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Evaluation and Enhancement of Reliability of Electrical Distribution System in the presence of Dispersed Generation

S. Jayalakshmi[a] V. Balaji[b] and S. Subramanya Sarma[c]

[a]Research Scholor, SCSVMV University Kanchipuram
E-mail: jayasriram23@gmail.com
[b]Principal, Saptagiri College Of Engineering Dharmapuri
[c]Research Scholor, Jnt University Anantapur
E-mail: sssarma.eee@gmail.com

Abstract : The distribution system is part of the electric power system that links the bulk transmission system and the individual customers. Modern Power systems are smart, interconnected, interdependent, load sharing and phased mission systems. Reliability of such complex power systems is very important in design, planning, installation and maintenance to provide electrical energy as economical as possible with an acceptable degree of reliability. In this paper, an analytical methodology for reliability evaluation and enhancement of electrical distribution systems is described and further an innovative cost effect index to improve the reliability of power systems is developed. The developed algorithm has been implemented on a sample distribution system, where distribution system reliability indices are calculated for an existing system without Dispersed Generation (DG) and compared to those calculated for the same system with some DG units running in parallel with the system. The results demonstrate that DG does improve the reliability of the distribution system.

Keywords : *Reliability Evaluation, Dispersed Generation, Reliability indeces, Failure and Repair rates, Gas Turbine*

1. INTRODUCTION

A distribution system links the bulk electric system to the customers whcih include sub-transmission lines, distribution substations, primary and secondary feeders, lateral distributors, distribution transformers, protection and sectionalizing equipments and secondary circuits related to supplying power to the customers. Most low voltage distribution systems are radial in nature because of their low cost and simple design. A radial system consists of a series of components between the substation and the load points. Failure of any of these components may result in outage at the load point.

Distribution systems were not originally designed to accommodate generation in itself. Hence increasing penetration level of DG is causing changes in the planning, operation and maintenance of distribution systems. Presence of DG in a distribution network affects network planning, operation and maintenance, auxiliary services, quality of service and regulatory aspects [1–4]. Ackerman et al. [5] have analyzed the term DG in detail. Usually in reference to this present paper, DG was considered as electricity generation systems connected to distribution networks, characterized by their small rating and located near connection points. Distribution system operators (DSOs) may have their own DG or may encourage large consumer to install DG which is owned and controlled by these customers. Availability of such customer owned and controlled DG may not be high, but may be of great help in improving the reliability indices of the distribution network.

The reliability of a distribution system may be increased by modifying failure rate and repair time of each section of the network. Such modifications may require additional investments which in the presence of DG may be mitigated. This will result in annual savings. The saturation of the existing networks and the continuous growth of the demand is encouraging DG to become a major source of electric energy in distribution systems.

2. DG AND ITS IMPACTS ON DISTRIBUTION SYSTEM AND RELIABILITY

Distributed generation units (also called decentralized generation, dispersed generation, and embedded generation) are small generating plants connected directly to the distribution network or on the customer site of the meter. In the last decade, the penetration of renewable and nonrenewable distributed generation (DG) resources is increasing worldwide encouraged by national and international policies aiming to increase the share of renewable energy sources and highly efficient micro-combined heat and power units in order to reduce greenhouse gas emissions and alleviate global warming.

The introduction of DG to distribution system can significantly impact the flow of power and voltage conditions at customers and utility equipment. These impacts may be either positively or negatively depending on the distribution system operating characteristics and the DG characteristics.

Positive impacts are generally called “system support benefits,” and include:

1. Power loss reduction
2. Improved utility system reliability
3. Voltage support and improved power quality
4. Transmission and distribution capacity release
5. Deferments of new or upgraded transmission and distribution infrastructure.
6. Easy and quicker installation on account of prefabricated standardized components.
7. Lowering of cost by avoiding long distance high voltage transmission.
8. Environment friendly where renewable sources are used.

Reliability assessment of distribution system is usually concerned with the system performance at the customer end, *i.e*. at the load points. The basic indices used to predict the reliability of a distribution system are: average load point failure rate, average load point outage duration and average annual load point outage time or annual unavailability. The basic indices are important from an individual customer point of view and also utility point of view. However they do not provide an overall performance of the system. An additional set of indices can be calculated using these three basic indices and the number of customers/load connected at each load point in the system. Most of these additional indices are weighted averages of the basic load point indices. The most common additional or system indices are; SAIFI, SAIDI, CAIFI, CAIDI, ASAI, ASUI, ENS and AENS. These indices are also calculated by a large number of utilities from system interruption data and provide valuable indications of historic system performance.

