A New Particle-Swarm-Based Algorithm for Distribution System Expansion Planning Including Distributed Generation

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Abstract
Distributed Generation (DG) is a new approach in the electricity industry to meet the electrical demand growth in a suitable manner. This paper presents a solution method for the distribution expansion panning problem including DG. The proposed algorithm is based on binary particle swarm optimization. The aim of the model is to find the optimal planning of the expansion to meet the load growth. This optimal cost includes the capital cost, the substation operational cost, feeder upgrade, power losses and the DG's. The proposed model decides the locations and size of the new facilities in the system as well as the amount of the purchased power from the main grid. The results show that the DG's introduce economical and electrical benefits to the system including improved voltage profile, feeders loading and losses

Keywords
Distribution system, planning, optimization, particle swarm, distributed generation

1. Introduction
Electric utilities have historically satisfied customer demand by generating electricity centrally and distributing it through an extensive transmission and distribution network. As demand increases, the utility generates more electricity. Once demand increases beyond a certain level, however, the capacity of the generation, transmission, and distribution systems can become constrained. The traditional utility response to these constraints is to build new facilities including generators, transmission, substations and distribution network [1-25]

An alternative approach under consideration by utilities is to satisfy demand locally and incrementally by investing in distributed generation. DG facilities are strategically sited to deliver electricity where it is needed. This can relieve capacity constraints on the generation, transmission, and distribution systems and obviate the need to build new facilities [15-25].

Different definitions regarding DG are used in the literature and in practice. These variations in the definition can cause confusion. A more generalized definition is proposed by Ackermann et al as follow; Distributed Generation is an electric power source connected directly to the distribution network or on the customer site of the meter [15].

Generally, DG can be best fitting into different applications, including; emergency or back-up supply, peak loads, consumer's complete requirements, shortage of generation, and combined with most of the other possible applications.

Therefore, the proper allocation of distributed generation may lead to the following system support benefits: Loss reduction, Improved utility system reliability, Voltage support and improved power quality, Transmission and distribution capacity release

and Deferments of new or upgraded TBD infrastructure

2. Discussion of the Problem

2.1 Problem Description
When the planning analysis predicts that the voltage will be too low or the current in a line or substation transformer will be too high in any node, investment in new capacity is required. Investment options are usually restricted to substation or feeder expansion. Planners then consider a few feasible alternatives for solving the problem and select the one that best meets their performance and cost objectives. This requires an established rule base. From experience, planners have learned that when the loading reaches a certain level, it is generally economical to build new capacity. The rules also state what capacity options to consider under which loading scenarios. This method works well when capacity options are limited to familiar choices (feeders, substations, etc.) and the economic environment is stable [1-14].

Given the value of the total operating costs, the planner makes investment decisions to improve the system and reduce costs. The planner selects from a menu of options that includes everything from traditional substation and feeder upgrades to DG. For each investment decision considered, the simulation and costing process is repeated. This process has the advantage of being able to fairly compare diverse expansion plan options on the same economic basis. Including DG in the simulations will allow the planner to directly evaluate the benefits of DG in comparison with other more traditional alternatives [15-25].

The previous trial and error process can be formulated mathematically as a nonlinear optimization problem with an objective function subjected to some constraints.

2.2 Problem formulation
The following sections describe the details of the proposed problem formulation:

2.2.1 The objective function
The proposed objective function for distribution system expansion will be considered as the sum of four terms: Cost of substation expansion (fixed & variable);

Cost of the new feeders upgrades (fixed); Cost of the distributed generation DG's (fixed & variable); and Cost of the energy losses (variable) [22,24].
The fixed cost is the investment cost includes the cost of the construction, equipments, labor … etc.
The variable cost is the cost of operation and maintenance of equipments and It mainly depends on equipments loading.
The mathematical formulation of the objective function [22, 24] is described in equations (1-5)

Minimize capital investment and operational cost

$$J = C_U + C_{DG} + C_F + C_L \quad (1)$$

Where

C_U =capital and operation cost for substation expansion

$$C_U = \sum_{i=1}^{TN}\sum_{u=1}^{TUi} C_{i,u}\sigma_{i,u} + 8760\sum_{t=1}^{T}\beta^t (\sum_{i=1}^{TN}\sum_{u=1}^{TUi} pf.C_e.S_{i,u}) \quad (2)$$

