RELIABILITY ASSESSMENT OF ACTIVE DISTRIBUTION NETWORKS CONSIDERING DISTRIBUTED ENERGY RESOURCES AND OPERATIONAL LIMITS

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ABSTRACT

This paper presents an analytical technique for reliability evaluation of distribution networks that considers Distributed Generation (DG) and switching actions in order to alleviate network constraints violation during the restoration process. Reliability indices have been assessed for scenarios with dispatchable and non-dispatchable DG and the results obtained emphasised the importance of considering operational limits of the network components, especially during the restoration process at high load levels.

INTRODUCTION

Reliability of supply in distribution networks is crucial for consumers and an accurate assessment of reliability is critical for any planning of new investments in distribution networks. Both analytical and simulation techniques are well known and have been used for assessing reliability of supply [1], [2]. Analytical techniques have been more frequently used for reliability assessment because of their lower computational effort. Yet, most analytical techniques do not include the effect of network constraints on supply restoration in the reliability analysis [3].

When a failure in a network component takes place, the affected area is isolated and actions for the supply restoration such as closing normally-open points are applied. Reliability becomes more critical at increased levels of loading because supply restoration can be unfeasible or limited when a failure takes place. Network constraints, e.g. lines capacity and voltage limits, have to be taken into consideration in order to provide more realistic reliability results. Overloading of lines when an alternative supply is applied through normally-open points was addressed in [4] to calculate feasibility of restoration at average load conditions. In [5] voltage drop constraints were included in the evaluation of distribution network reliability indices. Load shedding for network constraints alleviation was applied in [6].

The implementation of switching actions for isolation of failed devices and the connection of distributed generation (DG) to the grid represent potential solutions to support alleviation of network constraints during the restoration process. Consequently, reliability of supply in distribution networks can be improved by the application of these actions. DG impact on reliability indices in both islanding operation and network constraints alleviation was assessed in [7]. In this study, DG was connected in the normally-open point between two feeders, showing that support for alleviation of network constraints during restoration process can be effective. The capability of DERs to increase the transfer capacity between feeders was analyzed in [8] by defining the available transfer capacity for different levels of load. These publications demonstrated the potential benefits of DG to alleviate network constraints. However, no procedures have been found to assess reliability indices when both dispatchable and non-dispatchable DG and control actions are used to alleviate network constraints.

This paper proposes an extension of analytical methodology to assess the reliability of distribution networks in order to include network constraints when implementing actions for supply restoration. Switching actions and DG connections will be applied in order to alleviate network constraints and improve the reliability. The simulation results will be used to demonstrate the benefits of DG to alleviate network constraints during the restoration process. In addition to that, the effect of variable DG will be presented.

METHODOLOGY

The methodology presented in this paper is an extension of Failure Mode and Effect Analysis model (FMEA) based on minimal cut sets [9], which is the usual analytical technique for reliability evaluation in distribution networks [1]. This extension incorporates the calculation of reliability indices for the case when switching actions and DG are used to alleviate network constraints violations that appear in the post-fault restoration-of-supply process. The calculation steps for the methodology applied in the reliability assessment are shown in Fig. 1.

Reliability indices with isolation devices:

When a failure of network components in one or several sections causes an interruption of supply in distribution networks, the protection device trips and interrupts the supply in all the sections of its protected zone. The failed section is isolated by sectionalizers after isolation time t_{isol}. During the isolation time, the supply is interrupted in all the sections protected by the tripped device.

After the failure is isolated, supply at the load points (LP) upstream of the failed section can be restored by switching the tripped protection device of the affected area while the downstream load points continue to be interrupted until the failed component is repaired. The reliability indices of the load points with isolation devices can be determined as the summation of every contingency effect that interrupts the supply.

$$\lambda_{LPi} = \sum_{j=1}^{m} \lambda_j \, ; \; U_{LPi} = \sum_{j=1}^{m} U_j \, ; \; r_{LPi} = \frac{U_{LPi}}{\lambda_{LPi}} \qquad (1)$$

Where *m* is the number of contingencies in the network that cause interruption of supply in LP_i; λ_j, r_j and U_j are the average failure rate, outage duration and annual unavailability of contingency *j*; λ_{LPi}, r_{LPi} and U_{LPi} are the reliability indices of load point *i* with isolation devices. U_j is equal to $\lambda_j r_j$ for the load points downstream of the failed section and $\lambda_j t_{isol}$ for the load points upstream of the failed section.

