time step. Then, if a new outage happens in one of the systems, $D_s$ and $M_s$, the circuit breaker of the $M_s$ will open. In the $M_s$, all lines will be checked for failures. If the line containing the circuit breaker is failed, then the
circuit breaker should remain open regardless of the \( M_s \) mode. If not, the algorithm will check in which mode the \( M_s \) should operate in. If the \( M_s \) is supposed to operate in island mode during failures in the \( D_s \), the procedure will check for failed lines in the \( D_s \). In case of no failed lines in the \( D_s \), the failed sections in the \( M_s \) are disconnected and the circuit breaker closed. If the microgrid is in a supportive mode, where it can be islanded with parts of the \( D_s \) buses, the failed sections in the \( M_s \) are disconnected before the circuit breaker is closed.

This will result in the \( M_s \) being in one of three states during an outage in the \( P_s \): 1) in island mode, 2) in island mode with parts of the \( D_s \), or 3) connected to the \( D_s \) with the possibility of supply from the overlying network.

**Algorithm 2: Microgrid controller procedure**

```
1 Update sectioning time;
2 if \( cb \) is open and sectioning time \( \leq 0 \) or \( l \) recovered from failure then
3    Check \( l \) in \( M_s \) for failure;
4    if \( l \) with \( cb \) not failed then
5        if No failed \( l \) in \( D_s \) then
6            Disconnect failed sections;
7            Close \( cb \);
8        end
9    else
10       Disconnect failed sections;
11       Close \( cb \);
12    end
13 end
```

D. Load flow and optimization problem

To calculate the electrical consequence of a failure in the network when there are generation resources available, a load flow calculation needs to be performed. Since the network is radially operated, a Forward-Backward sweep (FBS) approach is used to perform the load flow calculation [34], [35]. The benefit of using an FBS approach is that the load flow components are calculated iteratively and do not need to go through the Jacobian matrix, as in the Newton-Raphson method. This way convergence problems arising from an ill-conditioned matrix of weak networks can be avoided.

The FBS approach calculates the load flow of the system by updating the power flow through the backward sweep before the buses voltage magnitude and angle are updated in the forward sweep. The method is based on [36].

**Backward sweep:** In the backward sweep, the active and reactive power over the lines is calculated. The active and reactive power over line \( l \) for iteration \( k \), \( P_l \) and \( Q_l \), is calculated by adding the accumulated active and reactive load, \( P_l^* \) and \( Q_l^* \), at the downstream buses and the accumulated active and reactive power losses, \( P_l^\text{loss} \) and \( Q_l^\text{loss} \), over the downstream lines including the power loss over line \( l \) and the load at the current bus

\[
P_l = P_l^* + P_l^\text{loss}
\]

\[
Q_l = Q_l^* + Q_l^\text{loss}
\]

where the accumulated active and reactive load at the buses are calculated as

\[
P_l^* = P_{i_l}^\text{load} + \sum_{d=0}^{d} P_{d_l}^\text{load}
\]

\[
Q_l^* = Q_{i_l}^\text{load} + \sum_{d=0}^{d} Q_{d_l}^\text{load}
\]

Here \( P_{i_l}^\text{load} \) is the active load at node \( i_l \), \( Q_{i_l}^\text{load} \) is the reactive load at node \( i_l \), and \( P_{d_l}^\text{load} \) and \( Q_{d_l}^\text{load} \) are the active and reactive loads at the downstream buses, respectively.

The accumulated active and reactive power losses are calculated as

\[
P_l^\text{loss} = R_l P_{i_l}^2 + Q_{i_l}^2 V_j^2
\]

\[
Q_l^\text{loss} = X_l P_{i_l}^2 + Q_{i_l}^2 V_j^2
\]

Here \( P_l^\text{loss} \) and \( Q_l^\text{loss} \) are the active and reactive power loss over line \( l \), respectively, and \( P_{d_l}^\text{loss} \) and \( Q_{d_l}^\text{loss} \) are the active and reactive power loss of the downstream lines, respectively.

The active and reactive power loss over a line is further calculated as

\[
P_l^\text{loss} = R_l P_{i_l}^2 + Q_{i_l}^2 V_j^2
\]

\[
Q_l^\text{loss} = X_l P_{i_l}^2 + Q_{i_l}^2 V_j^2
\]

Where \( R_l \) and \( X_l \) are the line resistance and reactance, respectively, and \( V_j \) is the voltage at the ending bus.

