

# An Analytical Method to Consider DG Impacts on Distribution System Reliability

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**Abstract**-- Distributed generation is expected to play an increasing role in emerging power systems. They use different type of resources and technologies to serve energy to power system. DG has positive and negative effects for both the utilities and customers. System and load point reliability indices are normally improved if DG is installed in a distribution network. On the other hand, DG has some specific characteristics which distinguish it from conventional generating units. Therefore, they should not be treated as conventional generating units to perform reliability evaluation. An appropriate model is required to be developed in order to assess impacts of DG on reliability indices. Impacts of DG implementation on distribution system reliability are investigated in this paper using a distribution test system. A reliability model for DG is developed and an analytical probabilistic approach is proposed for this purpose. Impacts of different parameters such as components failure rates, load and DG positions and DG generation parameters are included in the analysis.

**Index Terms**-- Distributed Generation, Distribution System, Reliability assessment.

## I. INTRODUCTION

Distributed generation (DG) is normally defined as small generation units (<10 MW) installed in distribution systems [1]. Distributed generation is expected to play an increasing role in emerging electric power systems. Studies have predicted that DG will be a significant percentage of all new generation going on line. It is predicted that they would have about 20% of new generations being installed [2]. They use different types of resources and technologies to serve energy to power systems. DG applications result in positive and negative side effects for both utility and customers [3], [4].

Reduction of system expansion costs, decreasing loss of power and reliability enhancement are some of the benefits of DG applications. In contrast, power quality issues, islanding operation and voltage control problem are among troublesome impacts of DG on power system [5].

Even though the concept of DG is not new, there is an increasing trend towards DG application in power systems. Environmental concerns, economical considerations, technological advancements and power system deregulation are known as accelerating factors for DG application.

Power system reliability received more attention now days. This is mainly due to wide use of electric energy in industrial, commercial and residential applications. As mentioned before, utilizing DG in power systems would considerably improve reliability indices. Distributed generation can improve the utility's ability to serve peak load on a feeder, and thus allows deferral of capital investment on a feeder. A common case where DG is effective and economical occurs when the DG helps to supply load during contingencies, until the utility can restore additional delivery capacity.

System and load point indices can be improved if DG is installed in distribution network. This is a important effect because This is specially important because most part of customer interruption is due to distribution system contingencies. The DG impact on the distribution system reliability is studied in different references [6],[7], [8]. On the other hand, DG has some specific characteristics, which distinguish it from conventional generating units. Therefore, they could not be treated neither as conventional generation nor substation to perform reliability evaluation. Nevertheless, in the above references, special condition of DG is not considered and the DG is considered to play the same role as conventional generating stations or distribution substation.

An analytical technique is presented in this paper to study the DG impact on the distribution system reliability. The paper is arranged as follows: next section broadly discusses the problem, its background and the requirement for an analytical model. There is a brief introduction to distribution system reliability assessment in section III. The proposed method is investigated in sections IV and V. The method is then applied to a sample distribution system in section VI and the results are compared for different DG modeling. The results show the application of the proposed approach to consider specific nature of DG in reliability evaluation.

## II. PROBLEM DEFINITION

This is an important point that DG has specific nature which discriminates it from generation stations or distribution substations.

Because of economic and technological purposes, DGs usually have modular structure in which several modules has to operate in parallel to produce the rated power. Therefore, any outage in modules results in reduction of output power. Thus, compared with conventional generating units, DG would experience more derated states. This is one difference between DG and conventional stations.

Main generating stations usually have 2-state model in which the can only toggle between up and down states. On the other hand, a 6-state model is usually applied for small station modeling, as shown in Fig. 1. As seen in Fig. 1, small

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generations may choose other states because of the system demand and derate states. In the case of DG, the model in Fig. 1 is extended more since DG can operate in several derated states.

