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OPTIMAL SIZING AND PLACEMENT OF DISTRIBUTED GENERATION SOURCES IN POWER SYSTEMS BASED ON ANALYTICAL METHOD AND DIGSILENT

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Abstract- This paper presents optimal location and sizing of Distributed Generation (DG) in network systems to provide the active and reactive power support, to minimize the system real and reactive power loss and to maintain the network voltage level. The proposed method is efficiently examined in DIgSILENT Power Factory in test system and comparative studies are made before and after installation of Distributed Generation. Results illustrate improvement in network voltage profile and reduction in system real and reactive power loss.

Keywords: Distributed Generation (DG), Optimal Sizing and Sitting, Power Loss, Voltage Profile.

I. INTRODUCTION

The ever-increasing need for electrical power generation, steady progress in the power deregulation and utility restructuring, and tight constraints over the construction of new transmission lines for long distance power transmission have created increased interest in distributed power generation. Distributed generation (DG) devices can be strategically placed in power systems for grid reinforcement, reducing power losses and on-peak operating costs, improving voltage profiles and load factors, deferring or eliminating system upgrades, and improving system integrity, reliability and efficiency [1-5]. These DG sources are normally placed close to consumption centers and are added mostly at the distribution level. They are relatively small in size (relative to the power capacity of the system in which they are placed) and modular in structure. A common strategy to find the site of DG is to minimize the power loss of the system [2-5].

Another method for placing DG is to apply rules that are often used in sitting shunt capacitors in distribution systems. A "2/3 rule" is presented in [8.6] to place DG on a radial feeder with uniformly distributed load, where it is suggested to install DG of approximately 2/3 capacity of the incoming generation at approximately 2/3 of the length of line.

This rule is simple and easy to use, but it cannot be applied directly to a feeder with other types of load distribution, or to a networked system. References [1-7] present power flow algorithms to find the optimal size of DG at each load bus in a networked system assuming that every load bus can have a DG source.

In this paper, analytical approaches for optimal placement of DG with unity power factor in power systems are presented. The method is presented to find the optimal bus for placing DG in a networked system based on bus admittance matrix, generation information and load distribution of the system. The proposed methods are tested by a series of simulations on an IEEE 6-bus test system [1], an IEEE 30-bus test system [11] and a subset of it, to show the effectiveness of the proposed methods in determining the optimal bus for placing of DG. The test system results are simulated networks at DIgSILENT Power Factory after reviewing protective devices and using algorithm with MATLAB and compare results.

In practice, there are more constraints on the availability of DG sources, and there may be only one or a few DGs with limited output available to be added. Therefore, in this study the DG size is not considered to be optimized. The procedure to determine the optimal bus for placing of DG may also needs to take other factors into account, such as economic and geographic considerations. These factors are not discussed in this paper.

II. OPTIMAL PLACEMENT OF DG IN NETWORKED SYSTEMS

To simplify the analysis, only one DG is considered to be added to the system. Consider the system shown in Figure 1 with a DG added to the system to reinforce it. The system has N buses and loads, and the DG is located at a bus, say bus j. The main external power is injected into bus 1, which is taken as slack bus. The objective is to find the bus to install the DG so that the total system power loss is minimized and the voltage level at each bus is held in the acceptable range, 1±0.05 pu.

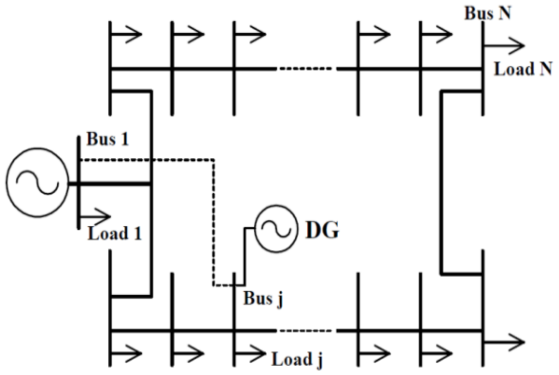

Figure 1. A networked power system [12]

