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Optimal DG Placement in Radial Distribution System with Various Load Clusters

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***Abstract:** A new methodology is developed for addressing the optimal DG placement problem (OPDG) in practical distribution system. The method takes all the possible load models and their combination. Using load clustering, load flow results are presented taking exponential models of each individual load model into account. This method closely resembles any practical distribution system and the analysis can be extended to real time case studies also. In this scenario, the optimal DG placement is considered by taking minimum voltage as a criteria for DG placement and sizing was determined by using PSO for total real power loss minimization. The proposed method was applied on standard IEEE 69 bus system and the results were demonstrated. The results demonstrate that besides the total real power loss minimization, incorporating DG also improved voltage profile and reduced reactive power loss also.*

***Keywords**: Distributed Generator (DG), Load Flow, Load Clustering, Load Modelling, Radial Distribution System.*

I. INTRODUCTION

The increase in demand in distribution system has made the several electric utilities to place small scale generation units near the consumers so that they can be put in service instantly [1]. The high environmental concern has forced to establish renewable DG's [2]. Most of the researcher's carried out optimal DG placement (OPDG) considering all the loads equivalent to constant power model. But the scenario in practical distribution system is totally different. There will be several complex loads falling into different categories like constant current loads, constant impedance loads, composite loads etc. [3], [4]. Some nodes can have only residential loads while some other can have only industrial loads/commercial loads/combination of any of the above. The realistic classification of loads and their location were considered based on certain assumptions. Now, in this load distribution scenario, the optimal DG placement was considered taking total power loss minimization as objective.

Exponential load models were considered for industrial, residential and commercial loads [5], [6]. The composite load model was considered as 40% Constant Power + 30% Industrial + 20% Residential + 10% Commercial [7].

The PSO algorithm was used to determine the size of DG that should be installed at a node so that P_{loss} is minimized [8], [9]. The location was determined by voltage magnitude index which was obtained after load flow analysis.

Backward-Forward sweep method of load flow was incorporated to obtain the voltage and current profiles [10]. This method uses simple KVL and KCL equations and network topology

The optimal DG problem was analysed after the load clustering was done to IEEE 69 bus system by incorporating all possible load models. This type of clustering is very essential for optimal DG placement in practical distribution system where practical RDShas voltage sensitive loads and several load clusters will be present in practical distribution system. This type of clustering closely resembles any practical distribution system and the analysis can be used by future researchers who want to study the DG impacts and placement in practical distribution scenario.

The DG placement has to be done at a proper node and with suitable sizing otherwise the power losses (both real and reactive power loss) will increase beyond the base case making the DG placement counterproductive[11], [12].

II. PROBLEM FORMULATION

The DG has to be placed at a suitable node of required size such that the total real power loss (P_{loss}) is minimized. Let the real power loss be $P_{loss}^{(o)}$ without any DG placement.

$$P_{loss}^{(o)} = \sum_{i=1}^{N_b} |I_i|^2 R_i \tag{1}$$

where

N_b –Total number of branches and $i \varepsilon N_b$

R_i– Resistance of i^{th} branch and

$|I_i|$– Current flowing in the i^{th} branch

The objective is to minimize P_{loss}

$F=Min\{P_{loss}^{DG}\}$

where

$$P_{loss}^{DG} = \sum_{i=1}^{N_b} \left|I_i^{DG}\right|^2 R_i \tag{2}$$

$\left|I_i^{DG}\right|$ - Magnitude of branch current in i^{th} branch after DG placement

DG operated at upf is considered here. This DG injects only real power at the desired node whose location and size is determined as follows.

Step1: Run the power flow program for the base case. Note down the magnitude of voltage at each node.

Step 2: Select the node with the minimum voltage as the candidate node for DG placement,becauseof the requirement to simultaneously improve the voltage profile together with real power loss minimization. Also note down the $P_{loss}^{(o)}$ i.e. base case real power loss.

