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Reliability Indices evaluation of Ring Distribution Systems without and with DG

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Abstract: *Distribution system reliability receives more attention nowadays. This is mainly due to the wide use of electric energy in industrial, commercial and residential applications. Reliability modeling and evaluating of ring distribution systems do not receive enough attention in the literature compared to the radial distribution systems. Many types of indices have been used toevaluatethe power distribution system. This study develops equations to evaluate the reliability indices of ring distribution systems without and with Distributed Generation (DG). The impact of DG on the reliability indices are studied assuming perfect switching.The study derives equations to calculate the frequency of failure "F_m", probability of failure "P_m" and average outage time of failure "U_m" at load points of ring distribution system, assuming that the DG is connected to specific load points. The method has been generalized to accommodate any number of locations supplied by DGs. Furthermore, a numerical example is presented, in which the difference between the reliability indices with and without DG is calculated.*

Key words: *Reliability Indices, Distributed Generation (DG), Ring Distribution Systems, Reliability Evaluation*

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I. INTRODUCTION

The reliability is the ability to generate and supply electric energy when required i.e. providing uninterrupted electrical power. Reliable power system is necessary to promote industrial growth and economic development. Assessment of customer power supply reliability is important to evaluate distribution systems operation[1, 2].

The customers' willingness to pay for a higher level of reliability has lead to deregulation of power systems, which creates a competitive market to meet customer demands. It follows that the traditional configurations of distribution systems is changing continuously. Consequently, it is necessary to investigate reliability enhancement of distribution systems and to evaluate the benefits received from reliability upgrades. The ultimate goal is to reduce the impact caused by failures of distribution systems so that electric utilities can provide continuous and high quality electric service to customers at reasonable rates [3].

The distribution reliability indices evaluate the impact of interruptions on customers. Nowadays the developments of automatically controlled production lines, information-network services, and energy-saving technologies and the proportion of digital and electronic loads, are increasing rapidly. The trend to connect distributed generation (private generator, wind and solar units) adds new challenge to researchers to evaluate reliability indices of complicated modern systems [4, 5, 6, 7].

In the recent years, utilities are devoting great deal of efforts to improve the performance of the distribution systems and subsequently its reliability. One of these efforts is to make the maximum possible use of the distributed generation (DG), which is normally connected to the distribution system. The reliability indices will change when DG is connected to distribution systems by minimizing the chance of power interruptions, which is one of the most important issues [5, 8].

DG refers to the power generation supplied by small generating units connected to the distribution systems. DG is playing an increasing role in the electric power systems, able to feed the electrical power required in a distributed manner [9, 10].

Distribution system is a portion of a power system that delivers energy from transformation points on the transmission system to the customer. Distribution systems are designed to be efficient at peak load demand [11].

II. MARKOV MODEL

Markov model is quite popular in the quantitative reliability analysis. This is because a simple and clear formula can be developed to calculate the reliability indices of distribution networks. Binary state Markov process type can be easily implemented in system reliability assessment. It's using two states; it basically operates with two central concepts called transition rates[10, 12].

- Failure rate "λ"
- Repair rate "μ"

Consider a simple single component system in Fig.1. The state space diagram illustrates that the system can be in two states model diagram represented by Unit Up (component is in a normal state) and Unit Down (component in failed state) [10, 12, 13].

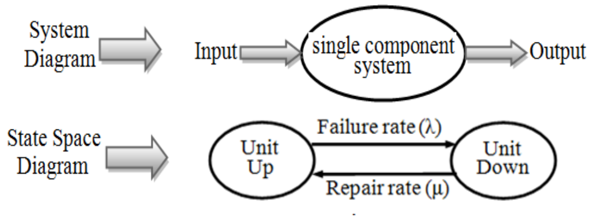

Fig.1. System and State Space Diagram of Single Component System

Two components in series or parallel are to be represented by a single model characterized by equivalent repair time "rs" and failure rate "λs" [12, 14, 15].
Table 1.1 summarizes the results.[15]

TABLE I: EQUIVALENT MODEL PARAMETERS FOR TWO COMPONENTS.

Model	***Series System***	***Parallel System***
Failure Rate "λ"	$\lambda_s = \lambda_1 + \lambda_2 = \sum_{i=1}^{m} \lambda i$	$\lambda_p = \frac{\lambda 1\, \lambda 2\, (r1 + r2)}{1 + \lambda 1 r1 + \lambda 2\, r2} \cong \lambda_1 \lambda_2 (r_1 + r_2)$
Repair Time " r"	$r_s = \frac{\lambda 1\, r1 + \lambda 2\, r2 + \lambda 1\, \lambda 2\, r1\, r2}{\lambda 1 + \lambda 2} \cong \frac{\Lambda 1\, R1 + \Lambda 2 R2}{\Lambda 1 + \Lambda 2} = \frac{\sum_{i=1}^{m} \lambda i\, ri}{\sum_{i=1}^{m} \lambda i}$	$r_p = \frac{r1\, r2}{r1 + r2}$

Where:
λ_s, λ_p : The failure rate of series and parallel system.
r_s , r_p : The repair time of series and parallel system.
μ_s, μ_p : The equivalent repair time **(**repair rate**)** of series and parallel system.
λ_1, λ_2: The failure rate of components *1,2*.
r_1 , r_2 : The repair time of components *1,2*.

A. Load Points Reliability Indices

The reliability of each of these terms i.e. frequency of failure "***Fm***", average annual outage time "***Um***" and average outage time "T_m" are determined by using states and transition rates. Thus, the reliability indices at any load point depend on the path between the load point and the source bus. The components on the path are connected in series. If all components availabilities are high, three reliability terms are evaluated for each load point as follows:[10, 12].

1- The frequency of failure at a load point situated on bus ***m***calculated from the equation:

$$F_m = \sum_{\alpha \epsilon sm} \lambda\alpha \ (1/yr) \qquad (1)$$

2- The average annual outage time at a load point *m* calculated from the equation:

$$U_m = \sum_{\alpha \epsilon sm} (\lambda\alpha \times r\alpha) \ (hr/yr) \qquad (2)$$

3- The average outage time of a load point *m*calculated from the equation:

$$T_m = \frac{Um}{Fm} = \frac{\sum_{\alpha \epsilon sm} (\lambda\alpha \times r\alpha)}{\sum_{\alpha \epsilon sm} \lambda\alpha} \ (hr) \qquad (3)$$

Where:*Sm* : The components on the path between the source bus ***S*** and the load point bus ***m***.
λ_α **:** The failure rate of component α, unit *(1/Year)*.

r_α : The repair rate of component α, unit *(hour)*.

