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Reliability Indices of Electrical Distributed Generation Systems

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Abstract — **This paper proposes to add to the reliability analysis of electric distributed generation systems two new indices, namely; the distributed generation average interruption frequency index *(DGIFI)* and the distributed generation average interruption duration index (*DGIDI*). The state duration sampling approach is employed as a platform to generate the expected operating cycles of the installed distributed generators for each sample year. Random variables are generated and incorporated with the state duration approach to model the uncertainties in the operation of the underlined systems. Reliability indices are estimated using Monte Carlo simulation based technique. The proposed indices are calculated for a sample reliability test system and the results obtained are presented and discussed.**

Index Terms—**Distributed generation, reliability indices, and Monte Carlo simulation.**

I. INTRODUCTION

RECENTLY electric power industry has experienced considerable changes with respect to structure, operation and regulation [1,2]. As a result, the traditional power system vertical structure consisting of generation, transmission and distribution has been modified to suit the new deregulated power market. In this competitive market, distribution companies encourage public investment to sustain the development in the power demand by allowing small investors to install and operate distributed generation (DG) units in their distribution network. These DG units are of limited size (50 MVA or less) and can be connected directly to distribution network or on the customer site of the meter [3]. From the system reliability perspective, DG helps improving the overall system reliability by adding system generation capacity, thus relieving transmission and distribution bottlenecks and at the same time supporting power system maintenance and restoration operations with the generation of temporary backup power [4,5]. However, as customers become more cost and service sensitive, it will be extremely difficult for the distribution companies to remain competitive unless they seek new avenues to reduce costs and still provide the acceptable reliability level required by the customers. Therefore, the movement towards deregulation will introduce a wide range of reliability issues that require to be addressed. In addition, the introduction of system reliability criteria that can integrate the uncertainties in the operation of the new structured distributed generation systems deem to be a must.

Recently, several publications attempted to address the reliability issues of the DG systems. Hegazy et al [6,7] presented a Monte Carlo based technique for the assessment of the adequacy and the security of distributed generation systems. Their conducted analyses led to the estimation of the typical reliability indices of the new structured system. Chowdhury, et al [8] developed a reliability model for determining the DG equivalence to a distribution facility for use in distribution system planning studies. Dugan et al. [9], Brown et al, [10], Mc Dermott et al., [11] are among several other publications that focused on the analysis of the impacts of the DG on the overall system reliability.

This paper thoroughly investigates the reliability issues associated with the stochastic nature of the new structured distribution systems. New reliability indices are proposed to judge the security and the adequacy of the service provided by the distributed generation. A general procedure to estimate the typical and the proposed indices is described and implemented on a sample reliability test system (RTS). The basic definitions of the typical distribution system reliability indices along with the introduction of the proposed DG indices are presented in the next section followed by the framework of the proposed procedure to calculate the reliability indices in Section III. The results of the reliability analysis of the RTS are presented and discussed in Section IV.

II. RELIABILITY INDICES

A. *Typical reliability indices*

Traditionally, the predictive reliability assessment of distribution systems requires the evaluation of two groups of indices namely, load point indices and system performance indices [12]. The load point indices are, the average load point failure rate (λ failures/year), the average load point outage rate (r hr/failure) and the average annual load point outage time (U hr/year). The system performance indices are the weighted averages of the load point indices. The most common system indices are the system average interruption frequency index (SAIFI), the average service availability index (ASAI), the system average interruption duration index (SAIDI) and the customer average interruption duration index (CAIDI). The defining equations for all these indices are given in appendix A. These indices reflect the inherent energy limitations of the considered system and ability of this system to supply all customers with electrical energy as continuously as possible. The evaluation of both load point indices and system performance indices can be done either analytically or using Monte Carlo simulation. Analytical techniques represent the system by a mathematical model and evaluate the reliability indices by solving this model. This technique doesn't apply to the case of distributed generation systems since these systems are operating in mostly random states. The analytical defining equations for these indices are found in [13]. Monte Carlo simulation methods, however, estimate the reliability indices by simulating the actual process and the random behavior of the system, which covers all the possible uncertainties in the system operation. Therefore, the authors adopted this method in handling the analysis of the system under study.

