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# Swarm Intelligence based Distribution Load Flow Method for Distributed Generation Planning

Naveen Jain*, Singh S N* and Srivastava S C*

*This paper presents a new swarm intelligence method of distribution load flow (DLF) suitable for systems with distributed generators. The proposed DLF method is able to incorporate all kind of voltage dependent load models. This load flow method avoids the problems faced by various methods in handling multiple PV buses and is also suitable for small-scale, medium-scale and large-scale distribution systems. The proposed DLF method is used for placing multiple fixed standard size capacitors. The optimal sitting and sizing of multiple DGs are also carried out utilizing a system loss reduction criterion. The proposed load flow algorithm is tested on distribution systems with fixed standard size capacitor and/or DG for various load models to show its effectiveness. Some existing DG planning results are compared to show the capability and the accuracy of the proposed algorithm.*

***Keywords:*** *Capacitor, Distributed generation, Distribution system, Load flow and Particle swarm optimization.*

## 1.0 INTRODUCTION

Distribution System (DS) planning is getting renewed attention amongst the power system community after proliferating application of Distributed Generation (DG) and power electronics based loads. The DG is usually a small electric power source connected directly to the DS or on the customer side of the meter and may be a feasible alternative for new capacity addition, especially in the competitive electricity market environment, as DG offers many benefits such as system loss reduction, voltage profile improvement, pollutants reduction, short start-up time, low investment risk, etc. [1–2]. The primary energy source of the DG can be either renewable such as wind, solar and biomass or non-renewable like gas, oil, etc. [3]. The DS is generally radial in nature with high line resistance to reactance ratio (R/X). It is well known fact that the Load Flow (LF) based on Newton-Raphson and Gauss-Seidel methods may not be able to solve a typical large size Radial Distribution System (RDS) with high value of line R/Xratio. In literature, several load flow approaches for the transmission and distribution systems have been suggested. Many good approaches have been suggested for distribution load flow using Forward-Backward Sweep (FBS) method as given in [4–21].

References [5, 7, 11–13, 21] incorporate DG buses, as PQ and PV nodes depending on the type of the DG and/or converter scheme. A table for DG models to be used in DLF study was also presented in [11]. Eminoglu *et al*. [22] presented a review of FBS-based DS power flow algorithms. It is found that very few work has been carried out considering the DG as a PV bus in the radial DS. If the system has more PV nodes, it is difficult to apply the venin method [13] and such problems may also be experienced with the other techniques. In [23], Acharjee *et al.*

*Department of Electrical Engineering, IIT Kanpur, Kanpur - 208 016, India, E-mail: njain@ieee.org, snsingh@iitk.ac.in, scs@iitk.ac.in.

presented a chaotic particle swarm optimization based load flow for transmission networks.

Many research on the DG planning have been carried out using Newton-Raphson or Gauss-Seidel based load flow methods, but these approaches may not convergence for typical practical DS [9, 20]. However, it appears from the literature that very few work incorporated the DG in DLF as PV model. It is difficult to incorporate multiple DG considering the PV node in the FBS load flow.

The problem of the DG planning is very important as it is well known fact that the capital cost of some of DGs is very high, therefore, DGs must be allocated suitably with high accuracy in optimal size to improve the system performance. Selecting the best place(s) with optimal size(s) in a large DS is a complex combinatorial optimization problem. Several placement methods have been used based on calculus-based methods, search-based methods and combinations of various approaches, such as gradient based algorithms, Hereford Ranch algorithm, heuristic iterative search method, analytical method, Tabu search, hybrid fuzzy genetic algorithm (GA) method, GA, linear programming (LP) method, etc. A review of various methods was presented in [24].

In this paper, a new constriction factor based particle swarm optimization (PSO) is proposed for the distribution load flow (DLF). The Proposed Method (PM) is quite suitable for planning and online applications as it is accurate, robust and applicable to any small-size, medium-size and large-size DS. To show its accuracy, it has been used in planning of- (i) capacitor using a Voltages Stability Index and voltage sensitivity (VSI), (ii) DG considering system power loss criterion utilizing PSO. The accuracy and effectiveness of the proposed load flow approach are demonstrated on 12-bus [8, 10, 25], 33-bus [14], 69-bus [6, 25–26], 41-bus [27] and 85-bus [19] distribution systems.

The paper is organized in six sections. The algorithm of PSO based DLF is presented in Section II. In Section III, algorithm for two planning problems are given, viz. (i) a voltage stability index and voltage sensitivity based capacitor planning; (ii) constriction factor approach based PSO for the DG planning using proposed DLF. In Section IV, voltage sensitivity index and DG impact on voltage profile are presented. In Section V, simulation results are presented. Finally, the paper is concluded in Section VI.

## 2.0 PSO BASED DISTRIBUTION LOAD FLOW

### 2.1 Particle Swarm Optimization Technique

The PSO algorithm is one of the fast growing evolutionary computational technique. The PSO is a population-based and self-adaptive technique, introduced originally by Kennedy and Eberhart in 1995 [28]. The PSO can be suitable for any type of function, which may be linear, non-linear, continuous, discrete, with no gradient, etc. It usually does not require crossover operation, mutation, even not reduce population size in subsequent iteration, etc. All these features make it a suitable optimization tool for practical problems.

The constriction techniques, having better ability to find optimal points in the search space, has been reported in [29] to solve various case problems. Constriction factor based PSO has been found to have superior convergence property on the benchmark functions. The limiting maximum velocity in the PSO can easily be taken as dynamic maximum range of the variable. It is being used in many practical applications including power systems.

