Research Article

Siting and Sizing of DG in Medium Primary Radial Distribution System with Enhanced Voltage Stability

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This paper intends to enumerate the impact of distributed generation (DG) on distribution system in terms of active as well as reactive power loss reduction and improved voltage stability. The novelty of the method proposed in this paper is the simple and effective way of sizing and siting of DG in a distribution system by using two-port Z-bus parameters. The validity of the method is verified by comparing the results with already published methods. Comparative study presented has shown that the proposed method leads existing methods in terms of its simplicity, undemanding calculation procedures, and less computational efforts and so does the time. The method is implemented on IEEE 69-bus test radial distribution system and results show significant reduction in distribution power losses with improved voltage profile of the system. Simulation is carried out in MATLAB environment for execution of the proposed algorithm.

1. Introduction

With the development of economy, load demands in distribution networks are sharply increasing. Hence, the distribution networks are operating more close to the voltage instability boundaries. The decline of voltage stability margin is one of the important factors which restrict the increase in load served by distribution companies [1]. Therefore, it is necessary to consider voltage stability with the integration of DG units in distribution systems. The insertion of DG presents opportunities as it leads many technical as well as economical benefits along with voltage stability attained due to reduction of line currents. Reduction of line currents also results in the line loss reduction. Planning issues, regulatory framework, and the availability of resources limit distribution network operators (DNOs) and developers in their ability to accommodate distributed generation but governments are incentivizing low carbon technologies, as a means of meeting environmental targets and increasing energy security. This momentum can be harnessed by DNOs to bring network operational benefits through improved voltage profile and lower line losses delivered by investment in DGs [2]. The main hurdles for the DNOs are the implementation

and reliability of the loss minimization technique; however researchers are trying hard to locate better techniques to exploit all possible benefits of DG [2].

This paper mainly focuses on the investigation of simple and efficient analytical approach for siting and sizing of DG for insertion in distribution system and evaluation of its performance in terms of system loss reduction and voltage profile correction. Two-port Z-bus parameters are utilized to find the expressions for designing DGs to be installed in distribution network. Optimal location and capacity of DG are calculated by the proposed method and results are compared with well-known exhaustive load flow (ELF) and results generated by software voltage stability and optimization (VS&OP) package [3]. Results show that proposed method follows similar prototype of those methods but with much less computational efforts and time.

Many methods of DG allocation, available in the literature, require complicated equations to solve which may further require calculations of many subcoefficients and rigorous iterative steps. Thus all those methods [4–12] gratuitously make the process time consuming and tedious especially for large systems. The proposed method directly utilizes the two-port Z-bus equations and converts them into power form to

FIGURE 1: Two-port distribution system network.

get both types of losses (active and reactive power losses) in the distribution system.

2. Proposed Methodology

This paper proposes an analytical method based on two-port Z-bus equations. It is observed that Z-bus equations in the modified form can give the optimal size of DG to be installed at each location and the proportional losses.

2.1. Two-Port Z-Bus Equations. Consider a distribution system as shown in Figure 1.

Two-port Z-bus equations for above system are

$$\begin{aligned} [V_1] &= [Z_{11}] [I_1] - [Z_{12}] [I_2] \\ [V_2] &= [Z_{21}] [I_1] - [Z_{22}] [I_2]. \end{aligned} \quad (1)$$

The negative sign indicates the opposite direction of I_2 as shown in Figure 1. Hence for a radial distribution system the two-port feeder equations can be written as

$$[V_G]_{GX1} = [Z_{GG}]_{GXG} [I_G]_{GX1} - [Z_{GL}]_{GXL} [I_L]_{LX1} \quad (2)$$

$$[V_L]_{LX1} = [Z_{LG}]_{LXG} [I_G]_{GX1} - [Z_{LL}]_{LXL} [I_L]_{LX1}, \quad (3)$$

where V_L , V_G , I_L , and I_G are column matrices of load and generator voltages and currents, respectively. G and L are generator and load buses, respectively.

The ratio of source to load voltage at light or no load condition can be written as

$$\frac{V_G}{V_L} = [\text{TVD}] = [Z_{GG}]^{-1} [Z_{GL}]. \quad (4)$$

$[Z_{GG}]$ & $[Z_{GL}]$ are corresponding partitioned portions of network Z_{bus} matrix. The above relation gives a *transmission voltage drop* (TVD) which is similar to the ILF matrix investigated in [13]. The TVD matrix will be of the dimension $G \times L$.

