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Implementation of Distributed Generation (IDG) algorithm for performance enhancement of distribution feeder under extreme load growth

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ABSTRACT

This paper presents a new algorithm, written in C-language for Implementation of Distributed Generation (IDG) to radial distribution feeder, heavily overloaded with non-uniformly distributed load. Majority of the existing algorithms are designed for distribution feeders with uniformly distributed load, working in single DG scenario. The applicability of these algorithms is restricted because of the unity power factor and high computational work. The methodology proposed in the research paper is capable of functioning under randomly distributed load conditions with low power factor for single DG as well as multi-DG system. The algorithm is based on analytical approach and is implemented to radial distribution network, considering the worse case scenario. The analyses carried out show that the algorithm can be applied to enhance the performance of distribution system in terms of node voltage profile improvement and power loss reduction. The simulation results indicate that IDG is capable of identifying the optimal location and size of DG in any problematic distribution system effectively. The results obtained are verified and are within the international standards limits.

1. Introduction

Before the advent of Distributed Generation (DG), mostly the distribution networks were designed to operate without any distributed resources along the feeder. The deregulation of electric power market and the global concerns about the environment have diverted the attention of distribution planners towards DG. The penetration of DG in the distribution system changes the power flow configuration in the traditional network of electric power distribution system from unidirectional to multidirectional system. The introduction of DG in the distribution system changes the operating features and has significant technical and economic impacts. One of the main obstacles for high DG penetration in the distribution feeder is the voltage rise effect which can be rectified by the selection of appropriate size and number of DGs [1]. The decreasing availability of natural resources and the increasing consciousness of environmental protection have rapidly increased the share of DG in the electricity supply. This share may increase to 20% in the European countries by the 2020 [2]. Distribution system performance can be improved with the effective integration of DG. Under such circumstances, the DG offers a feasible alternative to traditional sources of the electric power. The installation of small generating unit affects the operation of electric utility system in term of its performance improvement and reliability. The utilization of DG with optimal rating provides substantial relief to distribution network during the peak hour's demand [3]. Keeping this in view, the classical modeling and analyzing techniques must be revised. In past various optimization techniques for the voltage profile improvement, loss reduction, and optimal placement of DG in the electric distribution system have been proposed [4–7,8]. The mathematical analysis includes Gradient techniques, Successive Quadratic Programming (SQP) techniques, Karush Kuhn-Tucker non-linear programming techniques, and successive linear programming (SLP) techniques. Miu and Chiang have given a formulation for a large scale distribution network. They have analyzed a distribution network with the uniform and non-uniform load variations [7]. Wang and Nehrir have presented an analytical approach which is applicable only for the uniformly distributed load with unity power factor [8].

Majority of these techniques have the problem of excessive convergence time and premature convergence. Practically, it has been observed that majority of the distribution feeders are lengthy, heavily overloaded, having limited provision for future expansion and feeding non-uniform loads with non-unity power factor. In such scenario, the electric consumers are facing many problems because of the excessive voltage drop and power loss [9]. Poor equipment performance, overheating, nuisance tripping of over current protective devices and excessive burnouts are the sign of an unsatisfactory voltage profile. Unlimited voltage variation directly deteriorates the equipment life. Many industrial

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Nomenclature

ΔP_{loss}	incremental power loss
P_{loss}	power loss
dE_x	incremental voltage drop
E_{drop}	voltage drop
E_s	voltage at sending end of the feeder
E_x	voltage at distance "x" from sending end
E_r	voltage at receiving end of the feeder
ΔP_{lossDG}	incremental power loss with DG
P_{lossDG}	power loss with DG
dE_{xDG}	incremental voltage drop with DG
E_{dropDG}	voltage drop with DG
$\frac{dI}{dt}$	change in segment current without DG
$\frac{dI_{DG}}{dt}$	change in segment current with DG
θ_n	phase angle between voltage and current of nth segment
EP	voltage profile at different nodes without DG
EP_{DG}	voltage profile at different nodes with DG
EP_1	voltage profile index
$EPII_1$	voltage profile Improvement index
EP_2	modified voltage profile index
$EPII_2$	modified voltage profile improvement index
E_{nom}	nominal value of voltage in per unit
$E_{\max}$	maximum value of voltage in per unit
$E_{\min}$	minimum value of voltage in per unit
E_i	any value of voltage in per unit at node "i"
L_i	load supplied at ith node in per unit
K_i	weighting factor of different loads connected
$N = 0, 1, 2, \ldots$	number of nodes
I_N	load connected to "N" node in ampere
$Z_{0,1}, Z_{1,2}, \ldots Z_{n,n+1}$	impedance of nth segment of feeder in Ω per unit length
$R_{0,1}, R_{1,2}, \ldots R_{n,n+1}$	resistance of nth segment of feeder in Ω per unit length
$L_{0,1}, L_{1,2}, \ldots L_{n,n+1}$	inductance of nth segment of feeder in H per unit length
$x_{0,1}, x_{0,1}, x_{0,1}$	length of nth segment in meter
$I_{0,1}, I_{1,2}, \ldots I_{n,n+1}$	current flowing in nth segments of feeder in ampere
$n = 0, 1, 2, \ldots$	any number

consumers have experienced substantial financial losses resulting, obstacles in the good quality of the electricity supply. Non-uniform distribution of electric loads on the distribution feeder, the use of under sized conductors, remote location of transformers from the load centers, sub-standard jointing practices, and the long length of the distribution feeder are the major causes of the voltage drop and power loss. Continuously increasing demand of the electricity and proliferation of different non-linear loads such as rectifiers, switch mode power supplies, arc furnaces and other switching converters have also contaminated the quality of voltage for consumers having sensitive equipments. Lack of financial resources, unavailability of sophisticated technology and the non-implementation of long term planning has further deteriorated the quality of electric supply and complicated the distribution system. Haphazard distribution of electric loads over the feeder in general and mixed nature of loads in particular on the feeder causes sever problems of power quality i.e. the voltage drop and power loss. Such problems are detrimental to the consumers as well as to the electric utilities.

Under such circumstances, IDG tool has been design, which could be used to simulate and analyzed the feeder having non-uniform distribution of electric load. The analytical approach is adopted to enhance the power quality of distribution feeder in terms of the node voltage profile improvement and power loss reduction. It is too difficult to improve the performance of distribution system without optimal size and location of DG. In this context, IDG tool has been developed to identify the optimal size and placement of DG in the distribution system. Taking the real worse case scenario, the algorithm has been implemented on the 11 kV Panian radial distribution feeder with non-uniformly distributed loads. The feeder has 168 numbers of nodes and is almost about 100 km long, emanating from 132 kV Haripur grid station, Peshawar electricity supply corporation Pakistan. It has 132 numbers of transformers with total load of 8425 kVA.

The proposed method can be utilized effectively to increase the feeder performance, having non-uniformly distributed loads. Elaborative results are presented to assess the performance of distribution feeders as potential custom power solution. The feeder has been simulated in C-language and the results are verified analytically, which are within the acceptable limit of international standard. For convenience, the radial distribution feeder is divided into segments between the nodes. Non-uniform loads are connected to each node. The length and impedance for each segment are calculated. Mostly, the distribution feeders are lengthy and heavily overloaded in under-developed countries. Keeping in view of the complex nature of the feeders, it is essential to generalize these feeders so that one should be able to analyze them successfully. The same objective has been achieved by reducing the single line diagram of the feeder from 168 nodes to 38 nodes by adding the loads of laterals and sub laterals to subsequent nodes as shown in Fig. 5. However, practically it has been observed that it does not affect the analysis of the feeder.

