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Heuristic Algorithm for Optimal Location of DGs in Distribution System based on Probability of Power Availability

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Abstract: The increasing power demands and constraints on pollution are the main reasons for the growth of Distributed generation (DG) in distribution system with or without interconnection to the grid. Selection of DG location is an important concern for distribution system planners to get maximum benefits from the DG unit. The probability of power availability to the consumers which can be considered as one of the classical reliability indices is used as criteria for the DG location. This paper introduces classical node elimination technique for finding the power availability and then proposes a novel heuristic algorithm for the optimal DG location using probability of power availability as a reliability index. The overall approach is applied to three different networks (11-bus test system, IEEE-14 Bus and IEEE-RTS-96 systems) to investigate the impact of DG on system reliability. This probabilistic approach in the calculation of probability of power availability at the load bus which is considered here is a departure from the traditional deterministic methods. The methodology is validated with the Monte Carlo Simulation method.

Keywords: Reliability, Power Availability, Distribution Generation, Failure and Repair rates.

1. INTRODUCTION

There are several difficulties associated with the conventional generation to meet the increasing load demand in remote areas and even in urban distribution systems. Depletion of fossil fuels coupled with strict control on pollution led to the increased use of renewable energy based DGs to meet the load demand [1]-[2]. Many previous works have indicated that integration of DG with the grid improves the voltage profile, power quality and reduces the losses. Specifically efforts of earlier authors are focused on demonstrating the improvements in terms of reduced overloading on lines and transformers, reduced load that cannot be supplied, improved system side reliability and improvements in customer interruption indices etc [3]-[5]. However, proper planning and analysis is needed for the installation of the DG units in the network without violating the system constraints [6]. The unplanned location of DG Units leads to several problems with regard to reliability, protection, short circuit current and voltage profile. Le et. al., (2007) have shown that higher loss reductions can be achieved when DG is located at a bus close to remote end of the network [3]. Hung et. al., [2010] have clearly stated that DGs located near swing buses result only in negligible loss reduction [5]. Both of these works have used only radial networks in their investigations as many others did. Wang et. al., (2008) have proposed a new analytical method for reliability evaluation with DG and used a radial system with two DGs. Monte Carlo technique is accepted as the standard way to assess system reliability and IEEE-RTS-96 system, which is highly interconnected, is considered as the standard for bench marking purposes. However, Billinton et. al., (2009) stated that *"the original RTS-96 is a strong power and a weak distribution system"* and hence required modifications to determine LOLE for system adequacy [8] especially when DGs are connected. Various different reliability indices, algorithms, and different networks have been used by earlier researchers over the time. However, reliability in terms of

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power availability is not well explored. This paper investigates the probability of power availability at load buses on RTS-96 system with DGs included.

The reliability analysis for power availability at load buses in the interconnected power system is complex due to the large number of components connected and the network topology. Conventionally, reliability analysis is done by tracing the power flow paths [7]. Traditional methods are difficult to implement in large systems. Every component has its own Failure (λ) and Repair rates (μ). It is necessary to compute the equivalent failure and repair rates for the power system between the generator and load nodes to compute the probability of power availability using transient probability matrix etc. The probabilistic methods for the evaluation of operating reserves in power system are discussed in [9]. These methods involve large computation time. In Ref [11]-[25] attempts are made to determine the optimal location of DG using reliability as the main criterion and several reliability indices are discussed.

Hence, it is important that any new reliability evaluation technique should be tested on different suitable, standard systems. Inclusion of DGs in the system leads to various operating challenges to the operators including price, protection, maintenance and control. Hence reliability takes high priority for obvious reasons when DGs are included and obviously several works have been carried out so far to investigate various reliability parameters when DGs are included. Keeping in view of the above, this paper introduces a simplified approach for determining probability of power availability at the load buses. This approach utilizes node elimination method and validated by Monte Carlo technique. Monte Carlo technique is developed in MAT Lab code. A heuristic algorithm is developed for optimal location of DGs to improve probability of power availability at the load buses. Node elimination method overcomes the issues with tracing the multiple power flow paths and complex computations involving the inversion of the transient probability matrix for large systems; and thus becomes a powerful tool in analyzing large interconnected networks. Probability of Power availability is taken as a reliability index for this work. A simple 11 bus interconnected test system is presented to support the suggested approach, besides IEEE-14 bus and RTS-96 systems.

