Electrical Power and Energy Systems 33 (2011) 1489–1497

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

DG integrated multistage distribution system expansion planning

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ARTICLE INFO

Article history:
Received 26 June 2010
Received in revised form 28 February 2011
Accepted 3 June 2011
Available online 2 July 2011

Keywords:
Distributed generation
Genetic algorithm
Multistage distribution expansion planning
Optimal power flow

ABSTRACT

In this paper, a framework is presented to solve the problem of multistage distribution system expansion planning in which installation and/or reinforcement of substations, feeders and distributed generation units are taken into consideration as possible solutions for system capacity expansion. The proposed formulation considers investment, operation, and outage costs of the system. The expansion methodology is based on pseudo-dynamic procedure. A combined genetic algorithm (GA) and optimal power flow (OPF) is developed as an optimization tool to solve the problem. The performance of the proposed approach is assessed and illustrated by numerical studies on a typical distribution system.

1. Introduction

Expansion planning of the power distribution systems is one of major activities of distribution utilities to deal with electric power demand growth. Distribution system expansion planning consists of defining facilities to be installed and/or reinforced so that the system serves the forecasted demand at the lowest cost while satisfying operational constraints. Additionally, the system must provide acceptable customer outage profile to ensure that customer reliability requirements are satisfied.

Distribution expansion planning is a highly complex problem, where solution often involves the use of sophisticated mathematical modeling and intensive numerical computation. This problem involves a large number of local optimal solutions and when system size become large, the number of solutions grows exponentially.

Traditionally, distribution expansion planning is solved in two ways:

- *Static approach*, which considers only one planning horizon and determines the location, type, and capacity of new equipment that should be expanded and/or added to the system. In other words, full expansion requirements are determined in one planning period [1–5].
- *Multistage approach*, that defines not only optimal location, type and capacity of investment, but also the most appropriate times to carry out such investments, so that the continuing growth of the demand is always assimilated by the system in an optimal way. Multistage approach refers to expansion of the system in successive plans over several stages, representing the natural course of progression in development [6–12].

The multistage approach, due to the interdependency between stages, is far more challenging to formulate and solve but the solution offers a more useful result. In this paper, we analyze the multistage distribution expansion planning (MSDEP) problem.

Today, power system economic and operation environment has changed as new capacity options are expanded. Distributed Generation (DG) is one of these new options. The introduction of DG in power system changes the operating features and has significant technical and economic advantages. Thus, optimal placement and sizing of DG sources attract active research interests and several works have been done in this area [13–15].

Due to the low investment risk and flexibility, DG can be implemented as a possible solution in distribution system expansion planning [16] to provide more diversity of expansion solutions for distribution utilities. Adding DG sources to the planning options is resulting in challenges in the distribution expansion planning process since the traditional planning approach is now no longer appropriate in this new era. Consequently, expansion planning modeling should now consider not only the substations and feeders but also DG sources in expansion planning alternatives. Therefore, new strategies and models for distribution system expansion planning need to be developed to accommodate this challenge.

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doi:10.1016/j.ijepes.2011.06.031

Nomenclature

Indices

e	failure events
i	substations
j	feeder sections
k	distributed generation sources
d	load points
t	load levels
nf	number of potential and existing feeder section
ng	number of candidate sites of DG installation
ns	number of candidate and existing substations

Variables

v	value of objective function (\$/year)
ic	investment cost of the system (\$/year)
oc	operation cost of the system (\$/year)
rc	reliability cost of the system (\$/year)
C_{RF}	capital recovery factor
EC_{i-t}^{SS}	electricity market price at the ith substation during load level t (\$/MW h)
IC^{DG}	investment cost of DG sources (\$/MVA)
IC_j^{FD}	investment cost of the jth feeder section (\$)
IC_i^{SS}	fixed cost of the ith substation (\$)
OC_k^{DG}	operation cost of the kth DG source (\$/MVA h)
P_{d-t}^{LD}	real power demand of the dth load point at load level t (MW)
P_{i-t}^{SS}	dispatched real power from the ith substation at load level t (MW)
P_{k-t}^{DG}	generated power by the kth DG at load level t (MW)
S_{k-cap}^{DG}	total capacity of the kth DG source (MVA)
S_{k-t}^{DG}	generated power of the kth DG source (MVA)
S_{RS}^{DG}	reserve DG capacity (MVA)
S_{j-cap}^{FD}	maximum capacity of the ith feeder section (MVA)
S_{j-t}^{FD}	transmitted power in the jth feeder section (MVA) at load level t
S_{i-cap}^{SS}	capacity of the ith substation (MVA)
S_{i-t}^{SS}	dispatched apparent power from the ith substation at load level t (MVA)
T_t	time duration of load level t (h)
$\lambda_{d,e}$	average failure rate affected load point d in case of each failure event e
$f_d(r_{d,e})$	the per unit cost of outage, based on the outage time $r_{d,e}$ at the load point d
$r_{d,e}$	average restoration time affected load point d in case of each failure event e
V_{max}, V_{min}	maximum and minimum allowed operation voltage (V)
$V_{d\text{-}t}$	calculated voltage magnitude at the dth load point during load level t (V)
f_t	fitness function
dr	discount rate
n	life of the project (year)

Sets

S	set of existing and new substations
F	set of existing and upgraded feeder sections
G	set of all selected DG sources
T	set of all load levels
D	set of all demand nodes
E	set of all failure events

Despite the great variety of methods for traditional distribution system planning, there are few studies available in the literature for the problem considering DG sources. The possibility to consider DG as a feasible alternative to traditional distribution system planning is discussed in [17]. In [18], the authors present a network capacity single stage expansion algorithm based on successive elimination capable of deferring network expansion by optimally siting DG sources at new or existing substations. In [19] a distribution system planning method considering DG for peak cutting is proposed which aims to minimize the sum of feeder investments, DG investments, energy loss cost and the additional cost of DG sources. Effects of DG on substations expansion and reliability costs are not considered in this work. In [20], the authors develop a model for static distribution system planning, considering DG sources. Reliability benefits of DG sources and effect of load variation in the system are not considered in this work. In [21], a multistage model for distribution system planning considering DG option is presented. However, impact of DG sources on reliability improvement and also varying nature of load are not considered in the planning model. In some other papers, importance of DG consideration in distribution system planning has been discussed [22–24].