C_{DG}= capital and operation cost for DG

$$C_{DG} = \sum_{i=1}^{M} C_{fi}(S_{DGi}^{MAX} + BK)\sigma_{DGi} + 8760\sum_{i=1}^{T}\beta^t\sum_{i=1}^{M}(C_{ri}S_{DGi}) \quad (3)$$

C_F = capital cost for upgrading the feeders

$$C_F = \sum_{i=1}^{TN}\sum_{j=1}^{M} C_{ij}\sigma_{ij} \quad (4)$$

C_L= *cost of energy losses*

$$C_L = 8760\sum_{i=1}^{T}\beta^t (\sum_{i=1}^{TN}\sum_{j=1}^{M}\frac{\Delta V_{ij}^2}{|Z_{ij}|}.pf.C_e) \quad (5)$$

$$\beta^t = \frac{1}{(1+d)^t}$$

2.2.2 Constraints

The following constraints are considered in this work:
1) Total Power Conservation:
The summation of all incoming and outgoing power over the feeders, taking into consideration the feeder's losses and the power supplied by DG, if it exists, should be equal to the total demand at that bus.

$$\sum_{i=1}^{TN}(S_{ij} - \frac{\Delta V_{ij}^2}{|Z_{ij}|}) - \sum_{i=1}^{M} S_{ji} + S_{DGi} = D_j \quad (6)$$

2) Distribution Feeder's Thermal Capacity:
Power flow in feeders must be within their capacities.

$$S_{ij} \le S_{ij}^{MAX}\ \sigma_{ij} \quad (7)$$

3) Distribution Substation's Capacity:
The summation of total power delivered by the substation's transformers to the network must be within the substation's capacity limit.

$$\sum_{j=1}^{M} S_{Uij} \le S_{Ui}^{MAX} \quad (8)$$

4) DG Operation Limits:
The DG's generated power must be within the DG's capacity.

$$S_{DGi} \le S_{DGi}^{MAX}.\sigma_{DGi} \quad (9)$$

5) Voltage Drop Limits:
The voltage level at different buses must be within predetermined value

$$|V_i - V_j| \le \Delta V \quad (10)$$

3. Solution method

3.1 Methodology

The problem of distribution system expansion planning is modeled as a nonlinear optimization problem. A binary particle swarm based algorithm is used to optimize the capital investment and operational cost in new facility capacities (substation, feeders and DGs). The proposed model decides the capacity and location of the new facilities as well as the substation expansion and imported power from the grid through the system.
Two different scenarios may be applied to find the optimal expansion planning for the distribution system under study:
Scenario 1: consider the installation of DG units only to optimally cover the load demand with improved system performance.
Scenario 2: consider the installation of DG units in addition to expanding the existing substations (installing new transformers and feeders) to optimally cover the load demand with improved performance

3.2 Particle Swarm Algorithm

The particle swarm optimization algorithm (PSO) was introduced by James Kennedy and Russell Eberhart [6] in 1995 inspired by social behavior of bird flocking or fish schooling. PSO is a population-based heuristic search technique in which each particle represents a potential solution within the search space and it is characterized by a position, a velocity and a record of its past performance [26-29].
In solving optimization problems with PSO, each single solution is a "bird" in the search space. We call it "particle". All of particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles.
The particle swarm optimization concept consists of, at each time step, changing the velocity (accelerating) each particle toward its *pbest* and *gbest* locations (global version of PSO). Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward *pbest* and *gbest* locations. [26]

3.3 Binary PSO

The Binary PSO algorithm (BPSO) was introduced by Kennedy and Eberhart [28] to allow the PSO algorithm to operate in binary problem spaces. The BPSO has a structure almost identical to the standard PSO, where the velocity is still defined to be in the continuous space. However, the BPSO does not regard the velocities as velocities, but rather uses it to define the probability that a bit flip will occur. The only changes to the standard PSO algorithm is that the position vector of the particle is a vector of binary digits, rather than a vector of continuous values, and that the position update equation

Where S(x) is the sigmoid function

$$S(x) = \frac{1}{1+e^{-x}} \qquad (11)$$

The BPSO is susceptible to sigmoid function saturation, which occurs when velocity values are either too large or too small. In such cases the probability of a change in bit value approaches zero, thereby limiting exploration. For a velocity of 0, the sigmoid function returns a probability of 0.5, implying that there is a 50% chance for the bit to flip. Velocity clamping will delay the sigmoid function saturation from occurring.