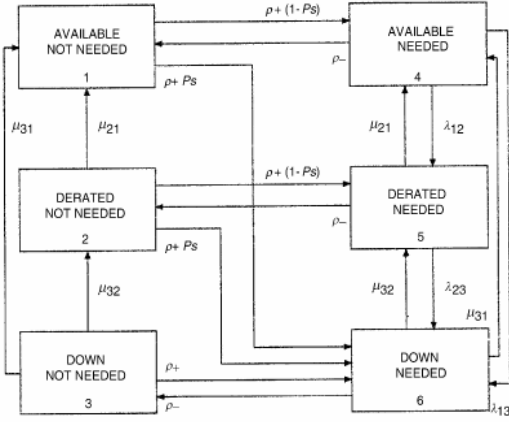


Fig. 1 Generating Station Models

Another difference is the behavior of resources used in DG to produce the electric energy. For example, Renewable energy technologies have considerable contribution in DG technologies which use green energy resources such as wind and solar energy to produce power. Their output power depends on the amount of available resource at each moment. Therefore, compared with conventional stations, the power produced by renewable energy may experience more fluctuations. The case does not usually happen in the conventional generating stations and hence, this phenomenon is not usually included in the traditional reliability evaluation methods for generating stations.

On the other hand, DG has intrinsic differences with distribution substation. One of the most important assumptions in distribution system reliability evaluation is that distribution substation can supply the loads demand completely. The case is not necessarily true for the DG. In cases when DG has the responsibility to energize the load in an island, the DG power and the load demand does not follow the same trend. This case may happen especially in some renewable generations. Thus, the island demand is likely to go beyond the DG capacity. In these cases, the system reaction would be to shed some loads or to disconnect DG from the island. The first reaction is happening when a load shedding schemes is applied in the distribution system. In the latter one, high difference between the DG power and the load demand can activates the DG frequency or voltage protection devices and the DG is prevented to energize the island any more. It has to be noted that DG can improve reliability through islanding operation. This benefit may be unattainable due to difference in the generation and the demand in island.

Based on the above issues, applying traditional reliability models, such as generation station or distribution can not properly reflect DG impact on the reliability and there is a need to develop suitable models. A model used to evaluate DG application must include different DG parameters and its intrinsic behaviors

Once the model is developed, it can be used to compare different DG technologies from the reliability point of view. It could be applied in DG sizing and sitting problems and helps to include DG impact in different optimization problems, such as distribution planning, operation planning and switching placement. Broadly speaking, the method would be used in any normative application. In fact, this is the main advantage of analytical analysis of reliability indices over the computer simulation.

The method is also unifies DG modeling in traditional distribution system reliability analysis frame work. This unification allows application of reliability enhancement method and practices in DG installation problem.

### III. DISTRIBUTION SYSTEM RELIABILITY EVALUATION

This section briefly discusses reliability evaluation techniques applied in distribution system. A sample distribution test system is shown in Fig. 2 .

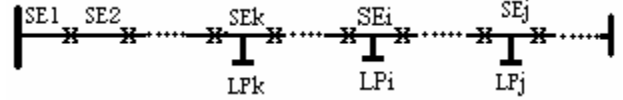


Fig. 2 Sample Distribution System

A distribution feeder consists of a set of series components, including lines, cables, disconnects, etc. A customer connected to any load point of such a system requires a set of component between load and supply points to be operating. These sets are designated as “cut-sets”. The reliability of load point  $LP_i$  can be calculated using minimal cut-set technique [9].

In this method, all of the minimal cut-sets which interrupt power to load point  $LP_i$  are identified. The failure rate  $\lambda_{C,i}$  and repair time  $r_{C,i}$  of the load point  $LP_i$  are the calculated as follows:

$$\lambda_{C,i} = \sum_{Allj} \lambda_j \quad (1)$$

$$r_{C,i} = \frac{U_i}{\lambda_i} \quad (2)$$

$$U_{C,i} = \sum_j \lambda_j r_j \quad (3)$$

In which  $\lambda_j$  is the failure rate of cut-set  $j$ ,  $r_j$  is its average outage time.  $U_i$  indicates unavailability of the load point  $LP_i$  and can be interpreted as the average time during a calendar year in which the load point  $LP_i$  is not energized.