In this paper, a new procedure for MSDEP is proposed in which the DG installation is considered as an option for system expansion planning in addition to upgrade and/or installation of substations and feeder sections. The developed model is based on minimization of overall cost in which reliability is included as customer outage cost (COC). Then, genetic algorithm (GA) combined with optimal power flow (OPF) is implemented to solve the optimization problem in which the optimal installation/upgrade of substations and feeder sections as well as DG installation requirements is determined. The pseudo-dynamic procedure [8] is used for multistage expansion methodology. Reliability and load variation over the year as well as optimal operation strategy of DG sources over the year is considered in the proposed model. This MSDEP model also determines the optimal size and location of the reserve feeder sections (feeder sections that are not usually operative except for power transfer between circuits during failures in the distribution system in a radial operation state).

The remainder of this paper is structured as follows: Section 2 presents mathematical formulation of the problem. Next, the hybrid GA–OPF methodology for the solution is provided in Section 3. General steps of the proposed multistage expansion planning algorithm are presented in Section 4. Section 5 presents the results obtained with the application of proposed method to a case study based on a typical distribution system. Finally, conclusions are given in Section 6.

2. Mathematical formulation

The objective of MSDEP is to supply the loads over the planning stages while the fixed costs corresponding to the investment in substations, feeder sections and DG sources as well as variable costs associated with operation and reliability of the system are minimized. The decision variables of the MSDEP are:

- Expansion capacity of existing substations.
- Location and capacity of new substations to be installed.
- Upgrade of existing feeder sections.

- Route and size of new feeder sections to be installed.
- Location, capacity, and generated power of DG sources to be installed.
- Construction time of each facility over the planning stages.

In the proposed MSDEP framework, all above decision variables are determined using mathematical optimization except the last one (construction time of equipment) which is determined using pseudo-dynamic approach [8]. In this approach, first a single stage (Static) optimization is formulated and then the optimum expansion profile is generated using a series of concatenated single stage employment of optimization algorithm. In the following subsections, the optimization formulation of the single stage planning is outlined.

2.1. Optimization problem

Mathematical formulation of the objective function is given in the following:

$$\text{Min} \quad v = ic + oc + rc \tag{1}$$

$$ic = C_{\mathrm{RF}}\left(\sum_{i\in\mathbf{S}} IC_i^{\mathrm{SS}} + \sum_{j\in\mathbf{F}} IC_j^{\mathrm{FD}} + \sum_{k\in\mathbf{G}} IC^{\mathrm{DG}}\left(S_{k-\mathrm{cap}}^{\mathrm{DG}} + S_{\mathrm{RS}}^{\mathrm{DG}}\right)\right) \tag{2}$$

$$oc = \sum_{t\in\mathrm{T}} T_t\left(\sum_{k\in\mathbf{G}} OC_k^{\mathrm{DG}} \times P_{k-t}^{\mathrm{DG}} + \sum_{i\in\mathbf{S}} EC_{i-t}^{\mathrm{SS}} \times P_{i-t}^{\mathrm{SS}}\right) \tag{3}$$

$$rc = \sum_{t\in\mathbf{T}} \frac{T_t}{8760} \sum_{d\in\mathbf{D}} \sum_{e\in\mathbf{E}} P_{d-t}^{\mathrm{LD}} \times f_d(r_{d,e}) \times \lambda_{d,e} \tag{5}$$

The problem has the following constraints:

– Capacities of the substations

$$0 \leqslant S_{i-t}^{\mathrm{SS}} \leqslant S_{i-\mathrm{cap}}^{\mathrm{SS}}, \quad \forall\, i \in \mathbf{S}, \quad \forall\, t \in \mathrm{T} \tag{6}$$

– Capacities of the feeder sections

$$S_{j-t}^{\mathrm{FD}} \leqslant S_{j-\mathrm{cap}}^{\mathrm{FD}}, \quad \forall\, j \in \mathbf{F}, \quad \forall\, t \in \mathbf{T} \tag{7}$$

– Capacities of the DG sources

$$S_{k-t}^{\mathrm{DG}} \leqslant S_{k-\mathrm{cap}}^{\mathrm{DG}}, \quad \forall\, k \in \mathbf{G}, \quad \forall\, t \in \mathbf{T} \tag{8}$$

– Voltage magnitude limit

$$V_{\min} \leqslant V_{d-t} \leqslant V_{\max}, \quad \forall\, d \in \mathbf{D}, \quad \forall\, t \in \mathbf{T} \tag{9}$$

– Radial network restriction

The value of the objective function (1) shows annualized cost of the project in \$/year. The first term in this objective function represents the total annual investment cost of new facilities to be installed and expansion cost of existing ones to be expanded. It must be noted that investment cost related to the existing equipment is set to zero. The maintenance cost of equipment during a useful lifetime is considered as a part of the fixed costs and added to the investment costs. The DG investment cost is the sum of each DG unit connected at a node in addition to the cost of a reserve unit at the same node [20]. In (2), C_{RF} is capital recovery factor which used to convert present amount of total investment cost into an annuity over the life of the project and defined as below [25]

$$\mathrm{C}_{\mathrm{RF}} = \frac{dr(1+dr)^n}{(1+dr)^n - 1} \tag{10}$$

where dr is discount rate and n is the life of the project in year.

The second term in the objective function (1) represents the annual operation cost of the system which depends on the amount of power to be purchased from the main market and/or generated by DG sources over the year. It should be noted that in order to have a more realistic estimate of the operation cost of the system in the presence of DG sources, we need to evaluate optimal operation strategy of DG sources considering varying demand levels. To limit the computational burden, the step-wise yearly load duration curve has been considered.

The third term in the objective function (1) represents the annual reliability cost which is defined as COC. The method of COC evaluation is described in the next subsection.

2.2. COC evaluation

Presence of DG sources in a distribution system can improve system reliability. When a circuit outage occurs, the DG can be used to support the alternate feeds through reserve feeders and hence improve the capability to supply the interrupted load points. Also, if the DG has sufficient capacity/capability, it can be operated in island mode to supply proportion of the system load. In these cases, there may be a short outage to the customers outside the faulted zone due to switching actions and disconnecting/re-energizing of DG sources. In this paper, impact of DG on system reliability is considered and simulated.