And

$$\text{TVD} \geq 1. \quad (5)$$

The TVD matrix thus formed gives the factor by which generator voltage is reduced to load voltage due to the drop across the impedance present in the power flow path from generator to respective load. Thus it can give the power contribution of each generator to each load as per the impedance encountered in the path so as to attain the total demand with maximum efficiency. The implication of TVD matrix is explained in the next section.

FIGURE 2: 7-Bus sample radial system.

2.2. Significance of TVD Matrix. It is assumed that the 7-bus sample radial distribution system as shown in Figure 2 has load A to E = 10 MW each which is fed by substation (S.S.) and DG. Each section of the line is of the same length, that is, 100 Km with line parameters in per unit per 100 km being $R = 10$ and $X = 25$. To demonstrate the utility of TVD matrix three cases with different line conditions are considered.

Case 1. Each section of the line has the same line parameters ($R = 0.5$ and $X = 0.25$ per unit).

Case 2. Values of line parameters between sections 2 and 3 are doubled.

Case 3. Values of line parameters between sections 3 and 6 are doubled.

For the cases mentioned above three TVD matrices are evaluated and are given as

$$\begin{aligned} [\text{TVD}]_1 &= \begin{matrix} & \begin{matrix} 2 & 3 & 4 & 5 & 6 \end{matrix} \\ \begin{matrix} \text{S.S.} \\ \text{DG} \end{matrix} & \begin{bmatrix} 0.75 & 0.50 & 0.50 & 0.50 & 0.25 \\ 0.25 & 0.50 & 0.50 & 0.50 & 0.75 \end{bmatrix} \end{matrix} \\ [\text{TVD}]_2 &= \begin{matrix} & \begin{matrix} 2 & 3 & 4 & 5 & 6 \end{matrix} \\ \begin{matrix} \text{S.S.} \\ \text{DG} \end{matrix} & \begin{bmatrix} 0.80 & 0.40 & 0.40 & 0.40 & 0.80 \\ 0.20 & 0.60 & 0.60 & 0.60 & 0.20 \end{bmatrix} \end{matrix} \quad (6) \\ [\text{TVD}]_3 &= \begin{matrix} & \begin{matrix} 2 & 3 & 4 & 5 & 6 \end{matrix} \\ \begin{matrix} \text{S.S.} \\ \text{DG} \end{matrix} & \begin{bmatrix} 0.20 & 0.60 & 0.60 & 0.60 & 0.80 \\ 0.80 & 0.40 & 0.40 & 0.40 & 0.20 \end{bmatrix} \end{matrix} \end{aligned}$$

Case 1. Since load A is at 100 Km from S.S. and 300 Km from DG, that is, three times of 100 Km, the corresponding factors of (TVD) matrix are 0.75 and 0.25, respectively. Similarly load E is at 300 Km from DG and 100 Km from S.S.; the corresponding TVD factors are 0.25 and 0.75, respectively. Whereas the loads B, C, and D are at the same distance from both S.S. and DG, the corresponding TVD factors are 0.50 for each.

Case 2. Load A is at the same distance from S.S. but the DG is now 400 Km away from it; the corresponding TVD factors for this condition are 0.80 and 0.20, respectively. Similarly load E is at the same distance from DG whereas S.S. is now 400 Km away from it, and the corresponding TVD factors are 0.20 and 0.80, respectively. The loads B, C, and D are at 300, 400, and 500 Km, respectively, from S.S. and 200, 300, and 400 Km, respectively, from DG. In other terms it can be said

TABLE 1: Analysis of TVD matrices obtained for 7-bus sample radial distribution system.