System Average Interruption Frequency Index (SAIFI) are defined as (4) where  $N_i$  is the number of customers connected to load point  $LP_i$  and  $NL$  is the number of load points.

$$SAIFI = \frac{\sum_{i=1}^{NL} \lambda_{C,i} N_i}{\sum N_i} \quad (4)$$

Another system index in reliability evaluation is System Average Interruption Duration Index (SAIDI) as (5).

$$SAIDI = \frac{\sum U_{C,i} N_i}{\sum N_i} \quad (5)$$

The energy indices for the overall distribution system are calculated based on average load demand.

$$ENS = \sum L_{av,i} U_{C,i} \quad (6)$$

#### IV. FRAME WORK

The goal of this section is to suggest a frame work for the assessment of the reliability impact of DG on distribution system. The model should consider intrinsic attributes of DG and the way it applied in distribution system.

A sample distribution system with DG is shown in Fig. 3.

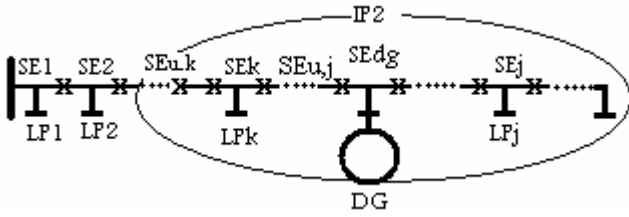


Fig. 3 Sample Distribution System With DG

This system is used to deduce models and relations. In this system,  $SE_k$  is a feeder section ended with circuit breakers.

It is also assumed that all failures are active. Therefore, in the event of a contingency on any section, both circuit breakers at its ends should be opened immediately.

Following assumptions are made in derivation and evaluating the proposed method:

- 1- continuity between load point and utility/DG is the sole reliability criterion.
- 2- DG can continue islanded operation if its output generation is greater than the load demand.
- 3- DG can energize the feeder during contingencies unless the contingency occurred on the DG section.
- 4- All load points are assumed to have the same load duration patterns and the feeder load is assumed to be uniformly distributed along the feeder. Therefore, each section is dedicated with a load point, as in Fig. 3.

It should be noted that DG could only help load points in the event of faults on the upstream side of the DG. In such cases, like the island  $IP_2$  shown in Fig. 3, an island may forms and the DG supplies the load demand in the island during loss of main supply. Thus, there must be at least one other sectionalizing device between DG and main circuit breaker in order to permits island formation during the repair time of damaged component.

For down stream faults, like  $LP_j$ , impact on the load point depends on sectionalizing devices which installed on the feeder between the load and faulted section. If there is not any sectionalizing device, load points are also disconnected due to the occurrence of fault.

For upstream faults, it is crucial to calculate islanding probability for the outage of each upstream section. The probability of islanding depends on numerous factors and will be discussed in the next section. In this step, it can be assumed that probability of maintaining island, for a specific condition formed due to the fault in section  $SE_i$  is  $IP_i$ . This

implies that, in the event of a failure on section  $SE_i$ , the DG continue supplying the feeder with the probability  $IP_i$ . The analyses should be completed for all sections in the upstream and downstream side of DG. It should be noted that, however, the analysis is different for load points on up and down stream side of the DG. If the DG is modeled as a distribution substation, it would supply all of the island loads and  $IP_i$  can be replaced by one, for all possible islands.

For each load point  $LP_k$ , the islanding probability of the load point is the islanding probability of smallest island which contains  $LP_k$ . If we consider sections on the upstream side of the DG and  $LP_k$ , the closest one  $SE_{u,k}$  determine the minimal island as shown in Fig. 3. For instance, for the load point  $LP_k$  on the upstream side of the DG,  $SE_{u,k}$  is  $SE_{k-1}$  and for the  $LP_j$  on the downstream, it is  $SE_{DG-1}$ . Therefore, we have:

$$IPLP_k = IP_{U,k} \quad (7)$$

when islanding is possible, the load network can be considered as a meshed network. In this case, methods correspond to the meshed network can be applied in reliability evaluation.

