

Reliability analyses on distribution networks
with dispersed generation: a review of the state
of the art

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Abstract

The electric power system is changing due to several reasons and among these one may find the deployment of dispersed generation (DG). The impact of DG into the electrical network has to be cautiously investigated, considering the several constraints that might arise, for instance, in what concerns reliability. This paper firstly describes the present situation of DG. Afterwards the several concepts around reliability are highlighted. Finally, the state of the art of the evaluation of the distribution networks reliability is reviewed, in presence or not of DG, indicating the different methodologies used.

Keywords: Reliability, Distribution Networks, Dispersed Generation

1. Introduction

The European electric power system is facing several modifications and developments at the generation, delivery and consumption levels, as well as in response to the adequacy and security of supply concerns driving the European Union's energy policy.

2. Dispersed Generation

At distribution level, steady progress in innovative energy conversion technologies (particularly cogeneration and renewable power generation) is promoting the installation of small- and medium-sized power plants, usually located nearby the final user and defined as Dispersed Generation or Distributed Generation (DG). Although some authors distinguish between these two terms, for the purposes of this article they shall be considered synonyms.

There is no global recognized definition of dispersed generation, however in the European legislation it is defined as electric power generation connected to distribution networks. [1]

One of the most accepted scientific definitions states that "DG is an electrical power source connected directly to the distribution network or on the customer site of the meter" [2],

In general, DG comprises units based on Renewable Energy Sources (RES) like wind turbines, photovoltaic panels, hydraulic micro turbines and other generators such as gas micro turbines, diesel engines and fuel cells, which are generally used for the combined production of electricity and heating (cogeneration or combined heat and power, CHP).

On the one hand a large-scale penetration of DG technologies within distribution networks (DN), will possibly reshape lower voltage grids towards new architectures displaying reduced power losses and improved system operation features such as black starting or intentional islanding capabilities. On the other hand, the various stages leading to a pervasive deployment

of DG technologies have to be carefully monitored and evaluated to understand the nature and level of impact on the distribution grid.

Nonetheless, the implementation of DG throughout the distribution networks raises several questions at both the technical and the regulatory level. Distribution systems were not originally designed to operate in the presence of several types of generation connected to them. To obtain a successful integration of DG units, it is essential to maintain the reliability and the continuity of the system, taking into account the growing influence of these generation technologies.

The deployment of DG is driven by its several practical advantages and by policy initiatives. Among them one can find: the potential reductions in greenhouse gas emissions; the increased energy efficiency (particularly from CHP); the deregulation and competition policy; the diversification of energy sources; the availability of modular generations plants; the ease of locating sites for smaller generators; the shorter construction times and lower capital costs for smaller plants; the possibility of locating the generation closer to load which may reduce transmission costs; and, in some countries, the national power requirements. [3]

Some authors also highlight DG's potential as standby/emergency generation and for peak shaving. [4]

Nevertheless, the impact of DG has to be carefully taken into consideration and studied. As a matter of fact, it modifies the characteristics and, potentially, the behaviour of the distribution network, impacting on voltage profiles and transients, losses, short-circuit level, selectivity of protections and it affects the congestion level, power quality and reliability. [5]. Furthermore it may create the need of redesign some of the protections of the system, particularly at the frontier between the transmission network and the distribution network so that they are able to cope with bidirectional flows. [6]

3. Reliability

According to a recent global survey to measure how electric utilities are progressing with smart grid initiatives [7], reliability emerged as the first reason why these initiatives are being implemented (operations costs savings coming in as second).

Reliability is a concept that addresses both the longer term adequacy of the electric system to supply energy to its customers, and with the shorter term security of supply. As a consequence, adequacy is particularly linked with the planning of the grid, and security with the operation of the grid.

These two aspects of reliability – adequacy and security – are defined, respectively, as “the ability of the system to supply the aggregate electric power and energy requirements within

current ratings and voltage limits, taking into account planned and unplanned component outages” and “the ability of the system to respond to disturbances arising within that system”. [8]

As not all interruptions have the same level of impact, degree of severity is of importance. In [9], 5 levels are defined based on duration and impact on customers, starting from “0” as the lowest and ending on “4” as the highest level.

3.1. Deterministic approach

Also known as the N-1 criterion, this traditional approach for reliability basically states that in a given network, when one of the components fails, the remaining grid will continue to supply all loads without overloading lines or exceeding voltage limits. [8]

Some criticism does exist on this approach as some events whose probability or impact is low may impose costly development measures and operational constraints. [10] states that “the traditional deterministic approach to security assessment often results in costly operating restrictions that are not justified by the corresponding level of risk”.