The overall organization of this paper is as follows. Section II presents the Node elimination method for the estimation of power availability. Section III provides the validation of Node elimination approach using Monte Carlo Simulation method. A new heuristic algorithm for the determination optimal DG location is illustrated in Section IV. The results and the effectiveness of the proposed algorithm are discussed in Section V and Section VI draws the conclusion.

2. NODE ELIMINATION METHOD

The Classical node elimination method is a known technique. It is used to reduce the equivalent electrical network to calculate power availability at load bus. The power supply node is considered as a current injection node and the load node where the availability is to be computed is treated as a current sink. The other load nodes do not have any current injection. To reduce the network the nodes at which the current does not enter or leave are eliminated. There by the equivalent network connecting the power supply node and the load node under consideration is obtained. The equivalent electrical network is described by the nodal equation [22].

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{22} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_n \end{bmatrix} \tag{1}$$

where the matrix Y_{Bus} in the above equation is the nodal admittance matrix and I & V are the nodal injected currents and voltages of the network.

For the reliability analysis each component in the network is modeled by failure (λ) and repair (μ) rates, which are assumed to be constant. This is the consequence of assuming exponential distribution of probability of component been in the ON or OFF state. In the formation of Y_{Bus} given in (1), to obtain equivalent failure rate each component is replaced by a resistor (R) and whose value is equal to failure rate (λ). Similarly to determine equivalent repair rate each component is replaced by capacitor (C) and whose value is equal to repair rate (μ). The equivalent failure, repair rates are obtained by solving nodal equation one by one shown in (1). The more details about equivalent failure and repair rates are available in reference [22].

From the above analysis it is clear that some currents are treated as injected currents at the power supply nodes and as output currents at the load nodes where the power availability is to be evaluated. At the remaining nodes the currents are made zero and the corresponding nodes are eliminated in the reduced network. Then (1) becomes as

$$\begin{bmatrix} I_A \\ I_B \end{bmatrix} = \begin{bmatrix} X & Y \\ Y^T & Z \end{bmatrix} \begin{bmatrix} V_A \\ V_B \end{bmatrix} \tag{2}$$

In (2), I_A is a vector containing the currents and I_B vector is null vector and the total Y_{Bus} is formed by the combination of matrices X, Y and Z.

For the elimination of nodes corresponding to I_B the following equations are used.

$$I_A = XV_A + YV_B \tag{3}$$

$$0 = I_B = Y^T V_A + ZV_B$$

$$V_B = -Z^{-1} Y^T V_A$$

$$I_A = (X - Z^{-1} Y^T V_A) V_A \tag{4}$$

The reduced Y_{Bus} is given in (5)

$$Y_{Bus}^{Reduced} = (X - Z^{-1} Y^T V_A) \tag{5}$$

From the reduced Y_{Bus} as will be explained later the failure and repair rates (λ_e & μ_e) for the equivalent component connecting generator and load nodes are obtained at each load bus. From these equivalent failure and repair rates, the probability of power availability at each load bus is obtained as $\dfrac{\mu_e}{\mu_e + \lambda_e}$.