B. New reliability indices

Unlike the utility substations, distributed generators are not scheduled to operate every hour of the day and therefore, typical reliability indices that reflect the frequency of the system interruptions and their duration need to be reinstated. In addition, the contribution of the DG units to the overall system capacity is administrated by the utility and usually limited to a preset value. Some utilities import up to 25% of their power capacity from DG units and others limit the penetration level to 10% [14]. The analysis conducted in this paper limits the share of the DG units in the system overall power capacity to 20%. Based on this percentage, the DG interruption is considered when the sum of all the DG power imported by the system at any hour of the day becomes lower than 10 % of the system overall power capacity (50% of the preset penetration level). Mathematically, The DG interruption frequency counter (DGIF) at any hour is incremented according to the following expression:

$$DGIF = DGIF + 1, \quad \text{if } \sum_{i=1}^{N} P_{DG}(i) < 0.1 \times \sum_{j=1}^{M} P_L(j) \tag{1}$$

Where, $P_{DG}(i)$ is the power generated by DG(i) at certain hour and P_L is the load power at this hour, N is the total number of DG units and M is the total number of system loads. The average distributed generation interruption frequency index *(DGIFI)* can be expressed by

$$DGIFI = \frac{1}{M_K} \sum_{k=1}^{M} DGIF(k) \tag{2}$$

Where, M_k is the total number of sample years and DGIF(k) the interruption frequency of year k.

The duration of the interruption is recorded for each interruption until the 10% threshold value is recovered. It is important to mention here that current engineering practice for DG/Utility interconnected systems is to de-energize all the DG units whenever an unexpected disturbance occurs in the system. Therefore a main feeder interruption will contribute to the DG interruption duration of the DG units connected to this feeder. The DG average interruption duration index (*DGIDI*) can be defined by:

$$DGIDI = \frac{\text{sum of all DG interruption durations}}{\text{total number of DG interruptions}} \tag{3}$$

The inclusion of both *DGIFI* and *DGIDI* in the analysis of distribution system reliability will indeed give more comprehensive view of the actual behavior of the DG system and therefore reflect the true characteristics of the system. The simulation procedure to perform this task is presented in the next Section.

III. SIMULATION PROCEDURE

In this Section, the proposed procedure to estimate the reliability indices of the new structured distribution system is discussed. First, the time sequential method is introduced as the base approach for modeling the operating history of each system component according to its probability distribution. Then, the proposed algorithm to calculate the load point and system performance indices is discussed.

A. Time sequential method

In time sequential simulation, a two-state-model (up state and sown state) is used to model the operation of each system component. System components include, main and lateral lines sections, transformers, switches, breakers and DG units. Fig. 1 shows an example of a two-state-model. The up state indicates that the component is in its operating state and the down state implies that the component is inoperable due to a failure or a scheduled off. A simulated history that shows the up and down times of each component in the system is generated in chronological order using random number generators and the probability distribution of the component operation and restoration parameters. A sequence of operating cycles of the system is obtained by combining the histories of all the components using the relationships between the component states and the system states.

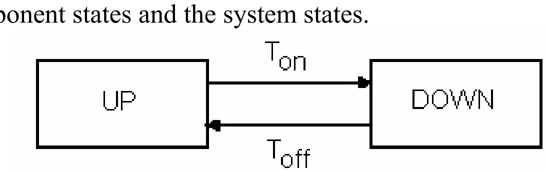

Figure 1: A two-state model of a DG

An example of the generated operating cycles of two independent DG units for a given sample year is shown in Fig. 2. the corresponding system state transition for this sample year is shown in Fig 2(c). In this example, the duration of the up state is operating time (T_{on}) and the duration of the down state is the down time (T_{off}). The parameters T_{on} and T_{off} are random variables and may have different probability distributions. The common probability distributions in distributions systems reliability analysis are, the Exponential, Gamma, Normal and Lognormal [15]. For the given example of the DG units, the sampling values for these two parameters can be calculated by drawing a random variable following the Exponential distribution such that:

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$$Ton = -\frac{1}{\lambda}.\ln U \qquad (4)$$

$$Toff = -\frac{1}{\mu}.\ln U' \qquad (5)$$

Where U and U' are two uniformly distributed random number sequences between [0,1] and λ is the outage rate (outages/hour) and μ is restoration rate (restoration/hour). A discussion on the significance of both λ and μ is provided is section IV.