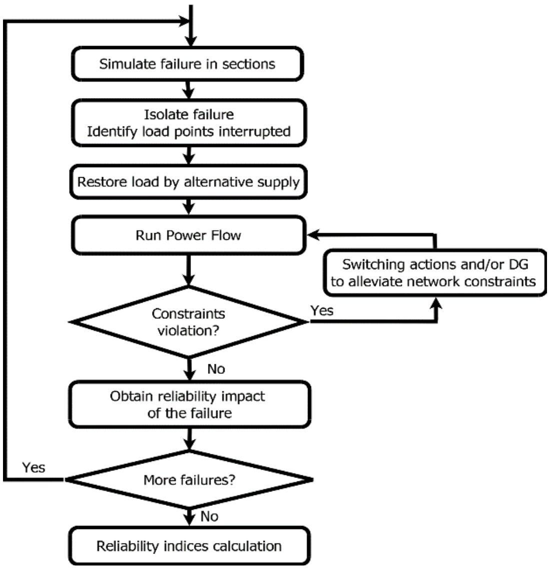

Fig. 1. Steps of the proposed methodology

Reliability indices for restoration by alternative supplies

After the fault isolation, the supply restoration of the interrupted load points is applied by providing alternative supply paths using normally-open points (if available). The load points reliability indices in the restored network configuration after contingency *j* are calculated by application of the connection mode techniques [9].The minimal cut sets of each load point are deduced from the supply paths.

The reliability indices of the restored load points by alternative supply are combined with the reliability indices of contingency *j* applying the principles presented in [1] for the malfunction of alternative supplies:

$$\lambda_{LPi,j} = \begin{cases} \lambda_j & LP_{i,j}\ not\ rest \\ \lambda_j\left(1 + \lambda_{LPr\,i,j} r_j\right) & LP_{i,j}\ rest \end{cases} \qquad (2)$$

$$U_{LPi,j} = \begin{cases} Uj & LP_{i,j}\ not\ rest \\ \lambda_j t_{sw}\left(1 - \left(P_o + U_{LPr\,i,j}\right)\right) & \\ \quad + \lambda_j r_j\left(P_o + U_{LPr\,i,j}\right) & LP_{i,j}\ rest \end{cases} \qquad (3)$$

$$r_{LPi,j} = U_{LPi,j} / \lambda_{LPi,j} \qquad (4)$$

Where $LP_{i,j}$ refers to load point *i* under contingency *j*; $\lambda_{LPi,j}$, $r_{LPi,j}$ and $U_{LPi,j}$ are the reliability indices of load point *i* after restoration of supply for contingency *j*; $\lambda_{LPr\,i,j}$ and $U_{LPr\,i,j}$ are the average failure rate and annual unavailability of alternative supply paths of load point *i* after contingency *j*; t_{sw} is the switching time of normally-open points that restores the supply; P_o is the failure probability of normally-open point switch when required to close.

Finally, the reliability indices of load point *i* are calculated by the addition of the resulting reliability indices for every contingency after the application of supply restoration by alternative supply, being *N* the total number of contingencies:

$$\lambda_{LPi} = \sum_{j=1}^{N} \lambda_{LPi,j} \, ; \; U_{LPi} = \sum_{j=1}^{N} U_{LPi,j} ; \; r_{LPi} = \frac{U_{LPi}}{\lambda_{LPi}} \qquad (5)$$

The restoration-of-supply actions may not be feasible if they result in constraint violations, e.g. line overloading, or voltage out of limits. Two possible solutions to alleviate these constraints are discussed below

Switching actions to alleviate network constraints

After restoration by alternative supplies, the algorithm identifies network constraint violations and applies configurable post-fault switching actions to supply the desired load points. After that, the supply in desired load points is restored by closing normally-open points while preserving the operational limits. The procedure to calculate the reliability indices of these restored load points is the one described in the previous subsection.