The proposed Node elimination method is applied on the 11 bus test system. The configuration of the systems and the DG unit location is shown in Figure 1. The 11 bus test system consists of number of circuit breakers, one Generating unit, two transformers, 5 load buses and three possible locations for adding DG. The DG is location is changed from locations 1, 2 and 3 to obtain its optimal location. For this system the failure and repair rates of the all the elements are given in the Table 1 [22]. The reduced Y_{Bus} which is given in (5) represents the nodal equation of the simplified network shown in Figure 2. The equivalent Failure and Repair rates between supply nodes and the load node under consideration are found from the reduced Y_{Bus} one at a time by treating λ as resistance (R) and μ as capacitance (C). Since the generator failure and repair rates are already included in the Y_{Bus} formation, the nodes 1 and 2 of generators in the reliability model of the network shown in Figure 2 have 1.0 availability and so can be clubbed together to evaluate the probability of availability of power at the load node. So the corresponding network elements between Generator 1, Generator 2 and load will be in parallel and over all equivalent λ & μ are evaluated. The same procedure is used if there are more than two generators. The availability of power at remaining load points are evaluated one by one by adapting the same procedure. The results obtained from this method are given in section V, Table 3.

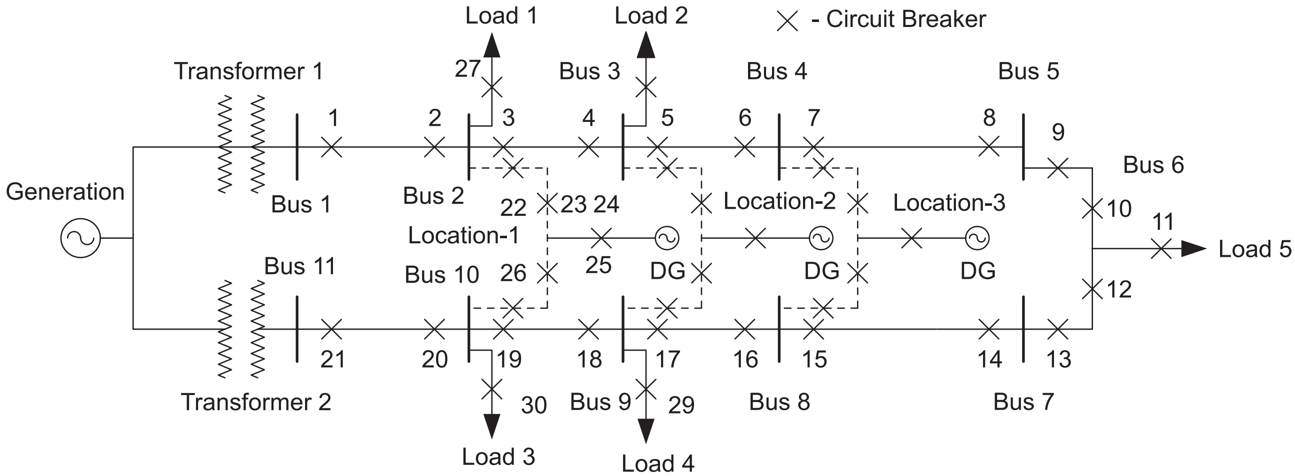

Figure 1: 11 bus test system

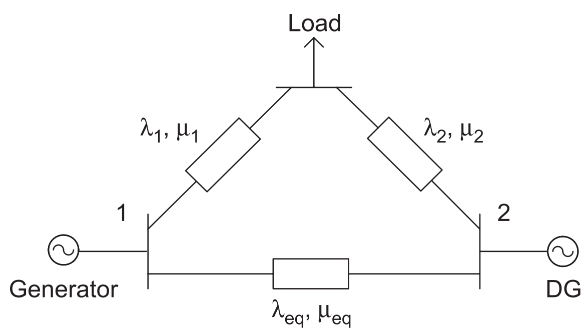

Figure 2: Reduced reliability network

Table 1
Reliability data for 11 bus system

Component	*Failure Rate λ (Failures/Yr)*	*Repair Rate μ (Repairs/Yr)*
C.B 1	0.1	20
2	0.3	10
3	0.2	30
4	0.6	40
5	0.5	20
6	0.2	10
7	0.4	10
8	0.1	10
9	0.3	20
10	0.2	40
11	0.3	10

