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Review of distributed generation planning: objectives, constraints, and algorithms

Rajendra Prasad Payasi[1]*, Asheesh K. Singh[1], Devender Singh[2]

[1]Department of Electrical Engineering, Motilal Nehru National Institute of Technology Allahabad, INDIA*
[2] Department of Electrical Engineering, Institute of Technology BHU, Varanasi, INDIA
[*]Corresponding Author: e-mail: payasirp@rediffmail.com, Mobile no: +91-9839835741

Abstract

The Distributed Generation (DG) technologies, which include both conventional and non-conventional type of energy sources for generating power, are gaining momentum and play major role in distribution system as an alternative distribution system planning option. The penetration of DGs is potentially beneficial if distributed generation planning (DGP) is optimal i.e. their site and size are selected optimally by optimization of single or multi-objective function under certain operating constraints. Many researchers have presented some rigorous optimization-based methods for DGP. This paper will review the various objectives, different constraints as well as optimization based models using conventional algorithms, intelligent searches and fuzzy set applications in DGP.

Keywords: Distributed Generation, distribution system, distributed generation planning.

1. Introduction

Distributed generation, unlike traditional generation, aims to generate part of required electrical energy on small scale closer to the places of consumption and interchanges the electrical power with the network. It represents a change in the paradigm of electrical energy generation. The distributed generation, also termed as embedded generation or dispersed generation or decentralized generation, has been defined as electric power source connected directly to the distribution network or on the customer site of the meter (Ackermann *et al*, 2001). The emergence of new technological alternatives allows the DG technologies in distribution network to achieve immense technical, economical and environmental benefits (Chiradejaand *et al*, 2004; El-Khattam *et al*, 2004; Pepermans *et al*, 2005). These benefits could be maximized by proper planning i.e. placement of DGs at optimum locations with optimum size and suitable type.

The environmental concerns and the limitations of conventional power stations have imposed the restrictions on new large scale conventional power station or expansion of existing conventional power stations. Moreover, concerns over security of fuel supply have led governments to set targets to diversify their energy mixes in forthcoming decades. The incentives are already in place to encourage renewable and combined heat and power developments pertaining to the distribution network. Voltage control, fault levels, reliability, and power losses are among the issues, faced in integrating DG into distribution network (Pepermans *et al*, 2005; Barker *et al*, 2000; Jenkins *et al* 2000; Willis *et al*, 2000; Jóos *et al* 2000; Edwards *et al*, 2000; Girgis et al 2001; Masters *et al*, 2002; Walling *et al*; 2008). In fact, the DG fundamentally changes the characteristics of network (Ault *et al*, 2000; Dugan *et al*, 2001).

In literature, various objective functions have been considered and optimized, subject to different operating constraints, using conventional methods, intelligent searches and fuzzy set application for DGP. After a detailed study of the large amount of literature, a review on DGP will summarize the objective function model, the constraint model, and the mathematical algorithms. These three components are succinctly discussed as follows.

The objective function may be single or multi-objective to achieve maximum benefit of DGs without violating the equality and inequality constraints of the system. The base objective is to minimize total real power loss in the system (Rau *et al*, 1994; Kim *et al*, 1998; Hedayati *et al*, 2008; Acharya *et al*, 2006; Singh *et al*, 2009; Gözel *et al*,2009; Singh *et al*, 2008; Nara *et al* 2001; Krueasuk *et al*, 2005; Lalitha *et al,* 2010; Hung *et al*, 2010). Other possible objectives may be to minimize real and reactive power loss (Popović *et al*, 2005) or to maximize DG capacity (Keane *et al*, 2005; Harrison *et al*, 2007; Dent *et al*, 2010; Dent *et al*, 2010;

Dent *et al*, 2010) or to maximize the social welfare and profit (Gautam *et al*, 2007). It is also reasonable to use comprehensive-objective model (El-Khattam *et al* 2005; Golshan *et al*, 2006; Jabr *et al*, 2009; Algarni *et al*, 2009; Vovos *et al*, 2005; Vovos *et al*, 2005; Harrison *et al,* 2008), and multi-objective model (Celli *et al,* 2005; Carpinelli *et al*, 2005; Ochoa *et al*, 2006; Haghifam *et al*, 2008; Singh *et al*, 2009; Elnasha *et al*, 2010; Abou *et al*, 2010; Kumar *et al*, 2010; Sutthibun *et al*, 2010; Ochoa *et al*, 2008; Rodriguez *et al,* 2009) as the goal of DGP formulation. The researchers have also studied the impact of DG on system reliability and security of supply system (Teng *et al*, 2002; Chaudhury *et al*, 2003; Mao *et al*, 2003; Zhu *et al*, 2006; Borges *et al*, 2006; Wang *et al* 2008; Wang *et al*, 2010) and found that these can be increased with proper DGP. The increasing connection of variable DGs (like wind power) present number of technical issues. The impact of inherent time-varying behavior of the demand and distributed generation on distribution system performance using appropriate DGP techniques have been studied in (EL-Khattam *et al*, 2006; Ochoa *et al*, 2008; Ochoa *et al*, 2008; Rodriguez *et al*, 2009; Keane *et al*, 2009; Khoddr *et al*, 2010; Dent *et al* 2010; Atwa *et al*, 2010). The optimal DGP has also been implemented in deregulated electricity market (Gautam *et al*, 2007; Kumar *et al*, 2010; El-Khattam *et al*, 2004; Singh *et al*, 2010; Porkar *et al*, 2010; Lezama *et al*, 2011). In literature, the single or multi objective functions have been considered with various constraints for DGP in order to meet the load demand with improved distribution system performance. These constraints are classified as equality and inequality constraints. The equality constraint is power conservation limit and inequality constraints, most commonly used, are thermal limit of feeder, power limit of transformer, voltage limit of nodes and DG power limit. Apart from these, the other inequality constraints such as three phase & single phase short circuit level (SCL), short circuit ratio (SCR) (Keane *et al*, 2005), inter tie power (Kim *et al*, 1998), and voltage step (Dent *et al*, 2010)] constraints have also been used in such studies.

The solution techniques for DGP have been evolving and number of approaches have been developed, each with its particular mathematical and computational characteristics. The most of the techniques discussed in last many years are classified as one of the three categories: Conventional methods, intelligent search-based methods and fuzzy set based method. The conventional methods include Linear Programming (LP), Non Linear Programming (NLP) like AC optimal power flow and continuous power flow, Mixed Integer Non-Linear Programming (MINLP), and Analytical approaches. The intelligent search-based methods are Simulated Annealing (SA), Evolutionary Algorithms (EAs), Tabu Search (TS), Particle Swarm Optimization (PSO) have been given wide spread attention as possible techniques to obtain the global optimum for the DGP problem. However, these methods require more computing time in general. Fuzzy set approaches has also been applied to DGP to address fuzziness associated with objectives and constraints.

The paper is organized as follows. Section 2 illustrates the possible objectives in the DGP literature. Section 3 presents the different constraints used. Section 4 presents the solution techniques for DGP. Section 5 presents the conclusion. The techniques, objectives, constraints, types of load and number of DGs, considered in literature, are summarized in Table 2 and 3 in appendix.

2. Objectives of Distributed Generation Planning

The majority of the DGP objectives were to minimize the real power loss in network. In addition, other technical indices such as reactive power loss, MVA capacity, Voltage profile, total spinning reserve, power flow reduction in critical line were used as objective function in the form of single or multi objective for optimization. The detailed discussions are presented as follows.

2.1 Minimize line loss: DGP deals with the optimal allocation of distributed generation, to obtain maximum benefit by minimizing total real power loss in the system. In (Rau *et al*, 1994; Kim *et al,* 1998), the basic formulation for loss minimization was done with the concept that a sum of all nodal injections of power in a network represents losses and the objective function (f) was expressed as:

$$f = \sum_{i=1}^{n} P_i \tag{1}$$

where, P_i is nodal injection of power at bus i, and n is total number of buses. In (Rau *et al*, 1994), further formulation was done according to second order method based on Newton's method, and in (Kim *et al*, 1998), further formulation was done according to Second order method and genetic algorithm.

In (Kim *et al*, 2002), authors expressed the objective function (f) by summing up energy loss costs for each load level as:

$$f = K_e \sum_{i=0}^{nl} T^i P^i_{loss} \tag{2}$$

where, K_e is constant for energy. P^i_{loss} is the power loss for load level i with a time duration T^i. nl is the number of load levels.

In (Wang *et al*, 2004), to find the optimal location of DG, objective function (f_j) for DG at bus j is as follows:

$$f_j = \sum_{i=1}^{j-1} R_{1i}(j)\left|S_{Li}\right|^2 + \sum_{i=j+1}^{N} R_{1i}(j)\left|S_{Li}\right|^2 , \qquad j = 2,3,\ldots\ldots N \tag{3}$$

where, $R_{1i}(j)$ is the equivalent resistance between bus 1 and bus i when DG is located at bus j, j≠1. S_{Li} is complex power.

$$R_{1i}(j) = \begin{cases} Real(Z_{11} + Z_{ii} - 2Z_{1i}), & i < j \\ Real(Z_{11} + Z_{(i-1)(i-1)} - 2Z_{1(i-1)}, & i > j \end{cases} \tag{4}$$

where, Z_{11}, Z_{ii}, Z_{1i} are the elements of impedance matrix.

when the DG is located at bus 1(j=1), the objective function will be as follows.

$$f_1 = \sum_{i=1}^{N} R_{1i}(j)\left|S_{Li}\right|^2 \tag{5}$$

The goal is to find the optimal bus m where the objective function reaches its minimum value as.

$$f_m = Min(f_j), \quad j = 1,2,\ldots\ldots N \tag{6}$$

In (Hedayati *et al*, 2008), the impact of DG in power transfer capacity of distribution network and voltage stability has been studied. The overall impact is positive due to the active power injection with objective to minimize the losses (1). In (Acharya *et al*, 2006; Singh *et al*, 2008; Lalitha *et al*, 2010; EL-Khattam *et al*, 2006; Hung *et al,* 2010) , problem was formulated using the expression for the total real loss (P_L) in power systems, as represented by (7) , popularly known as "exact loss formula" (Kothari *et al*, 2006).