Majority of the optimization techniques are complex, rigor and involved more mathematical computational work. Heuristic techniques provide empirical results and no performance guarantee; linear programming does not directly yield an improved estimate of the optimum and in successive linear programming, algorithm generates a sequence of infeasible points which can not be terminated early with optimal solution [10]. These techniques are useful only for on-line performance improvement calculation. Whereas, the implementation of IDG algorithm is easy, simple and no on-line calculations are required. The algorithm can be implemented easily with the personnel computer in off-line condition and no heavy computational work is required. The analyses show that optimum results for any problematic feeder can be achieved within the fraction of millisecond. The basic data for comprehensive algorithm is obtained from the single line diagram, generated during the field survey as depicted in Fig. 4. This data is stored as a "Data File", contains length ($X_{0-1}, X_{1-2}, \ldots, X_{n\text{-}n+1}$) of each feeder segment and load in amperes ($I_1, I_2, \ldots, I_n$) connected to each node. These known values are further used to calculate the total load (S_i), segment currents ($I_{0-1}, I_{1-2}, \ldots, I_{n+1}$) segment voltage drops ($V_{0-1}, V_{1-2}, \ldots, V_{n\text{-}n+1}$), node voltages ($V_1, V_2, \ldots, V_{n-1}, V_n$) and load currents ($I_1, I_2, \ldots, I_{n\text{-}1}, I_n$) as follows:

- $S_i = S_1 + S_2, \ldots, S_n$, where $S_1, S_2, \ldots, S_n$ are the known values of load connected to individual nodes and stored in the "Data File", where $i = 1, 2, \ldots n$.
- The voltage at the reference node (V_0) is known.
- $I_{Total} = I_{0-1} = \frac{S_i}{\sqrt{3}\text{kV}_0} = \frac{\text{KVA}_{Total}}{\sqrt{3}\text{kV}_0}$, where I_{Total} = total current supplied by the source at reference node.

Table 1
Eleven kilovolt feeder data used in the analysis.

S. no.	Segment length (km)	Resistance (Ω)	Inductance (mH)	Inductive reactance (Ω)	Impedance (Ω)
1	1.25	0.422	1.113	0.35	0.548
2	1.2	0.405	1.07	0.336	0.526
3	0.65	0.220	0. 579	0.182	0.285
4	0.35	0.118	0. 312	0.098	0.1534
5	0.65	0.220	0.579	0.182	0.285
6	1.70	0.574	0.1515	0.475	0.745
7	0.38	0.128	0.3386	0.1064	0.166
8	0.15	0.051	0.1336	0.042	0.066
9	0.75	0.253	0.6682	0.21	0.329
10	0.38	0.128	0.3386	0.1064	0.166
11	0.60	0.202	0.5346	0.168	0.263
12	0.95	0.321	0.8464	0.266	0.417
13	0.65	0.220	0.5791	0.182	0.285
14	0.25	0.084	0.2227	0.07	0.109
15	0.68	0.230	0.6059	0.1904	0.298
16	0.45	0.169	0.4009	0.126	0.21
17	0.25	0.084	0.2227	0.07	0.107
18	0.15	0.051	0.1336	0.042	0.066
19	0.25	0.084	0.2227	0.07	0.0.109
20	0.65	0.220	0.5791	0.182	0.285
21	1.25	0.422	0.1114	0.35	0.548
22	0.35	0.118	0.3118	0.098	0.1534
23	0.15	0.051	0.1336	0.042	0.066
24	0.57	0.192	0.5078	0.1596	0.25
25	0.25	0.084	0.2227	0.07	0.109
26	0.15	0.051	0.1336	0.042	0.066
27	0.25	0.084	0.2227	0.07	0.109
28	0.20	0.067	0.1782	0.056	0.087
29	0.40	0.135	0.3564	0.112	0.175
30	0.18	0.061	0.1604	0.0504	0.079
31	0.45	0.152	0.4009	0.126	0.197
32	0.25	0.084	0.2227	0.07	0.109
33	0.95	0.321	0.8464	0.226	0.417
34	1.25	0.422	0.1114	0.35	0.548
35	0.15	0.051	0.1336	0.042	0.066
36	0.75	0.253	0.6682	0.21	0.329
37	0.25	0.084	0.5791	0.07	0.109
38	0.65	0.220	0.5790	0.182	0.285

- The impedance of each feeder segment ($Z_{0-1}, Z_{1-2}, \ldots, Zn$) is known (Table 1 feeder data).
- $V_{0-1} = I_{0-1}Z_{0-1}$, the voltage drop for segment between nodes 0 and 1.
- $V_1 = V_0 - V_{0-1}$, voltage at node 1.
- $I_1 = \frac{S_1}{\sqrt{3}\text{kV}_1} = \frac{\text{KVA}_1}{\sqrt{3}\text{kV}_1}$, load current at node 1.
- $I_{1-2} = I_{0-1} - I_1$, current for segment between nodes 1 and 2.

Similarly the voltage drop for next segment, voltage at next node, load current for next node and segment current for next segment are computed, as shown in Table 2.

2. DG for performance enhancement of distribution feeder

DG is a concept of installing and operating small electric generators connected directly to the distribution network or at the customer side. The term DG can be described as small scale generating unit located in the vicinity of load centers [9,11,13,23]. The small size and the modularity of DG support a potentially broad range of customer and the grid-sited applications where the base power plants would prove to be impractical. A wide verity of DG technologies such as wind turbines, fuel cells, and photovoltaic can be considered as an alternative to capacity addition [9]. A study by the national gas foundation, USA concludes that by the year 2010, 30% of the new generation will be that of DG. The main reasons for the expected penetration of DG includes the trend of restructuring in electric power utilities, the availability of new generation technologies with the small ratings and overloading of the existing networks [11].

Presently, the electric utilities are exploring potential application for DGs at the utility-side of network. Consequently, they are fully integrated with the distribution system. Generally, DG has shown excellent performance in the areas having high density of electrical loads. They have also performed well in rural and isolated areas where the distribution feeder exceeds the standard limits and the voltage profile may be improved through the installation of a feasible DG technology. These technologies become feasible where the availability of electricity from the national grid is not a viable option [12]. The purpose of these technologies is to cope with the increasing demand of the electricity in certain areas and render certain activities self-sufficient in terms of power production. Significant benefits can be accrued by integrating DG with the utility network [14]. The technical requirements for a large scale and reliability enhancing integration of DG into the existing distribution system depend upon the evolution of the markets. These markets include that of customer-driven (back-up generation), utility distribution system enhancement, local micro-grid, interconnected local micro-grids, and interconnected local micro-grids with the utility network [15]. DGs are required to install in various sizes at utility location throughout the grid to meet the following needs [16]:

- Voltage profile improvement.
- Line loss reduction.
- Improved feeder performance and enhanced power reliability.
- Environmental friendly.
- Relieved transmission and distribution congestion.
- Reduce the operating cost due to peak shaving.
- Minimize the operation and maintenance cost.

Table 2
Existing system results without DG.