The failure rate and repair time of load point  $LP_k$ , when islanding is possible, can be calculated using (8), (9).

$$\lambda_{IS,k} = \sum_{j=1}^{ND} \sum_{i=1}^{NU} \lambda_{UK,i} \lambda_{DK,j} (r_{UK,i} + r_{DK,j}) \quad (8)$$

$$U_{IS,k} = \sum_{j=1}^{ND} \sum_{i=1}^{NU} \lambda_{UK,i} \lambda_{DK,j} r_{UK,i} r_{DK,j} \quad (9)$$

where,  $\lambda_{UK,j}$  and  $r_{UK,j}$  are, respectively, failure rate and repair time of sections  $SE_j$  on the upper stream of both DG and load point  $LP_k$ . The total number of upper side section is  $NU$ .  $\lambda_{DK,i}$  and  $r_{DK,i}$  are, respectively, failure rate and

repair time of sections  $SE_i$  located between the DG and load point  $LP_k$ . The total number of sections including the DG section is  $ND$ .

For each load point, failures on the associated section result in load point outage no matter whether DG exists or not. This should therefore be added to (8) and (9) as a first order minimal cut set. In addition, for the load points located on the down stream side of the DG, the load is also curtailed if a fault occurs on sections between the DG and the load. The effects of such sections should be added to (8) and (9). The results are shown in (10) and (11) for loads on upstream (USL) and down stream side of DG (DSL).

$$\lambda_{IS,k}^* = \begin{cases} \lambda_{IS,k} + \lambda_k & USL \\ \lambda_{IS,k} + \lambda_k + \sum_{i=1}^{ND} \lambda_{DK,i} & DSL \end{cases} \quad (10)$$

$$U_{IS,k}^* = \begin{cases} U_{IS,k} + U_k & USL \\ U_{IS,k} + U_k + \sum_{i=1}^{ND} U_{DK,i} & DSL \end{cases} \quad (11)$$

$$r_{IS,K}^* = \frac{U_{IS,k}^*}{\lambda_{IS,k}^*} \quad (12)$$

Where \* represents the modified index.

Considering that the load point  $LP_k$  can be islanded with the probability of  $IPLP_k$ , the failure rate and the associated outage time of load point  $LP_k$  are calculated using (13) and (14), respectively.

$$\lambda_{L,k} = IPLP_k \lambda_{IS,k}^* + (1 - IPLP_k) \lambda_{C,k} \quad (13)$$

$$r_{L,k} = IPLP_k r_{IS,k}^* + (1 - IPLP_k) r_{C,k} \quad (14)$$

The analysis can be performed for all load points on the feeder.

Comparing (13) and (1), the amount of change in the failure rate and outage time of load point  $LP_k$  will be:

$$\Delta \lambda_{L,k} = IPLP_k (\lambda_{IS,k}^* - \lambda_{C,k}) \quad (15)$$

Since the value of failure rate decreases when islanding is possible, it can be concluded from (15) that the failure rate of load point will reduced if DG is applied. The amount of reduction can be strongly affected by the load point islanding probability  $IPLP_k$ . Other load point and system indices can be calculated using the modified load point failure rates and outage times.

In the above calculations, it was assumed that islanding probabilities  $IP_i$  are known. These values are important factors for assessing the DG impacts on reliability indices. Derivation of islanding probability is illustrated in the next section.

## V. ISLANDING PROBABILITY

As seen in the previous section, probability of islanding of a load point has dominant effect on the amount of reduction in its failure rate and outage time. Various issues related to DG must be taken into account in islanding probability calculation.

To do so, we use a short-term analysis to incorporate various factors such as hourly load demand, DG resource variation and failure of DG components in the islanding probability calculation. We mean by "short-term" a time interval in which DG output power and load demand do not change considerably. Maintaining constant DG output needs that both DG resource and DG structure remain unchanged. The exact value of the time interval, in general, depends on the load demand and the DG resource behaviors.

At first, we need to calculate the probability of maintaining the island  $IP_i$  caused by outage of section  $SE_i$ . For each time interval  $T_j$ , the DG generation  $G_j$  is modeled as a normal distribution function with known mean and variance values. So, it would be possible to include DG resource variation in the calculation. We need also the load demand of the island  $L_{j,i}$  which is the sum of load demands in the island formed by outage of section  $SE_i$  at the time interval  $T_j$ .