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(P_iP_j - Q_iQ_j)\right] \tag{7}$$

where, $$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}Cos(\delta_i - \delta_j), \quad \beta_{ij} = \frac{r_{ij}}{V_iV_j}Sin(\delta_i - \delta_j);$$

$r_{ij}+ x_{ij}= z_{ij}$ are the *ij*th element of bus impedance matrix [Z_{bus}] , V_i , V_j are the voltages at *i*th and *j*th buses respectively, P_i and P_j are the active power injection at the *i*th and *j*th bus respectively, Q_i , Q_j are the reactive power injection at the *i*th and *j*th bus respectively, N is number of buses, δ_i and δ_j are voltage phase angle at ith and jth buses respectively.

In (Gözel *et al*, 2009), the objective function considered as total power loss (P_{loss}), to find the optimum location of DG and expressed as a function of the branch current injection.

$$P_{loss} = \sum_{i=1}^{nb}\left|B_i\right|^2.R_i = \left[R\right]^T\left|\left[BIBC\right]\cdot\left[I\right]\right|^2 \tag{8}$$

where,

R_i is the *i*th branch resistance, [*R*] is branch resistance row vector, *nb* is number of branches, *BIBC* is bus-injection to branch-current matrix, and [*I*] is the vector of the equivalent current injection for each bus except the reference bus.

2.2 Maximize Distributed Generation Capacity: The objective for optimal allocation of Distributed Generation (DG) has been taken as maximization of DG capacity in (Keane *et al,* 2005; Dent *et al,* 2010; Dent *et al*, 2010; Dent *et al*, 2010), Generation capacity is allocated across the buses such that none of the technical constraints is breached. The objective function is as follows:

$$f = \sum_{i=1}^{N} P_{DGi} \tag{9}$$

where, P_{DGi} is the DG capacity of the *i*th bus, and N is the set of possible locations. Without loss of generality it is assumed that there is one generator at each bus. In (Wang *et al,* 2004), assuming no expected load growth in the region of interest, the objective is to maximize the quantity of distributed generation connected to the system and expressed as follows:

$$f = \sum_{i=1}^{n}\left(P_{Gi} + jQ_{Gi}\right) \tag{10}$$

where, P_{Gi} and Q_{Gi} are the real and reactive power injections at each node *i,* respectively, *n* is total number of DG nodes. In (Harrison *et al,* 2005), the advantage of the commonly used technique of modeling, steady-state DGs used as negative load. The objective function is as follows:

$$f(\psi) = \sum_{i=1}^{n} - C_i \times MW_i^0(1-\psi_i) \tag{11}$$

where, ψ is capacity adjustment factor, MW^0 is initial active power capacity of DGs in pu, -*C* is capacity value in per unit megawatt of DG capacity, *i* is DG bus index, and *n* is number of buses available for capacity addition.

The objective in (Keane *et al*, 2007), was to maximize the amount of energy harvested per euro of investment by making best use of the existing assets and available energy resource. The objective function *J* (MWh/ €kV) is as follows:

$$J = \sum_{j=1}^{N}\sum_{i=1}^{N}\frac{P_{Availj}Plant_{ij}^{k}ELF_{ij}^{k-1}}{Conn\ Cost_{ij}V_{i}^{k-1}} \tag{12}$$

where, $P_{Avail\,j}$ is the jth energy sources. $Plant^{k}_{ij}$ are the control variables representing the fraction of $P_{Avail\,j}$ allocated to the ith bus on the kth iteration i.e. $0 \le Plant^{k}_{i\,j} \le 1$. M and N are the energy sources. Conn $Cost_{i\,j}$ is the connection costs of the jth energy resource at the ith bus. ELF_{ij}^{k-1} is the effective load factor of the jth energy source at the ith bus on the $(k-1)$th iteration. V_i^{k-1} (kV/MW) is the total voltage sensitivity of the ith bus to power injections at all other buses on the kth iteration.

In (Kumar *et al*, 2010), to obtain most appropriate DG location, nodal price variation at each bus and line loss sensitivity has been utilized as economical and operational criteria. Then mixed-integer non-linear programming (MINLP) approach was used to find the optimal location and the number of DG in appropriate zone. The objective function was to minimize the fuel cost of conventional and DG sources as well as to minimize the line losses in the network. In (Vovos *et al*, 2005), the maximum DG capacity has been determined by modeling DG as generators with negative cost coefficients. By minimizing the cost of these generators, the DG capacity benefits were maximized.

2.3 Social welfare and profit maximization: In (Gautam *et al*, 2007), the problem is formulated with two distinct objective functions, namely, social welfare maximization and profit maximization. Social welfare is defined as the difference between total benefit to consumers minus total cost of production (Rothwel *et al*, 2003). The objective function associated with social welfare has been formulated as quadratic benefit curve submitted by the buyer (DISCO), $B_i(P_{Di})$ minus quadratic bid curve supplied by seller (GENCO), $C_i(P_{Di})$ minus the quadratic cost function supplied by DG owner $C(P_{DGi})$.

$$f = \sum_{i=1}^{N}(B_i(P_{Di}) - C_i(P_{Di}) - C(P_{DGi})) \tag{13}$$

The profit maximization formulation is as follows:

$$Profit_i = \lambda_i \times P_{DGi} - C(P_{DGi}) \tag{14}$$

where, P_{DGi} denotes the DG size at node i; λ_i denotes the locational marginal price (LMP) at node i after placing DG; $C(P_{DGi}) = a_{DGi} + b_{DGi}(P_{DGi}) + c_{DGi}(P_{DGi})^2$ denotes the cost characteristic of DG at node i.

2.4 *Comprehensive-objective*: The comprehensive–objective aims to minimize cost of various components such as DGs investment, DGs operating cost, and total payments toward compensating for system losses. In (El-Khattam *et al*, 2005), total investment objective function is based on the supply chain model formulation. It aims to minimize the investment and operating costs of candidate local DGs, payments toward purchasing the required extra power by the DISCO, payment toward loss compensation services as well as the investment cost of other chosen new facilities for different scenarios. The DISCO may have the following alternative to serve its demand growth.

- Scenario A: Purchasing the required extra power from the main grid and pumping it to its distribution network through its junction substation with main grid
- Scenario B: Purchasing the extra power from an existing intertie and delivering it to its distribution network territory.
- Investing in DG as an alternative for solving the distribution system planning (DSP) problem without the need for feeder upgrading.

The objective function used in (El-Khattam *et al*, 2005) is as follows:

$$J = \sum_{i=1}^{N} C_{fi}(S_{DGi}^{Max} + BK)\sigma_{DGi} + 8760\sum_{t=1}^{T}\sum_{i=1}^{M}\beta^{t}C_{ri}S_{DGi} + 8760\sum_{t=1}^{T}\beta^{t}\sum_{i=1}^{TN}M\sum_{j=1}\frac{\Delta V_{ij}^{2}}{|Z_{ij}|}.pf.C_e$$

$$+\text{Cost of Scenario-A or + Cost of Scenario-B} \tag{15}$$

where,

Cost of Scenario-A is as follows.

$$C_A = \sum_{i=1}^{SS}\sum_{u=1}^{TU}C_{iu}\sigma_{iu} + \sum_{i=1}^{TN}\sum_{j=1}^{M}C_{ij}\sigma_{ij} + 8760\sum_{t=1}^{T}\beta^{t}\sum_{i=1}^{TU}pf\ C_e S_{iu}\sigma_{iu} \tag{15a}$$

Cost of Scenario-B is as follows.

$$C_B = \sum_{i=1}^{TN}\sum_{j=1}^{M}C_{ij}\sigma_{ij} + 8760\sum_{t=1}^{T}\beta^{t}\sum_{i=1}^{TU}pf\ C_{\text{int}}(S_{\text{int}})S_{\text{int}}\sigma_{\text{int}}(S_{\text{int}}) \tag{15b}$$

and

$$\beta^{t} = 1/(1+d)^{t} \tag{15c}$$

In the above formulation the factors such as backup DG unit capacity(BK), discount rate(d), investment cost(C_f) , operating cost(C_r), electricity market price(C_e), cost of feeder($C_{i,j}$), cost of transformer($C_{i,u}$), intertie power cost($Cint$), number of load buses(M), power generated from DG (S_{DG}), , power imported by intertie(S_{int}), transformer u in substation i dispatch power ($S_{i,u}$), number of substation(SS), incremental time interval(t), horizon planning year(T), total number of buses(TN), total number of substation transformers(TU), feeder segment impedance ($|Z_{ij}|$), system power factor(pf), DG binary decision variable (σ_{DG}), feeder i to j binary decision variable(σ_{ij}) transformer u in substation i binary decision variable (σ_{iu}), intertie binary decision variable (σ_{int}), DG capacity limit (S_{DGi}^{max}) were considered.