The total annual COC of the system is the sum of customer outage costs for all load levels over the year. The basic procedure used to evaluate the COC can be summarized in the following steps:

Step 1. Select a load level t from the given load levels in year.

Step 2. Find the average failure rate, $\lambda_{d,e}$, and the restoration time $r_{d,e}$ for affected load point d in case of each failure event e according to the network configuration and load transfer capability of alternate supplies (reserve feeders and/or DG sources).

Step 3. Evaluate the expected outage cost of the load point d caused by failure event e at load level t. (i.e., $P_{d-t}^{\mathrm{LD}} \times f_d(r_{d,e}) \times \lambda_{d,e}$, where, $f_d(r_{d,e})$ is the per unit (kW) cost of outage, based on the outage time $r_{d,e}$ at load point d).

Step 4. Repeat step 3 for all failure events in order to calculate the total outage cost for load point d (i.e., $\sum_{e\in\mathbf{E}} P_{d-t}^{\mathrm{LD}} \times f_d(r_{d,e}) \times \lambda_{d,e}$).

Step 5. Repeat steps 2–4 for all load points in the system. The total COC of the system, at the load level t is obtained as $\sum_{d\in\mathbf{D}}\sum_{e\in\mathbf{E}} P_{d-t}^{\mathrm{LD}} \times f_d(r_{d,e}) \times \lambda_{d,e}$.

Step 6. Repeat steps 1–5 for different load levels in year and obtain the total COC as $\sum_{t\in\mathbf{T}} \frac{T_t}{8760} \sum_{d\in\mathbf{D}}\sum_{e\in\mathbf{E}} P_{d-t}^{\mathrm{LD}} \times f_d(r_{d,e}) \times \lambda_{d,e}$.

3. Hybrid GA–OPF for optimization

The proposed planning objective and its related constraints formulate a mixed-integer nonlinear optimization problem. A heuristic optimization technique, based on genetic algorithm (GA) [26] and optimal power flow (OPF) has been applied to optimize the proposed planning model. In this approach discrete decision variables include substations locations and sizes, feeder sections structures and sizes, and DG locations and capacities are generated and searched by the GA. For each combination of above decision variables, the OPF is used to optimize the operating cost and determine the amount of power to be generated by the DG sources and imported from transmission grid.

Flow-chart of the proposed optimization approach is shown in Fig. 1. The main steps of the proposed hybrid GA–OPF approach for optimizing the planning model are detailed as follows.

3.1. Chromosome codification

The first issue that should be defined is the type of codification to be used, so that a chromosome represents candidate solution of the problem. In the proposed method each chromosome contains information about discrete decision variables and has three parts as shown in Fig. 2.

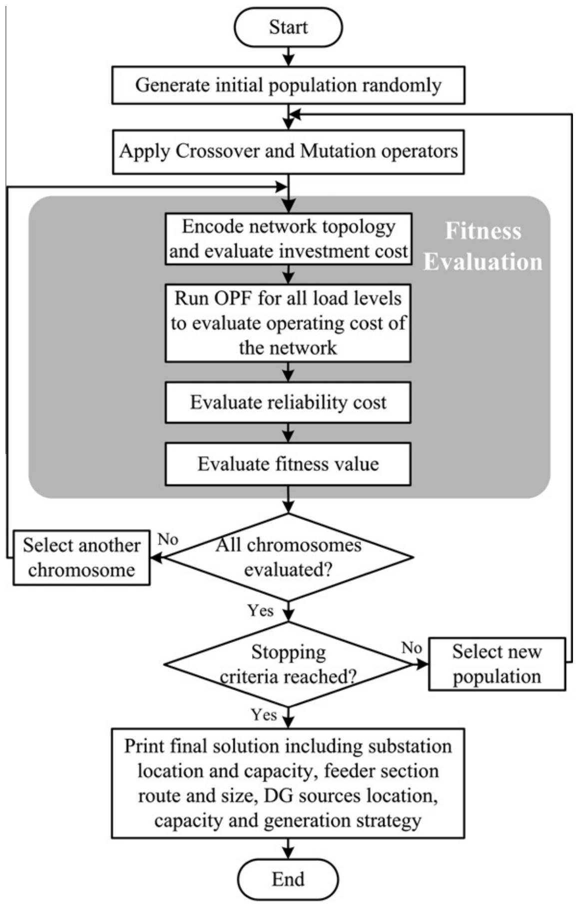

Fig. 1. Flow chart of hybrid GA–OPF optimization approach.

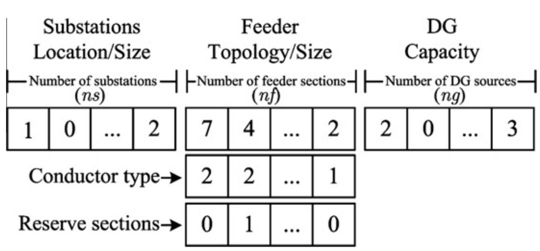

Fig. 2. Individual representing a distribution system configuration.

The first part containing decision information about substation sizing and siting, has *ns* genes where *ns* represents number of candidate and existing substations. In each gene, a 0 indicates that the corresponding substation has not been installed and an integer number shows the size number of the respective substation.

The second part which represents the network topology and feeder routes, has three strings each of them has *nf* genes where *nf* represents number of potential and existing feeder sections. The first string represents structure of the feeders based on integer permutation encoding. This string is composed of *nf* integers with values from 1 to *nf*, to represent *nf* different feeder sections. The sequence of these integers represents a structure of the network as follows. Initially no feeder section is assumed to be built. Starting with the first integer in the string the corresponding feeder section is built. The process is repeated for each next integer until the end of the string is reached. If building a feeder section would violate the radial constraint such as creating loops or connecting substations, then that feeder section installation is abandoned and the next integer in the chromosome is considered. This feeder section insertion scheme guarantees that the final network configuration will be radial.

The second string in the second part indicates conductor type in which each gene has an integer number showing conductor size number of the respective feeder section in the first string.