Component	*Failure Rate λ (Failures/Yr)*	*Repair Rate μ (Repairs/Yr)*
12	0.4	30
13	0.5	10
14	0.1	20
15	0.2	40
16	0.4	30
17	0.3	10
18	0.5	20
20	0.1	30
21	0.2	10
22	0.4	10
23	0.1	10
24	0.2	10
25	0.3	30
26	0.2	10
27	0.4	20
28	0.2	40
29	0.6	40
30	0.5	10
Generator	0.1	10
Transformer	0.1	10
DG	0.1	10

3. MONTE CARLO SIMULATION METHOD

The Monte Carlo Simulation method [8] is applied to evaluate the availability of power at consumer or load end for the 11 bus test system considered in this paper. After evaluation of the equivalent failure and repair rates from the node elimination method, the Monte Carlo method is adopted to estimate the power availability for the purpose of comparing the results with the proposed method. In this method the exponential probability distribution is assumed for the equivalent failure and repair rates for the power system components. The time to Fail and Repair are given as

$$\text{Time to Fail (on time)} = -\frac{1}{\lambda_e} \ln(1 - U) \tag{6}$$

$$\text{Time to Repair} = -\frac{1}{\mu_e} \ln(1 - U) \tag{7}$$

where λ_e, μ_e are the equivalent failure and repair rates for each load obtained from the electrical circuit approach discussed earlier. U is a uniformly distributed random number generated for each component separately for time to fail and time to repair.

After the node elimination method the network is reduced to delta as shown in Figure 2 and which consists of two paths from generator to load node. For the calculation of the mean time to fail and repair, an uniformly distributed random number (U) is generated using MATLAB code. Totally 12 years data is developed and the corresponding histograms are generated for each path as shown in Figure 3. Using these histograms the probability of power availability at load node is computed.

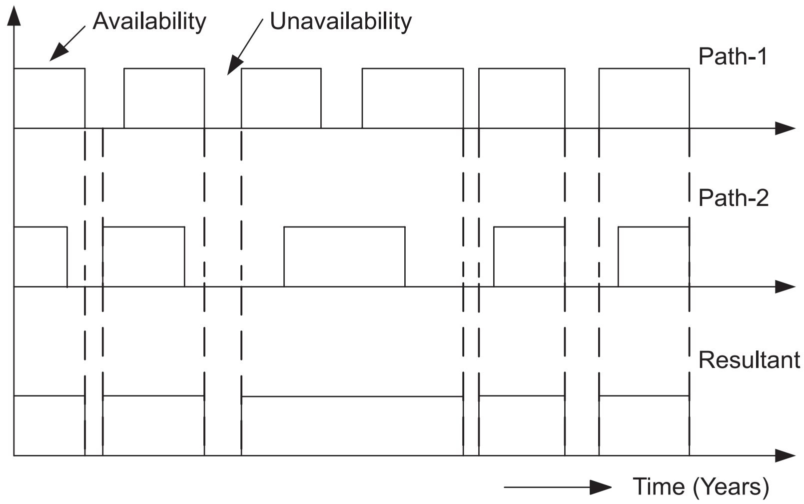

Figure 3: Generated Histograms for 12 Years

4. DETERMINATION OF OPTIMAL DG LOCATION USING A HEURISTIC ALGORITHM UNITS

In this section a new heuristic algorithm for determining optimal DG locations is presented. Buses with generators are avoided and the load buses far away from the generation are considered for initial DG location. In other words, this approach actually evaluates power availability at all the possible locations for DG as opposed to other search techniques. The proposed heuristic algorithm works well for inclusion of single DG or multiple DGs and it is explained in the steps provided below.

