Improvement of Reliability and Security of Electrical Power Distribution System Planning using Distribution Generator

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Abstract: *Distribution system is the most extensive part of the electrical power system, whose main function is to provide power to individual consumer premises. Due to its radial structure, the system suffers from low reliability issues thereby, exposing the system to the highest rate of interruptions. This research paper therefore, employed Distribution Generator (DG) to improve the reliability and security of the radial distribution system planning during disturbance. Forward and Backward Sweep (FBS) distribution load flow technique was performed for steady state and contingency. The reliability indices; Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy Not Supplied (EENS) and Expected Cost (ECOST) of interruptions were estimated. The DG model was incorporated in the system to improve the reliability indices. The simulation was carried out in MATLAB R2021a. The approaches were validated on standard IEEE 25-bus test system. The results showed that with application of the DG, the reliability and security of the system were improved compared with the contingency case. Thus, the approach of this research is suitable and effective for the reliability assessment of electrical distribution systems.*

Keywords: *Distribution system, Reliability, LOLP, LOLE, EENS, ECOST*

I. Introduction

Electrical distribution systems form the backbone of power delivery, bridging the gap between transmission networks and end-users [1]. However, due to their radial structure, these systems are prone to frequent disruptions, exposing consumers to unreliable power supply. Traditional methods such as Reliability Centered Maintenance (RCM) have been employed to address these issues but are limited to high costs and long implementation timelines. Distributed Generation (DG) emerges as a promising solution to enhance system reliability and mitigate the risk of outages [2, 3].

Distributed Generators (DGs) are electrical power resources that are directly connected to the power system [4]. These resources include a variety of energy sources, such as turbines, Photovoltaic's (PV), fuel cells and storage devices, with capacities in the range of 1 kW to 10 MW. Installing these recourses on distribution networks increase the network power quality, system reliability, improve the network voltage profile and reduce the network power loss [5]

The main objective of DG techniques is to transfer the load from peak hours to off peak hours. It is performed by providing the consumers incentives so that critical peak demand will be minimized [6]. The integration of DG also results in the highest loss reduction apart from providing back-up power during utility system outages for facilities requiring uninterrupted service and aids network stability in using fast response equipment for a secured distribution system [7-10]

It is based on the foregoing that this research paper employed DG to improve the reliability and security of the radial distribution system planning during disturbance.

A. Distribution system interruption

Momentary power interruptions or power outages are brief disruptions in electric service, usually lasting not longer than a few seconds. These interruptions are the result of temporary faults in the distribution of electricity [11]. Power interruption has the general consequence of throwing the electricity consumer into period of lack of electricity supply which may result in both material and economic loss. The most common causes of these interruptions are lightning strikes, fallen branches, or animals such as squirrels, coming into contact with power lines. In the past, these interruptions weren't as noticeable to consumers as they are today. However, with the use of advanced electronics, appliances can be more sensitive to the slightest variations in the power supply [12-15].

According to Elhaffar *et al* (2018) power interruption can be classified as; forced, emergent or planned interruption [11]:

i. Forced Interruption: This is primarily as a result of faulty situations in the power system which are normally initiated by electrical sensing devices called relays. It could also be as a result of over loading in a particular branch of the network which the relay is overseeing.

ii. Emergency Interruption: This is initiated by qualified personnel under emergency situations to avert any danger which may be as a result of temporary removal of load (load shedding) or as a result of poor supply from generation.

iii. Planned Interruption: This is deliberately initiated for the purpose of maintenance work on equipment or to connect new extensions to the existing ones.

B. Reliability assessment in distribution system

Reliability is one of the most important parameters to analyze the performance of the electrical distribution system [14].It also refers to the ability of power systems to perform their intended function of providing an adequate supply of electrical energy to customers efficiently with a reasonable assurance of continuity and quality**.** Managing bulk system reliability for a utility is essential and measurement of actual system reliability provides feedback to the planners on the performance of executed plans. It gives feedback to operation personnel on reliability effects of operating and maintenance practices. Thus, reliability assessment helps in system planning [13, 16-19].