3.2. Probabilistic methods

While deterministic approaches have the advantage of simplicity, probabilistic methods produce results that describe better real conditions, although in a more complex manner. [11] The traditional hierarchical levels (HL) for reliability evaluations divides the electric system in the following way:

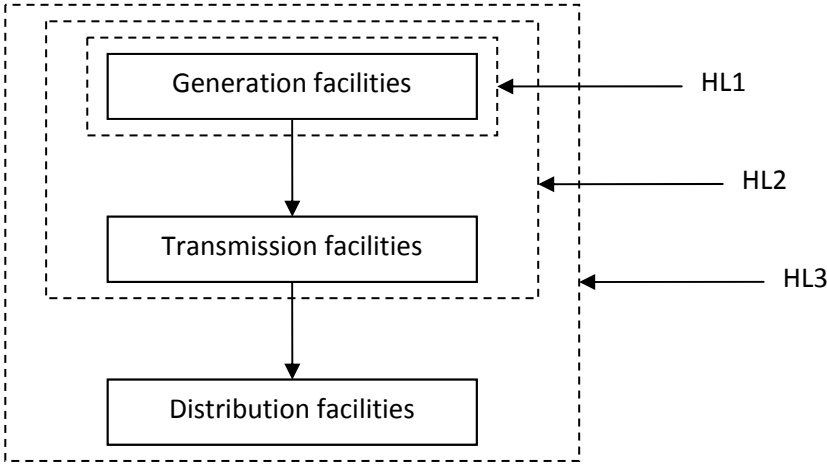


Figure 1 – Scheme of the traditional hierarchical levels for reliability [12]

HL1 tries to answer to the question of how much generation capacity needs to be installed and where, so that demand can be satisfied. It is used to define also which are the amounts of sufficient reserve power, and of preventive and corrective maintenance. The reserve power capacity is usually defined either, according to a percentage of the expected load, or according

to the capacity of one or more of the largest units, or by a combination of these two methods. The main indices for reliability are load based ones, as they are

- Loss Of Load Probability (LOLP)

“The probability that the load will exceed the available generation; it defines the likelihood of encountering trouble but not the severity” [3]

- Loss Of Load Expectation (LOLE)

“The average number of days on which the daily peak load is expected to exceed the available generating capacity; alternatively it may be the average number of hours for which the load is expected to exceed the available capacity, again it defines likelihood, not severity” [3]

- Loss Of Energy Expectation (LOEE), Expected Energy Not Supplied (EENS), Expected Unserved Energy (EUE)

“The expected energy that will not be supplied due to those occasion when the load exceeds the available generation; it encompasses the severity of the deficiencies as well as their likelihood – essentially the same as EENS, EUE or similar terms” [3]

HL1 reliability is usually analyzed at the steady state level and so, it is highly connected with adequacy.

Moreover, there are two possible approaches concerning the impact of DG at this level. The first one is to neglect DG. The second one is taking it into consideration, although as DG is not dispatchable and is usually dependent of intermittent energy sources, it should be taken cautiously. What arises at this level is that HL1 traditional definition may be reviewed in order to consider DG in an adequate manner.

HL2, includes not only the Generation system (and HL1), but also the transmission system, and aims at estimating the system ability to perform its function of moving energy provided by the generation system to the Bulk Supply Points (BSP). It is directly related with the coordination between planning and operation, or in other words between adequacy and security.

As a distribution system with dispersed generation can be somehow compared with a transmission system connected with traditional generation, some authors state that HL2 reliability assessment may be used to model dispersed generation, bearing in mind, however, that the objective of the distribution system is to supply end-customers, and of the transmission system, to supply BSP.

At the HL3 level, a traditional network gets its input directly from the HL2, due to the fact that a single BSP is generally used to connect the distribution network with the transmission network.

It is important to state that 80% to 95% of customer electricity unavailability is due to problems at distribution level, meaning thus that the impact of these networks is large. [13]

As the traditional distribution system just carries the energy from the BSP's into the final customers, a steady-state analysis is enough: the adequacy of supply studies thereby are predominant.

The aforementioned approach loses its validity when dispersed generation is included, as the energy inputs come from more than one point. Therefore, besides the traditional HL2 system, the distribution network itself becomes another HL2 system.

Furthermore, with the deployment of DG the question arises whether DG, in case of disruptions/disturbances at the transmission level, should be allowed to continue to supply the distribution network, thereby entering the so-called islanding mode or whether DG should be tripped due to safety constraints. If allowed, the usage of the islanding mode would increase the reliability levels in the areas of the distribution networks where enough DG and/or storage are available. But to do so the protection system has to be adapted to this new potential situation. Moreover, local frequency and voltage regulation abilities from the available DG and/or storage would be also needed.