S. no.	Segment current (A)	Segment voltage drop (V)	Node voltage (V)	Power loss (kW)
1	444.2	243.42	10756.58	83.266
2	433.7	228.126	10528.45	76.178
3	424.5	120.982	10407.47	39.644
4	419.2	64.137	10343.33	20.736
5	407.2	116.052	10227.281	36.478
6	401.9	299.415	9927.866	92.714
7	393.9	65.387	9862.479	19.860
8	392.6	25.91	9836.569	07.861
9	390.0	128.31	9708.259	38.481
10	382.0	63.412	9644.847	18.678
11	368.8	96.99	9547.857	27.475
12	351.8	146.70	9401.157	39.728
13	288.8	82.308	9318.848	18.49
14	262.5	28.612	9290.237	05.788
15	236.2	70.387	9219.85	12.832
16	234.9	49.329	9170.521	09.325
17	229.9	25.06	9145.461	04.428
18	201.6	13.305	9132.156	02.073
19	199.0	21.691	9110.465	03.326
20	197.7	56.344	9054.121	08.599
21	196.4	107.63	8946.491	16.278
22	163.2	25.035	8921.456	03.143
23	157.9	10.42	8911.036	01.272
24	155.3	38.82	8872.216	04.631
25	152.7	16.64	8855.576	01.959
26	147.4	9.728	8845.848	01.108
27	144.8	15.7832	8830.0648	01.761
28	143.5	12.485	8817.5798	01.379
29	135.5	23.71	8793.869	02.479
30	125.0	9.875	8783.99	00.953
31	67.0	13.199	8770.7958	00.682
32	61.7	6.73	8764.0658	00.320
33	59.1	24.64	8739.4258	01.121
34	57.8	31.674	8707.7518	01.410
35	47.3	3.122	8704.6298	00.114
36	44.7	14.70	8689.9298	00.505
37	42.1	4.588	8685.3418	00.149
38	40.8	11.628	8673.7138	00.366
Total voltage drop = 2326.2862			Total power loss = 605.45	

- Energy needs.
- Improve grid asset utilization.

3. Performance enhancement of distribution feeder

The proper size and placement of DG in the distribution network reduces the voltage drop and power loss significantly. The recent advancement in the power electronics and control technology with increasing demand for the electricity has made the DG, a viable option for performance improvement of the distribution feeder. It is envisaged that electric power distribution system having DG is more reliable. During the fault condition, when the utility main grid is unable to provide electrical energy to the consumers within the micro-grid, DG provides uninterruptible electric power to such consumers, thereby increasing the performance of distribution network [17]. The penetration of DG in low voltage distribution network is increasing worldwide. The saturation in the conventional resources of electric power generation compelled the electric utilities to utilize the locally available resources. The presence of local generation close to the load centers can increase the power quality and reliability of distribution system in term of voltage profile improvement and power loss reduction [18]. Fossil fuel based electric generation encountered the problem of heavy electric losses, almost 65% of the primary energy input [19]. The implementation of DG minimizes these losses significantly. In context of DG, different alternatives are available to distribution engineers to maximize the electrical energy saving. The application of photovoltaic (DG) system can be utilized for combined generation of electrical energy and refrigeration to preserve the fruit and food related items [20]. To improve the power quality and efficiency of distribution feeder, DGs are considered to be the best alternative. DGs offer tangible merits stemming from the possibility of cost-effective generation [21].

3.1. Voltage profile improvement (EPI) of distribution feeder

To keep the tail end customers voltage within permissible limits, DGs are installed in the distribution network. DG can provide portion of real and reactive power to the load which intern decreases the current along the feeder segment. This reduction of current causes the voltage boost up in magnitude at the customer terminals. To quantify the benefits of voltage profile improvement, a voltage profile improvement index has been introduced which is actually the ratio of voltages at different nodes when DG is connected to the system to the voltages at different nodes when DG is not implemented to the system under similar load conditions.

Mathematical notation is shown in Eq. (1).

$$EPII = \frac{EP_{DG}}{EP} \tag{1}$$

where $EPII$ is the voltage profile improvement index, EP_{DG} the voltage at different nodes when DG is incorporated in the network and EP is voltage at different nodes when there is no DG connection under similar load conditions.

The expression should be used only after defining the maximum and minimum allowable limits which are ±5% of the nominal voltage rating [22]. In per unit system the nominal voltage ratings are:

$$E_{nom} = 1.00p.u.$$
$$E_{\max} = 1.05p.u.$$
$$E_{\min} = 0.95p.u.$$

where E_{nom} is the nominal value of voltage in per unit, $E_{\max}$ the maximum value of voltage in per unit, and $E_{\min}$ is the minimum value of voltage in per unit.

Taking only the magnitude of voltage, the voltage profile improvement (EP1) for the ith node can be expressed as:

$$EP_i = \frac{(E_i - E_{\min})(E_{\max} - E_i)}{(E_{nom} - E_{\min})(E_{\max} - E_{nom})} \tag{2}$$

where E_i is the any value of voltage in per unit at ith node. The overall voltage profile index of the system is

$$EP_1 = \frac{1}{N}\sum_{i=1}^{n} EP_i \tag{3}$$

where N is the number of nodes.

The voltage profile improvement index $EPII$ stated in Eq. (1) can be rewritten as

$$EPII_1 = \frac{EP_{1DG}}{EP_1} \tag{4}$$

To achieve the accuracy in the results, a weighting factor based on importance of different loads is chosen. Normally, all nodes are equally weighted for which value of weighting factor (K) can be taken as 1 based on the analyses of the result. Keeping in view of weighting factor, the Eq. (2) can be modified as

$$EP_{2i} = \frac{(E_i - E_{\min})(E_{\max} - E_i)L_iK_i}{(E_{nom} - E_{\min})(E_{\max} - E_{nom})\sum_{K=1}^{n} L_iK_i} \tag{5}$$

where EP_{2i} is the voltage profile at ith node with weighting factor, L_i the load supplied at ith node in per unit, and K_i is the weighting factor at ith node.

The overall voltage profile index expressed in Eq. (3) can be rewritten as

$$EP_2 = \sum_{i=1}^{n} EP_{2i} \tag{6}$$

The corresponding voltage profile improvement index will be

$$EPII_2 = \frac{EP_{2DG}}{EP_2} \tag{7}$$

The general expression for the voltage profile of the distribution system can be rewritten as

$$EP = \sum_{i=1}^{n} E_iL_iK_i \tag{8}$$

where EP is the voltage profile, E_i the voltage of ith node in per unit, L_i the load supplied at ith node in per unit, n the number of node, and K_i is the weighting factor of ith node.

The general equation of the voltage profile is valid only when all the node voltages are within the permissible limit ±5 of the nominal voltage rating. The voltage profile index is 0 at 0.95 per unit and 1.05 per unit and has a maximum value of 1.0 when all the node voltages are at their nominal values. If any node voltage falls below or rises above the nominal voltage, the overall voltage profile of the system is affected adversely, indicating the exact picture of the effect of DG on the distribution system. The voltage profile of individual nodes will be negative if node voltage falls below $E_{\min}$ or rises above the $E_{\max}$, resulting reduction of the overall voltage profile index of the system.