The third string in the second part indicates reserve feeder sections. The abandoned feeder section in the first string can be chosen as reserve feeder section. So, for abandoned feeder sections if the corresponded gene in the third string is 0, it means that the respective abandoned feeder section has not been installed as reserve section. Similarly 1 means that abandoned feeder section has been installed as reserve section. It is evident that if a feeder section is inserted in the network topology as in operation one, then that feeder section cannot be a reserve section and hence the corresponding gene value in the third string is forced to be zero.

The third part of the chromosome representing the DG sources' capacity at candidate locations has *ng* genes where *ng* represents number of candidate sites for DG installation. In this part, each gene has 0 (indicating that DG source has not been installed in the corresponding site) or an integer number showing size number of the selected in operation DG source at respective location. (A decoding example based on proposed chromosome structure is given in Appendix A.)

3.2. Crossover and mutation

In each iteration, the GA uses the current population to create the children that make up the next generation using crossover and mutation operators. Through the crossover mechanism, the two chromosomes which are selected randomly from the current population are combined to produce two or more new chromosomes. The crossover operator is applied for different strings/parts of chromosomes, separately.

For the first string in the second part of chromosomes, which shows network configuration, the Order Crossover operator [27] is adopted. In this operator, two randomly selected chromosomes would produce two new chromosomes by choosing a subsequence from one chromosome and preserving the relative sequence order from the other one. This mechanism guarantees that there is no repeated integer in the produced strings (see Appendix B). Other parts/strings of the new chromosomes are the same as the old ones. For other strings/parts in the chromosomes, the crossover operator is performed in a replacement manner.

In the mutation mechanism, for each gene, a uniform random number is generated in the interval [0, 1]. If this number is lower than the mutation rate, the respective value of the current gene is swapped for another random value within a specific interval. For the first string in the second part of chromosomes, two randomly selected genes are displaced and produce a new chromosome.

3.3. Fitness evaluation

Fitness evaluation of each chromosome consists of following steps:

Step 1. Determine network topology and DG sources according to chromosome information and calculate the investment cost *ic* accordingly.

Step 2. Run OPF for each load level t using defined network topology and selected DG sources. In the OPF formulation, substations are modeled as PV generation units with generation cost equal to market price at different load levels. The DG sources are assumed to be modeled in constant power factor control mode [28]. The optimization model of OPF consists of constraints (6)–(9) with the following objective function:

$$f_t = \sum_{k \in \mathbf{G}} OC_k^{DG} \times P_{k-t}^{DG} + \sum_{i \in \mathbf{S}} EC_{i-t}^{SS} \times P_{i-t}^{SS} \quad \forall\, t \in \mathbf{T}. \tag{11}$$

If no feasible solution is found by OPF, a large number is assigned as penalty factor to f_t. To speed up the convergence properties of algorithm and at the same time, to use the information that may still be useful in rejected chromosomes, this penalty factor is linearly increased through iterations.

After solving the OPF problem for all load levels, the total operation cost *oc* of the chromosome can be calculated.

$$oc = \sum_{t \in \mathbf{T}} T_t \times f_t \tag{12}$$

Step 3. Evaluate reliability cost *rc* of the system as described in Section 2.2.
Step 4. Calculate fitness function as the inverse of the total cost (1).

3.4. Reproduction

The elitist strategy is employed to select a portion of the chromosomes with the best fitness values. The roulette wheel approach [26] is used for selecting the rest of the chromosomes to make sure that the number of a new generation is the same as that of the initial population.

After some predetermined iterations, the best solution for distribution system planning is determined.

4. Multistage expansion planning procedure

The proposed MSDEP methodology is based on a pseudo-dynamic procedure, and is divided into two phases. In the first phase, static model is used to achieve a solution that can meet the demand requirements of the final year of the study in an optimal manner. The horizon year static optimal design describes all the equipment that will be constructed during the period of the planning study. In the second phase, the effect of load growth is explicitly considered and successive concatenated single stage expansions of the distribution system are found. For each intermediate time stage between the base and the horizon year, it is necessary to determine an optimal intermediate system. The intermediate system utilizes only the set of equipment that has been specified from the horizon year static optimum system. After advancing through each of the intermediate time stages, each facility from phase one results will have a date describing its construction time. At the end of phase two, the complete solution is provided. The entire period of study is viewed as a continuous progression where the collection of the optimal system design for each intermediate time constitutes a series of system expansions that spans the base year to the horizon year [12].

The proposed MSDEP algorithm steps can be summarized as follows:

Step 1. Specify the planning study period and split it into time stages, for example in 2 year-long stages.
Step 2. Solve the optimization planning problem using hybrid GA–OPF approach with all existing and candidate equipment. The result is equipment that satisfies the horizon year load requirements.
Step 3. Select first intermediate time stage and specify the load growth for each load point.
Step 4. Solve the optimization problem using hybrid GA–OPF approach with the selected equipment in step 2. The result is the optimal system configuration for the current time stage.

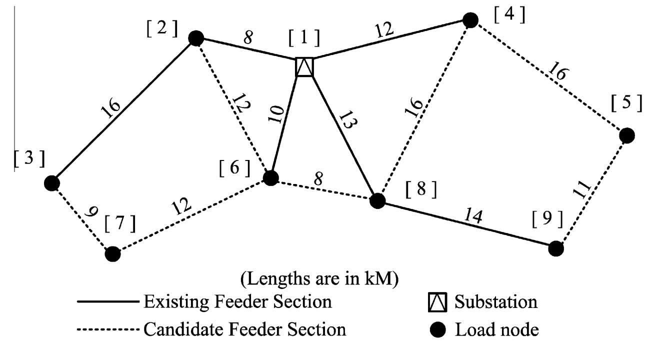

Fig. 3. Test distribution system.

Table 1
Annual peak demand of load points.

Load point	Load type	Peak demand (MVA)			
		Stage 1	Stage 2	Stage 3	Stage 4
2	Residential	5.3973	6.1860	6.6508	7.6400
3	Residential	4.4758	5.4800	6.7901	8.7200
4	Residential	5.3973	6.1860	6.6508	7.6400
5	Residential	–	–	3.4821	4.0000
6	Commercial	3.4891	3.7084	3.9870	4.5800
7	Commercial	–	4.4306	5.7455	7.2700
8	Industrial	4.6546	4.9472	5.3190	6.1100
9	Residential	3.6859	4.1618	4.4745	5.1400

Table 2
Sector customer damage functions used in the study.