**Forward sweep:** In the forward sweep, the bus voltage magnitudes and angles are updated by using the updated active and reactive power from the backward sweep. Then the voltage magnitude at bus \( i \) in relation to the voltage magnitude at bus \( j \) for iteration \( k \) can be calculated by

\[
V_i = V_j - I_i R_l + j X_l = \sqrt{V_j^2 - T_1 + T_2}
\]

where the term \( T_1 \) and \( T_2 \) are

\[
T_1 = 2(P_l R_l + Q_l X_l)
\]

\[
T_2 = (P_l R_l + Q_l X_l)^2
\]
The imaginary part of \( V \) is the cost of shedding load at node \( n \) while \( P \) of power lines, the load, and the generation. Here for shedding that specific load type. This is subjected total load shedded in the network based on the CENS can be seen in [38], [39].

**Optimization problem:** Since the system lines and the generation resources have limited capacity, an optimization problem is introduced to minimize the total shedded load in the network based on the price. The price is based on the Cost of energy not supplied (CENS) [37]. The CENS scheme, in Norway, is intended to give the DSOS incentive to build and operate the network with a focus on a socio-economic and reliable operation of the network. Similar schemes can be seen in [38], [39].

The optimization problem, in eq. (11) minimizes the total load shedded in the network based on the CENS for shedding that specific load type. This is subjected to load flow balance and capacity limitations over the power lines, the load, and the generation. Here \( C_n \) is the cost of shedding load at node \( n \) while \( P_n^s \) is the amount of shedded power at node \( n \). \( P_j^p \) is the production from generator \( j \). \( P_k^p \) is the load demand at node \( k \) while \( P_k^s \) is the power transferred over line \( i \). \( \gamma_i = 1 \) if line \( i \) is the starting point, \(-1\) if line \( i \) is the ending point. \( \lambda_j = 1 \) if there is a production unit at node \( j \), otherwise it is 0. \( \mu_k = 1 \) if there is a load on node \( k \), otherwise it is 0.

\[
\text{minimize } P_s = \sum_{n=1}^{N_n} C_n \cdot P_n^s \\
\text{subject to: } \sum_{i=1}^{N_i} \gamma_i \cdot P_i^d = \sum_{j=1}^{N_j} \lambda_j \cdot P_j^p - \sum_{k=1}^{N_k} \mu_k \cdot (P_k^d - P_k^s) \\
\min P_j^p \leq P_j^s \leq \max P_j^p \forall j = 1, \ldots, N_g \\
0 \leq P_k^s \leq P_k^d \forall k = 1, \ldots, N_n \\
|P_i^d| \leq \max P_i^d \forall i = 1, \ldots, N_l
\]

**E. Reliability indices**

There are different reliability indices used for measuring and quantifying the reliability in distribution systems. They can be divided into customer-oriented indices and load- and production-oriented indices [31]. The three basic reliability parameters are the fault frequency or the average failure rate, \( \lambda_s \), the annual average outage time, \( U_s \), and the average outage time, \( r_s \). In a radial network, the three different reliability parameters can be calculated as in eq. [12] eq. [13] and eq. [14]. Here, \( \lambda_i \) and \( r_i \) are the failure rate and outage time at load point \( i \), respectively. These equations are used to state the load-point reliability. However, these do not tell anything about the electrical consequence of a failure or the cost related to a failure.

\[
\lambda_s = \sum \lambda_i \\
U_s = \sum \lambda_i r_i \\
r_s = \frac{U_s}{\lambda_s} = \frac{\sum \lambda_i r_i}{\sum \lambda_i}
\]

**Load- and Production-oriented indices:** The load- and production-oriented indices aim to indicate the electrical consequence of failures in the system [31]. The total Energy not Supplied (ENS) in a system can be calculated as seen in eq. (15).

\[
\text{ENS} = U_s P_s 
\]

The interruption cost for the system can be calculated as seen in eq. [16] [39]. Here, \( c_i \) is the specific interruption cost for each customer category at load point \( i \).

\[
\text{CENS} = \sum \text{ENS} c_i 
\]

**Customer-oriented indices:** The customer-oriented indices aim to indicate the reliability of the distribution system based on the interruption experienced by the customers [31]. In this paper, three important indices will be investigated:

1) **System Average Interruption Frequency Index**

\[
\text{SAIFI} = \frac{\sum_{i=1}^{N_i} \lambda_i N_i}{\sum N_i} 
\]

where \( N_i \) is the total number of customers served, and \( \sum_{i=1}^{N_i} \lambda_i N_i \) is the total number of customer interruptions. SAIFI is a measure of the frequency of interruptions the customers in the system expect to experience. Any interruption seen from the consumer is counted as a fault, regardless of origin.