Before the DG is added to the system, the bus admittance matrix is:

$$Y_{bus}^0 = \begin{bmatrix} Y_{11}^0 & Y_{12}^0 & \dots Y_{1j}^0 & \dots & Y_{1N}^0 \\ \dots & & \dots & & \\ \dots & & \dots & & \\ Y_{N1}^0 & Y_{N2}^0 & ..Y_{Nj}^0 & \dots & Y_{NN}^0 \end{bmatrix} \tag{1}$$

where superscript 0 denotes the original system. Assuming that the DG is located at bus *j*, the system admittance matrix is changed then from Y_{bus}^0 to Y_{bus} by considering that bus 1 and bus j are connected together. Actually there is no line to connect those buses together, but the hypothetical line will help in finding the optimal location to add DG. Y_{bus} is one dimension less than Y_{bus}^0 except when the DG is located at bus 1. If the DG is at bus 1, Y_{bus} matrix will be the same as Y_{bus}^0. To obtain the new matrix Y_{bus} when the DG source is connected, we treat the system as connecting bus 1 and j by eliminating bus j in Y_{bus}^0 [10]. The new matrix is:

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1k} & \dots & Y_{1(N-1)} \\ \dots & & \dots & & & \\ \dots & & \dots & & & \\ Y_{(N-1)1} & Y_{(N-1)2} & \dots Y_{(N-1)k} & \dots & & Y_{(N-1)(N-1)} \end{bmatrix} \tag{2}$$

where:

$$Y_{11} = Y_{11}^0 + Y_{jj}^0 + 2Y_{1j}^0$$

$$Y_{1k} = Y_{1k}^0 + Y_{jk}^0, k = 2, ..., j-1$$

$$Y_{1k} = Y_{1(k+1)}^0 + Y_{j(k+1)}^0, k = j, ..., N-1$$

$$Y_{k1} = Y_{1k}, k = 2, ..., N-1$$

$$Y_{ik} = Y_{ik}^0, k \le (i,k) \le j-1$$

$$Y_{ik} = Y_{i(k+1)}^0, 2 \le i \le j-1, j \le k \le N-1$$

$$Y_{ik} = Y_{(i+1)k}^0, j \le i \le N-1, 2 \le k \le j-1$$

$$Y_{ik} = Y_{(i+1)(k+1)}^0, j \le (i,k) \le N-1$$

The new bus impedance matrix Z_{bus} is:

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1k} & \dots & Y_{1(N-1)} \\ \dots & & \dots & & & \\ \dots & & \dots & & & \\ Y_{(N-1)1} & Y_{(N-1)2} & \dots Y_{(N-1)k} & \dots & & Y_{(N-1)(N-1)} \end{bmatrix} \tag{3}$$

Suppose the complex load and generated power of the original system are:

$$S_L^0 = [S_{L1}^0, S_{L2}^0, ..., S_{Li}^0, ...S_{LN}^0] \tag{4}$$

$$S_G^0 = [S_{G1}^0, S_{G2}^0, ..., S_{Gi}^0, ...S_{GN}^0], i = 1, 2, ..., N \tag{5}$$

where $S_{Li}^0 = P_{Li}^0 + jQ_{Li}^0$ and $S_{Gi}^0 = P_{Gi}^0 + jQ_{Gi}^0$. A new load vector S_L is set up as follows:

$$S_L = [S_{L1}, S_{L2}, ..., S_{Li}, ...S_{LN}] \tag{6}$$

where:

$$S_{Li} = P_{Li} + jQ_{Li}$$

$$S_{Li} = 0 \;, \quad \text{for} \quad i = 1 \;\; \text{(slack bus)}$$

$$S_{Li} = S_{Li}^0 \;, \quad \text{for} \quad i = \text{load buses}$$

$$S_{Li} = \begin{cases} P_{Li}^0 - P_{Gi}^0 + j0 & P_{Li} > P_{Gi} \\ 0 & P_{Li} \le P_{Gi} \end{cases} \quad \text{for } i = P-V \text{ buses}$$

Note that at the slack bus (bus 1) $S_{L1} = 0$; It is assumed that the real and reactive power consumed by the load are supplied directly by the external generation at that bus. Also, at a voltage controlled (*P-V*) bus, $Q_{Li} = 0$; it is assumed that the load reactive power can be supplied by the external power source at the $P-V$ bus.