User sector	Interruption duration				
	1 min	20 min	60 min	240 min	480 min
Industrial	1.625	3.868	9.085	25.16	55.81
Commercial	0.381	2.969	8.552	31.32	83.01
Residential	0.001	0.093	0.482	4.914	15.69

Table 3
Loading and market price data used in the study.

Load level	Percentage of peak load (%)	Time duration (h)	Market price ($/MW h)
1 (high)	100	1500	70
2 (normal)	70	5000	49
3 (low)	50	2260	35

Table 4
Technical and economical characteristics of conductors used in the study.

Type	R (Ω/km)	X (Ω/km)	Capacity (MVA)	Failure rate (failure/kM year)	Repair time (h)	Cost[a] (M$/km)
1	0.1738	0.2819	12	0.096039	10.15	0.1
2	0.0695	0.2349	18	0.096039	10.15	0.15

[a] Cost of upgrade from type 1 to type 2 is 0.8 M$/km.

All selected equipment from this step is considered as existing components for the next step.

Step 5. If all intermediate time stages have been studied, stop. If not, then, select the next intermediate time stage, specify the load growth for each load point at that time stage and go to step 4.

5. Numerical example

The proposed multistage expansion planning methodology including DG, was applied to a 33-kV distribution system [20,29]. The system initially has one 40-MVA substation which can be upgraded to 80-MVA, six upgradable existing feeder sections, and seven routes for installing new feeder sections. This primary distribution system is shown in Fig. 3 where solid lines represent existing feeder sections in the initial radial system, and dotted lines represent possible routes for the expansion of the network. Table 1 gives the load points type and annual peak power demand requirements over the four stages of planning horizon. The customer sector interruption cost functions for different customer sectors used in the study are given in Table 2 [30].

Table 3 shows loading levels and market price data used in the case studies. In this table different loading levels of the system over the year are modeled as percentage of the peak load. Although it is assumed that all load points follow the same loading levels, this assumption is not mandatory for the proposed methodology. Different loading levels per load point over the year could also be used without the need of any modifications in the proposed model.

Technical and economical characteristics of the conductor types used in the expansion planning are given in Table 4. Other technical and cost parameters of the system are summarized in Table 5.

All load nodes are considered as candidate sites for DG installation. The candidate DG sources have sizes multiples of 1 MVA and maximum 4 MVA in operation plus 1 MVA reserve DG can be installed in each candidate site.

The method was implemented in MATLAB using some features of the primal–dual interior point based OPF solver in the MATPOWER suite [32]. In order to show application of the proposed MSDEP method and at the same time investigate impact of DG consideration in the system expansion planning, following two cases are studied:

Case 1: the MSDEP method is run without including DG investment options. This case shows traditional system expansion planning.

Case 2: the MSDEP method is run including DG investment options. Other input data in these cases are fixed and similar.

Figs. 4 and 5 graphically presents the final expansion plans for the two cases studied, where dark lines represent the feeder sections in operation, and dashed lines represent the reserve feeder sections. As can be seen, network configurations obtained in these two cases are different. Also, the need for substation upgrading is eliminated when DG is included in the planning options. This benefit is more attractive when expanding the existing substations is not possible due to geographical or other practical limitations.

Fig. 6 shows the expansion cost (value of objective function) over the planning stages for the two cases studied. The expansion cost, as shown in this figure, in case with DG is lower than that without DG in all planning stages. It is obvious that implementing DG as an alternative option in distribution expansion planning can provide plans with lower total cost. It is important to note that impact of DG integrating on the total planning cost improvement depends on characteristics of the distribution system under study. However, the proposed approach can be used by the planners to determine optimal integration of DG sources in the multistage distribution systems expansion.

Table 5
Technical/cost parameters.

Parameter	Value
Life time of the project (year)	30
Discount rate (%)	12.5
Maintenance cost during life time for all equipments	3% Of investment cost
Load power factor	0.85
DG operation power factor	0.9
Allowed voltage deviation (%)	5
Upgrading cost of the substation (M$)	0.8
DG investment cost (M$/MVA)	0.318
DG operation cost ($/MVA h)	50
Average time for switching actions and reconnecting DG time (h)	0.5

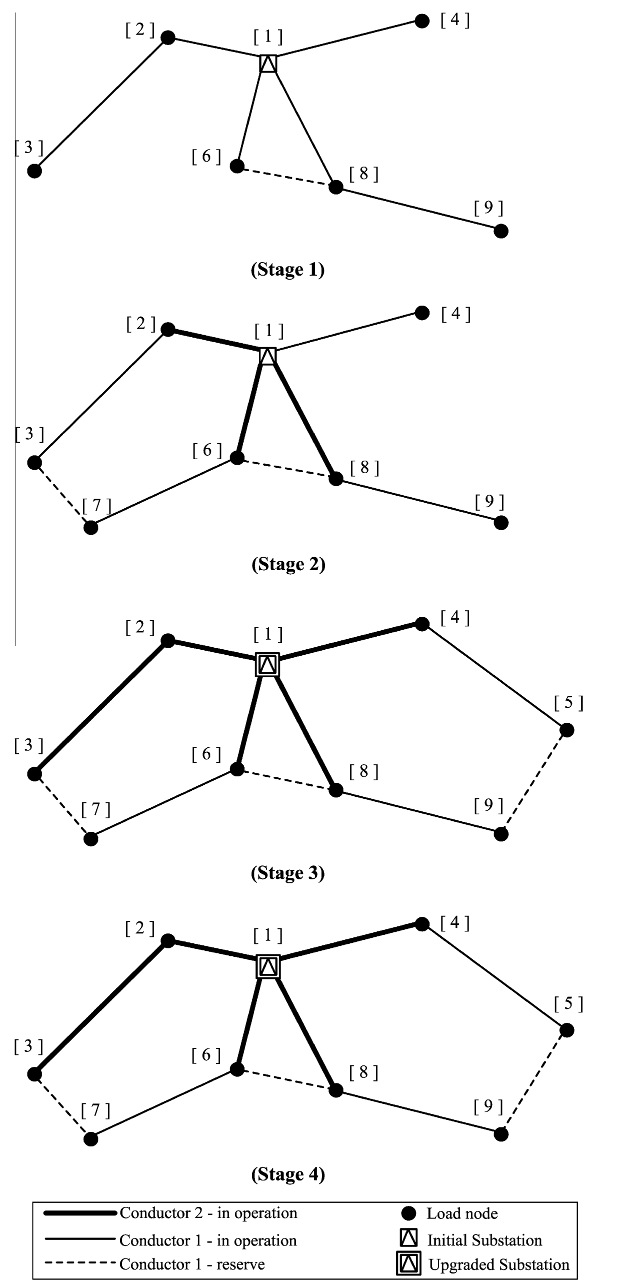

Fig. 4. Final expansion plans for case 1.