2) **System Average Interruption Duration Index**

\[
\text{SAIDI} = \frac{\sum U_i N_i}{\sum N_i} 
\]

where \( \sum_{i=1}^{N_i} U_i N_i \) is total number of customer interruption durations. SAIDI is a measure of the expected duration of interruptions a customer is expected to experience.

3) **Customer Average Interruption Duration Index**

\[
\text{CAIDI} = \frac{\sum U_i N_i}{\sum_{i=1}^{N_i} \lambda_i N_i} 
\]

CAIDI is the ratio between SAIDI and SAIFI and measures the average duration each given customer in the system is expected to experience.
F. Statistical analysis

1) Statistical difference: Statistical analysis is important to confirm the hypotheses made by researchers. A statistical test checking for equal means can be performed to quantify whether the result data sets from different scenarios differ. This is performed to determine if the result data sets are significantly different or not. There are two classes of hypothesis tests, namely 1) parametric \[41\] and 2) non-parametric \[42\]. Both classes are bounded by assumptions about the distribution of the result data sets. Parametric tests are restricted to normally distributed data sets with equal variance, while non-parametric tests have looser restrictions. For this reason, parametric tests have stronger statistical power, making them the preferred choice if the data set satisfies its assumptions. To decide which class of tests to use, an evaluation of the distribution of the results data set must be carried out.

The evaluation of normality can be done by performing an Anderson-Darling (AD) test. The AD test is used to establish if a data set comes from a population with a specific statistical distribution \[43\]. The outcome of the test is measured by the deviation $A^2$, between the number of samples and a weighted logarithmic expression of the data in the data set. An increasing deviation between $A^2$ and zero decreases the probability of the data set being of a specific statistical distribution.

If the AD test for normality fails, non-parametric tests must be used to check for equal means. In this paper, the Kolmogorov-Smirnov (KS) \[42\] test is used for this purpose. The KS test quantifies the distance between two data sets, indicating if the data sets are drawn from the same population.

2) Sensitivity analysis: Sensitivity analysis is important since it provides a mapping of the behavior of the model and illustrates how the results are affected by various parameters.

Factorial design is a more advanced form of sensitivity analysis used to investigate and understand the effect of independent input variables on a dependent output variable \[44\]. One of the biggest advantages of factorial design compared to a conventional sensitivity analysis, that only studies the effect of one variable at a time, is the ability to quantify both the influence the variables have on the output variable and on the other investigated variables. However, this drastically increases the number of combinations to investigate, which will lead to more simulation time, for example, a factorial design test with three factors that consider two levels each leads to a total of $2^3 = 8$ combinations.

IV. RELIABILITY TEST SYSTEM

A. Test network

The method is applied on the IEEE 33-bus system seen in Fig. 5. The IEEE 33-bus system is chosen since it is a commonly used network of a realistic size that might fit well with a medium-sized microgrid. However, since the network is operated fully radially without any backup connections, possible islanded operation with the microgrid will be investigated. The total load in the distribution system is scaled to approximately double the size of the traditional load values in the IEEE 33-bus system \[45\] to have a total load profile two to three times larger than the possible production from the microgrid.

The distribution system includes different types of loads, such as households, farms, industry, trade, and office buildings, to build a more dynamic customer profile in the system and include the priority of the loads. The load profiles are generated based on the FASIT requirement specification \[46\] where the weather data is collected from a location in eastern Norway. The reliability data of the system can be seen in Tab. 1.

| Section time [h] | Line | Transformer |
|------------------|------|-------------|
| Outage time [h]  | 4    | 8           |
| Failure rate [failure/year] | 0.07 | 0.007       |

Table I: Reliability data for the system

Figure 5: The topology of the distribution system (blue) and the microgrid (green)

B. Microgrid

The microgrid is placed on bus 33 at the end of the radial arm in the distribution system. The microgrid contains wind power, solar power, a battery, and some load. The specifications of the microgrid can be seen in Tab. 1. The wind and solar power profiles are generated based on weather data from the same location in Norway.