B. Reliability Indices

Electric utilities may use some or all of the reliability indices depending on their regulatory situations. SAIFI, SAIDI, and CAID are the most commonly used indices' identified by standard IEEE 1366-2003 "Guide for Electric Power Distribution Reliability Indices". The smaller these indices the betterthey are. Definitions of the three indices are as follows:

1- *System verage interruption frequency index* (SAIFI)

$$SAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}} = \frac{\sum (Fm \times Nm)}{\sum Nm} \text{(interruptions/ customer)} \quad (4)$$

2- *System average interruption duration index* (SAIDI)

$$SAIDI = \frac{\sum \text{Customer interruption durations}}{\text{total number of customers served}} = \frac{\sum (Um \times Nm)}{\sum Nm} \text{(hours / year /customer)} \quad (5)$$

3- Customer average interruption duration index (CAIDI)

$$CAIDI = \frac{\sum \text{Customer interruption durations}}{\text{total number of customers interruptions}} = \frac{SAIDI}{SAIFI} \text{(hours/ customer interruption)} \quad (6)$$

Where, N_m: is the number of customers in section or load point **m**.

III. RING DISTRIBUTION SYSTEM WITH DG

The addition of DG to a ring distribution system has the advantage of adding an alternative source, which can supply part of or all load points when needed. The ring distribution feeders with a DG as shown in fig.2, is used as a first step towards the general evaluation process as follows:

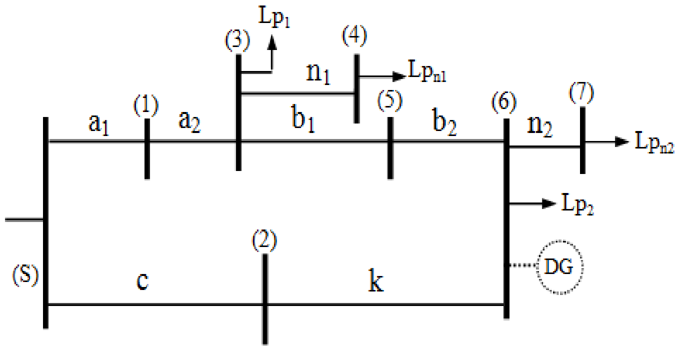

Fig.2. Ring Distribution System with Distributed Generation at Load Point Lp_2

Where,

S*:* is the source bus.

1,2,……..,7 : are the load buses.

a_1, a_2, b_1, b_2, c **&** k : are components of a ring distribution system to be studied .

Lp_1, Lp_2 **,** Lp_{n1} **&** Lp_{n2} : are load points.

C. Load Points Supplied Directly from Distributed Generation

To calculate the frequency of failure "F_m" and the probability of failure "P_m" a state-space diagram should be developed of all loads points system whether directly connected with distributed generation (DG) or not.

Fig.3, shows the state-space diagram of load point LP_2 for failure of components a_1, a_2, b_1, b_2, c and k, assuming LP_2 is directly connected to a distributed generation (DG), where DG availability equals A_{DG} and DG unavailability $\bar{A}_{DG}$. The failure states of $LP_2$are those included in the shaded area.

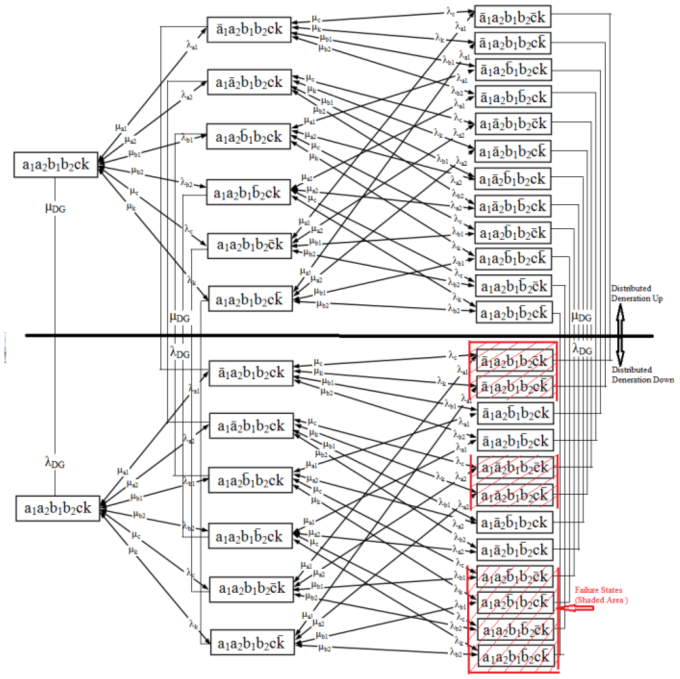

Fig.3. State-Space Diagram for Load Point Lp_2 of Fig. 2; which is Supplied Directly from the Distributed Generation for Failures in Components a_1, a_2, b_1, b_2 & c, k.

Where:

a_1, a_2, b_1, b_2& c, k : are respectively up-states of components a_1, a_2, b_1, b_2& c, k. (availability of components).

$\bar{a}_1, \bar{a}_2, \bar{b}_1, \bar{b}_2$& $\bar{c}, \bar{k}$: are respectively down-states of components a_1, a_2, b_1, b_2& c, k. (unavailability of components).

$\lambda_{a1}, \lambda_{a2}, \lambda_{b1}, \lambda_{b2}, \lambda_c, \lambda_k$ & λ_{DG}: are respectively failure rates of components a_1, a_2, b_1, b_2& c, k.

$\mu_{a1}, \mu_{a2}, \mu_{b1}, \mu_{b2}, \mu_c, \mu_k$& μ_{DG} : are respectively repair rates of components a_1, a_2, b_1, b_2& c, k.

