Optimal Location and Size of Different Type of Distributed Generation with Voltage Step Constraint and Mixed Load Models

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Abstract. The optimal location and size of distributed generation in distribution network are essentially affected by type of DG, constraints, and loading condition. The type of distributed generation (DG) categorized on the basis of their terminal characteristic in terms of active and reactive power delivering capability have been considered for study. The voltage step change that occurs on sudden disconnection of DG is one of constraints to limit the size of DG more than the voltage level constraint. The loads connected to network are normally voltage dependent and varies with seasonal atmospheric conditions. The voltage dependency and seasonal variation of load necessitate to represent the load by load models for analysis. In this paper, the study has been carried out for distributed generation planning (DGP) for different type of DG in 38-bus test distribution system with voltage step constraint including normally considered constraints i.e. bus voltage constraint, line power capacity constraint, and seasonal mixed load models. The analysis shows that optimal location and size are significantly affected by type of DG, voltage step constraint, and load models.

Keywords: Distributed generation, distribution system, distributed generation planning, load models.

1 Introduction

Distributed generation, also termed as embedded generation or dispersed generation or decentralized generation, is defined as small electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter [1]. The limitations of traditional generation and on the other hand immense technical, economical and environmental benefits of DG as well as technological development in DG have renewed the interest on DG [2]-[4]. The loss minimization in distribution network is one of the vital requirement to operate the system economically which could be achieved by proper distributed generation planning (DGP) i.e. by placement of distributed generations (DGs) at optimum

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locations with optimum size and suitable type corresponding to minimum power loss under certain constraints.

In practice, the loads in distribution network are voltage dependent and the major variations could be observed according to variations in seasonal weather conditions such as summer day, summer night, winter day, and winter night. The load at each bus may also be the composition of different kinds of voltage dependent loads such as industrial, residential, and commercial. The different types of voltage dependent loads are represented by basic load models as described in [5] and the concept of mixed load model along with seasonal variations in loads is adopted for DGP in [6]. The authors defined four major types of DGs but considered only one type of DG, which is capable of delivering both real and reactive power, for study in [7]. In [8], authors studied the effect of voltage step constraint on size of DGs connected at particular location for three operating power factors (0.95 lagging, unity, and 0.95 lagging). Thus mixed load model, types of DGs, and voltage step constraint are the important factors to be considered together for proper DGP.

In [9]-[11], different kinds of basic voltage dependent load models have been considered and compared with constant power load model. In [12]-[14], voltage independent variable loads have been adopted for DG placement. The DGP problem was also solved by adopting DG which can supply both real and reactive power but without considering load models and voltage step constraint in [15]-[21]. From literature survey [22], very few works have been found on implementation of voltage step constraint, mixed load model, and all major types of DGs in DGP. In [24], authors considered the different type of DG and mixed load models for DGP but not considered voltage step constraint.

In this paper, 38-bus system is adopted as described in [9], [10] (Fig. 7 in Appendix). The investigation regarding DGP analysis is performed considering summer day mixed, summer night mixed, winter day mixed, winter night mixed load models which include industrial, residential, and commercial load models at every bus in certain proportion (assumed as in Table II). The investigation also considered the voltage step limit of 3% along with bus voltage limits and line power capacity limit as constraints. The analysis has been performed corresponding to minimum P_L for different types of DGs under voltage step constraint.

The paper is structured as follows: Section II describes the types of DGs. In section III, phenomenon of voltage step has been illustrated with the help of a simple two-bus system. Section IV describes the load models and test cases considered for investigation. Section V describes the methodology adopted. Section VI presents the simulation results and analyses of studies. The last section VII presents the conclusion of the paper.

2 Type of Distributed Generation

There are different types of traditional and nontraditional DGs classified and described in [3] from the constructional, technological, size, and power time duration pint of view. The DGs have also been classified into four major types, based on terminal characteristics in terms of real and reactive power delivering capability, as described in [7]. In this paper, the four major types have been considered for comparative studies which are discussed as follows:

Type1. This type of DG is capable of delivering only real power. Photovoltaic, micro-turbines, and fuel cells, which are integrated to the main grid with the help of converters/inverters, are the examples of Type1. The converters/inverters-connected Type1 DG can control both real and reactive power outputs up to certain extent and may be categorized as Type2.

Type2. This type of DG is capable of delivering both real and reactive power. DG units based on synchronous machines (cogeneration, gas turbine, etc.) come under this type. In the present work the generation limits of the synchronous generators have not been considered explicitly. However, this is considered by constraining operating power factor in the range of 0.8 ld to unity.

Type3. This type of DG is capable of delivering only reactive power. Gas turbines in synchronous compensator mode and other sources of reactive power are the examples of this type.

Type4. This type of DG is capable to deliver real power but consumes reactive power. Mainly induction generators, which are used in wind farms, come under this category. The doubly fed induction generator (DFIG) systems may produce reactive power similar to synchronous generator and hence DFIG may be considered as Type2 DG.

In this paper, DGs adopted for studies are the basic DGs based on their terminal characteristic in terms of real and reactive power delivering capability.