3.2. Effect of voltage profile improvement on feeder performance

Practically it has been noticed that the majority of the distribution feeders are unbalanced, heavily over loaded, lengthy and utilizes unequal conductor size. In such circumstances, the voltage drop and power loss in various segments of the feeder crosses the standard tolerance limit. As a result, the poor voltage profile adversely affects power quality of the electric utility. To avoid such situation, an analytical approach is adopted to remedy the situation in the presence of IDG algorithm. This method enables to grasp the conflicting nature of non-uniformly distributed load which mainly causes the feeder performance issues. It is known that by improving the voltage profile of distribution feeder the active and reactive power losses are reduced [24]. The addition of DG to distribution network at optimal location can improve the voltage profile which in turn increases the operating efficiency of the distribution feeder [25]. The problems of voltage drop and power loss are minimized and the overall performance of the system is enhanced.

4. Distribution feeder performance enhancement analyses

In the existing competitive environment, utilities are facing the pressure of deregulation in the electric industry and the power quality awareness of the customers. It has become essential to enhance the feeder performance in terms of voltage drop and power loss reduction. Mostly the rural feeders of developed and underdeveloped countries are lengthy and overloaded with non-uniform loads. The radial distribution network of 11 kV Panian feeder of Haripur sub-division in the jurisdiction of Peshawar Electricity Supply Corporation (PESCO), Pakistan has been taken as case study. The data regarding the feeder segment length and non-uniform load connected to each node is collected by the field survey. Using this data, the single line diagram is constructed as depicted in Fig. 4. For convenience, the single line diagram has been reduced to 38 nodes by adding the loads of laterals and sub laterals as shown in Fig. 5. However, it does not affect the analysis of the feeder.

To simplify the analyses, the radial distribution feeder is divided into various segments between different nodes. Using the analytical method, the parameter values of these feeder segments including resistance, inductance, inductive reactance, impedance, and the power factor are calculated. To make our analysis more realistic, the power factor is taken as 0.9 in this particular case. Instead of using uniform loads, non-uniform loads are considered at each node. The current in each feeder segment is calculated by the application of Kirchhoff's current law. Capacitance and conductance of each segment is neglected due to its shorter length. All the parameter values are listed in Table 1. In order to quantify the effects of non-uniformly distributed load, model diagrams of distribution feeder when DG is not implemented and when DG is incorporated to the system, are simulated as illustrated in Figs. 1 and 2, respectively. The detailed analyses have been completed in three stages. In first stage, the voltage drop and power losses are analytically calculated when DG is not incorporated to the distribution system. In second stage, the voltage drop and power losses are determined analytically when DG is connected to the system. The difference of both the readings is listed in Table 5, showing the performance improvement of distribution feeder. In third stage, the simulations were performed again for above two stages with IDG algorithm and the results were verified analytically.

The distribution feeder is tested against some pre-determined planning criteria as a minimum requirement. That ensures the dis-

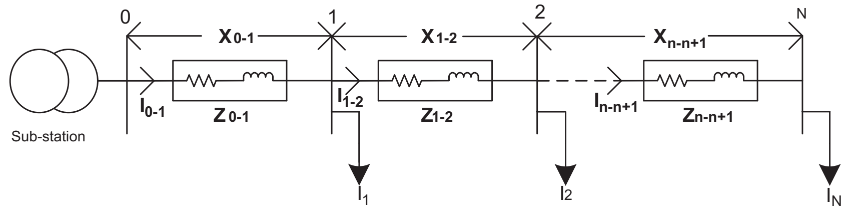

Fig. 1. Model diagram of feeder without DG.

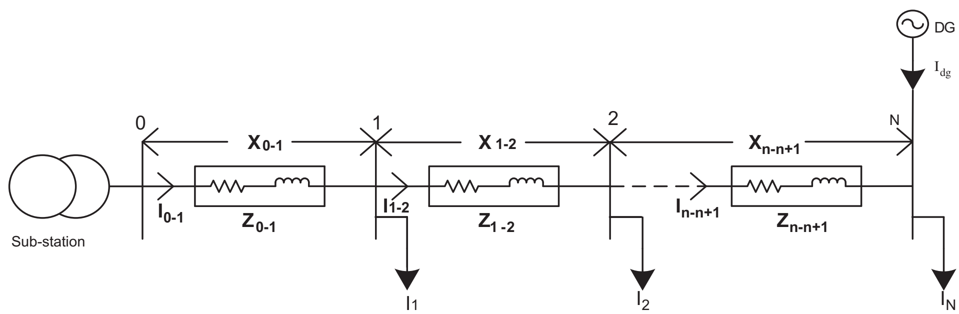

Fig. 2. Model diagram of feeder with DG.

tribution system design to meet specified standard guidelines for distribution system. According to IEEE standards, the voltage magnitude at all nodes of distribution feeder should be ±5% of rated value [26]. In order to bring the voltage drop at each node of the feeder to its specified limits, IDG tool is developed in which there is a provision of determining the size, position, and number of DGs required meeting standards and specification for performance of the feeder. In this particular case the 11 kV is selected as a reference voltage. During the simulation, the position and magnitude of DG is varied continuously and the values, within the acceptable limit, are stored. These stored values are tested for a series of checks and calculations to find the optimal position and location of the DG. The application of DG reduces the source current thereby minimizing the voltage drop (IZ) and power loss [27]. In this way, DG reduces the source current to a value at which all the node voltages are within the standard limit. Running this program, the feeder performance can be enhanced to considerable extent by obtaining the optimal values of DG size and location.

4.1. Power loss and voltage drop

The power loss and the voltage drop for different segments and nodes of the feeder are to be calculated by performing the analysis of feeder.

The incremental power loss for "n" segment is

$$\Delta P_{loss} = \int_{x=n}^{n+1} \frac{dI^2}{dt} \theta_{n+1} R_{n,n+1}\, dx \tag{9}$$

The total power loss for "n" segments is

$$P_{loss} = \int_0^1 \frac{dI^2}{dt} \theta_1 R_{0,1}\, dx + \int_1^2 \frac{dI^2}{dt} \theta_2 R_{1,2}\, dx + \cdots \int_n^{n+1} \times \frac{dI^2}{dt} \theta_{n+1} R_{n,n+1}\, dx \tag{10}$$

$$P_{loss} = \sum_{i=0}^{n} \frac{dI^2}{dt} \theta_{i+1} R_{i,i+1} \tag{11}$$

where $i = 0, 1, 2, \ldots n$ is the number of the feeder segment.

The incremental voltage drop for "n" segments is

$$dE_x = \int_{x=n}^{n+1} \frac{dI}{dt} \theta_{n+1} Z_{n,n+1}\, dx \tag{12}$$

The voltage drop at any point at distance "x" from the sending end of the feeder is

$$E_{drop}(x) = E_s - E_x \tag{13}$$

Voltage drop in any feeder segment is

$$E_{dropn,n+1} = \frac{dI}{dt} \theta_{n+1} Z_{n,n+1} \tag{14}$$

Total voltage drop

$$E_{drop} = E_s - E_r \tag{15}$$

4.2. Power loss and voltage drop with DG implementation

Now consider DG connected to "nth" node of the feeder as shown in Fig. 2. This will change the feeder current in each segment due to improvement in the voltage profile along the line. This change in segment current will cause the feeder current to decrease. The feeder current between the source and the location of DG will also change as a result of the injected current source (I_{dg}) [28]. This change in feeder current ($I'_{n,n+1}$) due to DG installation is determined for each feeder segment. Using the same Eqs. (9)–(15), the incremental power loss, total power loss, the incremental voltage drop and the total voltage drop can be calculated when DG is incorporated in the feeder.