3.4 The Proposed BPSO Algorithm

3.4.1 Solution Coding

Population is composed of N particles, [X_1, X_2, . Xn]

Each particle contains **m** values (binary).

Xi (0) = [Xi (1), Xi (2), ……; Xi (m)]

The total number of coordinates (m) equals the total possible locations of the distributed generators (DG) and the total number of transformers at all buses.

$$m = N_{DG} \times M_{DG} + N_T \times M_T$$

m : Total number of coordinates

N_{DG} :Number of system buses for possible DG installation

M_{DG} : Maximum number of DG considered at each bus

N_T : Number of system buses for possible transformer expansion

M_T : Maximum number of transformers at each bus

M_T	M_T	$\cdots$	$\cdots$	M_{DG}	M_{DG}	$\cdots$	$\cdots$

N_T N_{DG}

Fig. 1 particle coding

3.4.2 The Proposed Algorithm Steps

The major steps for solving the problem under study using BPSO algorithm described as follow:

Step 1: Initialization

a. Set the time counter **t = 0**
b. Generate **n** random particles,
c. Generate randomly initial velocities of all particles
d. Check that each particle has feasible solution
e. Adjust (randomly) the particle coordinates to be feasible solution
f. Each particle in the initial population is evaluated using the objective function.
g. Run the power flow
h. Check the feeder's thermal capacity.
i. If the feeder exceeds its capacity, go to step j, Otherwise, go to step k
j. Upgrade the feeders by replacing the feeder with higher capacity feeder.
k. Check the voltage for all buses. If the voltage is less than the minimum limit go to step j, else, go to step g
l. Add one DG unit at the buss. Go to step g
m. Check the voltage for all buses. If the voltage is more than the maximum limit go to step n, else, go to step m
n. Decrease the number of DG's at the bus by one unit. Go to step g
o. If the solution is feasible go to step q, Else, go to step p
p. Randomly adjust the solution to be feasible. Go to step g
q. Add the backup DGs. For each load if there is one or more DG then (BK=1), else (BK=0)
r. Evaluate the total cost

Step 2: Time updating

Update the time counter. t=t+1

Step 3: Velocity updating

Using the individual best and global best the velocity can be updated

Step 4: Position updating

The position is updated using the sigmoid function and keeping the position values to be either 1 or 0.

Step 5: Individual best updating

Each particle is evaluated according to the updated position and then updates individual best

Step 6: Global best updating

Search for the minimum value among the individual best then update the global best

Step 7: stopping criteria

If one of the stopping criteria satisfied then stop

4. Simulation Results

The system under study is shown in Fig. 2 and Tables 1 & 2 [8, 24]. It consists of one 132 KV/33 KV substation (40 MVA capacity) at bus 9 and eight loads (33 KV/11 KV service transformers) at buses 1-8 and four existing distribution feeders with a thermal capacity of 12 MVA and an impedance of Z=0.1738+j 0.2819 Ω/km. There is forecasted load growth of 28 % after 4 years of the base year and the power demand will be approximately 51.1 MVA. There should be a backup DG unit installed in case of any DG failure and for scheduled maintenance intervals. The system power factor is set to be 0.9 and the size of the DG's is multiple of 1 MVA. The maximum limit of the DG capacity at each bus is 4 MVA (4 DG units) plus the backup DG so that the percentage of the maximum DG power in the system is approximately 30% of the total peak demand. This limit is used to keep the concept of the DG not a centralized plant and take the most benefit from the existing substation and its sunk cost. The new transformer units used in case of substation expansion are two three phase 10 MVA transformers (132 KV/33 KV) .The system loads and the feeders characteristics are shown in table 1 and 2.