3 Voltage Rise and Voltage Step

The voltage rise is the increase in voltage with inclusion of DG, and voltage step change is instantaneous drop in voltage with loss of DG. The phenomenon of voltage step as explained by Dent *et al* [8], is different from voltage rise and is illustrated in this section with the help of Fig. 1. Bus 2, as depicted in Fig. 1, has a load as ($P_{D2}+jQ_{D2}$) and DG size as ($P_{DG2}+jQ_{DG2}$).The power flowing from bus-2 to bus-1 through line of impedance ($R+jX$) , when DG is connected at bus-2, would cause steady state voltage rise at bus 2 ($V_{rise\,2}$) as given below (assuming that the voltage at A remains constant as 1 p.u.) [8].

$$V_{rise\,2} = (P_{DG2} - P_{D2})R + (Q_{DG2} - Q_{D2})X \tag{1}$$

On subtracting the voltage at B without DG ($V_{WODG\,2}$) from the voltage at bus-2 with DG ($V_{WDG\,2}$), the voltage step at bus B ($V_{step\,2}$) on loss of the DG is given as follows.

$$V_{step\,2} = V_{WDG\,2} - V_{WODG\,2} = -(P_{DG2}R + Q_{DG2}X) \tag{2}$$

The voltage step limit is taken on the basis of full output of the DG. The voltage step limit is expected to restrict the DG size more than the normal voltage limit constraints. As per the UK standards V_{step} limit is specified as 3% for planned switching outages and 6% for unplanned outages whereas 5% is common in use in USA [8].

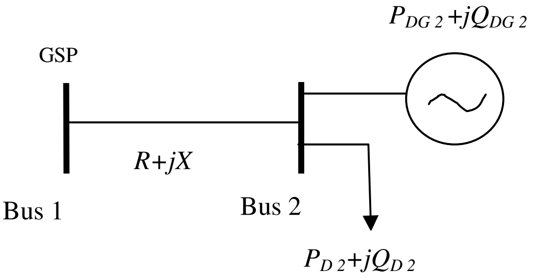

Fig. 1. Two-bus system for voltage step analysis

In this paper, study has been carried out for planned outages and V_{step} in p.u. has been calculated at i^{th} bus each step size of DG as follows:

$$V_{step\,i} = V_{WDG\,i} - V_{WODG\,i} \quad for\ i = 2\ to\ N_B \tag{3}$$

4 Load Models and Test Cases

To quantify the effect of different type of DGs, seasonal mixed load models (*SDM, SNM, WDM, WNM*), and voltage step constraints on DGP, a 38-bus distribution system [9],[10] is adopted. The line impedances, load data (balanced) and the line power limits, expressed in p.u. at the base voltage of 12.66 kV and base MVA of 1.0 MVA, are adopted [9], [10], and [24]. In conventional load flow analysis, the real and reactive power loads are assumed as constant i.e. not dependent on voltage or frequency. While in fact, the distribution loads are voltage dependent and practically these are industrial, residential, and commercial. A voltage dependent load model is a static load model that represents the power relationship to voltage as an exponential equation, which can be expressed in following form [5].

$$P_i = P_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\alpha} \tag{4}$$

$$Q_i = Q_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\beta} \tag{5}$$

Above equations (4) and (5) neglect the frequency dependence of distribution load, due to the fact that the frequency variation is relatively in narrow range. In practice, the load on each bus is composition of industrial, residential, and commercial which varies according to seasonal day, and night. Therefore, in this paper the load model at each bus is represented by following equations.

$$P_i = W_{1pi} \cdot P_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\alpha_i} + W_{2Pi} \cdot P_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\alpha_r} + W_{3Pi} \cdot P_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\alpha_c} \tag{6}$$

$$Q_i = W_{1Qi} \cdot Q_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\beta_i} + W_{2Qi} \cdot Q_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\beta_r} + W_{3Qi} \cdot Q_{0i}\left(|V_i| \big/ |V_{0i}| \right)^{\beta_c} \tag{7}$$

where, α_i and β_i are for industrial load model; α_r and β_r for residential load model; α_c and β_c for commercial load model. The values of α's and β's are zeros for constant power load model.

W_{1Pi} & W_{1Qi}, W_{2Pi} & W_{2Qi}, and W_{3Pi} & W_{3Qi} are the composition weights for real & reactive powers of industrial, residential and commercial loads respectively at bus *i*, except for unloaded buses (*UB*). The composition factors are assumed such that

$$W_{1Pi} + W_{2Pi} + W_{3Pi} = 1 \quad for\ i = 1\ to\ N_B\ ,\ i \neq UB \tag{8}$$

$$W_{1Qi} + W_{2Qi} + W_{3Qi} = 1 \quad for\ i = 1\ to\ N_B\ , i \neq UB\ . \tag{9}$$

The values for exponents of voltage for real and reactive component of summer day, summer night, winter day, and winter night loads are given in Table 1 [6]. The assumed composition weights of each load model at each bus is as shown in Table 2. In this study it is assumed that $W_{1Pi}=W_{1Qi}$, $W_{2Pi}=W_{2Qi}$, and $W_{3Pi}=W_{3Qi}$.