In (Golshan *et al*, 2006), authors emphasized on more comprehensive distributed-generation planning and included distributed generation, reactive sources and network configuration planning. The objective function is formulated to minimize the cost of power and energy losses and the total required reactive power. The cost function of optimization problem is as follows.

$$f(x) = k_p P_0(z_0) + k_e \sum_{i=0}^{n} T_i P_i(z_i) + k_q \sum_{l \in l_q} |q_l| \tag{16}$$

where,

$$z = \left[z_0^t z_1^t \ldots\ldots z_n^t \right]^t \tag{16a}$$

k_p, k_e, k_q are coefficients of power loss, cost of fuel, and cost of reactive power source (q_l) respectively. T_i represents the fraction of time that the load curve stays at level i. The power loss related to load level i is denoted by $P_i(z_i)$. q_l are sizes of reactive power sources that can be positive or negative depending on the presence of capacitive or inductive sources. N is number of load levels.

In (Algarni *et al*, 2009), authors have considered the goodness factor of DG units. The goodness factor is based on the computation of the incremental contribution of a DG unit to distribution system losses. The disco's objective functions have been formulated for disco-owned DG and investor-owned DG.

Objective function to minimize energy cost with disco-owned DG is as follows.

$$J_1 = \sum_{i=1}^{s} \rho^p P_{Gi} + \sum_{i=1}^{s} \rho^Q Q_{Gi} + \sum_{i=1}^{g} \left(A_i P_{DGi}^2 + B_i P_{DGi} + C_i \right) + \sum_{i=1}^{g} Q_{DGi}\, QCST_i^Q - \sum_{i=1}^{g} \alpha_i^{loss} \Delta P_i - \sum_{i=1}^{g} \beta_i^{loss} \Delta Q_i \tag{17}$$

where, the first component is the cost of power (P_G) purchased from the external grid at the rate of ρ^P \$/MWh. Second component denotes the payment for reactive power (Q_G) from the external grid at the rate of ρ^q \$/MVArh. Third components represent operational cost of DG for active power (P_{DG}) supplied. Fourth components denotes operation cost of DG for reactive power (P_{DG}) at the rate of $QCST^Q$ \$/MVArh. The last two terms represent the benefit or cost saving accrued by the disco due to increase in active and reactive power generation from DG units compared to that in the dispatch without goodness factor.

$$\Delta P_{DGi} = P_{DGi} - P_{DGi}^* \qquad i \in g \tag{17a}$$

$$\Delta Q_{DGi} = Q_{DGi} - Q_{DGi}^* \qquad i \in g \tag{17b}$$

The goodness factors α^{Loss} and β^{Loss} are used in conjunction with DG generated active and reactive power, respectively, to compute the cost savings to the disco. A, B, C are operating cost of a DG unit, g is set of buses with DG unit, and s is set of disco substation buses. P_{DG}^* and Q_{DG}^* are optimal active and reactive power from DG respectively. The disco's objective will be slightly modified when the DG units are investor-owned instead of utility owned. Such DG units will not be included in the disco's dispatch program, but their generation has to be absorbed by the disco based on prior arrangements, while making adjustments in its own resources.

The objective function to minimize energy cost with investor-owned DG is similar to (17), however the third term representing operational cost of DG is removed and the term price paid by the disco for energy purchased from the investor owned units is added, which results in (18) as follows.

$$J_2 = \sum_{i=1}^{s} \rho^p P_{Gi} + \sum_{i=1}^{s} \rho^Q Q_{Gi} + \sum_{i=1}^{g} \tau_i P_{DGi} + \sum_{i=1}^{g} Q_{DGi}\, QCST_i^Q - \sum_{i=1}^{g} \alpha_i^{loss} \Delta P_{DGi} - \sum_{i=1}^{g} \beta_i^{loss} \Delta Q_{DGi} \tag{18}$$

The third term is a constant term, and will not affect the optimization solution, if removed.

In (Ghosh *et al*, 2010), authors used N-R method for power flow solution. The main objective of the power flow solution has been directed towards optimization of the objective function (OF) as follows.

$$OF = C(P_{DG}) + W \times E \tag{19}$$

where, $C(P_{DG}) = a_{DG} + b_{DG}P_{DG} + c_{DG}(P_{DG})^2$, $C(P_{DG})$ is total cost of DG as a function of DG rating (P_{DG}), W is weighting factor, E is total active loss and. a_{DG}, b_{DG}, and c_{DG} are the quadratic cost coefficients of specified distributed generation.

In (Vovos *et al*, 2005); Vovos *et al*, 2005), the objective function, to minimize, is equal to the total benefit from new generation capacity and expected exports/imports. The objective function ($F(P_g, P_T)$) is as follows.

$$F(P_g, P_T) = \sum_{g=1}^{ng} C_g(P_g) + \sum_{T=1}^{nT} C_T(P_T) \quad (20)$$

where, $Cg(P_g)$ is the operational cost of generator (g) at the output (P_g), $C_T(P_T)$ is operational cost of generator at output (P_T), ng is capacity expansion locations (CELs), and nT is exports imports points (E/IPs).

2.5 Multi-objective (MO): Several single and comprehensive objective functions for DGP have been discussed above. The multi-objective concept is adopted for better DGP by accomplishing best compromise among various objectives. The MO permits a better simulation of real world, often characterized by contrasting goals, and gives the planner the capability of making the final decision by selecting, on the basis of an individual point of view, the best trade-off solution from a wide range of suitable solutions. In (Celli *et al*, 2005), the objective has been achieved by minimizing different functions which is expressed as:

$$Min\, C(X(U)) = Min[C_u, C_L, C_{NNS}, C_E] \quad (21)$$

where, $X(U)$ is a power flow solution calculated as function of vector U, which stores the data about the location and the size of generator. C_U is cost of network upgrading, C_L is cost of energy loss, C_{ENS} is cost of energy not supplied, C_E is cost of purchased energy. In (Carpinelli *et al,* 2005), the mathematical formulation of objective function is akin as (Celli *et al*, 2005) with three objectives as:

$$Min\, C(X(u)) = Min\,[F_1, F_2, F_3] \quad (22)$$

where, F_1 is cost of energy loss, F_2 is voltage profile, and F_3 is power quality. In (Ochoa *et al*, 2006; Singh *et al*, 2009; Ochoa *et al*, 2008), authors evaluated the impact of DG using Multi-objective performance index (IMO) considering range of technical issues as indices. In (Ochoa *et al*, 2006) seven indices, in (Singh *et al*, 2009) four indices, and in (Ochoa *et al*, 2008) six indices were used by strategically giving a relevance (weighting) factor to each index.

The multi-objective performance index in (Ochoa *et al*, 2006) is as follows.

$$IMO = w_1 ILP + w_2 ILQ + w_3 IVD + w_4 IVR + w_5 IC + w_6 ISC3 + w_7 ISC1 \quad (23)$$

Multi-objective performance index in (Singh *et al*, 2009) is as follows.

$$IMO = w_1 ILP + w_2 ILQ + w_3 IC + w_4 IVD \quad (24)$$

Multi-objective performance index in (Ochoa *et al,* 2008) is as follows.

$$IMO = w_1 ILP + w_2 ILQ + w_3 IVD + w_4 IC + w_5 ISC3 + w_6 ISC1 \quad (23)$$

where,

$$\sum_{i=1}^{NI} w_i = 1.0 \wedge w_i \in [0, 1]$$

In the above formulation the factors such as real power loss index(*ILP*), reactive power loss index (*ILQ*), voltage drop index (*IVD*), voltage regulation index (*IVR*), current capacity (of conductor) index(*IC*), three phase short circuit current index (*ISC3*), single phase to ground short circuit index (*ISC1*), relevance(weighting) factors(w_i), number of index(*NI*) were considered. Reference (Elnashar *et al*, 2010) considered an objective function consisting three parameters as Power loss (P_{loss}), short circuit current (I_{sc}), and voltage level (V_{level}) to optimize and represented as:

$$Max\, f(P_{loss}, I_{SC}, V_{level}) = \sum_{i=1}^{3} w_i \frac{F_i}{F_i^{\max}} \quad (26)$$

$$\text{with } 0 \le w_i \le 1 \quad and \quad \sum_{i=1}^{3} w_i = 1$$

where , F_i is the DG impact i, w_i is the weighting factor selected by planner indicating the relative importance of the DG impact i, F_i^{max} is the maximum value of DG impact i. The impact factor (*IF*) of any of the above quantities is defined as:

$$IF = \frac{value\ without\ DG - value\ with\ DG}{value\ without\ DG}$$

In (Abou *et al*, 2010), authors have considered the composite technical and economic benefits of DG in multi-objective function and optimized to reduce the voltage and frequency deviation. The components included in multi-objective function are voltage profile improvement (*VPI*), spinning reserve increasing (*SRI*), power flow reduction (*PFR*), and line loss reduction (*LLR*) expressed in percentage. The overall maximal composite benefit of DG (MBDG) was formulated as follows.

$$MBDG = w_1 VPI\% + w_2 SRI\% + w_3 PFR\% + w_4 LLR\% \quad (27)$$

$$\text{With} \quad 0 \le w_i \le 1 \quad and \quad \sum_{i=1}^{4} w_i = 1$$

where, w_1, w_2, w_3, and w_4 are benefit weighting factors for *VPI%, SRI%, PFR%* and *LLR%* respectively.