This stochastic based algorithm handles a population of individuals, in parallel, to probe capable areas of a multidimensional space where the optimal solution is searched. The individuals are called particles and the population is called a swarm. Each particle in the swarm moves towards the optimal point with adaptive velocity. The movement in terms of position and velocity of each particle of the swarm in multi-dimensional space is shown in Figure 1 and given by (1) and (2) as,

$$V_{wd}^{k+1} = \Gamma(V_{wd}^{k} + \phi_1\delta_1(pbt_{wd}^{k} - X_{wd}^{k}) + \phi_2\delta_2(Gbt_{gd}^{k} - X_{wd}^{k})) \quad .... (1)$$

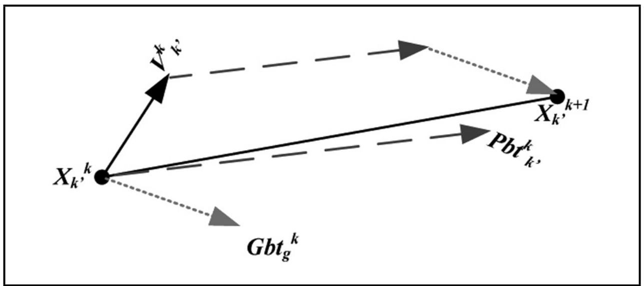


FIG. 1 MOVEMENT OF A PARTICLE IN THE PSO APPROACH.

where, $V_{wd}^{k}, \phi_1, \phi_2, X_{wd}^{k}, pbt_{wd}^{k}$ and $Gbt_{gd}^{k}$ are the velocity of particle *w*, two acceleration coefficients, position of particle *w*, the best position of particle *w* and best position among all the particles (all these at iteration *k* in *d* dimension), respectively,

where, $\Gamma = \dfrac{2}{\left|2 - \phi\sqrt{\phi^2 - 4\phi}\right|}$, $\phi = \phi_1 + \phi_2$ and $\phi > 4$

The value of $\phi$ is set to 4.1, which gives $\Gamma$ = 0.729.

$$X_{wd}^{k+1} = X_{wd}^{k} + V_{wd}^{k+1} \quad .... (2)$$

## 2.2 Load Model

The practical DS has several types of loads, such as constant power, constant current, constant impedance, small/large industrial, domestic, commercial, etc. The load characteristics have significant impact on the load flow solutions and its convergence. The active and reactive powers are generally expressed in polynomial or exponential form as [14],

$$P_{li} = P_{lo(i)}(V_i / V_0)^p \quad .... (3)$$

$$Q_{li} = Q_{lo(i)}(V_i / V_0)^q \quad .... (4)$$

where, $P_{li}$ and $Q_{li}$ are the active and the reactive power load demand at the bus-*i* where the bus voltage $V_i$ and $V_0$ is the nominal voltage. The *p* and *q* are the exponents for the voltage dependent loads, whereas $P_{lo(i)}$ and $Q_{lo(i)}$ are the real power and reactive power load demand at bus-*i* at the nominal voltage. The values of exponents are given in [14, 30].

## 2.3 Distribution Load Flow with DG

A 3-phase balanced network, with $n_b$ nodes, is considered in this study. The Sub-Station (SS) bus has been considered as slack bus. The DG node is taken as PQ bus and PV bus, separately. Although, PQ bus consideration is enough to observe the DG impact on the system, considering their fixed output, but PV bus consideration is used to check the effectiveness and the accuracy of the proposed PSO based DLF in the DG planning.

The sweep based DLF method can broadly be classified into two categories, based on- (i) Kirchhoff's formulation [4, 15–16, 20] (ii) Bi-quadratic equation algorithms [14, 17–18]. In a few work, the bi-quadratic method is used in modified way to improve computational time, simplicity of the algorithm, and to consider weekly meshed network, etc. [18]. In the literature the convergence criteria are used on active power mismatch, reactive power mismatch, voltage mismatch and current mismatch at each node irrespective of the nature of the load [22].

At any bus-*i*, the complex load demand can be expressed as,

$$S_{li} = P_{li} + jQ_{li}; \forall i = 2,3...n_b \quad .... (5)$$

The equivalent current injection is given as,

$$I_{li} = \left(\frac{P_{li} + jQ_{li}}{V_i}\right)^{*}; \forall i = 2,3,...n_b \quad .... (6)$$

In this work, the network topology based approach of DLF is referred from [20, 25]. The bus-injection to branch-current matrix, the branch current to bus-voltage matrix and equivalent current injections are formed similarly. A small DS of seven bus, as shown in Figure 2, is considered for the sake of simplicity to describe the basic approach of this work.

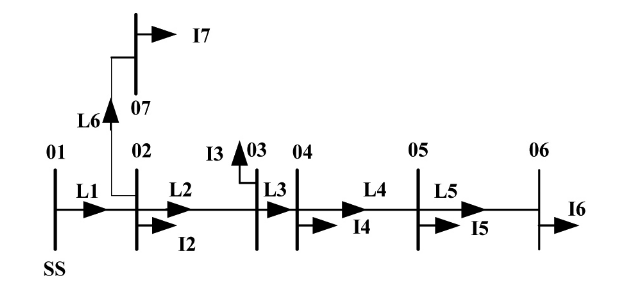


FIG. 2 RADIAL DISTRIBUTED SYSTEM (RDS).