The microgrid is operated in grid-connection mode most of the time, but if a line failure occurs in the distribution system or the microgrid, the microgrid will shift to island operation.
Table II: Microgrid specifications

| Component         | Specification               |
|-------------------|----------------------------|
| Battery           | Max capacity: 1 MWh         |
|                   | Inverter capacity: 500 kW   |
|                   | Efficiency: 0.95            |
|                   | Min SOC: 0.1                |
| Wind & Solar power| Max power: ∼ 3.5 MW         |
| Load              | Peak load ~ 200 kWh        |

**Battery strategy:** The battery in the microgrid is assumed to follow the power market in the system, meaning that the battery will sell and store energy based on wanting to profit from the stored energy. However, since this paper focuses on the reliability of electricity supply, the market strategy will be simulated by predicting the state of charge (SOC) levels of the battery. The SOC level is assumed to follow a uniform distribution between the minimum and the maximum SOC level of the battery. This can be assumed since no estimation has been done to evaluate a marked strategy for the battery. This will result in a more realistic analysis where the battery SOC level can vary during failures in the network.

**C. Description of the different scenarios**

The case study investigates three different scenarios, which are based on three different operating modes for the microgrid, namely: 1) *no support mode*, 2) *full support mode*, and 3) *limited support mode*. This paper aims to investigate how a microgrid with DG and an energy storage system impacts the reliability of electricity supply in a distribution system. This will be illustrated through the different scenarios for which the reliability of the electricity supply for both the distribution system and the microgrid will be investigated and evaluated.

1) **Scenario 1: No active participation, microgrid in survival mode:** The first scenario will include both the distribution system and the microgrid, both radially operated. For failures in the network, the microgrid will disconnect from the distribution system and operate in an island mode until the failure is removed.

The microgrid will not support the distribution system during the failure event and the microgrid must be self-sufficient during the outage time.

2) **Scenario 2: Active participation of the microgrid, microgrid with full support:** In the second scenario, active participation of the microgrid during failures will be considered. During failures, the microgrid will reconnect after the sectioning and provide electrical power support to the distribution system.

This is a more aggressive scenario where the outcome might result in the battery becoming empty relatively fast. In cases of no generation from the DGs in the microgrid, the loads in both the distribution system and the microgrid will be shedded.

3) **Scenario 3: Active participation of the microgrid, microgrid with limited support:** The third scenario also considers active participation from the microgrid and the resources in the microgrid. However, the battery will rather serve as a backup source and will therefore not participate in any market strategy. The battery will therefore be fully charged when a failure occurs. Instead of giving full support, the microgrid will focus on storing enough power in the battery to ensure that the load in the microgrid can be supported at peak load for at least four hours. This will result in a prioritizing of the microgrid load.

V. RESULTS AND DISCUSSION

This section presents the reliability results for the three described scenarios from both the distribution system and microgrid perspective. Finally, a factorial design study is presented for Scenario 3.

**A. The distribution system perspective**

Fig. 6 illustrates the distribution of ENS for the three different scenarios in the distribution system. A box plot of the same is illustrated in Fig. 7.

It can be observed from the box plot that there is a slight decrease in ENS for Scenarios 2 and 3 where the microgrid supports the distribution system during failures, compared to Scenario 1 where the microgrid operates in island mode during failures. This can be seen from the plots of the distributions, as the distribution for Scenarios 2 and 3 are slightly shifted to the left compared to Scenario 1. This result indicates that load shedding with lower ENS happens more frequently for Scenarios 2 and 3 compared to Scenario 1. In comparing Scenarios 2 and 3, there is a slight improvement when applying Scenario 3. This is mostly due to the state of the battery, which operates on standby and will most likely be fully charged when an outage appears in the system.
The result is more readable in Tab. III where the discussed reliability indices are presented for the three scenarios. Overall, the ENS decreases by 4.54% for Scenario 2 and 5.69% for Scenario 3 compared to Scenario 1. This effect could be increased by having multiple generation sources or microgrids spread around in the network. Since the microgrid is located at one spot in the microgrid, there will be several cases where the microgrid is unable to support the grid since the isolated part is not connected to the microgrid. In addition, since the microgrid prioritizes its own load, the distribution system will get less support.

