EVALUATION OF OPTIMAL ACCESS LOCATION AND CAPACITY OF DG FOR INSERTION IN DISTRIBUTION SYSTEM WITH CONDENSED POWER LOSSES SHOWING IMPROVED CRITICAL BUS VOLTAGE STIPULATION

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Abstract— *This paper intent to enhance the revenue of optimally planned distributed generation (DG) insertion in distribution system in terms of condensed active and reactive power losses, improved critical bus voltage and system voltage profile which may undeniably ensures aided load expansion and system stability. The novelty of this paper is a multi-objective approach based on two port transmission parameters for optimally determining the size and access point for DG insertion in distribution system. To validate the proposed method the results obtained are compared with already published Analytical Method and the well known Exhaustive Load Flow method. The Comparative study presented has shown that the proposed method leads existing methods in terms of its ease, reduced computational time and handling less number of variables. Despite of that cross verification of results with multi-objective approach assures the optimality of estimated parameters with improved efficiency. To exhibit the utility of the method, it is implemented on standard IEEE 16 bus, 33 bus and 69 bus test radial distribution systems. The simulation is carried out in MATLAB environment for execution of the proposed algorithm.*

Key words- *Modified transmission parameters method, Distributed generation, Distribution power loss, Critical bus voltage, System voltage profile.*

Nomenclautre

of	objective function	Q_{SS}	reactive supply from sub-station, MVAR
n	number of buses	P_{di}	active power demand at bus i, Kwatt
m	number of generator buses	Q_{di}	reactive power demand at bus i, KVAR
nl	number of load buses	P_{DG}	active power capacity of DG, MW
br	number of branches	Q_{DG}	reactive power capacity of DG, MVAR
SE	sources of energy	**KVA**	Kilo Volt amp
P_{loss}	active loss, Kwatt (kilowatt)	OPF_{DG}	Operating power factor of DG
Q_{loss}	reactive power loss, KVAR (Kilo volt amps reactive)	PF_{load}	power factor of load

$\mathbf{P_i}$	active power injection at bus i, MW (Megawatts)	$\mathbf{P_{load}}$	combined active load supplied by DG
$\mathbf{Q_i}$	reactive power injection at bus i, MVAR (Megavolt amps reactive)	$\mathbf{Q_{laod}}$	combined reactive load supplied by DG
$\mathbf{P_{SS}}$	active power supply from sub-station, MW	P_{di}	active power demand at bus i, Kwatt

1. Introduction

Tremendous growth in population and available energy sources shows an inversely proportional ratio. This adverse circumstance provides a vent for the search of new energy sources. A renewable energy source is the most suitable option to comply this inverse ratio. The progression from passive distribution network to active due to the insertion of DG presents opportunities. Governments are incentivizing low carbon technologies, as a means of meeting environmental targets with enhanced energy security. This thrust can be harnessed by Distribution Network Opera- tors (DNOs) to bring network operational benefits through lower losses delivered by investment in DG [1]. For the DNOs the main hurdles are the implementation and reliability of the DG installation strategies as well as techniques; however researchers are trying hard to locate superior techniques to exploit all possible benefits of DG [2]. This paper mainly focuses on the evaluation of impacts of DG allocation on system losses, voltage profile improvement of system and critical bus. Transmission parameters are utilized to find the expressions for designing DGs to be installed in distribution network. Optimal access location and capacity of DG is calculated by the proposed method and results are compared with Improved Analytical (IA) method [3, 4] and Exhaustive Load Flow (ELF) method. The proposed method follows similar trend of results obtained by those methods but with less computational efforts and computational time. Despite of that it provides aided advantage of the guaranteed optimality of the evaluated parameters due to multi constraint approach.

Many methods of DG allocation, available in the literature need complicated equations to solve which may further require many sub-coefficient calculations, rigorous iterative steps etc. Thus all those methods [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] gratuitously make the process time consuming, tedious especially for large systems. Apart from this all those methods provide solution based on single objective i.e. loss minimization whereas proposed method provides multi constraint based solution to enhance the degree of guaranteed optimality of the parameters. The proposed method utilizes the transmission equations and converts it into power form to get both types of losses (active and reactive power losses) as well as capacity of DG to be inserted in the distribution system which provide the ease in calculations as well as reduces the computational time.

2. Method

2.1 Objective Function

Optimal injection point is the location in radial distribution network at which if the power is injected the minimum power loss with satisfied operating constraints will occur. The operating constraints may be voltage profile of the system, overall power generation capacities and radial structure of network. Therefore for investigating optimum location with minimum power loss as the objective function is formulated as,

$$of = \min \sum_{i=1}^{br} P_{loss,j}, i \qquad (1)$$

Subjected to: satisfied constraints
i is the load bus at which DG is installed.

2.2.1. Load balance constraint

$$P_{ss} + P_{DG} - \sum_{i=1}^{nl} P_{di} - \sum_{j=1}^{br} P_{loss} = 0$$

$$Q_{ss} + Q_{DG} - \sum_{i=1}^{nl} Q_{di} - \sum_{j=1}^{br} Q_{loss} = 0$$

2.2.2. Voltage constraint

At each bus, voltage must be within standard limits
$V_i^{\min} \langle V_i \langle V_i^{\max}$, Where V_i is the voltage at bus i, $V^{\min}$ and $V^{\max}$ are minimum and maximum limits of the bus voltage.

2.2.3. Capacity constraint

Current through each branch in the network should be within thermal limits of conductor,
$I_{i,i+1} \le I_{i,i+1\max}$, Where $I_{i,i+1\max}$ is the maximum loading on branch between i and i + 1. i, i+1 is the current flowing through the ith branch.

2.2.4 Real power generation constraint

$P_{DGi\,\min} \langle P_{DGi} \langle P_{DGi\,\max}$, Where P_{DGimin} and P_{DGimax} are the minimum and maximum limits of active power capacity of DG to be installed at bus i.

