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PSO based Multi-Criteria Placement and Impact Evaluation of Distributed Generators in Indian Context

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This paper presents a new approach for optimal placement of Distributed Generators (DGs) utilizing a generic multi-objective performance function considering dynamic relevance (weight) factors and various levels of the DG penetration. The suggested approach can place the fixed size as well as the variable size of multiple DGs in single or multiple stage(s), considering any type of load model. The technical performance of the system, with the dynamic relevance factors is found to be better than with the fixed relevance factors approach. The effect of considering system constraints on the DG size and its location has been studied. A look up table approach is also suggested to place the DG at locations other than the most optimal one. The impact of the DG placement on the system voltage profile and line loss has also been investigated on 33-bus and 41-bus (Indian system) distribution systems. The critical cases with extreme DG output power and distribution load demand are simulated on these systems to study the technical viability of the DG planning under such circumstances.

Keywords: *Distributed generation, Multi-objective function and Particle swarm optimization.*

1.0 INTRODUCTION

Distributed Generation (DG) has emerged as a key option for promoting energy security with minimum environmental impact. The DGs can be (a) Renewable Energy Sources (RES) such as wind turbine, Solar Photo Voltaic (SPV), bagasse cogeneration and biomass gasifier, (b) non-renewable sources such as internal combustion engine, fuel cell and micro turbine, etc. The DGs are being incorporated in the present distribution systems as these offer several advantages, such as technical, economic and environmental. Considering these facts, the renewable as well as non-renewable DG technologies are expected to be used increasingly in the future [1, 2]. Hence, the optimal placement and sizing of the DGs have attracted attention of the power system researchers.

In recent years, studies have been conducted considering various techniques for locating the DG units in distribution feeders. In [2–7], the placement of the DG was carried out addressing multi-objectives of the DG planning. The various objectives were combined together using weight factors approach. The value of weight factors was taken fixed as per the choice of the utility. It is mentioned in [8] that a systematic method of effectively determining the proper weight of each objective is a subject for future study as it is a tedious work for the utility. In [9–12], the placement of the DG was carried out to minimize the system loss as a single objective in the planning of single DG or multiple DGs using either analytical or heuristic method. Esmin *et al.* [13] established a relation between loss reduction and voltage collapse problems, and the loss reduction was obtained in the area most vulnerable to the

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voltage collapse. Hasan *et al*. [14] proposed a method based on continuation power flow. The placement of the DG was considered at the buses most sensitive to the voltage collapse.

Celli *et al.* [15] presented a methodology for the DG sizing and siting, which permits the planner to decide the best compromise between the cost of network upgrading, power loss, energy not supplied, and energy required by the served customers. The implemented technique is based on a Genetic Algorithm (GA) and an ε-constrained method. Haghifam *et al*. [16] used the concept of Pareto optimality based on the non-dominant sorting genetic algorithm for the optimization problem. Nekooei *et al.* [17] presented a harmony search based optimal placement of DGs. However, it provides a trade-off solution. Ochoa and Harrison [18] proposed an approach to determine the optimal accommodation of the DG (renewable) in a way that minimizes the system energy losses. In addition, coordinated voltage control and dispatchable DG power factor, were embedded in the approach to explore the extra loss reduction benefits. The trade-off between energy losses and more generation capacity was also investigated.

Soroudi *et al*. [19] proposed a model to simultaneously optimize two objectives, benefits

NOMENCLATURE			
DG	Distributed generation.	$Q_{l(i)}$	Reactive power demand at bus i (MVAr).
EQ_{dg}	Energy from the DG (MWh).	$Q_{lo(i)}$	Constant reactive power demand at bus i (MVAr).
EQ_{ss}	Energy from the SS (MWh).	$Q_{L(x)0}$	Base case reactive power line loss (MVAr).
f_m	Multi-criteria objective function.	$Q_{L(x)dg}$	Reactive power line loss with DG (MVAr).
GE_{dg}	Gas emission from the DG supply (kg).	Q_{ss}	Reactive power in-feed from the SS (MVAr).
GE_{ss}	Gas emission from the main supply (kg).	RES	Renewable Energy Sources.
GR_{dg}	Gas emission rate in the DG supply (kg/MWh).	R	Real number.
GR_{ss}	Gas emission rate in the main supply (kg/MWh).	$SLIP$	Distribution system real line loss index.
i	Bus index count, i =1, 2,...n.	$SLIQ$	Distribution system reactive line loss index.
n	Total number of the system buses.	$SGEI$	Distribution system gas emission index.
n_l	Total number of the system branches.	$SVPI$	Distribution system voltage performance index.
$P_{dg(i)}$	Real power generation by the DG at bus i (MW).	SS	Substation.
P_{dg}	DG size (MW) at unity power factor.	SPV	Solar photo voltaic.
$P_{l(i)}$	Real power demand at bus i (MW).	x	Line index count, x =1,2,..n_l.
$P_{lo(i)}$	Constant real power demand at bus i (MW).	X	Particle swarm position vector.
$P_{L(x)0}$	Base case real power line loss (MW).	y	Gas index count, y =1, 2 and 3.
$P_{L(x)dg}$	Real power line loss with DG (MW).	V	Particle swarm velocity vector.
P_{ss}	Real power in-feed from the SS (MW).	V_i	Voltage at bus i (p.u.).
p, q	Exponents for the voltage dependent loads.	α_t	Relevance factor for term t of f_m (t =1, 2, 3, 4).
$Q_{dg(i)}$	Reactive power by the DG at bus-i (MVAr).	ψ	DG penetration level (%).
$Q_{dg\max(i)}$	Maximum reactive power generation capacity of the DG at bus-i (MVAr).	$\sigma(y)$	Weighting factor for y^{th} gas.
		Z	Integer number.

of distribution network operators and the DG owners, and determined the optimal schemes of sizing, placement and specially the timing of investments on the DG units and network reinforcements over the planning period. A two-stage heuristic method is utilized to solve the formulated planning problem. In [20], for DG sizing and siting, the economic factors are considered along with the loss minimization in the distribution system and the objective function is purely expressed in monetary terms. Keane and Malley [21] explained the background of the technical constraints faced by embedded generation projects, and a methodology was developed using linear programming to determine the optimal allocation of the embedded generation with respect to the constraints. D. Singh *et al.* [22] analyzed the effect of various types of loads on the DG planning. Singh *et al*. [23] presented a methodology based on nodal pricing for optimally allocating the DG for profit, loss reduction, and voltage improvement. The paper also addressed voltage rise issues on an existing Indian rural distribution network.

The conventional computing paradigms often face difficulty dealing with practical problems, such as those characterized by discontinuous and non-convex problem with multi-modality. Therefore, Particle Swarm Optimization (PSO) is selected, in this study, as a tool to solve such a complex and nonlinear multi-objective problem. It is a zero-order, non calculus based approach (no gradient required). It can effectively solve discontinuous, multi-modal, non-convex problems. It is inherently continuous in terms of handling design variables [13, 24–28]. In [29], Gonzalez *et al.* solved the DG placement problem by minimizing network power loss and the cost of the power produced from the DG as well as conventional power plant using the discrete PSO and the optimal power flow. The solution of the objective function provided a trade-off solution of the DG capacity addition and loss minimization by minimizing a single objective function, which has been made of two conflicting objective functions. Moradini and Abedini [30] proposed a method for optimal placement of the DG utilizing GA and PSO techniques. The GA was applied to determine the optimal location whereas the PSO is used to find optimal size of the DG, therefore, the total time to solve the problem is more than the either method to be applied alone. In [31], Maciel presented a multi-objective approach to the distribution network planning process using Multi-Objective Evolutionary Particle Swarm Optimizer (MEPSO). The performance of the MEPSO was found better than other methods such as non dominated sorting GA-II, multi-objective Tabu search, etc.