The relationship between the bus current injection and the branch current is expressed as,

$$\begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} \quad \text{.... (7)}$$

or, in compact form, $[L]=[BIBC][I]$ .... (8)

where, $[L]$ and $[I]$ are the branch current and the bus injection matrices, respectively. The network topological matrix *BIBC* is the bus injection to line current matrix. Using Kirchhoff's voltage law in the network of Figure 2,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & Z_{56} & 0 \\ Z_{12} & 0 & 0 & 0 & 0 & Z_{27} \end{bmatrix} . \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \end{bmatrix} \quad \text{.... (9)}$$

Above matrix expression can be written as,

$$[\Delta V] = [BCBV].[L] \quad \text{.... (10)}$$

where,

$$[BCBV] = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & Z_{56} & 0 \\ Z_{12} & 0 & 0 & 0 & 0 & Z_{27} \end{bmatrix}$$

$$[\Delta V] = [BCBV].[BIBC].[I] \quad \text{.... (11)}$$

$$[\Delta V] = [LFM].[I] \quad \text{.... (12)}$$

*BCBV* is the branch current to bus voltage matrix. Equation (6) is used to determine current vector $[I]$ at every bus in $K^{th}$ iteration and it is used in (12) to determine $[\Delta V]$ vector for $K^{th}$ iteration. The following expression is used to update the voltage in $(K+1)^{th}$ iteration.

$$[V^{K+1}] = [V^0] + [\Delta V^{K+1}] \quad \text{.... (13)}$$

The algorithm of the proposed PSO-DLF is shown in Figure 3 and can be summarized in the following steps:

a) Input the system data and prepare $[BIBC]$ matrix, which will remain constant throughout the iterations.

b) Initialize all node voltages. Consider the DG as negative load.

c) Calculate equivalent current injection at every node using (6) and prepare the matrix $[L]$ using (7).

d) Calculate the branch voltage drop using (9) and, update the bus voltage matrix using (13).

e) The convergence criterion in this DLF is on change in the bus voltage during subsequent iterations. If, it is less than a preset error tolerance $\varepsilon_v$, process will terminate.

*Else*, go to step-c and the process continues till convergence is achieved.

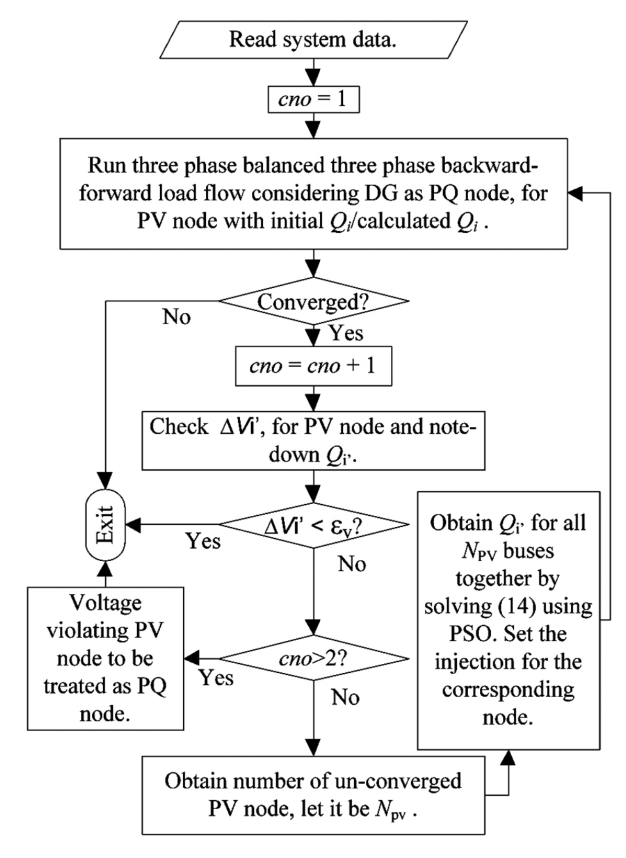


FIG. 3 ALGORITHM FOR PSO BASED LOAD FLOW.

The above steps are carried out considering the DG as negative load or a PQ bus. In case, the DG bus is considered as PV node(s), following steps are to be followed.

f) The DG node(s) is/are to be broken, *i'*-*i''*, as shown in Figure 4. The power injection at fictitious bus *i'* is maintained as shown in Figure 4, and it is treated as negative load [21].

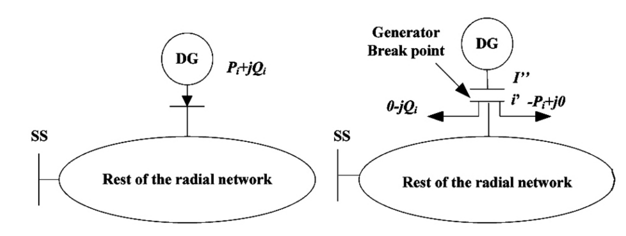


FIG. 4 TREATMENT OF THE PV NODE IN THE RADIAL DISTRIBUTION SYSTEM.

g) The DLF steps a-e are executed. If the situation converges with the PV node voltage within the specified limit, $\Delta V_{i'} = \left|V_{spec(i')} - V_{i'}\right|, i' \in \{\text{set of PV nodes}\}$, the algorithm will stop and the results are displayed.

h) If the PV bus voltage is out of the bound, then the reactive power compensation is required. The procedure to obtain reactive power injection is as following.