In ([Kumar *et al*, 2010), the objective is to minimize the total load curtailment during restoration (single-step) after long interruption. The objective function is constrained by penalizing any solution that violates network constraints. Hence, a penalty/weight which depends on constraint and extent of its violation is multiplied with each term of objective function (*f*). The objective for single-step restoration consists of four terms:

- The load that cannot be supplied and have to be curtailed due to constraint violations (S_C)
- Bus voltage violations (V_V)
- Branch current violations (I_V)
- Substation transformer load-limit violation (S_{TV})

Each term contributes a penalty term and is considered as ratio (unit less) for dimensional uniformity and normalization. Therefore, the final objective function is the weighted sum of all these penalties and expressed as follows.

$$Min\ f = W_{load} S_C + W_{IV} I_V + W_{VV} V_V + W_{TV} S_{TV} \tag{28}$$

where,

$$S_C = \left[\frac{S_{Total} - S_{Supplied}}{S_{Total}} \right] \tag{28a}$$

$$S_{Total} = \sum_{i=1}^{N} S_i(T_0) \tag{28b}$$

$$S_{Supplied} = \sum_{i=1}^{N} S_i(T_0)\sigma_i \tag{28c}$$

The terms used are total number of buses (*N*), initiation of restoration process (T_0) , Load demand at initiation of restoration process ($S_i(T_0)$), binary decision variable for load (σ_i). W_{load} , W_{IV} , W_{VV} , and W_{TV} are weights for S_C , I_V, V_V, and S_{TV} respectively.

The objective function considered in (Sutthibun *et al,* 2010) was to minimize the real power loss (P_L), emission (E_{pg}) , and the contingency in terms of severity index (*SI*) while subjected to power balance constraint and power generation limit. The multi-objective function (*F*) is the weighted sum of individual objective expressed as follows.

$$F = w_1 P_L + w_2 E_{pg} + w_3 SI \tag{29}$$

where, w_1, w_2, and w_3 are weight factors whose values are between 0.2 to 0.6 with condition $w_1 + w_2 + w_3 = 1$.

The choice of weighting factors depends on the objective (merit) which is required to be more mitigated i.e. if DG is introduced to mitigate a certain objective to overcome a specific problem, the corresponding weighting factors are increased compared to other factors (Abou *et al*, 2010).

3. Constraints of Distributed Generation Planning

The single or multi-objective function is minimized or maximized according to its formulation for optimum location and size of DG with the constraints in order to keep the operating condition within limit. The researchers have considered different inequality constraints including few similar constraints. The common constraints, almost adopted by every author, are node voltage and line loading. The other constraint may be equality constraint (power balance equation), number of DGs, transformer capacity, maximum DG power generation (active and reactive), power factor of DG, intertie power capacity, and short circuit current etc. These constraints are detailed as follows.

3.1 Equality constraints

3.1.1 Active power balance limit (APBL): The total active power generation of the traditional generation (P_{GT}) and DG units (P_{DGT}) must cover the total load demand (P_{DT}) and the total active power loss (P_{LT}). This has been considered in (Singh *et al*, 2009; El-Khattam *et al*, 2005; Golshan *et al*, 2006; Singh *et al*, 2009; Abou *et al* 2010; Vovos *et al*, 2005; Kumar *et al,* 2010; Roa-Sepulveda *et al*, 2003; Vovos *et al*, 2005) and expressed as:

$$P_{GT} + P_{DGT} - P_{DT} - P_{LT} = 0 \tag{30}$$

3.1.2 Reactive Power Balance Limit (RPBL): The total reactive power generation of the traditional generation (Q_{GT}) and DG units (Q_{DGT}) must cover the total load demand (Q_{DT}) and the total active power loss (Q_{LT}). This has been considered in (Singh *et al*, 2009; El-Khattam *et al*, 2005; Vovos *et al*, 2005; Kumar *et al,* 2010; Roa-Sepulveda *et al*, 2003; Vovos *et al*, 2005) and expressed as:

$$Q_{GT} + Q_{DGT} - Q_{DT} - Q_{LT} = 0 \tag{31}$$

3.2 *Inequality constraints*

3.2.1 *Voltage profile limits* (VPL): The bus voltage (V_i) at bus i is restricted by its upper and lower limits (V_i^{min} and V_i^{max}) for all buses as:

$$V_i^{\min} \le V_i \le V_i^{\max} \ , \quad \forall\, i \in \{ number\ of\ buses \} \tag{32}$$

This constraint has been considered almost in all references pertaining to DGP.

3.2.2 *Line thermal limit* (LTL): These constraints represent maximum power flow in line and are based on thermal and stability consideration. The power carrying capacity of feeders is represented by MVA limits (S_k) through any feeder (k) must be well within the maximum thermal capacity (S_k^{max}) of the lines. References (Keane *et a*l, 2005; Popović *et al*, 2005; Gautam *et al* 2007; El-Khattam *et al*, 2005; Haghifam *et al*, 2008; Singh *et al*, 209; Jabr *et al*, 2009; Algarni *et al*, 2009; Vovos *et al*, 2005; Kumar *et al,* 2010; Keane *et al,* 2007; Singh *et al*, 2008; Krueasuk *et al*, 2005; Lalitha *et al*, 2010; Vovos *et al*, 2005; Harrison *et al*, 2007; Harrison *et al*, 2008; Mao *et a*l, 2003; Wang *et al*, 2010; EL-Khattam *et al*, 2006; Ochoa *et al,* 2008; Rodriguez *et al*, 2009; Dent *et al*, 2010; Atwa *et al*, 2010) have considered this constraint and expressed as:

$$S_k \le S_k^{\max} \ , \quad \forall\, k \in \{ number\ of\ lines \} \tag{33}$$

3.2.3 Phase angle limit (PAL): The bus voltage angle (δ_i) at bus *i* is restricted by its upper and lower limits (δ_i^{min} and δ_i^{max}) for all buses as:

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \ , \quad \forall\, i \in \{ number\ of\ buses \} \tag{34}$$

This has been considered in (Kumar *et al*, 2010; Roa-Sepulveda *et al*, 2003).

3.2.4 Traditional active power generation limits (TAPGL): The power from traditional generator (P_t) must be restricted by its lower and upper limits (P_t^{min} and P_t^{max}) as:

$$P_t^{\min} \le P_t \le P_t^{\max} \tag{35}$$

Reference (Algarn *et al*, 2009) considered only upper limit while references (Gautam *et al,* 2007; Jabr *et al*, 2009; Abou *et al*, 2010) considered both upper and lower limits.

3.2.5 Traditional reactive power generation limits (TRPGL): The power from traditional generator (Q_t) must be restricted by its lower and upper limits (Q_t^{min} and Q_t^{max}) as:

$$Q_t^{\min} \le Q_t \le Q_t^{\max} \tag{36}$$

Reference (Algarni *et al*, 2009) considered only upper limit while references (Gautam *et al*, 2007; Jabr *et al*, 2009) considered both upper and lower limits.

3.2.6 Substation transformer capacity limit (STCL): The total power supplied by the substation transformer (S_{load}^{total}) be within the substation's transformer capacity limit (S_{sst}^{max}). It is expressed as:

$$S_{load}^{total} \le S_{sst}^{\max} \tag{37}$$

It has been used in (Keane *et al*, 2005; El-Khattam *et al*, 2005; Kumar *et al*, 2010; Vovos *et al*, 2005; Keane *et al*, 2007; Vovos *et al*, 2005; Harrison *et al*, 2007) .

3.2.7 DG active power generation limits (DGAPGL): The active power generated by each DG (P_{dg}) is restricted by its lower and upper limits (P_{dg}^{min} and P_{dg}^{max}) as:

$$P_{dg}^{\min} \le P_{dg} \le P_{dg}^{\max} \tag{38}$$

In (El-Khattam *et al*, 2005; Kumar *et al*, 2010), authors have considered only upper limit while in (Algarni *et al*, 2009; Abou *et al*, 2010; Kumar *et al*, 2010; Roa-Sepulveda *et al*, 2003; Lee *et al,* 1998; Harrison *et al,* 2007; Borges *et al*, 2006; EL-Khattam *et al*, 2006; Rodriguez *et al*, 2009; Hung *et al*, 2010), authors have considered both lower and upper limits. There is no defined limit (upper) on the amount of generation through DG. However, in (Popović *et al*, 2005; Kumar *et al*, 2010), the maximum DG installed capacity limits have been considered as 20% and 30% of rated capacity substation respectively.

3.2.8 DG reactive power generation limits (DGRPGL): The reactive power of each DG is restricted by its lower and upper limits (Q_{dg}^{min} and Q_{dg}^{max}) as:

$$Q_{dg}^{\min} \le Q_{dg} \le Q_{dg}^{\max} \tag{39}$$

In (El-Khattam *et al,* 2005; Kumar *et al*, 2010), authors have considered only upper limit while in (Algarni *et al*, 2009; Kumar *et al*, 2010; Roa-Sepulveda *et al*, 2003; Lee *et al,* 1998) authors have considered both lower and upper limits.

3.2.9 Number of DG Limit (NDGL): The number of DG (N_{dg}) must be less than or equal to the maximum number of DG (N_{dg}^{max}) as:

$$N_{dg} \le N_{dg}^{\max} \tag{40}$$

This constraint has been used in (Algarni *et al*, 2009; Nara *et al*, 2001).