In this paper, a generic multi-objective function based heuristic method is proposed for the multiple DGs sizing and siting. The proposed method uses "forward/backward sweep" method of radial distribution load flow. Therefore, it has less chance to face convergence problem. Recursive load flow based capacitor planning is also done prior to the DG placement, which can maintain voltage under limits, while the RES DG output is not available.

The multi-objective performance function in the proposed algorithm is quite generic and further addition of unit-less indices is easily possible as per the utility's requirement up to the desired DG penetration level (PL). The choice of sub-optimal solution is suggested using a look-up table approach, when deployment of the DG at optimal location is not possible owing to physical constraints, mainly in case of the wind DG and the SPV DG, or if the DG is going to be planned in already existing distribution network. The impact of constraint on size and location is also studied. A new dynamic relevance factors (weight) method to place the DG is proposed and the system technical performance using this approach is found better than that with the fixed relevance factors approach with less DG penetration need. The method is tested on 33-bus and 41-bus (Indian) radial distribution systems considering constant power and composite load models. Impacts of the DG on system performance are investigated to assess the future potential of the DGs.

The paper is organized in seven sections. In section 2, a multi-objective function is formulated for the DG placement. In sections 3 and 4, a Modified

Particle Swarm Optimization (MPSO) approach is discussed and applied to the DG placement problem. In section 5, test systems and simulation results are presented. In section 6, impact analyses of the DG placement are considered to see the future viability of the DG. In section 7, a brief discussion of the results is presented. Finally, the paper is concluded in section 8.

2.0 PROBLEM FORMULATION

The main objective of the DG placement is to get the maximum possible benefits by improving the system performance. The proposed approach incorporates the fixed size and the variable size DG. For the fixed size DG, algorithm finds out optimal location, and for the variable size DG, it gives both optimal location and optimal size.

The problem of the DG placement can be formulated as a non-linear optimization problem. The objective is to minimize a multi-objective function, comprising of the improvement in the system voltage profile, reduction in the environmental emission and line losses, with the DG placement in the distribution system considering its Penetration Level (PL). In this study, no direct inclusion of economic factor is considered. However improvement in the system performance in terms of reduction in losses, pollutants and voltage profile improvement are analyzed as indirect economic benefits. The MPSO is used as a tool to provide the optimal solution to this optimization problem.

2.1 Mathematical Formulation of DG Placement

A balanced 3-phase network is considered in this study and the DG is simulated as negative load. The study is planned for the utility defined - (i) fixed size, (ii) variable size of the DG. In this study, a multi-objective function is formulated, which includes four unit-less indices and each index is assigned a relevance factor either fix or dynamic. In general, the value to each factor depends upon the objective of the DG planning. Assigning a value to the relevance factor is quite subjective and requires experience as wrong value of the relevance factor may lead to non-optimal planning. Therefore, looking into the need of selecting an optimal value of the relevance factors, an approach is proposed in this work, which can provide technically better solution with less penetration level.

In this study, reactive power compensation is supported by fixed size capacitor. It helps system to maintain voltage profile in 0.95–1.0 p.u. during critical hours when the RES DG is not available to supply power. In this work, the reactive power support from the DG can also be sought, but it depends upon the reactive power handling capacity of the DG.

The multi-objective function is formulated, mathematically as $0 \leq \alpha_1, \alpha_2, \alpha_3, \alpha_4 \leq 1$ and $\alpha_1+\alpha_2+\alpha_3+\alpha_4 = 1$.

$$\text{Min. } f_m = \alpha_1(\text{SLIP}) + \alpha_2(\text{SLIQ}) + \alpha_3(\text{SVPI}) + \alpha_4(\text{SGEI}) \quad \text{....(1)}$$

Some of the indices are taken from [2] to form *MOF* for the DG placement using the MPSO method. The relevance factors are considered to give the corresponding importance to each impact indices in the presence of the DG. The utility, which is undergoing the DG placement, can choose suitable relevance factors according to the installation requirements [3].

2.2 Distribution System Real and Reactive Line Loss Index (SLIP and SLIQ)

One of the basic aims to place the DG is to reduce the line loss, which varies with the system loading conditions. With the inclusion of the DG, even with enough increased penetration level, at non-optimal location with non-optimal size, losses can be even higher than without any DG connected (more than 5 times in extreme cases) [32]. As the DG size increases the system loss reduces (increased investment in the DG related capital cost) but beyond a specific value of the overall DG size, the system loss starts increasing [10]. Therefore, the DG should be placed at the optimal location with optimal size to achieve suitable penetration level. The general expressions for the *SLIP* and *SLIQ* are given below.

(a) Distribution System Real Line Loss Index (SLIP)

$$SLIP = \left[\sum_{x=1}^{n_l} P_{L(x)dg} / \sum_{x=1}^{n_l} P_{L(x)0} \right] \quad ....(2)$$

(b) Distribution System Reactive Line Loss Index (SLIQ)

$$SLIQ = \left[\sum_{x=1}^{n_l} Q_{L(x)dg} / \sum_{x=1}^{n_l} Q_{L(x)0} \right] \quad ....(3)$$

The placement of the DG may have significant impact on reactive power loss [33, 34].

2.3 Distribution System Voltage Performance Index (SVPI)

The second important benefit of the DG is the improvement in the system voltage profile. Sometimes, placement of the DG improves the voltage stability and effectively reduces the system loss [13, 14, 20, 35]. The *SVPI* is an index, calculated using the following expression,

$$\begin{aligned} &SVPI = \beta_1 \left|1 - \min(V_i, \forall i \in n)\right| + \beta_2 \left|\max(V_i, \forall i \in n) - 1\right| \\ &\text{where,} \begin{cases} \beta_1 = 0; \text{if } V_i \geq 1, \forall i \in n \text{ else } \beta_1 = 1; \\ \beta_2 = 0; \text{ if } V_i < 1, \forall i \in n \text{ else } \beta_2 = 1; \end{cases} \end{aligned} \quad ....(4)$$

where, V_i and n are the voltage at a bus-i (in p.u.) and the total number of buses in the distribution system, respectively.

The bus voltage of the substation is assumed to be unity p.u. throughout this study and action of controlling devices viz. On Load Tap Changer (OLTC), station capacitor, etc. are assumed to keep it constant.

2.4 Distribution System Gas Emission Index (SGEI)

This index is related to an important social benefit of the DG to reduce the pollutants emission in the atmosphere due to electrical power generation. The *SGEI* is an indicator of the pollutant gas reduction using the DG technology such as the SPV and the wind type DGs, as the pollutants produced by them are almost negligible. This index can be calculated as follows for the three pollutants (CO_2, NO_X and SO_2),

$$SGEI = \sum_{y=1}^{3} \sigma(y)(SGEI(y)) \quad ....(5\text{-a})$$

$$\text{Where } SGEI(y) = \left[GE(y)_{DG} / GE(y)_0 \right] \quad ....(5\text{-b})$$

$$\begin{aligned} GE(y)_{DG} &= (GR(y))_{ss} (EQ)_{ss} \\ &+ (GR(y))_{DG} (EQ)_{DG} \end{aligned} \quad ....(5\text{-c})$$

$$GE(y)_0 = (GR(y))_{ssy} (EQ)_{ss} \quad ....(5\text{-d})$$

$$\text{with } 0 \leq \sigma(y) \leq 1 \text{ and } \sum_{y=1}^{3} \sigma(y) = 1$$

where, $GE(y)_0$ and $GE(y)_{DG}$ are gas emission in base case system (kg) and gas emission of the system including the DG in the system (kg), respectively.