4.3. Optimal placement of DG

The confirmed solution of DG allocation can be achieved by complete enumeration of all the possible combinations of sites and sizes of DGs in the electric power distribution system. Narayan S Rau and Yih-heui wan have presented an algorithm for distribution system, called as second order algorithm [29]. The second order algorithm is applicable to a feeder having limited number of nodes. Furthermore, the incorrect assessment of weighting factors α and β can affect the results adversely. According to the zero point analysis the best location for DG is usually at the end of feeder with most heavily loaded branch [26]. Raj Kumar Jaganathan and Tapan Kumar Saha described that the distributions losses can be minimized by placing DG by rule of thumb, 2/3 rule which is most frequently used for capacitor placement in the distribution system [30]. Artificial intelligence techniques and genetic algorithm are efficient tools used to solve the optimization problems. Karen Nan Miu, Hsiao-Dong Chiang have analyzed a distribution network with analytical approaches for uniform and non-uniform load variations at unity power factor [7]. Majority of these techniques are used on the assumption of uniformly distributed load and have the obstacle of excessive convergence time and pre mature convergence.

In this paper, the analytical approach is applied for radial distribution feeder with non-uniform load and power factor other than unity. The application of IDG tool to 11 kV Panian radial distribution feeder of Haripur Sub-division Peshawar Electricity Supply Corporation (PESCO) Pakistan identify the optimal location at node number 30 for DG_1 and at node number 14 for DG_2.

4.4. Implementation of IDG algorithm

It has been observed that during the design of electric power distribution system, the engineers are forced to adopt some unrealistic assumptions to make the model more acceptable. Uniform load distribution, uniform feeder size, constant loads, equal spacing, and the unity power factor are the most common assumptions made in the simulation process. However, in the real life scenario, the situation is quite different from these assumptions. Under such circumstances, a cumbersome job is required by the engineers in the real world of electric power distribution system. Many issues like technical, environmental, operational, economic and social are being encountered during the implementation of DGs [31].

The urban and the rural distribution feeders in the developing and under developing countries are extremely over loaded due to the following reasons:

- The use of undersized conductors.
- Sub-standard jointing practices.
- Remote location of transformers from loads.
- Rapid increase in the domestic power consumption.
- Incorrect assessment of consumer load.
- Fast expansion in the industrial sector.
- Growing demand of electric power in suburbs.

The stated reasons have created many problems both for the electric utilities as well as the consumer, like;

- Unscheduled load shedding.
- Excessive voltage drop.
- Huge power losses.
- Frequent failures in protective systems.
- Financial losses (consumer/utilities).

In such scenarios, the utilization of locally available resources, the DGs, provides considerable relief to generation, transmission, and distribution networks in a very cost effective way. In order to overcome these problems and to provide reliable electric power, IDG tool has been implemented on 11 kV radial distribution network.

Using the analytical approach, the feeder is divided into a number of sections, called segments. During the execution of IDG algorithm, the calculation of segment data is of great importance for which initial grid voltage, number of nodes, segment length and load (in amperes) connected to each node are provided by the user. This input data can be provided either through key board or file depending upon the needs of user. The accuracy of the simulation greatly depends on the input information. Therefore, much care is required for precise and accurate collection of input data.

The IDG algorithm has the ability to calculate the segment data, including the segment resistance, inductance, inductive reactance, impedance, segment current, voltage drops, node voltages, power factor, and power losses. The algorithm can be run for manual DG implementation as well as for an automatic one. In manual operation, the location and capacity of DG(s) is given by the user. The rest of the values are calculated by IDG tool. Whereas, in automatic mode, after determining the need for DG_1, it tries to find the optimum solution by implementing a single DG_1 of varying capacity on each and every node one by one, while keeping the DG_1 capacity less than the grid capacity. However, when a single DG_1 is not able to normalize the node voltages, it incorporates another DG_2, following the same procedure of varying capacity automatically on each and every node one by one. For an accumulative capacity not more than the grid capacity, the optimum solution in this particular case with two DGs at different nodes is found for the feeder.

The IEEE standards allow only ±5% variations in voltage magnitude of rated value at all nodes of distribution feeder [22]. In these analyses 11 kV has been selected as grid voltage for which the feeder voltage must not exceed the maximum (11.55 kV) and minimum (10.45 kV) permissible values at each node. Proposed algorithm tries all possible combinations of DG(s) and simultaneously keeps a check to find out the optimum rating of DG(s) and its location(s). The introduction of DG(s) in the feeder changes the segment currents distribution. Obviously, it minimizes the grid current, thereby; reducing the segment currents which intern optimizes the node voltages and power losses. IDG algorithm is implemented in three steps.

In first step, the input data including, the grid voltage, number of nodes, segment length and load (in amperes) connected to each node is provided either through keyboard or file. Based upon the input information, all the segment parameters are calculated automatically.

In second step, the simulation is performed to see whether the DG(s) are required or not. If the results are within the specified limits, then total voltage drops and power losses are determined for the feeder. Observing the outputs on the screen, the user has the option to save the outputs in the file which can be used to create voltage profile and power loss curves and other analyses.

In third step, after the identification of DG(s) requirement, the DG(s) are connected in the feeder to find the optimum solution.

The most distinguishing property of designed algorithm lies in its modular programming approach. Any kind of alteration in its design is easily incorporated whenever it is required. Flow chart for the algorithm is shown in Fig. 3. It can be implemented through the following steps:

(i) Select the feeder reference voltage and calculate the total number of nodes.
(ii) Find the segment length and load (in amperes) connected to each node.
(iii) Determine the feeder parameters including segment resistance, inductance, inductive reactance, impedance, length, segments currents, node voltages, power losses and power factor for each feeder segment.
(iv) Confirms the voltage limits for each node ±5% of the rated value.
(v) If node voltages are out of limit, then connect the $DG_1$to "nth" node
(vi) Evaluate the change in each segment current due to DG_1 and calculate the node voltages.
(vii) If node voltages are out of limit, change the location of DG_1until all the node voltages are within acceptable range.