3.2.10 Short circuit level limit (SCLL): A short circuit calculation is carried out to ensure that fault current with DG (SCL_{WDG}) should not increase rated fault current of currently installed protective devices (SCL_{rated}) as:

$$SCL_{WDG} \le SCL_{rated} \tag{41}$$

In (Keane *et al*, 2005; Popović *et al* , 2005; Elnashar *et al*, 2010; Vovos *et al*, 2005; Keane *et al*, 2007; Vovos *et al*, 2005), authors have considered this constraint for reliable operation of protective devices.

3.2.11 Intertie's delivery power limit (IDPL): The intertie's delivery power cost rates (C_{int} (S_{int})) are predetermined by Distribution Company (DISCO) and contracts of other identities. The rate of charge depends on the amount of power purchased by DISCO. This concept has been used in (El-Khattam *et al*, 2005) as:

$$C_{\text{int}}(S_{\text{int}}) = MF(MVA_{\text{lim}it}) \cdot C_e \ , \quad \forall \ S_{\text{int}} \in \{ MVA_{\text{lim}it} \} \tag{42}$$

where, $MF\ (MVA_{limit})$ is multiplying factor of intertie power limit (MVA_{limit}), C_e is electricity market price, S_{int} is amount of power imported through the intertie.

3.2.12 Power factor limit (PFL): Distributed generators have been assumed to operate in power factor control mode. This necessitates a constraint on power factor (Jabr *et al*, 2009; Vovos *et al*, 2005; Vovos *et al*, 2005; Harrison *et al*, 2007; Harrison *et al*, 2008) and expressed as:

$$Cos(\phi_{DG}) = P_{DG} \Big/ \sqrt{P_{DG}^2 + Q_{DG}^2} = constt. \tag{43}$$

where, P_{DG} is real power output of DG, Q_{DG} is reactive power output of DG, $Ø_{DG}$ is constant power factor angle of DG.

3.2.13 Tap position limit (TPL): The tap positions of voltage regulators (VRs) were considered in (Golshan *et al*, 2006; Lee *et al*, 1998). The tap position (n_t) must be between lower and upper limits (n_t^{min} and n_t^{max}) as:

$$n_t^{\min} \le n_t \le n_t^{\max} \tag{44}$$

3.2.114 Total line loss limit (TLLL): In (Popović *et al,* 2005), total line loss limit has also been considered to maximize the capacity of DG in a system. The total line loss with distributed generation (P_{DGTLL}) must be less than total line loss without DG (P_{TLL}) as:

$$P_{DGTLL} \le P_{TLL} \tag{45}$$

3.2.15 Short circuit ratio limit (SCRL): SCR is the ratio of generator power P_{DG} (MW) at each bus to short circuit level (SCL) at each bus SCL_{BUS} (MVA). The connection of induction generator to high impedance circuit may lead to voltage instability problems if SCR is not kept within acceptable limits (Holdsworth et al, 2001; European Standard EN50160, 1994). If the SCR is small enough, the transient voltage dip will be limited, and the system will remain stable. So, the allowable ratio is set to a lower value, such as 6%. The value of SCR must be less than 10% as recommended in (European Standard EN50160, 1994). The SCRL has been expressed as:

$$\frac{P_{DG\,i}}{SCL_i \cdot Cos(\phi)} \times 100 \ \le \ 10\% \ , \quad \forall \ i \in N \tag{46}$$

where, SCL_i refers to the SCL at the *i*th bus, *Cos(Ø)* is the power factor at the generator, and *N* is the number of buses. This constraint has been considered in (Keane *et al*, 2007).

3.2.16 Voltage step limits (VSL): Voltage step change in the network occurs on sudden disconnection of a distributed generator. It has been implemented to security constrained optimal power flow (SCOPF) where contingency is an outage of a new DG (Dent *et al*, 2010). The voltage step constraint has been expressed as :

$$V_b - V_s^+ \le V_{n',b} \le V_b + V_s^+ \ , \quad \forall\ n' \in N \tag{47}$$

where, the terms used are an outage of generator (n'), contingency voltage at bus b ($V_{n',b}$) , pre-outage voltage (V_b), voltage step (V_s^+).

4. Mathematical Algorithm and Solution Techniques for DGP

The objective functions and the constraints are discussed in the preceding two sections as the optimization formulation of DGP. This section discusses the mathematical algorithm to solve the optimization-based DGP problem. The algorithms are classified into three groups. (1) Conventional methods such as linear programming, non-linear programming (AC optimal power flow, continuous power flow), mixed integer non-linear programming (MINLP), and analytical approach. (2) Intelligent searches as Simulated Annealing (SA), Evolutionary Algorithm, Tabu Search (TS), and Particle Swarm Optimization (PSO), Ant Colony System Algorithm (ACSA). (3) Fuzzy Set Theory (FST) to address technical and economic risk. The techniques used in literature for DGP are summarized in Table 1.

4.1 *Conventional methods*

4.1.1 *Linear programming* (LP):The LP-based technique is applied in (Keane *et al*, 2005; Abou et al, 2010; Keane *et al*, 2007) after formulating linear equation for constraints and objective functions. The LP approach has better convergence property, it can quickly identify infeasibility, and it accommodates large variety of power system operating constraints including contingency constraints. The LP method can handle only linear constraints and objective. Nonetheless, despite the number of advantages, its range of application in OPF field is restricted because of the inaccurate evaluation of system losses and inadequate capability to find the exact solution (Zhang *et al*, 2007)

4.1.2 *Nonlinear programming* (NLP): To solve a nonlinear programming problem, the first step in this method is to choose a search direction in iterative procedure, which is determined by the first partial derivatives of the equation (the reduced gradient). Therefore, these methods are referred to as the first-order method such as the generalized reduced gradient (GRG) method (Wu *et al*, 1979)].

The sequential quadratic programming (Keane *et al,* 2007) and Newton's method require the computation of the second order partial derivatives of the power- flow equations and other constraints (the Hessian) and are therefore called second order methods. The second order algorithm was implemented in (Rau *et al*, 1994) and computed the amount of resources in selected nodes to achieve desired optimizing objective i.e. minimization of losses. NLP implementations to large scale power system characteristically suffer from the following two major problems (Zhang *et al*, 2007) .

- Even though it has global convergence, which means the convergence can be guaranteed independent of the starting point, a slow convergence may occur because of zig zaging in search direction.
- Different "optimal" solutions are obtained depending on the starting point of the solution because the method can only find a local optimal solution.

4.1.3 Mixed-integer nonlinear programming (MINLP): The DGP can be formulated as a MNLP optimization method with integer variables with values of 0 and 1 to represent whether a new DG source should be installed. In (El-Khattam *et al*, 2005), the proposed model integrated comprehensive optimization model and planner's experience to achieve optimal sizing and siting of distributed generation. The model is formulated as mixed-integer-nonlinear in General Algebraic Modeling System (GAMS) (Brooke *et al*, 1998) using binary decision variables. In (Kumar *et al*, 2010), this approach was used to determine optimal location and number of DGs in pool as well as hybrid electricity market. The main contribution of work is: (i) to find most appropriate zone for DG placement based on real power nodal price and real power loss sensitivity index as an economic and operational criterion, (ii) to determine optimal location and number of distributed generators in the identified zone based on mixed-integer nonlinear programming-based approach, and (iii) to find the impact of demand variation. The optimization problem has been formulated in GAMS using SNOPT solver (Brooke *et al*, 1998). MATLAB and GAMS interfacing has been used to solve load flow at base case to obtain load flow data and other parameters required for modeling algebraic equation in GAMS (Ferris, 1999). In (Atwa *et al,* 2010), a probabilistic-based planning technique was proposed for determining the optimal fuel mix of different types of renewable DG units (i.e. wind–based DG, solar DG, and biomass DG) in order to minimize the annual energy losses without violating the system constraints. The problem was formulated as MINLP, taking into consideration the uncertainty associated with the renewable DG sources as well as the hourly variations in the load profile.

4.1.4 Optimal Power Flow-based Approach (OPFA): The references (Harrison *et al*, 2005; Gautam *et al* , 2007; Jabr *et al*, 2009; Algarni *et al*, 2009; Vovos *et al*, 2005; Vovos *et al*, 2005; Harrison *et al*, 2007; Harrison *et al*, 2008; Dent *et al*, 2010; Dent *et al*, 2010) have implemented optimal power flow mechanism for DGP. In (Harrison *et al*, 2005), optimal power flow (OPF) has been implemented considering 'reverse load-ability' approach to maximize capacity of DG and identify available headroom on system within the imposed thermal and voltage constraints. In (Gautam *et al* , 2007), the traditional OPF algorithm for cost minimization is modified to incorporate the demand bids, in addition to the generation bids. Locational Marginal Price (LMP) is determined as the Lagrangian Multiplier of the power balance equation in OPF. The base case OPF based on social welfare maximizing algorithm evaluated the generation dispatch, demand and prices at each of the nodes. The nodal prices so obtained are indicator for identifying candidate nodes for DG placement. The placement is intended to meet the demand at a lower price by changing the dispatch scenario. In (Algarni *et al*, 2009), the goodness factors of DG units are integrated directly into the distribution system operation model based on OPF framework for incremental contribution of DG unit to active and reactive power losses termed as incremental loss indices (ILI). The works in (Jabr *et al*, 2009; Vovos *et al*, 2005; Vovos *et al*, 2005) deal with generation capacity allocation considering additional constraints imposed by the power system tolerance to fault levels using optimal power flow mechanism. Authors in (Harrison *et al*, 2007; Harrison *et al*, 2008) used OPF with genetic algorithm DG capacity evaluation. In (Dent *et al*, 2010) voltage step constraints have been incorporated within an established OPF based method for determine the network capacity of network to accommodate DG. In (Dent *et al*, 2010), the maximization of total generation has been assessed under network security constraints using an OPF model which was solved by gradually adding limited numbers of line outage contingencies, until a solution to the complete problem is obtained. Apart from above OPF-based method also has been used in (Dent *et al,* 2010) for evaluating the maximum capacity of variable DG.