2.5 DG Placement Considerations

The DG placement is proposed to be carried out keeping the following key points under consideration,

(1) In both the cases, the bus with minimum value of either the Loss Index (*LI*) (when α_1=1 and α_2=α_3=α_4=0) or *MOF* value is considered for the DG placement.

(2) In case 2, the DG size is also determined corresponding to the minimum value of the *LI* or *MOF*.

(3) Operating power factor of the DG is assumed to be unity and, hence, injected power is only real power [4, 12, 22, 34, 36–38]. It is generally found that the maximum benefit can be extracted when the DGs are operated at unity power factor because the cost of real power is higher and the DG size is very small as compared to the conventional

power plant [4, 22]. It is also reported in literature [39] that the impact of the DG active power support on voltage profile often more than that with the reactive power support. However, it may also be dependent on the utility decision based on the IEEE standard 1547 [40].

(4) The placement of the DG is subject to the following equality constraints,

$$P_{ss} + \sum_{i=2}^{n} P_{dg(i)} - \sum_{i=2}^{n} P_{l(i)} - \sum_{x=1}^{nl} P_{L(x)} = 0 \quad \text{....(6-a)}$$

$$Q_{ss} + \sum_{i=2}^{n} Q_{dg(i)} - \sum_{i=2}^{n} Q_{l(i)} - \sum_{x=1}^{nl} Q_{L(x)} = 0 \quad \text{....(6-b)}$$

and the inequality constraints

$$V_{min} \leq V_i \leq V_{max} \quad \text{....(6-c)}$$

$$0 \leq P_{DG(i)} \leq \psi \times \sum_{i=2}^{n} P_{lo(i)} \quad \text{....(6-d)}$$

$$0 \leq Q_{DG(i)} \leq Q_{DG\,max(i)} \quad \text{....(6-e)}$$

$$\sum_{x=1}^{nl} P_{L(x)dg} \leq \sum_{x=1}^{nl} P_{L(x)0} \quad \text{....(6-f)}$$

$$\sum_{x=1}^{nl} Q_{L(x)DG} \leq \sum_{x=1}^{nl} Q_{L(x)0} \quad \text{....(6-g)}$$

where, V_{min} and V_{max} are the minimum and the maximum bus voltage limits in the system.

The maximum reactive power generation capacity of the DG at a bus is taken as zero, which can be assigned non zero value to consider the reactive power support within limits imposed by 6(e) as the algorithm suggested in Section IV is quite general

2.6 Load Modeling

In the practical power systems, different categories and types of loads, such as domestic, industrial and commercial loads, might be present. The nature of these loads is such that their active and reactive power demands are dependent on the voltage and frequency of the system. Moreover, load characteristics have significant effect on the load flow solutions and its convergence. Generally, active and reactive powers are expressed as an exponential function of voltage. The exponential load models at nominal voltage (1.0 p.u.), can be given as:

$$P_{l(i)} = P_{lo(i)}(V_i)^p \quad \text{....(7)}$$

$$Q_{l(i)} = Q_{lo(i)}(V_i)^q \quad \text{....(8)}$$

In this study, forward/backward sweep method of distribution load flow is used and it is given in [41, 42] exclusively considering the DG operation as a PQ and PV node. In this study, the loads such as the constant power, small industrial motors, industrial, residential and commercial loads, are considered. Typical values of the p and q for these loads are taken from [22, 43].

3.0 MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

The Particle Swarm Optimization (PSO) algorithm is a population based approach, which is introduced originally by Kennedy and Eberhart in 1995 [24]. Shi and Eberhrt in 1998 proposed modified particle swarm optimizer by introducing a parameter “Inertia weight”, which changes with every iteration count and its large value facilitates global search, while small value facilitates local exploration [25, 28]. This stochastic-based algorith m handles a population (randomly intialized) of individuals inspired by social behavior of bird flocking, fish schooling, etc. The individuals are called particles in the multi dimentional search space. Their population is called a swarm and represents candidate solutions. Each particle in the swarm moves towards the optimal point with adaptive velocity as it is guided by their personal best (*pbest*), for exploiting the best results found so far by each of the particles, and the global best (*gbest*), the best solution found so far by the whole swarm for encouraging further exploration and information sharing between the particles. Thus, it controls the balance between the local and the global exploration of the problem space and helps to overcome premature convergence and also enhances the searching ability. The velocity and, thereby, position of the particle is modified using (9)-(10).

$$V_{md}^{k+1} = \omega V_{md}^{k} + C_1R_1(pbest_{md}^{k} - X_{md}^{k}) + C_2R_2(gbest_{d}^{k} - X_{md}^{k}) \quad ....(9)$$

$$X_{md}^{k+1} = X_{md}^{k} + V_{md}^{k+1} \quad ....(10)$$

where $X_{md}^{k} = [x_{m,1}, x_{m,2}, .., x_{m,n_d}]$ and $V_{md}^{k} = [v_{m,1}, v_{m,2}, .., v_{m,n_d}]$ represent the position and the velocity of the m^{th} particle at iteration k, respectively; $d = 1, 2, \ldots, n_d$, $m = 1, 2, \ldots, N$ and N is the size of the swarm and n_d is the dimension of the problem (in this problem number of DGs in one stage to be placed). The C_1 and C_2 are positive acceleration coefficients, which control the particle's individual and social movements. The range of C_1 and C_2 can be taken between [1.5–2.0] and [2.0–2.5], respectively. Both of these can be set equal to a value 2, although other values are also observed in the literatures [13]. R_1 and R_2 are uniformly distributed random numbers in the range [0, 1] used to introduce the stochastic nature. The inertia weight of the particles, ω, controls the exploration properties of the PSO algorithm. A large value of ω facilitates global search, while small ω facilitates local exploration. Therefore, in MPSO, it is suggested to choose large value of ω at the beginning of the optimization process and gradually reduce it in the successive iterations. This can be done very well by linearly decreasing function as given in (11) [26–28].

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \times iter \quad ....(11)$$

where, ω_{max} and ω_{min} are the initial inertia (maximum value) and final inertia (minimum value) factors, whereas, *iter* and $iter_{max}$ are the current iteration number and the maximum iteration number, respectively. During the iterative procedure, the velocity and position of the particles are updated. This procedure is repeated till the convergence criterion is achieved. The next section is meant to demonstrate how this method is applied in a power system for the DG placement.

4.0 PROPOSED DG PLACEMENT ALGORITHM

Two cases are considered for the DG placement study with various DG penetration levels. The flow chart of the algorithm for both the cases is shown in Figure 1 and the major steps are as following.

Step 1: (*Input System Data and Initialize*): In this step, the distribution system configuration data with constraints, load data, PSO parameters and DG size range are specified.

Step 2: The "forward/backward sweep" method of the distribution load flow is run for the base case analysis to store the base case results which will be used while evaluating (1). The capacitors can be placed, if voltage profile is found below 0.95 p.u., prior to the DG placement at the location where the voltage is found minimum. If system voltage is still below 0.95 p.u., this process will continue till the system voltage reaches 0.95 p.u.

Step 4: The bus number 2 is initially selected as a candidate location of the DG for the following cases and all possible combination of locations are generated with respect to the bus 2 (for multiple DGs in single stage). All the other buses are tried one by one for optimal solution as per the algorithm for the two cases discussed below:

Case 1 (Fixed size DG): In this case, the value of LI or MOF is calculated for the fixed size DG at all the nodes of the system one by one using the load flow. A look up table (optimal DG size versus LI/MOF value at each node) is prepared for all the system nodes. The suitable node for the DG placement is one, which has no constraint violation and has minimum LI or MOF. This process is repeated till selected DG penetration level is achieved.