The paper mainly focuses on analyzing and evaluating the reliability in order to improve the reliability of power system but not for analyzing in terms of the interruption cost in case of power failure. A detailed performance analysis has been carried out on IEEE 33-bus and IEEE 69-bus radial distribution networks to demonstrate the effectiveness of the optimal DG placement on system voltage profile and branch power losses and various Reliability indices were calculated by analytical method which determines reliability of the system.

3. PROBLEM FORMULATION

3.1. Distribution System Reliability Analysis

Reliability indices of a distribution system are functions of component failures, repairs and restoration times which are random by nature. As factors are random in nature, reliability indices are also random in nature.

The predictive reliability assessment of distribution systems requires the evaluation of two groups of indices namely, load point indices and system performance indices. 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 or average annual unavailability (U hr/year). Analytically, these indices are calculated using the following equations:

$$\lambda_s = E\lambda_i \tag{1}$$

$$r_s = \frac{\sum \lambda_i r_i}{\sum \lambda_i} \tag{2}$$

$$U_s = \lambda_s r_s \tag{3}$$

Where i is the number of feeder sections (main or laterals) connecting the load point to the supply and s is the name of this load point. The most common system indices are

System Average Interruption Frequency Index (SAIFI) : The average number of interruptions per customer served per year.

$$\text{SAIFI} = \frac{\text{Total Number of Customer Interruptions}}{\text{Total number of customers served}} = \frac{\sum \lambda_i N_i}{\sum N_i}$$

System Average Interruption Duration Index (SAIDI) : The average interruption duration per customer served per year.

$$\text{SAIDI} = \frac{\text{Sum of Customer Interruption Durations}}{\text{Total number of customers}} = \frac{\sum U_i N_i}{\sum N_i}$$

Expected Interruption cost (ECOST): ECOST is a comprehensive value based reliability index and is used for this study

$$\text{ECOST} = \sum_{i=1}^{n} L_i C_i \lambda_i$$

Average Energy Not Supplied (AENS): The average energynot supplied per customer served per year.

$$\text{ANES} = \frac{\text{Total Energy not supplied}}{\text{Total number of customers}} = \frac{\sum U_i L_i}{\sum N_i}$$

Where λ_i is the failure rate (fails/year)

N_i is the number of customers of load point i

U_i is the annual outage time

L_i is the average load connected to load point i

C_i is the cost of interruption (Rs/KW) for the i^{th} bus

n is the number of load points in the feeder

C_i is evaluated using Composite Customer Damage Function (CCDF) and. CCDF shows the cost of interruption as a function of interruption duration.

3.2. Objective Function

The selection of the best places for installation and preferable size of DG unit bank is a complex discrete optimization problem. The first step in an optimization procedure is to define the objective function. The impact of implementing renewable distributed generation, storage systems, and conventional generation on the reliability of distribution network is studied in this work. To evaluate the reliability of distribution networks containing Photo Voltaic (PV) and Wind Turbine (WT) generations, stochastic models have to be built to deal with the uncertainty of these resources.

3.3. Load Flow Analysis

Distribution systems are fed at one point and have a radial structure. Due to its low memory requirements, computational efficiency and robust convergence characteristic, the load flow is computed by Forward-Backward Sweep method [10] applied to radial distribution networks.

3.4. Distributed Generation Models

In this study, the reliability of distribution system containing renewable resources such as wind and solar energy was assessed. It is well known that due to the fact that solar insolation and wind speeds are both intermittent, the output powers of PV and WT systems are not deterministic. That brings up the need for a stochastic model to simulate PV and WT outputs. The stochastic model is a simulation-based technique to describe a non-deterministic behavior and the randomness of the system. The probability distribution, therefore, can be used to predict the output power of PV and WT. In order to find statistical data of the wind speed and solar insolation, meteorological data of a variety of weather conditions at one location must be measured. In this study, the distribution system contains distributed gas turbines (DGT's). The output power of the DGT's is modeled. The storage systems is needed to decrease the peak load since the peak of the output power of the PV's and the peak load do not occur at the same time in most load profiles.