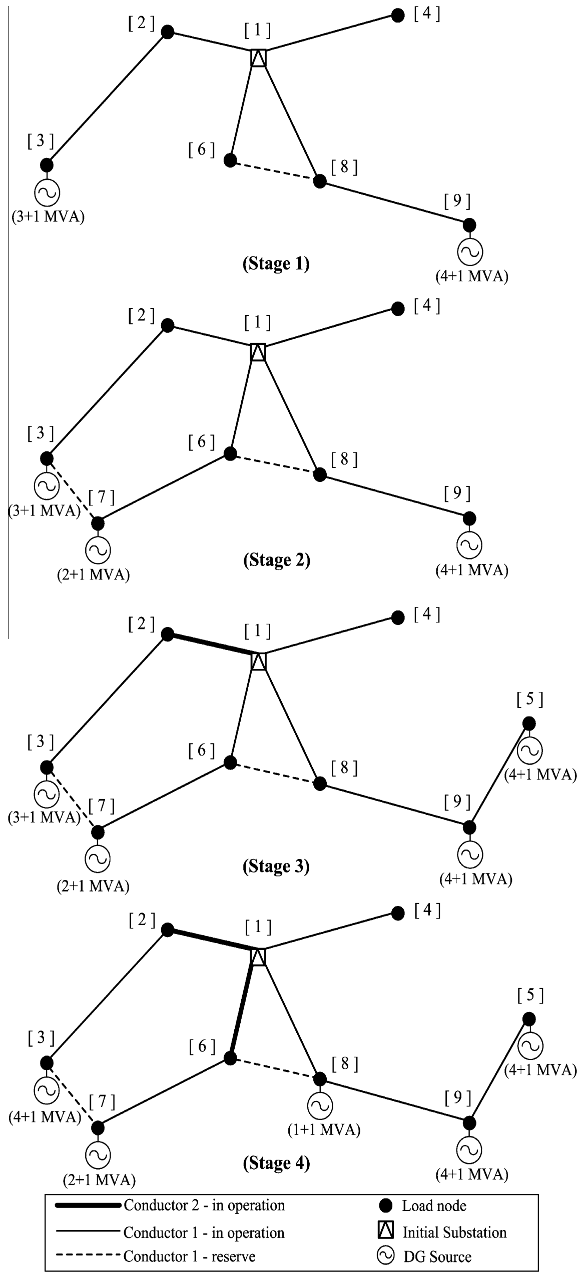

Fig. 5. Final expansion plans for case 2.

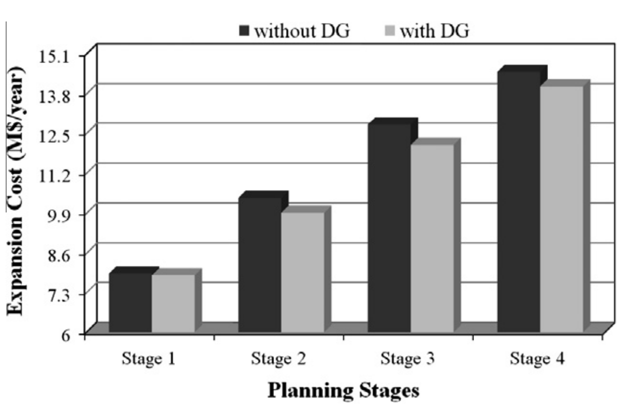

Fig. 6. Total expansion cost for two cases studied.

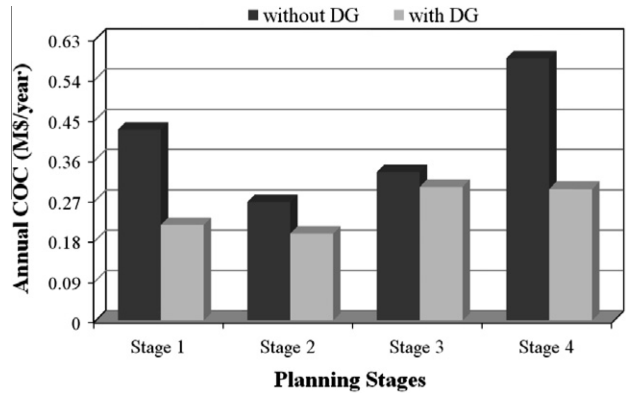

Fig. 7. Annual COC for two cases studied.

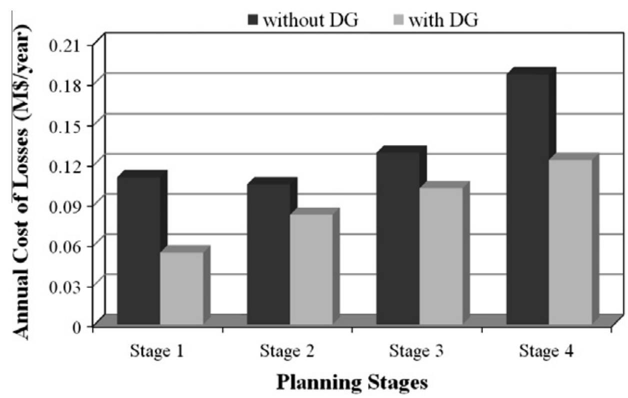

Fig. 8. Annual cost of energy losses for two cases studied.