One of the tools used for reliability assessment is reliability indices which reflect the adequacy of overall system supply and indicate the system behaviour and response [12].These indices in distribution system reliability evaluation can be divided into two fundamental groups. The first group contains the three basic load point indices: failure rate, outage duration, and annual outage time [17]. The second group contains the system performance indices, in which the most commonly used ones are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI) and Average Service Unavailability Index (ASUI) [20-23].

In addition, Expected Energy Not Supplied (EENS), Average Energy Not Supplied (AENS), Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE) and Expected Cost of interruptions (ECOST), respectively are for load buses that are directly connected to the bus due to the outage of the bus. However, among the different reliability parameters, this research paper considered the LOLP, LOLE, EENS and ECOST for analysis of reliability performance indices at load buses of electrical distribution system [21, 24, 25].

C. Distributed generation and its benefits

Distributed Generation (DG) is any source of electric energy of limited capacity that is directly connected to the distribution system or a sub-transmission system on the customer side. DG is one of the alternative solutions to traditional power system operation so as to meet electric energy demands. They are distributed closer to the loads throughout the power system and can be in form of mini – hydro, solar and wind system or in the form of fuel -based systems [26-28].

The DG technologies can be broadly classified as renewable energy technologies (Photovoltaic (PV) and wind turbine, hydro, geothermal, tidal and bio fuel), non-renewable energy technologies (combustion turbines and fuel cells) and storage energy. Various DGs technologies are shown in Figure 1 [18]. The renewable DG technologies especially Photovoltaic (PV) system is arguably the widely used capital-intensive renewable technology with minimum maintenance, environmentally friendly, ability for off-grid application and short time for design, installation and start up, compared to other DG technologies [2, 29, 30]

In this research paper, the renewable DG technologies are considered as a viable option due to their environmental benefits [5, 19]. In addition, interconnection of DG units into distribution system offers numerous benefits to power system. DG is considered as a least-cost planning alternative because of its integration being closer to load centre, thereby brings about reduction of distribution cost as well as saving of fuel. Furthermore the integration of DG reduces power demand from central plant, which in turn reduces the wholesale power price by supplying excess power to the grid. Furthermore, DG can be installed in small increments to meet an increase in load growth, by sizing it in small increments to supply the load requirement [20, 29, 30].