4.1.5 Analytical approaches (AA): Various analytical methods have been formulated in (Wang *et al*, 2004; Acharya *et al*, 2006; Gözel *et al*, 2009; Hung *et al*, 2010) for placement of DG with their optimal size in distribution network.

In (Wang *et al,* 2004), goal is to find the optimal bus, where objective function reaches its minimum value. The steps are as follows.

- Admittance matrix is calculated without DG, then admittance matrix, impedance matrix, and equivalent resistances are calculated for different DG location.
- Objective function values for DG are calculated at different buses to find the optimal bus m.
- If all the voltages were in acceptable range when the DG is located at bus m, then bus m is optimal site.
- If some bus voltage does not meet the voltage rule, then move the DG around bus m to satisfy the voltage rule.
- If there is no bus that can satisfy the voltage regulation rule, then try a different size of DG and repeat the procedure.

In (Acharya *et al*, 2006) , authors used the concept that approximate loss follows the same pattern as calculated by accurate load flow. Using this concept load flow analysis required only two times, one for the base case and another at the end with DG to obtain the final solution. The optimum size of DG for each bus is calculated using equation obtained by equating the rate of change of losses with respect to injected power to zero. Then approximate loss is computed for each bus by placing DG of optimum size. The bus corresponding to minimum loss will be the optimum location. After that the load flow analysis with DG gives the final result.

In (Gözel *et al*, 2009), the method is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which were developed based on the topological structure of distribution systems and is widely implemented for load flow analysis of distribution system. The proposed method requires only one base case load flow. To determine the optimum size the formula was derived as the derivative of the total power losses per each bus injected real powers equated to zero. The optimum size DG is placed at each bus and loss is calculated. The bus corresponding to minimum power loss will be the optimum location if approximate bus voltages are within limit otherwise omit DG from that bus and choose next higher loss bus and voltages are checked for acceptable limit to find optimum location.

In (Hung *et al*, 2010) , authors developed a comprehensive formula by improving the analytical method proposed in (Acharya *et al*, 2006) to find the optimum sizes and optimal location of various types of DG. Authors considered four major types of DG based on their terminal characteristics in terms of real and reactive power delivering capability.

4.1.6 Continuation power flow (CPP): The method for placement of DG based on the analysis of power flow continuation and determination of most sensitive buses to voltage collapse is described in (Hedayati *et al*, 2008). According to procedure, most sensitive bus to voltage collapse or maximum loading is determined by executing the continuous power flow program. After determination of sensitive bus, one DG unit with certain capacity is installed on that bus. After installation of the DG unit, the power flow program is executed and the objective function is calculated. If the estimation of objective function is inappropriate, then algorithm would iterate till the objective function is estimated.

4.2 Intelligent search-based methods

The heuristic methods based on intelligent searches have been implemented in DGP to deal with local minimum problems and uncertainties. These methods are also being combined with conventional optimization methods and fuzzy set theory to solve DGP problem.

4.2.1 Simulated annealing (SA): Simulated Annealing (SA) is a process in which the optimization problem is simulated an annealing process. It has the ability of escaping local minima by incorporating a probability function in accepting or rejecting new solutions. SA was introduced by Kirkpatrick, Gelatt, and Vecchi in 1983 (Vidal, 1993). Due to its implementation simplicity and good results, its use has been growing since mid 80s (Roa-Sepulveda *et al*, 2003). In (utthibun *et al,* 2010), authors presented a model to determine the optimal location and size of DG in order to minimize the electrical loss, emission, and contingency using SA as optimization tool. The initial temperature and cooling procedure are of paramount important for the good use of SA. The algorithm is based on initialization, perturbation, cooling schedule, and acceptance probability.

4.2.2 Evolutionary algorithms (EAs): An EA is different from conventional optimization methods and it does not need to differentiate cost function and constraints. EAs are population based optimization process and converge to the global optimum solution with probability one by a finite number of evolution steps performed on a finite set of possible solutions (Goldberg , 1989; Pham *et al*, 2000). EAs, including Evolutionary Programming (EP), Evolutionary Strategy (ES), and Genetic Algorithm (GA) are artificial intelligence methods for optimization based on natural selection, such as mutation, recombination, crossover, reproduction, selection etc. Mutation randomly perturbs a candidate solution; recombination randomly mixes their parts to form a novel solution; crossover involves choosing a random position in the two strings and swapping the bits that occur after this position; reproduction replicates the most successful solutions found in a population; whereas selection purges poor solutions from a population.

These methods share many similarities. The EP is introduced first, and followed by ES and GA (Goldberg, 1989; Lai *et al*, 1996). The simple and improved versions of EAs have been implemented in literature for DGP considering single and multi-objective function subjected to different constraints. The possibility to solve efficiently the optimal siting and sizing of distributed generators through GA was demonstrated in (Silvestri *et al*, 1999). Improved Herefoord Ranch Algorithm (HRA) was implemented with single objective function to minimize the active power loss and compared with Second-order method, simple GA (SGA), HRA, improved SGA in (Kim *et al*, 1998). GA has been used in (Popović *et al*, 2005; Singh *et al*, 2009; Singh *et al*, 2008; Harrison *et al*, 2007) to handle single objective. It has been used in (Celli *et al*, 2005; Carpinelli *et al*, 2005; Singh *et al*, 2009; Abou *et al*, 2010; Rodriguez *et al*, 2009) to handle multi-objective (MO) model including ε-constraint technique in (Celli *et al*, 2005; Carpinelli *et al*, 2005) for DGP problem. In (Kumar *et al*, 2010), the DG integration approach with MO model was implemented for service restoration under cold load pickup using GA. GA has also been used to evaluate the DG impact on reliability along with DG planning (Popović *et al*, 2005; Teng *et al*, 2002; Borges *et al*, 2006). GA combined with OPF has also been used in DGP. In (Harrison *et al*, 2007; Harrison *et al*, 2008), authors have emphasized that GA combined with Optimal power flow provide the best combination of sites within a distribution network for connecting a predefined number of DGs. In (Ochoa *et al*, 2008), a multi-objective programming approach based on non-dominated sorting genetic algorithm (NSGA) is applied in order to find configuration that maximize the integration of distributed wind power generation(DWPG) while satisfying voltage and thermal limit.

4.2.3 Tabu search algorithm (TSA): The TS algorithm was first developed by Glover and Hansen both in 1986 for solving combinatorial optimization problems (Pham *et al*, 2000). It is an efficient combinatorial method that can achieve an optimal or suboptimal solution within a reasonably short time. It does not need many iteration counts to obtain better solution. It is able to eliminate local minima to search area beyond local minima. It is based on moves, neighborhood, tabu list, aspiration, intensification, and diversification. In (Golshan *et al*, 2006) the TS was implemented to determine the installation locations, sizes and operation of Distributed generation resources (DGRs) and reactive power sources (RPSs) in a distribution system along with tap positions of voltage regulators (VRs) and network configuration. In the algorithm various memory structures such as short, intermediate and long term memories have also been used. In this work forbidden moves are introduced to tabu lists by recording numbers that corresponds exclusively to each forbidden move.

In (Nara *et al*, 2001), the tabu search application for finding the optimal allocation of DGs from a view point of loss minimization has been illustrated. To simplify the algorithm, the determination algorithm of the allocation of DGs and the search algorithm of the sizes of DGs were disconnected, and decomposition / coordination technique was introduced in the algorithm.

4.2.4 Particle swarm optimization (PSO): Particle Swarm Optimization (PSO) is population based optimization method first proposed by Kennedy and Eberchart in 1995, inspired by social behavior bird flocking or fish schooling (Kennedy *et al*, 1995).The PSO was applied to different areas of electric systems (Valle *et al*, 2008; Al-Rashidi *et al*, 2009) . It is population based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience (This value is called Pbest), and according to the experience of a neighboring particle (This value is called Gbest), made use of the best position encountered by itself and its neighbor. In (Krueasuk *et al*, 2005), the PSO method has been implemented to determine the optimal location and sizes of multi-DGs to minimize the total real power loss of the distribution systems. A two-stage methodology was used for the optimal DG placement in (Lalitha *et al*, 2010). In the first stage, fuzzy approach was used to find the optimal DG locations and in second stage, PSO was used to find the size of the DGs corresponding to maximum loss reduction.

4.2.5 Ant colony system algorithm (ACSA): Ant colony algorithms are based on the behavior of social insects with an exceptional ability to find the shortest paths from the nest to the food sources using a chemical substance called pheromone (Dorigo *et al*, 2004). ACS is the extended from of ant colony optimization (ACO), and it has a better performance than ACO in most engineering applications (Chu *et al*, 2004; G´omez *et al,* 2004; Teng *et al*, 2003; Vlachogiannis *et al*, 2005). In (Wang *et al*, 2008) , authors used ACS algorithm to optimize the re-closer (or DG) placement for a fixed DG (or re-closer) allocation to enhance the reliability and suggested that idea can be extended to the simultaneous placement of both re-closers and DGs.