To find the optimal point to place the DG, we set up an objective function for DG at each bus j as follows:

$$f_j = \sum_{i=1}^{j-1} R_{1i}(j)|S_{Li}|^2 + \sum_{i=j+1}^{N} R_{1i}(j)|S_{Li}|^2, j = 2, ...N \tag{7}$$

where $R_{1i}(j)$ is the equivalent resistance between bus 1 and bus *i* when DG is located at bus j, $j \ne 1$.

$$R_{1i}(j) = \begin{cases} \text{Real}(Z_{11} + Z_{ii} - 2Z_{1i}) & i < j \\ \text{Real}(Z_{11} + Z_{(i-1)(i-1)} - 2Z_{1(i-1)}) & i > j \end{cases} \tag{8}$$

When the DG is located at bus 1 $(j = 1)$, the objective function will be:

$$f_1 = \sum_{i=1}^{N} R_{1i}|S_{Li}|^2 \tag{9}$$

Note that in this case, Y_{bus} (Z_{bus}) will be the same as Y_{bus}^0 (Z_{bus}^0) and $R_{11} = 0$. The goal is to find the optimal bus m where the objective function reaches its minimum value.

$$f_m = \min(f_j) \;, \; j = 1, 2, ...N \tag{10}$$

The theoretical procedure to find the optimal bus to place DG in a networked system can be summarized as follows:

1) Find the matrix Y_{bus}^0 and set up the load vector S_L.

2) Compute Y_{bus} and the corresponding Z_{bus} for different DG locations.

3) Calculate the equivalent resistances according to (8).
4) Use (7) and (9) to calculate objective function values for DG at different buses and find the optimal bus m.
5) If all the voltages are in the acceptable range when the DG is located at bus m, then bus m is the optimal site.
6) If some bus voltages do not meet the voltage rule, then move the DG around bus m to satisfy the voltage rule.
7) If there is no bus that can satisfy the voltage regulation rule, try a different size DG and repeat steps 5) and 6).

The procedure is summarized in the flow chart shown in Figure 2. Though the discussed method assumes here only one DG source is added to the system, it can be easily extended to the systems with multiple DG sources. By connecting all the DG buses and slack bus together through hypothetical lines, the new Y_{bus} matrix and the corresponding objective function can be established by the method presented above.

III. SIMULATION RESULTS IN NETWORKED SYSTEMS

All of the process using MATLAB (for algorithm execution and math equations) and DIgSILENT Power Factory (network simulation and short circuit and load flow calculations) soft wares is simulated and they are executed on illustrated distribution network.

A. 6-Bus Test System

The 25 kV IEEE 6-bus system shown in Figure 3 [1], which can be considered as a sub transmission /distribution system, was used to verify the method presented in the previous section. The parameters of this system are given in Table 1. A 5-MW DG was added to reinforce the system. Total system power loss was obtained from the results of power flow studies when DG was placed at different buses.

It is noted that minimum power loss is achieved when DG is placed at bus 3. The values of the objective function for the system were obtained by applying the proposed analytical approach when the DG was placed at different buses.

It is also noted that the objective function is also at its minimum when the DG is placed at bus 3, indicating that the result obtained from the proposed analytical method is the same as the simulation result.

You can see the Bus voltage before DG connecting in table 2 and table 4 show's Bus voltage after DG connecting in bus 3. Table 3 shows the Bus and line parameters before DG connecting and table 5 Bus and line parameters after 5 MW DG connecting in Bus 3.

It is useful if compare the results in Tables 2 and 4, and Tables 3 & 5 with together before and after DG connection in bus 3.

B. 30-Bus Test System

The proposed method was also tested on IEEE 30 bus test system shown in Figure 4, which can be considered as a meshed transmission/sub-transmission system [11].