2.2.5. Reactive power generation constraint

$Q_{DGi\,\min} \langle Q_{DGi} \langle Q_{DGi\,\max}$, Where Q_{DGimin} and Q_{DGimax} are the minimum and maximum limits of reactive power capacity of DG to be installed at bus i.

2.3. DG Models

DGs may be represented by their power injection capabilities and the power factor (p.f.) at which they operate. Table 1 gives information about basic four DG models which are generally used in power system. The proposed algorithm is applicable for all the four models mentioned in Table 1.

Table 1

DG Models [18]

OPF_{DG}	DG Model	Power injection capability	Example
unity	Type 1	Active power only	Solar, photovoltaic cells, fuel cells etc with power factor control.
zero	Type 2	Reactive Power only	Synchronous compensators such as gas turbines.
$0 < OPF_{DG} < 1$, lagging	Type 3	Active and reactive power both	Synchronous generators such as combustion turbines, combined turbines etc.
$0 < OPF_{DG} < 1$, leading	Type 4	Active power and consumes reactive power	Wind turbines

The proposed algorithm is applicable for all the four models mentioned above.

2.4. Modified Transmission Parameters Method (MTP)

The proposed Modified Transmission Parameters Method (MTP) utilizes two port transmission equations in its modified form to find the optimal access location, optimal capacity at that location, power factor and according to that suitable type of the DG to be installed in the distribution system.

Two Port Transmission Equations for any power system can be represented as

$$V_1 = A\,V_2 + B\,I_2 \tag{2}$$
$$I_1 = C\,V_2 + D\,I_2 \tag{3}$$

Two port transmission equations given by (2) and (3) can reveal the feeder condition also. Hence for a radial distribution system the feeder equations can be written as

$$[V_G] = [A][V_L] + [B][I_L] \tag{4}$$
$$[I_G] = [C][V_L] + [D][I_L] \tag{5}$$

$L \forall L_1, L_2, \cdots L_{nl}$, $G \forall G_1, G_2, \cdots G_m$

where,

$[V_L]_{L\times 1}$ = Column matrix of load voltages.

$[V_G]_{G\times 1}$ = Column matrix of generator voltages.

$[I_L]_{L\times 1}$ = Column matrix of load currents.

$[I_G]_{G\times 1}$ = Column matrix of generator currents.

Rearranging equation (4) the ratio of load to source voltage at no load or light load condition can be obtained

$V_L/V_G = [A]^{-1}$ (6)

But the value of [A] in terms of Z-parameters is

$[A] = [Z_{11}/Z_{21}]$

Therefore, $[A]^{-1} = [Z_{11}/Z_{21}]^{-1}$

$= [Z_{21}]\,[Z_{11}]^{-1}$ (7)

$= [Z_{LG}][Z_{GG}]^{-1}$ (8)

$[Z_{GG}]$ & $[Z_{LG}]$ are corresponding partitioned portions of network Z_{bus} matrix. The above relation would give the factor by which the source voltage get transformed into load voltage due to I^2R and I^2X losses encountered in the power flow path. Therefore this factor can be defined as **Impedance Loss Factor** (ILF) [19] and the matrix thus formed as ILF matrix having dimension L×G.

Thus, $ILFij \leq 1$ (9)

$i \forall L_1 , L_2 , \cdots L_{nl}$, $j \forall G_1 , G_2 , \cdots G_m$

This factor can also be used for the finding the economic load dispatch. It can give the most economic proportion of the power which may be supplied by each source present in the system to individual load so as to accomplish the total demand with maximum efficiency.

2.4.1. Optimal Loss

Equation (4) can be rearranged as

$[V_L] = [A]^{-1}[V_G]-[A]^{-1}[B][I_L]$ (10)

But, $[A]^{-1}= [Z_{LG}][Z_{GG}]^{-1}$

and $[A]^{-1}[B] = [Z_{LL}]$

thus rewriting equation (10) as

$[V_L] = [Z_{LG}][Z_{GG}]^{-1}[V_G]-[Z_{LL}][I_L]$ (11)

where, $[Z_{LL}]_{L\times L}$ is corresponding partioned portion of Z_{bus} matrix.

After pre-multiplying by $[I_L]_{L\times L}$ the equation (11) can be rewritten as

$$\begin{aligned}[I_L]_{L\times L}[V_L]_{L\times 1} &= [I_L]_{L\times L}[[Z_{LG}][Z_{GG}]^{-1}]_{L\times G}[V_G]_{G\times 1} - [I_L]_{L\times L}[Z_{LL}]_{L\times L}[I_L]_{L\times 1} \\ &= [I_L]_{L\times L}[A]^{-1}_{L\times G}[V_G]_{G\times 1} - [I_L]_{L\times L}[Z_{LL}]_{L\times L}[I_L]_{L\times 1} \\ &= [I_L]_{L\times L}[ILF]_{L\times G}[V_G]_{G\times 1} - [I_L]_{L\times L}[Z_{LL}]_{L\times L}[I_L]_{L\times 1} \end{aligned} \quad (12)$$

Thus, Power consumed in load = $[P_{Load}]_{L\times 1} = \sum_{i=1}^{nl}\sum_{j=1}^{nl}[I_L]_{i\times j}[V_L]_{i\times 1}$ (13)

Power supplied from generators = $[P_G]_{L\times 1} = \sum_{i=1}^{nl}\sum_{j=1}^{nl}\sum_{k=1}^{m}[I_L]_{i\times j}[ILF]_{i\times k}[V_G]_{k\times 1}$ (14)

Transmission power losses = $[P_{Loss}]_{L\times 1} = \sum_{i=1}^{nl}\sum_{j=1}^{nl}[I_L]_{i\times j}\,[Z_{LL}]_{i\times j}[I_L]_{i\times 1}$ (15)