The study is performed considering practical situations of load as follows: 1) each bus having mix of industrial, residential, and commercial load in certain proportion; 2) Load vary with seasonal day and night. Apart from these situations, *T1,T2,T3* and *T4* have been considered for comparative study. A 38-bus system is assumed to be supplying power to mixed of industrial, residential, and commercial load without violating voltage step constraint as well as usually adopted constraints i.e. bus voltage limits and line capacity limit. The following test cases are considered for optimal size and location for constant and seasonal mixed load models considering P_L minimization as objective function.

1) Type 1 DG with and without *VSL* constraint.
2) Type 2 DG with and without *VSL* constraint
3) Type 3 DG with and without *VSL* constraint
4) Type 4 DG with and without *VSL* constraint

Table 1. Typical load types and exponent values [6]

Load type		Exponent values					
		Industrial		Residential		Commercial	
		α_i	β_i	α_r	β_r	α_c	β_c
Summer	Day	0.18	6.00	0.72	2.96	1.25	3.50
	Night	0.18	6.00	0.92	4.04	0.99	3.95
Winter	Day	0.18	6.00	1.04	4.19	1.50	3.15
	Night	0.18	6.00	1.30	4.38	1.51	3.40

Table 2. Value of Relevant Factors of load Models at Each bus

Bus no	$W_{1Pi}=W_{1Qi}$	$W_{2Pi}=W_{2Qi}$	$W_{3Pi}=W_{3Qi}$
2	0.2000	0.6000	0.2000
3	0.1500	0.6500	0.2000
4	0.2000	0.5000	0.3000
5	0.1100	0.3400	0.5500
6	0.1000	0.3500	0.5500
7	0.3000	0.5000	0.2000
8	0.3000	0.5000	0.2000
9	0.0800	0.2000	0.7200
10	0.0800	0.2000	0.7200
11	0.1200	0.2000	0.6800
12	0.2500	0.3000	0.4500
13	0.2500	0.3500	0.4000
14	0.2000	0.3000	0.5000
15	0.0500	0.3000	0.6500
16	0.0800	0.2000	0.7200
17	0.0800	0.2000	0.7200
18	0.3000	0.4000	0.3000
19	0.3000	0.4000	0.3000
20	0.3000	0.4000	0.3000
21	0.3000	0.4000	0.3000
22	0.3000	0.4000	0.3000
23	0.3500	0.4500	0.2000
24	0.2000	0.6500	0.1500
25	0.2000	0.6500	0.1500
26	0.1000	0.2500	0.6500
27	0.1000	0.2500	0.6500
28	0.1000	0.3000	0.600
29	0.2500	0.3500	0.4000
30	0.5000	0.3000	0.2000
31	0.2500	0.3500	0.4000
32	0.3000	0.5000	0.2000
33	0.2500	0.3000	0.4500

5 Proposed Methodology

The methodology adopted for DG analysis uses incremental power flow and exhaustive search method to obtain the optimal location and size of DG for real power loss (P_L) minimization. The details of problem formulation, indices calculations, computational procedure for the purpose of database generation, and analysis of results, are given in the following sections. Further, the implementation procedure is also discussed.

5.1 Formulation

The optimal location and size of DG are determined by minimization of real power loss in distribution system with operating constraint of the system. The total real power loss is expressed as follows [11],[24].

$$P_L = \sum_{i,j \in N_L} \frac{P_{ij}^2 + Q_{ij}^2}{|V_i|^2} r_{ij} \tag{10}$$

Loss is function of all system bus voltage (V_i), line resistances ($r_{i,j}$), α, and β. The total losses mainly depend on voltage profile.

The apparent power intake (S_{intake}) at main substation is expressed as:

$$S_{intake} = [(P_{intake})^2 + (Q_{intake})^2]^{1/2} \tag{11}$$

where, P_{intake} at the main substation is represented as:

$$P_{intake} = P_1(V, P_0, Q_0, \alpha, \beta) = \sum_{i=1}^{N_B} P_{0i}(|V_i|/|V_{0i}|)^{\alpha} + P_L \tag{12}$$

and Q_{intake} at the main substation is represented as:

$$Q_{intake} = Q_1(V, P_0, Q_0, \alpha, \beta) = \sum_{i=1}^{N_B} Q_{0i}(|V_i|/|V_{0i}|)^{\beta} + Q_L \tag{13}$$

And total system power requirement is expressed as:

$$S_{sys} = [(P_{intake} + P_{DG})^2 + (Q_{intake} + Q_{DG})^2]^{1/2} \tag{14}$$

where, $Q_{DG} = 0.0$ for T1; $P_{DG} = 0.0$ for *T3* $Q_{DG} =$ - ve for *T4*

It is observed that for a distribution system

$$\sum_{i=1}^{N_B} P_0(|V_i|/|V_{0i}|)^{\alpha} > P_L \tag{15}$$

$$\sum_{i=1}^{N_B} Q_0(|V_i|/|V_{0i}|)^{\beta} > Q_L \tag{16}$$

Thus the P_{intake} and Q_{intake}, expressed as (12) and (13) respectively are largely decided by bus voltages (V_i) and load exponents (*α's* and *β's*), not by P_L and Q_L.