- ***The frequency of failure of load point*** = [DG in failure (down) states i.e. $\bar{A}_{DG}\times\Sigma$ frequency of transition from any state to any failure state (shaded area)] + [DG in failure (up) states i.e. $A_{DG}\times\Sigma$ frequency of transition from any state to any failure state (shaded area)] (7)
- ***The probability of failure of load point*** = [Down / Up state of DG×Σ failure states in the related DG zone (shaded area)] (8)

From the state- space diagram in fig. 3. and equation (7), the frequency of failure of load point **Lp2** can be formulated as follows:

$$F_{Lp2}= \bar{A}_{DG} [\bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c A_k (\lambda_c + \lambda_k) + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c A_k (\lambda_c + \lambda_k) + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c A_k (\lambda_c + \lambda_k) + A_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c A_k (\lambda_c + \lambda_k) + A_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k (\lambda_{a1} + \lambda_{a2} + \lambda_{b1} + \lambda_{b2}) + A_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k (\lambda_{a1} + \lambda_{a2} + \lambda_{b1} + \lambda_{b2})]$$

$$+ A_{DG} \lambda_{DG} [\bar{A}_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} \bar{A}_c A_k + \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} \bar{A}_c A_k + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c \bar{A}_k + A_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c \bar{A}_k]$$

(9)

Where:

$A_{a1}, A_{a2}, A_{b1}, A_{b2}$& A_c, A_k : are respectively the availabilities of components a_1, a_2, b_1, b_2& c, k .

$\bar{A}_{a1}, \bar{A}_{a2}, \bar{A}_{b1}, \bar{A}_{b2}$& $\bar{A}_c, \bar{A}_k$: are respectively the un availabilities of components a_1, a_2, b_1, b_2& c, k .

It can be simplified equation (9):

$$F_{Lp2}= \bar{A}_{DG}[\{ (A_c A_k)(\lambda_c + \lambda_k) \} \{ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} + A_{a1} A_{a2} A_{b1} \bar{A}_{b2}\} + \{ (A_{a1} A_{a2} A_{b1} A_{b2}) (\lambda_{a1} + \lambda_{a2} + \lambda_{b1} + \lambda_{b2}) \} (\bar{A}_c A_k + A_c \bar{A}_k)]+ A_{DG} \lambda_{DG} [(\bar{A}_c A_k + A_c \bar{A}_k) \{ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} + A_{a1} A_{a2} A_{b1} \bar{A}_{b2}\}] \quad (10)$$

Furthermore it can be generalized as follows:

$$F_{Lp2} = \bar{A}_{DGm}\,[\{\prod_{i\,\in Rt2} Ai(\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj)\sum_{i\,\in\,Rt2}\lambda i\} + \{\prod_{i\,\in Rt1} Ai\ (\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\sum_{i\,\in\,Rt1}\lambda i\}] + A_{DGm}\,\lambda_{DGm}\,[(\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\{\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj\}] \quad (11)$$

To cover all possible cases that may occur assume a radial element $\boldsymbol{n_2}$ is connected to the load point $\boldsymbol{Lp_2}$ of the ring system as shown in fig.2. To consider the failure of component $\boldsymbol{n_2}$ it is clear that such failures lead to the interruption of both the route to sources buses and the route to distributed generation at the same time.

In other words, frequency of failure of load points $\boldsymbol{Lp_{n2}}$ in equal to that of $\boldsymbol{Lp_2}$ plus equation (12).

$$\sum_{i\,\in\,Rtn\,2}\boldsymbol{\lambda i} \qquad (12)$$

The sum of equations (11) and (12) represents the total frequency of failure of load points, and is as follows:

$$\boldsymbol{F_2 = \bar{A}_{DGm}\,[\{\prod_{i\,\in Rt2} Ai(\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj)\sum_{i\,\in\,Rt2}\lambda i\} + \{\prod_{i\,\in Rt1} Ai\ (\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\sum_{i\,\in\,Rt1}\lambda i\}] + A_{DGm}\,\lambda_{DGm}\,[(\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\{\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj\}] + (\sum_{i\,\in\,Rtn2}\lambda i)} \qquad (13)$$

Where:

$\prod_{i\,\in Rtn}\boldsymbol{Ai = A_1{\times}A_2{\times}\,A_3{\times}}$ ..… where A_1, A_2 and A_3 , ……. are components between the source bus $\boldsymbol{S}$ and the load point $\boldsymbol{m}$.

From fig.3. the probability of failure of load point $\boldsymbol{Lp2}$ can be formulated as follows:

$$\mathbf{P_{Lp2}} = \bar{A}_{DG}\ [\bar{A}_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} \bar{A}_c A_k + \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} \bar{A}_c A_k + A_{a1} A_{a2} A_{b1} \bar{A}_{b2} \bar{A}_c A_k + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c \bar{A}_k + A_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c \bar{A}_k] \qquad (14)$$

This equation can be simplified as follows:

$$\boldsymbol{P_{Lp2}} = \bar{A}_{DG}[\ (\bar{A}_c A_k + A_c \bar{A}_k)\ \{\ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} + A_{a1} A_{a2} \bar{A}_{b1} A_{b2} + A_{a1} A_{a2} A_{b1} \bar{A}_{b2}\}\ ] \qquad (15)$$

It can be generalized as follows:

$$\boldsymbol{P_2} = \bar{A}_{DG}\ [(\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\ \{\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj\}] \quad (16)$$

Again to consider radial elements connected to any load point in a ring system the following probability of failure should be added as follows:

$$\sum_{i\in Rtn2}\boldsymbol{\bar{A}i} \ = \ \sum_{i\in Rtn2}(\boldsymbol{1-Ai}) \qquad (17)$$

The sum of equations (16) and (17) represents the total probability of failure of load points, and be as follows:

$$\boldsymbol{P_2 = \bar{A}_{DG}\ [(\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\,\in Rt2\\ j\,\neq\, i}} Aj)\ \{\sum_{i\in Rt1}(1-Ai)\prod_{\substack{j\,\in Rt1\\ j\,\neq\, i}} Aj\}] + (\sum_{i\in Rtn2}(1-Ai))} \qquad (18)$$

Where:

$\boldsymbol{Rt_1}$ **:** represents the components of route between first substation power and distributed generation (DG).

$\boldsymbol{Rt_2}$ **:** represents the components of route between other substation power and distributed generation (DG).

$\boldsymbol{Rt_{n2}}$ **:** represents the components of route if radial elements are connected to a load point $\boldsymbol{m}$ of a ring system.

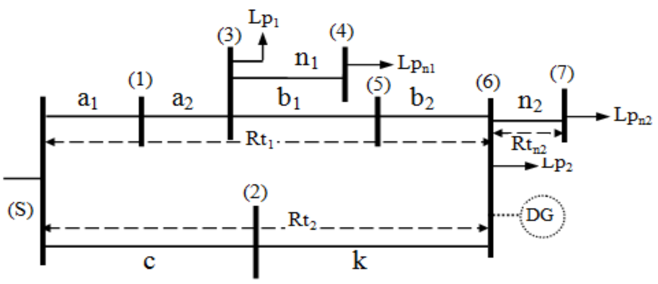

Fig.4. Shows Routs of Load Point Lp_2 (Rt_1 ,Rt_2 & Rt_{n2}).