Step 3: Place the DG at the location obtained in Step 2. Run the PSO algorithm in order to determine the size of the DG.This is done as follows:

(i) Randomly generate swarm of DG size's between $P_{DG(min)}$ to $P_{DG(max)}$ using the formula

$$P_{DG} = P_{DG(min)} + (rand)\,[P_{DG(max)} - P_{DG(min)}] \quad (3)$$

$P_{DG(min)}$ = 60 kW; $P_{DG(max)}$ = 2,000 kW

(ii) The generated DG swarms are given to PSO algorithm. PSO algorithm returns the DG size corresponding to minimum total real power loss as the fitness function is given as total real power loss. The PSO algorithm is discussed in Section (III).

Step 4: The obtained DG size is placed at the node obtained in step (2) and the power flow programme is again executed.

Step 5: Note down the real and reactive power loss after the DG placement. Note down the voltage profile after placement.

The constraints for the above problem are

(i) Voltage Statutory Limits

$|V_k|^{min} < |V_k|^{DG} < |V_k|^{max}$ where

$|V_k|^{DG}$ – Voltage magnitude at k^{th} node after DG Placement

where $|V^{min}| = 0.95\,pu$; $|V^{max}| = 1.05\,pu$

(ii) Size Constraints

The capacity of DG to be installed should be less than or equal to 0.30 times than the substation capacity.

III. PSO ALGORITHM

The PSO algorithm for minimization problem is enumerated as follows [13], [14], [15]:

Notation:

Let the Swarm size be denoted by 'N', and dimension be denoted by 'D'.

Let swarm be represented as

$X = [X_1, X_2, \ldots X_N]^T$

Each particle Xi where i=1 to N is written as

$X_i = [Xi_{,1}, Xi_{,2}, \ldots Xi_{,D}]$

Same notation holds good with velocity also

i.e. $V = [V_1, V_2, \ldots V_N]^T$

$V_i = [Vi_{,1}, Vi_{,2}, \ldots Vi_{,D}]$

Where i is 1 to N and j is 1 to D

$Pbest_{i,j}^k$ is personal best of j^{th} component of i^{th} particle in k^{th} iteration.

$Gbest_j^k$ is j^{th} component of best individual till the k^{th} iteration.

Step 1: Initialize all the PSO parameters. The parameters are

initialized as follows to the current problem.

Population size (N) = 30

Minimum inertial weight (W_{min}) = 0.4

Maximum inertial weight (W_{max}) = 0.9

Maximum number of iterations (K_{max}) = 600

Personal acceleration coefficient $C_1 = 2$

Global/Social acceleration coefficient $C_2 = 2$

Step 2: Set iteration count (K) = 1

Step 3: Generate random positions (initially) as follows:

Assume 'X' ranging X^{min} to X^{max}

$$X = X_{min} + rand\,[X^{max} - X^{min}] \quad (4)$$

Assume Initial velocity = 10% of X

Step 4: Find $F_i^k = F(X_{i,j}^k)\,\forall$'i' and

Find index of best particle b (where bεi)

Step 5: Initialize $Pbest_{i,j}^k = X_i^k$ and $Gbest_j^k = X_b^k$

Step 6: Find $W = W_{max} - \frac{K}{K_{max}}(W_{max} - W_{min})$ (5)

Calculate

$$V_{i,j}^{k+1} = W \times V_{i,j}^k + C_1 \times rand \times \lfloor Pbest_{i,j}^k - X_{i,j}^k \rfloor + C_1 \times rand \times \lfloor Gbest_j^k - X_{i,j}^k \rfloor ;\ \forall_j \text{ and } \forall_i \quad (6)$$

Update$X_{i,j}^{k+1} = X_{i,j}^k + V_{i,j}^{k+1}$ (7)

Step 7: Evaluate $F_i^{k+1} = F(X_i^{k+1})\,\forall$ the particles 'i'and find the index of the best particle b_1

Step 8: For ∀ the particle 'i' update the Pbest as follows.