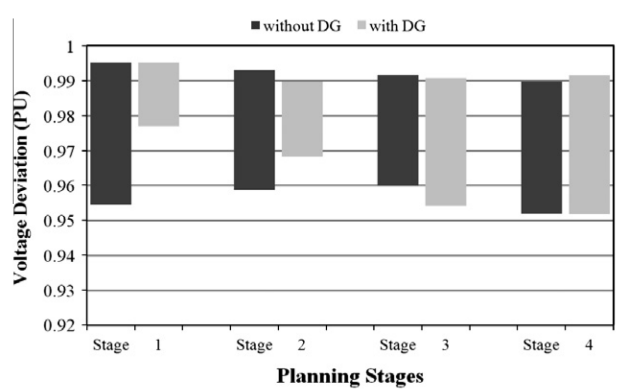

Fig. 9. Variation range of voltage at load points.

Fig. 7 shows the COC values over the planning stages for the two cases studied. By comparison of COC values in these two cases, it is clear that introducing DG to the multistage distribution expansion planning reduces the COC during the planning stages and provides more opportunities for reliability improvement rather than the traditional planning options and helps the distribution utility keep its customers satisfied.

Annual cost of energy losses in the two above cases over the planning stages are compared in Fig. 8. The figure shows a reduction in the annual cost of losses in all planning stages when DG is integrated in expansion planning model.

Table 6
Detailed cost items obtained in case studies.

Cost item	Without DG				With DG			
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
Feeder investment cost (M$)	0.8	4.425	4.8	0	0.8	2.1	1.7	0.75
Substation investment cost (M$)	0	0	0.8	0	0	0	0	0
DG investment cost (M$)	–	–	–	–	2.862	0.954	1.590	0.954
Total investment cost (M$)	0.8	4.425	5.6	0	3.662	3.054	3.290	1.704
Annual DG operation cost (M$/year)	–	–	–	–	1.408	2.233	3.115	3.832
Annual cost of purchased power (M$/year)	7.390	9.534	11.707	13.914	5.755	7.068	8.259	9.677
Total annual operation cost (M$/year)	7.390	9.534	11.707	13.914	7.163	9.301	11.374	13.509

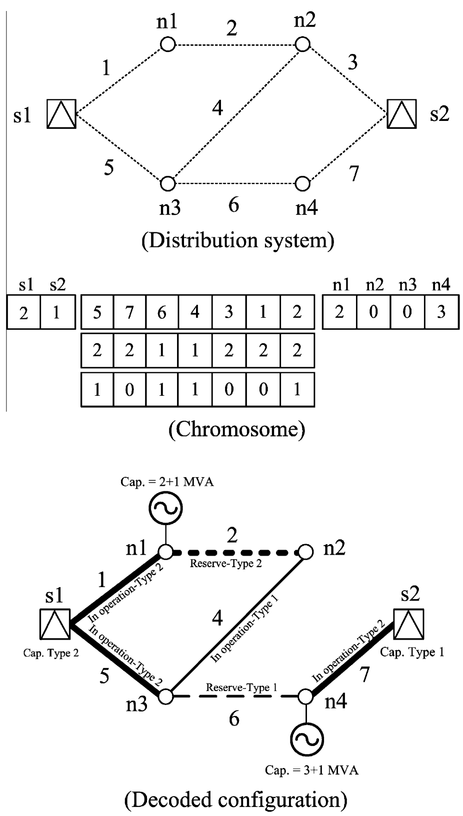

Fig. A.1. Decoding example.

Fig. 9 compares variation range of voltage at load points over the planning time stages for the two cases studied. It is clear that the presence of DG in MSDEP provides better voltage profile in most of planning time stages. Other obtained numerical results of these cases are listed in Table 6.

6. Conclusion

A model for multistage distribution system expansion planning in the presence of DG, based on a pseudo-dynamic methodology, is proposed in this paper. The model takes into account the reliability improvement, load variation and operating strategy of DG sources. The proposed model properly handles voltage, equipment capacity and radial configuration constraints. A hybrid GA/OPF approach is employed as the solution tool to optimize the related objective function.

The capability and the performance of the proposed model have been demonstrated using case studies done on a typical distribution system. Comparison with the traditional system expansion has also been made, which shows that the integrating of DG sources in expansion planning of power distribution system can results an expansion plan that has a lower cost and a higher reliability level. In this work, the MSDEP problem was formulated from the distribution utilities point of view and assuming they owned all the DG sources. Customer owned or non-utility DG sources would affect the problems differently. The authors are investigating approaches so that the non-utility DG sources can be modeled in multistage distribution system planning.

Appendix A

A.1. A decoding example

As shown in Fig. A.1, a chromosome is used to illustrate the decoding procedure in this Appendix. The distribution system related to the chromosome has seven potential feeder sections numbered from 1 to 7. The decoding steps can be summarized as follows:

Step 1. Substations s1 and s2 have capacity indexes c2 and c4, respectively.
Step 2. The sequence of feeder sections is (5 7 6 4 3 1 2): starting with the first integer the corresponding feeder section is built. In this process feeder sections 6 and 3 are abandoned because building these feeder sections will connect the two substations. Feeder section 2 is also abandoned because it creates a loop.
Step 3. Abandoned feeder sections (6, 3 and 2) can be built as reserve feeder sections according to their related gen values in the third string of the second part of the chromosome. Corresponding values for feeder sections 6 and 2 are 1. So, they are selected as reserve feeder section in the system structure.
Step 4. Conductor size of each feeder section is determined based on corresponding conductor indexes in the second string of the second part of the chromosome.
Step 5. According to the gene values in the third part of the chromosome two nodes (n1 and n4) are selected for DG installation, as it shown in Fig. A.1.

Appendix B

B.1. Crossover operator

This Appendix provides the crossover operator for the first string in the second part of the chromosome [31]. This operator is based on Order Crossover, which builds two new chromosomes by choosing a sub-sequence from one parent and preserving the relative sequence order from the other parent [26]. For example, two parents (with two random cut points marked by '|') P_1 = (1 2 3|4 5 6 7|8 9) and P_2 = (4 5 2|1 8 7 6|9 3) would produce two children in the following way. First, the segments between cut points are copied into the offspring: C_1 = (xxx|4 5 6 7|xx) and C_2 = (xxx|1 8 7 6|xx). Next, starting from the second cut point of one parent, the genes from the other parent are copied in the same order, omitting symbols already present. On reaching the end of the string, this is continued from the first place in the string. The sequence of the feeder sections in the second parent from the second cut point is: 9–3–4–5–2–1–8–7–6. After removal of feeder sections 4–7, which are already in the first offspring, we get 9–3–2–1–8. This sequence is placed in the first offspring (starting from the second cut point): $O_1 = (2\ 1\ 8|4\ 5\ 6\ 7|9\ 3)$. Similarly we obtain another offspring: $O_2 = (3\ 4\ 5|1\ 8\ 7\ 6|9\ 2)$.