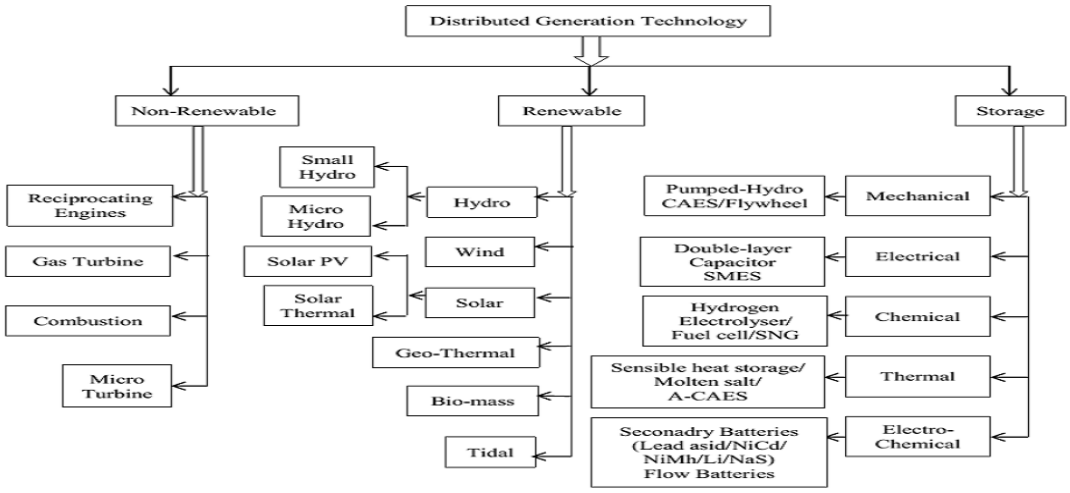

Figure 1: Distributed Generation Technologies

II. Materials and Method

The main objective function of installing DG in the distribution system is to minimize the power losses that would enhance the voltage magnitudes of the system within prescribed allowable values of ±5 %., as well as improve the system reliability indices with 20% DG penetration level. Hence, the objective function was formulated according to Equations (1) to (8) as:

$$OF = \sum_{i=1}^{N} \left(\sum \left[f_1(x), f_2(x), f_3(x) \right] \right) \tag{1}$$

$$f_1(x) = \sum_{i=1}^{N} I_i^2 R_i \tag{2}$$

$$f_2(x) = \sum_{Qi=1}^{N} V_{VCi} * V_{VPi} \tag{3}$$

$$f_3(x) = T = \sum_{t=1}^{T} (LOLP, LOLE, EENS, ECOST) \tag{4}$$

$$LOLP = \sum \left(P(Y) \times \frac{N_0}{N_t} \right) \tag{5}$$

$$LOLE = LOLP \times T \tag{6}$$

$$EENS = \sum_i \left(\sum_k L_k h_i t_i \right) \tag{7}$$

$$ECOST = \sum_i \left(\sum_k L_k h_i C_{ik}(t_i) \right) \tag{8}$$

Where; f_1 is the total active power loss of the system, f_2 is the voltage profile of the systems, f_3 is the system reliability indices, x is the variable constant, I_i is the branch current at bus i, R_i is the constant resistance of the system, V_{VCi} is the voltage violation constraint, V_{VPi} is the voltage penalty factor, N is the number of buses, N_0 is the number of occurring days of that group in observation period of 1 year and Nt is the total number of days in the observation period. $P(Y)$ is the cumulative probability of capacity outage state of Y after the unit is added,, N_o number of possible state, Y is the outage, $T = 360$ days, if the load model is an annual continuous load curve with day maximum load, and if the load model is an hourly load curve, $T = 8760$ hours,, where, t_i is the interruption time, L_k is the load, h_i is the failure rate., where, $C_{ik}(t_i)$ is the customer interruption cost with interruption duration t_i .

A. Data Source

The implementation of the approach was done on standard IEEE 25-bus power system shown in Figure 2. The test system is a circuit model used to test common features of distribution analysis software, operating at 4.16 kV. It is an unbalanced radial distribution system test feeder formed as a result of two pieces of IEEE 13- bus distribution system test feeder.