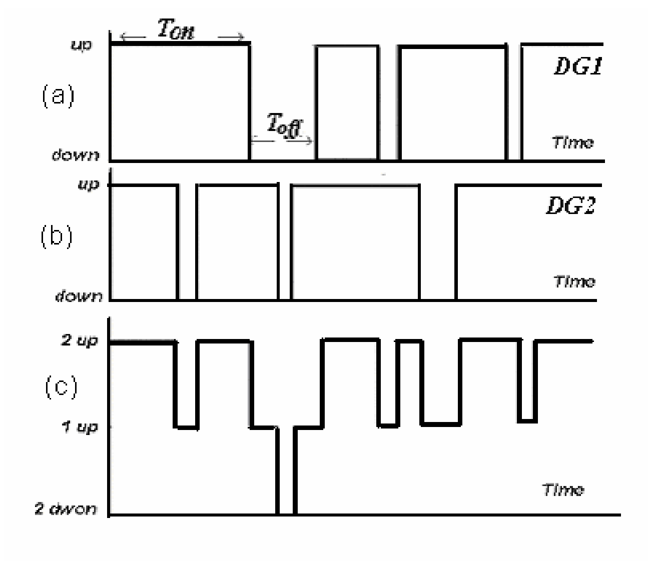

Fig. 2: (a) DG1 operation/repair history, (b) DG2 operation/repair history and (c) A two-DG system state transition process

B. Simulation algorithm

The implemented algorithm to estimate the reliability indices using time sequential method and Monte Carlo simulation is summarized as follows:

First, obtain simulated up-down operating histories of all the system components by generating a random number and convert this number into T_{on} and T_{off} according to the component probability distribution.

Second, for each minimum system transition state, determine the location of the failed component, and the failed main feeder that this failed component is connected to.

Third, determine the affected load points connected to the failed main feeder and the failure durations of these load points according to the configuration and protection scheme of the failed feeder.

Then, determine the laterals, which are connected to the failed main feeder and the effects of the failed load points connected to these laterals.

Repeat for each failed lateral until all the laterals connected to the failed main feeder are evaluated.

Finally, calculate the three basic load point indices caused by each line section operating history using (6)-(8) and evaluate the system performance indices using the equations given in Appendix A.

V. CASE STUDY

The structure of the sample distribution system under study is shown in Fig. 3. This system comprises 3 radial feeders with 7 main sections, 6 laterals and 6 load points. Each load point of the A, B and C load points is assumed to supply 100 customers and the other load points D, E and F are supplying 80 customers giving a total of 540 customer in the system. Five customer controlled DG units are located at load points A to E and running in parallel with the system. These DG units can be used as an alternate supply. The component data required for the calculations of reliability indices are assumed to be as follows:

Main feeder: 0.1 failures/km/year with 2 hours average repair time.

Lateral: 0.3 failures/km/year with 1-hour average repair time.

Transformers, 1-3 failures/year with 10- hour repair time.

Switches are automatically operated and therefore the switching time is negligible. The simulation was performed for 10,000 sample years.

The impact of the distributed generators on the reliability of the system under study is examined by comparing the reliability indices for the following two cases:

Case I: the load point indices and the overall system indices are evaluated with all the DG units are not available. The procedure described earlier in this section is used to perform the simulation. The substation ratings are assumed to be sufficient to meet the peak load demand at any time of the year.

Case II: the same analysis was performed with the DG units are operating in parallel with the according to their operating cycle. The penetration level of all the DG units is limited to 20% of the system peak load. The switching time of DG units is assumed lognormally distributed.