References

[1] Ponnavaikko M, Prakasa Rao KS. An approach to optimal distribution system planning through conductor gradation. IEEE Trans Power Appl Syst 1982;101(6):1735–42.
[2] Fawzi TH, Ali KF, El-Sobki SM. A new planning model for distribution systems. IEEE Trans Power Appl Syst 1983;102(9):3010–7.
[3] Aoki K, Nara K, Satoh T, Kitagawa M, Yamanaka K. New approximate optimization method for distribution system planning. IEEE Trans Power Syst 1990;5(1):113–26.
[4] Boulaxis NG, Papadopoulos MP. Optimal feeder routing in distribution system planning using dynamic programming technique and GIS facilities. IEEE Trans Power Deliv 2002;17(1):242–7.
[5] Zhao H, Wang Z, Yu DC, Chen X. New formulations and hybrid algorithms for distribution system planning. Electr Power Compon Syst 2007;35(4):445–60.
[6] Sun DI, Farris DR, Cote PJ, Shoults RR, Chen MS. Optimal distribution substation and primary feeder planning via the fixed charge network formulation. IEEE Trans Power Appl Syst 1982;101(3):602–9.
[7] Mikic OM. Mathematical dynamic model for long-term distribution system planning. IEEE Trans Power Syst 1986;1(1):34–40.
[8] Ramirez IJ, Gonen T. Pseudo-dynamic planning for expansion of power distribution systems. IEEE Trans Power Syst 1991;6(1):245–54.
[9] Miranda V, Ranito JV, Proenca LM. Genetic algorithms in optimal multistage distribution network planning. IEEE Trans Power Syst 1994;9(4):1927–33.
[10] Vaziri M, Tomsovic K, Bose A. A directed graph formulation of the multistage distribution expansion problem. IEEE Trans Power Deliv 2004;19(3):1335–41.
[11] Kuwabara H, Nara K. Multi-year and multi-state distribution systems expansion planning by multi-stage branch exchange. IEEE Trans Power Deliv 1997;12(1):457–63.
[12] Temraz HK, Salama MMA. A planning model for siting, sizing and timing of distribution substations and defining the associated service area. Electr Power Syst Res 2002;62(2):17–29.
[13] Barin A, Pozzatti LF, Canha LN, Machado RQ, Abaide AR, Arend G. Multi-objective analysis of impacts of distributed generation placement on the operational characteristics of networks for distribution system planning. Int J Electr Power Energy Syst 2010;32(10):1157–64.
[14] Khalesi N, Rezaei N, Haghifam MR. DG allocation with application of dynamic programming for loss reduction and reliability improvement. Int J Electr Power Energy Syst 2011;33(2):288–95.
[15] Khan H, Choudhry MA. Implementation of distributed generation (IDG) algorithm for performance enhancement of distribution feeder under extreme load growth. Int J Electr Power Energy Syst 2010;32(9):985–97.
[16] Dugan RC, McDermott TE, Ball GJ. Distribution planning for distributed generation. In: Proc rural electric power conference; 2000. p. C4/1–C4/7.
[17] Dugan RC, McDermott TE, Ball GJ. Planning for distributed generation. IEEE Ind Appl Mag 2001;7(2):80–8.
[18] Brown RE, Pan J, Feng X, Koutlev K. Siting distributed generation to defer T&D expansion. In: Proc IEEE/PES transmission and distribution conference and exposition, vol. 2; 2001. p. 622–27.
[19] Ouyang W, Cheng H, Zhang X, Yao L. Distribution network planning method considering distributed generation for peak cutting. Energy Convers Manage 2010;51(12):2394–401.
[20] El-Khattam W, Hegazy YG, Salama MMA. An integrated distributed generation optimization model for distribution system planning. IEEE Trans Power Syst 2005;20(2):1158–65.
[21] Haffner S, Pereira LFA, Pereira LA, Barreto LS. Multistage model for distribution expansion planning with distributed generation—Part II: Numerical results. IEEE Trans Power Deliv 2008;23(2):915–23.
[22] Ault GW, McDonald JR. Planning for distributed generation within distribution networks in restructured electricity markets. IEEE Power Eng Rev 2000;20(2):52–4.
[23] Espie P, Ault GW, Burt GM, McDonald JR. Multiple criteria decision making techniques applied to electricity distribution system planning. IEE Proc Gener Transm Distribut 2003;150(5):527–35.
[24] The distribution working group of the IEEE power system planning and implementation committee, planning for effective distribution. IEEE Power Energy Mag 2003; 1(5): 54–62.
[25] Stoll HG. Least-cost electric utility planning. New York: Wiley; 1989.
[26] Gen M, Cheng R. Genetic algorithms and engineering design. New York: Wiley; 1997.
[27] Michale Wicz Z. Genetic algorithm + data structure = evolution program. New York: Springer-Verlag; 1996.
[28] Harrison GP, Piccolo A, Siano P, Wallace AR. Hybrid GA and OPF evaluation of network capacity for distributed generation connections. Electr Power Syst Res 2008;78(3):392–8.
[29] Quintana VH, Temraz HK, Hipel KW. Two-stage power system distribution planning algorithm. IEE Proc 1993;140(1):17–29.
[30] Billinton R, Wang P. Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques. IEEE Trans Power Syst 1998;13(4):1245–50.
[31] Irving MR, Luan WP, Daniel JS. Supply restoration in distribution networks using a genetic algorithm. Int J Electr Power Energy Syst 2002;24(6):447–57.
[32] Zimmerman RD, Murillo-Sánchez CE, Thomas RJ. MATPOWER steady-state operations, planning and analysis tools for power systems research and education. IEEE Trans Power Syst 2011;26(1):12–9.