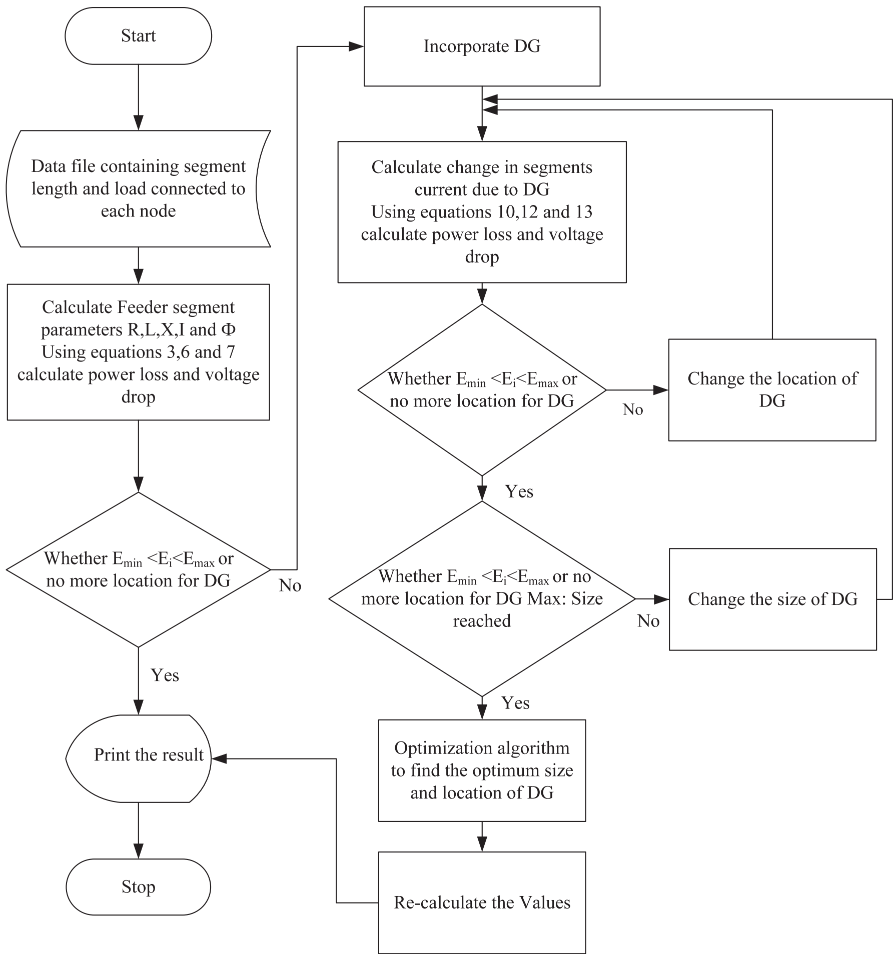

Fig. 3. Flow chart for calculating the voltage drop and power loss, without and with DG.

(viii) If node voltages are still out of limit, also start changing the size of DG_1 in a step of 0.01 A along with locations.

(ix) If node voltages are still out of range, connect DG_2 to "*n*th" node along with DG_1 and repeat the process from step (vi) to step (viii) for DG_1 and DG_2, simultaneously until the optimal solution is obtained.

(x) Calculate the total voltage drop and power loss.

(xi) The position(s) and size(s) of the DG(s) will be the required optimal location and size.

(xii) Save the results in data file.

4.5. Salient features of the IDG tool

IDG tool is design in "C"-language and is very flexible in its application. Because of its modular programming, user can make the alteration according to his own needs and requirements as and when required. Salient features are listed as below.

1. Ability to find optimum solution for distribution feeder having uniform/non-uniform loads.
2. Two different input modes; through keyboard or file, depending upon the requirement of user.
3. Initial (grid) voltage, number of nodes, segment length and segment load current are given by the user.
4. Automatically calculates segment current, resistance, inductance, inductive reactance, impedance, node voltage, and segment power loss.
5. The user has the option for either a manual DG implementation or an automatic one.
6. DG(s) position and capacity given by user in manual mode. While the rest of the values are calculated by the tool.
7. In automatic mode after determining the need for a DG, it tries to find an optimum solution first by implementing a single DG of varying capacity on each and every node of the distribution feeder one by one, while keeping the DG capacity less than the grid (source) capacity.
8. When a single DG is not able to normalize the nodes voltage, it incorporates another DG, through the same procedure, of varying capacity automatically on each and every node one by one, finding the optimum solution as two DG(s) at different nodes, having an accumulated capacity not exceeding the grid (source).
9. It tries all possible combinations of DG(s) and simultaneously keeps a check to find out the optimum rating of DG(s) and location(s).
10. After reaching an optimum solution, it calculates total power loss and voltage drop for the whole feeder.
11. Viewing the output on screen the user has the option to save the output in a file, which can later be used to create graphs and other analyses.
12. The tool has been designed by using a modular programming approach, enabling an efficient enhancement/alteration, as and when required.

5. Case study

The 11 kV Panian radial distribution feeder of Haripur Sub-division Peshawar Electricity Supply Corporation (PESCO) Pakistan has been taken as case study. It is 98.9 km long and emanates from 132 kV Haripur grid station. The feeder comprises of 168 nodes, feeding different categories of loads including residential, agricultural, commercial and Industrial. The total number of consumers fed by the selected feeder is 6948. The category wise distribution of these consumers is illustrated in Table 6. The model diagrams of the feeder when DG is not implemented and when DG is incorporated, are depicted in Figs. 1 and 2. The values of line resistance, inductance, inductive reactance, impedance, segment voltage drop, node voltage, and line power loss are calculated for each segment as listed in Table 1. The values of these parameters depend upon the wire factor which changes with change in size of conductor.

The analysis is completed in the following three steps.

5.1. Step 1

In this step, the single line diagram shown in Fig. 4 has been developed on the bases of data collected during the field visit. To simplify the system, the parent diagram of feeder is modified to 38 nodes system as depicted in Fig. 5. The parameter values were calculated according to the information and data collected during the field survey as listed in Table 1. The current in each section is determined. The total feeder load calculated during the field survey is 8425 kVA.

5.2. Step 2

As described earlier, the feeder mainly comprises of non-uniformly distributed loads. For such type of feeders, different simulation techniques can be utilized. In this particular analysis, the simulation is based upon analytical approach. The current distribution diagram is generated as mentioned above. The modified feeder diagram is simulated with IDG algorithm for the existing load condition. The detailed analytical results presented in Tables 2 and 3 provides the actual information regarding the existing system segment voltage drop, power loss and nodes voltage under fully loaded condition. Both the results indicate high voltage drop (21%) and power loss (8%). The voltage profile and power loss curves are presented in Figs. 6 and 7, respectively. The curve shown in Fig. 6 indicates the sharp and non-uniform variations in the node voltages of the feeder. Many reasons are responsible for this unequal node voltage deviations, the non-uniform distribution of load is one out of them. Examining the existing conditions of the feeder, it is observed that the voltage of node numbers 1 and 2 falls within the acceptable range whereas, all the rest of nodes voltages