Equation (15) can give total power losses occurred in the system supplied by all available sources in the system. To calculate the optimal loss the DG is placed on each bus (excluding the sub-station) and the corresponding losses are calculated by using equation (15) whereas various optimal losses are calculated by using equations,

$$\text{Optimal power loss} = \min \sum_{i=1}^{nl} \sum_{j=1}^{nl} [I_L]_{i\times j} [Z_{LL}]_{i\times j} [I_L]_{i\times 1} \text{ KVA} \tag{16}$$

$$\text{Optimal active power loss} = \min \sum_{i=1}^{nl} \sum_{j=1}^{nl} [I_L]_{i\times j} [R_{LL}]_{i\times j} [I_L]_{i\times 1} \text{ KWATT} \tag{17}$$

$$\text{Optimal reactive power loss} = \min \sum_{i=1}^{nl} \sum_{j=1}^{nl} [I_L]_{i\times j} [X_{LL}]_{i\times j} [I_L]_{i\times 1} \text{ KVAR} \tag{18}$$

2.4.2 Optimal access location

To trace optimal access location, DG is installed at each bus separately (excluding the sub-station) and corresponding losses are calculated by using equation (16), (17) and (18). The priority list is prepared by arranging the buses in ascending order of the losses evaluated after DG insertion at various locations. Top ranking bus is considered as the Optimal Access Location for DG installation.

2.4.3 Optimal DG capacity

Impedance Loss Factor (ILF) given by the equation (9) plays an imperative role in calculating the approximate value of DG capacity. The 7 Bus sample radial distribution system fed by Sub-Station (S.S.) and DG as shown in Fig. 1 is considered with different combinations of line parameters for demonstrating the significance of ILF matrix.

Case 1: each section of the line has same line parameters (R = 0.5 and X = 0.25 per unit).
Case 2: values of line parameters between section 2 to 3 are doubled.
Case 3: values of line parameters between section 3 to 6 are doubled.

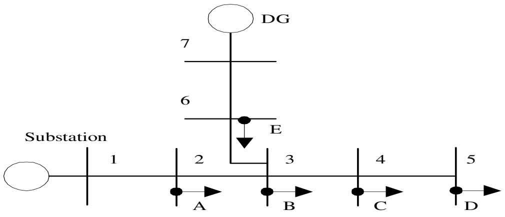

Fig. 1. 7 Bus Sample Radial System

For the system shown in Fig. 1 the proportion of desired load sharing between the available sources is given by $[\mathrm{ILF}]_{\mathrm{i}}$, $[\mathrm{ILF}]_{\mathrm{ii}}$, and $[\mathrm{ILF}]_{\mathrm{iii}}$ matrices for cases 1, 2 and 3 respectively.

$$[\mathrm{ILF}]_{\mathrm{i}} = \begin{array}{c} \\ \begin{array}{c}2\\3\\4\\5\\6\end{array} \end{array} \begin{array}{c} \overbrace{\begin{array}{cc}\text{S.S.} & \text{DG}\end{array}} \\ \begin{bmatrix} 0.75 & 0.25 \\ 0.50 & 0.50 \\ 0.50 & 0.50 \\ 0.50 & 0.50 \\ 0.25 & 0.75 \end{bmatrix} \end{array} \quad [\mathrm{ILF}]_{\mathrm{ii}} = \begin{array}{c} \\ \begin{array}{c}2\\3\\4\\5\\6\end{array} \end{array} \begin{array}{c} \overbrace{\begin{array}{cc}\text{S.S.} & \text{DG}\end{array}} \\ \begin{bmatrix} 0.80 & 0.20 \\ 0.40 & 0.60 \\ 0.40 & 0.60 \\ 0.40 & 0.60 \\ 0.20 & 0.80 \end{bmatrix} \end{array} \quad [\mathrm{ILF}]_{\mathrm{iii}} = \begin{array}{c} \\ \begin{array}{c}2\\3\\4\\5\\6\end{array} \end{array} \begin{array}{c} \overbrace{\begin{array}{cc}\text{S.S.} & \text{DG}\end{array}} \\ \begin{bmatrix} 0.20 & 0.80 \\ 0.60 & 0.40 \\ 0.60 & 0.40 \\ 0.60 & 0.40 \\ 0.80 & 0.20 \end{bmatrix} \end{array}$$

Suppose load A is 10 MW then it should be supplied by both S.S. and DG according to the value of impedance encountered in the path so as to obtain the balanced distribution of losses between the sources. In case 1 as per ILF S.S. should supply 0.75×10=7 MW and DG should supply 0.25×10=2.5MW whereas in case 2, S.S. should supply 0.80×10 = 8MW and DG should supply 0.20×10= 2 MW and in case 3, S.S. will supply 0.20×10= 2 MW and DG will supply 0.80×10 = 8MW. Similarly loads B to E should be shared according to corresponding values of ILF matrix so as to attain economic load dispatch. Tables 2, 3 and 4 show that the minimum loss with improved voltage profile can be obtained only if the power is shared according to the ILF matrix