Concerning the reliability indices, at this level they are customer-based, such as:

- System Average Interruption Frequency Index (SAIFI)

“The average number of interruptions per customer served per year” [3]

- Customer Average Interruption Frequency Index (CAIFI)

“The average number of interruptions per customer affected per year” [3]

- System Average Interruption Duration Index (SAIDI)

“The average interruption duration per customer served per year” [3]

- Customer Average Interruption Duration Index (CAIDI)

“The average interruption duration per customer interruption” [3]

- Average Service Availability Index (ASAI)

“The rating of the total number of customer hours that service was available during a year to the total customer hours demanded” [3]

- Average Energy Not Supplied (AENS)

“The average energy not supplied per customer served per year” [3]

3.2.1. Stochastic and analytic simulation methods

The methods of probabilistic assessment are divided in two groups: stochastic methods and analytic ones. Historically, these two probabilistic approaches to reliability co-existed, the first one being more studied in Europe and the second one in North-America. One of the most important papers on probabilistic assessment is [14] where two methods representing the two approaches are described. The stochastic method examined was developed at Enel, Italy, and bases itself on the “cost of reliability”, which is computed using a Monte Carlo simulation (MCS). It has an advantage in the fact that it takes into consideration, theoretically, “any random variable, any contingency and of adopting operation policies similar to the real ones”. The second approach, analytical, mainly developed in the University of Saskatchewan, Canada, is based on contingency enumeration and involves the analysis of the adequacy evaluation of the composite system, taking in consideration “all possible contingency states”.

3.3. Cost/Benefit analysis

The cost/benefit analysis of reliability and of the possible options to improve it has been subject to several studies. In [10] two typical ways of converting predicted reliability to a cost value are stated, which are, a customer damage function and a constant rate. The first one is derived from “surveys which estimated what consumers would be willing to pay, either in increased rates or for backup service”. The second one “is used to construct the cost from an aggregated index for a specific location and time.”

At this level, one cannot forget the impact of performance-based rates, also called performance-based indices, which are “regulatory statutes that reward utilities for good reliability and penalize them for poor reliability” [15]. In what concerns the impact of DG, the increased reliability derived from islanding potential of distribution networks with DG and/or storage, may have also an impact on terms of the revenues at this level, due to the increase of the overall indices.

3.4. Reliability on distribution

Several studies have been done addressing the distribution networks reliability evaluation, some of them including DG. Furthermore, several methods were used to perform that evaluation, the ones that seem to be the most relevant being already mentioned before.

The new methods and techniques on reliability are usually tested on a model. Between these models we may find the reliability test system (IEEE-RTS) described in [16] and reshaped in [17]. Also the Roy Billinton test system [18] is used, being particularly useful its development described in [19] (RBTS), where a electrical distribution system to be used in reliability assessment is defined.

Table 1 presents the most representative cases on the field. Based on this table one can state that the most common approaches to the assessment of reliability are either the stochastic or the analytical. It is also possible to find a combination of both approaches, such as in [21] where they are merged. Moreover, several variations do exist in the methods, for instance, between the stochastic approaches, one may find sequential or non-sequential Monte Carlo methods. Furthermore, in terms of indices used, SAIDI, SAIFI and EENS/EUE are the most usual. In addition, the attention on the impact of DG on the distribution networks reliability has increased in the late years and in the overall, more than half of the papers address it. Finally, it is possible to observe that the test systems used most commonly are either the RBTS, the IEEE-RTS or a real network, usually local.

Table 1 – Research made on reliability analysis on distribution networks in the late years

#	Paper title	First author	Year	Method	Reliability Indices used	DG assessed	Test System
1	Reliability analysis of distribution networks with local generation using fuzzy sets [20]	Seitz	1993	Fuzzy set theory	EENS	yes	Real networks
2	Evaluation of reliability indices and outage cost in distribution systems [21]	Allan	1995	Combination of MCS with analytical techniques	CAIDI, SAIFI	no	IEEE-RTS
3	Effective techniques for reliability worth assessment in composite power system networks using Monte Carlo simulation [22]	Sankarakrishnan	1996	MCS	PLC, EENS, ECOST, IEAR	no	IEEE-RTS
4	Reliability evaluation of distribution system with non-exponential down times [23]	Asgarpoor	1997	MCS with component state duration sampling method	SAIFI, SAIDI, CAIDI, ASAI	no	RBTS
5	Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques [24]	Billinton	1998	Analytical approach and time sequential MCS	EENS, ECOST, IEAR	no	RBTS