At PV bus, the PSO based optimization is carried out with the following objective function.

$$\min\left[F_2 = \sum_{i'}^{N_{PV}} \left(\left|V_{spec(i')} - V_{i'}\right|\right)\right] \quad \forall i' \in S_{PV} \ldots (14)$$

where, $V_{spec(i')}$, $V_{i'}$ and $S_{PV}$ are specified PV bus voltage at $i'^{th}$ bus, calculated voltage at $i'^{th}$ bus and a set of PV buses, respectively.

Equation (14) is to be minimized by the reactive power injection, subject to the reactive power handling capability of the DG. It is important to note that in this method the particles search the solution only in the range of the reactive power handling capacity defined in the PSO algorithm. If the bus voltage is found within the limit, the bus will be retained as PV bus, else it is treated as PQ type, with reactive power injection provided by the PSO algorithm fixed, which will be corresponding to the either of the boundary values of the reactive power limits.

i) To calculate the amount of reactive power compensation, following steps are adopted as:

1. *Input Data:*

- PSO-data and initial swarm population between minimum and maximum reactive power limits of the DG at $i'^{th}$ bus, [$Q_{min}$, $Q_{max}$].
- System constraints, various coefficients, etc.
- Swarm population size and maximum iterations.

- DG real power injection.

2. *Evaluate the fitness of the function*: The evaluation of the objective function (14) is carried out.
3. *Modify velocity vector in (k+1)$^{th}$ iteration* according to local and global best positions using (1) and then update position vector using (2).
4. *Terminate on, if:*

   $X_{k'}^{k+1} - X_{k'}^{k} < \varepsilon_q$, or $Iter \geq Iter_{max}$
   where, $\varepsilon_q$ and $Iter_{max}$ are tolerance error and maximum iteration, respectively. Store the value of the injected reactive power $Q_{i'}$. *Else* go to step i.2.

j) The DLF steps a–e are to be executed with obtained $Q_{i'}$ and if the PV node voltage is the same as the specified voltage, the node will remain PV, else it is to be treated as PQ node with the obtained reactive power, $Q_{i'}$, fixed corresponding to either the minimum reactive power or maximum reactive power limit of the DG.

In, the proposed solution techniques described, the LU decomposition, formation and insertion of Jacobian matrix or the admittance matrix are no longer necessary only the LFM matrix given in (12) is necessary to solve the load flow of the system. Therefore, the proposed method saves considerable computational time and can be used in planning as well as for online applications as it also offers very good convergence for any size of the DS.

## 3.0 VOLTAGE STABILITY INDEX AND DG IMPACT ON VOLTAGE PROFILE

The voltage stability index (VSI) is a well-known indicator to identify weak system buses. Many researchers have already addressed it well. In [31], a voltage stability analysis technique was proposed using VSI at each node to identify the most sensitive bus (near the voltage collapse) and is derived from a bi-quadratic equation, which is generally used for the voltage calculation in the DLF algorithms [14, 17–18]. It is presented below in brief. Apart of RDS as given in Figure 5, is considered. The line current can be written as either,

$$I_{mn} = \left(\frac{P_n + jQ_n}{V_n}\right)^* \quad \text{or}$$

$$I_{mn} = \left(\frac{V_m\angle\delta_m - V_n\angle\delta_n}{R_{mn} + jX_{mn}}\right) \qquad \text{.... (15a)}$$

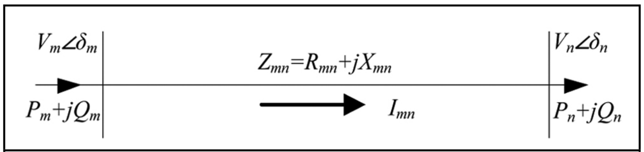


FIG. 5 A PART OF RDS.

The bi-quadratic equation relating the voltage magnitude at the sending-end, receiving-end and power at the receiving end of the branch, can be written by eliminating $I_{mn}$ in (15-a) as [14, 17–18],

$$V_n^4 + 2V_n^2(P_nR_{mn} + Q_nX_{mn}) - V_m^2V_n^2 + (P_n{}^2 + Q_n{}^2)\,|\,Z_{mn}{}^2\,| = 0 \qquad \text{.... (15b)}$$

where, $V_m$ and $V_n$ stand for the voltage magnitudes at bus-*m* and bus-*n*, respectively, and $Z_{mn}$ is the line impedance. $R_{mn}$, $X_{mn}$, $P_n$ and $Q_n$ are the line-resistance, reactance, transferred active and transferred reactive powers, respectively, as shown in Figure 5.

The Voltage Stability Indicator (VSI) at the receiving end bus of the line as follows can be calculated as

$$\Gamma_{VSI}(n) = V_m^4 - 4(P_nX_{mn} + Q_nR_{mn}) - 4V_m^2(P_nR_{mn} + Q_nX_{mn}) \qquad \text{.... (16)}$$

The VSI measures the level of voltage stability of RDSs and utility can take an appropriate action if the index indicates a poor level of stability. The DS bus, at which the value of the VSI, $\Gamma_{VSI}$, is found minimum, is the most sensitive to the voltage collapse [31]. To analyze the

DG impact on the line voltage profile, the voltage drop can be found using (17) and the line impedance for part of the line shown in Figure 5, as follows [32],

$$|\Delta V|^2 = \left( \frac{(R_{mn}P_n + X_{mn}Q_n)^2 + (X_{mn}P_n - R_{mn}Q_n)^2}{V_n} \right) \quad (17)$$

## 4.0 CAPACITOR AND DG PLANNING

The capacitor and DG placement can be carried out keeping the following points under consideration,

i. The VSI criterion is considered for the first capacitor sitting and if further capacitor placement is required, it is to be placed using voltage sensitivity approach till the system voltage constraint limits are satisfied.

ii. Loss criterion is used for the DG placement.

iii. The reactive power generation of the DG at a bus is taken fixed (PQ bus). A variable reactive power injection, within the limits can also be considered (PV bus).

iv. The DG size (MW) is taken between zero and the sum of the total equivalent real power load demand.

v. Constant power and mixed load models are considered in this study.