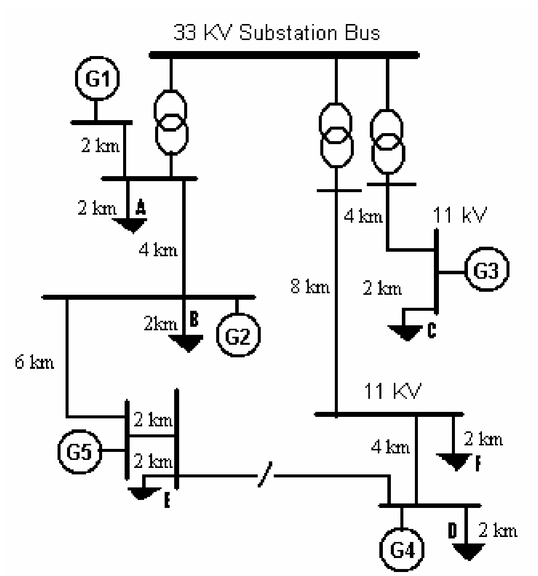

Fig3. The sample distribution system under study

C. Results

The procedure described in Section IV is implemented in this study to investigate the reliability of the system under study. The simulation results are used to calculate the following load point and system indices and their probability distributions:

- Average load point failure frequency (λ failures/year).
- Average load point failure duration (r hours/year) and the probability distribution of failure durations.
- The average value of the annual outage time (U hours/year).
- Average values of the following system indices:
    1. SAIFI (interruptions/customer-year),
    2. SAIDI (hours/customer-year)
    3. CAIDI (hours/customer-interruption),
    4. ASAI.

  and the associated probability distributions of these indices.
- The average distributed generation interruption frequency index *(DGIFI* interruption/year) and the distributed generation average interruption duration index (*DGIDI* hours/year) and the probability distribution of these two newly introduced DG system indices.

Table1 summarizes the calculated load point's indices for all the system load points in all the three study cases. In this table λ is in failures/year, r is in hr/failure and U is in hr/year. The Monte Carlo based mathematical equations used to calculate these indices are as follows:

$$\lambda_i = \frac{N}{\sum T_{on}} \tag{6}$$

$$r_i = \frac{\sum T_{off}}{N} \tag{7}$$

$$U_i = \lambda_i r_i \tag{8}$$

Where i refer to the line section and N is the number of transitions between up and down states during the total sample years.

Table 1. Load point indices for case I

Load point	Index		
	λ	r	U
A	2.25	0.87	1.95
B	2.1	1.43	3.08
C	1.80	2.02	3.60
D	1.80	0.88	1.60
E	1.80	1.67	3.05
F	1.80	1.67	3.08

The calculated load points indices for the system when all the DG units are operated according to their simulated operation cycles are presented in Table 2. It is important to note here that both the frequency of interruptions λ and the durations of these interruptions r improved for all load points when the DG units are allowed to supply the loads in case of loss of the utility grid power.

Table 2. Load point indices for case II

Load point	Index		
	λ	r	U
A	2.15	0.87	1.95
B	1.91	1.14	2.43
C	1.68	1.33	2.44
D	1.72	0.89	1.60
E	1.56	1.37	2.51
F	1.43	1.00	1.86

The average values of the distribution system reliability indices are given in Table 3 for the two studies cases. The mathematical equations used to estimate these indices are given in Appendix A. The comparison between system indices for case I and Case II, indicates that the overall system reliability has improved with the contribution of the DG units to the overall system capacity. This improvement is evident in the reduction of CAIDI when customers experienced less interruption durations and also in the in ASAI where the availability of the system energy at anytime is becomes close to 100%.

Table 3: System reliability indices

System Index	Case I	Case II
SAIFI	1.09389	1.0045
CAIDI	2.3973	2.1973
ASAI	0.9997	0.9998
SAIDI	2.7090	2.5490

In addition to the typical system indices, the average distributed generation interruption frequency index *(DGIFI*) and the distributed generation average interruption duration index (*DGIDI*) are calculated using (1)-(3). The numerical values obtained for DGIFI = 2.45 interruptions/DG-day and for DGIDI = 3.79 hours/DG-day. It is important to mention here that these indices are expressed in per day values not per year as typical indices are, since the contribution of the installed DG units is limited to 20% of the system capacity and as a result they do not run 24 hours per day.