A. Another method for the fixed size DG placement using the PSO can be similar to case 2, where the only difference is that the

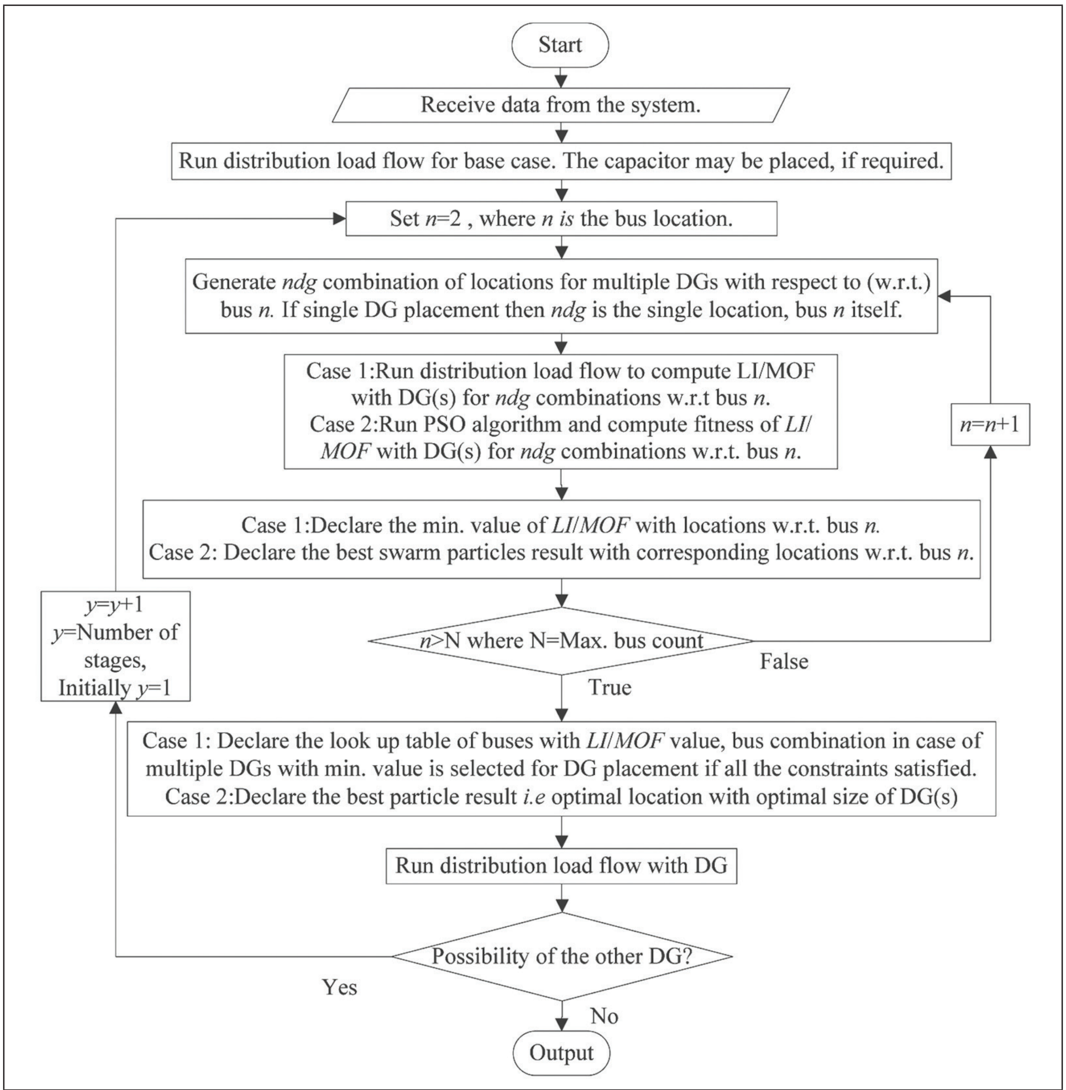

FIG. 1 ALGORITHM FOR DISTRIBUTED GENERATOR(S) PLACEMENT.

entire particles in the swarm are to be fixed size in place of variable size.

B. *Case 2 (Variable size DG)*: The steps used in this case, using the MPSO, are given below.

Step (a): (*Initialization of the parameters*): In the present formulation, the objective function (1) is having P_{DG}, Q_{DG} and dynamic relevance factors as a continuous variable parameter. The P_{DG} and Q_{DG} are initialized with uniformly distributed pseudo random numbers, e.g.,

$$P_{DG} = \text{rand}\left[0, (\psi \times \sum_{i=2}^{n} P_{10(i)})\right],$$

where ψ is the penetration level in percentage. The particle swarm variables are equal to the number of DGs in single stage of the placement. The penetration level is defined as the ratio of capacity factor times the DG power installed to the feeder capacity of the system [32]. For the sake of simplicity, the capacity factor is assumed to be 50% in this study, but this algorithm can work with any value of the capacity factor, irrespective of the DG type.

The pseudo code for generating dynamic relevance factors of (1), which is to be further optimized in this algorithm, is given below in (12).

$$\left.\begin{aligned}
&\phi_t = \Theta_t \times \text{rand}(N,1) + \beta_t; \forall t, \left\{ t \in \Box \left| 1 \le t \le 4 \right.\right\};\\
&\text{for } \varepsilon=1:N\\
&\quad \text{for} \chi=1:t\\
&\qquad \Gamma_\chi = \phi_\chi(\varepsilon,:) / \sum_{\chi=1}^{\chi=t} \left(\phi_\chi(\varepsilon,:)\right);\\
&\quad \text{end}\\
&\alpha(\varepsilon,:) = \Gamma_\chi;\\
&\text{end}
\end{aligned}\right\} \quad (12)$$

where, t-Number of relevance factors; ϕ_t-N-random numbers for t^{th} relevance factor; *rand*-Random number instruction for generating uniformly numbers in the range, [0 1]; Θ_t-Constant coefficient, $\left\{\Theta_t \in \Box \left| 0 \le \Theta_t \le 1 \right.\right\}$; N-Number of particles in a swarm; β_t-Fixed biasing weight, $\left\{\beta_t \in \Box \left| 0 \le \beta_t \le 1 \right.\right\}$; α_t-t^{th} relevance factor; ε-Archive index for storing relevance factors; χ-Index for relevance factor; Γ_t-Random number, $\left\{\Box \in \Gamma_t \left| 0 \le \Gamma_t \le 1 \right.\right\}$; so that $\sum_{t=1}^{t=4} \alpha_t = 1;$

These four relevance factors are taken as additional variables in the PSO, which are optimized along with the DG size while getting the optimal location and size of the DG. The $P_{dg,i}$ variable of the string of the swarms is defined as $P_{dg,i}$=[$P_{dg,1}$, $P_{dg,2}$, ...$P_{dg,N}$]. The population size is N, defined for the node where the DG is to be placed. The position of m^{th} particle X_m as well as its velocity V_m in the search space is randomly initialized in this step. The vector X is a string of swarm particles representing the DG sizes. At beginning, these are randomly generated between the set limits (zero to the DG penetration level). The vector V is the velocity of the swarm particles. Maximum value of V is taken as 20% of the DG penetration level and minimum value of V is the negative value of the maximum value of V. At beginning, these are also randomly generated between the limits of V. During each iteration, the values of X and V are updated according to Eqns. (9) and (10). The inertia weight factor limits are set as 0.9 and 0.4 [26, 27].