Case	Corresponding [TVD] matrix	Load bus	Impedance covered in the path		Load (MW)	(% Power shared)		Load shared (MW)	
			S.S.	DG		S.S.	DG	S.S.	DG
Case 1	[TVD] ₁	2	1/4th	3/4th	10	75	25	7.5	2.5
		3	2/4th	2/4th	10	50	50	5.0	5.0
		4	2/4th	2/4th	10	50	50	5.0	5.0
		5	2/4th	2/4th	10	50	50	5.0	5.0
		6	3/4th	1/4th	10	25	75	2.5	7.5
		Net capacity			50	50	50	25	25
Case 2	[TVD] ₂	2	1/5th	4/5th	10	80	20	8.0	2.0
		3	3/5th	2/5th	10	40	60	4.0	6.0
		4	3/5th	2/5th	10	40	60	4.0	6.0
		5	3/5th	2/5th	10	40	60	4.0	6.0
		6	4/5th	1/5th	10	20	80	2.0	8.0
		Net capacity			50	44	56	22	28
Case 3	[TVD] ₃	2	4/5th	1/5th	10	20	80	2.0	8.0
		3	2/5th	3/5th	10	60	40	4.0	6.0
		4	2/5th	3/5th	10	60	40	4.0	6.0
		5	2/5th	3/5th	10	60	40	4.0	6.0
		6	1/5th	4/5th	10	80	20	8.0	2.0
		Net capacity			50	56	44	28	22

TABLE 2: Estimation of power loss if the substation and DG are scheduled for different values.

Case	DG _{capacity} , MW		Total load (MW)	S.S. _{supply} , MW		Power Loss, MW	Power loss reduction (%)	Voltage profile	
	As per TVD	Scheduled		As per TVD	Scheduled			Min	Max
Case 1	25	25	50	25	25	2.08	60	0.97 @ 3	1.000 @ 6
		30			20	2.22	55	0.94 @ 3	1.000 @ 6
		20			30	2.19	52	0.94 @ 3	1.002 @ 6
Case 2	28	28	50	22	22	3.52	68	0.96 @ 3	1.001 @ 6
		35			15	3.8	58	0.94 @ 2	1.005 @ 6
		15			35	3.75	57	0.93 @ 3	1.008 @ 5
Case 3	22	22	50	28	28	2.072	61	0.95 @ 3	1.000 @ 6
		32			18	2.12	56	0.93 @ 3	1.051 @ 5
		18			32	2.23	56	0.93 @ 3	1.038 @ 5

that these loads are at 60% of distance from S.S. and at 40% of distance from DG and the corresponding TVD matrices for each of them are 0.40 and 0.60, respectively.

Case 3. Load E is at the same distance from DG but the S.S. is now 400 Km away from it; the corresponding TVD factors for this condition are 0.80 and 0.20, respectively. Similarly load A is at the same distance from S.S. whereas DG is now 400 Km away from it, and the corresponding TVD factors are 0.20 and 0.80, respectively. The loads B, C, and D are at 200, 300, and 400 Km, respectively, from S.S. but at 300, 400, and 500 Km, respectively, from DG. In other terms it can be said that these loads are at 40% of distance from S.S. and at 60% of distance from DG and the corresponding TVD matrices for each of them are 0.60 and 0.40, respectively.

From the analysis of three cases and the corresponding TVD factors it can be observed that the TVD matrix gives the

accurate idea of the proportion of impedance encountered in the path between respective load and the generator feeding that load. Thus TVD factor can play a decisive role in recommending the proportion of power contribution from each generator present in the system to the loads which will give the minimum power losses. The detailed analysis is furnished in Tables 1 and 2.

Thus from Table 2 it is clear that if DG and S.S. are scheduled according to TVD factor, the voltage profile improvement as well as power loss reduction is significant whereas the load sharing with different values will result in reduced power loss minimization percentage as well as declined voltage profile. Hence TVD factor can be considered as the decisive factor for DG capacity planning.

2.3. *Optimal Loss.* Optimal loss calculation assortment of equations can be developed as given below.

FIGURE 3: Flowchart of proposed method.

FIGURE 4: Comparative representation of three methods of loss minimization for 69-bus radial distribution system.

FIGURE 5: Optimal capacity of DG calculated for each location in the system.

FIGURE 6: Voltage profile correction of system.