Table 2

Analysis of ILF matrices obtained for 7 bus radial system

Case	**Corresponding [ILF] matrix**	**Load bus**	**Impedance in the power flow path from source up to load**		**Load (MW)**	**Power received from source (%)**		**Load shared (MW)**	
			S.S.	**DG**		**S.S.**	**DG**	**S.S.**	**DG**
Case 1	$[\text{ILF}]_{i}$	2	1/4th	3/4th	10	75	25	7.50	2.5
		3	2/4th	2/4th	20	50	50	10.0	10
		4	2/4th	2/4th	30	50	50	15.0.	15
		5	2/4th	2/4th	15	50	50	7.5	7.5
		6	3/4th	1/4th	10	25	75	2.5	7.5
			Net Capacity		85	50	50	42.5	42.5
Case 2	$[\text{ILF}]_{ii}$	2	1/5th	4/5th	10	80	20	8.0	2.0
		3	3/5th	2/5th	20	40	60	8.0	12.0
		4	3/5th	2/5th	30	40	60	12.0	18.0
		5	3/5th	2/5th	15	40	60	6.0	9.0
		6	4/5th	1/5th	10	20	80	2.0	8.0
			Net Capacity		85	44	56	36	49
Case 3	$[\text{ILF}]_{iii}$	2	4/5th	1/5th	10	20	80	2.0	8.0
		3	2/5th	3/5th	20	60	40	12.0	8.0
		4	2/5th	3/5th	30	60	40	18.0	12.0
		5	2/5th	3/5th	15	60	40	9.0	6.0
		6	1/5th	4/5th	10	80	20	8.0	2.0
			Net Capacity		85	56	44	49	36

Table 3

Estimation of Power loss if the substation and DG is scheduled as per ILF

Case	**Net Impedance faced (%)**		**Total load (MW)**	**Required capacity (MW)**		**Power Loss, MW**	**Power Loss (%)**
	S.S.	**DG**		**S.S.**	**DG**		
Case 1	50	50	85	42.5	42.5	2.056	2.33
Case 2	44	56	85	36	49	3.543	4.16
Case 3	56	44	85	49	36	2.068	2.43

Table 4

Estimation Power loss if the substation and DG is scheduled for different values

Case	$DG_{capacity}$, MW		Total load (MW)	S.S.$_{supply}$, MW		Power Loss, MW	Power Loss (%)	Voltage Profile	
	As per MTP	Scheduled		As per MTP	Scheduled			Min	Max
Case 1	42.5	42.5	85	42.5	42.5	2.056	2.33	0.994@4	1.000@6
		30			55	2.067	2.43	0.983@4	1.000@6
		55			30	2.065	2.42	0.951@4	1.002@6
Case 2	36	36	85	49	49	3.543	4.16	0.991@3	1.001@6
		25			60	3.554	4.18	0.971@4	1.005@6
		48			37	3.549	4.17	0.977@4	1.008@5
Case 3	49	49	85	36	36	2.068	2.43	0.998@4	1.000@6
		36			49	2.079	2.45	0.964@4	1.051@5
		55			30	2.079	2.45	0.966@3	1.038@5

Thus from above analysis it is clear that ILF matrix will give an appropriate proportion of load sharing between available sources as per the impedance encountered in the power flow path of the respective source to load. So this matrix can be considered as a decisive factor during the planning of DG capacity. Thus the power which should be contributed by an individual generator to meet each load can be obtained from following equation,

Power supplied from generators = $[P_G]_{L\times 1} = \sum_{i=1}^{nl}\sum_{j=1}^{nl}\sum_{k=1}^{m} [I_L]_{i\times j}[ILF]_{i\times k}[V_G]_{k\times 1}$

$$= \begin{array}{c c} & \overbrace{\begin{array}{cccc} G_{1SUPPLY} & G_{2SUPPLY} & \cdots & G_{mSUPPLY} \end{array}} \\ \begin{array}{c} L_1 \\ L_2 \\ \vdots \\ L_{nl} \end{array} & \left[\begin{array}{cccc} I_{L1}ILF_{L1G1}V_{G1}+ & I_{L1}ILF_{L1G2}V_{G2}+\cdots & & +I_{L1}ILF_{L1Gm}V_{Gm} \\ I_{L2}ILF_{L2G1}V_{G1}+ & I_{L2}ILF_{2G2}V_{G2}+\cdots & & +I_{L2}ILF_{L2Gm}V_{Gm} \\ \vdots & \vdots & \ddots & \vdots \\ I_{Lnl}ILF_{nl1G1}V_{G1}+ & I_{Lnl}ILF_{LnlG2}V_{G2}\cdots+ & & I_{Lnl}ILF_{LNLGm}V_{Gm} \end{array}\right]_{Lnl\times 1} \end{array} \tag{19}$$

From the matrix given by equation (19) the power contributed by the generators placed at any particular location can be obtained which is actually similar to the T-index value explained in [11]. Here the summation of all row elements should be 1 which represents that 100% load will be supplied by generators present in the system. Similarly summation of elements of column gives the total power supplied by G^{th} column generator to the loads present in that system and individual element of the column is the desirable share of the respective load from respective generator. Thus the summation of all elements of each column can give the maximum capacity of the corresponding generator. So if a new DG is installed in the system replacing any particular load bus then power contribution from all existing generators will be modified as some of the power will now be shared by newly installed DG. Since DG is installed by replacing any load bus, the total number of generators are increased by one reducing the load buses by one thus now the dimension of matrix $[P_G]$ given by equation (19) will be $(L_{nl}-1)\times 1$. Thus the restructured matrix can be rewritten as

$$= \begin{array}{c|ccccc|l} & G_{1SUPPLY} & G_{2SUPPLY} & \cdots & G_{mSUPPLY} & DG_{SUPPLY} & \\ L_1 & I_{L1}ILF_{L1G1}V_{G1} & +I_{L1}ILF_{L1G2}V_{G2} & +\cdots+ & I_{L1}ILF_{L1Gm}V_{Gm}+ & I_{L1}ILF_{L1DG}V_{DG} & \\ L2 & I_{L2}ILF_{L2G1}V_{G1} & +I_{L2}ILF_{L2G2}V_{G2} & +\cdots+ & I_{L2}ILF_{L2Gm}V_{Gm}+ & I_{L2}ILF_{L2DG}V_{DG} & \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \\ L_{nl-1} & I_{Lnl-1}ILF_{Lnl-1G1}V_{G1}+ & I_{Lnl-1}ILF_{Lnl-1G2}V_{G2}+ & \cdots & +I_{Lnl-1}ILF_{Lnl-1Gm}V_{Gm} & +I_{Lnl-1}ILF_{Lnl-1DG}V_{DG} & _{Lnl-1\times 1} \end{array} \qquad (20)$$