D. Load Points not directly supplied from The Distributed Generation

This part includes all load points other than those supplied directly from the distributed generation (DG).

This case represents load points which can be supplied from the distributed generation, when the route between them and the source bus is interrupted. An example of this case is load points Lp_1 and Lp_{n1} of the distribution system as shown in fig.2.

Fig.5 shows the state-space diagram of load point LP_1 for failure of components a_1, a_2, b_1, b_2, c and k, assuming LP_1 is not directly connected to a distributed generation (DG). The failure states are those included in the shaded area.

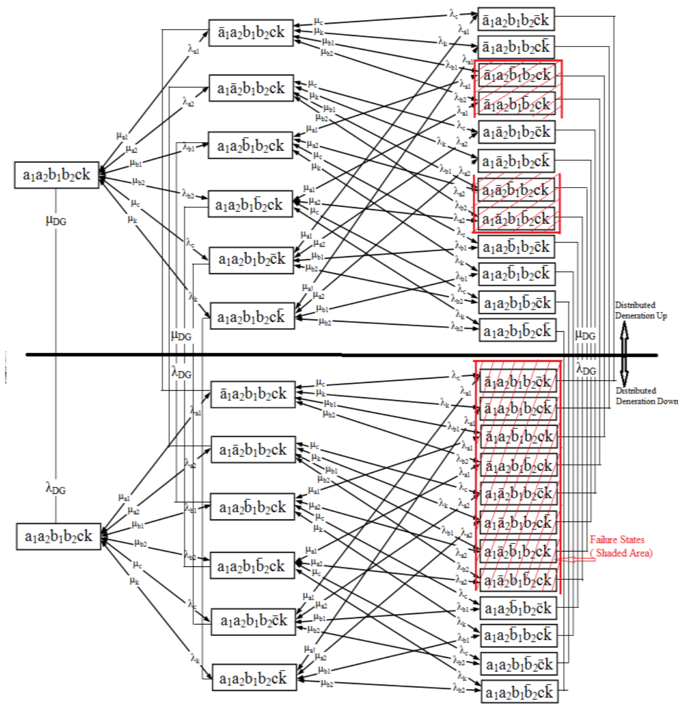

Fig.5. State-Space Diagram for Load Point Lp_1 of Fig.2 ; which is supplied not directly from The Distributed Generation for Failures in Components a_1, a_2, b_1, b_2 & c, k.

From equation (7) and the state- space diagram in fig.5, the frequency of failure of load point Lp_1 can be formulated as follows:

$F_{Lp1} = \bar{A}_{DG}\ [\ (\ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c A_k\ )(\ \lambda_{b1} + \lambda_{b2} + \lambda_c + \lambda_k\ ) + (A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c A_k\ )\ (\lambda_{b1} + \lambda_{b2} + \lambda_c + \lambda_k\ ) + (\ A_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c A_k\ )(\ \lambda_{a1} + \lambda_{a2}\ ) + (\ A_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c A_k)\ (\lambda_{a1} + \lambda_{a2}\ ) + (\ A_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k\ )(\ \lambda_{a1} + \lambda_{a2}\ ) + (\ A_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k\ )(\ \lambda_{a1} + \lambda_{a2}\ )] + A_{DG}\ [\ (\ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c A_k\ )(\ \lambda_{b1} + \lambda_{b2}\ ) + (\ A_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c A_k + A_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c A_k\ )(\ \lambda_{a1} + \lambda_{a2}\ ) + (\ \bar{A}_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k + \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} \bar{A}_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c \bar{A}_k\ )\ \lambda_{DG}\ ]$ (19)

Can be simplified as follows:

$F_{Lp1} = \bar{A}_{DG}\ [\ (A_c A_k\ )\ (A_{b1} A_{b2})\ (\ \bar{A}_{a1} A_{a2} + A_{a1} \bar{A}_{a2}\ ))\{(\ \lambda_{b1} + \lambda_{b2}) + (\ \lambda_c + \lambda_k\ )\} + (\ A_{a1} A_{a2})\ (\lambda_{a1} + \lambda_{a2}\ )\{\ (\ \bar{A}_{b1} A_{b2} + A_{b1} \bar{A}_{b2}\ )(\ A_c A_k) + (\bar{A}_c A_k + A_c \bar{A}_k\ )(\ A_{b1} A_{b2}\ )\}\ ] + A_{DG}\ [(A_c A_k\ )\{(A_{b1} A_{b2})(\bar{A}_{a1} A_{a2} + A_{a1} \bar{A}_{a2}\ )(\ \lambda_{b1} + \lambda_{b2}) + (A_c A_k\ )(A_{a1} A_{a2})(\ \bar{A}_{b1} A_{b2} + A_{b1} \bar{A}_{b2})(\ \lambda_{a1} + \lambda_{a2})\} + \{\ (A_{b1} A_{b2})\ (\bar{A}_c A_k + A_c \bar{A}_k\ )(\ \bar{A}_{a1} A_{a2} + A_{a1} \bar{A}_{a2})\ \lambda_{DG}]$(20)

$F_{Lp1} = \bar{A}_{DGm}\ [\ \prod_{i\in Rt2} Ai \prod_{i\in Rt4} Ai\ (\ \sum_{i\in Rt3}(1 - Ai) \prod_{\substack{i\in Rt3 \\ i\neq j}} Aj)\ (\ \sum_{i\in Rt4} \lambda i + \sum_{j\in Rt4} \lambda j\ ) + (\prod_{i\in Rt3} Ai \sum_{i\in Rt3} \lambda i\ )$
$\{(\sum_{i\in Rt4}(1 - Ai) \prod_{\substack{j\in Rt4 \\ i\neq j}} Aj\ ) \prod_{i\in Rt2} Ai + (\ \sum_{i\in Rt2}(\ 1 - Ai) \prod_{\substack{j\in Rt2 \\ i\neq j}} Aj\ ) \prod_{i\in Rt4} Ai\ )\}\ ]$

(21)

If radial elements are connected to a load point of a ring system as shown in fig.2, the following term should be added to equation (21).