Multiplying both sides by $[Z_{GG}]_{GXG}^{-1}$ (2) will be rewritten as

$$[Z_{GG}]_{GXG}^{-1}[V_G]_{GX1} = [I_G]_{GX1} - [Z_{GG}]_{GXG}^{-1}[Z_{GL}]_{GXL}[I_L]_{LX1}. \quad (7)$$

Thus,

$$[I_G]_{GX1} = [Z_{GG}]_{GXG}^{-1}[V_G]_{GX1} + [Z_{GG}]_{GXG}^{-1}[Z_{GL}]_{GXL}[I_L]_{LX1}. \quad (8)$$

Pre-multiplying equation (8) by $[V_G]_{GXG}$, and rewritten as;

$$\begin{aligned} [V_G]_{GXG}[I_G]_{GX1} &= [V_G]_{GXG}[Z_{GG}]_{GXG}^{-1}[V_G]_{GX1} \\ &+ [V_G]_{GXG}[Z_{GG}]_{GXG}^{-1}[Z_{GL}]_{GXL}[I_L]_{LX1}. \end{aligned} \quad (9)$$

Thus, (9) can be written in power form as

$$\begin{aligned} S_{\text{generator}} &= S_{\text{generator loss}} \\ &+ S_{\text{power supplied by each generator to load,}} \end{aligned} \quad (10)$$

where

$$\begin{aligned} \text{Power developed by generators} &= S_{\text{generator}} \\ &= [V_G]_{GXG}[I_G]_{GX1} \end{aligned}$$

Power loss supplies by generators

$$= S_{\text{generator loss}} = [V_G]_{GXG}[Z_{GG}]_{GXG}^{-1}[V_G]_{GX1} \quad (11)$$

Load contribution of each generator

$$\begin{aligned} &= S_{\text{load contribution of each generator}} \\ &= [V_G]_{GXG}[Z_{GG}]_{GXG}^{-1}[Z_{GL}]_{GXL}[I_L]_{LX1} \\ &= [V_G]_{GXG}[TVD]_{GXL}[I_L]_{LX1}, \end{aligned}$$

where $[Z_{GG}]_{GXG}$ = Corresponding partitioned portion of Z_{bus} matrix. $[Z_{GL}]_{GXL}$ = Corresponding partitioned portion of Z_{bus} matrix. $[V_G]_{GX1}$ = Column matrix of generator voltages. $[I_L]_{LX1}$ = Column matrix of load currents. $[V_G]_{GXG}$ = unity matrix of dimension $G \times G$,

with all diagonal elements replaced by respective generator voltages.

Thus,

Active power developed by generators

$$= [P_{\text{generator}}]_{G \times 1} = \sum_{i=1}^m \sum_{j=1}^m [V_G]_{i \times j} [I_G]_{j \times 1} \quad (12)$$

Active load contribution from all generators

$$= [P_{\text{LOAD}}]_{G \times 1} = \sum_{i=1}^m \sum_{j=1}^m \sum_{k=1}^{nl} [V_G]_{i \times j} [\text{TVD}]_{j \times k} [I_L]_{k \times 1} \quad (13)$$

Active power losses supplied by generators

$$= [P_{\text{loss}}]_{L \times 1} = \sum_{i=1}^m \sum_{j=1}^m [V_G]_{i \times j} [Z_{GG}]_{j \times j}^{-1} [V_G]_{i \times 1}, \quad (14)$$

where m is total number of generators and nl is the total number of load buses.

Equation (13) will give the power contribution of each generator to the system load. So it may also be used for calculation of DG capacity. Equation (14) will give total active power losses supplied by available sources in the system. This equation is used for loss calculation of the system with DG installed at any particular load bus and, thus, it can be used for finding the optimal location for DG insertion.

2.4. Optimal DG Capacity. As explained in Section 2.2. transmission voltage drop obtained by (4) plays an important role in calculating the approximate value of DG capacity. Equation (13) can be used for developing the equation for DG capacity evaluation which is given as