4.3 Fuzzy set theory (FST)

The concept of fuzzy set theory was introduced by Zadeh (Zadeh, 1965) as a formal tool for dealing with uncertainty and soft modeling and widely used in power systems (Momoh *et al*, 1995). A fuzzy variable is modeled by a membership function which assigns a degree of membership to a set. Usually, this degree of membership varies from zero to one.

The data and parameters used in DGP are usually derived from many sources with a wide variance in their accuracy. For example, load is considered as known and specified in almost all methods, in spite of having a high uncertainty. In addition electricity market price, cost of DG, peak power saving etc. may be subjected to uncertainty to some degree. Therefore, uncertainties due to insufficient information may generate uncertain region of decisions. Consequently, the validity of the results from average values cannot represent the uncertainty level. To account for the uncertainties in information and goals related to multiple and usually conflicting objectives in DGP, the use of fuzzy set theory may play a substantial role in decision-making.

The fuzzy sets may be assigned not only to objective functions, but also to constraints (Kim *et al*, 2002; Haghifam *et al*, 2008; Lalitha *et al,* 2010; Ekel *et al*, 2006). In (Kim *et al*, 2002), power loss costs of distribution systems was taken as objective function, and number or size of DGs and deviation of voltage were taken as constraints. This objective function and constraints were transformed into multi-objectives functions and modeled with fuzzy sets to evaluate their imprecise nature. The authors obtained compromise solution of multi-objectives and imprecise information using goal programming and GA. In (Haghifam *et al*, 2008), multi-objective model consists of monetary cost index, technical risk and economic risk. In (Lalitha *et al,* 2010), authors implemented fuzzy set theory in power loss index (PLI) and nodal voltage to obtain DG suitability index (DSI) as output. The modeling of uncertainty in load, voltage and loading constraints can be implemented as (Popovic *et al*, 2004; Ramirez-Rosado *et al*, 2004; Haghifam *et al*, 2007) .The multi-objective allocation of resources has been done using Bellman-Zadeh approach and developed corresponding Adaptive Interactive Decision-Making System(AIDMS) in (Ekel *et al*, 2006). In (Haghifam *et al*, 2008), the objects were the minimization of technical and economic risks, and operation and planning costs. A fuzzy approach was used for the modeling of load and electricity price uncertainties and related risks. To solve this multi-objective problem, the concept of Pareto optimality, based on non-dominant sorting genetic algorithm (NSGA-II) (Deb *et al*, 2000), was used.

Fuzzy Set Theory enables the integration of the effects of parameters uncertainties into the analysis, offers a better compromised solution, and eliminates the need for many simulation runs (El-Khattam *et al*, 2004). The fuzzy set methods offer the decision maker with alternatives for selecting the location and size of DG.

Table 1. Summery of techniques used in literature

Techniques	References
Linear programming(LP)	Keane *et al*, 2005; Abou *et al*, 2010; Keane *et al*, 2007.
Non-linear programming (NLP)	Rau *et al*, 1994.
Mixed-integer non linear programming(MINLP)	El-Khattam *et al*, 2005 ; Kumar *et al*, 2010 ; Zhang *et al* 2007.
Optimal power flow-based approach (OPFA)	Harrison *et al*, 2005; Gautam *et al* , 2007; Jabr *et al*, 2009; Algarni *et al*, 2009; Vovos *et al*, 2005; Vovos *et al*, 2005; Harrison *et al*, 2007; Harrison *et al*, 2008; Dent *et al*, 2010; Dent *et al*, 2010; Dent *et al,* 2010.
Analytical analysis(AA)	Wang *et al*, 2004; Acharya *et al*, 2006; Gözel *et al*, 2009; Hung *et al*, 2010 .
Continuous power flow(CPF)	Hedayati *et al*, 2008 .
Simulated annealing(SA)	Sutthibun *et al,* 2010 .
Evolutionary algorithms(EA)	Kim *et al*, 1998; Popović *et al*, 2005; Singh et al, 2009; Celli *et al*, 2005; Carpinelli *et al*, 2005; Celli *et al*, 2005; Carpinelli *et al*, 2005; Haghifam *et al*, 2008;Singh *et al*, 2009; Abou *et al*, 2010 ; Kumar et al, 2010; Kim *et al*, 2002; Haghifam *et al*, 2008;Singh *et al*, 2008; Harrison *et al*, 2007; Harrison *et al*, 2008; Teng *et al*, 2002; Borges *et al*, 2006 ; Ochoa *et al*, 2008; Rodriguez *et al*, 2009.
Tabu search algorithm(TSA)	Golshan *et al*, 2006 ; Nara *et al*, 2001
Particle swarm optimization(PSO)	Krueasuk *et al*, 2005 ; Lalitha *et al*, 2010.
Ant colony system algorithm(ACSA)	Wang *et al*, 2008.
Fuzzy set theory(FST)	Kim *et al*, 2002; Haghifam *et al*, 2008; Lalitha *et al,* 2010; Ekel *et al*, 2006.

5. Conclusion

The general background, objectives, constraints, and solution algorithms of Distributed Generation Planning (DGP) have been discussed. The objectives have been classified as single objective, comprehensive objective and multi-objective. In literature, different types of objective functions have been optimized for DGP using different conventional and artificial intelligent methods. The constraints have been classified as equality and inequality constraints. There are two types of equality constraints and sixteen types of inequality constraints. The techniques implemented in literature of DGP are summarized in Table 1. The Objectives, constraints, load level, systems, numbers of DGs, and algorithms, used in literature, are summarized in Table 2 and 3. The single and multi-objective functions, subjected to different operating constraints, have been studied by number of authors for optimal DGP. As a typical optimization problem, DGP may be solved with conventional optimization algorithms like LP, NLP, or MINLP. Due to the nonlinearity of power systems, LP loses accuracy due to linear assumptions. Consideration of nonlinear algorithms and integer variables will make the running time much longer and the algorithm possibly less robust. The algorithms based on intelligent searches such as SA, EA, TS, PSO, and ACSA can address the integer variable very well. SA provides better solution but it requires excessive computation time. GA is capable of evaluating a solution near global minima computationally intensive. TS is an efficient combinatorial method that can achieve an optimal or sub optimal solution within a reasonably short duration. The PSO and ACSA have not been paid much attention. However, these are more heuristic than conventional optimization techniques and needs further investigation regarding performance on different larger systems with their improved versions. Another interesting aspect is to include fuzzy set theory to model the uncertainties in objective function, load, generation, electricity price, and constraints for better compromised solution.

Appendix

Table 2. Summery of objectives, load models, and DG locations considered in literature for DGP using conventional techniques

Techniques	References	Objective, (Constraints)	Load Model And System	DG Locations
LP	Keane *et al*,2005	Maximize DG capacity.(BVL , LTL, STCL, SCLL, DGAPGL,SCRL)	One load level and Irish 6 bus system	multiple
	Abou *et al*, 2010	Minimize multi-objective including voltage profile improvement, spinning reserve increase, power flow reduction in critical lines and total line loss reduction. (APBL, BVL, LTL, TAPGL, DGAPL, NDGL,)	One load level and 8 bus system	single
	Keane *et al*, 2007	Maximize the amount of DG energy harvested. (LTL, SCLL, SCRL, STCL)	One load level and 8 bus system	multiple
NLP	Rau *et al*, 1994	Minimize real power loss (unconstrained)	One load level and 6 bus system	Multiple
MINLP	El-Khattam *et al*, 2005	Minimize cost of investment and operation of DGs, losses cost and cost of purchasing power by DISCO from grid. (APBL, RPBL, BVL, LTL, STCL, DGAPGL, DGRPGL, IDPL)	One load level and 9 bus system.	Multiple
	Kumar *et al*, 2010	Minimize total fuel cost of DG and conventional generators, and Line losses(BVL, PAL, APBL,RPBL, LTL,TAPGL,TRPGL, NDGL, DGAPGL, DGRPGL)	One load level and IEEE 24 bus system	Single and multiple
	Atwa *et al*, 2010	Minimize annual energy loss. (VBL,LTL,APBL,RPBL,DGAPGL)	Variable load(42 bus system)	Multiple(Mix sources)
OPF-Based	Harrison *et al*, 2005	Maximize DG capacity.(BVL)	Multi load level and 9 bus system	Multiple
	Gautam *et al*, 2007	Maximize social welfare and profit. (BVL, APBL,RPBL, LTL,TAPGL,TRPGL)	One load level and 9 bus system	Single
	Jabr *et al*, 2009	Maximize DG capacity and minimize loss. (BVL, LTL,APBL,RPBL,TAPGL,TRPGL, PFL)	One load level ,and 69 bus system	Multiple
	Algarni *et al*, 2009	For disco owned:	One load level and	Multiple