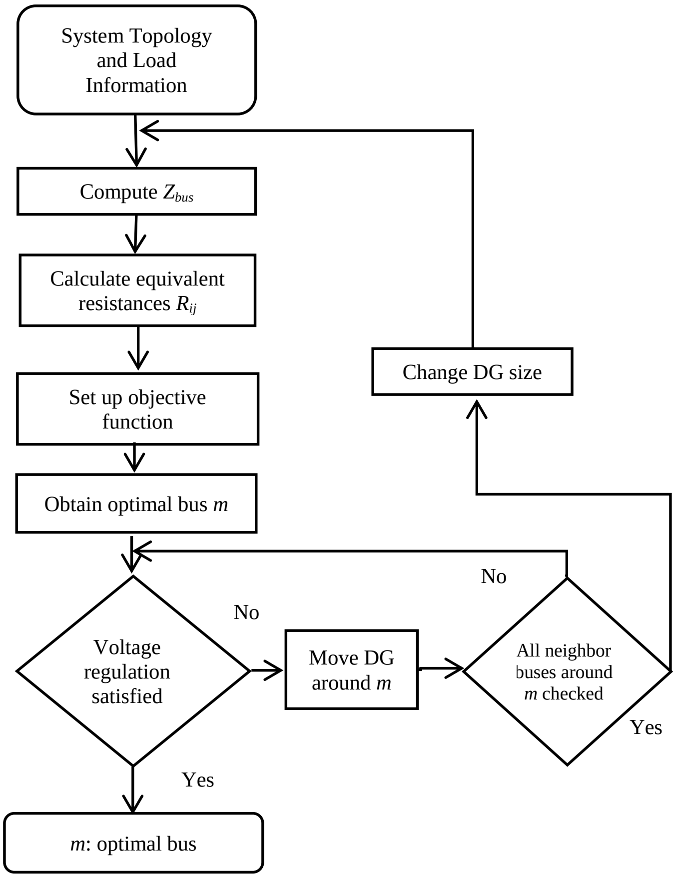

Figure 2. Flowchart of the optimal bus to place DG

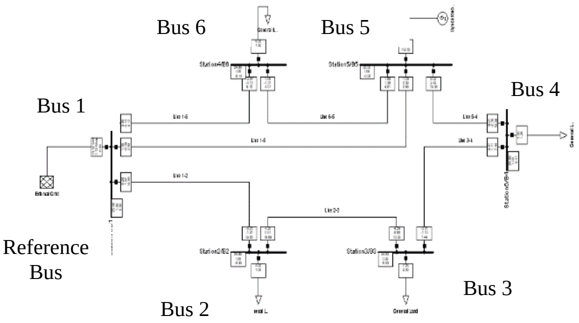

Figure 3. Reformed network of IEEE 6-bus system in DIgSILENT

Table 1. Parameters of IEEE 6-bus system [1]

Bus Data			
Bus No.	Voltage (pu)	Bus Power (MVA)	
1	1.0+j0.0	Slack bus	
2	-	-4.0 -j1.00	
3	-	-7.25-j2.00	
4	-	-5.00-j1.25	
5	$\lvert V_5 \rvert = 1.0$	8.00	
6	-	-5.00-j1.50	
Line Data			
From	To	Z_{serial} (pu)	Y_{shunt} (pu)
1	2	0.2238+j0.5090	j0.0012
2	3	0.2238+j0.5090	j0.0012
3	4	0.2238+j0.5090	j0.0012
4	5	0.2238+j0.5090	j0.0012
5	6	0.2238+j0.5090	j0.0012
6	1	0.2276+j0.2961	j0.0025
1	5	0.2603+j0.7382	j0.0008

Table 2. Bus voltage before DG connecting in 6-bus

Rtd. V 25 KV			
Bus No.	Bus Voltage (KV)	pu	deg
B1	25.00	1.00	0.00
B2	24.00	0.96	-0.35
B3	24.83	0.92	-0.53
B4	24.88	0.94	-0.41
B5	25.00	1.00	-0.08
B6	24.25	0.97	-0.10