For the cost data, the electricity market price is considered to be 70 $/MWh for purchasing power from the main grid. The price of the DG unit is 0.5 M$/MVA and the running cost of the DG is assumed to be 50 $/MWh. The fixed cost of the new 10 MVA transformer is 0.2 M$. The cost of upgrading the feeders by adding parallel feeder to the existing feeder with same capacity is 0.12 M$/km. The discount rate is considered to be 12.5%. The total system demand is also shown in Fig.2. [24]

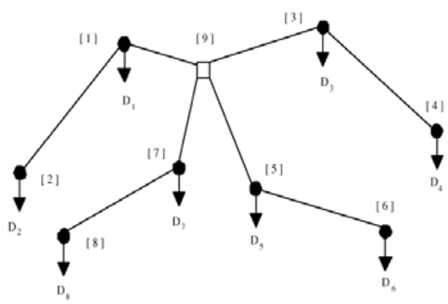

Fig.2 System under Study

Table 1. System loading

Bus	Base Year, MVA	Horizon year, MVA
1	5.98	7.64
2	6.83	8.72
3	5.98	7.64
4	3.13	4.00
5	4.78	6.11
6	4.02	5.14
7	3.59	4.58
8	5.69	7.27

Table 2. The feeder's characteristic

From	To	Resistance	Reactance	Length
9	1	1.390	2.255	8
9	3	2.085	3.383	12
9	5	2.259	3.664	13
9	7	1.738	2.819	10
1	2	2.780	4.510	16
3	4	2.780	4.510	16
5	6	2.433	3.946	14
7	8	2.085	3.383	12

The optimization model of the distribution expansion problem is used to meet the expected demand by choosing the optimum solution between expanding the existing substation or installing the DG's in the load buses. Expanding the existing substation, including installing new transformers units and upgrading the feeders if they exceed their thermal limits by replacing the existing feeder by another feeder with higher capacity. The cost of the importing power is calculated for the existing substation as well as the new expansion.

Table.3 Substation Expansion .vs. DG

	Considering Substation Expansion Only	Considering DG& Substation Expansion
Number of New Transformers	2	0
Expanding Substation Fixed Cost (M$)	0.4	0
Total Supplied Capacity (MVA)	54.1186	52.0847
substation purchased power (MVA)	54.1186	32.0847
Expanding Substation Variable Cost (M$)	89.769	53.221
Expanding Substation Total Cost (M$)	90.169	53.221
Number of DG	0	20
DG Fixed Cost (M$)	0	12.5
DG Variable Cost (M$)	0	23.696
DG Total Cost (M$)	0	36.196
Number of Feeders Upgrades	3	0
Feeders Fixed Cost (M$)	4.5	0
Total Losses (MVA)	3.0186	0.9847
Losses Cost (M$)	5.0071	1.6334
Total Planning Cost (M$)	99.676	91.050

Table 3 shows the obtained results. The first column represents the substation expansion option without installing any distributed generator. Two transformers are installed to meet the demand and three feeders are upgraded since their power flow is higher than their thermal capacity. On the other hand, the second column represents the optimal solution if the DG option is considered with the substation expansion. The DG option provides 8.7% less total planning cost. The optimal locations and size of the DG is shown in fig.3. Each DG unit has capacity of 1 MVA and the optimal locations and sizes of the DG are 4 units (4 MVA) at buses 1,2,4,6 and 8 with additional unit at each bus as a back-up.

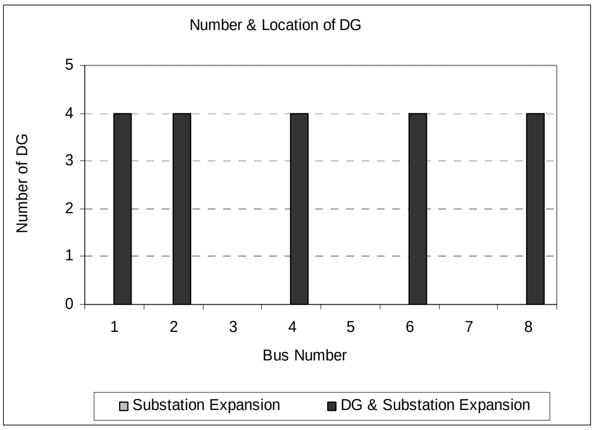

Fig.3 Number and Location of DG's

In the substation expansion there are three feeders upgraded since their power flow exceeds the thermal capacity. The existing feeders (12 MVA) are replaced with higher capacity feeders (20 MVA). In the DG option there is no feeders need to be upgraded because the present of the DG in the load side.