$$\sum_{i\ \in\ Rtn\,1} \boldsymbol{\lambda i} \qquad (21)$$

The total frequency of failure of load points, of Lp_1 is

$$F_1 = \bar{A}_{DGm} \Big[\prod_{i\in Rt2} Ai \prod_{i\in Rt4} Ai \Big(\sum_{i\in Rt3}(1-Ai)\prod_{\substack{i\in Rt3\\ i\neq j}} Aj\Big)\Big(\sum_{i\in Rt4}\lambda i+\sum_{j\in Rt4}\lambda j\Big)+\Big(\prod_{i\in Rt3} Ai \sum_{i\in Rt3}\lambda i\Big)\Big\{\Big(\sum_{i\in Rt4}(1-Ai)\prod_{\substack{j\in Rt4\\ i\neq j}} Aj\Big)\prod_{i\in Rt2} Ai + \Big(\sum_{i\in Rt2}(1-Ai)\prod_{\substack{j\in Rt2\\ i\neq j}} Aj\Big)\prod_{i\in Rt4} Ai \Big)\Big\}\Big] + A_{DGm}\Big[\prod_{i\in Rt2} Ai \Big\{\Big(\prod_{i\in Rt4} Ai \Big(\sum_{i\in Rt3}(1-Ai)\prod_{\substack{i\in Rt3\\ i\neq j}} Aj\Big)\sum_{i\in Rt4}\lambda i\Big) +\Big\{\prod_{i\in Rt3} Ai \Big(\sum_{i\in Rt4}(1- Ai)j\in Rt4i\neq jAj\Big)\, i\in Rt3\lambda i\Big)\Big\} + \Big\{i\in Rt4Ai\big(i\in Rt2(1-Ai)j\in Rt2i\neq jAj\big)\big(i\in Rt3(1-Ai)i\in Rt3i\neq jAj\big)\,\lambda_{DGm}\Big\}\Big]+\sum_{i\,\in\, Rtn\,1}\lambda i \qquad (22)$$

From fig.5and equation (8) the probability of failure of load point Lp1 can be formulated as follows:

$$\boldsymbol{P_{Lp1}} = \bar{A}_{DG}\,[\,\bar{A}_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c A_k + \bar{A}_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c A_k + \bar{A}_{a1} A_{a2} A_{b1} A_{b2} \bar{A}_c A_k + \bar{A}_{a1} A_{a2} A_{b1} A_{b2} A_c \bar{A}_k + A_{a1} \bar{A}_{a2} \bar{A}_{b1} A_{b2} A_c A_k + A_{a1} \bar{A}_{a2} A_{b1} \bar{A}_{b2} A_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} \bar{A}_c A_k + A_{a1} \bar{A}_{a2} A_{b1} A_{b2} A_c \bar{A}_k\,]+ A_{DG}\,[\,\bar{A}_{a1} A_{a2} \bar{A}_{b1} A_{b2} A_c A_k + \bar{A}_{a1} A_{a2} A_{b1} \bar{A}_{b2} A_c A_k + A_{a1} \bar{A}_{a2} \bar{A}_{b1} A_{b2} A_c A_k + A_{a1} \bar{A}_{a2} A_{b1} \bar{A}_{b2} A_c A_k\,] \qquad (23)$$

Can be simplified as follows:

$$\boldsymbol{P_{Lp1}} =\bar{A}_{DG}\,[\,(\bar{A}_{a1} A_{a2}) \{(A_{b1} A_{b2})(\bar{A}_c A_k +A_c \bar{A}_k) + (A_c A_k)(\bar{A}_{b1} A_{b2} + A_{b1} \bar{A}_{b2})\} + (A_{a1} \bar{A}_{a2}) \{(A_{b1} A_{b2})(\bar{A}_c A_k +A_c \bar{A}_k) + (A_c A_k)(\bar{A}_{b1} A_{b2} + A_{b1} \bar{A}_{b2})\}\,]+ A_{DG}\,[(A_c A_k) (\bar{A}_{b1} A_{b2} + A_{b1} \bar{A}_{b2}) (\bar{A}_{a1} A_{a2} + A_{a1} \bar{A}_{a2})] \qquad (24)$$

This equationcan be generalized as follows:

$$\boldsymbol{P_{Lp1}} = \bar{A}_{DGm}\Big[\Big\{\prod_{i\in Rt4} Ai \Big(\sum_{i\in Rt2}(1 - Ai)\prod_{\substack{j\in Rt2\\ j\neq i}} Aj\Big) + \prod_{i\in Rt2} Ai \Big(\sum_{i\in Rt4}(1 - Ai)\prod_{\substack{j\in Rt4\\ j\neq i}} Aj\Big)\Big\}\Big(\sum_{i\in Rt3}(1 - Ai)j\in Rt3j\neq iAj\Big)\Big]+ A_{DGm}\,[i\in Rt2Ai\,(\,i\in Rt4(1-Ai)j\in Rt4j\neq iAj)(i\in Rt3(1-Ai)j\in Rt3j\neq iAj)] \qquad (25)$$

If radial elements are connected to a load point Lp1 of a ring system the following term should be applied to the probability of failure as follows:

$$\sum_{i\in Rtn1} \bar{A}i = \sum_{i\in Rtn1}(1 - Ai) \qquad (26)$$

The total probability of failure of load point $\boldsymbol{Lp_1}$is as follows:

$$\boldsymbol{P_1 = \bar{A}_{DGm}\Big[\Big\{\prod_{i\in Rt4} Ai \Big(\sum_{i\in Rt2}(1 - Ai)\prod_{\substack{j\in Rt2\\ j\neq i}} Aj\Big) + \prod_{i\in Rt2} Ai \Big(\sum_{i\in Rt4}(1 - Ai)\prod_{\substack{j\in Rt4\\ j\neq i}} Aj\Big)\Big\}\Big(\sum_{i\in Rt3}(1 - Ai)j\in Rt3j\neq iAj\Big)\Big] + A_{DGm}\,[i\in Rt2Ai\,(\,i\in Rt4(1-Ai)j\in Rt4j\neq iAj)(\,i\in Rt3(1-Ai)j\in Rt3j\neq iAj)] + \sum_{i\in Rtn1}(1 - Ai)} \qquad (27)$$

Where:
$\boldsymbol{Rt_3}$ **:** are represents the components of route between first source and load point ***m***.
$\boldsymbol{Rt_4}$ **:** are represents the components of route between load point ***m*** and distributed generation (DG).
$\boldsymbol{Rt_{n1}}$ **:** are represents the components of route if radial elements are connected to a load point ***m*** of a ring system.