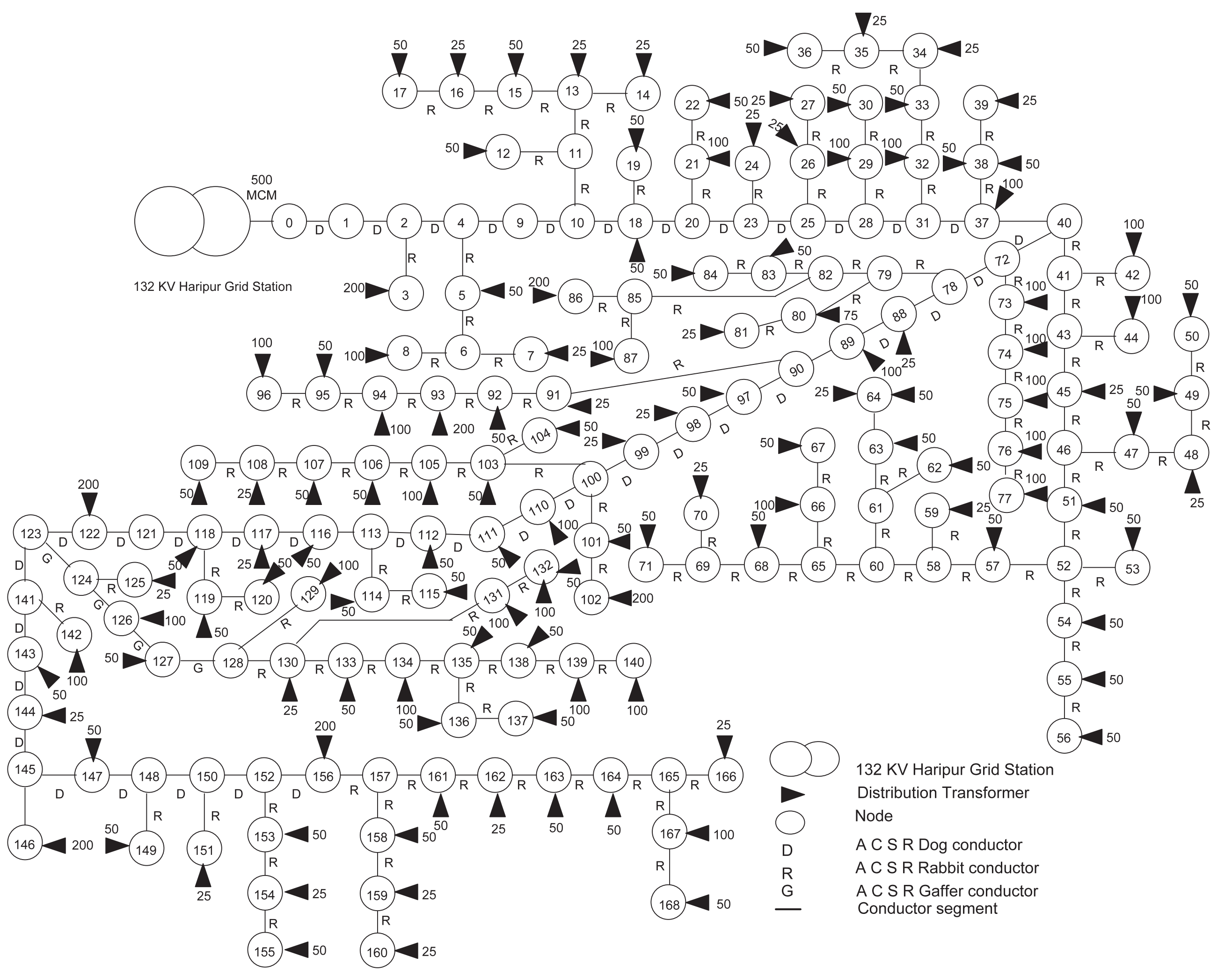

Fig. 4. Single line diagram of Panian feeder.

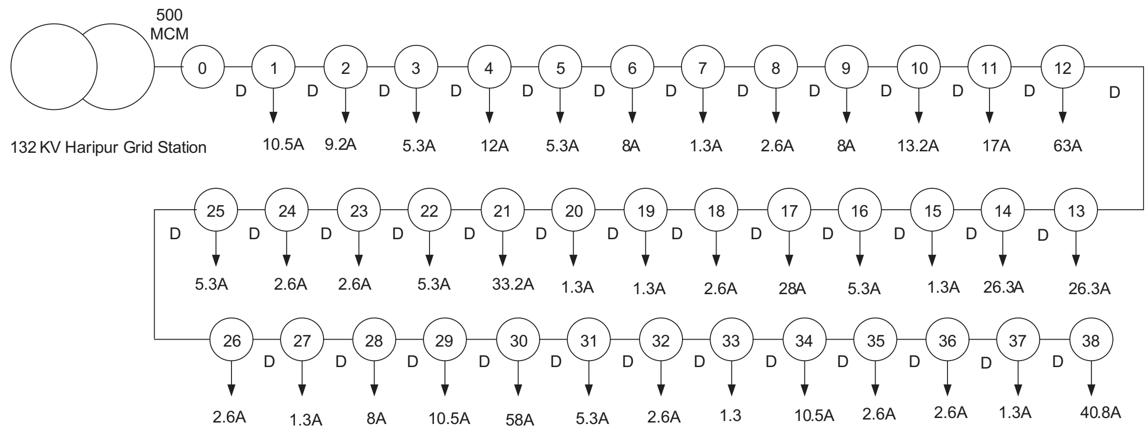

Fig. 5. Modified single line diagram of system under study.

Table 3
Existing System results with DG.

S. no.	Segment current (A)	Segment voltage drop (V)	Node voltage (V)	Power loss (kW)
1	128.96	70.67	10929.330	7.0180
2	118.46	62.31	10867.020	5.6833
3	109.26	31.139	10835.880	7.7595
4	103.96	15.947	10819.934	1.2753
5	91.96	26.210	10793.724	1.8600
6	86.66	64.562	10729.162	4.311
7	78.66	13.057	10716.105	0.792
8	77.36	5.105	10711.00	0.305
9	74.76	24.596	10668.404	1.414
10	66.76	11.082	10675.322	0.5705
11	53.56	14.086	10661.236	0.5795
12	36.56	5.374	10655.862	0.429
13	26.44	7.535	10648.327	0.1540
14	52.74	5.748	10642.579	0.2336
15	40.84	12.17	10630.409	0.384
16	39.54	7.789	10622.62	0.2376
17	34.24	3.732	10618.888	0.09854
18	6.24	0.412	10618.476	0.0020
19	3.64	0.396	10618.08	0.0011
20	2.34	0.666	10617.414	0.0012
21	1.04	0.569	10616.845	0.0005
22	32.16	4.933	10611.912	0.122
23	37.46	2.472	10609.44	0.072
24	40.06	10.015	10599.425	0.308
25	42.66	4.649	10594.775	0.153
26	47.96	3.165	10591.611	0.117
27	50.56	5.511	10586.1	0.215
28	51.86	4.512	10581.588	0.1802
29	59.86	10.475	10571.113	0.484
30	70.36	5.558	10565.555	0.302
31	67.0	13.199	10552.356	0.682
32	61.7	6.725	10545.631	0.320
33	59.1	24.644	10520.987	1.121
34	57.8	31.674	10489.313	1.41
35	47.3	3.122	10486.191	0.114
36	44.7	14.706	10471.485	0.506
37	42.1	4.589	10466.896	0.150
38	40.8	11.628	10455.268	0.366
Total voltage drop = 544.732			Total power loss = 39.732	

are out of standard limit. Analyzing the voltage profile of existing system, the severe nature of the power quality problem can be concluded. Under such a deteriorated condition, both the reliability as well as the efficiency of the distribution system is badly affected. The power curve of Fig. 7 shows that there is significant power loss at node numbers 1, 2, and 6. Up to node number 21; sharp variations in power loss are recorded. After that, the power loss reduces almost to zero up to node number 38. In the beginning of feeder, the large amount of current flow which causes the substantial power loss on initial nodes of the network. Significant reduction in the power loss has been observed at the tail end of the feeder. Both the curves of Figs. 6 and 7 illustrate the excessive voltage drop and power loss in the initial nodes of the network.

5.3. Step 3

In order to bring the voltage drop and power loss within the acceptable limit, the system was simulated again in with IDG algo-

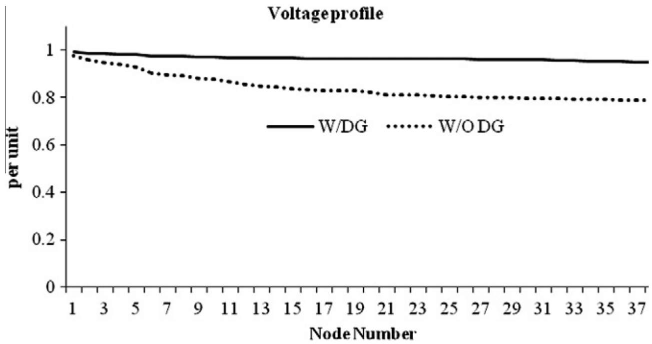

Fig. 6. Voltage profile without and with DG.