The total system loss minimization formulation utilizes an objective function, $F_l$, given as:

$$\min \left[ F_l = \sum_{x=1}^{n_l} P_{Loss(x)} \right] \quad .... (18)$$

subject to equality and in-equality constraints,

$$g_p(y) = 0, \ \in S_y, \ (p = 1, 2, \ldots, k.) \quad .... (19)$$

$$h_q(y) \leq 0, \ \in S_y, \ (q = 1, 2, \ldots, l.) \quad .... (20)$$

where, $P_{Loss}$ and $n_l$ are the real power loss in a branch and total number of lines in a distribution system, respectively. The $g$ and $h$ are the $k$-number of equality and the $l$-number of inequality constraints, respectively, $y$ is the decision variable vector and $S_y$ is the permissible set of $y$. The equality constraints include power balance at every node and condition for the constant slack bus voltage. The inequality constraints include limits on the DG size, bus voltage and system loss with the DG and the capacitor.

All the bus locations except the slack bus (SS-bus) are evaluated for possible location for the capacitor DG placement in stages as per the algorithm described. Literature also suggests that the placement in stages may be a good idea [30, 33].

### 4.1 Capacitor Planning

The standard size capacitors are placed as an economical way to provide reactive power compensation. The reactive power handling capability of the DG is usually very less. It also depends on the type of the DG whether it is renewable or non-renewable type and directly connected to the system or through power electronics converter/inverter devices.

The step-wise algorithm for the capacitor placement is given as follows-

1. If $N_C$ capacitors are to be placed, a matrix $S_C=[C_1,C_2,\ldots C_{NC}]$ of size $1\times N_C$, which comprised a set of standard capacitors (in MVAr), is to be prepared according to the system's reactive power load demand by the utility.
2. The capacitor out of matrix $S_C$ is to be placed first where VSI is found minimum. The VSI for all the buses is to be calculated using (16).
3. Select number of stages.
4. If $N_C>1$, further capacitors are to be placed utilizing voltage sensitivity with respect to the reactive power injection criterion.

5. If voltage constraint is not satisfied, then step 4 will be repeated with minimum size capacitor out of matrix $S_C$ till the voltage constraint, are satisfied.

### 4.2 DG Planning using Constriction Factor Approach based PSO Algorithm

In this work, a constriction factor approach based PSO (CFPSO) method, to solve optimal location and size of DGs, has been carried out using the proposed PSO-DLF. The DG placement algorithm does not utilize type of the DG (firm capacity or non-firm capacity). If, it is with firm capacity then placement of the capacitor may be avoided, *else* it should be placed to hold the voltage profile in the normal operating range while the DG is not in operation. The initial values of the DGs size are randomized for all definite particles of the PSO. Moreover, the PSO algorithm is executed to optimize the fitness function (18). The steps used in the proposed algorithm are given below.

The point-wise algorithm is given as follows:

1. Take the input data including system data (DG type, constraints) and PSO data (population, initialisation).
2. Evaluate the fitness of the function.
3. Modify velocity vector in ($k$+1) iteration according to the local and the global best positions using (1) and then update position vector using (2).
4. Check convergence as $X_{i'}^{k+1} - X_{i'}^{k} < \varepsilon_P$ or *Iter* $\geq Iter_{max}$, where $\varepsilon_P$ is the tolerance error. *If* satisfied, record the optimal size and fitness value at bus-2 and repeat the same for rest of the nodes one by one. Determine the optimal size and location among them. Then, go to step 5, *else*, go to step 2.
5. Check the algorithm termination condition, *if* any of (i) Penetartion Level (PL) $\aleph_{PL}$ (PL is defined as the ratio of capacity factor times the DG power installed to the feeder capacity of the system" [5]) or (ii) $\Delta P_L$ (real power loss improvement) or (iii) allowed stages, gets satisfied. Record the optimal size(s) and location(s) of the DG(s).

## 5.0 SIMULATION RESULTS

The effectiveness of the proposed method (PM) of the PSO-DLF is tested on 12-bus [8, 10, 25], 33-bus [14], 69-bus [6, 25–26], 41-bus [27] and 85-bus [19] DSs for the base case and for the planning of the capacitor and the DG. The 12-bus, 33-bus, 69-bus and 41-bus DSs are taken with constant power loads. The 85-bus system is taken with mixed load models. The allocation of the mixed loads in 85-bus DS is shown in Table 1. The DLF is solved using tolerance $\varepsilon$ of $10^{-5}$ p.u. for convergence on MATLAB™ platform. For PSO algorithm, the maximum iteration is considered as the termination criterion.