The above objectives are subject to the following set of power flow, line capacity limit, voltage limits and voltage step limit

$$P_i = \sum_{j=1}^{N_B} |V_i||V_j|[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)], \ for\, i = 1\, to\, N_B \tag{17}$$

$$Q_i = \sum_{j=1}^{N_B} |V_i||V_j|[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)], \ for\, i = 1\, to\, N_B \tag{18}$$

$$P_{i,j} = |V_i|^2 G_{ij} - |V_i||V_j|[G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}], \ for\ i, j \in N_L \tag{19}$$

$$Q_{i,j} = -|V_i|^2 B_{ij} - |V_i||V_j|[G_{ij}\sin\theta_{ij} + B_{ij}\cos\theta_{ij}], \quad for\ i, j \in N_L \tag{20}$$

$$V_{\min} \le |V_i| \le V_{\max}, \quad for\ i = 1\ to\ N_B \tag{21}$$

$$S_{i,j} \le CS_{i,j}^{\max}, \quad for\ i, j \in N_L \tag{22}$$

$$V_{step\,i} \le V_{step\,i}^{\max}, \quad for\ i = 1\ to\ N_B \tag{23}$$

$$S_{DG} \le S_{intake} \tag{24}$$

In this paper voltage limits and VSL are taken as follows:

$$V_{\min} = 0.95\,\text{p.u.},\ V_{\max} = 1.05\,\text{p.u., and}\ V_{step\,i}^{\max} = 0.03 \times V_{WDG\,i}$$

5.2 Indices to Quantify the Benefits of DG

To compare the results, the indices are defined as follows [10].

Real Power Loss Index (PLI). The real power loss index is defined as :

$$PLI = \frac{P_{LWDG}}{P_{LWODG}} \times 100 \tag{25}$$

The lower values of this index indicate better benefits in terms of real power loss reduction accrued to DG.

Reactive Power Loss Index (QLI). The reactive power loss index is defined as:

$$QLI = \frac{Q_{LWDG}}{Q_{LWODG}} \times 100 \tag{26}$$

The lower values of this index indicate better benefits in terms of reactive power loss reduction accrued to DG.

Voltage Profile Index (VPI). It is related to the maximum voltage drop between a node and root node among the voltage drops between root node and each node. The lower values of this index indicate better performance of network. The *VPI* can be defined as:

$$VPI = \max\left(\frac{|V_1| - |V_i|}{|V_1|}\right) \times 100, \quad for\ i = 2\ to\ N_B \tag{27}$$

Line Capacity Index (LCI). The power flows may diminish in some sections of the network and released more capacity with the power supplied near to the load. This index provides important information about the level of power flows/currents through the network regarding maximum capacity of distribution lines. Lower values of this index indicate more capacity available. Index values equal to 100 % indicate that line limit constraint is active. This is defined as:

$$LCI = \max\left(\frac{|\mathrm{S_{ij}}|}{|\mathrm{CS_{ij}}|}\right) \times 100,\ for\ ij\ set = 1\ to\ N_L \tag{28}$$

Apparent Power Intake (S_{intake}) Index (SII). The lower value of this index indicates more capacity release of substation. This index is defined as

$$SII = \frac{|S_{\text{intake}\ WDG}|}{|S_{\text{intake}\ WODG}|} \times 100 \tag{29}$$

5.3 Computational Procedure

For investigation, different types of DGs based on terminal characteristics in terms of power delivering capability has been adopted to perform comparative study for better DGP corresponding to minimum P_L. The data base, using Newton Raphson power flow method, for the 38-node distribution system is obtained without and with DG at different node.

In this paper, single DG placement is studied. The algorithm is based on incremental power flow. In this algorithm the value of $|S_{DG}|$ is incremented in steps (0.005 p.u. in present study) till maximum limit (S_{intake}) is reached. The process is repeated assuming DG location at each bus. The size of DGs are considered in practical range decided as equal to or less than power intake at main substation. The step size of power factor is taken as 0.01. The range of power factor is taken between 0.99 to 0.8 leading for *T2* and 0.99 to 0.8 lagging for *T4*. The relevant quantities such as P_L, Q_L, S_{intake}, P_{intake}, Q_{intake}, S_{sys}, *NVLVB, NLCLVL, NVSLVB, PLI, QLI, VPI, LCI*, V_i, *and* S_{ij} are evaluated using load flow study at every node with different type and size of DGs and power factors, and stored. Then from the data base, the required values corresponding to minimum P_L under voltage step limit (*VSL*) , bus voltage limits, and line capacity as constraints are determined using exhaustive search algorithm (given in Appendix) . The computational procedure is described in the following steps.