If $F_i^{k+1} < F_i^k$ then set $Pbest_i^{k+1} \rightarrow X_i^{k+1}$

$$Pbest_i^{k+1} \rightarrow Pbest_i^k$$

Step 9: Update Gbest as follows.

If $F_{b1}^{k+1} < F_b^k$ then set $Gbest_i^{k+1} \rightarrow Pbest\ b_1^{k+1}$ and set $b \rightarrow b_1$

Else $Gbest^{k+1} \rightarrow Gbest^k$ and

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Set k=k+1 and

Run the program till $k=k_{max}$

Step 10: Print $Gbest^k$

IV. Modelling Of Realistic Loads In RDS

Exponential modelling of load is done as follows.

$$P_i^L = P_i^{L(N)} \left[\frac{|V_i|}{|V_i^N|}\right]^{\alpha} \quad (8)$$

$$Q_i^L = Q_i^{L(N)} \left[\frac{|V_i|}{|V_i^N|}\right]^{\beta} \quad (9)$$

where

$P_i^{L(N)}$ - Real power load at i[th] node at nominal voltage

P_i^L - Real power load at i[th] node at a voltage v_i

$Q_i^{L(N)}$ - Reactive power load at i[th] node at nominal voltage

Q_i^L - Reactive power load at i[th] node at a voltage v_i

α - Exponent corresponding to real power load

β - Exponent corresponding to reactive power load

The dependency of voltage variations on the load is modelled as given Table 1.

Table 1.The Typical Values of α *and* β

Type of Load	A	B
Constant Power Load [3]	0	0
Constant Current Load [3]	1	1
Constant Impedance Load [3]	2	2
Industrial Load [5]	0.18	6
Commercial Load [5]	1.51	3.40
Residential Load [5]	0.92	4.04

Composite load is assumed to be 40% Constant Power + 30% Industrial + 20% Residential + 10% Commercial[7].

The size of DG corresponding to 8 different scenarios is presented in the following work.

Case 1: Only constant power load

Case 2: Only constant current load

Case 3: Only constant impedance load

Case 4: Only industrial load

Case 5: Only commercial load

Case 6: Only residential load

Case 7: Only composite load

Case 8: Load clustering (proposed)

The loads in the IEEE 69 bus RDSare clustered as follows by taking the following assumptions.

(i) Industrial $P_{Load} \geq 400$ kW

(ii) Composite 150 kW $\leq P_{Load} < 400$ kW

(iii) Commercial 75 kW$\leq P_{Load} < 150$ kW

(iv) Residential $P_{Load} < 75$ kW

The Fig.1 represents the combination of different loads.

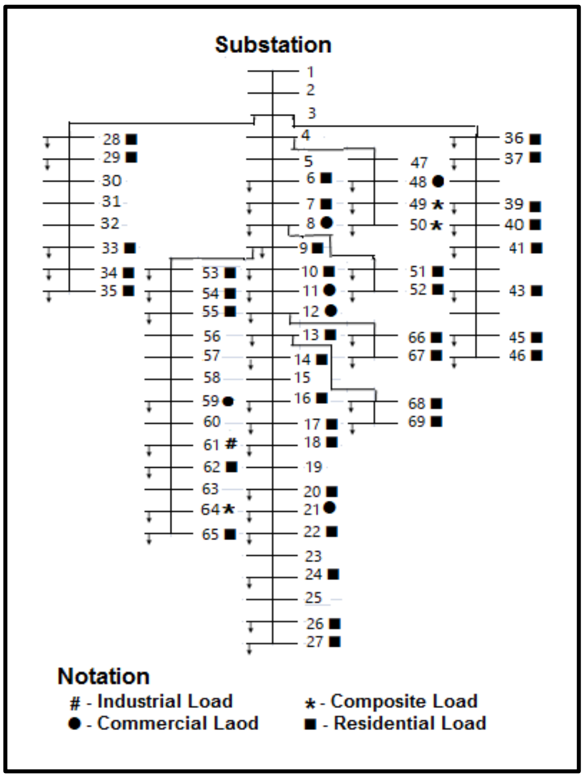

Fig. 1. Standard IEEE 69 Bus System after Load Clustering

The nodes obtained after the above assumption are depicted in Table 2.