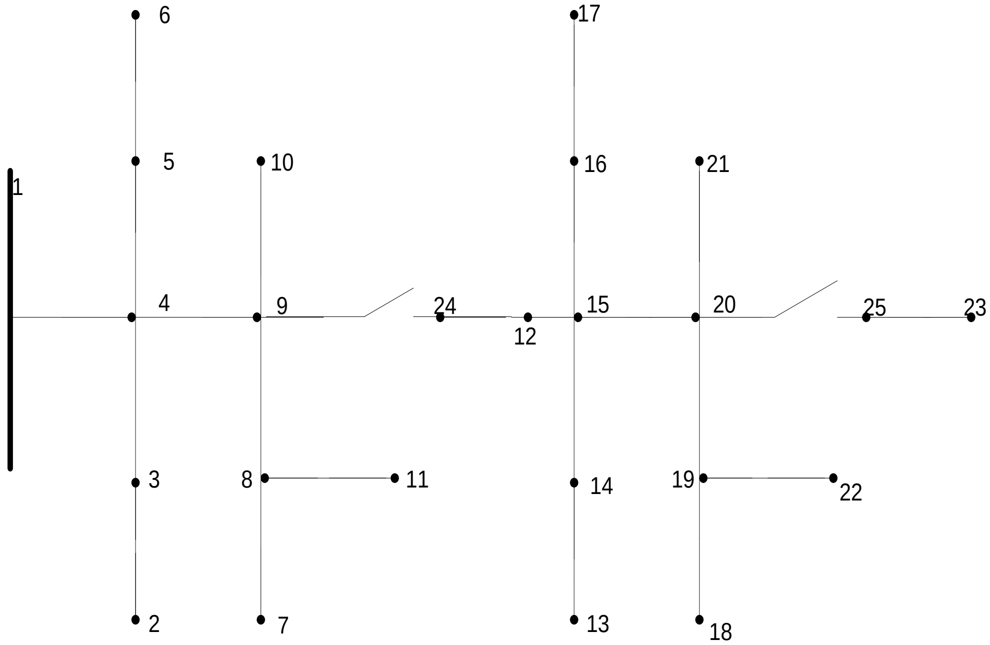

Figure 2: IEEE 25-Bus Test System

B. Load Flow for steady state and contingency

The Forward and Backward Sweep (FBS) distribution load flow analysis was performed for steady state and contingency on IEEE 25- bus system shown in Figures 2, in order to obtain the system conditions prior to the contingencies.

The Forward and Backward Sweep (FBS) distribution load flow is the most popular distribution load flow technique due to its high computational efficiency, low memory requirements and fast convergence characteristic

By considering a single line diagram of distribution network shown in Figure 3, the current and the voltage at a node in the network can be determined using Equations (9) to (14).

$$I_i^k = \frac{S_i^*}{\left(V_i^{k-1}\right)^*} \tag{9}$$

$$J_L^K = I_i^K + \sum branches\ derived\ \ from\ node\ K \tag{10}$$

$$V_i^K = V_j^K - Z_L \times J_L^K \tag{11}$$

$$S_i^K = V_i^K \left(I_i^K\right) \tag{12}$$

$$\Delta P_i^K = \mathrm{Re}\,al\left[S_i^K - S_i\right] \tag{13}$$

$$\Delta Q_i^K = imag\left[S_i^K - S_i\right] \tag{14}$$

Where; S_i^* is the given apparent load of the i^{th}node, I_i^k is the current of i^{th}node in iteration k, V_i^{k-1} is the voltage of i^{th} node in iteration k-1, L is the branch index , J_L^K is the current of L^{th} branch in iteration K , V_i and V_j are the voltages of two nodes that are connected through a branch with impedance equal to Z_L ., ΔP_i^K is active power mismatch in iteration k, ΔQ_i^K is the reactive power mismatch in iteration k, S_i is the apparent power of load.