Step 1: Read of load data, line data, number of buses, DG power increment (ΔS_{DG}), α and β for all load models, voltage limits, voltage step limit, and DG power factor decrement (ΔPF_{DG}) for *T2* and *T4*.

Step 2: Select one of the load models (mixed and constant load models) by selecting exponent values, α and β.

Step 3: Run power flow program without DG ($P_{DG} = 0$, $Q_{DG} = 0$,) and save the data (P_L, Q_L, S_{intake}, P_{intake}, Q_{intake}, S_{sys}, *NVLVB, NLCLVL*, V_i, *and* $S_{i,j}$).

Step 4: Select one of types of DG.

Step 5: Decrement power factor by ΔPF_{DG} from 0.99 for *T2* and *T4* till 0.8 and skip this step for *T1* and *T3*

Step 6: Select one of the buses.

Step 7: Increment DG value by $\Delta S_{DG.}$

Step 8: Run power flow program and save the data. (*DG_bus*, P_{DG}, Q_{DG}, P_L, Q_L, S_{intake}, P_{intake}, Q_{intake}, S_{sys}, *NVLVB, NLCLVL, NVSLVB, PLI, QLI, VPI, LCI*, V_i, *and* $S_{i,j}$)

Step 9: Go to *step 7* if ($P_{DG} \leq P_{intake}$ and $Q_{DG} \leq Q_{intake}$).

*Step*10: Go to step 6 to select next bus , make DG value in previous bus zero, till all the buses considered.

*Step*11: Go to step 5 for type 2 and type 4 DG till PF_{DG} is 0.8 and skip this step for type 1 and type 3 DG.

*Step*12: Go to step 4 to select other type of DG.

*Step*13: Go to step 2 till all the mixed load models are selected.

Step 14: The database obtained in terms of DG_bus, P_{DG}, Q_{DG}, P_L , Q_L, S_{intake}, P_{intake}, Q_{intake} , S_{sys}, *NVLVB, NLCLVB, NVSLVB, PLI, QLI, VPI, LCI,* V_i , *and* S_{ij} used to obtain value of quantities (for zero value of *NVLVB*, *NLCLVL*, and *NVSLVB*) corresponding to minimum P_L as listed in Table 3 and 4 using exhaustive search algorithm (given in Appendix).

5.4 Implementation Strategy

The placement will depend on many other factors such as availability of space and practical suitability. If all the locations are available, then one location corresponding to lowest aggregate energy loss for all the four seasonal load conditions may be implemented.

The energy loss in p.u. is expressed as:

$$Energy\ Loss = w_{SD}.P_{LSD} + w_{SN}.P_{LSN} + w_{WD}.P_{LWD} + w_{WN}.P_{LWN} \quad (30)$$

and

$$w_{SD} + w_{SN} + w_{WD} + w_{WN} = 1 \quad (31)$$

where, w_{SD}, w_{SN}, w_{WD}, w_{WN} are the normalized durations corresponding to summer day mixed (*SDM*), summer night mixed (*SNM*), winter day mixed (*WDM*), and winter night mixed (*WNM*) load conditions respectively. P_{LSD}, P_{LSN}, P_{LWD}, P_{LWN} are real power loss for *SDM, SNM, WDM,* and *WNM* load conditions respectively.

In this paper, the values for normalized weights are assumed as follows.

$$w_{SD}=0.33;\ w_{SN}=0.33;\ w_{WD}=0.17;\ w_{WN}=0.17$$

6 Simulation Results and Discussion

In this section, the summary of simulation results obtained for various test cases is presented. The *NVSLVB* for different load models with different types of DG are summarized in Table 3. The quantities P_{DG}, Q_{DG}, PF_{DG}, *DG-bus,* and S_{sys}, corresponding to minimum P_L with voltage step constraint are presented in Table 4. The indices corresponding to minimum P_L are depicted in Figs. 2 to 6. The values considered for comparison and discussion related to different kind of DGs are under *VSL* constraint. The analysis based on Table 3 and 4 is as follows.

6.1 Effect of Load Models in NVSLVB *(Table III)*

It is observed that for constant power load *NVSLVB* is more severe in case of *T1* and *T2* compared to *T3* and *T4* whereas for voltage dependent load models it is lesser incase of *T1* and *T2*, and zero in case of *T3* and *T4*. The *NVSLVB*s show that in case of load models, the *VSL* constraint is less severe for *T1* and *T2*, and not effective for *T3* and *T4*.

6.2 Load Models

Constant Power Load Model (Cons) (Table 4). The P_L with *T2* is 0.0822 p.u. which is less compare to other types of DGs and without DG. The P_{DG} is 1.368 p.u., at 0.8 leading power factor, which is less than *T1* and *T4*. The location of *T1*, *T2*, and *T4* is at bus 6 whereas bus 30 is for *T3*.

Summer Day Mix Load Model (SDM) (Table 4). The P_L for *T2* is 0.0939 p.u. whereas it is more for other types of DGs and without DG case. The value of P_{DG} for *T2* is 0.72 p.u. at 0.8 leading power factor, which is less than with *T1* and *T4*. The location of different types of DGs is different i.e. the location of *T1* and *T4* is 9, *T2* is 29, and *T3* is 30.