DG to alleviate network constraints

The use of both conventional and renewable DG is also considered in the methodology to alleviate network constraints violation during the restoration-of-supply process. To calculate the impact of DG connection in the restored network configuration, a new procedure is proposed.

Reliability indices of the restored network configuration including DG are determined. The procedure to assess these reliability indices of a certain load point *i* are:

1. Determine the minimal cut sets and reliability indices of the alternative supply paths by normally-open points
2. For each DG combination capable of alleviating the network constraints:
   a. Obtain additional minimal cut sets of DG supply paths that are not common to minimal cut sets of the alternative supply paths in 1
   b. Obtain equivalent reliability indices of previous additional minimal cut sets by series association

3. As each DG combination is capable of alleviating the network constraints, additional reliability indices introduced by all DG combinations in 2 are obtained from parallel association of their reliability indices
4. Effect of additional reliability indices from DG combinations in 3 is added to reliability indices of alternative supply paths in 1

Once the load point reliability indices for the alternative supply with DG have been determined, they are combined with the reliability indices calculated for the restoration by alternative supplies.

CASE STUDY

Test network

The proposed methodology was applied to the European MV distribution network benchmark [10], a test system for evaluating the integration of DER and smart grid technology.

For the reliability assessment studies, a set of the following assumptions were made:

- Each feeder has a circuit breaker and each load point has one input and one output sectionalizer
- Statistics of failure rates and repair/restoration times for general power components were collected from [11]. Bus components were assumed to be fully reliable and average repair times were used for those components with urgent and non-urgent repair times. Other statistics used were the failure isolation time of 0.5 hours, switching time of 1 hour, P_o in tie switches of 0.06 and reliability indices of DG λ_{DG}=1 failures/year and λ_{DG}=24 hours/failure
- Voltage limits in buses were $\pm$10% of nominal voltage
- Number of consumers connected to each load point were assumed to be as in TABLE I

TABLE I. Number of consumers in Load Points of the test network

LP	1	2	3	4	5	6	7
Consumers	15,000	0	500	400	680	510	70
LP	8	9	10	11	12	13	14
Consumers	530	480	450	310	14,000	30	510

- As load points 1 and 12 represent other feeders, these loads were disconnected when a failure happened in the sections 0-1 and 0-12, respectively.

The peak load value was selected according to [10]. The load in bus 1 was reduced by 1.3 MW to avoid overloading of the transformer supplying Feeder 1 in the reference case. The thermal ratings were 10 MVA for cable and 6.75 MVA for aerial lines according to data in [10].

Two DGs were considered, one non-dispatchable generator in bus 6 with maximum and minimum generation of 2.8 MW and 0.6 MW respectively, and one dispatchable generator in bus 14 with rated power 1 MW. The non-dispatchable generation values were estimated in order to show the impact of the DG variability on the reliability.

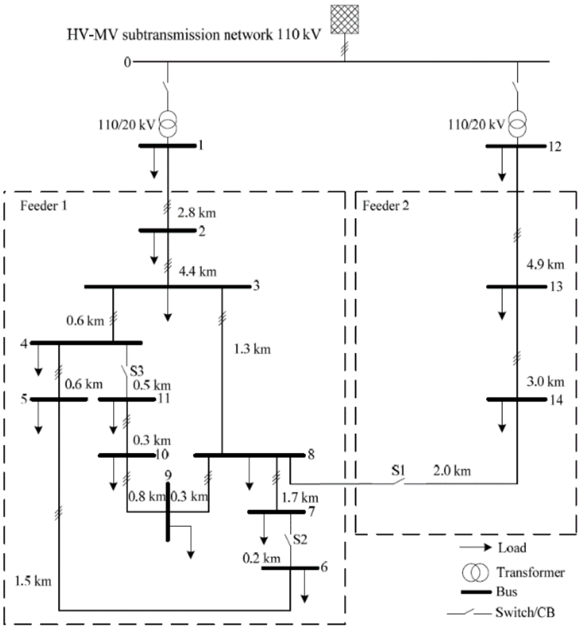

Fig. 2. Topology of European MV distribution network benchmark

Reliability indices:

The reliability contribution of the failure at each section in the test network was evaluated in this point. Failures of several sections at the same time were not considered here as their contribution to reliability is less significant than those failures of single sections, even though the methodology supports their assessment.