Various DG models considered for this work

1. Photo Voltaic based Renewable Energy DG
2. Wind Turbine based Renewable Energy DG
3. Gas Turbine based Distributed Generation

3.5. Load Model

Weather conditions and seasonal events affect the load. Fortunately, most of these events take place at the same time annually. Therefore, the behavior of power system loads is a frequent pattern during normal conditions. A time varying load model can be developed by using historical data. Monthly and hourly weight factor data are used to construct a load model. To find the predicted load for load point at any desired instant of time $P_i(t)$ is used.

$$P_i(t) = w_h(h) * w_m(m) * P_L(i)$$

Where

$w_h(h)$ is hourly weight factor

$w_m(m)$ is monthly weight factor

$P_L(i)$ is peak load for load point

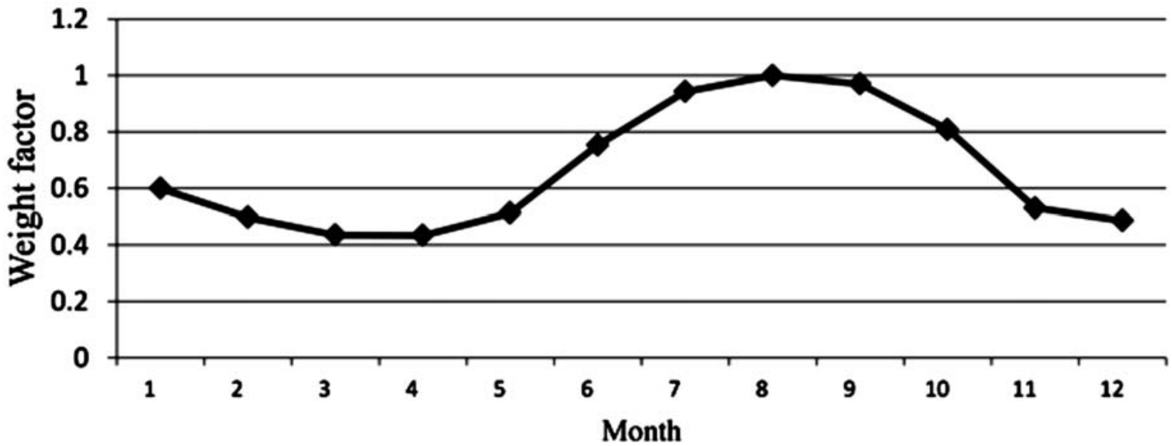

Figure 1: Monthly weight factor for Load modeling

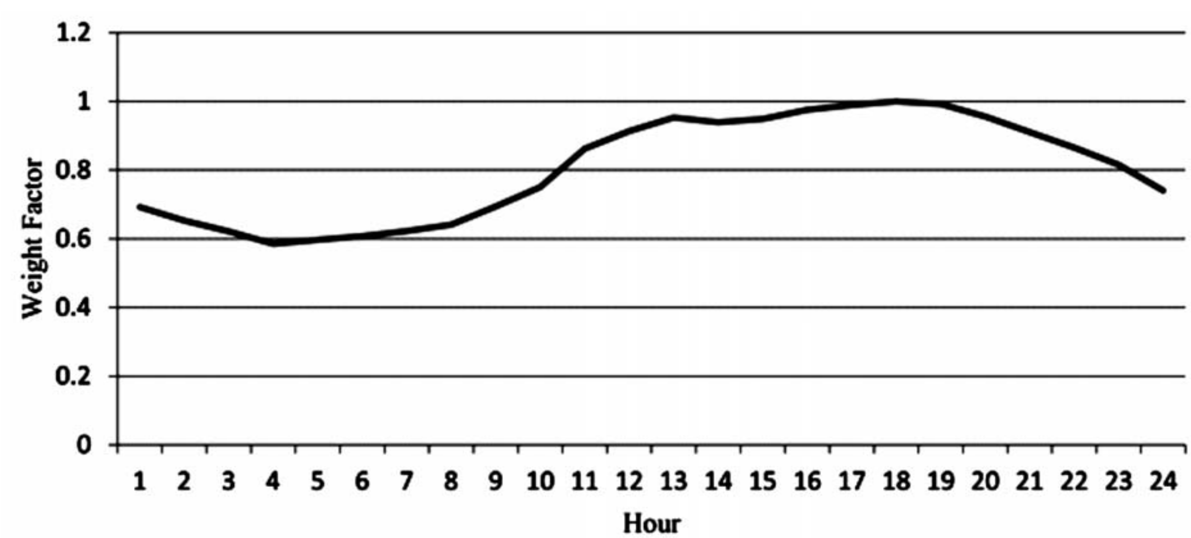

Figure 2: Hourly weight factor for Load modeling

4. SIMULATION ALGORITHM

This work describes algorithm to evaluate reliability of a distribution network that does not contain DGs, and for a distribution network containing DGs. The results from the algorithm give a clear vision of how DGs can impact the reliability. Load Flow is performed on RBTS Bus 2 system with developed stochastic DG models to simulate the uncertainty of these resources. The algorithm proposed in this work has been developed in MATLAB environment.