The probability distribution of all the calculated system indices is recorded for the main 8 km feeder and depicted in figures 4-9. Fig 4 portrays the probability distribution of SAIFI weighted by the percentage of customers connected to the load points supplied by this feeder. The corresponding probability distribution of the durations of system interruptions is shown in Fig. 5. The distribution of the customer interruptions durations each year is given in Fig6. The average system availability probability distribution is illustrated in Fig. 7. The probability distribution of the average distributed generation interruption frequency and the distributed generation average interruption duration are shown in Fig 8 and Fig. 9 respectively.

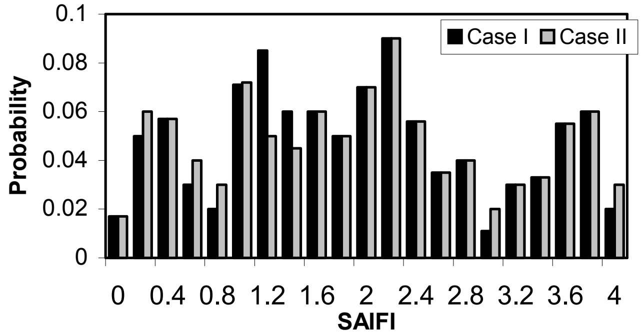

Fig. 4. The probability distribution of weighted system interruption frequency

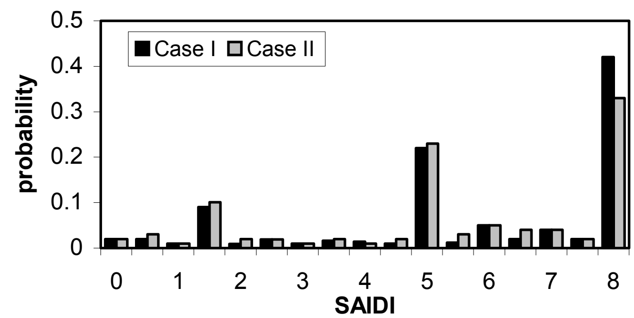

Fig. 5. The probability distribution of the durations of system interruptions

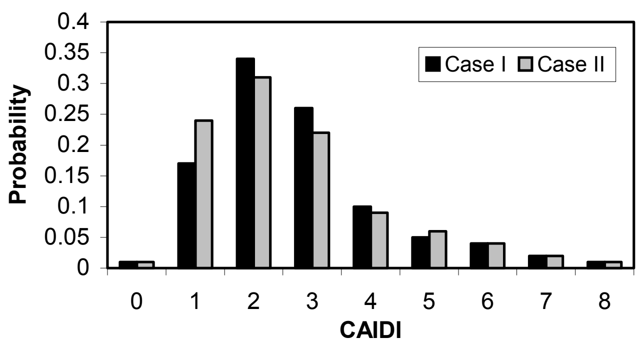

Fig. 6. The probability distribution of the durations of system interruptions

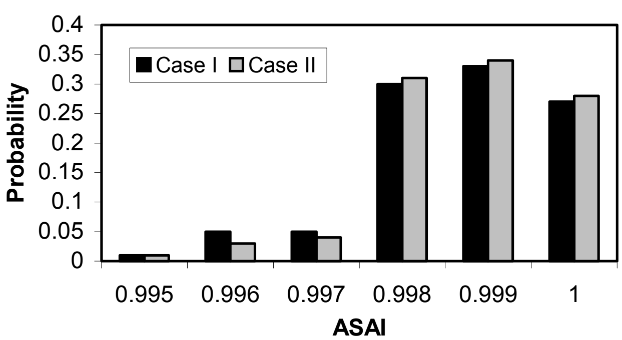

Fig. 7. The average system availability probability distribution

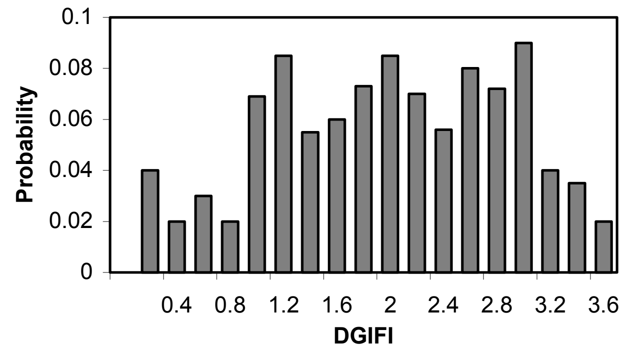

Fig. 8 The average distributed generation interruption frequency

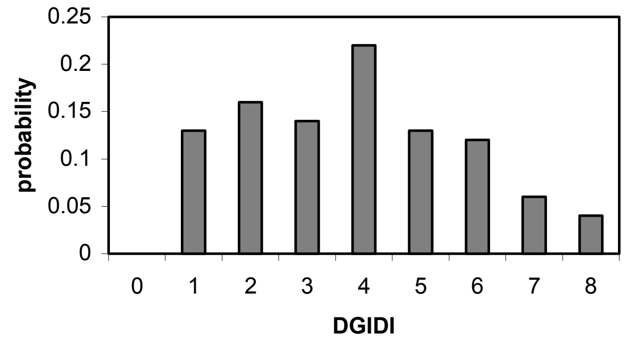

Fig. 9. The distributed generation average interruption duration

VI. DISCUSSION

The implementation of the different distribution system technologies in real life distribution system is still in its starting phase. Therefore, there is a lack of recorded data for the history of the operation of distributed generation units. To conduct the reliability analysis in this study, numerical values for λ (the outage rate) and μ (restoration rate) were assumed. Based on engineering guidelines. The factors considered to set these guidelines and therefore produce an acceptable estimate of both λ and μ are the size of the DG unit, the technology used to generate electric power and the function of the DG. For instance, a 50 MW DG unit is considered a gas generator installed in an industrial facility rather than a residential neighborhood. In addition, this industrial DG will deliver electric power to the network during the off work periods only while a residential DG might contribute to the system capacity most of the day. The author anticipates that with the widespread use of the DG and the undergoing research in this area, typical values of λ and μ will become available in the near future.