Table 2. Node Numbers Obtained for Different Types of Loads

Type of Load	Node number
Industrial	61
Composite	49, 50, 64
Commercial	8, 11, 12, 21, 48, 59
Residential	6, 7, 9, 10, 13, 14, 16, 17, 18, 20, 22, 24, 26, 27, 28, 29, 33, 34, 35, 36, 37, 39, 40, 41, 43, 45, 46, 51, 52, 53, 54, 55, 62, 65, 66, 67, 68, 69

V. Results

The test system considered here has 69 buses and 68 branches with a total demand of3.8 MW and 2.69 MVAR [16].

Case 1: Only Constant Power Model:

The improvement in the system performance after the DG placement is publicized in Table3.The total real power loss obtained before DG placement was 225.1051 kW. The minimum voltage of 0.90918 pu was obtained at 65th node. DG installation at 65th node of size 1438.6 kW reduced the total real power loss to 112.2143 kW. The minimum voltage recorded was 0.96549 pu at 27th node, thus improving the overall minimum voltage in the system.

Table 3. Improvement in System Performance for Different Load Models after DG placement

Type of Load Model	Before DG Placement			DG Size, kW	After DG Placement			Loss Reduction, %	
	Total Real Power Loss, kW	Total Reactive Power Loss, kVAR	Minimum Voltage (p.u) @Node		Total Real Power Loss, kW	Total Reactive Power Loss, kVAR	Minimum Voltage (p.u) @node	Real Power	Reactive Power
Constant Power	225.1051	102.2583	0.90918@65	1438.6	112.2143	55.2360	0.96549@27	50.15	45.98
Constant Current	191.5903	87.8819	0.91669 @65	1327.5	105.2374	51.9814	0.96480 @61	45.07	40.85
Constant Impedance	167.2435	77.4063	0.92256 @65	1228.6	98.8191	48.9980	0.96421 @61	40.91	36.70
Industrial	175.1483	80.7428	0.91875 @65	1247.0	89.6328	45.1232	0.96356 @61	48.82	44.11
Commercial	165.1174	76.4831	0.92221 @65	1216.2	94.7580	47.2431	0.96376 @61	42.61	38.23
Residential	170.8951	78.9591	0.92032 @65	1237.1	93.9439	46.9496	0.96364 @61	45.03	40.51
Composite	189.7385	87.0630	0.91593 @65	1307.2	99.5201	49.5017	0.96408 @61	47.54	43.14
Clustering (Proposed)	175.5855	80.9664	0.91862 @65	1251.7	91.2954	45.9150	0.96365 @61	48.01	43.29

Table 4. Voltage Improvement @65th Node after DG Placement

Type of the Model	Voltage @65th Node before DG Placement	Voltage @65th Node after DG Placement	Voltage Improvement, %
Constant Power	0.90918	0.98104	7.90
Constant Current	0.91669	0.97876	6.77
Constant Impedance	0.92256	0.97704	5.91
Industrial	0.91875	0.97660	6.30
Commercial	0.92221	0.97643	5.88
Residential	0.92032	0.97656	6.11
Composite	0.91593	0.97780	6.75
Clustering (Proposed)	0.91862	0.97670	6.32

Table 5. Voltage Improvement @27th Node after DG Placement

Type of the Model	Voltage @ 27th Node before DG Placement	Voltage @ 27th Node after DG Placement	Voltage Improvement, %
Constant Power	0.95626	0.96541	0.97

The voltage at 65th node before and after DG placement was 0.90918 pu and 0.98104 pu respectively, thus improving 7.90% as shown in Table 4. Table 5 shows the voltage at 27th node before DG placement as

0.95626 pu. The voltage profile for constant power model is graphically represented in Fig. 2.