Step (b): (*Calculating the Objective Function*): The quality of an individual string of the population is found using the fitness function evaluation. After formulating and randomly initializing the particles in a feasible solution space, each string is evaluated, using evaluation of the objective function (1). The calculation of the objective function (1) is carried out by "forward/backward sweep" method of the distribution load flow. Within the context of the PSO applications to the DG siting and sizing problem, inequality constraints, representing the permissible limits on the power generation by the DG, P_{dg}, bus voltage limit, etc., are handled during the PSO run using penalty factor approach. The particle, which violates the constraints, is penalized but allowed to participate in determining personal best and global best solutions in the iteration.

Step (c): (*Calculation of pbest*): Using (13), the objective function for each particle in the population of the current iteration is compared with its value in the previous iteration and the position of the particle getting a lower objective function value as *pbest* for the current iteration is stored as,

$$\text{pbest}_m^{k+1} = \begin{cases} \text{pbest}_m^k & \text{if } f_m^{k+1} \ge f_m^k \\ x_m^{k+1} & \text{if } f_m^{k+1} \le f_m^k \end{cases} \quad ...(13)$$

where, k is the iteration number, and f_m is the objective function value, evaluated for the particle.

Step (d): (*Calculation of gbest*): In this step, the best objective function associated with the *pbest* among all particles in the current iteration is compared with that in the previous iteration and the lower value is chosen as the current overall *gbest*.

Step (e): (*Update Velocity*): After calculation of the *pbest* and *gbest*, the velocity of the particles for the next iteration should be modified by using (9). In the velocity updating process, ω, the inertia weight, and C_1,C_2 the acceleration coefficients, represent the weighting of the stochastic acceleration terms that pull each particle towards the individual best position and the overall best position, should be selected in advance.

Step (f): (*Update Position*): The position of each particle at the next iteration (k+1) is modified using (10).

Step (g): (*Check Convergence Criterion*): If minimum value of the objective function (1) is obtained, then declare the result as the optimal location and size, and go to Step (h) for checking the possibility of another DG, to be determined by selected DG penetration level. Otherwise, the program goes to the Step (b) after incrementing the bus count.

Step (h): (*Stopping Criterion*): If the DG penetration level is achieved, the program is terminated.

5.0 SIMULATION RESULTS

The proposed method for the DG siting and sizing is demonstrated on the 33-bus [10, 44] and the 41-bus (Indian system) [45] distribution systems. In this work, a constant power and a mixed type of voltage dependent load is considered, where p and q vary according to the nature of the load and their values are taken from [22, 43]. The allocation of the mixed loads in both the systems is shown in Table 1. In the 41-bus system, load at buses 40 and 41 are assumed to be 75% of its actual value as given in [45].

TABLE 1

LOAD ALLOCATION

Load component	33-bus system	41-bus Indian system
Small industrial motors	6, 7	7, 32–33
Constant power	2–5, 8–21	2–6, 9
Industrial	30–33	8
Residential	22–24	34–41
Commercial	25–29	10–31

The MPSO parameters are given in Table 2. The value of σ for all the three gases is taken equal. It is also assumed that both RESs (SPV and wind plants) do not emit any gas as these are neglibile in comaparison to those produced by the conventional coal fired plants. For the sake of the simplicity, the conductor capacity is assumed to be same as the maximum demand of the system. The minimum load of the system in a day is assumed to be 50% of the peak load of the day. The fixed standard size capacitors of 0.3, 0.6 and 0.75 MVAr capacities are considered in this study.

TABLE 2

PSO PARAMETERS IN TEST CASES

Population size	Maximum iteration	ω_{max}	ω_{min}	C_1	C_2
50–10000	50	0.9	0.4	2.0	2.0

5.1 Fixed Size DG in 33-Bus System with Mixed Load

In this case, the fixed size DG (3.0 MW) is considered for placement. The real power line loss index (*SLIP*) is only considered for the DG placement, as the line loss reduction approach is widely used in the DG placement by the utility. The results for the base case with constant power/ mixed load model and with the fixed size DG are shown in Table 3. It is important to note that the same size of the DG, when placed at different location, causes different line loss as shown in Figure 2(a). Therefore, in practical case, such analysis must be carried out before placing the DGs. Hence, the need arises for such study which gives an idea about the choice of location for the fixed size DG in such a situation when the physical constraints do allow the DG to be placed at optimal location. Figure 2(a) hints some other sub-optimal bus locations, corresponding to the DG sizes and their loss index. Looking into Figure 2(a), one can conclude that bus-5, 7, 26 and 27 may also be other good choices for the fixed size DG of 3.0 MW size. This helps utility to take decision for the DG placement other than the optimal location. The voltage profile with and without the DG are shown in Figure 2(b). The voltage profile for light load with the full DG capacity is somewhat higher than 1.0 p.u. but less than 1.05 p.u., which is due to the reverse power flow [37].

TABLE 3			
RESULTS IN 33-BUS SYSTEM			
	Base case with constant power load	**Base case with mixed load**	**Fixed size DG with mixed load**
DG size (MW)	-	-	3.0
Optimal location	-	-	6
Line loss (MVA)	0.211 + j0.143	0.178 + j0.121	0.1 + j0.075
Min. voltage (p.u.)	0.9038 (18)	0.908(18)	0.95 (18)
Max. voltage (p.u.)	1.0 (1)	1.0 (1)	1.0 (1)

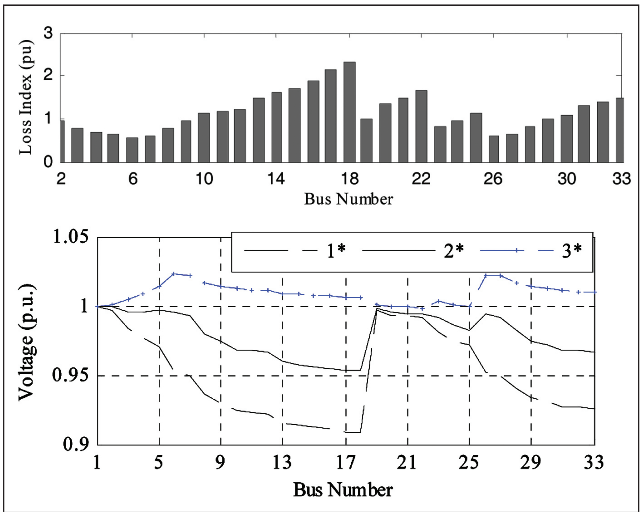

FIG. 2 (A) LOSS INDEX V/S DG LOCATION IN 33-BUS DISTRIBUTION SYSTEM. (B) VOLTAGE PROFILE IN 33-BUS DISTRIBUTION SYSTEM WITH MIXED LOAD MODEL AND FIXED DG. [1*-BASE CASE, 2*-FULL DG OUTPUT AT PEAK LOAD, 3*-FULL DG OUTPUT AT MINIMUM LOAD].

5.2 Single DG of Variable Size in 33-Bus System with Constant Power Load Model

1) Without voltage constraint: This case is simulated to see the impact of constraints on the DG size and its optimal location. Only one DG is considered for the placement without voltage constraints, same as the case taken in [10] on the 33-bus system for loss minimization. Hence, only Loss Index (LI) is considered as it is similar to the case of the real power loss minimization. The base case results of the load flow on the 33-bus system are shown in Table 3. The results of the DG placement for one DG, without considering the constraint, are presented and compared with [10] in Table 4.The result of the proposed approach is in close agreement with the result of [10] for the 33-bus system. Figures 3(a) and 3(b) are showing LI values, optimal DG size and voltage profile at each node of the system.