TABLE-1

LOAD COMPOSITION IN 85 BUS SYSTEM

| **Load component** | **85-bus system** | | |
|---|---|---|---|
| Small industrial motors | 7, 32–33 | Industrial | 8 |
| Commercial | 10–31 | Residential | 34–41 |
| Constant power | 2–6, 9, 42–84 | Constant current | 85 |

For the sake of the simplicity, the feeder capacity is assumed to be same as the maximum demand. One unit of either capacitor or DG is considered to be placed in each stage of the planning. The change in the system loss with respect to the base case for subsequent stages should be at least 2.5%. The CFPSO parameters are population size, maximum iteration, $\phi$ and $\Gamma$ are selected as 25, 25, 4.1 and 0.729, respectively.

A sub-set of standard capacitors, $S_C$ = [0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2] MVAr, is to be taken for placement. The capacitor sub-set is chosen based on the base case voltage profile, type of DG, percent reactive power compensation, etc. The average plant capacity factor is assumed to be 50%. Table 2 shows the Load Scaling Factor (LSF) for every hour of a day.

### 5.1 Validation of DLF

#### *5.1.1 12-bus RDS (Practical Indian System):*

The proposed PSO-DLF is compared with the results of [10] and DIgSILENT™ Power

| TABLE 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| LOAD SCALING FACTOR FOR HOURLY VARYING LOAD IN DS | | | | | | | | |
| HOUR | 0–1 | 1–2 | 2–3 | 3–4 | 4–5 | 5–6 | 6–7 | 7–8 |
| LSF | 0.65 | 0.61 | 0.57 | 0.52 | 0.5 | 0.53 | 0.6 | 0.68 |
| HOUR | 8–9 | 9–10 | 10–11 | 11–12 | 12–13 | 13–14 | 14–15 | 15–16 |
| LSF | 0.8 | 0.85 | 0.87 | 0.89 | 0.83 | 0.85 | 0.88 | 0.98 |
| HOUR | 16–17 | 17–18 | 18–19 | 19–20 | 20–21 | 21–22 | 22–23 | 23–24 |
| LSF | 0.99 | 0.98 | 1 | 0.95 | 0.88 | 0.83 | 0.7 | 0.6 |

Factory software (version 14.0) [34] to validate its accuracy. In Table 3, difference in voltage with the two methods is zero except at node-7, which is also negligible. Also, the similar results are obtained in [8, 25]. In Table 4, the load flow voltage results and the calculated reactive power requirement by the PM are to those with the DIgSILENT™ Power Factory. Here, a DG of 0.28 MW (PV bus) is placed at node-9 (may not be optimal) with ±0.85 power factor. The PM provides the load flow solution in 0.2 sec.

| TABLE 3 | | | |
|---|---|---|---|
| LOAD FLOW VOLTAGE SOLUTION (P.U.) FOR 12-BUS SYSTEM WITH NO DG | | | |
| **Volt. (bus) [10]** | **Volt. (bus) (#PM)** | **Volt. (bus) [10]** | **Volt. (bus) (#PM)** |
| 1.0 (1) | 1.0 (1) | 0.9637 (7) | 0.9638 (7) |
| 0.9943 (2) | 0. 9943 (2) | 0.9553 (8) | 0.9553 (8) |
| 0.9890 (3) | 0. 9890 (3) | 0.9473 (9) | 0.9473 (9) |
| 0.9806 (4) | 0.9806 (4) | 0.9445 (10) | 0.9445 (10) |
| 0.9698 (5) | 0.9698 (5) | 0.9436 (11) | 0.9436 (11) |
| 0.9665 (6) | 0.9665 (6) | 0.9434 (12) | 0.9434 (12) |
| Total loss =0.02071+ j 0.0081 MVA same as in [10]. #PM-Proposed Method. | | | |

| TABLE-4 | | | |
|---|---|---|---|
| LOAD FLOW VOLTAGE SOLUTION (P.U.) FOR 12-BUS SYSTEM WITH DG AT BUS-9 OF 0.28 MW AS PV MODEL | | | |
| **Volt. (bus) [34]** | **Volt. (bus) (PM)** | **Volt. (bus) [34]** | **Volt. (bus) p.u. (PM)** |
| 1.0 (1) | 1.0 (1) | 0.9889 (7) | 0.9903 (7) |
| 0.9971 (2) | 0.9973 (2) | 0.9926 (8) | 0.9934 (8) |
| 0.9947 (3) | 0.9953 (3) | **1.0 (9)** | **1.0 (9)** |
| 0.9908 (4) | 0.9926 (4) | 0.9973 (10) | 0.9970 (10) |
| 0.9889 (5) | 0.9906 (5) | 0.9965 (11) | 0.9965 (11) |
| 0.9887 (6) | 0.9904 (6) | 0.9963 (12) | 0.9963 (12) |
| [Total loss 0.0061+j 0.0023 MVA, Injected reactive power $Q_i$'=0.0883 MVAr (PM)] [Total loss0.0060+j 0.0022 MVA, Injected reactive power $Q_i$'=0.0886 MVAr [34]. | | | |

### *5.1.2 41-Bus RDS (Indian Practical System) with Multiple DGs (PV-PQ Bus)*

In this case, four DGs are considered. Out of them, three are considered as PV nodes and one as PQ node. Three DGs (voltage control mode) with capacities 5 MW, 6.4 MW, 12 MW are placed at nodes 19, 21 and 41 with ±0.85 power factor, respectively. One DG (power factor control mode) is considered at bus 10with capacity 2 MW at unity power factor. The results of the proposed PSO-DLF are compared with that of DIgSILENT™ Power Factory. The result of bus voltages and calculated reactive power requirement to maintain PV bus voltages by the PM and those with the DIgSILENT™ software quite close, which can be seen in Table 5. A critical case has also been simulated, in which, load on bus-36 is raised to 1.46 p.u. The DIgSILENT™ does not converge for the case whereas the PM converges. It shows poor voltage, 0.6219 p.u., at bus-36 with reactive power compensation at bus-41 of $Q_{i'}$ = 7.4369 MVAr (maximum upper boundary). Still the bus is violating the voltage constraint and is to be treated as PQ bus. The algorithm is run on MATLAB™ platform, where a Pentium PC computer with 2 GHz CPU is used. The PM provides the load flow solutions in 0.95-second without any optimal coding.