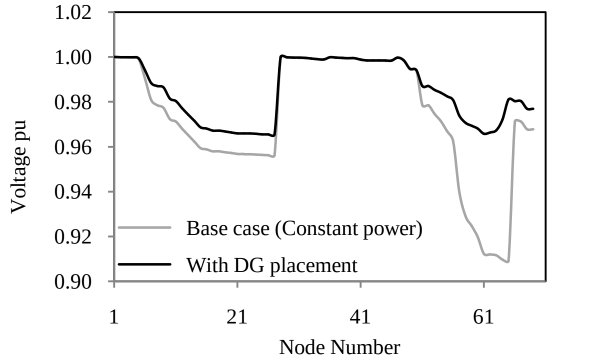

Fig. 2. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Constant Power Model

Case 2: Only Constant Current Model:

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 191.5903 kW. The minimum voltage of 0.91669pu was obtained at 65th node. DG installation at 65th node of size 1327.5 kW reduced the total real power loss to 105.2374 kW. The minimum voltage recorded was 0.96480pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 65th node before and after DG placement was 0.91669pu and 0.97876pu respectively, thus improving 6.77% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.91956pu and voltage improvement after DG placement as 4.92%. The voltage profile for constant current model is graphically represented in Fig. 3.

Table 6. Voltage Improvement @61st Node after DG Placement

Type of the Model	Voltage @ 61st Node before DG Placement	Voltage @ 61st Node after DG Placement	Voltage Improvement, %
Constant Current	0.91956	0.96480	4.92
Constant Impedance	0.92520	0.96421	4.22
Industrial	0.92150	0.96356	4.56
Commercial	0.92486	0.96376	4.21
Residential	0.92303	0.96364	4.40

Composite	0.91881	0.96408	4.93
Clustering (Proposed)	0.92144	0.96365	4.58

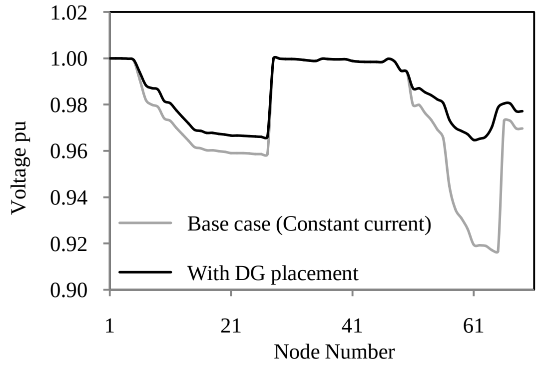

Fig. 3. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Constant Current Model

Case 3: Only Constant Impedance Model:

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 167.2435 kW. The minimum voltage of 0.92256pu was obtained at 65th node. DG installation at 65th node of size 1228.6 kW reduced the total real power loss to 98.8191 kW. The minimum voltage recorded was 0.96421pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 65th node before and after DG placement was 0.92256pu and 0.97704pu respectively, thus improving 5.91% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.92520puand voltage improvement after DG placement as 4.22%. The voltage profile for constant impedance model is graphically represented in Fig. 4.