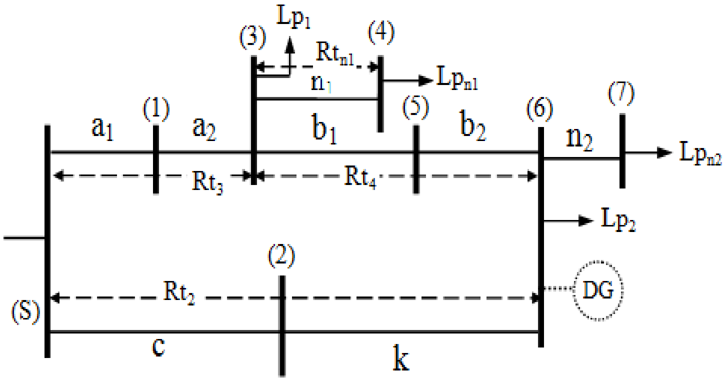

Fig.6. Shows Routs of Load Point Lp_1 (Rt_3 ,Rt_4 & Rt_{n1}).

IV. NUMERICAL EXAMPLE

The same data given in reference[16]is used in this study. Fig.7 shows a ring distribution system consisting of nine line segments. The rate of failure, repair time of failure and availability for each segment as well as for distribution transformers are listed in table II.

The distributed generation data are assumed as follows:

DG_2 at bus 2:

Capacity =10 MVA

Availability A_{DG2} = 0.96

λ_{DG2} = 0.4/year

μ_{DG2} = 9.6/year

DG_8 at bus 8:

Capacity =11 MVA

Availability A_{DG8} = 0.96

λ_{DG8} = 0.4/year

μ_{DG8} = 9.6/year

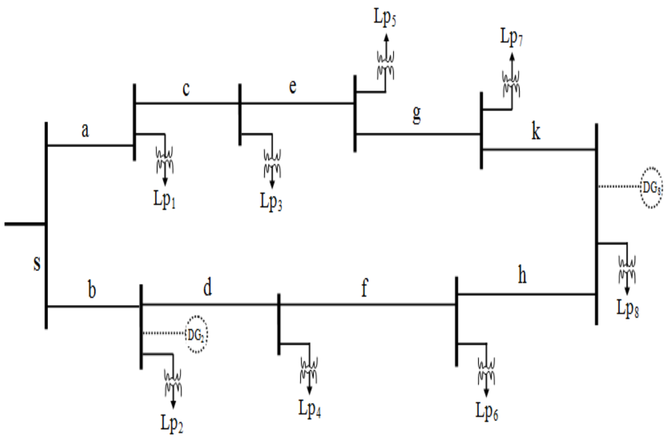

Fig.7. A Ring Distribution System.

TABLE II: RATE OF FAILURE " λ", REPAIR TIME"r " AND "A"OF LINE SEGMENTS AND DISTRIBUTION TRANSFORMERS FOR THE RING DISTRIBUTION SYSTEM SHOWN IN FIG.7.

Component	***λ (1/yr)***	***r (hr)***	***λ × r (hr/yr)***	***Availability***
a	0.5	2	1	0.9998854
b	0.6	3	1.8	0.9997946
c	0.6	3	1.8	0.9997946
d	0.65	3.5	2.275	0.9997403
e	0.7	4	2.8	0.9996805
f	0.75	4	3	0.9996577
g	0.8	5	4	0.9995436
h	0.8	5	4	0.9995436
k	0.8	5	4	0.9995436
Distribution transformers (DT) at load busses	0.05	6	0.3	0.9999658

E. The System without Distributed Generation

The frequency of failure "F_m", the average annual outage time "U_m" and the average outage time "T_m" of load points of the ring distribution system have been calculated using equations (1),(2) ,(3) and table I . Results are listed in table.III plus the number of customers "***Nm***" at load points.

TABLE III: VALUES OF N_m, F_m AND U_m OF LOAD POINTS OF RING DISTRIBUTION SYSTEM SHOWN IN FIG.7 WITHOUT[DG]

Load Points	*Number of Customers "Nm"*	*Frequency of Failure "F_m" (1/yr)*	*Average Annual Outage Time "U_m" (hr/yr)*	*Average Outage Time " T_m" (hr)*
Lp_1	1000	0.733057	1.222103	1.667132
Lp_2	2000	0.977167	1.903700	1.948184
Lp_3	2400	1.543379	2.685589	1.740071
Lp_4	800	1.838559	3.569523	1.941479
Lp_5	900	2.346981	4.460467	1.900512
Lp_6	2500	2.578335	5.149854	1.997356
Lp_7	600	2.922639	5.936611	2.031251
Lp_8	700	2.999757	6.166407	2.055636
$\sum Nm = 10900$				

Values of "$N_m \times F_m$" and "$N_m \times U_m$" are listed in table IV. These values are needed for the calculation of reliability indices of the ring distribution system of fig.7.

TABLE IV: VALUES OF "$N_m \times F_m$" AND "$N_m \times U_m$" OF LOAD POINTS OF THE RING DISTRIBUTION SYSTEM IN FIG.7, ASSUMING [DG] DOES NOT EXIST.

Load Points	$N_m \times F_m$	$N_m \times U_m$
Lp_1	733.0570	1222.1030
Lp_2	1954.3340	3807.4000
Lp_3	3704.1096	6445.4136
Lp_4	1470.8472	2855.6184
Lp_5	2112.2829	4014.4203
Lp_6	6445.8375	12874.6350
Lp_7	1753.5834	3561.9666
Lp_8	2099.8299	4316.4849
	$\sum(Nm \times Fm)$ = 20273.8815	$\sum(Nm \times Um)$ = 39098.0418

The reliability indices can be calculated as follows:

SAIFI=$\frac{\sum(Nm \times Fm)}{\sum Nm}=\frac{20273.8815}{10900}$=1.8600(interruptions/customer)

SAIDI=$\frac{\sum(Nm \times Um)}{\sum Nm}=\frac{39098.0418}{10900}$= 3.5870(hours/year /customer)

CAIDI=$\frac{SAIDI}{SAIFI}=\frac{3.5870}{1.8600}$= 1.9285 (hours/customer interruption)

- Value of **SAIFI** describes number of interruptions per year of each customer connected to ring distribution system, its value is acceptable compared to general standard of IEEE and some studies (Ref 12, 17, 16, 18, 15, 19, and 20).
- Value of **SAIDI** describes duration of interruptions per year of each customer connected to ring distribution system; its value is high compared to general standard of IEEE and some studies (Ref 12, 17, 16, 18, 15, 19, and 20).
- Value of **CAIDI** describes time required to restore service to each customer per interruption connected to ring distribution system, its value is high compared to general standard of IEEE and some studies (Ref 12, 17, 16, 18, 15, 19, and 20).