Historical data can be used to calculate mean and variance for the DG resource variation. The probability of island formation in the time interval  $T_j$  consists of two components:

- 1- The probability that the load demand is smaller than the amount of DG generation resource permitted:  $IPB_{j,i}$
- 2- The probability that DG can generate  $G_j$  and no failure encountered in the time interval:  $IPH_{j,i}$

So, the probability of maintaining an island in the time interval  $T_j$  due to failure in section  $SE_i$  is:

$$IP_{i,j} = IPB_{i,j} IPH_{i,j} \quad (16)$$

The first part of islanding probability reflects the probability that the DG generation is greater than the island load, i.e.  $P(G_j > L_{j,i})$ . It is calculated using load duration curve and the DG resource probability distribution functions. If the DG is modeled as the central station, this part can be neglected and replaced by one in calculations.

The second part of the islanding probability reflects the possibility of generating this amount of power due to DG component situation. Therefore, this means that there are enough components in "up" state to generate the required amount power. On the other hand, since it was assumed that the DG output does not change within the time interval  $T_j$ , the probability of generating  $G_j$  has to be multiplied by the probability of not to transfer to lower capacity level, that is:

$$IPH_{j,i} = P(P_{DG} \geq G_j)P(NT) \quad (17)$$

$$P(NT) = (1 + (\lambda_{G_j}^+ - \lambda_{G_j}^-)T_j) \quad (18)$$

Where,  $P(P_{DG} \geq G_j)$  is the probability that the DG generation is equal or greater than  $G_j$ ,  $P(NT)$  is the probability that DG does not leave its state to a lower generation state.  $\lambda_{G_i}^+$  is the rate of transition to higher generation levels and  $\lambda_{G_i}^-$  is the rate of transition to lower generation levels.

Both generation probability and transmission rates can be obtained using the frequency and duration approach [9].

To do the analysis for an interested period of time, the period can be divided into several short-term time interval and the analysis is performed for each time interval. The islanding probability is calculated and resulting load point failure rates and outage time are also obtained. The results are aggregated to find the average failure rate and outage time for each load point in the time period of interest.

$$\overline{\lambda_{L,k}} = \frac{1}{NTI} \sum_{j=1}^{NTI} \lambda_{L,k} \quad (19)$$

$$\overline{U_{L,k}} = \frac{1}{NTI} \sum_{j=1}^{NTI} U_{L,k} \quad (20)$$

Where,  $NTI$  is the number of short-term time intervals designed in the interested period of time. If the analysis is to be performed for a long period, for example a year, it is possible to choose some representative days. The analysis done for days and the results are then weighted according to the occurrence number of each day in a year.

In the next section, the application of the proposed technique is examined using a test system for a period of 24 hours.

## VI. METHOD APPLICATION

In this section, the method is applied to a sample test system. The application of the proposed method to analyze the DG impact is investigated.

A distribution test system is shown in Fig. 4, which consists of 7 sections, 7 load point and one DG which is installed on the 4<sup>th</sup> section. Reliability data for all feeder sections are given in Table I. The failure rate of each section and its load are assumed to be proportional to the section length. Section loads are given in per unit based on the feeder peak load. The peak load of the feeder is assumed to be 4 MW and the total DG power is 2 MW.

The DG has 2 identical generating units. Thus, it has one derated state and its state diagram is similar to that shown in Fig. 1.

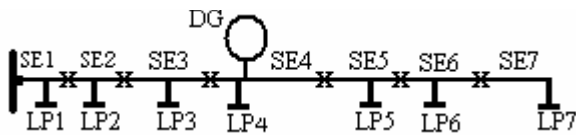


Fig. 4. Distribution Test System

Table I. Section Data

	Length (KM)	Failure Rate (f/yr)	Repair Time (hr)	Section Load (pu)
SE1	1	0.0650	5	0.1111
SE2	2	0.1300	5	0.2222
SE3	3	0.1950	5	0.3333
SE4	1	0.0650	5	0.1111
SE5	1	0.0325	5	0.0556
SE6	1	0.0650	5	0.1111
SE7	1	0.0325	5	0.0556

Basic reliability data of the DG are shown in Table II.