Since the main purpose of this study is to evaluate the reliability of distribution systems containing DGs, the following assumptions were made which should not have a significant effect on the results:

1. Only primary main feeder failures are included in the analysis.
2. Only permanent faults are included in the study.
3. All protection devices operate successfully to isolate faults.
4. Each section is protected by a breaker to isolate faults.
5. It takes 1 hr to transfer loads from the failed feeder to a neighboring feeder through a normal operating point.
6. Each circuit breaker is controlled by a bi-directional protection device.

The following steps are the simulation procedures of reliability evaluation of distribution networks containing DGs:

1. Generate the time to failure for each distribution component using Equations.
2. Generate the operating / repair history for each distributed generator using Equations.
3. Check the time to failure of each component of distribution system is less than 8760 hr, if no one go to step 1.
4. Select the distribution component that has the least time to failure.
5. Find the affected load points connected to the failed feeder, and divide it to two groups. First group, load points can be restored. Second group, load points cannot be restored.
6. Generate the time to repair and determine interruption energy for group one.
7. Determine the total power of distributed generator that connected to failed feeder by using DG model feeder, and determine the total load of group 2.
8. If total power generation is greater than or equal the total load of group 2, go to step 10.
9. Generate the time to repair and determine interruption energy for group one.
10. Find the distribution component that has next smallest time to failure. If it is less than 8670, go to step 5 or go to next step if not.
11. Repeat steps 1-10 until reached the maximum number of cases
12. Determine SAIFI, SAIDI, and EENS by using the Equations.

5. RESULTS AND DISCUSSION

Many distribution network reliability studies reported in the literature have used the RBTS Bus 2 or Bus 4. These networks offer the information needed to conduct a reliability study. The system of RBTS Bus 2 without having DG units is shown in Figure 3. The system of RBTS Bus 2 with having DG units is shown in Figure 4.

Table 1
Feeder Lengths Data

Feeder Length in km	*Feeder section numbers*
0.6	4, 6, 9, 14, 15, 18, 24, 29, 31, 32
0.75	1, 2, 3, 5, 7, 10, 12, 13, 20, 25, 27, 30, 35
0.8	8, 11, 16, 17, 19, 21, 22, 23, 26, 28, 33, 34, 36