Fig.8. displays Simulation of values of Reliability Indices of Ring Distribution System without DG.

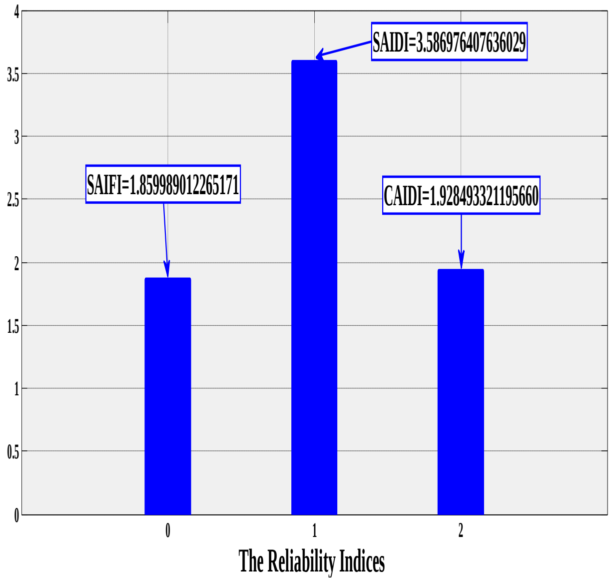

Fig.8. Simulation of Values of Reliability Indices of Distribution System without DG

F. The System with Distributed Generation

It is assumed that DG_2 can supply load points, Lp_2 and Lp_4 and that DG_8 can supply load points Lp_1, Lp_3, Lp_5, Lp_6, Lp_7 and Lp_8 with their average loads at permissible voltage levels.

Table V shows the components consists the routes to both the sources buses and the corresponding distributed generation. This table is prepared to simplify the calculation of the different parts of equations (13), (18), (22) and (27).

TABLE V: THE ROUTES BETWEEN THE LOAD POINTS AND BOTH THE SOURCES BUSES (I&II) AND THE DISTRIBUTED GENERATION [DG].

Load Points	*Substation "I"*	*Substation "II"*	DG_2	DG_8
Lp_1	a &DT	b, d, f, h, k, g, e, c &DT	−	k, g, e, c &DT
Lp_2	a, c, e, g, k, h, f, d & DT	b &DT	DG	−
Lp_3	a, c & DT	b, d, f, h, k, g, e & DT	−	k, g, e &DT
Lp_4	a, c, e, g, k, h, f & DT	b, d & DT	d & DT	−
Lp_5	a, c, e &DT	b, d, f, h, k, g &DT	−	k, g &DT
Lp_6	a, c, e, g, k, h &DT	b, d, f & DT	−	h & DT
Lp_7	a, c, e, g & DT	b, d, f, h, k & DT	−	k & DT
Lp_8	a, c, e, g, k & DT	b, d, f, h & DT	−	DG

The Frequency of Failure "F_m", The Probability of Failure "P_m", The Average Annual Outage Time "U_m" and The Average Outage Time "T_m" of load points of the ring distribution system have been calculated using equations (1) (2) (3) (13) (18) (22) and (27) .

TABLE VI: VALUES OF F_m, P_m, U_m AND T_m OF LOAD POINTS OF THE RING DISTRIBUTION SYSTEM SHOWN IN FIG.7. WITH [DG].

Load Points	*Frequency of Failure "F_m" (1/yr)*	*Probability of Failure "P_m"*	*Average Annual Outage Time "U_m" (hr/yr)*	*Average Outage Time "T_m" (hr)*
Lp_1	1.28991×10^{-3}	2.26058×10^{-7}	1.98298×10^{-3}	1.53730
Lp_2	0.10863×10^{-3}	0.21412×10^{-7}	0.18782×10^{-3}	1.72904
Lp_3	2.38118×10^{-3}	4.65567×10^{-7}	4.08396×10^{-3}	1.71510
Lp_4	3.34330×10^{-3}	7.43888×10^{-7}	6.52539×10^{-3}	1.95178
Lp_5	3.02597×10^{-3}	6.70845×10^{-7}	5.88465×10^{-3}	1.94472
Lp_6	5.95054×10^{-3}	13.6267×10^{-7}	11.9533×10^{-3}	2.00878
Lp_7	2.51545×10^{-3}	6.10248×10^{-7}	5.35310×10^{-3}	2.12809
Lp_8	0.34568×10^{-3}	0.78328×10^{-7}	0.68709×10^{-3}	1.98764

Comparing results of tabels III,VI and Fig.9 show that T_m is reduced to a high extent when distributed generation connection to distribution system this can DG_2 and DG_8.

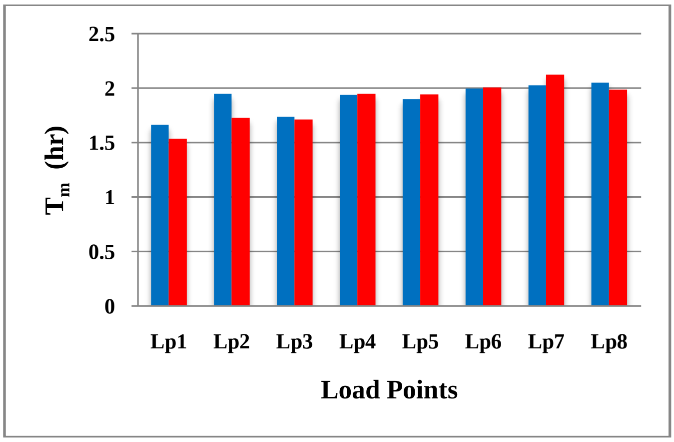

Fig.9. Comparison the Results of the Average Outage Time of Load Points between without DG and with DG.

$N_m \times F_m$ and $N_m \times U_m$ are computed and listed in table VII to be used in calculating the reliability indices of the ring distribution system with distributed generation.

TABLE VII: VALUES OF $N_m \times F_m$ AND $N_m \times U_m$ FOR LOAD POINTS OF FIG.7.