Active load contribution from all generators

$$= [P_{\text{load}}]_{Gm \times 1} = \sum_{i=1}^m \sum_{j=1}^m \sum_{k=1}^{nl} [V_G]_{i \times j} [\text{TVD}]_{j \times k} [I_L]_{k \times 1} \quad (15)$$

$$= \begin{matrix} G_{1\text{SUPPLY}} \\ G_{2\text{SUPPLY}} \\ \vdots \\ G_m \end{matrix} \begin{matrix} L_1 & L_2 & \dots & L_{nl} \\ \hline V_{G1} \text{TVD}_{G1L1} I_{L1} + & V_{G1} \text{TVD}_{G1L2} I_{L2} + & \dots & + V_{G1} \text{TVD}_{G1Lnl} I_{nl} \\ V_{G2} \text{TVD}_{G2L1} I_{L1} + & V_{G2} \text{TVD}_{G2L2} I_{L2} + & \dots & + V_{G2} \text{TVD}_{G2Lnl} I_{nl} \\ \vdots & \vdots & \ddots & \vdots \\ V_{Gm} \text{TVD}_{mGmL1} I_{L1} + & V_{Gm} \text{TVD}_{mGmL2} I_{L2} & \dots & + V_{Gm} \text{TVD}_{mGmLnl} I_{nl} \end{matrix}_{m \times 1}.$$

From the matrix given by (15) the power contribution of the generators to each load present in the system can be obtained which is actually similar to the T-index value explained in [14]. Here each row of the matrix gives equation for evaluating the power supplied by respective generator to loads present in the system and each individual term of the equation indicates the fraction of load contributed by it. Thus the equation explored at each

row will give the maximum capacity of the respective generator.

Now if DG is installed at i th load bus then that load bus is considered as the generator bus so the total number of generator buses is increased by one and the number of load buses is decreased by one. So the modified matrix P_{load} with new dimension as $(m+1) \times 1$ will be

$$[P_{\text{load}}]_{(m+1) \times 1} = \begin{matrix} G_{1\text{SUPPLY}} \\ G_{2\text{SUPPLY}} \\ \vdots \\ \text{DG}_i \\ \vdots \\ G_{m+1} \end{matrix} \begin{matrix} L_1 & L_2 & \dots & L_{nl-1} \\ \hline V_{G1} \text{TVD}_{G1L1} I_{L1} + & V_{G1} \text{TVD}_{G1L2} I_{L2} + & \dots & + V_{G1} \text{TVD}_{G1Lnl-1} I_{nl-1} \\ V_{G2} \text{TVD}_{G2L1} I_{L1} + & V_{G2} \text{TVD}_{G2L2} I_{L2} + & \dots & + V_{G2} \text{TVD}_{G2Lnl-1} I_{nl-1} \\ \vdots & \vdots & \ddots & \vdots \\ V_{\text{DG}_i} \text{TVD}_{\text{DG}_i L1} I_{L1} + & V_{\text{DG}_i} \text{TVD}_{\text{DG}_i L2} I_{L2} + & \dots & + V_{\text{DG}_i} \text{TVD}_{\text{DG}_i Lnl-1} I_{nl-1} \\ \vdots & \vdots & \ddots & \vdots \\ V_{G_{m+1}} \text{TVD}_{m+1G_{m+1}L1} I_{L1} + & V_{G_{m+1}} \text{TVD}_{m+1G_{m+1}L2} I_{L2} & \dots & + V_{G_{m+1}} \text{TVD}_{m+1G_{m+1}Lnl-1} I_{nl-1} \end{matrix}_{(m+1) \times 1}. \quad (16)$$

TABLE 3: Comparative analysis of three methods of loss minimization for 69-bus system.