Table 3. Bus and line parameters before DG connecting

Station	Active power [MW]	Reactive power [MVar]	Power factor	Current [KA]	Loading [%]
B1 external grid	13.32	1.72	0.99	0.31	-
Line 1-2	8.28	1.97	0.97	0.20	19.65
Line 1-5	1.09	-0.39	0.94	0.03	2.68
Line 1-6	3.95	0.13	1.00	0.09	9.12
B2 general load	4.00	1.00	0.97	0.10	-
Line 1-2	-8.25	-1.91	-0.97	0.20	19.65
Line 2-3	4.25	0.91	0.98	0.10	10.09
B3 general load	7.25	2.00	0.96	0.17	-
Line 2-3	-4.24	-0.90	-0.98	0.10	10.09
Line 3-4	-3.01	-1.10	-0.94	0.07	7.44
B4 general load	5.00	1.25	0.97	0.12	-
Line 3-4	3.01	1.11	0.94	0.07	7.44
Line 5-4	-8.01	-2.36	-0.96	0.19	19.38
B5 synchronous machine	8.00	4.18	0.89	0.21	112.83
Line 1-5	-1.09	0.39	-0.94	0.03	2.68
Line 5-4	8.03	2.42	0.96	0.19	19.38
Line 6-5	1.06	1.38	0.61	0.04	4.01
B6 general load	5.00	1.50	0.96	0.12	-
Line 1-6	-3.94	-0.13	-1.00	0.09	9.12
Line 6-5	-1.06	-1.37	-0.61	0.04	4.01

Table 4. Bus voltage after DG connecting

Rtd. V 25 KV			
Bus No.	Bus voltage (KV)	pu	deg
B1	25.00	1.00	0.00
B2	24.91	0.99	-0.21
B3	24.88	0.95	-0.25
B4	24.90	0.96	-0.22
B5	25.00	1.00	-0.22
B6	24.96	0.99	-0.07

Table 5. Bus and line parameters after DG connecting

Station	Active Power [MW]	Reactive Power [MVar]	Power Factor	Current [KA]	Loading [%]
B1 external grid	8.28	2.79	0.95	0.20	-
Line 1-2	5.36	2.11	0.93	0.13	13.29
Line 1-5	-0.09	0.03	-0.94	0.00	0.22
Line 1-6	3.02	0.65	0.98	0.07	7.13
B2 general load	4.00	1.00	0.97	0.10	-
Line 1-2	-5.35	-2.08	-0.93	0.13	13.29
Line 2-3	1.35	1.08	0.78	0.04	4.00
B3 general load	7.25	2.00	0.96	0.17	-
DG	5.00	-0.00	1.00	0.12	100.00
Line 2-3	-1.34	-1.08	-0.78	0.04	4.00
Line 3-4	-0.91	-0.92	-0.70	0.03	3.00
B4 general load	5.00	1.25	0.97	0.12	-
Line 3-4	0.91	0.92	0.70	0.03	3.00
Line 5-4	-5.91	-2.17	-0.94	0.15	14.59
B5 synchronous machine	8.00	3.03	0.94	0.20	96.93
Line 1-5	0.09	-0.03	0.94	0.00	0.22
Line 5-4	5.92	2.21	0.94	0.15	14.59
Line 6-5	1.99	0.86	0.92	0.05	5.00
B6 general load	5.00	1.50	0.96	0.12	-
Line 1-6	-3.01	-0.65	-0.98	0.07	7.13
Line 6-5	-1.99	-0.85	-0.90	0.05	5.00

The system has 30 buses (mainly 132 kV and 33 kV buses), 41 lines and 6 generator buses. The system bus parameters are given in Table 6. Bus data are given in Table 7. A 15 MW DG (about 5% of the total system load of 283+*j*126.2 MVA) is considered to be added to reinforce the system. The total power loss of the system reaches a minimum value when DG is located at bus 5, as shown in Figure 6. The optimal bus determined by the method proposed in this study is also bus 5.

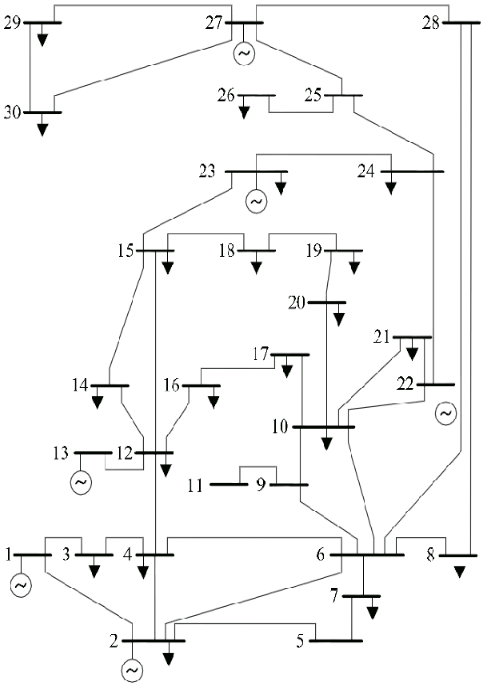

Figure 4. Reformed network of IEEE 30 buses system [14]