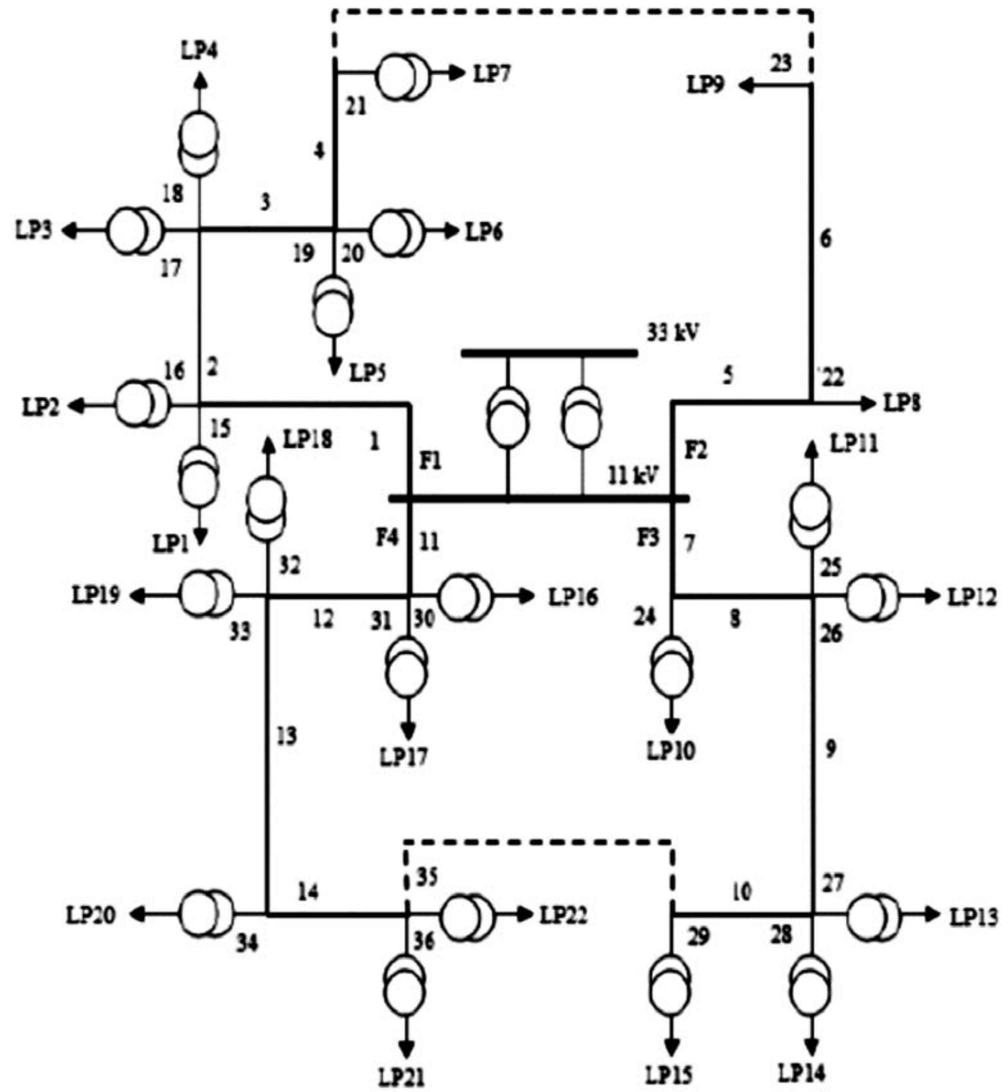

Figure 3: Distribution network for RBTS bus 2 without DGs

Table 2
Load Points Data

Load Point	*Peak Load (MW)*	*No. of customers per load point*
1, 2, 3,10,11,4,5	0.8668	210
13,14,20,21	0.5660	1
6,7,15,16,22	0.4540	10
8	1.0000	1
9	1.1500	1
12,17,18,19	0.4500	200

Table 3
Reliability Indices of Distribution Elements

Element	*Failure rate λ*	*Repair time r*
Transformers (11/0.415 kV)	0.015 (f/yr)	10 hr
Lines (11kV)	0.0650 (f/yr*km)	5 hr