Summer Night Mixed Load Model (SNM) (Table 4). The P_L for *T2* is 0.1051 p.u. whereas it is more for other types of DGs. The P_{DG} of *T2* is 0.528 p.u. ,at 0.80 leading power factor, which is less than other type of DGs. The location of *T1* and *T4* is 12, *T2* is 31, and *T3* is 30 .

Winter Day Mixed Load Model (WDM) (Table 4). The P_L with *T2* is 0.1129 p.u. which is less than without DG (0.1644p.u.) and with other types of DGs cases. The P_{DG} is 0.436 p.u. ,at 0.8 leading power factor, which is less than T1 and T4. The location of *T2* and *T3* in this case is same as in case of *SNM* i.e. bus 31 and 30. The location for *T1* and *T4* is bus 14.

Winter Night Mixed Load Model (WNM) (Table 4). The P_L for *T2* is 0.1229 p.u. which is less than without DG (0.1636 p.u.) , and with other type of DGs cases. P_{DG} of *T2* is 0.3280 p.u. (at $PF_{DG} = 0.80$ leading) which is less than with other type of DGs cases. The location is different for each type of DG.

Discussion. From Table IV, it is observed that in order to minimize P_L , the P_L is minimum for all seasonal load models only with *T2* compared to other type of DGs. It is seen that depending on the type of DG the optimal locations varies significantly from one type to other. The optimum P_{DG} is minimum with *T2* compared to with *T1* and *T4* for all load models. The operating power factor for *T2* is 0.8 leading. The S_{sys} is lowest with *T1* when voltage dependent load models are considered. However, this was not observed for constant power loads. The S_{sys} is maximum with *T3* for all load models, because this type of DG improves the voltage profile thereby increasing the load. Also higher P_L is observed in case of *T3* for all load models.

In case of *T4* the optimal performance is observed at 0.99lag (closer to unity). This suggests that such DGs are to be used at unity power factor or with power factor constraints if possible. However in certain case it is not possible to run the DG on unity power factor (such as induction generator). Therefore, in simulation they are to be represented as having reactive power (fixed or variable).The leading power factor demand from *T2* remain around 0.8 but does not increase on expense of real power.

Table 3. NVSLVB for Various Load Models without VSL constraint

System condition	DG Type	*NVSLVB (out of 38)*				
		Cons	*SDM*	*SNM*	*WDM*	*WNM*
Minimum P_L	*T1*	25	11	7	0	0
	T2	25	5	3	0	0
	T3	3	0	0	0	0
	T4	9	0	0	0	0

Table 4. DG size and location corresponding to Minimum P_L With VSL Constraint

Load model	*W/WO DG*	DG Type	P_{DG} *(p.u.)*	Q_{DG} *(p.u.)*	PF_{DG}	*DG bus*	S_{sys}	P_L*(Mini.)* *(p.u.)*
Cons	*WODG*	-	-	-	-	-	4.5963	0.1889
	WDG	*T1*	2.0400	0.0	1.0	6	4.4930	0.1010
		T2	1.3680	1.0260	0.8 ld	6	4.4706	0.0822
		T3	0.0	1.2500	0.0	30	4.5308	0.1342
		T4	2.2572	-0.3216	0.99 lg	6	4.5097	0.1150
SDM	*WODG*	-	-	-	-	-	4.4372	0.1667
	WDG	*T1*	1.0200	0.0	1.0	9	4.4477	0.1104
		T2	0.7200	0.5400	0.8 ld	29	4.4534	0.0939
		T3	0.0	1.1250	0.0	30	4.4678	0.1295
		T4	1.1039	-0.1573	0.99 lg	9	4.4531	0.1166
SNM	*WODG*	-	-	-	-	-	4.4304	0.1654
	WDG	*T1*	0.7300	0.0	1.0	12	4.4380	0.1169
		T2	0.5280	0.3960	0.8ld	31	4.4471	0.1051
		T3	0.0	1.1100	0.0	30	4.4660	0.1296
		T4	07920	-0.1129	0.99 lg	12	4.4415	0.1211
WDM	*WODG*	-	-	-	-	-	4.4224	0.1644
	WDG	*T1*	0.6000	0.0	1.0	14	4.4333	0.1207
		T2	0.4360	0.3270	0.8 ld	31	4.4374	0.1129
		T3	0.0	1.1150	0.0	30	4.4622	0.1286
		T4	0.6534	-0.0931	0.99 lg	14	4.4364	0.1243
WNM	*WODG*	-	-	-	-	-	4.4159	0.1636
	WDG	*T1*	0.4500	0.0	1.0	15	4.4235	0.1273
		T2	0.3280	0.2460	0.8 ld	32	4.4281	0.1229
		T3	0.0	1.1150	0.0	30	4.4620	0.1287
		T4	0.4851	-0.0691	0.99 lg	14	4.4240	0.1296

6.3 Indices for Comparison

The indices *PLI, QLI, VPI*, *LCI*, and *SII* are depicted in Figs. 2 to 6 and discussed as follows.