Table 6. Parameters of IEEE 30-bus system [11]

From Bus	To Bus	*R* (pu)	*X* (pu)	*B* (pu)	*V* line (KV)
1	2	0.0192	0.0575	0.0528	132
1	3	0.0452	0.1852	0.0408	132
2	4	0.057	0.1737	0.0368	132

3	4	0.0132	0.0379	0.0084	132
2	5	0.0472	0.1983	0.0418	132
2	6	0.0581	0.1763	0.0374	132
4	6	0.0119	0.0414	0.009	132
5	7	0.046	0.116	0.0204	132
6	7	0.0267	0.082	0.017	132
6	8	0.012	0.042	0.009	132
6	9	0	0.208	0	132
6	10	0	0.556	0	132
9	11	0	0.209	0	132
9	10	0	0.11	0	132
4	12	0	0.2559	0	132
12	13	0	0.14	0	33
12	14	0.1231	0.2559	0	33
12	15	0.0663	0.1304	0	33
12	16	0.0945	0.1987	0	33
14	15	0.221	0.0.1997	0	33
16	17	0.0524	0.1923	0	33
15	18	0.1073	0.2185	0	33
18	19	0.0639	0.1292	0	33
19	20	0.034	0.068	0	33
10	20	0.0936	0.209	0	33
10	17	0.0324	0.0845	0	33
10	21	0.0348	0.0749	0	33
10	22	0.0727	0.1499	0	33
21	22	0.0116	0.0236	0	33
15	23	0.1	0.202	0	33
22	24	0.115	0.179	0	33
23	24	0.132	0.27	0	33
24	25	0.1885	0.3292	0	33
25	26	0.2544	0.38	0	33
25	27	0.1093	0.2087	0	33
28	27	0	0.396	0	33
27	29	0.2198	0.4153	0	33
27	30	0.3202	0.6027	0	33
29	30	0.2399	0.4533	0	33
8	28	0.0636	0.2	0.0428	132
6	28	0.0169	0.0599	0.013	132

In this system:
Total loss from line flows = 0.1533418+j0.3293267
Total shunt loss = 0.00000000-j0.2661092
Slack bus power = 2.3873-j0.1765
Total Generation = 2.98734+j1.313224
Total Load = 2.834+j1.25
System loss = 0.15334+j0.06322
The power flow solution is shows in Table 8.