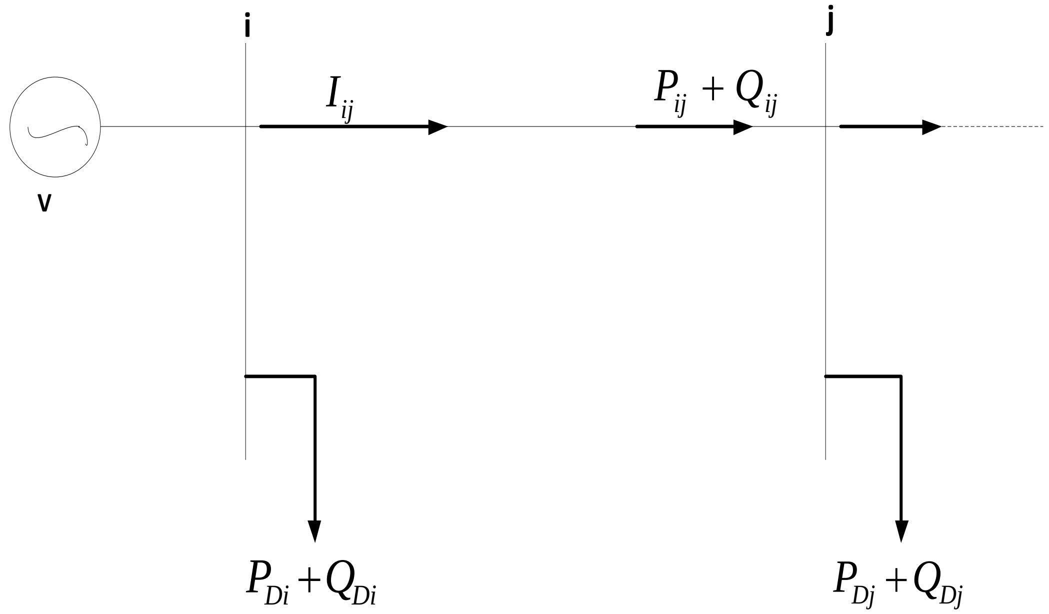

Figure 3: Single Line Diagram of Distribution Network

Then, after running the system at steady state, contingency was introduced by increasing the load on the distribution system by 20 % loading in all the load to check the stability of the system during failure of the components (generators and distribution line).Real power generation within permissible limits for slack bus and other system generation buses will be monitored. In addition, voltage violations were monitored for any bus close to the voltage rating limit of ± 5% (0.95 pu and 1.05 pu).

The simulation for FBS distribution load flow for steady state and contingency was carried out in MATLAB R2021a according to the following steps:

Step 1: System data such as distribution line, generation and load data were input;
Step 2: The FBS load flow at a given steady state operating condition of the power system was performed.
Step 3: The load on the distribution system was increased by 20 % loading in all the load buses and FBS load flow was repeated;
Step 4: The system active and reactive power were calculated, respectively;
Step 5: The system bus voltage at each iteration was calculated and updated;
Step 6: The convergence was checked for voltage mismatch,
Step 7: The system power loss was calculated

C. Estimation of the reliability indices

In other to investigate the reliability of the distribution system after performing the FBS load flows to obtain the system capacity outage during contingency. The following reliability indices; Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy not Supplied (EENS) and Expected Cost (ECOST) of interruption of the systems using Equations (5) to (8) were evaluated using MATLAB R2021a. The reliability data for each component provided in the reliability library of MATLAB were used for the analysis. These indices were based on two reliability data: the system's failure rate (λ_i) and repair time (r_i).

In this research paper, three scenarios of different values of failure rate and repair time were carried out to evaluate the reliability indices in the distribution system:

Scenario i: $\lambda_i = 0.2$ f/yr ; $r_i = 12$ hrs

Scenario i: $\lambda_i = 0.4$ f/yr ; $r_i = 12$ hrs

Scenario i: $\lambda_i = 0.2$ f/yr ; $r_i = 24$ hrs

D. FBS load flow with DG

The FBS distribution load flow technique was performed with 20% DG penetration level. Critical buses were identified and ranked based on network power loss. With DG integration into the network, mathematical modeling of FBS load flow with DG was formulated. From a single line diagram of a distribution network shown in Figure 4 with generator arbitrarily connected, the load flow calculation for the distribution network without and with DG was computed.

The current in the network is given in Equation (15).

$$I_{DG} = \left(\frac{S}{3V}\right)^{*} \tag{15}$$

The voltage magnitude of all nodes in FBS was calculated using Equation (11).The apparent powers of loads with new obtained voltages of all nodes were calculated using Equations (13) and (14), respectively.