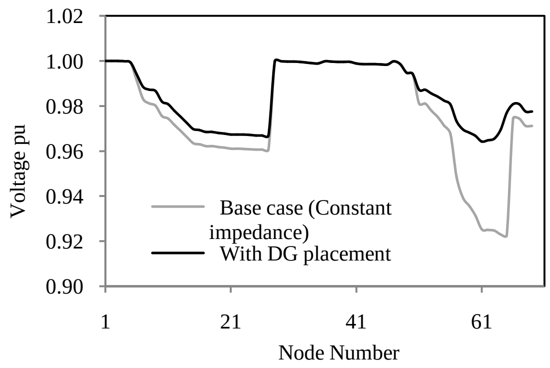

Fig. 4. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Constant Impedance Model

Case 4: Industrial Load Model:

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The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 175.1483 kW. The minimum voltage of 0.91875pu was obtained at 65th node. DG installation at 65th node of size 1247 kW reduced the total real power loss to 89.6328 kW. The minimum voltage recorded was 0.96356pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 65th node before and after DG placement was 0.91875pu and 0.97660pu respectively, thus improving 6.30% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.92150pu and voltage improvement after DG placement as 4.56%. The voltage profile for industrial load model is graphically represented in Fig. 5.

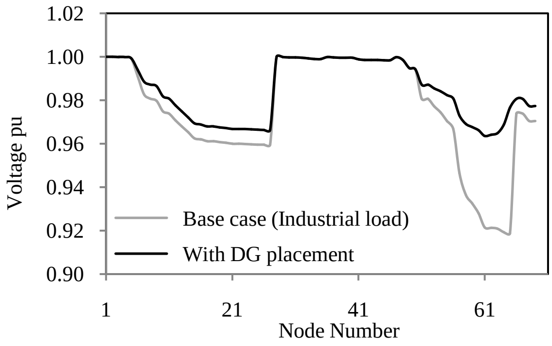

Fig. 5. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Industrial Load Model

Case 5: Commercial Load Model:

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 165.1174 kW. The minimum voltage of 0.92221pu was obtained at 65th node. DG installation at 65th node of size 1216.2 kW reduced the total real power loss to 94.7580 kW. The minimum voltage recorded was 0.96376 pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 61th node before and after DG placement was 0.92221pu and 0.97643purespectively, thus improving 5.88% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.92486pu and voltage improvement after DG placement as 4.21%. The voltage profile for commercial load model is graphically represented in Fig. 6.

Case 6: Residential Load Model:

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 170.8951 kW. The minimum voltage of 0.92032 pu was obtained at 65th node. DG installation at 65th node of size 1237.1 kW reduced the total real power loss to 93.9439 kW. The minimum voltage recorded was 0.96364 pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 65th node before and after DG placement was 0.92032 puand 0.97656 pu respectively, thus improving 6.11% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.92303 pu and voltage improvement after DG placement as 4.40%. The voltage profile for residential model is graphically represented in Fig. 7.

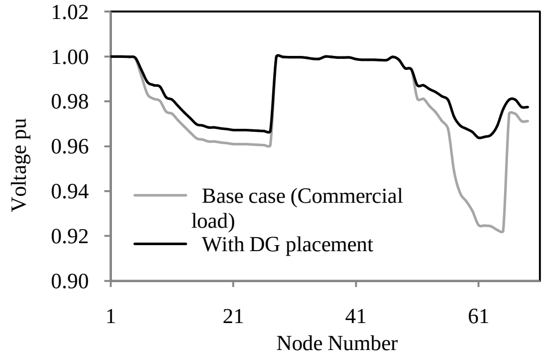

Fig. 6. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Commercial Load Model

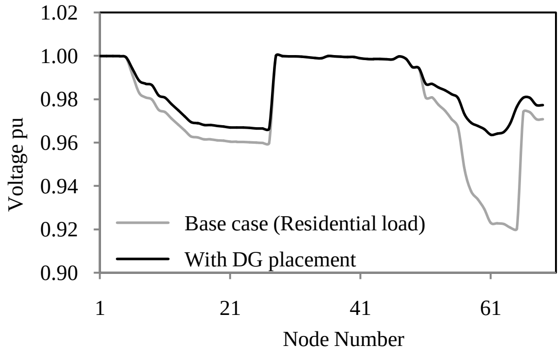

Fig. 7. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Residential Load Model

Case 7: Composite Load Model:

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 189.7385 kW. The minimum voltage of 0.91593pu was obtained at 65th node. DG installation at 65th node of size 1307.2 kW reduced the total real power loss to 99.5201 kW. The minimum voltage recorded was 0.96408 pu at 61st node, thus improving the overall minimum voltage in the system.