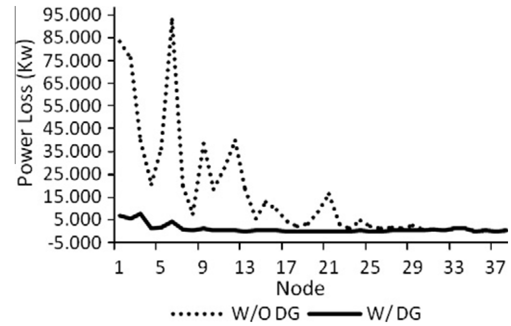

Fig. 7. Power loss curve without and with DG.

rithm for above mentioned two steps. The salient features of IDG tool enable us to identify the optimal size, location, and number of DGs in the distribution system.

The detailed simulation results as illustrated in Table 4, provide two number of DGs (DG1 and DG2) having sizes of 3.722 MVA and 2.28 MVA, respectively. The program has also determined the optimal placement for DG1 and DG2 at node numbers 30 and 14, respectively. The analytical and simulation results of algorithm were tested and verified. The detailed study of the results show a remarkable reduction in the voltage drop and power loss as listed in Table 5.

The voltage profile and the power loss curves for the system having DGs are shown in Figs. 6 and 7, respectively. The detailed investigation of voltage profile depicted in Fig. 6 and the simulation results of Table 4 indicates the maximum improvement in nodes voltage of the feeder. Without IDG tool, the voltage of only first two nodes was within permissible limit. Implementation of IDG algorithm changes all nodes voltages to an acceptable range (above 10,450 V). The voltage profile has been smoothened to a great extent as shown in Fig. 6. The voltage drop has been reduced from 21% to 4.9% which is well within the acceptable limit. The net reduction of 16.05% in voltage drop has been achieved, showing an excellent performance of IDG algorithm.

Table 4
Simulation results with DG.

S. no.	Segment current (A)	Segment voltage drop (V)	Node voltage (V)	Power loss (kW)
1	129.7	69.8	10930.200	7.09682
2	119.2	61.583	10868.618	5.7545
3	110.0	30.783	10837.835	2.65444
4	104.7	15.777	10822.058	1.295
5	92.7	25.942	10796.116	1.885
6	87.4	63.968	10732.148	4.3827
7	79.4	12.99	10719.158	0.80853
8	78.1	5.044	10714.115	0.3088
9	75.5	24.379	10689.736	1.44288
10	67.5	8.718	10681.018	0.41632
11	54.3	14.027	10666.991	0.597069
12	37.3	15.256	10651.735	0.446082
13	25.7	7.192	10644.543	0.144895
14	52.0	5.597	10638.946	0.22815
15	41.2	12.062	10626.885	0.389562
16	39.9	7.73	10619.155	0.241787
17	34.9	3.756	10615.398	0.10277
18	6.6	0.426	10614.972	0.002205
19	4.0	0.431	10614.541	0.00135
20	2.7	0.756	10613.786	0.001599
21	1.4	0.753	10613.032	0.000827
22	31.8	4.792	10608.241	0.119453
23	37.1	2.396	10605.845	0.069681
24	39.7	9.742	10596.102	0.3032
25	42.3	4.553	10591.549	0.150971
26	47.6	3.074	10588.475	0.114704
27	50.2	5.403	10583.072	0.212628
28	51.5	4.434	10578.638	0.179027
29	59.5	10.247	10568.391	0.477934
30	70.0	5.425	10562.967	0.297675
31	66.8	12.942	10550.025	0.677703
32	61.5	6.619	10543.406	0.319127
33	58.9	24.09	10519.315	1.112315
34	57.6	30.998	10488.317	1.39968
35	47.3	3.055	10485.263	0.113263
36	44.7	14.433	10470.829	0.505767
37	42.1	4.531	10466.298	0.149547
38	40.8	11.418	10454.88	0.36518
Total voltage drop = 545.12			Total power loss = 34.814	

Table 5
Comparison of voltage drop and power loss without and with DG.

Voltage drop		
Voltage drop without DG (V)	Voltage drop with DG (V)	Reduction in voltage drop (V)
2326.2862	544.732	1781.5542
Power loss		
Power loss without DG (kW)	Power loss with DG (kW)	Reduction in power loss (kW)
605.45	39.732	565.718

Table 6
Tariff wise number of consumers.

S no.	Category	No. of connection
1	Domestic S/phase	6667
2	Domestic 3/phase	100
3	Commercial S/phase	120
4	Commercial 3/phase	09
5	Agriculture 3/phase	07
6	Water supply	15
7	Industrial	30
Total = 6948		

The application of IDG tool also minimizes the power loss from 8% to 0.51%. The total reduction of 7.49% has been observed. After implementing IDG tool the power loss of 83.266 kW at node number 1 and 76.178 kW at node number 2 has been reduced to 7.09682 kW and 5.7545 kW, respectively as observed in the power loss curve of Fig. 7. The relevant curve indicates power loss of few kilowatts (23.06846 kW) in the first five nodes of the feeder. All the remaining nodes have power loss less than 1 kW except node numbers 33 and 34 which have the power loss of 1.112 kW and 1.4 kW, respectively. It is also noticed that the heavy power loss at node number 6 has been reduced from 92.714 kW to 4.3827 kW which reflects the effectiveness and successfulness of IDG algorithm.

10 MVA source has been utilized for the existing feeder. During implementation of algorithm, the performance of the feeder has been enhanced, while using only two DGs, having the accumulative capacity of 6.002 MVA, almost 60.02% of the main source capacity. The analyses illustrate the fact that IDG tool can be implemented successfully to identify the optimal size and location of DG(s) and rectify the problems of voltage drop and power loss of any distribution feeder, having non-uniformly distributed load.

6. Conclusion

A comprehensive algorithm for the Implementation of Distributed Generation (IDG) has been developed to identify the optimal size and location of DG in the distribution system. The proposed method can be utilized effectively to increase the feeder performance having non-uniformly distributed loads. Elaborative results are presented in the case study to assess the performance of distribution feeders as potential custom power solution. The structure of IDG tool is more flexible and capable of optimizing any complex feeder up to *n*th number of nodes. The algorithm can be run either for manual DG implementation or an automatic one. It has the ability to calculate automatically segment data, including the segment resistance, inductance, inductive reactance, impedance, segment current, voltage drops, node voltages, power factor, and power losses. IDG algorithm tries all possible combination of DG(s) and simultaneously keeps a check to find out the optimum rating DG(s) and location(s). The accuracy of the simulation greatly depends on the input information.

The proper size and placement of DG in the distribution network reduces the voltage drop and power loss significantly. Application of DG reduces the source (grid) current thereby minimizing the voltage drop (IZ) and power loss (I^2R). Therefore, DG minimizes the source current to a value at which all the node voltages are within the standard limit. Non-uniform distribution of loads in the feeder is mainly responsible for power quality issues. The recent advancement in the technology and increasing demand for electricity has made the DG, a viable alternative for performance improvement of distribution feeder. More benefits can be accrued by integrating DG with electric utility network.

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