#	Paper title	First author	Year	Method	Reliability Indices used	DG assessed	Test System
6	Reliability evaluation of electric transmission and distribution systems [25]	Meeuwssen	1998	DISREL	SAIFI, SAIDI, CAIDI, ASUI, EENS	no	IEEE-RTS, Ad-Hoc system, real network
7	Integrated reliability evaluation of generation, transmission and distribution systems [26]	Leite da Silva	2002	Non-sequential MCS	SAIFI, SAIDI, CAIDI, ENS, LOLC	no	IEEE-RTS
8	Reliability modelling of distributed generation in conventional distribution systems planning and analysis [27]	Chowdhury	2003	DISREL	EENS	yes	Ad-Hoc test system
9	Modelling and analysis of distribution reliability indices [28]	Balijepalli	2004	MCS	SAIFI, SAIDI	no	Comparison with an analytical system method. Real network
10	Reliability evaluation of distribution system connected photovoltaic generation considering weather effects [29]	Cha	2004	Sequential MCS	SAIDI, SAIFI	yes	Ad-Hoc test system

#	Paper title	First author	Year	Method	Reliability Indices used	DG assessed	Test System
11	Distributed generation impacts on electric distribution systems reliability: sensitivity analysis [30]	Falaghi	2005	Failure mode and effect analysis	SAIFI, SAIDI, CAIDI	yes	Real network
12	An analytical method to consider DG impacts on distribution system reliability [31]	Fotuhi-Firuzabad	2005	Analytical method	SAIFI, SAIDI, ENS	yes	Islanding analysis, Ad-Hoc test system
13	A reliability assessment methodology for distribution systems with distributed generation [32]	Duttagupta	2006	MCS, Folk-Fulkerson algorithm	HLOLE, FLOL, EUE	yes	RBTS
14	Reliability evaluation of underground distribution networks using representative networks [33]	Silva	2006	Representative networks	SAIFI, SAIDI	no	Real network
15	Assessing the contribution of distributed generation to system security [34]	Allan	2006	Engineering Recommendation P.2/5	EENS	yes	Several real networks
16	Impact of distributed generation on reliability evaluation of radial distribution systems under network constraints [35]	Neto	2006	Analytical simulation method	SAIDI, SAIFI, ASAI, AENS	yes	Real network

#	Paper title	First author	Year	Method	Reliability Indices used	DG assessed	Test System
17	A new intelligent search method for composite system reliability analysis [36]	Patra	2006	MCS with Multi-Objective Particle Swarm	LOLP, LOLE, EUE	no	IEEE-RTS
18	The effect of distributed generation on distribution system reliability [37]	Yuan	2007	Interval Mathematics	SAIFI, SAIDI, CAIDI, ASAI, ASUI	yes	RBTS
19	Distribution system reliability evaluation considering DG impacts [38]	Wang	2008	Analytical method	SAIFI, SAIDI, CAIDI, ASAI	yes	Ad-Hoc test system
20	Reliability assessment in power distribution networks by logical and matrix operations [39]	Midence	2008	MCS	SAIFI, SAIDI, EENS, SCOC	no	IEEE 123 node test feeder
21	Integrated Reliability Evaluation of Distribution and Sub-Transmission Systems Incorporating DG [40]	Andrade	2009	Sequential MCS	SAIFI, SAIDI, EENS, ECOST	yes	Results presented in the RBTS and in a real network
22	Assessing the contributions of microgrid to the reliability of distribution networks [41]	Costa	2009	MCS	SAIFI, SAIDI, CAIDI, ASAI	yes	Ad-Hoc test system

4. Summary and Conclusions

The growing usage of DG creates the need to evaluate its impact at all levels. One of the most important of these levels is reliability, as the electric industry is deemed to be a sector where system adequacy and security of supply are essential to our society.

On this paper, reliability was discussed with its main concepts, methods, indices and test systems. The question of how to consider DG at HL1 was addressed and the issue of how to include it in an adequate manner was raised. Moreover, the impact that DG may have in terms of performance-based indices was also stated.

A comprehensive review was made on what has been done in the past years concerning the assessment of distribution networks reliability, either including or not including DG. This review indicated the methods, indices and models used by different teams.

As the amount of DG is still growing, the need for advanced methods for reliability evaluation will further increase in the future. Thereby, in terms of future work, the intention is to collect and analyze data from smart grid demonstrators and pilot projects [42], in order to feed them in model(s) assessing the reliability implications of such distribution network concepts embedding new technologies.

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