| TABLE 5 | | | |
|---|---|---|---|
| LOAD FLOW VOLTAGE SOLUTION (P.U.) FOR 41-BUS SYSTEM | | | |
| **VOLT. (BUS) [34]** | **VOLT. (BUS) PM** | **VOLT. (BUS) [34]** | **VOLT. (BUS) PM** |
| 1.0 (1) | 1.0 (1) | 0.9904 (23) | 0.9904 (23) |
| 0.9968 (2) | 0.9968 (2) | 0.9890(24) | 0.9890 (24) |
| 0.9784 (3) | 0.9784 (3) | 0.9888 (25) | 0.9888 (25) |
| 0.9646 (4) | 0.9646 (4) | 0.9848 (26) | 0.9848 (26) |
| 0.9617 (5) | 0.9617 (5) | 0.9815 (27) | 0.9815 (27) |
| 0.9613 (6) | 0.9612 (6) | 0.9791 (28) | 0.9791 (28) |
| 0.9609 (7) | 0.9607 (7) | 0.9804 (29) | 0.9804 (29) |
| 0.9548 (8) | 0.9547 (8) | 0.9802 (30) | 0.9802 (30) |
| 0.9621 (9) | 0.9616 (9) | 0.9801 (31) | 0.9801 (31) |
| **0.9643 (10)** | **0.9643 (10)** | 0.9800 (32) | 0.9800 (32) |
| 0.9621 (11) | 0.9622(11) | 0.9949 (33) | 0.9948 (33) |
| 0.9620 (12) | 0.9620 (12) | 0.9937 (34) | 0.9936 (34) |
| 0.9974 (13) | 0.9975 (13) | 0.9924 (35) | 0.9924 (35) |
| 0.9824 (14) | 0.9824 (14) | 0.9923 (36) | 0.9923 (36) |
| 0.9921 (15) | 0.9921 (15) | 0.9910 (37) | 0.9909 (37) |
| 0.9920 (16) | 0.9918 (16) | 0.9909 (38) | 0.9908 (38) |
| 0.9968 (17) | 0.9968 (17) | 0.9908 (39) | 0.9907 (39) |
| 0.9990 (18) | 0.9990 (18) | 0.9880 (40) | 0.9880 (40) |
| **1.0 (19)** | **1.0 (19)** | **1.0 (41)** | **1.0 (41)** |
| 0.9922 (20) | 0.9922 (20) | Total system loss | Total system loss |
| **1.0 (21)** | **1.0 (21)** | 0.8089 + j0.8566 (MVA) | 0.8085 + j0.8563 (MVA) |
| 0.9905 (22) | 0.9905 (22) | | |

The PSO-DLF is also tested for the base case on 33-bus [6] and 69-bus [14] systems. The results of the 33-bus and 69-bussystems are exactly matching up to four decimal places with [6] and [14], respectively. In 85-bus system, voltage profile at 83 buses are same, up to four decimal places, as in [19]. In Table 6, calculated reactive power at PV buses are given by PM and [34].

### *5.1.3 Radial Feeder with Constant Power Loads*

**i) Single DG (PQ bus) without capacitor**

In this case, one DG is assumed to be of firm capacity and no capacitor support is considered for the placement. Since, the connected DG is with firm capacity, the need of the capacitor can be avoided as the system voltage with DG will always remain within the specified limits. The base case results of the load flow on the 69-bussystem and the 33-bus system (*both with constant power load model*) are shown in Table 7.

The impact on the results of the 69-bus and 33-bus DSs with the placement of one DG are presented in Tables 8–9, respectively. The voltage constraint is relaxed in the 33-bus system for the first DG placement to compare with the analytical methods [25–26]. Otherwise the optimal size is 2.881 MW at bus-7 with minimum bus voltage of 0.9501 at bus-18.

| TABLE 6 | | | | | | |
|---|---|---|---|---|---|---|
| CALCULATED REACTIVE POWER AT PV BUSES IN 41-BUS RDS | | | | | | |
| **Method** | **[34]** | | | **PM** | | |
| PV node | 19 | 21 | 41 | 19 | 21 | 41 |
| $Q_i$, (MVAr) | –0.17 | 3.26 | –2.82 | –0.1726 | 3.0225 | –2.8157 |

| TABLE 7 | | |
|---|---|---|
| BASE CASE RESULTS OF 69-BUS AND 33-BUS SYSTEMS | | |
| **Test system** | **69-bus** | **33-bus** |
| Total Power loss (MVA) | 0.219+j0.102 | 0.211+j0.143 |
| Min. Volt. p.u. at bus | 0.9092 (65) | 0.9038 (18) |
| Max. Volt. p.u. at bus | Sub-Station bus-1 | |
| Min.VSI at bus | 0.6833 (65) | 0.6065 (18) |