1. Read the Failure and Repair Rates of all the components of the network.
2. Identify the possible DG locations. The following criteria are used in choosing the initial location of DGs.
   (a) Availability of space for locating DG
   (b) Nearness to the load centers
   (c) Availability of RE Sources
   (d) Availability of maintenance crew
3. Fix the first DG location and vary the location of the second DG to identified locations one by one. For each of these locations, conduct Proposed Node Elimination Method to find the single optimal location for second DG. Among the possible locations, obtain the probability of power availability at each load node. Calculate the overall probability of power availability considering all the load nodes. The overall probability of power availability is obtained by summing up the computed probability of power availability at each load bus divided by number of load buses.
4. Using the probability of power availability criterion, the first possible optimal location is identified as the one which gives the maximum overall probability of power availability (If only one DG is used, then the optimization process is stopped here).
5. Repeat step-3 by shifting the location of the first DG while fixing the second DG at the optimal location obtained in step 4. Once again the optimal location of first DG is obtained.

6. Step 5 is repeated alternatively shifting the location of one DG while fixing the location of the second DG.
7. Step 6 is repeated till the most optimal locations for the both DGs are obtained.

5. CASE STUDIES

Three systems have been considered to evaluate the proposed approach. A simple 11 bus test system, IEEE-14 bus system and the IEEE-RTS-96 are used. It should be noted that these three networks are interconnected systems and hence determination of DG location becomes an important task. For all the three networks, the probability of power availability at load bus is taken as the index to identify the optimal location of DG. The power availability at load buses with DG and without DG is investigated. The methodology is applied on the 11 bus test system, IEEE 14 bus system and IEEE RTS-96 system. The 11 bus test system consists of one Generating unit and one DG unit. The Node elimination method is applied on 11 bus test system with one DG. The DG location is changed from locations 1, 2 and 3 to obtain its optimal location. The IEEE 14 bus system shown in Figure 4 consists of 5 Generating units and 8 loads along with a DG unit. The DG Unit is placed at different buses to study the power availability at each load bus. Based on the overall probability of power availability at all the load buses, the optimal location of DG unit is obtained. The equivalent failure and repair rates for components between the buses of IEEE 14 bus system are given in Table 2 [22].