Bus numbers	Calculated loss at different DG location			Bus numbers	Calculated loss (Kw) at different DG location		
	VS&OP	IA	Proposed method		VS&OP	IA	Proposed method
Without DG	219.28	219.28	183.726 + 83.215 <i>i</i>	Bus 61	22.62	23.45	23.22
Bus 02	219.19	219.20	196.512 + 88.981 <i>i</i>	Bus 62	24.54	25.68	25.95
Bus 03	219.10	219.13	204.169 + 92.157 <i>i</i>	Bus 63	27.42	29.03	29.06
Bus04	218.86	218.94	203.994 + 91.736 <i>i</i>	Bus 60	33.85	36.73	36.09
Bus 05	216.57	217.07	202.239 + 89.698 <i>i</i>	Bus 64	39.81	43.16	41.43
Bus 06	185.25	189.55	176.392 + 76541 <i>i</i>	Bus 59	42.52	46.77	44.97
Bus 07	154.08	160.96	149.418 + 62.817 <i>i</i>	Bus 58	50.52	55.89	53.63
Bus 08	146.64	154.24	142.988 + 59.555 <i>i</i>	Bus 65	60.19	66.00	62.81
Bus 09	143.47	150.96	140.037 + 58.036 <i>i</i>	Bus 57	71.74	79.38	75.02
Bus 10	157.57	163.20	150.880 + 6.3061 <i>i</i>	Bus 56	116.38	125.62	117.22
Bus 11	158.79	164.15	151.218 + 63.496 <i>i</i>	Bus 55	124.41	133.35	124.13
Bus 12	164.25	168.83	155.161 + 66.041 <i>i</i>	Bus 54	132.67	141.12	131.18
Bus 13	171.66	175.52	161.445 + 69.624 <i>i</i>	Bus 53	138.61	146.60	136.21
Bus 14	175.54	178.90	164.182 + 71.518 <i>i</i>	Bus09	143.47	150.96	140.03
Bus 15	177.79	180.76	165.576 + 72.683 <i>i</i>	Bus 08	146.64	154.24	142.98
Bus 16	178.08	180.99	165.530 + 72.761 <i>i</i>	Bus 51	153.42	160.33	148.81
Bus 17	178.80	181.60	165.929 + 73.093 <i>i</i>	Bus 07	154.08	160.96	149.41
Bus 18	178.82	181.62	165.938 + 73.099 <i>i</i>	Bus 10	157.57	163.20	150.88
Bus 19	179.89	182.62	167.029 + 73.676 <i>i</i>	Bus 11	158.79	164.15	151.21
Bus 20	180.52	183.20	167.519 + 73.957 <i>i</i>	Bus 12	164.25	168.83	155.16
Bus 21	181.47	184.08	167.756 + 74.179 <i>i</i>	Bus 66	164.07	169.15	156.52
Bus 22	181.53	184.14	168.075 + 74.313 <i>i</i>	Bus 67	164.19	169.26	156.63
Bus 23	182.19	184.77	168.964 + 74.728 <i>i</i>	Bus 13	171.66	175.52	161.44
Bus 24	183.53	186.06	170.176 + 75.332 <i>i</i>	Bus 52	169.73	175.43	163.22
Bus 25	186.31	188.74	173.070 + 76.726 <i>i</i>	Bus 14	175.54	178.90	164.18
Bus 26	187.53	189.71	174.004 + 77.188 <i>i</i>	Bus 68	175.01	178.99	165.50
Bus 27	187.89	190.25	174.562 + 77.459 <i>i</i>	Bus 16	178.08	180.99	165.53
Bus 28	219.24	219.24	204.274 + 92.411 <i>i</i>	Bus 69	175.06	179.99	165.55
Bus 29	219.27	219.27	204.296 + 92.461 <i>i</i>	Bus 15	177.79	180.76	165.57
Bus 30	219.26	219.27	204.295 + 92.464 <i>i</i>	Bus 17	178.80	181.60	165.92
Bus 31	219.26	219.26	204.294 + 92.464 <i>i</i>	Bus 18	178.82	181.62	165.93
Bus 32	219.26	219.26	204.289 + 92.464 <i>i</i>	Bus 19	179.89	182.62	167.02
Bus 33	219.25	219.25	204.279 + 92.462 <i>i</i>	Bus 20	180.52	183.20	167.51
Bus 34	219.24	219.24	204.272 + 92.462 <i>i</i>	Bus 21	181.47	184.08	167.75
Bus 35	219.25	219.25	204.278 + 92.465 <i>i</i>	Bus 22	181.53	184.14	168.07
Bus 36	219.23	219.24	204.272 + 92.407 <i>i</i>	Bus 23	182.19	184.77	168.96
Bus 37	219.25	219.25	204.279 + 92.421 <i>i</i>	Bus 24	183.53	186.06	170.17
Bus 38	219.23	219.23	204.266 + 92.406 <i>i</i>	Bus 25	186.31	188.74	173.07
Bus 39	219.23	219.23	204.263 + 92.403 <i>i</i>	Bus 26	187.53	189.71	174.00
Bus 40	219.23	219.23	204.263 + 92.403 <i>i</i>	Bus 27	187.89	190.25	174.56
Bus 41	219.19	219.19	20.4227 + 92.367 <i>i</i>	Bus 6	185.25	189.55	176.39
Bus 42	219.27	219.17	204.211 + 92.349 <i>i</i>	Without DG	219.28	219.28	181.45
Bus 43	219.17	219.17	204.209 + 92.347 <i>i</i>	Bus 5	216.57	217.07	202.23
Bus 44	219.17	219.17	204.209 + 92.347 <i>i</i>	Bus 49	216.95	216.96	202.27
Bus 45	219.16	219.16	204.204 + 92.343 <i>i</i>	Bus 50	216.95	216.96	202.27