| TABLE 8 | | | |
|---|---|---|---|
| ONE DG IMPACT RESULTS IN THE 33-BUS SYSTEM | | | |
| **Method** | **PM** | **AM*-1 [26]** | **AM*-2 [25]** |
| Optimal bus location | 6 | 6 | 6 |
| Opt. DG size (MW) | 2.59025 | 2.4903 | 2.49 |
| Real power loss (MW) | 0.11101 | 0.11105 | 0.11124 |
| React power loss (MVAr) | 0.0817 | – | – |
| Min. volt p.u. (bus) | 0.9424 (18) | – | – |
| Max. volt. p.u. (bus) | 1 (1) | – | – |
| *Analytical method (AM). | | | |

| TABLE 9 | | | |
|---|---|---|---|
| ONE DG IMPACT RESULTS IN THE 69-BUS SYSTEM | | | |
| **Method** | **PM** | **AM-1 [26]** | **AM-2 [25]** |
| Optimal bus location | 61 | 61 | 61 |
| Opt. DG size (MW) | 1.813 | 1.8090 | 1.81 |
| Real power loss (MW) | 0.0798 | 0.0799 | 0.07991 |
| React power loss (MVAr) | 0.0391 | – | – |
| Min. volt. p.u. (bus) | 0.9690 (27) | – | – |
| Max. volt. p.u. (bus) | 1 (1) | – | – |

### ii) Two DGs (PQ model) without capacitor

In this case, second stage DG is considered for placement in continuation to *case B* for 45% penetration level limit and the results are presented in Table 10. For both the systems, the PM provides the solution where as analytical methods (AM) [25–26] did not suggest any placement of the multiple DGs. The voltage profile is also obtained for the time varying load, with minimum load being 50% of the peak load of the day, and with maximum DG output and it is found within the acceptable limits (0.95–1.05 p.u.).

### iii. Radial Feeder with Mixed Power Loads with Standard fixed size Capacitors and Single DG (PV Model)

In this case, one DG (PV type) with 50% penetration level and ±0.85 power factor is considered for the placement. Five capacitors,

| TABLE 10 | | | |
|---|---|---|---|
| IMPACT RESULTS OF TWO DGs* IN THE 69-BUS AND 33-BUS SYSTEMS | | | |
| **Method** | **PM** | | **AM-(1-2) [25–26]** |
| | **69-bus** | **33-bus** | |
| II Optimal bus location | 17 | 25 | Does not propose the solution |
| II Optimal DG size (MW) | 0.5178 | 0.6803 | |
| Real Power loss (MW) | 0.0720 | 0.1062 | |
| React Power loss (MVAr) | 0.0360 | 0.08454 | |
| Min. Volt. p.u. at bus | 0.9820 (65) | 0.9527(18) | |
| Max. Volt. p.u. at bus | 1 (1) | 1 (1) | |
| *With previous DG intact with optimal size at optimal location. | | | |

| TABLE 11 | | | | |
|---|---|---|---|---|
| IMPACT RESULTS OF DG (PV MODEL) AND CAPACITORS IN 85-BUS DS | | | | |
| **Capacitor/DG size (bus no.)** | **Line loss** | | **Min. voltage** | |
| | **MW** | **MVAr** | **p.u.** | **Bus no.** |
| Base case(–) | 0.2536 | 0.1585 | 0.8829 | 54 |
| 0.15(42,43,55,71,77,84), 0.3(51), 0.45(47,54), 0.60(75) MVAr | 0.2111 | 0.1196 | 0.9525 | 56 |
| 2.3107 MW (8) | 0.0907 | 0.0392 | 0.9892 | 56 |
| With $Q_{i'}$= –0.8122 MVAr the voltage at bus-8 is 1.0 p.u. | | | | |

$S_C$ = [0.15, 0.3, 0.45, 0.6] MVAr, are considered for placement. The first capacitor of 0.15 MVAr, is placed at bus-54 (VSI=0.6076). The minimum system voltage with the placement of all these capacitors is 0.9409 p.u. Eight extra capacitors, each of 0.15 MVAr (smallest size of $S_C$), are placed to meet the voltage constraint. The results are presented in Table 11.

In this case, the DG can be considered with non-firm capacity as the capacitor support is planned to maintain voltage profile at or above 0.95 p.u. Even with the DG output power being zero or less than the rated output. Such kind of situation usually happens with the solar photovoltaic and wind DGs, which are intermittent. The voltage profile is also tested for time varying load with minimum load being 50% of the peak load of the day (Table 2), and with the peak DG output. The voltages are found within the acceptable limits (0.95–1.05 p.u.). The open source tool box Power System Analysis Tool (PSAT) did not converge even for the base case of this typical distribution network.

## 6.0 CONCLUSIONS

This paper proposes a new particle swarm optimization based distribution load flow to incorporate DG as PV or PQ node. The important feature of the proposed load flow is its simplicity, reliability and high accuracy to handle multiple DGs together. The effectiveness of the proposed algorithm, in solving base case, multiple capacitors and multiple DGs allocation problem, have been demonstrated on 12-bus, 33-bus, 41-bus, 69-bus and 85-bus distribution systems with constant power load and mixed load models. The DG placement results on various test cases reveal that the proposed method utilizing the PSO-DLF provides as accurate results as any commercial grade software and analytical methods for single DG placement problem. The proposed method also provides reliable solution for multiple DGs placement. The placement of third DG in 33-bus and 69-bus systems is not recommended as it violates real power loss reduction benefit and penetration level constraints by adding another DG. Hence, the optimal number of the DG for the considered systems is two with constant power load model.

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