The voltage at 65th node before and after DG placement was 0.91593 pu and 0.97780pu respectively, thus improving6.75% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as

0.91881pu and voltage improvement after DG placement as 4.93%. The voltage profile for composite load model is graphically represented in Fig. 8.

Case 8: Load clustering model (Proposed):

The improvement in the system performance after the DG placement is publicized in Table 3. The total real power loss obtained before DG placement was 175.5855 kW. The minimum voltage of 0.91862pu was obtained at 65th node. DG installation at 65th node of size 1251.7 kW reduced the total real power loss to 91.2954 kW. The minimum voltage recorded was 0.96365 pu at 61st node, thus improving the overall minimum voltage in the system.

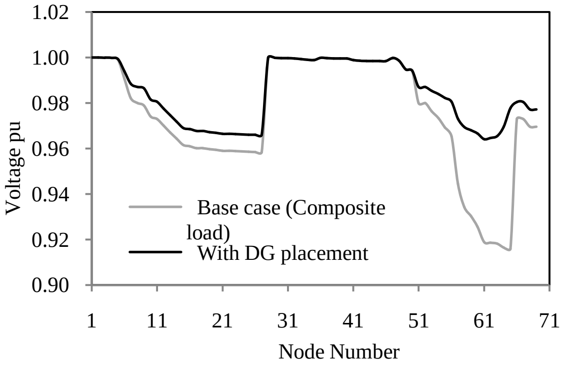

Fig. 8.Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Composite Load Model

The voltage at 65th node before and after DG placement was 0.91862pu and 0.97670purespectively, thus improving 6.32% as shown in Table 4. Table 6 shows the voltage at 61st node before DG placement as 0.92144pu and voltage improvement after DG placement as 4.58%. The voltage profile for load clustering model is graphically represented in Fig. 9.

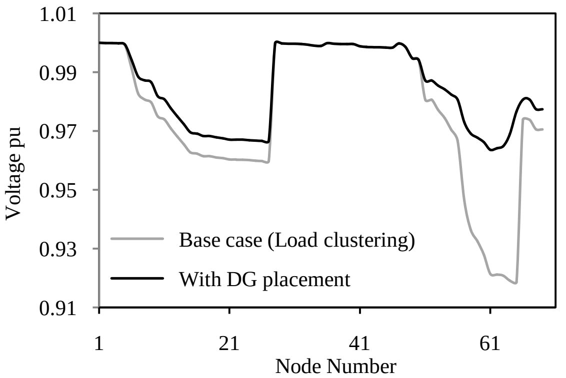

Fig. 9. Voltage Profile with and without DG Installation for IEEE 69 Bus System Considering Only Load Clustering Model

It can be concluded that the total real power loss corresponding to constant power type of load representation is highest (225.1051 kW) among all the cases taken over. The minimum voltage (0.96549pu) after DG placement for constant power load type was observed at 27th node while for all the other type of load types (including the proposed load clustering model), the minimum voltages were obtained at the 61st node.

The installation of DG size that was required to obtain minimum total real power loss was highest (1438.6 kW) for constant power type of load representation when compared to all the other types of load types (including the proposed load clustering method). Even though all the voltage profile graphs corresponding to eight different cases appear to be similar in shape, it is essential to discuss all the cases in stability point of view.

VI. CONCLUSIONS

Load clustering method was developed for addressing the optimal DG placement problem in practical distribution system.Since the location of DG was determined by minimum voltage magnitude index and DG size at that location was determined by considering total real power loss minimization objective, it was observed that placing of DG not only reduced the total real power loss but also improved the voltage profile and reduced total reactive power loss simultaneously.

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