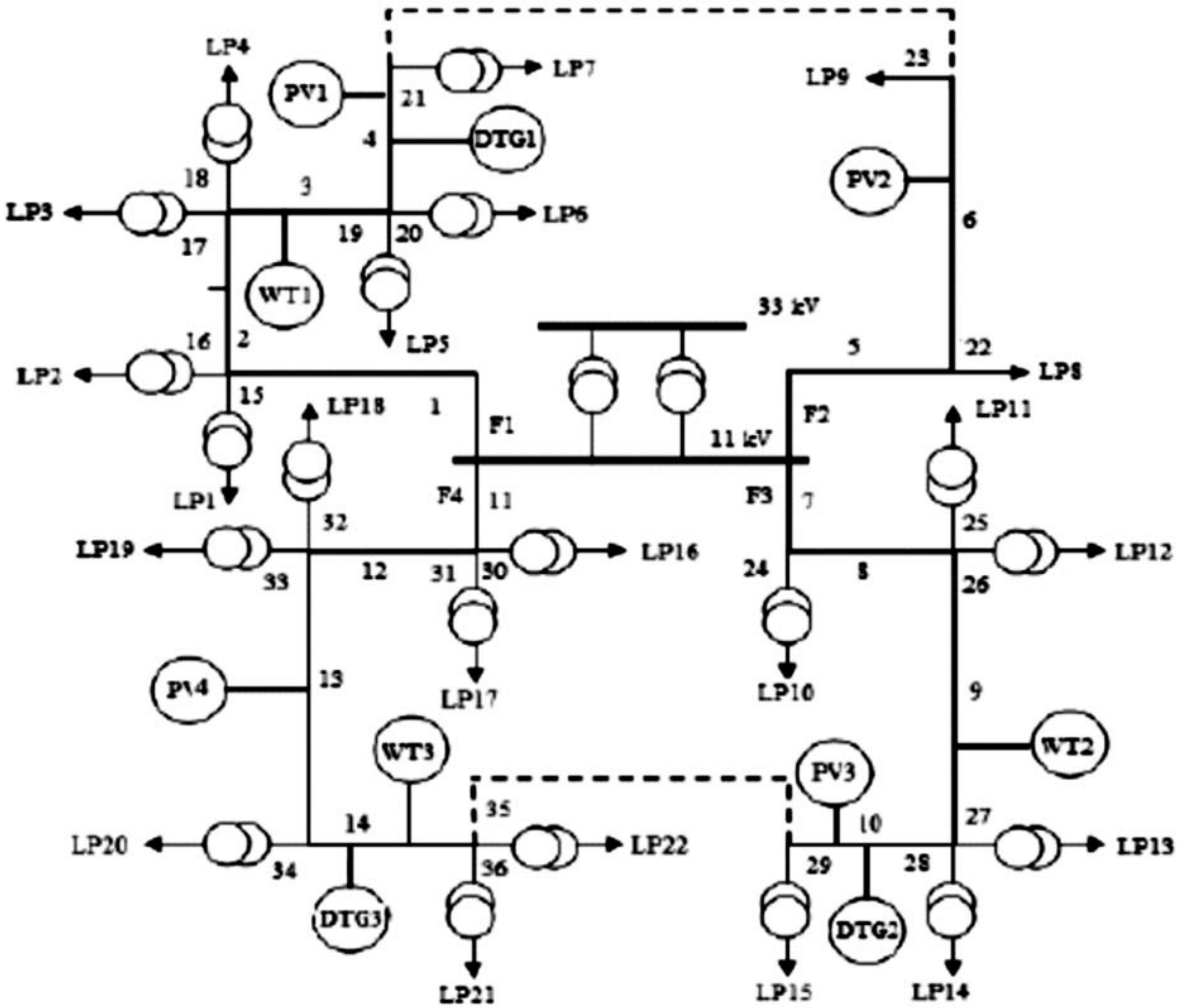

Figure 4: Distribution network for RBTS bus 2 with DGs

The maximum output power of each PV plant is 1.5 MW. The failure rate and average repair time of PV generators are taken to be 0.1 f/yr and 20 h, respectively. The capacity of the storage system is 0.7 MWh and the converter is rated at 0.3 MW. The maximum output power of each WT is 2 MW. The failure rate and average repair time of WT's are 0.25 f/yr and 20 h, respectively . The rated power of each gas generators is 2 MW. The failure rates and average repair time of the DGTs are 0.25 f/yr and 8 h respectively. The solar insolation data is given in Table 4. The wind velocity and wind turbine data are given in Table 5. The PV efficiency and K_C and are assumed to be 0.1 and 0.2 respectively.

Table 4
The Monthly Light Intensity (kWh/day/m^2)

Month	*Intensity*	*Month*	*Intensity*
January	5.92	July	11.23
February	7.16	August	10.50
March	8.78	September	9.22
April	10.23	October	7.59
May	11.11	November	6.17
June	11.42	December	5.52

Table 5
The Wind Velocity and Wind Turbine Data (m/s)

Wind Velocity	*Standard Deviation*	*Cut in Velocity*	*Rated Velocity*	*Cut Off Velocity*
4.05	2.7	2.5	10.55	22.22

The modified RBTS Bus 2 has four micro grids. Micro grid 1 contains feeder 1 and is supplied by PV1, WT1, and DGT1. Micro grid 2 contains feeder 2 and is supplied by PV2. Micro grid 3 contains feeder 3 and is supplied by PV3, WT2, and DGT2. Micro grid 4 contains feeder 4 and is supplied by PV4, WT3, and DGT3. If there is enough power generation to supply the feeder loads during a permanent fault, the micro grids can operate in islanded mode.