The amount of power Loss in the presence of DG is given in Equation (16):

$$P_{Loss}^{with.DG} = 3R_G \times (I_S)^2 + 3(1-G)R \times (I_L)^2 \tag{16}$$

Appropriate size for a DG unit for power loss reduction is given in Equation (17).

$$\Delta P_{Loss} = \frac{R_G\left(\left\{S_L^* \cdot V_{DG}^* - S_{DG} \cdot V_L^*\right\}^2 - \left(\left\{S_L^* \cdot V_{DG}^*\right\}^2\right)\right)}{3\left(\left|V_L^\circ\right| \cdot \left|V_{DG}^*\right|\right)^2} \tag{17}$$

Where; $P_{Loss}^{without.DG}$ is the power loss without DG, R_G is the resistance of the generator, I_L is the current of customer terminal, P_{Loss}^{withDG} is the power loss with DG, P_{Loss1} is the power loss from the substation to DG location, P_{Loss2} is the power loss from DG location to load location, G and I are distance between substation to DG and to load respectively, I_S and I_L are the branch current, R is the resistance of network.

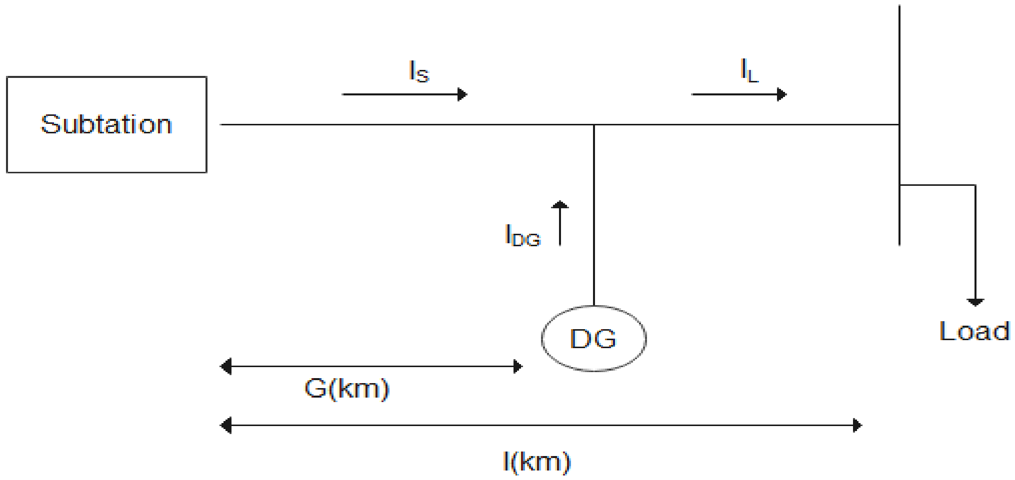

Figure 4: Distribution Network with incorporation of DG

The simulation for FBS distribution load flow with 20% DG penetration level was carried out in MATLAB R2021a, according to the following steps:

Step 1: The system data (distribution line, generation and load data) and the values of DG parameters are input;
Step 2: Iteration count was set as $i = 0$;
Step 3: The FBS load flow at a given steady state and contingency operating condition of the power system were performed;
Step 4: The system reliability indices were evaluated;
Step 5: The FBS load flow with DG at contingency was performed;
Step 6: The DG branch current was calculated,
Step 7: The system was checked for any increment in the system fault current and switching relay was implemented;
Step 4: The system active and reactive power were calculated, respectively;
Step 5: The system bus voltage at each iteration was calculated and updated;
Step 6: The convergence was checked for voltage mismatch,
Step 10: The system losses and total power losses were calculated;
Step 11: The system reliability indices were calculated and updated and then stop.