The desired capacity of the DG is the summation of terms of power contribution of DG to each load. Therefore DG capacity can be calculated by

$$\text{DG capacity, } S_{DG} = I_{L1}ILF_{L1DG}V_{DG} + I_{L2}ILF_{L2DG}V_{DG} + \cdots + I_{Lnl-1}ILF_{Lnl-1DG}V_{DG}$$

$$= \sum_{i=1}^{nl} I_{Li} \times ILF_{LiDG} \times V_{DG} \ \text{MVA} \qquad (21)$$

The MVA capacity obtained by equation (21) is actually the combined load supplied by DG, so the value of combined load will be,

P_{load} = real (S_{DG}) MW (22)
Q_{load}=imaginary (S_{DG}) MVAR (23)

The capacity obtained by equation (21) will be a complex quantity giving both real as well as reactive power supplied by the DG which can also be used for calculation of power factor of the DG.

2.4.4. Operating power factor (OPF)

As explained in section 2.5.3 the DG capacity can be evaluated by equation (21) which is the summation of the desired contribution of DG to the loads present in the system. Therefore the complex value of DG capacity calculated by equation (21) can give the value of combined load supplied by DG. To transfer maximum possible power, if the load is absorbing the reactive power then DG should supply it and vice a versa. In case of source the leading power factor means, source is absorbing reactive power. On the other hand, the lagging power factor means source is supplying reactive power which is just differing to load power factor conventions [20]. Therefore by using equations (22) and (23) power factor of DG can be written as

$$OPF_{DG} = \alpha \cos(\tan^{-1}(Q_{load} / P_{load})) \qquad (24)$$

Where, α = lagging if PF_{load} is lagging,
= leading if PF_{load} is leading.

2.4.5. DG Type

As per the proposed method according to the evaluated power factor and power injection requirement the suitable DG Type for the given network is recommended from the Table 1.

3. Results and Analysis

3.1. Test Systems

To validate the proposed method, it is tested on three test systems and the results are compared with well known Exhaustive Load Flow method and already published Improved Analytical method based on exact loss formula [3, 4].

(i) 16-bus radial test distribution system with a total real and reactive load of 28.7 MW and 5.9 MVAr, respectively [21].
(ii) 33-bus test radial distribution system with a total real and reactive load of 3.7 MW and 2.3 MVAr, respectively [22].
(iii) 69- bus radial distribution system with a total real and reactive load of 3.8 MW and 2.69 MVAr, respectivey [23].

3.2. Assumptions

1. Maximum active and reactive power limit of DG for different test systems is assumed to be equal to the total active and reactive load of the system.
2. The lower and upper voltage limits for DG are set at 0.95–1.05 pu.

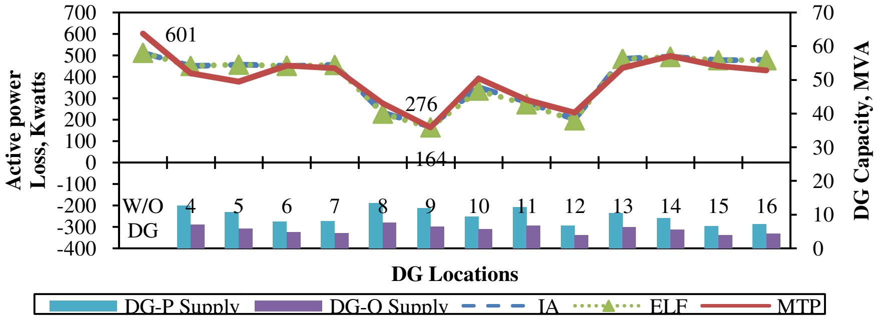

Fig. 2. Optimal access location according to the losses and capacity of DG at respective location in 16-bus radial distribution system

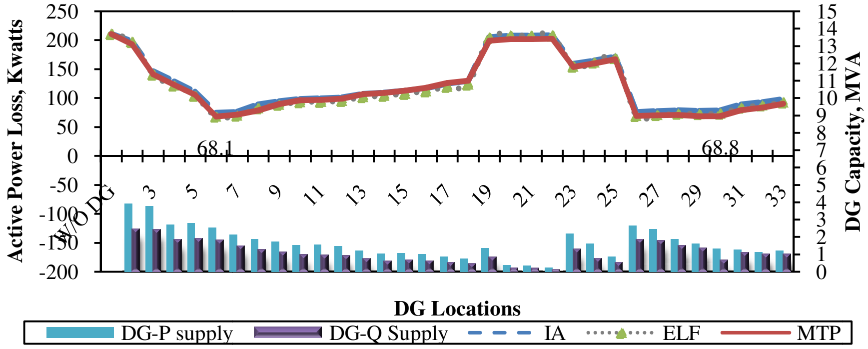

Fig. 3. Optimal access location according to the losses and capacity of DG at respective location in 33-bus radial distribution system

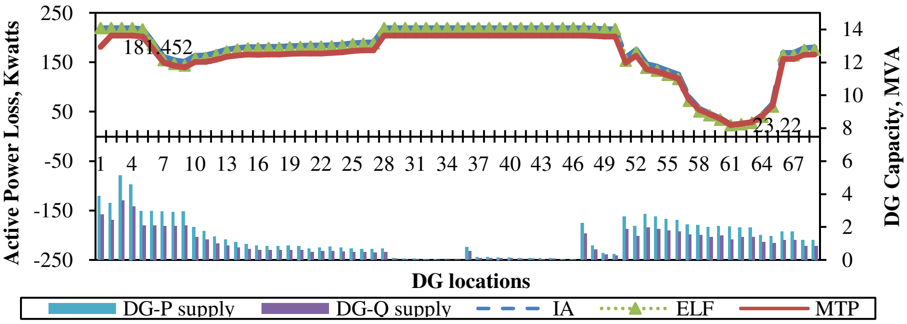

Fig. 4. Optimal access location according to the losses and capacity of DG at respective location in 69-bus radial distribution system