TABLE 4		
ONE DG PLACEMENT RESULTS IN 33-BUS SYSTEM		
Method	**PM***	**NAM [9]***
DG size	2.5904	2.49
Optimal location	6	6
Real power loss (MW)	0.11100	0.11124
React. power loss (MVAr)	0.0817	-
Minimum voltage (p.u.)	0.9424 (18)	-

*PM-Proposed Method, Naresh Acharya et al. Method-NAM [9]

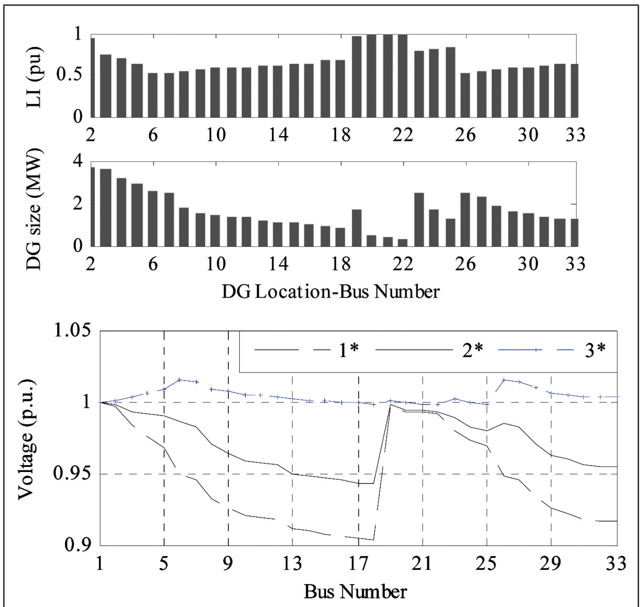

FIG. 3 (A) (TOP) LOSS INDEX AND (BOTTOM) DG SIZE IN 33-BUS DISTRIBUTION SYSTEM. (B) VOLTAGE PROFILE IN 33-BUS DISTRIBUTION SYSTEM WITHOUT INCLUDING CONSTRAINTS FOR CONSTANT POWER LOAD MODEL. [1*-BASE CASE, 2*-FULL DG OUTPUT AT PEAK LOAD, 3*- FULL DG OUTPUT AT LIGHT LOAD].

2) *With all the constraints*: In this case, all the constraints, as mentioned in 5(a) and 5(g), are included for the DG placement using Loss Index (*LI*) minimization. The maximum allowed penetration is taken as 40%. The optimal location, size and system loss with all the constraints considered in this study are bus-7, 2.888 (MW) and (0.1148+j0.0907) MVA, respectively. The minimum system voltage is 0.95 p.u. at bus 18. It is interesting to see that the DG size increases along with the change in the optimal location with slightly increases in the loss. Hence, it can be concluded that the constraints are having significant role in influencing the placement results. Another point to observe is that the almost all the loss index are below unity except a few, as shown in Figure 4(a), since loss with the DG is less than the base case, except in a few cases, and the entire loss index at respective nodes are calculated for their optimal size.

The utility can choose other bus for the DG placement just by analyzing Figure 4(a), looking at their available DG size and physically suitable location. The voltage profiles under this case are shown in Figure 4(b).

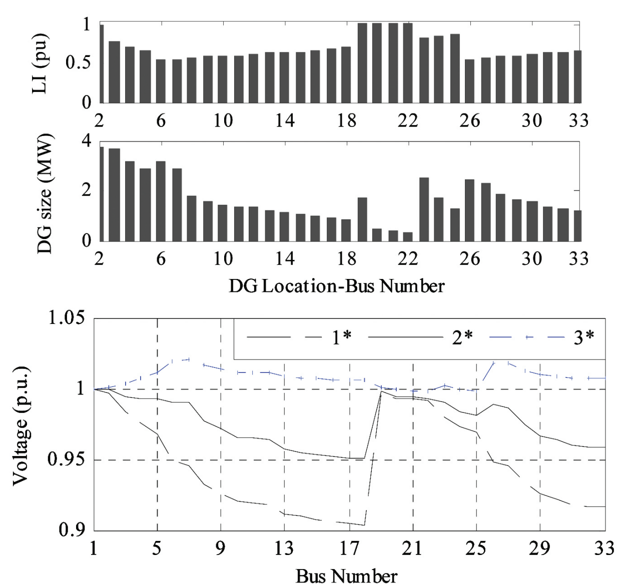

FIG. 4 (A) (TOP) LOSS INDEX AND (BOTTOM) DG SIZE IN 33-BUS DISTRIBUTION SYSTEM. (B) VOLTAGE PROFILE FOR 33-BUS DISTRIBUTION SYSTEM INCLUDING ALL CONSTRAINTS FOR CONSTANT POWER LOAD.
[1*-BASE CASE, 2*-FULL DG OUTPUT AT PEAK LOAD, 3*- FULL DG OUTPUT AT MINIMUM LOAD].

In this case, the continuous support from the DG is required else its voltage profile may go below 0.95 as no capacitor support for reactive power compensation has been planned.

The DG penetration obtained in this case is 38.9% and there is little scope for further addition of the DG under allowed penetration limit. The complete look-up table is shown in Table 5. Only, one look-up table is presented in this paper. The *LI* and the DG size values in Table 5 are rounded-off to the second digit after decimal point.

TABLE 5

LOOK-UP TABLE FOR 33-BUS SYSTEM WITH CONSTRAINTS

Bus No.	LI value (p.u.)	DG size (MW)	Bus No.	LI value (p.u.)	DG size (MW)
1	0.99	3.72	18	0.72	0.85
2	0.79	3.65	19	1.02	1.73
3	0.73	3.18	20	1.03	0.483
4	0.67	2.91	21	1.03	0.423
5	0.55	2.97	22	1.03	0.34
6	0.54	2.89	23	0.84	2.474
7	0.58	1.79	24	0.86	1.714
8	0.60	1.56	25	0.88	1.304
9	0.61	1.40	26	0.56	2.454
10	0.61	1.37	27	0.57	2.284
11	0.62	1.33	28	0.60	1.86
12	0.64	1.17	29	0.61	1.65
13	0.65	1.12	30	0.62	1.545
14	0.66	1.06	31	0.65	1.355
15	0.67	1.00	32	0.66	1.30
16	0.70	0.90	33	0.68	1.23

5.3 Fixed capacitors and DGs in 33-Bus and 41-Bus Systems with Mixed Load Model

In this case, the criterion for number of DGs to be placed is determined by maximum allowable penetration level. Single and the multiple DGs are considered for placement in 33-bus and 41-bus (Indian) systems with mixed load model. The variable size DG is allowed up to the maximum penetration level is all these systems for the DG placement. For the DG placement, all indices are considered, and relevance factors of the indices under this case are:

(i) the utility defined fixed values

(ii) dynamic values.

1) With All Indices of MOF in 33-bus system: In this study, five fixed size capacitors are placed to improve voltage profile to 0.95 p.u.

The random generation of the four dynamic relevance factors in a specific range, defined by the utility (0.6–0.98, 0.01–0.3, 0.06–0.14, 0–0.09), is shown in Figure 5. These relevance factors are generated in such a way that their sum will always be unity and used in the PSO algorithm for the obtaining optimal DG location and size with optimal relevance factors.

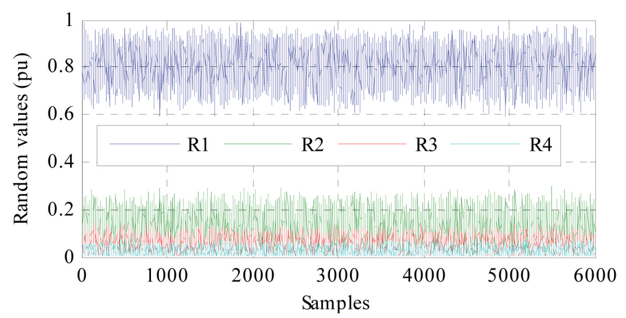

FIG. 5 RANDOM RELEVANCE (WEIGHT) FACTORS [R1-*SLIP*, R2-*SLIQ*,R3-*SVPI*,R4-*SGEI*].