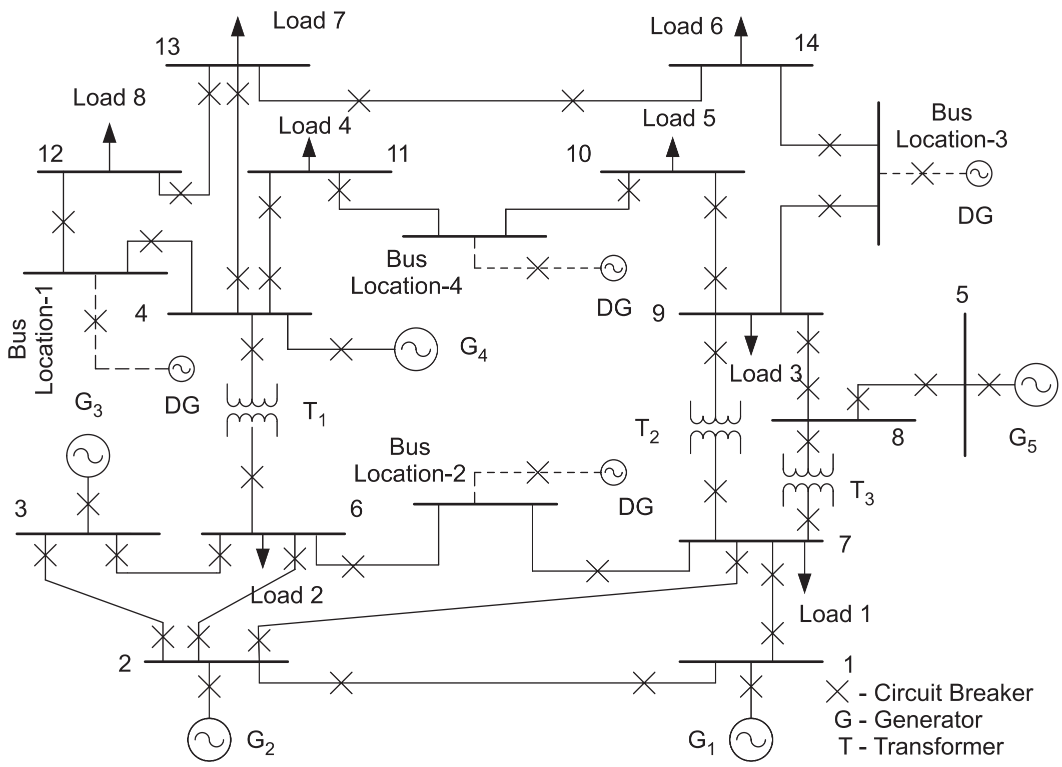

Figure 4: IEEE 14 Bus reliability test system

The proposed Node elimination method is helpful to the power system planners for the determination of availability of power at a load bus. For complex and higher bus system, the available methods are quite difficult and take much time to evaluate the power availability at load bus. The proposed method does not require tracing of power flows or complex matrix computations and hence, is simple and can be easily applied to any type of system. The power availability at different loads without and with installation of DG Units in the 11 bus test system and the IEEE 14 bus systems are shown in Table 3 and 4. From this the overall probability of power availability in 11 bus test system is computed as 0.6292 and in IEEE 14 bus system is computed as 0.9401.

Table 2
Reliability data for 14 bus system

From Bus	*To Bus*	*Failure Rate λ (Failures/Yr)*	*Repair Rate μ (Repairs/Yr)*
1	2	0.5	7.5
1	7	0.8	13.333
2	3	0.5	12
2	6	0.9	5
2	7	0.4	5
3	6	0.3	13.333
4	6	0.8	4
4	11	0.6	13.333
4	12	0.7	17.142
4	13	0.3	7.5
5	8	0.7	6.667
6	7	0.7	7.5
7	8	0.6	4.285
7	9	0.5	6.315
8	9	0.4	12
9	10	0.5	12
9	14	0.2	8
10	11	0.3	13.333
12	13	0.4	5
13	14	0.7	6.667

Table 3
Power availability at different load nodes without and with DG for 11 bus test system

Load No	*Without DG*	*Location-1*	*Location-2*	*Location-3*
1	0.6801	0.8398	0.6806	0.7905
2	0.6214	0.8520	0.7807	0.8011
3	0.6222	0.7786	0.7411	0.7478
4	0.6424	0.7940	0.7471	0.8144
5	0.5601	0.5668	0.5706	0.8999

Table 4
Power availability at different load nodes without and with DG for IEEE 14 bus system

Load No	*Without DG*	*Location-1*	*Location-2*	*Location-3*	*Location-4*
1	0.9674	0.9674	0.9822	0.9810	0.9801
2	0.9676	0.9697	0.9826	0.9736	0.9799
3	0.9676	0.9779	0.9726	0.9836	0.9763
4	0.9282	0.9288	0.9637	0.9657	0.9812
5	0.9147	0.9148	0.9588	0.9645	0.9834
6	0.9171	0.9187	0.9612	0.9840	0.9594
7	0.9518	0.9564	0.9738	0.9753	0.9730
8	0.9397	0.9698	0.9678	0.9682	0.9677

The loads away from the generation may not meet the power quality requirements. So the installation of DG unit in the system at different locations is required to improve the probability of power availability in the system. The power availability at load buses with the installation of DG unit at different locations is given in Table 3 and 4 for the 11 bus test system and IEEE 14 bus system. The total probability of power availability of the system at different location of DG units is given in Table 5(a) and (b). IEEE-RTS-96 [10] system is used to demonstrate the effectiveness of proposed approach and is shown in Figure 5. The optimal location of DGs in IEEE single area RTS-96 system is investigated and the probability of power availability at each location is shown in Table 6(a) with single DG and Table 6(b) shows the total probability of power availability for different locations of DG.