Table III: Reliability indices for the distribution system

| Scenario | ENS  | SAIFI | SAI DI | CAIDI |
|----------|------|-------|--------|-------|
| S1       | 39.8014 | 5.3953 | 9.9347 | 1.8414 |
| S2       | 37.9930 | 5.4143 | 9.8339 | 1.8163 |
| S3       | 37.5350 | 5.4655 | 9.7854 | 1.8032 |

By analyzing the other reliability indices, some small differences between the different scenarios can be observed. The failure duration for the system decreases with support from the microgrid. The reason for this is that some load points will experience a decreased period of shedding. However, the failure frequency will increase. In most cases, the microgrid generation and battery are unable to preserve supply during the whole outage period, resulting in some load points experiencing a new outage period when the generation is low or the battery is empty.

Statistical testing was performed on the results from the three different scenarios. First, the AD test was used to investigate if the results are normally distributed. As seen in Tab. IV the normality test failed, indicating that none of the results are normally distributed. The test statistics, \( A^2 \), are very high, indicating with high certainty that the result is not normally distributed. This can also be seen by investigating the distributions in Fig. 9.

Table IV: Statistical test of the three scenarios in the distribution system

| Scenario | AD test \( A^2 \) | Scenarios | KS test p-value |
|----------|-------------------|-----------|-----------------|
| S1       | 22.61             | S1 vs. S2 | 0.00            |
| S2       | 22.46             | S1 vs. S3 | 0.00            |
| S3       | 24.73             | S2 vs. S3 | 0.63            |

B. The microgrid perspective

The result as seen from the microgrid perspective is evident in Fig. 8. A box plot of the same result is illustrated in Fig. 9. The differences between the scenarios are more clear when investigating them from the perspective of the microgrid. Here, Scenario 1 will result in most shedding, since the microgrid has to survive in island mode during the failure in the distribution system without backup supply. Scenario 2 is somewhat better since the microgrid will reconnect to the distribution system. For situations where the microgrid is in the same sub-system as the main feeder of the distribution system, the microgrid will be ensured supply. Scenario 3 is the case that will give a very small ENS. The outliers in the box plot are a result of failures inside the microgrid and a high impact low probability case. This case is a result of two failures happening in close approximation, leading to a discharged battery before the last failure is removed.

The reliability indices for the microgrid can be seen in Tab. V. The indices indicate that there is a considerable decrease in the interruption duration for Scenario 3 compared to the other. Scenario 3 also leads to a lower interruption frequency. The ENS for Scenario 3 has decreased by 71.55% compared to Scenario 1, whereas the ENS for Scenario 2 has decreased by 16.87%.
The reliability indices for the microgrid are shown in Table V.

|         | S1     | S2     | S3     |
|---------|--------|--------|--------|
| **ENS** | 0.2851 | 0.2370 | 0.0811 |
| **SAIFI** | 0.9609 | 1.0350 | 0.8616 |
| **SAIDI** | 4.0188 | 3.254  | 1.024  |
| **CAIDI** | 4.1825 | 3.1440 | 1.1884 |

The same statistical tests were performed on the reliability result for the microgrid. The result can be seen in Table VI. None of the results passed the normality test, which can be expected based on the distribution of the result. The same non-parametric test was performed with a significance level of 5%. The outcome shows that all the scenario results are significantly different from each other. The result illustrates the importance of backup supply for the microgrid, either through the distribution system or through the microgrid sources. Since all the scenarios are significantly different, Scenario 3 is the best scenario seen from the microgrid perspective when measuring ENS.