PLI and QLI (Fig. 2&3): These indicate that loss reduction is less in case of voltage dependent load models compared to constant power load model for all types of DGs. Further, for all load models, the loss reduction is more in case of *T2* compared to other types of DGs.

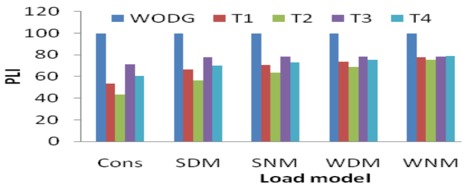

Fig. 2. *PLI* for minimum. P_L

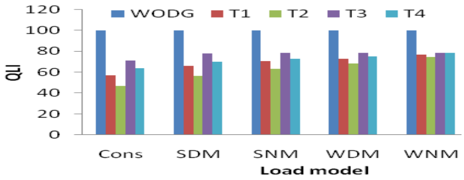

Fig. 3. *QLI* P_L Configuration

VPI (Fig. 4): This index indicates that voltage is improved when DG is connected. It is also observed that in case of constant power load model the improvement is more compared to voltage dependent load models for all types of DGs, which indicate that assumption of constant power load will not depict the real situation.

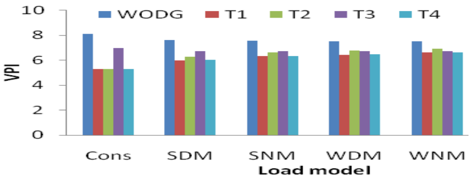

Fig. 4. VPI minimum. P_L

LCI (Fig. 5): This index indicate that assumption of constant load model shows more capacity release whereas assumption of mixed load models show almost nil capacity release for *T1,T2,* and *T4*. Further some capacity release is observed for *SDM*, *SNM*, and *WDM* in case of *T3*.

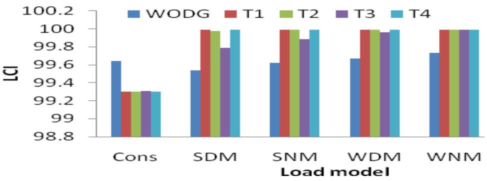

Fig. 5. *LCI* for minimum. P_L

SII (Fig.6): This index indicates that assumption of constant power load model shows more reduction in S_{intake} compared to voltage dependent load model for all type of DGs.

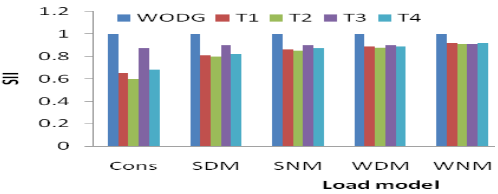

Fig. 6. *SII* for minimum. P_L

Thus, above indices reveal that assumption of constant power load model would show different value of losses, bus voltages, capacity release, and S_{intake} reduction compared to what would result in operational stages when voltage dependency comes into effect. Further, values of indices are also different of different types of DGs.

6.4 Implementation Criterion

The optimum location obtained corresponding to minimum loss are different for different seasonal mixed load models (Table 4). The single location for different types of DGs is obtained on the basis of minimum energy loss using (30) as shown in Table 5 and 6 corresponding to without and with inclusion of *VSL* constraint respectively, and observed that energy loss is minimum for *T2* in both cases (with and without *VSL* constraint) compared to other types of DGs.

Table 5. Optimum Location and Size without *VSL* Constraint

DG Type	DG bus	P_{DG} (p.u.)	Q_{DG} (p.u.)	$\mathrm{PF}_{\mathrm{DG}}$	Energy loss (p.u.)
T1	13	0.905	0	1	0.11774
T2	31	0.748	0.561	0.8 ld	**0.10424**
T3	30	0.0	1.125	0	0.12921
T4	12	1.119	-0.159	0.99 lg	0.12245

Table 6. Optimum Location and Size with *VSL* Constraint

DG Type	DG bus	P_{DG} (p.u.)	Q_{DG} (p.u.)	PF_{DG}	Energy loss (p.u.)
T1	12	0.730	0.0	1	0.11895
T2	29	0.720	0.540	0.8ld	**0.10791**
T3	30	0.0	1.125	0	0.12921
T4	12	0.950	-0.135	0.99lg	0.12286

7 Conclusions

The different types of DGs based on their terminal characteristics in terms of power delivering capability, constant power load model as well as mixed load model, and voltage step constraint have been considered for optimum location and size of DG corresponding to minimum real power loss and minimum energy loss in 38 bus distribution system.

The investigations show that in case of Type1and Type2 the numbers of voltage step limit violated buses are reduced drastically for voltage dependent loads compared to the case when constant power load models are considered. In case of Type3 and Type4 DGs, Voltage step constraint is less effective for constant power load model and not effective for the mixed load models.