Table 5

Performance analysis of proposed method

Test Systems	Methods	Optimal Location	Optimal Size (MVA)	Operating Power Factor	Type	Loss, kw (without DG)	Loss, kw (with DG)	Percentage of loss reduction	Critical bus
16 Bus system	MTP	9	11.79	0.98	Type 1	601	164.01	67.93 %	12
	IA	9	13.09	0.98	Type 1	511.43	166.31	67.48 %	12
	ELF	9	13.16	0.98	Type 1	511.43	164.01	67.93 %	12
33 Bus System	MTP	6	3.141	0.85	Type 3	211.1	68.1	67.25 %	32
	IA	6	3.02	0.85	Type 1	211.2	74.89	64.54 %	18
	ELF	6	3.10	0.85	Type 1	211.2	68.2	67.70 %	18
69 Bus System	MTP	61	2.37	0.82	Type 3	181.45	23.22	87.20 %	65
	IA	61	2.22	0.82	Type 1	219.28	23.45	89.31 %	65
	ELF	61	2.24	0.82	Type 1	219.28	22.62	89.68 %	65

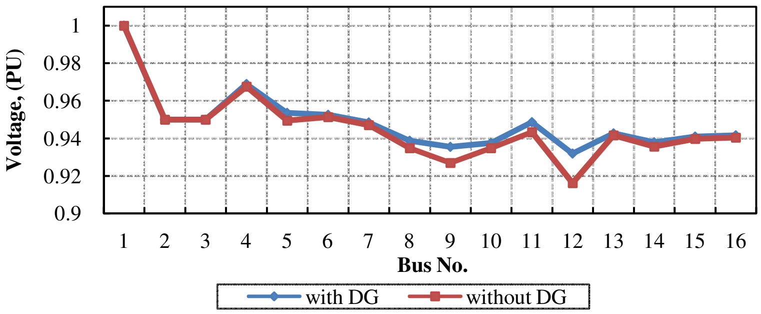

Fig. 5. Voltage profile rectification after insertion of DG at bus 9 in 16 bus system

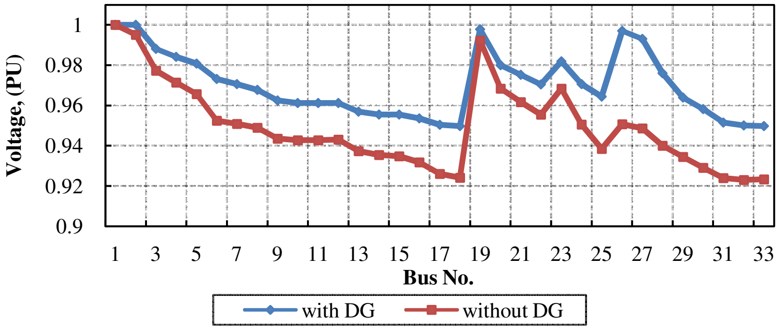

Fig. 6. Voltage profile rectification after insertion of DG at bus 6 in 33 bus system

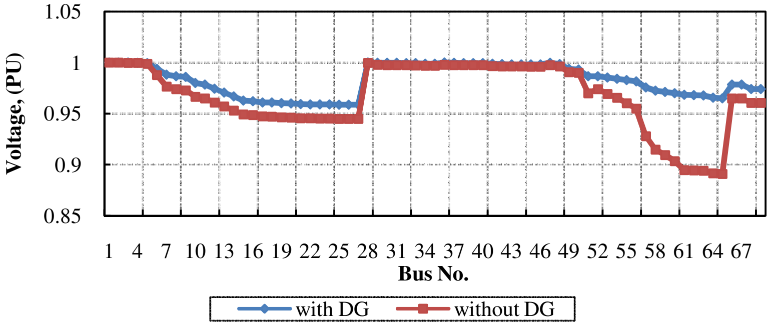

Fig. 7. Voltage profile rectification after insertion of DG at bus 61 in 69 bus system

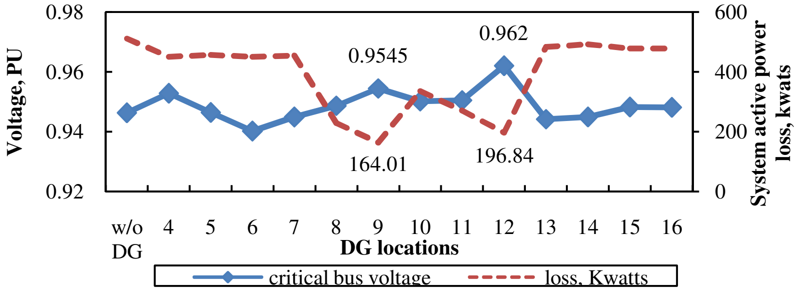

Fig. 8. Effect of DG installation at various buses on critical bus voltage stability and corresponding losses of 16 bus system