Table 7. Bus data of IEEE 30-bus system

Bus No.	Type	Generation		Load		Bus Voltage (pu)	$Q_{min.}$	$Q_{max.}$	$V_{min.}$	$V_{max.}$
		Real	Reactive	Real	Reactive					
1	Swing	0	0	0	0	1.06	0	0	1.00	1.00
2	*P-V*	0.4	0	0.217	0.127	1.045	-0.4	0.5	0.95	1.05
3	*P-Q*	0.2	0	0	0.3	1.01	-0.1	0.4	0.95	1.05
4	*P-Q*	0	0	0.3	0	1.082	-0.06	0.24	0.95	1.05
5	*P-V*	0	0	0.942	0.19	1.01	-0.4	0.4	0.95	1.05
6	*P-Q*	0	0	0	0	1.071	-0.06	0.24	0.95	1.05
7	*P-Q*	0	0	0	0	1	0	0	0.95	1.05
8	*P-V*	0	0	0.058	0.02	1	0	0	0.95	1.05
9	*P-Q*	0	0	0.112	0.075	1	0	0	0.95	1.05
10	*P-Q*	0	0	0	0	1	0	0	0.95	1.05
11	*P-V*	0	0	0.076	0.016	1	0	0	0.95	1.05
12	*P-Q*	0	0	0.228	0.109	1	0	0	0.95	1.05
13	*P-V*	0	0	0	0	1	0	0	0.95	1.05
14	*P-Q*	0	0	0.062	0.016	1	0	0	0.95	1.05
15	*P-Q*	0	0	0.082	0.025	1	0	0	0.95	1.05
16	*P-Q*	0	0	0.035	0.018	1	0	0	0.95	1.05
17	*P-Q*	0	0	0.09	0.058	1	0	0	0.95	1.05
18	*P-Q*	0	0	0.032	0.009	1	0	0	0.95	1.05
19	*P-Q*	0	0	0.095	0.034	1	0	0	0.95	1.05
20	*P-Q*	0	0	0.022	0.007	1	0	0	0.95	1.05
21	*P-Q*	0	0	0.175	0.112	1	0	0	0.95	1.05
22	*P-Q*	0	0	0	0	1	0	0	0.95	1.05
23	*P-Q*	0	0	0.032	0.016	1	0	0	0.95	1.05
24	*P-Q*	0	0	0.087	0.067	1	0	0	0.95	1.05
25	*P-Q*	0	0	0	0	1	0	0	0.95	1.05
26	*P-Q*	0	0	0.035	0.023	1	0	0	0.95	1.05
27	*P-Q*	0	0	0.024	0	1	0	0	0.95	1.05
28	*P-Q*	0	0	0	0	1	0	0	0.95	1.05
29	*P-Q*	0	0	0.024	0.009	1	0	0	0.95	1.05
30	*P-Q*	0	0	0.106	0.019	1	0	0	0.95	1.05

Table 8. Power flow solution of IEEE 30-bus system

Bus .No	Generation		Load demand		Bus Voltages Solved	
	Real	React	Real	React	Volt Mag.	Ang. (deg.)
1	2.3873	-0.1765	0	0	1.06	0
2	0.4	0.5204	0.217	0.127	1.045	-5.0361
3	0.2	0.1917	0	0.3	1.01	-9.8046
4	0	0.2271	0.3	0	1.082	-18.3703
5	0	0.3574	0.942	0.19	1.01	-13.5302
6	0	0.1931	0	0	1.071	-15.0062
7	0	0	0	0	1.0399	-15.1913

8	0	0	0.058	0.02	1.0244	-16.1105
9	0	0	0.112	0.075	1.0458	-15.0062
10	0	0	0	0	1.0792	-15.5341
11	0	0	0.076	0.016	1.0151	-8.7828
12	0	0	0.228	0.109	1.0026	-12.0551
13	0	0	0	0	1.0105	-10.1343
14	0	0	0.062	0.016	1.0311	-15.9467
15	0	0	0.082	0.025	1.0267	-16.0779
16	0	0	0.035	0.018	1.0293	-15.7442
17	0	0	0.09	0.058	1.0204	-16.2135
18	0	0	0.032	0.009	1.0135	-16.8029
19	0	0	0.095	0.034	1.0089	-17.0388
20	0	0	0.022	0.007	1.0119	-16.8652
21	0	0	0.175	0.112	1.0154	-16.5169
22	0	0	0	0	1.0171	-16.4866
23	0	0	0.032	0.016	1.0206	-16.5169
24	0	0	0.087	0.067	1.021	-16.7487
25	0	0	0	0	1.0518	-16.1605
26	0	0	0.035	0.023	1.0348	-16.5526
27	0	0	0.024	0	1.0239	-7.2915
28	0	0	0	0	1.0121	-10.7532
29	0	0	0.024	0.009	1.0605	-16.6376
30	0	0	0.106	0.019	1.0497	-17.427

IV. CONCLUSIONS

Analytical approaches are presented in this paper to determine the optimal location for placing DG in networked systems to minimize power losses. The proposed approaches are not iterative algorithms, like power flow programs. Therefore, there is no convergence problems involved, and results could be obtained very quickly. A series of simulation studies were also conducted to verify the validity of the proposed approaches, and results show that the proposed method works well. In practice, there are other constraints which may affect the DG placement. Nevertheless, methodology presented in this study can be effective, instructive and helpful to system designers in selecting proper sites to place DGs.

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