Fig.4 shows the bus voltage profile of the two options. It is clear that the voltage profile in DG case is better than the voltage profile in the substation expansion case. The lowest bus voltage in the substation expansion option is 0.928. On the other hand, the lowest bus voltage in the DG option is 0.962. This improvement is one of the main benefits of using the DG in the distribution system.

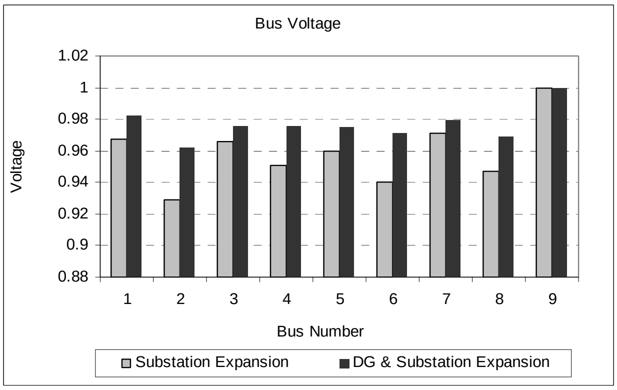

Fig.4 Bus Voltage

Fig.5 shows the percentage feeder's loadings. It is obvious that the feeders in the DG option are less loaded because the DG's can limit the feeder's power flow to their thermal capacity limit. This is another benefit of using the DG in the distribution system which is decrease the percentage loading in the feeders which result decreasing the system losses and increase the opportunity of using the same system feeders in the expansion planning without need for feeder upgrading.

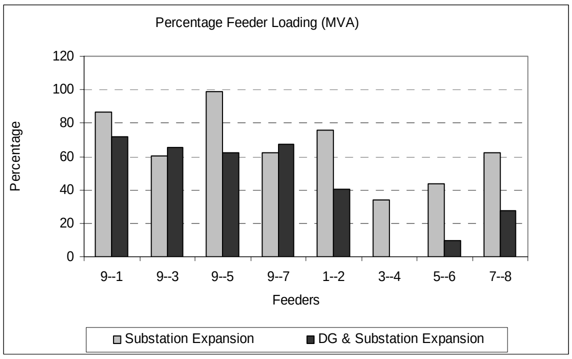

Fig.5 Percentage Feeder Loadings

The percentage of the load supplied from the substation and from the DG in the DG option is shown in the Fig. 6.

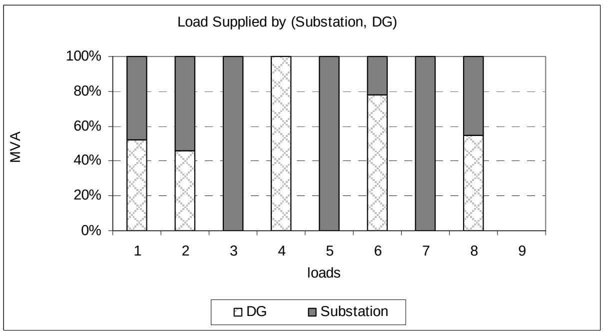

Fig.6 Load Supplied by Substation and DG for the DG option

5. Conclusion

In this paper a method based on binary particle swarm optimization is implementing to solve the distribution system expansion problem. The traditional options of the distribution planning are considered beside the distributed generator (DG) as a new attractive option. The aim of the model is to find the optimal planning cost of the expansion to meet the load growth. This cost includes the capital cost and the operational cost of the substation and the DG's. The cost also includes the cost of the power losses in the system and the cost of the feeders upgraded when their power flow exceeds their thermal capacity limit. The proposed model decides the locations and size of the new facilities in the system as well as the amount of the purchased power from the main grid through the main substation.
The results show that the DG's introduce economical and electrical benefits to the system. The planning cost of the DG option is better than the planning cost of the substation expansion by 8.7%. The voltage profile of the DG option is better than the voltage profile of the substation expansion. DG improves the percentage power loading of the feeders and keeps the power flow through the feeders reduced. As a result the losses in the system are reduced.

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