Results of reliability indices were obtained for the following scenarios:

A: Restoration by alternative supply available, no network constraints were considered

B: Restoration by alternative supply available, network constraints alleviated by switching actions

C: Restoration by alternative supply available, network constraints alleviated by DG, maximum non-dispatchable DG

D: Restoration by alternative supply available, network constraints alleviated by DG, minimum non-dispatchable DG

The comparison of scenarios A and B shown in Fig. 3 and in TABLE II and III demonstrates that including the network constraints evaluation in the supply restoration is required to a more realistic reliability assessment at high loading conditions.

The results showed that DG alleviated network constraints and improved the reliability indices. If DG output was sufficiently high to alleviate every network constraint violation situation, as it was the case of the maximum non-dispatchable generation in scenario C, the reliability indices were close to the reliability indices calculated after the restoration by alternative supply without considering network constraints (scenario A). However, the reliability indices were worse when the variable generation was reduced (scenario D of Fig. 3 and TABLE II) because the DG was not capable of alleviating all the network constraints.

In the analysed case, different locations of DG within Feeders 1 and 2 showed similar reliability indices if the available DG generation level used to alleviate network constraints was similar or larger.

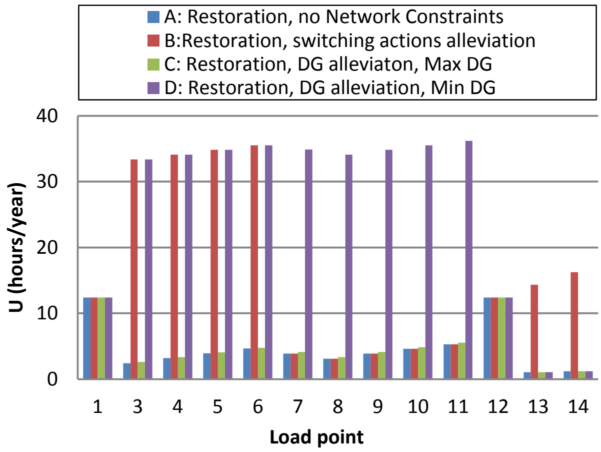

Fig. 3. Average load points unavailability for the test network

TABLE II. Customer and energy reliability indices in Feeder 1

Scenario	SAIFI	SAIDI	CAIDI	ASAI	ENS	AENS
A	0.489	3.83	7.83	1.000	16.61	0.004
B	0.489	20.26	41.47	0.998	84.88	0.022
C	0.493	4.02	8.15	1.000	17.46	0.004
D	0.488	34.76	71.19	0.996	150.20	0.038

TABLE III. Customer and energy reliability indices in Feeder 2

Scenario	SAIFI	SAIDI	CAIDI	ASAI	ENS	AENS
A	0.150	1.19	7.91	1.000	0.68	0.001
B	0.150	16.14	107.56	0.998	9.26	0.017
C and D	0.150	1.19	7.91	1.000	0.68	0.001

The impact of other load demand levels was also evaluated in order to identify if network constraints violations were registered. The restoration configurations by alternative supply were evaluated for average demand (54% of peak value) case, but no violation was occurred. This was because the loads in Feeders 1 and 2 were low compared to the operational limits. Different loading conditions as well as different thermal ratings and voltage limits may cause again additional constraints violation during the restoration. Consequently, the impact of switching actions and DG on reliability would be more significant.

CONCLUSIONS

An analytical methodology for reliability assessment of distribution networks that takes into account network constraints has been proposed. The methodology integrates the reliability impact of network constraints alleviation by switching actions and DG. An innovative extension to assess reliability of alternative supply paths including DG has been presented. The extension has been proven to be valid for any scenario of DG location in the network, number of generators and variability of generation.

The case study analysed reflects the relevance and importance of considering network constraints evaluation in restoration of supply actions, especially in cases of high demand or restrictive operational limits. Variability of DG can have a significant impact on the capacity used to alleviate network constraints, and consequently on reliability indices.

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