VII. CONCLUSIONS

This paper proposes to introduce the average distributed generation interruption frequency index (DGIFI) and the distributed generation average interruption duration index (DGIDI) to the reliability analysis of distributed generation systems. The state duration sampling approach is employed as a platform to generate the expected operating cycles of the installed distributed generators and the uncertainties in the operation of the system is modeled using random variables. A Monte Carlo simulation based technique was applied to calculate system reliability indices The results obtained in this study indicated that distributed generation units if well managed can give good support to the performance of the existing system. This support can be evident in boosting the available capacity of the system or reducing the average system interruption times per year. The main difficulty in developing the proposed model is the lack of recorded operating history of the existing DG units.

VIII. Appendix A
System Reliability Indices

The estimated system indices in the conducted reliability analysis in this paper are calculated using the following equations:

1. System average interrution frequency index, *SAIFI*

$$SAIFI = \frac{\sum_{i=1}^{R} \lambda_i N_i}{\sum_{i=1}^{R} N_i} \qquad (A.1)$$

2. System average interruption duration index, *CAIDI*

$$CAIDI = \frac{\sum_{i=1}^{R} U_i N_i}{\sum_{i=1}^{R} \mu_i N_i} \qquad (A.2)$$

3. System service availability index, *ASAI*

$$ASAI = \frac{\sum_{i=1}^{R} 8760 N_i - \sum_{i=1}^{R} U_i N_i}{\sum_{i=1}^{R} 8760 N_i} \qquad (A.3)$$

4. System average interruption duration index, *SAIDI*

$$SAIDI = \frac{\sum_{i=1}^{R} U_i N_i}{\sum_{i=1}^{R} N_i} \qquad (A.4)$$

Where, λ_i, is the failure rate, U_i is the annual outage time, N_i is the number of customers at load point i and,R is the set of load points in the system.

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