### Table VI: Statistical test of the three scenarios in the microgrid

| Scenario | AD test $A^2$ | Scenarios | KS test $p$-value |
|----------|---------------|-----------|------------------|
| S1       | 173.86        | S1 vs. S2 | 0.00             |
| S2       | 174.77        | S1 vs. S3 | 0.00             |
| S3       | 271.12        | S2 vs. S3 | 0.00             |

### C. Sensitivity analysis

A factorial design study was performed on Scenario 3, which was chosen based on the results obtained from the reliability assessment. Since there was no significant difference between the results from Scenario 2 and 3 for the distribution system and Scenario 3 gave the best overall result for the microgrid, this is the most appropriate case to investigate further. The investigated parameters and parameter values can be seen in Table VII. Any lower limit value for the battery capacity was not chosen since the battery in Scenario 3 is dimensioned for the peak load in the microgrid. If the battery capacity value is decreased, Scenario 3 as it is illustrated in this study is not applicable.

### Table VII: Parameter values used in the factorial design study

| Name            | Battery [MWh] | Line [failures/year] | Transformer Name |
|-----------------|---------------|----------------------|------------------|
|                 | 1             | 2                    | Bat1             |
|                 | 2             | 4                    | Bat2             |
| Outage time [h] | 2             | 4                    | Out1             |
|                 | 4             | 8                    | Out2             |
|                 | 6             | 10                   | Out3             |
| Failure rate    | 0.05          | 0.005                | Fail1            |
|                 | 0.07          | 0.007                | Fail2            |
|                 | 0.09          | 0.009                | Fail3            |

The results from the factorial design study are illustrated in Fig. 10 for the distribution system and in Fig. 11 for the microgrid. The plots indicate both the effect each parameter has on the ENS in the system and how the parameters affect each other.

When investigating the result from the distribution system (Fig. 10), an increased battery capacity does not contribute to any considerable improvement of the ENS. The effect is, as expected, mirrored by the increase of the battery capacity. This illustrates that the saturation level is not met. In addition, since the system is relatively large, so multiple scenarios will lead to situations where the microgrid is unable to support all the isolated load points in the distribution system, the total support will be seen as small.

However, the change of ENS is larger when investigating the failure rate and the outage time. This is especially for situations with either a high failure rate or outage time compared to the other parameter. Overall, the failure rate affects the ENS in the distribution system the most.

Investigating the result from the microgrid perspective (Fig. 11), the battery capacity holds a more im-
important role compared to the distribution system. This effect is considered when comparing the battery capacity with the higher outage time of the components. This is a result of the microgrid being able to supply the microgrid load for more hours during special high impact low probability events, as discussed. The outage time is also important for the reliability of the microgrid. This effect illustrates the importance of being able to restore supply faster.

![Interaction plot for the distribution system](image1.png)

![Interaction plot for the microgrid](image2.png)

VI. CONCLUDING REMARKS

The reliability of electricity supply has been investigated from both the distribution system’s and the microgrid’s point of view. The impact of the microgrid on the reliability in the distribution system based on the reliability indices is not considerably large in this case. This result is dependent on multiple factors such as the availability of wind and solar power in the microgrid, the load in the system at the time of the fault, where the fault occurred, the location of the microgrid, and the dimensioning of the load in the distribution system compared to the generation in the microgrid. Based on the statistical tests, there is a significant difference between having support from the microgrid compared to no support. The results indicate that this may have a significant impact on the reliability of the distribution system. However, this is dependent on which criteria the DSO gives priority to. This will most likely be either measured in ENS or based on cost benefit analysis.

When investigating the different scenarios for both the distribution system and the microgrid, Scenario 3 is the best cross-over strategy for both systems. This is related to the statistical test illustrating that Scenario 3 does not differ significantly from the other best cases for the two systems. However, due to the possibility of additional load shedding in the microgrid for Scenario 3 related to a low probability case, the microgrid could take some precautions like having an additional backup to give sufficient power. In addition, the distribution system and the microgrid should have some agreement related to such support, which also could include agreements related to situations with high impact low probability for the microgrid.

In the end, the outage time, the sectioning time, and the probability of failure were selected based on mean values from Norwegian failure statistics. However, if the parameters followed probability distributions instead, the results would have been different. This is considered an area for future work. Parts of the effect are investigated and presented in the factorial design study, but it is not fully accounted for. An additional important finding is that, in such a network, different scenarios can occur where the microgrid is unable to provide support, for example, if the isolated part of the network does not include the microgrid. Since all of these scenarios are possible outcomes, they will be added to the failure statistic and increase the similarity of the scenarios. Therefore, it could be of value to investigate the same idea with multiple microgrids or other sources scattered throughout the system and therefore, obtain more possible sub-systems with generation units.

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