Table II. DG Reliability Data

DG output	Cum. Probability	$\lambda^+$	$\lambda^-$
0.00	1.00	1.8	0.0
0.50	0.95	0.2	0.30
1.00	0.60	0.0	0.10

The load duration data is given in Table III in which the feeder load for a sample day is presented.

Table III. Load Duration Data

Time Interval (hr)	Feeder Load (pu)	Feeder Load (MW)
0-6	0.25	1.0
6-12	0.75	3.0
12-19	0.5	2.0
19-24	1.0	4.0

Table IV shows the DG resource distribution for different time intervals. For each time interval, the mean value of the resource power is given. It is assumed that the resource has the normal distribution and its standard deviation is 10 percents of its mean value.

Table IV. DG Resource Variation

Time Interval (hr)	Resource power (pu)	Resource Power (MW)
0-6	0.25	0.5
6-9	0.5	1.0
9-12	1.0	2.0
12-24	0.75	1.5

Comparing data in Table III and Table IV, it is obvious that both resource and load are constant in 3-hours time intervals. Thus, the day is divided into 8 time interval.

The analysis is performed for 3 DG models: first, to the DG as distribution substation, then as central station and finally as the proposed model. Considering DG as a distribution substation, we mean DG acts as an alternative supply without capacity limitations. When modeled as conventional station, it was assumed that the DG produces its nominal capacity i.e. 2 MW all the time. It was mentioned in sections IV and V that the calculation can be performed for substation or central unit by ignoring the islanding probability or the resource limitation, respectively. The results for average failure rates are given in Table V. The results for unavailability are tabulated in Table VI.

Table V. Results for Failure Rates

LP	Initial Failure Rate	DG as Substation	DG as Conventional	Proposed Method
1	0.065000	0.065000	0.065000	0.065000
2	0.195000	0.130019	0.178705	0.194089
3	0.390000	0.195014	0.210863	0.358395
4	0.455000	0.065000	0.096700	0.126424
5	0.487500	0.097500	0.129200	0.158924
6	0.552500	0.130014	0.164355	0.196555
7	0.585000	0.097543	0.137165	0.174317

Table VI. Results for Unavailability

LP	Initial Unavailability	DG as Substation	DG as Conventional	Proposed Method
1	5.0	5.0	5.00	5.00
2	10.0	5.0	8.75	9.93
3	15.0	5.0	5.81	13.38
4	20.0	5.0	6.22	7.36
5	25.0	10.0	11.22	12.36
6	30.0	10.0	11.63	13.15
7	35.0	10.0	12.03	13.94

In these tables, second columns show the reliability indices for different load points before DG installation. The results of proposed method is shown in the last columns and can be compared with the results associated with other modeling.

It can be seen from the results that the reliability indices will experience considerable changes when DG modeling is changed. The difference in the results are more for load points which are located far from the DG. Therefore, using inappropriate model to study the DG impact can result in misleading results.

Comparing the failure rates and unavailability associated with two cases of with and without DG installation, in 2<sup>nd</sup> and 5<sup>th</sup> columns, it can be seen that DG installation can improve reliability indices considerably and the effects are more obvious for ending sections of the feeder.

## VII. CONCLUSION

This paper proposed an analytical approach to study the DG impacts on distribution system reliability indices. The method includes intrinsic attributes of both DG and distribution system, such as change in the DG resource, failure of the DG components and change in the load demand.

The islanding probability is calculated for the outage of each section of the distribution feeder. Both DG generation and load demand are incorporated in islanding probability calculation. A DG generation consists of its resource behavior and its components situation. Thus, all important factors are considered in the proposed technique.

The method is then applied to a sample distribution feeder. The DG impacts on load point indices are calculated through different DG models. The results presented indicate that the DG modeling is one of the most important factors in the analysis and attention should be paid to this issue in the reliability assessment.

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