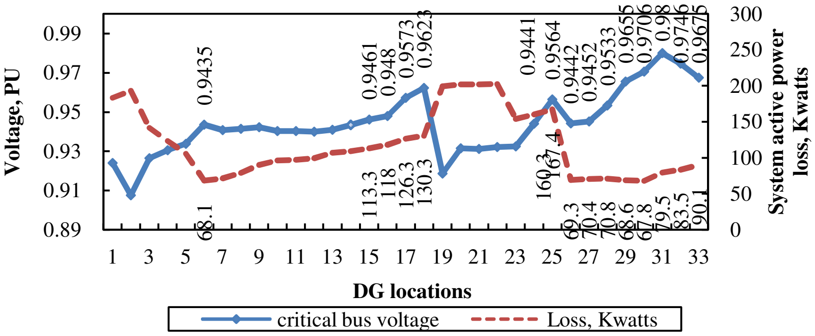

Fig. 9. Effect of DG installation at various buses on critical bus voltage stability and corresponding losses of 33 bus system

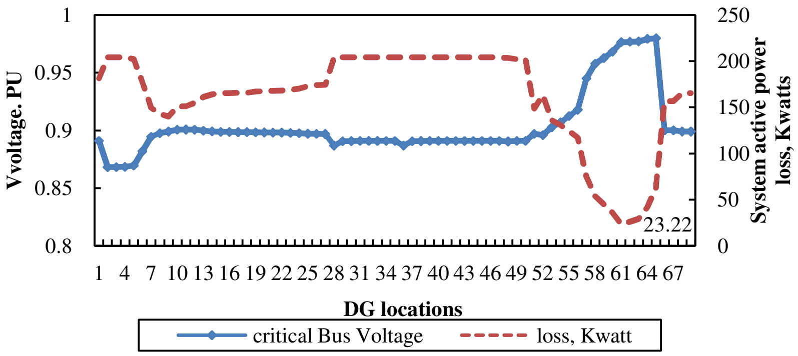

Fig. 10. Effect of DG installation at various buses on critical bus voltage stability and corresponding losses of 69 bus system

Table 6

Performance analysis of buses showing better critical bus voltage improvement after DG insertion

System	Location	Critical bus voltage	Losses, kwatts	% Loss reduction	Required DG capacity, MVA	Suitable for DG allocation
16 bus system	Without DG	0.9163	511.43	-	-	-
	Bus 9	0.9545	164.01	67.93	11.78	**Yes**
	Bus 12	0.962	196.84	61.67	6.55	**Conditionally Yes**
33 bus system	Without DG	0.924	211.1	-	-	-
	Bus 6	0.944	68.1	67.74	3.14	No
	Bus 15	0.946	113.3	46.33	1.287	No
	Bus 16	0.948	118	44.10	1.191	No
	Bus 17	0.957	126.3	40.17	1.024	No
	Bus 18	0.962	130.3	38.27	0.897	No
	Bus 25	0.956	167.4	20.70	1.018	No
	Bus 27	0.945	70.4	66.65	3.033	No
	Bus 28	0.953	70.8	66.46	2.414	No
	Bus 29	0.966	68.6	67.50	2.121	No
	Bus 30	0.970	67.8	67.88	1.499	**Yes**
	Bus 31	0.980	79.5	62.34	1.674	No
	Bus 32	0.975	83.5	60.45	1.528	No
	Bus 33	0.967	90.1	57.32	1.585	No
69 bus system	Without DG	0.891	181.5	-	-	-
	Bus 61	0.9684	23.2	87.21	2.368	**Yes**
	Bus 62	0.9766	25.9	86.12	2.416	**Yes**
	Bus 63	0.9769	29.1	83.97	2.41	No
	Bus 64	0.9773	41.4	77.19	1.839	No
	Bus 65	0.98	62.8	65.40	1.789	No

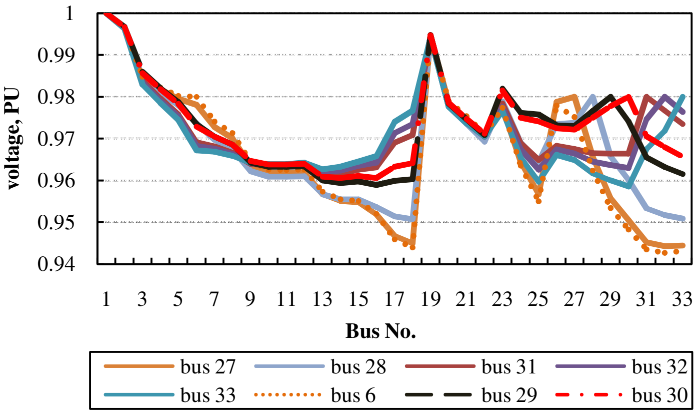

Fig. 11. Voltage profile correction of 33 bus system after DG Insertion at all candidate optimal locations.

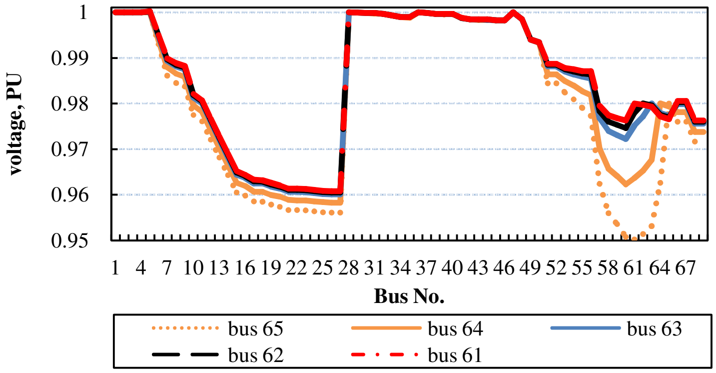

Fig. 12. Voltage profile correction of 69 bus system after DG Insertion at all candidate optimal locations.