III. Results and Discussion

The simulation results for the IEEE 25-bus distribution system for the steady state showed that buses 6, 12, 17 and 20 with the voltage magnitude values of 1.0591, 0.9390, 0.9275 and 0.9246 p.u, respectively, were the weak buses with values outside the statutory limit of ±5 % tolerance margin of the voltage criterion as shown in Figure 5. At 20% load increment, the simulation results showed that buses 5, 6, 7, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 20, 22, 23 and 24, with voltage magnitude values of 0.8910, 0.8110, 0.9060, 0.8910, 0.8980, 0.9260, 0.8700, 0.8970, 0.9020, 0.9140, 0.9100, 0.9430, 0.9390, 0.8810, 0.8420, 0.8120 and 0.8430 p.u, respectively, were the potential buses for the integration of DG in the system due to their voltage magnitude value which fell short of the ±5 % acceptable voltage tolerance margin. Furthermore, with DG value of 10 MVar each was placed on buses 5, 6, 7, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 20, 22, 23 and 24, respectively. It was observed that the value of voltage magnitude of buses were improved to 1.0489, 1.0410, 1.0370, 0.9590, 1.0480,1.0460, 1.0120, 1.0470, 1.0050, 0.9590, 0.9610, 1.0250, 0.9570, 1.0330, 1.0140, 1.0030 and 1.0370 p.u., respectively.

The total active and reactive power loses in the system were 469.38 MW and 393.18 MVarat steady state as displayed in Figure 6, respectively. In addition, at contingency, the total active and reactive power losses in the distribution system increase to 563.36 MW (20.02 %) and 471.81 MVar (19.99 %). It was also observed that the total active and reactive power loss in the distribution system were reduced to 418.26 MW (10.89 %) and 380 MVar (3.35 %) with application of DG

In addition, the distribution system has a stable reliability index at steady state. It was observed, that the values of LOLP, LOLE, EENS and ECOST of interruption of the system for the three scenarios of failure rate and repair time of 0.2 f/yr and 12 hrs; 0.4 f/yr and 12 hrs; 0.2 f/yr and 24 hrs, respectively were the same at steady state as shown in Table 1.It was also observed, that the values of LOLP, LOLE, EENS and ECOST of interruption of the system for the three scenarios of failure rate and repair time of 0.2 f/yr and 12 hrs; 0.4 f/yr and 12 hrs; 0.2 f/yr and 24 hrs, respectively increased as the failure rate and repair time varied at contingency..In addition, with application of DG it was observed, that the values of LOLP, LOLE, EENS and ECOST of interruption of the system for the three scenarios of failure rate and repair time of 0.2 f/yr and 12 hrs; 0.4 f/yr and 12 hrs; 0.2 f/yr and 24 hrs, respectively were reduced and very close to steady state value as the failure rate and repair time varied