Table 5
(a) Total probability of power availability at different locations of DG for 11 bus test system

Location	*Probability of Power availability*
Location – 1	0.7662
Location – 2	0.7040
Location – 3	0.8107

Table 5
(b) Total Probability of power availability at different locations of DG for IEEE 14 bus system

Location	*Probability of Power availability*
Location – 1	0.9467
Location – 2	0.9701
Location – 3	0.9745
Location – 4	0.9751

Table 6
(a) Power availability at different locations of DG for IEEE single area RTS-96 system

Load No	*Without DG*	*DG at Bus 5*	*DG at Bus 9*	*DG at Bus 10*	*DG at Bus 11*
1	0.8558	0.8550	0.8212	0.8343	0.8280
2	0.8191	0.8206	0.8199	0.8217	0.8208
3	0.5586	0.6654	0.6848	0.6940	0.6276
4	0.8469	0.8490	0.8400	0.8401	0.8492
5	0.8122	0.8127	0.8101	0.8333	0.8137
6	0.8122	0.8122	0.8111	0.8333	0.8137
7	0.8129	0.8130	0.8135	0.8138	0.8142
8	0.8368	0.8369	0.8311	0.8375	0.8425
9	0.8596	0.8602	0.8666	0.8633	0.8647
10	0.8573	0.8807	0.8316	0.8573	0.8626
11	0.8188	0.7779	0.6864	0.7616	0.8115
12	0.8325	0.8325	0.8419	0.8325	0.8325
13	0.8451	0.8456	0.8422	0.8487	0.8597
14	0.7885	0.7885	0.8111	0.7366	0.7885
15	0.7636	0.7636	0.7666	0.7785	0.7636
16	0.8683	0.8684	0.8528	0.8613	0.8683
17	0.8085	0.8085	0.8121	0.8311	0.8511