3.3 Comparative analysis

3.3.1. Optimal access location and capacity evaluation

Figures 2-4 and Table 5 show the active and reactive power capacities of DG required to install at each location evaluated by MTP and the losses calculated by the MTP as well base methods (IA and ELF) with DG of estimated capacity installed at each bus individually at a time. It is observed that the losses as well as optimal size calculated by implementing proposed method follows the similar trend line as that of the results obtained by ELF and IA method which validates the proposed method. A Fig. 2 shows that in 16 bus system the optimal location obtained is bus number 9 at which if a Type 1 DG of 11.78 MVA is installed, 67.93 % loss can be minimized. Similarly Fig. 3 and 4 show that in 33 bus system if a Type 3 DG of 3.14 MVA and in 69 bus system a Type 3 DG of 2.368 MVA is installed 67.25 % and 87.20 % of loss respectively can be minimized. Table 5 reflects performance analysis of the proposed method as compared to other two methods. The evaluated performance reveals that the proposed method provides the similar results in case of loss minimization, optimum location investigation and optimum capacity calculation. Results vary in case of DG Type recommendation. All methods suggest Type 1 DG to install at optimal location i.e. bus 9 in 16 bus system. Whereas in 33 and 69 bus system base methods start assessment with Type 1 DG and as per the DG Type rest of the calculations were performed. After execution of entire calculations the result analysis concludes that Type 3 DG is more suitable then Type 1 DG which may require reassessment of DG design. On the contrary, the proposed method considers DG Type as post determined factor which depends on the estimated DG capacity and power factor. In this regards base methods may found to be uncertain about DG type suggestion and computationally more demanding as compared to proposed method. Apart from this base methods furnish siting and sizing by considering loss minimization as single objective whereas the proposed method investigates optimal location and capacity by considering loss minimization as prime objective and cross verifies the results by examining the stability of system after DG insertion by critical bus voltage and the system voltage profile correction. In 16 bus and 69 bus system DG design suggested by the proposed method is analogous to that of the design suggested by base methods. But in 33 bus system interesting variation in results can be observed which is discussed in section 3.3.3

3.3.2. Voltage profile correction

The effect of DG insertion at an evaluated optimal location given in Table 5 on the voltage profile of the systems is shown in Fig. 5, 6 and 7. It can be observed that an improvement in voltage profile after DG installation at an evaluated optimal access location is possible. Despite of that especially the improvement in voltage profile of critical bus which is highly voltage collapse prone is significant in all the test systems. In spite of that if DG is installed at an optimal access location recommended in Table 6 then undeniably better voltage profile improvement may be attained which can be observed from Figures 11 and 12. This verifies the enhanced optimality of solution obtained by the proposed method. This aided advantage of proposed method may be also beneficial in multiple DG allocation procedures.

3.3.3. Impact on Critical Bus

A number of trails on the performance of the proposed technique have been carried out on the test systems to determine the impact of DG allocation at an evaluated optimal location on the critical bus voltage profile. Optimality of locations estimated for three test systems by proposed method is confirmed by observing impact of DG insertion on critical bus voltage improvement shown in Fig. 8, 9 and 10. From those figures it is clear that in all test systems as compared to any other location insertion of DG at an evaluated optimal injecting location with the estimated size, power factor and type shows the momentous improvement in the critical bus voltage profile as well as loss minimization. Some contradictory results may be observed in 33 bus and 69 bus systems. Detailed analysis of impact of DG insertion at evaluated optimal access point of each test system is discussed as follows;

a) 16 bus system

A Table 5 shows that if loss minimization is considered as an objective then in 16 bus system bus 9 is incontestably the optimal access location for DG but if critical bus voltage improvement is also investigated then bus 12 would be a better option of being optimal access location with slightly less percentage of loss reduction. Table 6 shows that if DG is installed at bus 12 better critical voltage improvement with approximately equal loss reduction can be achieved with nearly half capacity i.e. 6.55 MVA.

b) 33 bus system

If only loss minimization is considered as an objective, optimal access location suggested by all the three methods is bus 6 and optimal capacity estimated is approximately 3.1MVA with nearly 68% loss reduction. But results furnished by proposed method in Table 6, recommend bus 30 as viable optimal location which may provide approximately same % loss reduction with DG of only 1.5 MVA capacity. Despite of that as discernible from Fig. 11, if DG is installed at any one of the buses such as 15, 16, 17, 18, 25, 27, 28, 31, 30, 32 or 33 critical bus (bus 32) shows much improved voltage correction as compared to the condition with DG installed at bus 6. But if the DG is installed at any one of the buses like 15, 16, 17, 18, 25, 32 or 33 then critical bus voltage improvement can be achieved but by compromising loss reduction percentage. Whereas Fig. 11 resists buses 27 and 28 of being better candidate optimal locations as DG installation at both the locations shows insipid improvement in system voltage profile. But Table 6 and Fig. 11 authenticates the substantiation of bus 30 as promising optimum location because approximately similar loss reduction is possible by DG insertion at bus 27, 28, 29 or 30 but DG capacity required to be installed at buses 27, 28 and 29 is high as compared to that of DG required at bus 30 with much improved critical bus voltage correction as well as system voltage profile.

c) 69 bus system

Considering loss minimization as an objective all the three methods recommend bus 61 as the best candidate optimal access location for DG with approximately same DG size. Fig. 10 shows that rather than bus 61 if DG is installed at any one of the buses 62, 63, 64 or 65 better critical bus voltage correction is possible but with less loss reduction. Whereas Fig. 12 and Table 6 provides the candidature of only two buses 61 and 62 of being appropriate optimal access location for DG showing nearly similar impact on loss reduction, critical bus voltage correction and voltage profile improvement of the system with approximately same size.

4. Conclusion

The paper has proposed an analytical Modified Transmission Parameters method for evaluation of optimal access location and capacity for DG insertion in primary distribution network. Novelty of the proposed method lies in its simplicity in implementation and robustness. Multi objective criteria make the method more compatible in the field of DG designing and offer a superior environment to the researchers in this field for enhancing the solution space. The proposed methodology is applied for allocation of single DG in a given distribution network but it may also be efficiently applicable for multiple DG allocation.

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