The power loss , power intake and DG size are less for Type 2DG compared to other types of DGs. The energy loss is also less for Type 2 DG in both cases (without and with *VSL* constraint). The values of indices of constant power load model are significantly different than mixed load models.

Appendix

Search Algorithm for Minimum P_L

```
Step 1 : load the database files.
Step 2 : assign $k=1$, $min\_loss = P_L$ without $DG$, and $k_{max}$ = no. of set of data.
Step 3 : read $P_L(k)$, $NVLVB(k)$, $NLCLVL(k)$, $NVSLVB(k)$, $P_{DG}(k)$, $P_{intake}(k)$.
Step 4 : if $P_L(k) > min\_loss$, go to Step 7.
Step 5 : if $((NVLVB(k)=0)$ && $(NLCLVL(k)=0)$ && $(NVSLVB=0)$ &&
           $(P_{DG}<P_{intake},))$ continue
         else go to Step 7. % (NVSLVB is not considered for without VSL).
Step 6 : $min\_loss = P_L(k)$
Step 7 : $k_{minpl}=k$ ,
         %($k_{minpl}$ is assigned the value of $k$ corresponding to minimum $P_L$).
Step 8 : if $k = k_{max}$ , go to Step 10.
Step 9 : $k=k+1$, go to Step 3.
Step10: print $DG\_bus(k_{minpl})$, $P_{DG}(k_{minpl})$ , $Q_{DG}(k_{minpl})$ , $PF_{DG}(k_{minpl})$ , $P_L(k_{minpl})$ ,
         $Q_L(k_{minpl})$, $S_{intake}(k_{minpl})$, $P_{intake}(k_{minpl})$,$Q_{intake}(k_{minpl})$,$S_{sys}(k_{minpl})$, $NVLVB(k_{minpl})$,
         $NLCLVL(k_{minpl})$, $NVSLVB(k_{minpl})$, $PLI(k_{minpl})$, $QLI(k_{minl})$, $VPI(k_{minpl})$, $LCI(k_{minpl})$.
Step11: go to Step 1 till all the files are selected.
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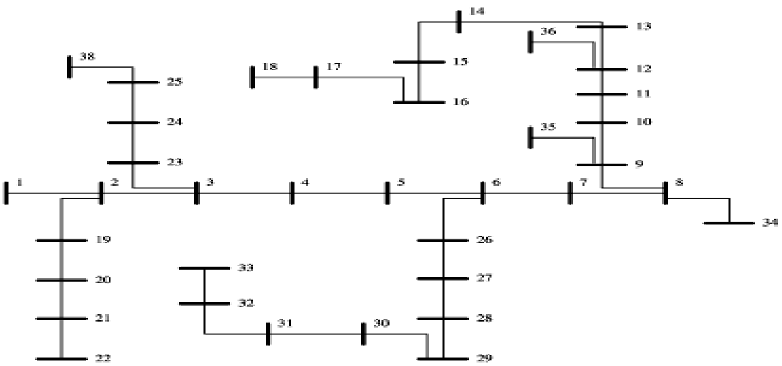

Fig. 7. 38-bus distribution system [9], and [10]

Nomenclature

α, β	Voltage exponent of real and reactive load.
Cons	Constant power load model.
SDM,SNM	Summer day and Summer night mixed load models
WDM,WNM	Winter day and Winter night mixed load models
$CS_{i,j}$	MVA capacity of line *i-j* (p.u.).
S_{intake}	Apparent power (MVA) intake at bus 1 (p.u.).
S_{sys}	Apparent power (MVA) taken by system from all sources (DG and grid) (p.u.).
NLCLVL	Number of line capacity limit violated lines.
NVLVB	Number of voltage limit violated buses.
NVSLVB	Number of voltage step limit violated buses.
P_{0i}, Q_{0i}	Real and reactive load at bus *i* at nominal voltage (p.u.).
P_D, Q_D	Total system real and reactive power demand (p.u.).
P_{DG}, Q_{DG}, S_{DG}	Real, reactive, and MVA power of DG (p.u.).
P_i, Q_i	Real and reactive power injection at bus i (p.u.).
P_{intake}, Q_{intake}	Real and reactive power intake at main substation (p.u.).
P_L, Q_L	System real and reactive power loss (p.u.).
$P_{i,j}$, $Q_{i,j}$, $S_{i,j}$	Real, reactive and MVA Power flows in line *i-j* (p.u.).
T1,T2,T3,T4	Type1, Type2, Type3, and Type4 DG,
V_{0i} , V_i	Nominal voltage at *i*th bus (p.u.), Voltage of *i*th bus (p.u.).
$V_{step\ i}$, *VSL*	Voltage step at *i*th bus (p.u.), Voltage step limit (%).
WDG, *WODG*	With and without DG.
WVSL, *WOVSL*	With and without *VSL*.
N_B , N_L	Number of buses and number of lines.
ld, lg	Leading, lagging power factors
$Y_{ij}=G_{ij}+jB_{ij}$	Elements of the bus admittance matrix corresponding to buses *i* and *j*.
r_{ij}	Resistance of line *i-j* (p.u.).

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