The results for the 33-bus system are shown in Figures 6(a, b) and Table 6. Due to already placed capacitors, one DG with optimal size can only be placed subject to the voltage constraint in the critical case of light load considering the full capacity of the DG. The system voltage profile is above 0.95 p.u. with no DG capacity at peak load in the system, which is due to the fixed capacitors.

Here also, look-up table can be prepared, if required by the utility, as has been shown in previous case (Table 5). By looking into Figure 6(a), it is quite clear that there are many other good locations to place the DG, where technical performance of the system may be slightly inferior (more *MOF* value) but with less DG capacity requirement. Therefore, when the DG placement is not possible at optimal location, the utility can make decision to place DG at another sub-optimal location.

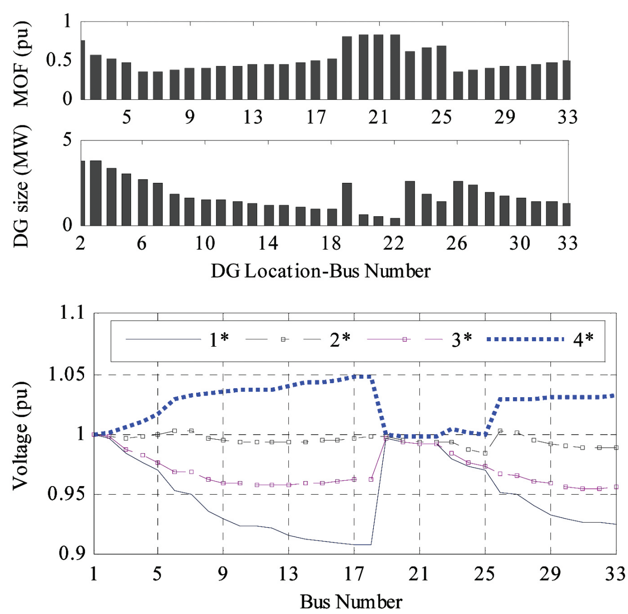

FIG. 6 (A) (TOP) LOSS INDEX (P.U.) AND (BOTTOM) DG SIZE 33-BUS SYSTEM (OPTIMIZED WEIGHT). (B) VOLTAGE PROFILE FOR 33-BUS DISTRIBUTION SYSTEM FOR MIXED LOAD MODEL.
[1*-BASE CASE, 2*-CAPACITOR-FULL DG OUTPUT AT PEAK LOAD, 3*-NO DG OUTPUT BUT CAPACITOR AT PEAK LOAD, 4*- CAPACITOR-FULL DG OUTPUT AT MINIMUM LOAD].

It is shown in Table 6 that the DG penetration requirement is less with the dynamic relevance factors approach. It can help the utility to reduce the capital investment cost. The system technical performance results are also improved using the optimal weight factor approach. The values of the optimal relevance factors are shown in Table 6.

2) With All Indices of MOF in 41-bus Indian system: In this case study, all the indices are considered for the placement of the DG in same way as the previous case study. The 41-bus Indian system is selected for this case study as it is a special system, where substation is connected to four feeders which are independent. The allowed DG penetration level is considered to be 45%. In this case, same random values of relevance factors, as shown in Figure 7(a), are used in all the four stages of the DG planning.

TABLE 6

RESULTS IN 33-BUS SYSTEM WITH MIXED LOAD

Capacitor/DG size	Bus location	Line loss		Min.voltage	
		MW	MVAr	(p.u.)	Bus no.
Base case	–	0.1783	0.1211	0.9080	18
0.3,0.3,0.3,0.6,0.3 MVAr	13,16,18,30,33	0.1563	0.1084	0.9555	32
Fixed rel. factors (SLIP, SLIQ, SVPI, SGEI): 0.6, 0.2, 0.1, 0.1					
PL- 38%, 2.76 MW	6	0.0650	0.0527	0.9837	25
Opt. rel. factors (SLIP, SLIQ, SVPI, SGEI): 0.814, 0.015, 0.087, 0.084					
PL-37.7%, 2.64 MW	6	0.0645	0.0522	0.9838	25