TABLE 3: Continued.

Bus numbers	Calculated loss at different DG location			Bus numbers	Calculated loss (Kw) at different DG location		
	VS&OP	IA	Proposed method		VS&OP	IA	Proposed method
Bus 46	219.16	219.16	204.204 + 92.343 <i>i</i>	Bus 48	218.52	218.55	203.65
Bus 47	218.99	219.03	204.083 + 91.952 <i>i</i>	Bus 4	218.86	218.94	203.99
Bus 48	218.52	218.55	203.657 + 90.906 <i>i</i>	Bus 47	218.99	219.03	204.08
Bus 49	216.95	216.96	202.270 + 87.523 <i>i</i>	Bus 3	219.1	219.13	204.16
Bus 50	216.95	216.96	202.270 + 87.522 <i>i</i>	Bus 45	219.16	219.16	204.20
Bus 51	153.42	160.33	148.819 + 62.547 <i>i</i>	Bus 46	219.16	219.16	204.20
Bus 52	169.73	175.43	163.220 + 68.138 <i>i</i>	Bus 43	219.17	219.17	204.20
Bus 53	138.61	146.6	136.219 + 56.099 <i>i</i>	Bus 44	219.17	219.17	204.20
Bus 54	132.67	141.12	131.189 + 53.571 <i>i</i>	Bus 42	219.27	219.17	204.21
Bus 55	124.41	133.35	124.139 + 50.011 <i>i</i>	Bus 41	219.19	219.19	204.22
Bus 56	116.38	125.62	117.224 + 46.495 <i>i</i>	Bus 2	219.19	219.2	204.23
Bus 57	71.74	79.38	075.022 + 32.560 <i>i</i>	Bus 39	219.23	219.23	204.26
Bus 58	50.52	55.89	053.634 + 25.481 <i>i</i>	Bus 40	219.23	219.23	204.26
Bus 59	42.52	46.77	044.974 + 22.625 <i>i</i>	Bus 38	219.23	219.23	204.26
Bus 60	33.85	36.73	36.095 + 20.018 <i>i</i>	Bus 34	219.24	219.24	204.27
Bus 61	22.62	23.45	23.220 + 13.647 <i>i</i>	Bus 36	219.23	219.24	204.27
Bus 62	24.54	25.68	25.951 + 14.985 <i>i</i>	Bus 28	219.24	219.24	204.27
Bus 63	27.42	29.03	29.066 + 16.642 <i>i</i>	Bus 35	219.25	219.25	204.27
Bus 64	39.81	43.16	41.438 + 23.092 <i>i</i>	Bus 33	219.25	219.25	204.27
Bus 65	60.19	66.00	62.811 + 33.680 <i>i</i>	Bus 37	219.25	219.25	204.27
Bus 66	164.07	169.15	156.526 + 65.745 <i>i</i>	Bus 32	219.26	219.26	204.28
Bus 67	164.19	169.26	156.631 + 65.790 <i>i</i>	Bus 31	219.26	219.26	204.29
Bus 68	175.01	178.99	165.503 + 71.004 <i>i</i>	Bus 30	219.26	219.27	204.29
Bus 69	175.06	179.99	165.554 + 71.030 <i>i</i>	Bus 29	219.27	219.27	204.29

Thus the desired capacity of the DG is the summation of terms of power contribution of DG to each load

$$\begin{aligned}
 DG_{\text{capacity},i} &= V_{DG_i} TVD_{DG_i L1} I_{L1} + V_{DG_i} TVD_{DG_i L2} I_{L2} \\
 &+ \cdots + V_{DG_i} TVD_{DG_i L_{n-1}} I_{L_{n-1}} \\
 DG_{\text{capacity},i} &= \sum_{i=1}^k \sum_{j=1}^n V_{DG_i} TVD_{DG_i L_j} I_{L_j},
 \end{aligned} \quad (17)$$

where k is the total number of generator buses and n is the total number of load buses.