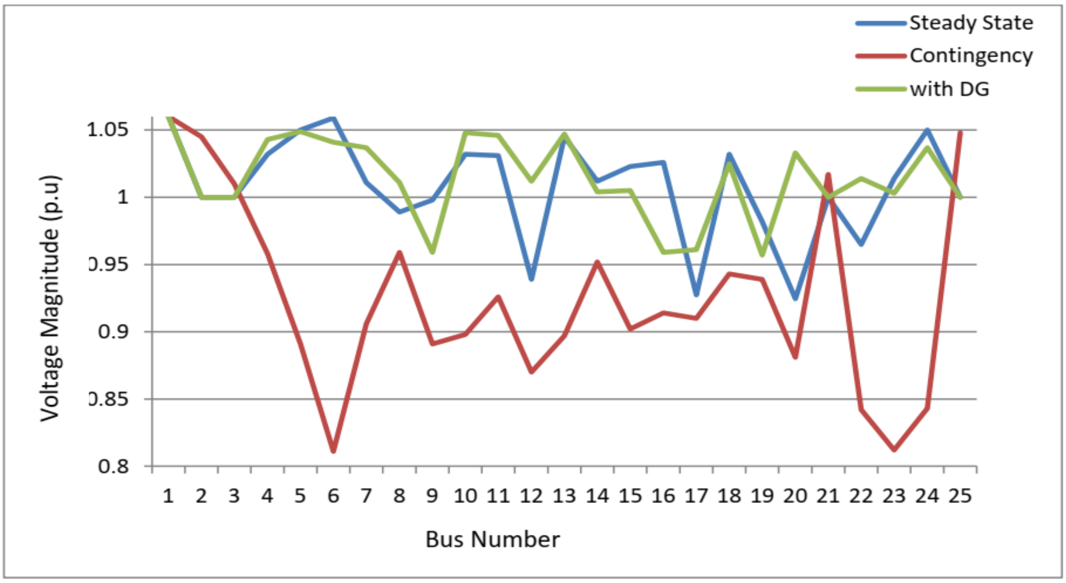

Figure 5: Comparison of Voltage Magnitude of IEEE 25-Bus System

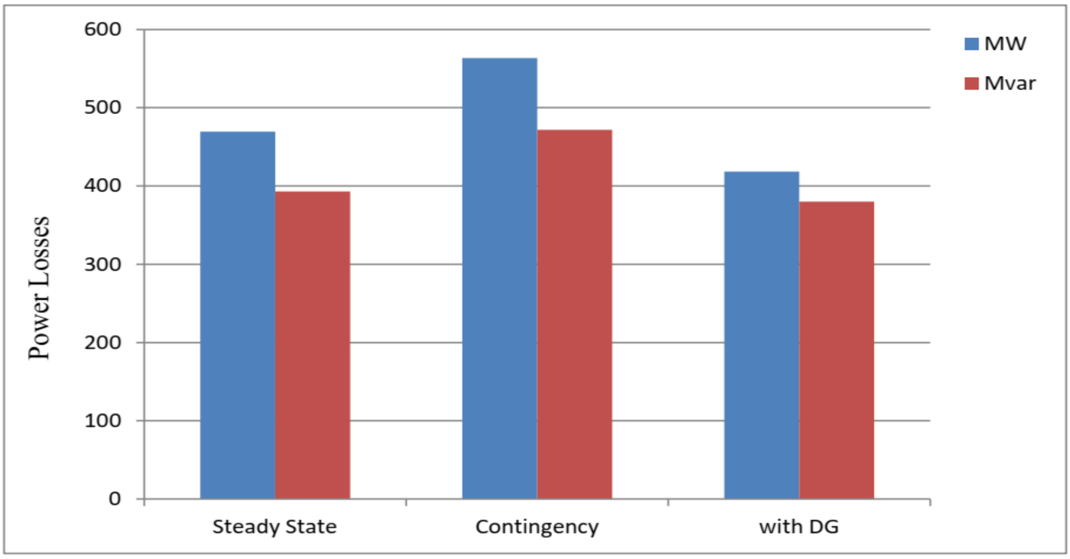

Table 6: Comparison of Power Losses Result of IEEE 25-Bus System

Table 1: Comparison of Reliability Indices of IEEE 25- Bus System

	Total Reliability Index			
	LOLP	LOLE (%)	EENS (MWh/yr)	ECOST ($/yr)
Steady State	0.9080	0.9470	125.47	23602.3
		Contingency		
Scenario i	1.0009	3.9278	145.55	28323.6
Scenario ii	1.0069	4.2927	146.37	28396.6
Scenario iii	1.0021	3.9290	145.65	28324.0
		with DG		
Scenario i	0.9096	1.8110	129.72	23856.7
Scenario ii	0.9371	1.5366	130.43	25302.0
Scenario iii	0.9066	1.8078	129.72	23858.7

IV. Conclusion

This study has successfully presented the improvement of the reliability and security of electrical distribution system planning with DG interconnection to provide effective solutions for the reliable functioning of the power system during interruption. The FBS distribution load flow technique at steady state and contingency with incorporation of DG were performed to determine the security status and reliability of the power system. The approach was validated on IEEE 25-bus power system. The results of the analysis revealed that: with incorporate DG model on distribution system, the system voltage magnitude was improved while the active and reactive power loss of the system was reduced. The reliability and security of the system were improved compared with the contingency case. The results verified the effect of DGon the reliability of electrical power system during voltage collapse.

V. References

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