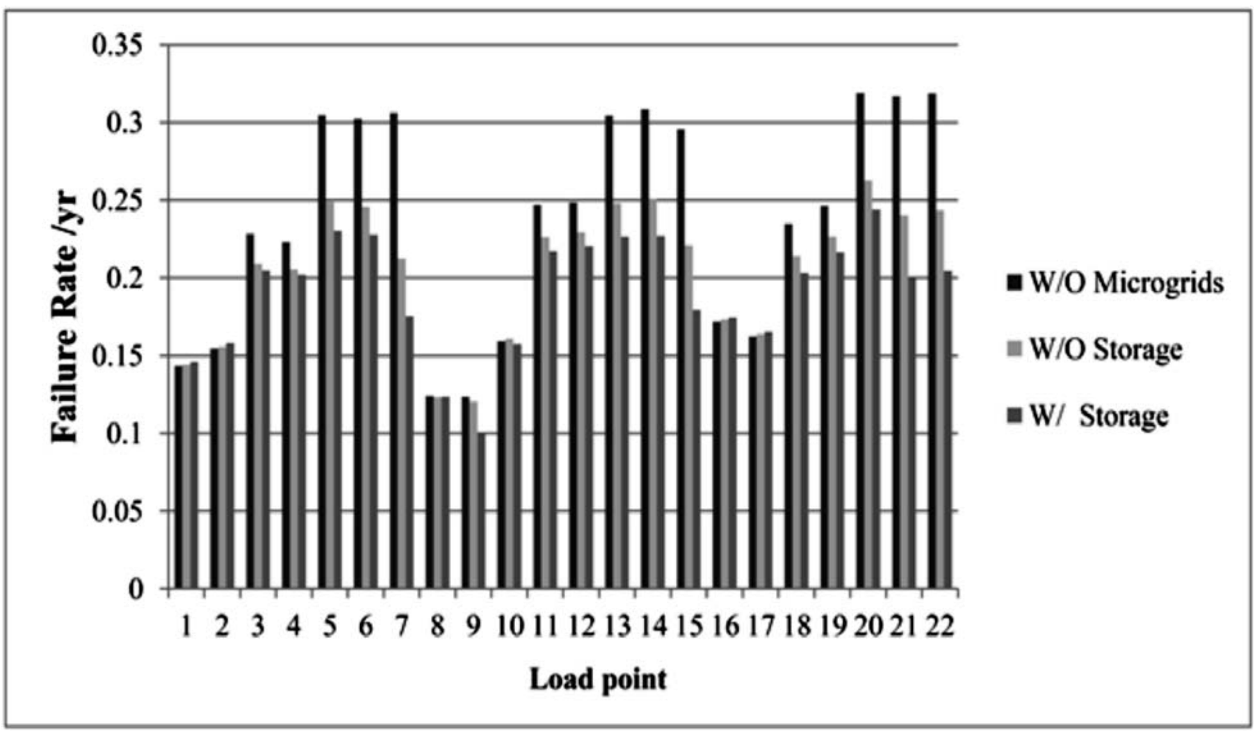

Figure 5: Failure rate of all load points

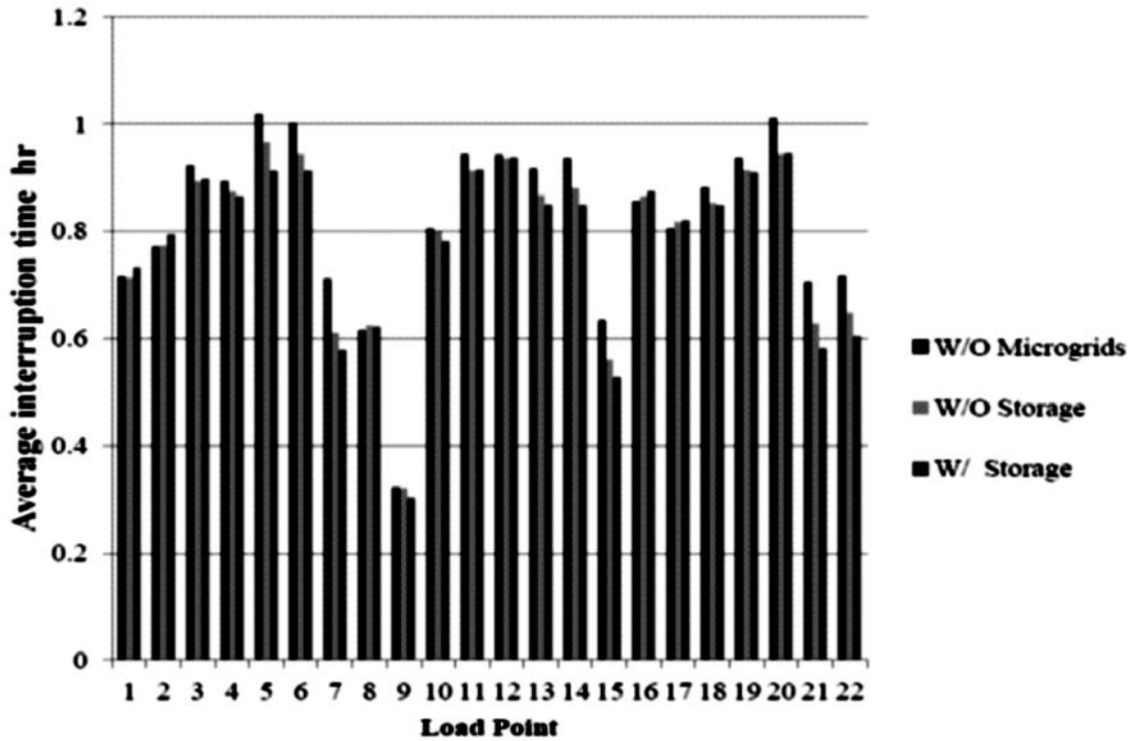

Figure 6: Average interruption time of all load points

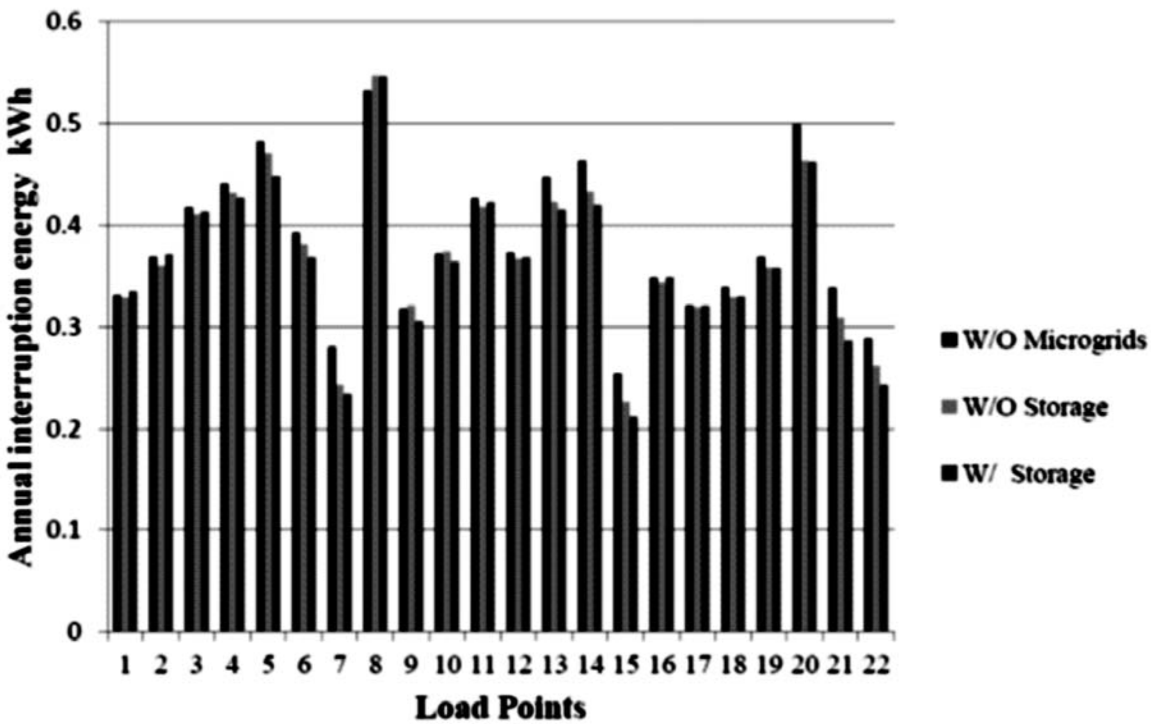

Figure 7: Average interruption energy of all load points

Table 6
Reliability indices of Tested Distribution system

Reliability index	*CASE 1 With out DGs*	*CASE 2 With DGs*	*CASE 3 With DGs & Storage*
SAIFI (/yr)	0.2094	0.1934	0.1875
SAIDI (hr/yr)	0.8631	0.8512	0.8449
AENS (Mwh/yr)	8.3998	8.1945	7.9987

From the above results, the implementation of DG's in distribution networks can improve the reliability of distribution networks by offering a back up source when the main source is not available. It is observed that the overall reliability indices have improved, which is shown in Table 6. Based on the observation from results, it was concluded that reliability improvement associated in the presence of micro grids not only depends on the size of the DGs but also on location and distribution of DGs. These results take into account random events and factors such as failures, variation in WT and PV output power, and the repair time.

6. CONCLUSION

The implementation of renewable resources in distribution networks is promising in many aspects such as reducing green gas emissions, improving reliability of power services and reducing the power losses on transmission networks. To accommodate these resources in the distribution network, new technologies must be adopted to deal with the complexity and intermittency of the renewable resources. Micro grids could pave the way to integrate solar energy and wind energy in distribution systems, which can deal with different modes of operation such as islanded mode and interconnected mode.

In this study, a reliability evaluation was conducted on a test distribution network. RBTS Bus2 data have been used because it offers very detailed information on each distribution component such as the failure rate and average restoration time of its circuits, transformers and breakers. Since the original RBTS Bus2 does not contain any distributed generation, the system has been modified to include PV's, WT's, and DGT's.

In order to evaluate the reliability of distribution networks containing PV and WT which are random in their output production, probabilistic techniques must be used for this task. Failures rates and average restoration times were assigned to all distributed energy resources, and these indices were taken into account in reliability assessment studies. Common indices such as SAIFI, SAIDI and AENS have been calculated to evaluate the reliability of the distribution network in three cases without DGs, with DGs and with DGs and storage system. The impact of the DGs in case of the islanded mode has been investigated. Simulation studies have shown that the implementation of DGs in the distribution system can improve the reliability. In the system with DGs case, SAIFI, SAIDI and AENS were improved by 7.64%, 1.4%, and 2.4%, respectively. In the system with DGs and storage case, SAIFI, SAIDI, and AENS were improved by 10.60%, 2.12%, and 4.76%, respectively.

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