OPF-Based		Minimize cost of active and reactive power from substation bus, cost of active and reactive power from DG, and cost of DG active and reactive power in conjunction with goodness factor. For investor owned: Minimize cost of active and reactive power from substation bus, cost of energy purchased from DG, and cost of DG active and reactive power in conjunction with goodness factor. (BVL, LTL, TAPGL, TRPGL, DGAPGL, DGRPGL)	18 & 69 bus system	
	Vovos *et al* 2005	Maximize the new generation capacities and energy export. (BVL,DGAPGL,PFL,LTL,IDPL)	One load level and 12 bus system	single
	Vovos *et al*, 2005	Maximize the new generation capacities and energy export. (BVL,PFL,LTL, STCL)	One load level, and 12 bus system	multiple
	Harrison *et al,* 2007	Maximize DG capacity. (BVL,LTL,PFL, DGAPGL)	One load level, and 69 bus system	multiple
	Harrisson *et al,* 2008	Maximize incentive to DNO by optimizing DG capacity and loss reduction(VBL,PFL,LTL)	One load level, and 69 bus system	multiple
	Dent *et al,* 2010	Maximize total DG active power capacity (VSL, BVL, DGAPGL ,and usual OPF constraints)	One load level, and 10 bus system of U. K. distr. Sys.	multiple
	Dent *et al* , 2010	Maximize total DG active power capacity (Usual OPF constraints for each contingency)	One load level , and IEEE 73-bus system consists of three area	multiple
	Keane *et al,* 2010	Maximize DG capacity (VBL,LTL,APBL,RPBL,STCL)	One load level(UK GDS network)	Multiple(variable)
AA	Wang *et al*, 2004	Minimize real power losses. (BVL)	Time-varying and Time-invariant load, 6 & 30 bus system	Single
	Acharya *et al,* 2006	Minimize real power loss. (unconstrained)	One load level and 30,33 &69 bus system	Single
	Gozel *et al,* 2009	Minimize real power loss. (BVL)	One load level and 12 bus system	single
	Hung *et al*, 2010	Minimization of loss(VBL,DGAPGL)	One load level (16,33, and 69 test system)	Multiple(mix sources)
CPF	Hydayati *et al,* 2008	Minimize real power loss. (BVL)	One load level and 34 bus system	Multiple

Table 3. Summery of objectives, load models, and DG locations considered in literature for DGP using AI techniques

Techniques	References	Objective, (Constraints)	Load Model And System	DG Locations
SA	Sutthibun *et al*, 2010	Minimize multi-objective function includes power loss, emission, and severity index, (APBL, TAPGL)	One load level and 33 bus system	multiple
HHRA	Kim *et al,* 1998	Minimize real power loss, (BVL)	One load level and	Multiple

				6,14 and 30 bus system	
EA	GA	Popovic *et al,* 2005	Maximize DG capacity (BVL, LTL, DGAPGL, DGRPGL, SCLL, TLLL)	Multi-load level and 75 bus system	Multiple
		Singh *et al*, 2009	Minimize real power loss(APBL, RPBL, BVL)	Multi load level and 30 bus system	Single and multiple
		Singh *et al,* 2009	Minimize performance indices include real power loss, reactive power loss, line power flow, and node voltage, (APBL, BVL, LTL)	Constant, residential, industrial and commercial load models and 16 & 37 bus system	Single
		Abou *et al,* 2010	Minimize multi-objective function includes voltage profile improvement, spinning reserve increase, power flow reduction in critical lines and total line loss reduction, (APBL, BVL, LTL, TAPGL, DGPL, NDGL,)	One load level and 8 bus system	single
		Kumar *et al,* 2010	Minimize multi-objective function includes Load to be curtailed, bus voltage violation, branch current violation, substation transformer over loading, (BVL, LTL, STCL, DGAPGL, DGRPGL)	One load level and 33bus system	multiple
		Kim *et al,* 2002	Minimize power loss cost, (BVL,DGPGL,APBL)	Multi load level, and 12 bus system	multiple
		Silvestri *et al,* 1999	Minimize sum of cost of power loss, network reinforcement and energy production cost, (not mentioned)	One load level, and 43 and 93 bus systems	single
		Singh *et al,* 2008	Minimize real power loss (BVL, LTL)	Multi load level, and 16, 37, and 75 bus system	single
		Lalitha *et al,* 2010	Minimize real power loss, (BVL , LTL)	One load level, and 33 bus system	multiple
		Harrison *et al,* 2007	Maximize DG capacity, (BVL,LTL,PFL, DGAPGL)	One load level, and 69 bus system	multiple
		Harrisson *et al*, 2008	Maximize incentive to DNO by optimizing DG capacity and loss reduction, (VBL,PFL,LTL)	One load level, and 69 bus system	multiple
		Teng *et al*, 2002	Maximize the DG benefit cost ratio (BCR), (BVL, LTL)	One load level, and 40 bus system	multiple
		Borges *et al,* 2006	Maximize the DG benefit cost ratio, (BCR), (BVL, DGAPGL	One load level , and 39 bus system	Single
	SPEA2	Rodriguez *et al*, 2009	Minimize multi-objective function includes annual DG dispatched energy for local ancillary, annual DG curtailed energy, CO_2 emission, and voltage quality index, (VBL,LTL, DGAPGL)	Stochastic load(UKGDS radial network)	single
	GA and ε-constrained Method	Celli *et al,* 2005	Minimize multi-objective function include cost of network upgrading, energy purchased, energy losses and energy not supplied, (as per ε- constrained method)	Peak load with constant growth rate and 78 bus system	Multiple
	GA and ε-	Carpinelli *et al,*	Minimize multi-objective function include	Peak load with	Single

EA	constrained method	2005	cost of energy losses, improvement in voltage quality and harmonic distortion, (as per ε- constrained method)	constant growth rate and 18 bus system	
	NSGA	Haghifam *et al,* 2008	Multi-objective function are in three groups: (i) cost (ii) technical risk (iii) technical risk. Minimize multi-objective function include (i) Cost of energy losses, investment cost of DG units; operation and maintenance cost; (ii) substation loading, line loading; voltage. (iii) cost of power purchased from grid, cost of power generated by DG, (BVL, LTL)	Aggregated load and 9 bus system	multiple
		Ochoa *et al,* 2008	Multi-objective functions are to maximize energy export, minimize real power loss, and minimize single phase short circuit level, (VBL, LTL)	Time varying load(33 bus system)	Single (variable)
TS		Golshan *et al*, 2006	Minimize cost function including cost of power loss at peak load time, cost of fuel served for energy loss and the cost of reactive sources, (APBL, BVL, TAPGL, TRPGL,TPL)	Peak load and multi load level ,and 33 & 69 bus system	Multiple
		Nara *et al,* 2001	Minimize real power loss, (DGAPGL, DGRPGL, NDGL)	Multi load level , and 28 sections and 78 sections	multiple
PSO		Krueasuk *et al*, 2005	Minimize total real power loss, (BVL, LTL, APBL)	One load level, and 33 and 69 bus systems	multiple
		Lalitha *et al,* 2010	Minimize real power loss, (BVL , LTL)	One load level, and 33 bus system	multiple
ACSA		Wang *et al*, 2008	Optimize Multi-objective function consists of SAIFI and SAIDI, (target value of SAIFI and SAIDI)	One load level, and 39 and 394 bus system	multiple
Fuzzy set theory		Haghifam *et al,* 2008	Multi-objective function are in three groups: (i) cost (ii) technical risk (iii) technical risk. Minimize multi-objective function include (i) Cost of energy losses, investment cost of DG units; operation and maintenance cost; (ii) substation loading, line loading; voltage. (iii) cost of power purchased from grid, cost of power generated by DG, (BVL, LTL)	Aggregated load and 9 bus system	multiple
		Kim *et al,* 2002	Minimize real power loss cost, (BVL, DGAPGL, APBL)	Multi load level, and 12 bus system	multiple
		Lalitha *et al,* 2010	Minimize real power loss, (BVL , LTL)	One load level, and 33 bus system	multiple

Note:

APBL =	Active power balance limit,	TAPGL =	Traditional active power generation limit	IDPL =	Intertie delivery power limit
RPBL =	Reactive power balance limit,	TRPGL =	Traditional reactive power generation limit,	TLLL =	Total line loss limit
BVL =	Bus voltage limit,	STCL =	Substation transformer capacity limit,	SCRL =	Short circuit ratio limit
LTL =	Line thermal limit,	DGAPGL=	DG active power generation limit,	PFL =	Power factor limit
PA,,L =	Phase angle limit,	DGRPGL=	DG reactive power generation limit,	TPL =	Tap position limit
SCLL =	Short circuit level limit,	NDGL =	Number of DG limit,	VS L =	Voltage steep limit

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Biographical notes

Rejendra Prasad Payasi received the B.E. degree from Govt. Engineering College, Rewa (M.P.), India, in 1980, the M. Tech. degree in Electrical Engineering from Institute of Technology (IT), Banaras Hindu University (BHU), Varanasi, India , in 1983. Currently he is pursuing the Ph. D. degree in Electrical Engineering under QIP from Motilal Nehru National Institute of Technology, Allahabad, India. He is associate Professor with the Department of Electrical Engineering, Kamla Nehru Institute of Technology, Sultanpur (U.P.), India. His research interests are distributed generation planning and distribution system analysis.

Asheesh K. Singh received the B.Tech. degree from HBTI, Kanpur, India, the M.Tech. degree from the REC, Kurukshetra, India, and the Ph.D. degree from the Indian Institute of Technology, Roorkee, India, in 1991, 1994, and 2007, respectively. Since 1995, he has been on the academic staff of MNNIT, Allahabad, India, where he is now Associate Professor with the Department of Electrical Engineering. His research interests are application of soft computing techniques in power systems, distributed generation, power quality and reliability.

Devender Singh received the B. E. degree in electrical engineering from Sardar Vallabhbhai National Inatitute of Ttechnology, Surat, India, in 1993, the M.E. Degree in electrical engineering from Motilal Nehru National Institute, Allahabad India, in 1999, and Ph.D. in electrical engineering from Institute of Technology (IT), Banaras Hindu University (BHU), Varanasi, India. Presently, He is Professor with the Department of Electrical Engineering, IT, BHU. His research interests are distributed generation planning, state estimation, short term forecasting, and AI application in power system.

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