2.5. Optimal Location. Steps to find the optimum location are given below.

Step 1. Calculate the system losses without DG by using (14).

Step 2. Put DG at every load bus and calculate the losses by updating (14) and corresponding DG capacity by using (17).

Step 3. Compare the losses with the base case (without DG).

Step 4. Prepare the priority list in ascending order of losses calculated for each location of DG.

Step 5. Top ranking bus is considered as the optimum location for DG installation.

Step 6. The capacity of DG calculated for that location is considered as the optimum capacity of DG at that location. From (17) corresponding optimal DG capacity at optimal location can be evaluated.

3. Flowchart for Proposed Method

See Figure 3.

4. Results and Analysis

4.1. Test System. The proposed method is tested on 69-bus radial distribution system with a total real and reactive load of 3.8 MW and 2.69 MVar, respectively [15]. An analytical software tool has been developed in MATLAB environment to execute the proposed algorithm.

TABLE 4: Summarized results of three methods.

Methods	Optimal location	Optimal size (MVA)	Base active loss, kw (without DG)	Reduced active loss (kw)
Proposed method	61	2.368	181.452	23.22
VS&OP	61	2.2429	219.28	23.45
ELF	61	2.2219	219.28	22.64

TABLE 5: Voltage profile of the system.

Methods	Voltage @ bus without DG		Voltage @ bus with DG	
	Min	Max	Min	Max
Proposed method	0.91 @ 65	1.01 @ 1	0.96 @ 28	1.00 @ 1
VS&OP	0.90 @ 65	1.00 @ 1	0.95 @ 27	1.00 @ 1
ELF	0.91 @ 65	1.00 @ 1	0.94 @ 27	1.00 @ 1

4.2. Assumptions. (1) Designing of DG is performed at peak load only. (2) Maximum active and reactive power limit of DG for different test systems is assumed to be equal to the total active load of the system. (3) The lower and upper voltage thresholds for DG are set at 0.95–1.05 pu.

4.3. Simulation Results. Table 3 and Figure 4 show the comparative analysis of three methods of loss minimization for 69-bus system. Results show that the proposed method follows the similar trend line as that of the results generated by VS&OP package as well as ELF. The priority list shown in Table 3 indicates that bus 61 is the best location for installing the DG. The next suitable locations are buses number 60, 62, 63, and so forth. Other two methods can calculate only active power losses whereas proposed method gives both active and reactive loss reductions. Figure 5 indicates the optimal capacity of DG at corresponding location which will give the minimum possible power losses. Hence it is observed that if DG is installed at bus 61 with capacity of 2.03 MWatts and 1.22 MVAR recommended by proposed method then maximum loss reduction is possible. Since DG installation at suitable location reduces the power flows of many lines in the system which in turn reduces the overall I^2R loss and improves the corresponding node voltages, it is seen that DG insertion at the appropriate location can improve the voltage profile of the system which can be observed from Figure 6. Table 4 gives the summarized results of all the three methods which indicate that the proposed method shows enhanced optimality of solution. Table 5 indicates the voltage profile of the system for case (i) without DG and case (ii) with DG installed at optimum location, that is, bus 61. It indicates that the proposed method suggests the location as well as capacity of DG which will give improved voltage profile as compared to other methods.

5. Conclusion

This paper presents a novel method which uses two-port Z-bus equations for finding the optimal location and optimal size at that location. It avoids the time consuming and cumbersome iterative approach for handling the undemanding problem of designing the new DG to be installed in radial distribution system. The proposed method for designing DG to install in distribution system is tested on 69-bus test distribution system and results are verified by comparing with well-known exhaustive load flow solutions and results generated by already published VS&PO package. The proposed method provides an efficient tool for distribution system loss calculation, for loss minimization, and for designing the DG to install in system to attain enhanced voltage stability. The method is applied for single DG allocation but it can also be implemented for multiple DG allocation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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