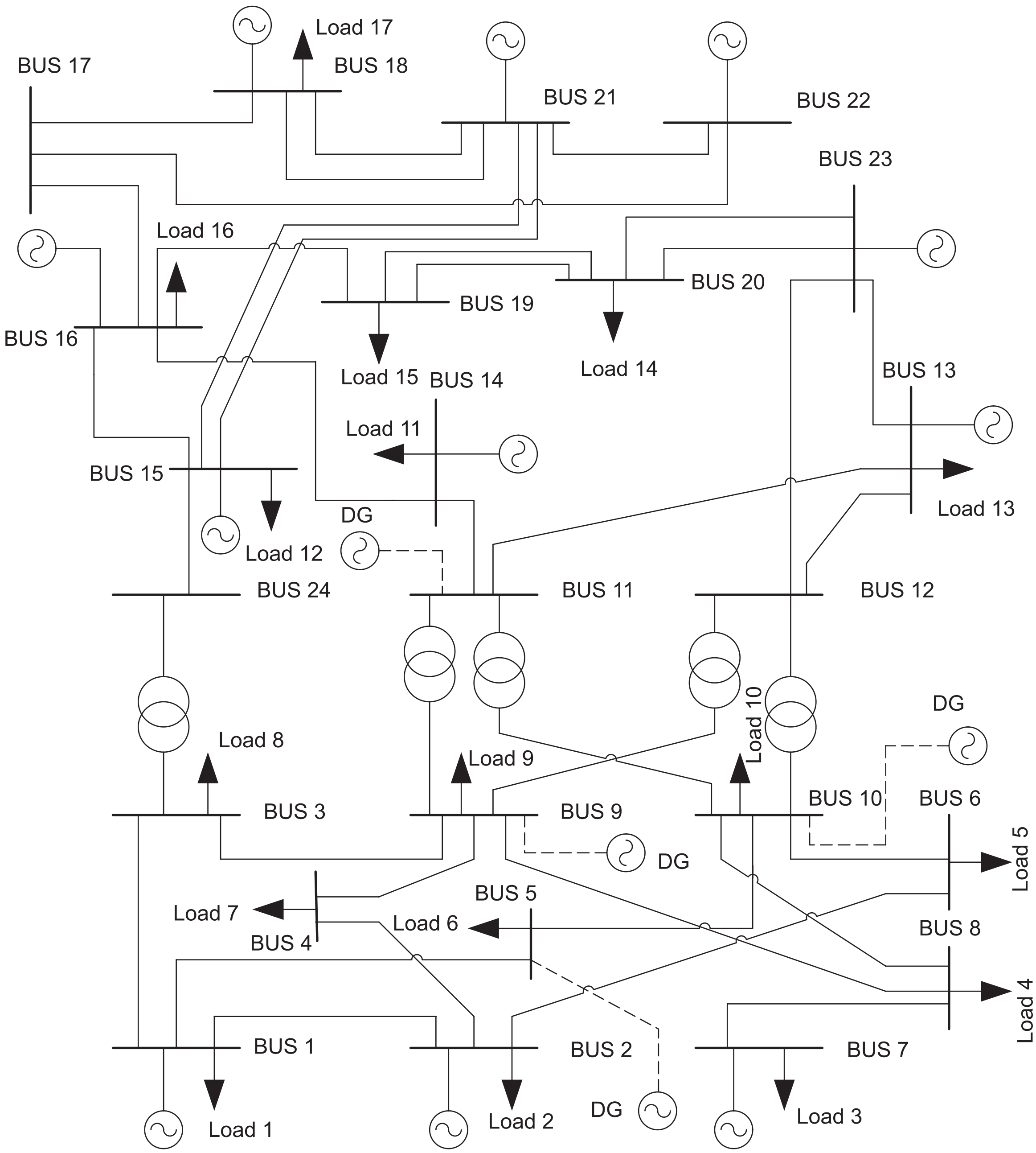

Figure 5: Optimal location of DG in IEEE single area RTS-96 system.

Table 6
(b) Total probability of power availability at different locations for IEEE single area RTS-96 system

DG Location	*Power Availability*
Without DG	0.8099
At bus 5	0.8171
At bus 9	0.8088
At bus 10	0.8118
At bus 11	0.8183

The optimal location of the DG is shown as the one which gave maximum probability of power availability. In this paper DG unit is installed at different locations to investigate the power availability at each load bus. With the installation of DG unit the power availability is increased compared to normal system (without DG). At location-4 in IEEE 14 bus system, the probability of power availability is more compared to other locations. Similarly at location-3 in 11 bus test system the probability of power availability is more.

When there are more than one DG to be installed in the system then using the heuristic algorithm described in section IV, the probability of power availability at load nodes for different DG locations are calculated and the optimal locations of the DGs is obtained for the system under consideration. The results obtained for IEEE RTS-96 system with two DGs are given in Table 7. Initially fixing one DG at Bus 5, the optimal location of the second DG is found to be Bus 11. Then fixing the second DG at Bus 11, the optimal location for the first DG is at Bus 9. This procedure is repeated according to the heuristic algorithm described in section IV and the optimal location is found to be 11 and 9 Buses. For the validation of methodology proposed, Monte Carlo method is applied on the 11 bus test system and the results are shown in Table 8.

Table 7
Total probability of power availability based on Heuristic algorithm for IEEE RTS 96 system

DG Locations (Buses)	*Total power availability*
11, 5	0.8166
11, 9	0.8693
11, 10	0.8239
9, 5	0.8155
9, 10	0.8189

Table 8
Comparison probability of power availability obtained by Node elimination method and Monte Carlo method for 11 bus test system with DG at location 3

Load NO	*Node Elimination Method*	*Monte Carlo method*
Load 1	0.7905	0.8019
Load 2	0.8011	0.8218
Load 3	0.7478	0.8
Load 4	0.8144	0.8233
Load 5	0.8999	0.9111

6. CONCLUSION

A new heuristic method is proposed to determine the optimal location for DGs in the interconnected power system and the same is applied to three different networks. The Node elimination technique for determining the power availability is illustrated and validated using the standard Monte Carlo simulation method. Detailed reliability analysis with and without DGs has been carried out and the performance of the proposed approach is found to be satisfactory. The results suggest that it is important that the locations of DG to be properly identified to enhance power availability and reliability.

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