Load Points	$N_m \times F_m$	$N_m \times U_m$
Lp_1	1.289912	1.982979
Lp_2	0.217258	0.375648
Lp_3	5.714830	9.801494
Lp_4	2.674636	5.220311
Lp_5	2.723374	5.296189
Lp_6	14.876337	29.883340
Lp_7	1.509267	3.211857
Lp_8	0.241979	0.480966
	$\sum$(**Nm × Fm**)= 29.247593	$\sum$ (**Nm × Um**) = 56.252785

From the above tables, the following the reliability indices can be calculated :

$$SAIFI=\frac{\sum(\mathbf{Nm\times Fm})}{\sum Nm}=\frac{29.247593}{10900}=0.002683(\text{interruptions/customer})$$

$$SAIDI=\frac{\sum(\mathbf{Nm\times Um})}{\sum Nm}=\frac{56.252785}{10900}=0.005161(\text{hours/year/customer})$$

$$CAIDI=\frac{SAIDI}{SAIFI}=\frac{0.005161}{0.002683}=1.923330(\text{hours/customer interruption})$$

- Number of interruptions during year of each customer connected to ring distribution system described by value **SAIFI** is very low compared to general standard of IEEE and some studies (Ref 8, 16, 17, 21, 22, 23 and 24).
- Duration of interruptions during year of each customer connected to ring distribution system described by value **SAIDI** is very low compared to general standard of IEEE and some studies (Ref 8, 16, 17, 21, 22, 23 and 24).
- Time required to restore service to each customer per interruption is connected to ring distribution system described by value **CAIDI** is low compared to general standard of IEEE and some studies (Ref 8, 16, 17, 21, 22, 23 and 24).

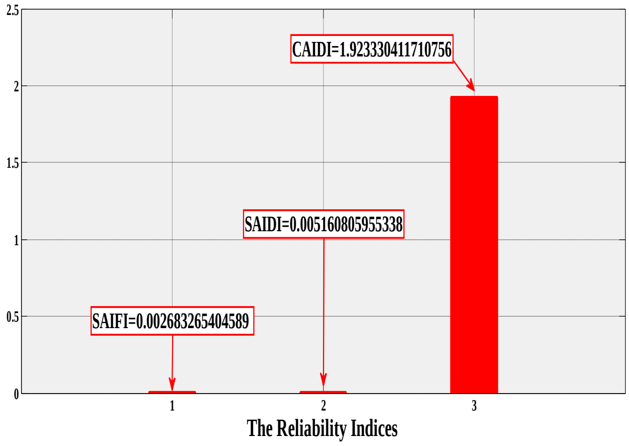

Fig.10. Simulation of Values of Reliability Indices of Distribution System with DG

G. Comparison the Results between System without DG and System with DG

Reliability indices for the system without and with distributed generation are given in table VIII and fig.11 had shown simulation of the comparison results the reliability indices for the system without and with distributed generation.

TABLE VIII: RELIABILITY INDICES FOR THE RING DISTRIBUTION SYSTEM OF FIG.7 WITHOUT AND WITH DG.

Reliability Indices	**Ring Distribution System**	
	Without DG	**With DG**
SAIFI	1.8600 (inter. / cu.)	0.0026 (inter. / cu.)
SAIDI	3.5870 (hr / yr /cu.)	0.0051 (hr / yr /cu.)
CAIDI	1.9285 (hr/cu. inter.)	1.9233 (hr/cu. inter.)

The reliability indices SAIFI, SAIDI and CAIDI for a ring distribution system with distributed generation are improved by factors ranging from 0.002 to 1.9 times those of the system without distributed generation.

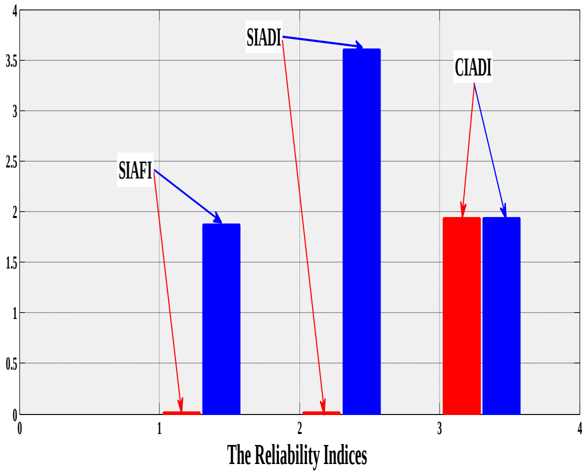

Fig.11. Simulation of the Comparison Results the Reliability Indices for the Ring Distribution System without and with DG.

V. CONCLUSIONS

Distribution system reliability receives more attention nowadays due to the wide use of electric energy in industrial, commercial and residential applications. In this work equations are derived to calculate the reliability indices of ring distribution systems equipped without and with distributed generation assuming perfect switching. The derived equations and the developed methodology and tables can be applied to any ring distribution system with many distributed generation locations.

A numerical example is presented for a ring distribution system, with and without distributed generation. Comparing the results of the reliability indices are shown in table VIII and fig.11. The following can be concluded:

- Average outage time "T_m" of load points improves to a great extent when they are supplied by distributed generation (see table VI and fig.9).
- The frequency of failure "F_m", probability of failure "P_m" and average annual outage time "U_m" of load points improve to a great extent when distributed generation are connected to distribution system as shown in table VI.
- The reliability indices (***SAIFI***, ***SAIDI*** and ***CAIDI***) of ring distribution systems improves when DG are connected to it, as follows:

Number of interruptions per year of each customer connected to ring distribution system improves from 1.860 to 0.0026.Duration of interruptions per year of each customer connected to ring distribution system improves from 3.5870 to 0.0051. Time required to restore service to each customer per interruption connected to ring distribution system improves from 1.9285 to 1.9233.

The Comparison results of reliability indices between the ring distribution system and radial distribution system (see in reference [6]) without and with distributed generation shown in table IX.

TABLE IX: THE RELIABILITY INDICES FOR RING AND RADIAL DISTRIBUTION SYSTEMS WITHOUT AND WITH DG

Reliability Indices	Without DG		With DG	
	Radial Distribution System	Ring Distribution System	Radial Distribution System	Ring Distribution System
SAIFI	1.624	1.860	0.360	0.0026
SAIDI	5.160	3.587	1.475	0.0051
CAIDI	3.180	1.929	4.08	1.923

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