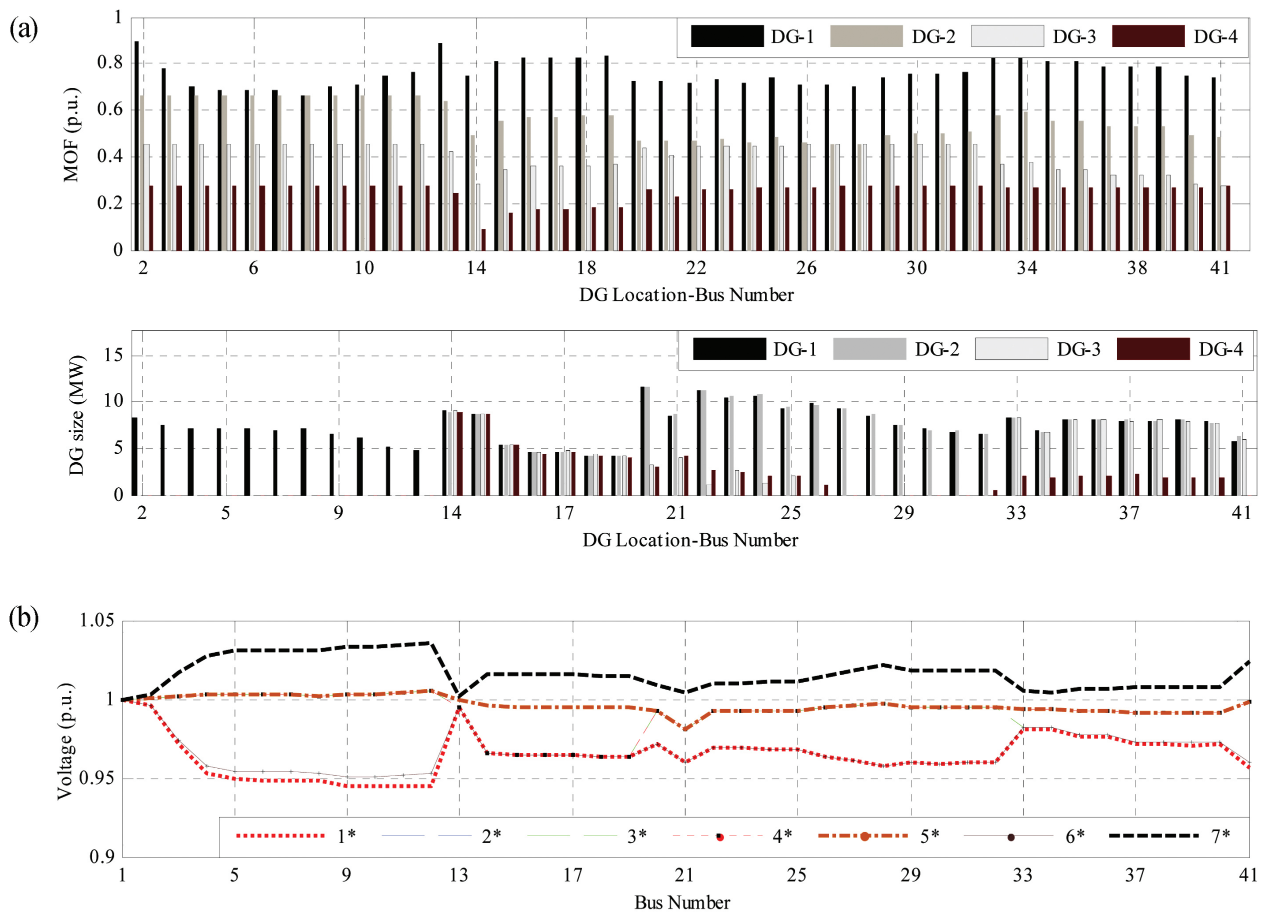

FIG. 7 (A) (TOP) *MOF* INDEX (P.U.) AND (BOTTOM) DG SIZE IN 41-BUS INDIAN SYSTEM (OPTIMIZED RELEVANCE FACTORS) [CONSIDERING PREVIOUS STAGE(S) OPTIMAL DG(S) INTACT AT OPTIMAL LOCATION(S)].
(B) VOLTAGE PROFILE FOR 41-BUS DISTRIBUTION SYSTEM WITH MIXED LOAD MODEL
[1*-BASE CASE, {2*TO 5* IS WITH 1 DG, 2 DGS, 3 DGS AND 4 DGS, RESPECTIVELY}, 6*-CAPACITOR-NO DG OUTPUT AT FULL LOAD, 7*- CAPACITORS-FULL DGS OUTPUT WITH MINIMUM LOAD].

The proposed algorithm suggests four DGs at different locations in the various feeders. One DG is placed in each stage of the DG planning and the optimal relevance factors are shown for each stage of the DG placement in Table 7.

The results of this case are shown in Table 8. Figures 7(a) and 7(b) show the values of *MOF*, DG size and voltage profile at each bus with the multiple DGs placement. Figure 7(a) shows the DG size and *MOF* values at all the network buses and can be used when the practical constraints do not allow the DG to be placed at the optimal location. Another suitable location and corresponding size can be selected from the figure itself. This case justifies the importance of the multiple DGs, where different feeders are connected at the substation, and require more than one DG for improving the system performance, since adding one DG in one feeder mainly improves technical performance of that feeder only.

TABLE 7

OPTIMAL RELEVANCE FACTORS IN 41-BUS SYSTEM WITH MIXED LOAD

Stage	SLIP	SLIQ	SVPI	SGEI
1.	0.8859	0.0263	0.0783	0.0095
2.	0.8859	0.0263	0.0783	0.0095
3.	0.8859	0.0263	0.0783	0.0095
4.	0.8162	0.1198	0.0620	0.0021

Table 8 shows that the technical performance of the system is better with the dynamic relevance factors approach with less DG penetration, as compared to that with the fixed relevance factors approach. Figure 7(b) shows that the voltage profile is within 0.95–1.05 p.u. limit for all the critical cases viz. system with full DG output at light load condition of the day or no DG capacity available at peak load of the day. In later case, the capacitor maintains the system voltage profile above 0.95 p.u.

6.0 IMPACT ANALYSIS OF THE DG

6.1 Voltage Profile

The voltage profile is analyzed for the constant power and the mixed type of loads in the 33-bus and 41-bus (Indian) systems. The voltage profile is found with the limits of 0.95–1.05 p.u. for all the cases as shown in Figures 6(b) and 7(b) for various penetration levels. The voltage constraint violation case is prescribed in Figure 3(b). The Figure 6(b) and 7(b) justify the importance of the reactive power compensation by capacitor with the RES DG, as when the DG is not available the system voltage may come to the level of the base case. The Improvement in the system minimum voltage with the DG is found to be approximately 0.86–4.64% in the various cases.

6.2 Loss Reduction

As reported in the various literatures, the system loss can easily be reduced by installing the capacitor and the DG. Tables 3, 4, 6 and 8 show considerable amount of line real and the reactive powers loss reduction, which justify the deployment of the DGs, and capacitors, in distribution system. The system loss reduction due the DG placement at optimal or sub-optimal location can be significantly achieved. It is found to be approximately 43-90.34% observed in the various cases of the DG placement.

7.0 DISCUSSION

The 41-bus practical Indian distribution system is highly glossy system with four feeders connected to the sub-station. This system is selected to observe the technical impacts of the DG in a real system. The backward forward sweep based load flow has converged successfully with constant and voltage dependent loads that mimics to the practical loading condition. The optimal location as well as the optimal DG size may vary with the load models. The reduction in the line loss and improvement in the voltage profile are significant.

TABLE 8

RESULTS IN 41-BUS SYSTEM FOR 45% DG PENETRATION

Capacitor/DG size	Opt. bus location	Line loss		Min. voltage	
		MW	MVAr	(p.u.)	Bus no.
Base case	–	1.3387	1.4171	0.9448	12
0.75,0.3, 0.3 MVAr	12,39,41	1.3316	1.4096	0.9502	10
Fixed relevance factors: 0.6, 0.2, 0.1, 0.1					
PL-44.98%, 7.33, 9.41, 9.34, 6.21 MW	8,28,41, 14	0.1333	0.1411	0.982	21
With optimal relevance factors - Table 7					
PL-42.835%, 7.1097, 8.844, 5.89, 8.6 MW	8,28,41, 14	0.1286	0.1361	0 .982	21

The optimal location for fixed standard size DG is same as the optimal location for variable size DG considering relaxed voltage constraint. In practical scenarios, the optimal location may not be feasible due to physical constraints, especially for renewable DGs. Therefore, a look up table for other potential locations has been suggested. This may probably help the DG planners significantly.

Most of the DG technologies are costly and some of them are intermittent due to dependency on natural resources. The DG placement in stages has added advantage that the actual load growth can easily be incorporated at any stage of the planning and gives flexibility in distribution network expansion.

The proposed approach attempts to overcome the problem of weight selection in the weighted sum objective function, which were earlier taken as per the utility's choice [2–7]. The results with the optimal weight factors are found to be better than the constant weight factors as these factors, have been optimized utilizing the PSO method.

It is observed that if a DG planning is not tested on critical scenarios, sometimes it leads violation of the system constraints. This is very much important with intermittent DG to be placed in distribution network, where the load as well as DG output can vary to their extreme. In the proposed approach, the optimal planning results have been tested for the critical scenarios. The results of these cases assure the operation of any kind of DGs placed in the distribution network may not violate the voltage limits, which may reduce number of disconnection of the DG due to overvoltage and reduce un-served energy cost.

8.0 CONCLUSION

This paper presents a new approach based on multi-objective performance function for the multiple DGs placement. The proposed method has considered fixed size as well as variable sizes up to the allowed penetration level of the DGs. Modified Particle Swarm Optimization (MPSO) has been used to obtain the optimal solution with a dynamic relevance factors approach. The studies have been carried out with constant power load model as well as with mixed load model for the DG placement on the 33-bus and the 41-bus (Indian) distribution systems.

The impacts of the DG planning on the system voltage profile and line loss have been investigated. The system real power loss improves by 43–58.86% (approximately) and minimum voltage level by 2.96–4.64% (approximately) in case of 33-bus system at various DG penetration level with fixed as well as variable size DG. The system real power loss improves by 90.34% (approximately) and minimum voltage level by 3.34% (approximately) with four DGs at 42.8% DG penetration level in the 41-bus Indian system. The proposed algorithm uses the dynamic relevance factors approach which gives better solution with less requirement of the DG penetration as compared to fixed relevance factors approach. It works efficiently with small, medium and larger distribution system as well. A look up table approach has been suggested, when the renewable energy type DG placement is supposed to deviate from its optimal solution. The DG planning study, carried out in this paper, may provide guidance to the utilities for future deployment of the DGs.

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